SUSY Searches at ATLAS

The Author’s Preferred Selection

Antonella De Santo
University of Sussex
Birmingham, 31 October 2012
Outline

Introduction

>> Supersymmetry and all that

The LHC and ATLAS

>> Status

SUSY searches at ATLAS

>> The author’s preferred selection

Conclusions
The (Very Resilient) Standard Model

Matter (Fermions)
3 quark generations
3 lepton generations

Forces (Bosons)
EWK – $\gamma$, Z, $W^\pm$
Strong – gluons

Mass
Higgs boson

And Antimatter Too…
The (Very Resilient) Standard Model

**Matter (Fermions)**
- 3 quark generations
- 3 lepton generations

**Forces (Bosons)**
- EWK – $\gamma$, $Z$, $W^\pm$
- Strong – gluons

**Mass**
- Higgs boson

*Pre-4Jul2012*

* *= yet to be discovered

A De Santo, SUSY at ATLAS

And Antimatter Too...
The (Very Resilient) Standard Model

**Matter (Fermions)**
- 3 quark generations
- 3 lepton generations

**Forces (Bosons)**
- EWK – $\gamma$, $Z$, $W^\pm$
- Strong – gluons

**Mass**
- Higgs boson

And Antimatter Too…
Some Outstanding Issues

**Hierarchy problem**

In absence of protective symmetries, Higgs mass can acquire radiative corrections from fermionic loops

$$\delta m_H^2 \propto \Lambda_{\text{cutoff}}^2$$

If no new physics before Planck scale, need fine-tuning to keep Higgs mass relatively small

Weak Scale  The Desert ??  Planck scale

(Non-)Unification of forces

A De Santo, SUSY at ATLAS
Supersymmetry (SUSY)

New symmetry between bosons and fermions

Every SM particle has a supersymmetric partner with $\Delta(\text{spin})=1/2$

Extended Higgs sector: $h, H, A, H^\pm$

**Natural solution to hierarchy problem**

Exact cancellation of loop contributions

**Gauge unification**

Possible in SUSY theories

**Dark Matter candidate**

If R-parity is conserved, stable LSP

(More on R-parity later)

**SUSY is a broken symmetry**

No superpartners observed with same mass but different spin

$$R = (-1)^{3(B-L)+2S}$$

$$R(\text{SM}) = +1$$

$$R(\text{SUSY}) = -1$$

Mechanism for SUSY-breaking unknown

---

A De Santo, SUSY at ATLAS
The Elephant in the Room

A De Santo, SUSY at ATLAS

$m_H \sim 125 \text{ GeV}$
m_H regularized by scalar top mass, still possible to have natural SUSY with a relatively light stop / sbottom

Naturalness achievable even if 1st/2nd-generation squark masses are O(TeV)

Relatively light gluino

Electroweak sector also light

A De Santo, SUSY at ATLAS
Search Strategy

At the LHC, SUSY cross-sections are dominated by the production of coloured sparticles (squarks and gluinos)

**R-parity Conserving (RPC) Models**

Sparticles produced in pairs

**Decay chains** (jets, leptons, ... ) terminating with a stable and neutral LSP (neutralino or gravitino)

LSP leaves the detector unseen

→ **Missing transverse energy** ($E_T^{\text{miss}}$)

No mass peaks, signal in tails

A De Santo, SUSY at ATLAS

**R-parity Violating (RPV) Models**

LSP need not be stable or neutral

Can have mass peaks

Not-so-large $E_T^{\text{miss}}$

**Other Scenarios**

Displaced vertices

Slow highly hadronising particles

...
The minimal SUSY extension of the SM (MSSM) has got 105+19 free parameters

Unmanageable!

**Top-down approach**

**Models of SUSY breaking** – cMSSM/mSUGRA, GMSB, etc

Fix a limited number of parameters at some higher energy scale, then extrapolate back to the EWK scale & predict phenomenology

Search for a wide range of signatures – if null result, set limits in parameter space

**Bottom-up approach**

**Phenomenological Models** – Assume some sparticle mass hierarchy

**Simplified Models** – Consider individual decays as separate building blocks

**Model-independent limits on “effective cross-section”**

\[ \sigma \times \varepsilon \times A \]

(A=acceptance, \(\varepsilon=\)efficiency)

(ie a limit on the number of events in the signal region – for a given luminosity)

A De Santo, SUSY at ATLAS
**ATLAS Detector**

**Multi-purpose detector**
- Large acceptance (~4π coverage) and hermeticity
- Excellent particle identification and reconstruction
- Excellent $E_T^{miss}$ and jet reconstruction
- Excellent vertex reconstruction

**Inner Detector** ($|\eta|<2.5, B=2T$)
- Si pixels and strips, TRT straws
- Tracking and vertexing, $e/\pi$ separation
- $\sigma_p / p_T \sim 3.8 \times 10^{-4} p_T (GeV) \oplus 0.015$

**Hadron Calorimeter** ($|\eta|<4.9$)
- Fe-scintillator tiles (barrel)
  - $\sigma_E / E \sim 50% / \sqrt{E (GeV)} \oplus 0.03$
- Cu/W-Lar (endcap)
  - $\sigma_E / E \sim 90% / \sqrt{E (GeV)} \oplus 0.07$
- Trigger and measurement of jets and $E_T^{miss}$

**EM Calorimeter** ($|\eta|<4.9$)
- Pb-Lar Accordion
- $e/\gamma$ trigger, id and measurement
- $\sigma_E / E \sim 10% / \sqrt{E (GeV)}$

**Muon Spectrometer** ($|\eta|<2.7$)
- Air-core toroids with gas-based muon chambers
- Muon trigger and measurement
- $p_T$ resolution <10% up to ~1TeV

A De Santo, SUSY at ATLAS
A Collaborative Effort

38 Countries
174 Institutions
3000 Scientists
1000 Students

A De Santo, SUSY at ATLAS
ATLAS Datasets

**Instantaneous Luminosity**
Peak luminosity – $3.65 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$

**Datasets for SUSY analyses**
- **2010**: ~35 pb$^{-1}$
- **2011**: 4.7 fb$^{-1}$ (7 TeV)
- **2012**: 5.8 fb$^{-1}$ analysed (8 TeV)

A De Santo, SUSY at ATLAS
Lots of SUSY Results…

### 2011 Data (7 TeV)

| Short Title of the Paper | Date | \(|s| (\text{TeV})| | L (fb^{-1})| | Document | Site+Material | Journal |
|--------------------------|------|----------------|---------------|----------------|-------------|--------|
| Disappearing track + jets + Emmiss | 10/2012 | 7 | 4.7 | 1210.0552 | LH4 | Submitted to JHEP |
| 1-2 leptons + 1-lepton + jets + Emmiss (GSMS) | 10/2012 | 7 | 4.7 | 1210.1281 | LH4 | Submitted to EPJC |
| 1-2 leptons + 1-lepton + jets + Emmiss (AMSB) | 10/2012 | 7 | 4.7 | 1210.1693 | LH4 | Submitted to PRL |
| 3 leptons + jets + Emmiss (Heavy stop) | 06/2012 | 7 | 4.7 | 1200.0969 | LH4 | Submitted to JHEP |
| 1-2 leptons + 1-2-leptons + jets + Emmiss (Light Stop) | 06/2012 | 7 | 4.7 | 1209.2190 | LH4 | Submitted to PRL |
| 2 leptons + Emmiss (GSM) | 06/2012 | 7 | 4.7 | 1208.8973 | LH4 | Submitted to JHEP |
| 1-2 leptons + 2-4 jets + Emmiss | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to PRL |
| 2 leptons + 3-4 jets + Emmiss (Very light stop) | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to JHEP |
| 3 leptons + Emmiss (Direct gaugino) | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to JHEP |
| 1 jet + 3 jets + Emmiss (Heavy stop) | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to PRD |
| 0 lepton + 1-2 jet + 5-6 jets + Emmiss (Heavy stop) | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to PRD |
| 0 lepton + 1-2 jet + Emmiss | 06/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to JHEP |
| 0 lepton + 3 jets + Emmiss (Group mod. stop,bino) | 07/2012 | 7 | 4.7 | 1208.4848 | LH4 | Submitted to JHEP |
| 0 lepton + 0-6 jets + Emmiss | 06/2012 | 7 | 4.7 | 1206.1766 | LH4 | Submitted to JHEP |
| Electroweak continuum (KPI) | 06/2012 | 7 | 2.05 | 1206.0887 | LH4 | Submitted to JHEP |
| Disappearing track + jets + Emmiss (Direct gaugino) | 04/2012 | 7 | 2.05 | 1204.2190 | LH4 | Submitted to JHEP |
| \(1\) lepton + 1-2 jet + Emmiss (GMSB) | 04/2012 | 7 | 2.05 | 1204.2190 | LH4 | Submitted to JHEP |
| \(2\) jets + \(1\) lepton + Emmiss (GMSB) | 02/2012 | 7 | 2.05 | 1202.0969 | LH4 | Submitted to JHEP |
| \(b\)-jets + 6-8 leptons + Emmiss (Group med. stop,bino) | 02/2012 | 7 | 2.05 | 1202.0969 | LH4 | Submitted to JHEP |
| 2 same-sign leptons + 1 jet + Emmiss | 02/2012 | 7 | 2.05 | 1202.0969 | LH4 | Submitted to JHEP |
| 2 b-jets + Emmiss (Direct sbottom) | 12/2011 | 7 | 2.05 | 1212.3322 | LH4 | Submitted to JHEP |
| Disappearing track + jets + Emmiss (AMSB Strong Prod.) | 02/2012 | 7 | 1.02 | 1202.0969 | LH4 | Submitted to JHEP |
| 2 photons + Emmiss (GSM) | 11/2011 | 7 | 1.04 | 1119.2226 | LH4 | Submitted to JHEP |
| 0 lepton + \(1\)-2 jets + Emmiss | 10/2011 | 7 | 1.34 | 1119.2226 | LH4 | Submitted to JHEP |
| 1 lepton + \(1\)-2 jets + Emmiss | 08/2011 | 7 | 1.04 | 1109.6805 | LH4 | Submitted to JHEP |
| 0 lepton + \(0\)-2 jets + Emmiss | 08/2011 | 7 | 1.04 | 1109.6805 | LH4 | Submitted to JHEP |
| Electroweak continuum (KPI) | 06/2011 | 7 | 1.07 | 1106.3989 | LH4 | Submitted to JHEP |

### 2012 Data (8 TeV)

| Short Title of the Conf Note | Date | \(|s| (\text{TeV})| | L (fb^{-1})| | Document | M bile | Note |
|-----------------------------|------|----------------|---------------|----------------|--------|------|
| 0 leptons + \(\geq 2\) jets + Emmiss | 08/2012 | 8 | 5.3 | ATLAS-CONF-2012-109 | | |
| 0 leptons + \(\geq 6\) jets + Emmiss | 08/2012 | 8 | 5.3 | ATLAS-CONF-2012-103 | | |
| 1 lepton + \(\geq 4\) jets + Emmiss | 08/2012 | 8 | 5.3 | ATLAS-CONF-2012-104 | | |
| 2 same-sign leptons + \(\geq 3\) jets + Emmiss | 08/2012 | 8 | 5.3 | ATLAS-CONF-2012-105 | | |

A De Santo, SUSY at ATLAS

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Lots of SUSY Results...
Lots of SUSY Results…

A De Santo, SUSY at ATLAS
R-parity Conserving SUSY
Strong production and RPC SUSY

Broad searches

To cover as many signatures as possible from a broad range of scenarios

- short / long cascades
- high-pT jets (including b-jets)
- possibly one or more leptons (different flavours)
- possibly photons
- moderate-to-large $E_T^{\text{miss}}$

Understanding of SM backgrounds crucial

QCD, W/Z+jets, ttbar, …

From (or verified in) control regions

A De Santo, SUSY at ATLAS
+ 0-lepton + $E_T^{\text{miss}}$ (aka “classic” 0-lep)

Jets from gluino and/or squark decays

Large missing transverse energy ($E_T^{\text{miss}}$) from escaping neutralinos

Veto events with isolated electrons or muons

12 signal regions

$$m_{\text{eff}}(N_j) = \sum_{i=1}^{N_j} p_{T,jet,i} + E_T^{\text{miss}}$$

$N_j$ = all signal jets

$m_{\text{eff(incl.)}}$: all jets with $p_T>40$ GeV

A De Santo, SUSY at ATLAS
0-lepton + $E_T^{\text{miss}}$ – Background Estimation

Four control regions (CR) for each of the twelve signal regions (SR)

<table>
<thead>
<tr>
<th>CR</th>
<th>SR background</th>
<th>CR process</th>
<th>CR selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRY</td>
<td>$Z(\rightarrow \nu\nu)$+jets</td>
<td>$\gamma$+jets</td>
<td>Isolated photon</td>
</tr>
<tr>
<td>CRQ</td>
<td>QCD jets</td>
<td>QCD jets</td>
<td>Reversed $\Delta \phi$(jet, $E_T^{\text{miss}}$)$<em>{\text{min}}$ and $E_T^{\text{miss}}$/m$</em>{\text{eff}}$(Nj) cuts</td>
</tr>
<tr>
<td>CRW</td>
<td>$W(\rightarrow \ell\nu)$+jets</td>
<td>$W(\rightarrow \ell\nu)$+jets</td>
<td>30 GeV &lt; $m_T(\ell, E_T^{\text{miss}})$ &lt; 100 GeV, b-veto</td>
</tr>
<tr>
<td>CRT</td>
<td>$t\bar{t}$ and single-$t$</td>
<td>$t\bar{t} \rightarrow bbqq' \ell\nu$</td>
<td>30 GeV &lt; $m_T(\ell, E_T^{\text{miss}})$ &lt; 100 GeV, b-tag</td>
</tr>
</tbody>
</table>

Background from combined likelihood fit to all CRs – accounting for all correlations

$$N_{\text{proc (SR, scaled)}} = N_{\text{proc (CR, obs)}} * \left[ \frac{N_{\text{proc (SR, raw, proc)}}}{N_{\text{proc (CR, raw, proc)}}} \right]$$

**Transfer factors** link CR measurement to SR background estimate

A De Santo, SUSY at ATLAS
**0-lep + $E_t^{\text{miss}}$ – Results & Interpretation**

Good agreement between observations and SM expectations

Data from all the channels are used to set limits on SUSY models
Profile log-likelihood ratio test and CLs prescription to derive 95% CL exclusion regions

Exclusion limits obtained by using the SR with the best expected sensitivity at each point

**$\tan$β =10, $A_0 = 0$, $\mu > 0$ (MSUGRA/CMSSM models)**

Limit on $m_{1/2} \sim 340$ (710) GeV at high (low) $m_0$ values

Equal mass light-flavor squarks and gluinos excluded below 1500 GeV

Strong production of gluinos and 1st/2nd-generation squarks, with direct decays to jets and neutralino
(all other sparticles, including 3rd-generation squarks, are decoupled)

A De Santo, SUSY at ATLAS
Compressed Scenarios

Models with compressed MSUGRA scenarios

$\Delta M/\Delta M_{SUSY}$ from 0.85 to 0.15

Basic sparticle content and spectrum similar to CMSSM, but sizes of all mass splittings controlled by a compression factor.

Signal regions with softer cuts allow to go to lower $\Delta M/\Delta M_{SUSY}$

Gain in sensitivity for gluino masses below ~1.2 TeV

A De Santo, SUSY at ATLAS
**0-lepton + Multi-jets + $E_T^{\text{miss}}$ – Strategy**

**Extension of “classic” 0-lepton analysis**
Provides increased sensitivity to models with many-body decays or sequential cascade decays to coloured particles

**Signal regions with many high-$p_T$ jets, plus $E_T^{\text{miss}}$ and lepton veto**

**Data-driven approach**

$E_T^{\text{miss}}$ resolution dominated by stochastic fluctuations of jets

\[
\sigma^2 \left( E_T^{\text{miss}} \right) \sim H_T = \sum_{\text{jets}} p_T
\]

(sum over jets with: $p_T > 40 \text{ GeV}$, $|\eta| < 2.8$)

A De Santo, SUSY at ATLAS

<table>
<thead>
<tr>
<th>Signal region</th>
<th>7j55</th>
<th>8j55</th>
<th>9j55</th>
<th>6j80</th>
<th>7j80</th>
<th>8j80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of isolated leptons ($e, \mu$)</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet $p_T$</td>
<td>&gt; 55 GeV</td>
<td>&gt; 80 GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet $</td>
<td>\eta</td>
<td>$</td>
<td>&lt; 2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of jets</td>
<td>$\geq 7$</td>
<td>$\geq 8$</td>
<td>$\geq 9$</td>
<td>$\geq 6$</td>
<td>$\geq 7$</td>
<td>$\geq 8$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/\sqrt{H_T}$</td>
<td>&gt; 4 GeV$^{1/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8 TeV, 5.8 fb$^{-1}$
+0-lepton + Multi-jets + $E_t^{\text{miss}}$ – Results

- **Background Sources**
  - Multi-jet QCD + Fully hadronic ttbar: Dominant
  - Semi- and fully leptonic ttbar: Significant
  - W/Z+jets: Small

**Simplified gluino-neutralino model**

$$\tilde{g} + \tilde{g} \rightarrow (t + \bar{t} + \tilde{\chi}_1^0) + (t + \bar{t} + \tilde{\chi}_1^0)$$

**ATLAS Preliminary**

- **Data 2012 ($\sqrt{s} = 8$ TeV)**
- **Background prediction**
- **Multi-jets (incl. $t\bar{t} \rightarrow q\bar{q}$)**
- **Sherpa $t\bar{t} \rightarrow q\bar{q}$**
- **Sherpa $W \rightarrow (\ell\nu,\ell\tau\nu)$**
- **Sherpa $Z \rightarrow \nu\nu$**
- **SUSY $\tilde{g}=900, \tilde{\chi}_0=150$**

**Multi-jet control region**
- 6 jets $p_T > 55$ GeV
- Multi-jet background from 5 jets $p_T > 55$ jets

**Results**
- Small overlap with standard 0-lep+jets+Etmiss searches
Presence of lepton provides extra advantages compared to purely hadronic searches

**Triggering**
efficient single lepton triggers

**Background suppression**
QCD background greatly reduced by lepton requirement

**Background modelling**
using data-driven techniques

Additional variables used in the event selection:

\[
\begin{align*}
    m_T &= \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \left(1 - \cos(\Delta\phi(\ell, E_T^{miss}))\right)} \\
    m_{eff} &= p_T^\ell + \sum_{i=1}^{N_{jet}} p_T^{jet(i)} + E_T^{miss}
\end{align*}
\]

Transverse mass between selected lepton and \(E_T^{miss}\) vector

Effective mass (all jets >40 GeV)
1-lepton + jets + $E_T^{\text{miss}}$ – Event Selection and Backgrounds

One Signal Region

<table>
<thead>
<tr>
<th>signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{lep}}$</td>
</tr>
<tr>
<td>$p_T^\ell$ (GeV)</td>
</tr>
<tr>
<td>$p_T^Z$ (GeV)</td>
</tr>
<tr>
<td>$N_{\text{jet}}$</td>
</tr>
<tr>
<td>$p_T^{\text{jet}}$ (GeV)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ (GeV)</td>
</tr>
<tr>
<td>$m_T$ (GeV)</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}/m_{\text{eff}}$</td>
</tr>
<tr>
<td>$m_{\text{eff}}$ (GeV)</td>
</tr>
</tbody>
</table>

QCD background using “loose-tight” Matrix Method
use data with “loose” lepton to estimate data with “tight” lepton

Non-QCD background dominated by top and W+jets
Use binned fit in CRs to adjust background normalisations

All other backgrounds from simulation

8 TeV, 5.8 fb$^{-1}$
1-lepton + jets + $E_{t}\text{miss}$ – Results

Observed number of events in data consistent with SM

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Muon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Fitted background events</td>
<td>$9.0 \pm 2.8$</td>
<td>$7.7 \pm 3.2$</td>
</tr>
<tr>
<td>Fitted $t\bar{t}$ events</td>
<td>$6.0 \pm 2.2$</td>
<td>$2.6 \pm 1.9$</td>
</tr>
<tr>
<td>Fitted W/Z+jets events</td>
<td>$1.5 \pm 0.7$</td>
<td>$4.2 \pm 2.3$</td>
</tr>
<tr>
<td>Fitted other background events</td>
<td>$1.0 \pm 0.7$</td>
<td>$0.9 \pm 0.3$</td>
</tr>
<tr>
<td>Fitted multijet events</td>
<td>$0.4 \pm 0.6$</td>
<td>$0.0 \pm 0.0$</td>
</tr>
<tr>
<td>MC expected SM events</td>
<td>9.5</td>
<td>11.5</td>
</tr>
<tr>
<td>MC expected $t\bar{t}$ events</td>
<td>5.7</td>
<td>4.6</td>
</tr>
<tr>
<td>MC expected W/Z+jets events</td>
<td>2.4</td>
<td>6.0</td>
</tr>
<tr>
<td>MC expected other background events</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Data-driven multijet events</td>
<td>0.4</td>
<td>0.0</td>
</tr>
</tbody>
</table>

95% CL limits on visible cross-section

MSUGRA/CMSSM limits from combination of statistically independent e & mu channels

8 TeV, 5.8 fb$^{-1}$

1-lep competitive with 0-lep at high $m_0$, where gluino production is dominant

A De Santo, SUSY at ATLAS
In MSSM, gluino is Majorana
Same-sign lepton pairs will be produced in half of the dilepton events originating from a SUSY cascade
Gluinos decay with equal probability to quark/anti-squark or anti-quark/squark pairs
SS dilepton pairs can originate from
\[ \tilde{g}\tilde{g} \rightarrow t\tilde{t_1}\tilde{t_1}^*, tt\tilde{t_1}\tilde{t_1}^*, \tilde{t}\tilde{t_1}\tilde{t_1} \]
Followed by \[ \tilde{t_1} \rightarrow b\tilde{\chi}_1^\pm \] or \[ \tilde{t_1} \rightarrow t\tilde{\chi}_1^0 \]

Event selection
2 SS leptons (e, mu) with \( p_T > 20 \) GeV
>=4 high-pT jets (>50 GeV)
\[ E_{T_{miss}} > 150 \) GeV

No significant excess observed

A De Santo, SUSY at ATLAS

A De Santo, SUSY at ATLAS

\[ m_{0}\ \text{[GeV]} \]

\[ 500 \text{ GeV} \]

\[ 600 \text{ GeV} \]

\[ 700 \text{ GeV} \]

\[ 800 \text{ GeV} \]

\[ 900 \text{ GeV} \]
GMSB 2-lepton Searches (including taus)

In Gauge-Mediated SUSY-Breaking (GMSB) models, the LSP is the gravitino, the next-to-lightest SUSY particle (NLSP) determines the phenomenology.

\[ \text{NLSP} = \text{stau} \rightarrow \text{enhanced taus} \]

\[ \text{NLSP} = \text{selectron/smuon} \rightarrow \text{enhanced e}/\mu \]

Six exclusive channels:
(e-e, e-\mu, \mu-\mu)+jets+E_{T}^{\text{miss}}

(=1\tau_{\text{had}}, \geq 2\tau_{\text{had}}, \text{e}/\mu+1\tau_{\text{had}})+jets+E_{T}^{\text{miss}}

Gluino masses excluded up to 1.3 TeV

\[ 7 \text{ TeV, 4.7 fb}^{-1} \]

A De Santo, SUSY at ATLAS
Photon Signals from GGM SUSY

In the “gluino–bino” model (“squark-bino” model), the NLSP is bino-like and, except for the gluino (squark), all other sparticles are “decoupled” (too heavy to be measured)

\[ 2 \times \left\{ \tilde{\chi}_1^0 \rightarrow \gamma \tilde{G} \right\} = 2 \gamma + E_T^{\text{miss}} \]

Gluino-bino models: exclude gluino masses up 1.07 TeV

In the minimal GMSB model (SPS8) the only free parameter is SUSY-breaking scale \( \Lambda \)

Lower limit on \( \Lambda \) is 196 TeV (\( \rightarrow 1.4 \text{ TeV} \) limit on UED compactification scale \(1/R\))

Squark-bino models: exclude gluino masses up 870 GeV
m_H regularized by scalar top mass, still possible to have natural SUSY with a relatively light stop / sbottom

Naturalness achievable even if 1^{st}/2^{nd}-generation squark masses are O(TeV)

Relatively light gluino

Electroweak sector also light
Gluino-Mediated 3rd Generation

Greatest sensitivity from channels that are good at suppressing top-rich backgrounds

0-lep+multijets + $E_T^{\text{miss}}$

SS 2-lep + jets + $E_T^{\text{miss}}$

3 b-jets + $E_T^{\text{miss}}$

Also 3lep+jets+$E_T^{\text{miss}}$, slightly more sensitive nearer diagonal

Gluino masses excluded up to $\sim 1080$ GeV
Direct Sbottom Searches

3-lep + jets + $E_t^{\text{miss}}$

2 b-jets + $E_t^{\text{miss}}$  Exploits 2-body decay kinematics
SR dependent on $m(\text{sbottom})-m(\text{LSP})$

ATLAS Preliminary

Observed limit ($\pm 1\sigma_{\text{exp}}$)
Expected limit ($\pm 1\sigma_{\text{exp}}$)

All limits at 95% CL$_S$
Scalar Top (stop) Searches – Strategy

Rich phenomenology, dependent on $m(\text{stop})-m(\text{LSP})$ and on nature of intermediate particles (chargino, heavy neutralino, slepton,…)

- $\text{top}+\text{LSP}$ if kinematically allowed, and no gauginos
- chargino+$b$, if chargino present
- virtual $W$, if no chargino
- charm+$\text{LSP}$ (via loop) – last option

Variety of signatures requires range of strategies to cover all available possibilities (and challenges)

**Very light stop** – soft objects, large SM backgrounds

**Light stop** – very similar to ttbar

**Heavy stop** – low cross-sections

A De Santo, SUSY at ATLAS
Searching for the Stop at 7 TeV

Searches tailored to stop mass range

**Very Light stop – 2 soft leptons**

\[ \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm \]

**Light stop – 1-2 bjets + 1-2 lep**

**Medium stop – 2 lep+mT2**

**Heavy stop – 0-lep+b-jets**

\[ \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^\pm \]

**Heavy stop – 1-lep+b-jets**

A De Santo, SUSY at ATLAS
Summary of Stop Searches (7 TeV)

The absence of any significant excess above SM background expectations is translated into 95% CL exclusion limits for all the considered channels.

\( m(\text{stop}) < 200 \text{ GeV} \)

Look at

\[ \tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm, \]
\[ \tilde{\chi}_1^\pm \rightarrow W^{(*)} + \tilde{\chi}_1^0 \]

with

either \( m_{\tilde{\chi}_1^\pm} = 106 \text{ GeV} \)

or \( m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0} \)

\( m(\text{stop}) > 200 \text{ GeV} \)

\[ \tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0 \]

assumed to dominate

A De Santo, SUSY at ATLAS
**EW SUSY – Charginos, Neutralinos, Sleptons**

**Direct Gaugino Searches**
- chargino-chargino: 2-lep
- chargino-neutralino: 3-lep + 2-lep (when one lepton not seen)

**Direct Slepton Searches**
- slepton-slepton: 2-lep

A De Santo, SUSY at ATLAS
Weak SUSY – Charginos and Sleptons

Consider purely leptonic decays of chargino pairs

**Simplified models with intermediate slepton**

Signature: \(\text{2-lep} + \text{E}_{T}^\text{miss}\)

Search also sensitive to direct slepton production (beyond LEP)

Chargino pairs \(\rightarrow\) 2lep + \(\text{E}_{T}^\text{miss}\) (with intermediate slepton)

ATLAS

\[
\int L \, dt = 4.7 \, \text{fb}^{-1}\quad \sqrt{s} = 7\, \text{TeV}
\]

\(\tilde{\chi}_i^+ \tilde{\chi}_i^- \rightarrow 2 \times \nu (\bar{\nu}) \rightarrow 2 \times h \tilde{\chi}_1^0\)

\[
m_{\nu}^2 \cdot m_{\tilde{\chi}_1^0}
\]

\[
m_{\tilde{\chi}_i} - m_{\tilde{\chi}_1} = 0.5
\]

Slepton pairs \(\rightarrow\) 2lep + \(\text{E}_{T}^\text{miss}\)

ATLAS

\[
\int L \, dt = 4.7 \, \text{fb}^{-1}\quad \sqrt{s} = 7\, \text{TeV}
\]

\(\tilde{\ell} \tilde{\ell} \rightarrow \nu \bar{\nu} \tilde{\chi}_1^0 \tilde{\chi}_1^0\)

\[
m_{\nu}^2 \cdot m_{\tilde{\chi}_1^0}
\]

\[
m_{\tilde{\ell}} - m_{\tilde{\ell}} = 0.5
\]

\[\text{Lepton} = \text{electron, muon}\]
Weak SUSY – Charginos and Neutralinos

Leptonic decays of chargino-neutralino pairs

**Simplified models with/without intermediate slepton**

Signature: \(3\text{-lep} + \not{E}_T + (Z\text{-request/veto and/or } m_T(v,\text{lep}) > 90 \text{ GeV})\)

Gain from combining also with 2-lep signature (if one lepton is unseen)

Also consider more complex models with intermediate slepton – **pMSSM**

\(\mu = \text{higgs mass parameter}\)

\(M_{1,2} = \text{gaugino mass}\)

Lepton = electron, muon

\(\mu = 100 \text{ GeV}\)

\(\mu = 140 \text{ GeV}\)

\(\mu = 250 \text{ GeV}\)
RPV SUSY and All That
R-parity Violation (RPV)

R-parity conservation is hinted by proton stability, but not strictly required

Proton decay can be prevented by other symmetries that require lepton or baryon number conservation but violate R-parity

(can also accommodate non-zero neutrino masses and neutrino mixing)

General R-parity violating term

\[
W_{RPV} = \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^C + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^C + \epsilon_{ij} \hat{L}_i \hat{H}_u + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C
\]

If R-parity is violated

- Sparticles can be produced in odd numbers
- LSP can be coloured and/or electrically charged
- LSP can be unstable
  * LSP mass peaks (from SM final-state particles)
  * potentially, long-lived LSP
  * missing transverse energy may be small
RPV 4-leptons

Trilinear lepton-number-violating RPV: \[ W_{RPV} = \lambda_{ijk} L_i L_j E_k \]

Can have both charged leptons and neutrinos in the LSP decay → high lepton multiplicity and moderate values of \( E_{t\text{miss}} \)

Assume single coupling dominance, with \( \lambda_{121} \) as the only non-zero coupling chosen as a representative model with multiple e / \( \mu \) in final state

**Scenario #1**
Lightest chargino and neutralino only sparticles below the TeV scale
RPV 3-body decay of LSP to eee or e\( \mu \nu \) states (BR = 50 % each)

**Scenario #2**
\((m_{1/2}, \tan \beta)\) slice of MSUGRA/CMSSM (containing BC1 benchmark point [Allanach et al.])
\( m_0 = A_0 = 0, \mu > 0, \lambda_{121} = 0.032 \)
Both strong and weak production
Light stau is LSP in most of parameter space
\( \tilde{\tau}_1 \rightarrow \tau e\mu\nu \) or \( \tilde{\tau}_1 \rightarrow \tau eee\mu \)
RPV 4-leptons

>= 4 leptons (e, m)
No SFOS pairs with mass below 20 GeV
No SFOS pairs within +/- 10 GeV of Z mass

**SR1:** $E_T^{miss} > 50$ GeV  (missing momentum from neutrinos)

**SR2:** $m_{eff} > 300$ GeV  (large multiplicity of high-$p_T$ objects)

<table>
<thead>
<tr>
<th>Chargino masses up to 540 GeV excluded for LSP masses above 300 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Values of $m_{1/2}$ below 820 GeV are excluded when $10 &lt; \tan \beta &lt; 40$</td>
</tr>
</tbody>
</table>
RPV Scalar Tau Neutrino (eμ resonance)

Search for an excess at high values of the opposite-charge eμ invariant mass spectrum

Signal possibly originating from resonant decays of neutral sparticles in RPV SUSY

Tau sneutrino = LSP

1.07 fb⁻¹, 7 TeV

Update in preparation

Null result translates into limit on σ × BR and on the coupling constants as a function of the mass of the scalar neutrino

A De Santo, SUSY at ATLAS
RPV SUSY models also allow for LFV interactions through the t-channel exchange of a scalar quark.

\[ \frac{d\sigma}{dt} = \left| \lambda'_{131} \lambda'_{231} \right|^2 \hat{t}^2 / \left[ 64 N_c \pi \hat{s}^2 \left( \hat{t} - m_t^2 \right)^2 \right] \]

A De Santo, SUSY at ATLAS
A Lot More Results...
RPV and Long-Lived Particles

Various possibilities

RPV scenarios with $\lambda, \lambda', \lambda'' < 10^{-7}$  $\rightarrow$ displaced vertex

Low chargino-neutralino mass splitting ($\sim$100 MeV)  $\rightarrow$ "kink" from low-$p_T$ $\pi$

Long-lived gluino from heavy-squark-mediated decay  $\rightarrow$ R-hadrons

Weak coupling of NLSP to gravitino in GMSB models  $\rightarrow$ stable sleptons

Challenging analyses

Require dedicated effort (on tracking etc)
Some results from LL particle searches

**LL AMSB chargino → neutralino + pion**

\[ \tan \beta = 5, \mu > 0 \]

**Doubly displaced vertex with high-\( p_T \) muon**

\[ \sigma \cdot \text{BR} \, [\text{pb}] \]

\[ \int L dt = 4.4 \, \text{fb}^{-1} \]

\[ \text{ATLAS} \]

\[ \text{Observed 95\% CL limit (1 \sigma_{	ext{obs}})} \]

\[ \text{Expected 95\% CL limit (1 \sigma_{	ext{exp}})} \]

\[ \text{ATLAS (7 TeV, 1.02 fb}^{-1}, \text{strong prod.)} \]

\[ \text{LEP2 exclusion} \]

\[ \text{Stable } \tilde{\chi}_1 \]

**Metastable Chargino**

**Displaced Vertex**
A Lot More Results...

... but...
Summary and Conclusions
Desperately Searching SUSY (in Every Corner...)
Conclusions

**ATLAS has produced an impressive range of results from SUSY searches in 2011 and 2012 collision data**

*Sadly, no SUSY just yet 😞*
Conclusions

ATLAS has produced an impressive range of results from SUSY searches in 2010 and 2011 collision data

Sadly, no SUSY just yet 😓

It was not around the corner!!
Conclusions

ATLAS has produced an impressive range of results from SUSY searches in 2010 and 2011 collision data

Sadly, no SUSY just yet 😞

It was not around the corner

Plenty of corners still to explore...
Conclusions

ATLAS has produced an impressive range of results from SUSY searches in 2010 and 2011 collision data

Sadly, no SUSY just yet 😞

Plenty of corners still to explore...

... and plenty of data too!
Can’t We See the Wood for the Trees ??

A De Santo, SUSY at ATLAS