Searching for SUSY at ATLAS
SUSY mass scale: \textit{a priori} knowledge

Upper mass scale constrains
- Unification of couplings if mass scale is not too large
- Fine tuning problem less severe if mass scale is not too large
- Perfect DM candidate if mass scale not too large

Lower mass scale constrains
- Bounds from low energy experiments
- Tevatron bounds (e.g. gluino and squark mass)
- Bounds from LEP (e.g. chargino, slepton, neutralino)

Are there SUSY particles at a scale of 0.2 - few TeV?
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Are there SUSY particles at a scale of 0.2 - few TeV?

SUSY searches at LHC will teach us if this story is correct.
If R-Parity is conserved then SUSY particles are pair produced

LHC:

Due to strong force dominant production of squarks and gluinos (if not too heavy) Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

Mass pattern in general SUSY unknown! Searches need to be quite general and model-parameter-independent
Event found in signal region of jet+ $E_t^{\text{miss}}$ analysis.

3 jets with $p_T$ of approximately 400 GeV, 120 GeV, 60 GeV and $E_t^{\text{miss}}$ of approximately 420 GeV.
Searches presented today

- **Jets + lepton + \( E_t^{\text{miss}} \)**
- **Jets + \( E_t^{\text{miss}} \)**
- **Jets + b-tag + \( E_t^{\text{miss}} \)**
- **Dilepton + \( E_t^{\text{miss}} \)**
- **Multileptons + \( E_t^{\text{miss}} \)**
- **Photons + jets + \( E_t^{\text{miss}} \)**
- **e mu**
- **Slow Moving Particle**

- **PRL paper**
- **submitted to PLB**
- **preliminary/paper soon**
- **preliminary/papers soon**
- **in pipeline**
- **(UED published 3.1 pb-1)**
- **preliminary/paper soon**
- **submitted to PLB**

*Similar conclusions/channels for Universal Extra Dimension, ADD, Little Higgs, ....*
Jets + lepton + $E_T^{\text{miss}}$

- First ATLAS SUSY paper
  - arXiv:1102.2357 Accepted by PRL
- Expected to be less effected by potentially “dangerous” QCD background, main background $W$ and top pairs
- Analysis cuts follow quite closely previous ATLAS MC studies
- 1 electron or muon with $p_T$ > 20 GeV
- 3 jets with $p_T$ > 60, 30, 30 GeV
- $E_T^{\text{miss}}$ > 125 GeV and $E_T^{\text{miss}}$ > 0.25 * $M_{\text{eff}}$
- Transverse mass > 100 GeV
- $M_{\text{eff}}$ > 500 GeV

Definition of $W$ and top control regions:

- $30 < E_T^{\text{miss}} < 80$ GeV
- $40 < \text{transverse mass} < 80$ GeV
  - Veto b-tag: W control region
  - Apply b-tag: top pair control regions

$M_{\text{eff}} \equiv \sum_{i=1} p_T^{\text{jet},i} + \sum_{i=1} p_T^{\text{lep},i} + E_T^{\text{miss}}$
Jets + lepton + $E_T^{\text{miss}}$

- Fits to control regions predict the number of Top, W and QCD events in the signal region
- Several cross checks performed (e.g. tests with alternative control regions)

Profile likelihood ratio test + toys

$$\Lambda(\mu) = -2(\ln L(n|\mu, \hat{b}, \hat{\theta}) - \ln L(n|\hat{\mu}, \hat{b}, \hat{\theta}))$$

Main result: Table and 95% CL

Limits on Cross section * Acceptance * effi.

Electron channel: **0.065 pb**

Muon channel: **0.073 pb**
Jets + $E_T^{\text{miss}}$

Very simple model-independent classification of signal regions:

Low and high mass dijets (squarks $\rightarrow$ quark neutralino)

Region A and B

Low and high mass 3-jets (associated squark/gluino and gluino pair production):

Region C and D

Trigger efficiency close to 1 for all signal and control regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$p_T &gt; 120$ GeV, $E_T^{\text{miss}} &gt; 100$ GeV, $\Delta \phi &gt; 0.4$</td>
</tr>
<tr>
<td>B</td>
<td>$p_T &gt; 40$ GeV, $E_T^{\text{miss}} &gt; 100$ GeV, $\Delta \phi &gt; 0.4$</td>
</tr>
<tr>
<td>C</td>
<td>$m_{\text{eff}} &gt; 500$ GeV, $m_{T2} &gt; 300$ GeV</td>
</tr>
<tr>
<td>D</td>
<td>$m_{\text{eff}} &gt; 1000$ GeV, $m_{T2} &gt; 1000$ GeV, $\Delta \phi &gt; 0.4$</td>
</tr>
</tbody>
</table>

TABLE I: Criteria for admission to one of the four signal regions A to D. All variables are defined in the text.
Main work:
Typically 2-4 control region measurements or “data driven” methods performed for each background (and each signal region)

Examples:
- **QCD**: control regions with inverted cuts e.g. $\delta \phi(\text{jet,MET})$, determination without MC but smearing data with the measured detector response.
- **Z+ jets**: $Z \rightarrow \mu\mu$, $Z \rightarrow ee$ and W control regions
- **W+ jets**: $W \rightarrow \mu\nu$ and $W \rightarrow ev$ control regions, tau embedding
- **Top pairs**: Top control regions with or without lepton, and W embedding
### Jets + $E_{t}^{\text{miss}}$: Results

**Signal region A, B, C, D exclude non-SM process within acceptance**

> **efficiency.**

**SUSY model-independent search**

- **Interpretation:** Take the signal region with the largest expected sensitivity
- **Show reach of the search for 2 examples**

<table>
<thead>
<tr>
<th>Signal region</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>QCD</strong></td>
<td>7 $^{+8}_{-7}$[u+j]</td>
<td>0.6 $^{+0.7}_{-0.6}$[u+j]</td>
<td>9 $^{+10}_{-9}$[u+j]</td>
<td>0.2 $^{+0.4}_{-0.2}$[u+j]</td>
</tr>
<tr>
<td><strong>W+jets</strong></td>
<td>50 $^{+10}_{-8}$[j] ± 5[$\mathcal{L}$]</td>
<td>4.4 $^{+1.8}_{-0.5}$[j] ± 0.5[$\mathcal{L}$]</td>
<td>35 ± 9[u] $^{+10}_{-8}$[j] ± 4[$\mathcal{L}$]</td>
<td>1.1 ± 0.7[u] $^{+0.3}_{-0.2}$[j] ± 0.1[$\mathcal{L}$]</td>
</tr>
<tr>
<td><strong>Z+jets</strong></td>
<td>52 $^{+15}_{-13}$[j] ± 6[$\mathcal{L}$]</td>
<td>4.1 $^{+2.1}_{-0.8}$[j] ± 0.5[$\mathcal{L}$]</td>
<td>27 $^{+10}_{-6}$[j] ± 3[$\mathcal{L}$]</td>
<td>0.8 ± 0.7[u] $^{+0.6}_{-0.5}$[j] ± 0.1[$\mathcal{L}$]</td>
</tr>
<tr>
<td><strong>t\overline{t} and t</strong></td>
<td>10 $^{+0}_{-3}$[j] ± 1[$\mathcal{L}$]</td>
<td>0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] ± 0.1[$\mathcal{L}$]</td>
<td>17 ± 1[u] $^{+0.6}_{-0.4}$[j] ± 2[$\mathcal{L}$]</td>
<td>0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] ± 0.0[$\mathcal{L}$]</td>
</tr>
<tr>
<td><strong>Total SM</strong></td>
<td>118 $^{+35}_{-23}$[j] ± 12[$\mathcal{L}$]</td>
<td>10.0 ± 4.3[u] $^{+4.8}_{-1.9}$[j] ± 1.0[$\mathcal{L}$]</td>
<td>88 ± 18[u] $^{+26}_{-18}$[j] ± 9[$\mathcal{L}$]</td>
<td>2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] ± 0.2[$\mathcal{L}$]</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>87</td>
<td>11</td>
<td>66</td>
<td>2</td>
</tr>
</tbody>
</table>

1.3, 0.35, 1.1 and 0.11 pb respectively at 95% confidence.
Jets + $E_t^{\text{miss}}$ : Results

Simple MSSM Model with light 1$^{\text{st}}$ and 2$^{\text{nd}}$ gen. squarks, gluinos and a massless neutralino

Exclusion reach not strongly sensitive to sign$(\mu)$, tan$\beta$ and $A_0$

1 sigma total experimental uncertainty band shown (shows roughly the 1 and 3 sigma exclusion)
Jets + $E_t^{\text{miss}}$ : Results

**ATLAS**

$L^\text{int} = 35 \text{ pb}^{-1}, \sqrt{s} = 7 \text{ TeV}$

0 lepton combined exclusion

- **Observed 95% CL limit**
- **Median expected limit**
- **Expected limit $\pm 1\sigma$**

- **LEP $\tilde{g}$**
- **FNAL MSUGRA/CMSSM, Run I**
- **D0 MSUGRA/CMSSM, Run II**
- **CDF MSUGRA/CMSSM, Run II**

$\sigma_{\text{SUSY}} = 0.1 \text{ pb}$

$\sigma_{\text{SUSY}} = 1 \text{ pb}$

$\sigma_{\text{SUSY}} = 10 \text{ pb}$

**Reference point**

**MSUGRA/CMSSM**: $\tan \beta = 3, A_0 = 0, \mu > 0$.

**Shows best mSUGRA fits to low energy data $\Rightarrow$ excluded**

*(here arxiv 1102.4693, M0=75, M1/2=329 GeV)*
Consider the signal region with the best expected upper limit.
Automatically chosen by limit setting algorithm.
Other Interpretations possible!

Example:
How can a theorist use these data?

Signal efficiency * acceptance provided for each signal region and analysis channel
(see ATLAS public SUSY results webpage)
Les Houches Accord SUSY steering files provided

Validate your “local” setup

Interpret the data with your favored model.
Jets + $E_T^{\text{miss}}$ with b-tag

0 and 1-lepton channel also studied for events with b-tag to enhance sensitivity to 3rd generation
Slightly modified selection criteria
Aim is here to maximize sensitivity to e.g.

$0\ell : \tilde{g} \to \tilde{b}_1 b$
$\tilde{b}_1 \to b\chi_1^0$

$1\ell : \tilde{t}_1 \to b\chi_1^\pm$
$\chi_1^\pm \to \tilde{\chi}_1^0\ell^\pm\nu$

<table>
<thead>
<tr>
<th></th>
<th>0-lepton</th>
<th>1-lepton Monte Carlo</th>
<th>1-lepton data-driven</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ and single top</td>
<td>$12.2 \pm 5.0$</td>
<td>$12.3 \pm 4.0$</td>
<td>$14.7 \pm 3.7$</td>
</tr>
<tr>
<td>W and Z</td>
<td>$6.0 \pm 2.0$</td>
<td>$0.8 \pm 0.4$</td>
<td>-</td>
</tr>
<tr>
<td>QCD</td>
<td>$1.4 \pm 1.0$</td>
<td>$0.4 \pm 0.4$</td>
<td>$0^{+0.4}_{-0.0}$</td>
</tr>
<tr>
<td>Total SM</td>
<td>$19.6 \pm 6.9$</td>
<td>$13.5 \pm 4.1$</td>
<td>$14.7 \pm 3.7$</td>
</tr>
<tr>
<td>Data</td>
<td>15</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>
Jets + $E_t^{\text{miss}}$ with b-tag

Here $\tilde{t}_1$ is the lightest quark and produced in 100% of the gluino decays (or directly produced) and the stop decays via $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$

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Exclusion of gluinos below 520 GeV for stops in the range 160-240 GeV

Sbottom_1 produced via gluino or directly and decay via $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$,

$\Rightarrow$ Limit on gluino mass of 590 GeV
Jets + $E_t^{\text{miss}}$ with b-tag

Interpretation within mSUGRA

Combination of 0 and 1 lepton channel with b-tag

Also here strong limits in mSUGRA phase space (here shown at high tan beta)
Dilepton + $E_t^{\text{miss}}$ (OS/SS)

2 leptons with $p_T > 20$ GeV + $E_t^{\text{miss}}$ cut

- Fake background estimation by solving linear equations to get the fake probability for a “tight” lepton selections via a “loose” selection
- Top background estimated with control region

Exclusion plot shown for a phenomenological MSSM scenario which allows sleptons in the decay chains $M(\text{Squark/gluino}) > M(\text{chi2}) > M(\text{slepton}) > M(\text{chi1})$

Shown is a compressed (“soft” particles) and a favorable scenario (“harder” particles)
Dilepton + $E_{t}^{\text{miss}}$ (flavour subtraction)

Search for events with $E_{t}^{\text{miss}}$, opposite charge and identical flavour (ee, $\mu\mu$)

SM processes do equally produce ee+$\mu\mu$ and emu events

⇒ Background can be subtracted!

In SUSY events the production of the two leptons can be correlated

$\tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}^{\pm} \ell^{\pm} \rightarrow \tilde{\chi}_{1}^{0} \ell^{\pm} \ell^{\mp}$

due to lepton flavor conservation in the decays.

\[ S = \frac{N(e^+e^-)}{\beta(1-(1-\tau_e)^2) - \frac{N(e^+\mu^-)}{1-(1-\tau_e)(1-\tau_\mu)} + \frac{\beta N(\mu^+\mu^-)}{(1-(1-\tau_\mu)^2)}] \]

\[ S_{\text{obs}} = 1.8 \pm 0.2(\beta) \pm 0.01(\tau_e) \pm 0.01(\tau_\mu) \]

$S_{\text{expected}} = 1.98 \pm 0.79(\text{stat.}) \pm 0.78(\text{sys.})$
Electron Muon Resonance

Generic Search for a electron muon resonance

Selection: e and mu of opposite charge
\( p_{T,\text{lepton}} > 20 \text{ GeV} \) and not cut on MET

Determination of the instrumental (single and double fake) again via soft/tight equations

Limits on \( R_p \) violating \( \tilde{\nu}_\tau \) production extending previous searches at high mass
Search for R-hadrons (stable hadrons including a stable gluino, stop or sbottom)

Selection: $E_{t}^{\text{miss}} > 40$ GeV for triggering + track with $p_T > 50$ GeV

Two complementary subsystems used to measure SMPs

1. Tile sampling calorimeter
   iron+plastic scintillators, time resolution of 1-2 ns, calibrated with muons from Z decays

2. Pixel detector:
   $dE/dx$ is measured with the charge loss of clusters formed with the pixels

Background estimates and signal distributions for the pixel and tile mass measurements
Stable Massive Particle Search

Measure dE/dx to determine $\beta\gamma$ via Bethe/Bloch formula for Pixel and beta of the tile calorimeter

$\rightarrow$ Transform these measurements into mass via $M = p / \beta\gamma$

Background determined via random picking of momentum, tile, pixel information

Final signal regions defined by requiring cuts on both mass measurements

No events after final selections

$\rightarrow$ New strongest limits on stable the masses of $\tilde{g}, \tilde{t}$, and $\tilde{b}$
The search has begun

SUSY seems not to lie “just around the corner” of the LEP/Tevatron reach

ATLAS has presented the most stringent limits to date in various scenarios

mSUGRA: $M_{\text{squark}} = M_{\text{gluino}} > 775$ GeV

Expect sensitivity beyond 1 TeV already for 2011
EXTRA SLIDES
Why SUSY?

Most studied new physics theory at LHC for several reasons:

- Fermion and Boson loops protect the Higgs mass at large energies (reduces “fine tuning”)

- SUSY is a broken symmetry and thus offers (with R-parity conservation) perfect candidates for Dark Matter with a WIMP mass of O(100) GeV

- Gauge couplings unification, “radiative” EWSB, ...
Non gaussian tail of the jet response function

\[ R_2 = \frac{p_T (p_T + p_T^\text{miss})}{|p_T + p_T^\text{miss}|}. \]

Events in which requirements have been used to associate the source of the \( P_T^\text{miss} \) with only one of the jets. The Gaussian core of the jet response function is removed by the selection requirements on \( E_T^\text{miss} \). For each \( p_T \) bin the tails at low \( R_2 \) are subsequently used, together with the central Gaussian part of the response function (measured separately), and a set of low-E_T^\text{miss} seed events to form the fully data-driven QCD determination.
Distribution of $m_{\text{eff}}$ in the dileptonic $Z$+jets control region for the $\geq 2$-jet selection. Pre-selection requirements have been applied. The missing transverse momentum requirement has been applied using the value that would be obtained if the leptons were not observed, $|p_T^{\text{miss}} + p_T(l^+) + p_T(l^-)| > 100$ GeV. In addition a requirement on the dileptonic invariant mass $70$ GeV $< m_{ll} < 110$ GeV.
Effective mass  The scalar sum of transverse momenta defined by:

\[ M_{\text{eff}} \equiv \sum_{i=1}^{n} |p_T^{(i)}| + E_T^{\text{miss}} \]  

where \( n \) is the number of jets (two or three) defining the analysis channel, \( p_T^{(i)} \) is the transverse momentum of the \( i^{th} \) jet (ordered descending in \( |p_T| \)), and \( E_T^{\text{miss}} \) is defined in (1). The effective mass is sensitive to the centre-of-mass energy of the parton–parton collision. Selections demanding progressively larger \( M_{\text{eff}} \) tend to give sensitivity to progressively heavier coloured sparticles.

Stransverse mass  The \( m_{T2} \) variable is the generalization of the transverse mass to pair decays [40]. For a final state consisting of two visible objects with transverse momenta \( p_T^{(1)} \) and \( p_T^{(2)} \) respectively, and with missing transverse momentum \( \slashed{p}_T \), it is defined by

\[ m_{T2} \left( p_T^{(1)}, p_T^{(2)}, \slashed{p}_T \right) \equiv \min_{q_T^{(1)} + q_T^{(2)} = E_T^{\text{miss}}} \left\{ \max \left( m_T \left( p_T^{(1)}, q_T^{(1)} \right), m_T \left( p_T^{(2)}, q_T^{(2)} \right) \right) \right\} \]  

where \( m_T \) is the transverse mass

\[ m_T^2 \left( p_T^{(i)}, q_T^{(i)} \right) \equiv 2|p_T^{(i)}||q_T^{(i)}| - 2p_T^{(i)} \cdot q_T^{(i)} \]  

and the minimization is over all values of the two undetectable particles’ possible missing transverse momenta \( q_T^{(1,2)} \) consistent with the \( E_T^{\text{miss}} \) constraint. This variable gives the largest possible event-by-
1 lepton channel details

Selection criteria
1 lepton channel details

Fits to alternative control regions
The Phenogrid2 allows the presence of sleptons in the gluino and squark decays chains:
\(m(3\text{rd generation})=2000\ \text{GeV},\)
\(m(\text{slepton}_R)=m(\text{slepton}_L),\)
\(m(\text{squark}_R)=m(\text{squark}_L).\)

Two scenarios are considered:
a less favourable scenario, PhenoGrid2a with a very compressed spectrum yielding softer values of the discriminant variables, defined by
\(m(\text{chi}_2^0)=M-50\ \text{GeV},\)
\(m(\text{chi}_1^0)=M-150\ \text{GeV}\) and \(m(\text{slepton}_L)=M-100\ \text{GeV},\) where \(M\) is the minimum of the gluino and squark mass

and a more favourable one, PhenoGrid2b with \(m(\text{chi}_2^0)=M-100\ \text{GeV},\)
\(m(\text{chi}_1^0)=100\ \text{GeV}\) and \(m(\text{slepton}_L)=M/2\ \text{GeV}\)
2 lepton SS/OS msugra limit

ATLAS Preliminary
2-lepton analysis (OS and SS)
No correlations between the measurements of momentum, $dE/dx$ (Pixel), and Beta (Tile)

Exploited to estimate the amount of background arising from instrumental effects.

Estimates for the background mass distributions from $dE/dx$ (Pixel) and beta (Tile) are obtained by independently combining random momentum values (from the momentum distribution obtained after all kinematic cuts) with random measurements of $dE/dx$ Pixel and beta Tile respectively to yield mass estimates.
SMP search

- Signal region and 2d plots

![Diagram showing signal region and 2D plots](image-url)