SUSY searches with the ATLAS detector

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Overview of the talk

- SUSY at the LHC
- The ATLAS detector
- SUSY final states
- Analysis strategy
- Recent results
  - Inclusive 0/1/2-lepton searches
  - Third generation searches
  - RPV and long-lived sparticles
- Summary and conclusions
SUSY at the LHC

- Supersymmetry is a favoured extension of the Standard Model (SM)
- Postulates a matter-force symmetry, introducing a superpartner for each SM particle, with spin altered by $\frac{1}{2}$
- Allows solutions to open questions of the SM
  - Fine tuning of the Higgs mass
  - Hierachy problem
  - Unification of fundamental interactions
  - Provides a possible candidate for the Dark Matter (Lightest Supersymmetric Particle, LSP)
- General SUSY has a total of more than 100 parameters
  - There is a huge phase space to look into, with many possible different signatures
The ATLAS experiment

Multi-purpose collider detector for high-precision SM measurements and searches beyond SM

- Tracking system in $|\eta| < 2.5$ (silicon pixels/strips and TR tracker) with insertable b-layer
- EM (liquid Ar) and hadronic (scintillating tiles) calorimeters covering $|\eta| < 4.9$
- Muon spectrometer for muon identification with $\Delta p_T/p_T < 10\%$ up to 1 TeV
- Two magnet systems (toroidal and solenoidal)

Data collected in Run-2 at $\sqrt{s} = 13$ TeV: 3.2 fb$^{-1}$ in 2015 (shown here), 12.1 fb$^{-1}$ in 2016 (not shown)
SUSY final states of interest

- All final states characterized by large missing transverse energy $E_T^{\text{miss}}$ and energetic jets: they cover a wide range of models with complementary approach
- Analyses shown here include scenarios which violate R-parity (RPV) and the search of long-lived particles

SUSY searches with the ATLAS detector - A. Ventura
SUSY signal properties

- SUSY processes are generally characterized by large activity in the event, so they have high values of:

\[ H_T = p_T^\ell + \sum_{i=1}^{N_{\text{jet}}} p_{T,j} \]

\[ m_{\text{eff}} = p_T^\ell + \sum_{i=1}^{N_{\text{jet}}} p_{T,j} + E_T^{\text{miss}} \]

\[ m_T = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos[\Delta \phi(p_T^\ell, p_T^{\text{miss}})])} \]

\[ m_{T2}(p_T^1, p_T^2, p_T^{\text{miss}}) = \min_{q_{T,1} + q_{T,2} = p_T^{\text{miss}}} \{ \max[ m_T(p_T^1, q_{T,1}), m_T(p_T^2, q_{T,2}) ] \} \]

- Mass splitting between SUSY particles can be:
  - **Large** ⇒ production of boosted unstable particles (W, Z, top).
  - **Small** ⇒ presence of soft objects escaping reconstruction/detection: an additional hard jet (from ISR) is often required to get more boost, but introduces ISR systematics to be studied.

- N.B.: in the following, only \( e^\pm \) and \( \mu^\pm \) are considered as «leptons»
Typical analysis strategy

- Data selected in the trigger plateau, asking for good data-taking conditions and optimal event reconstruction.

- Monte Carlo (MC) samples generated to optimize event selection in given signal regions (SRs).

- Background estimates based on
  - Definition of dedicated control regions (CRs) optimized on MC for each relevant source of background, orthogonal to SRs;
  - Data driven techniques (e.g. for QCD);
  - Fully relying on MC for rare background sources (like dibosons or Higgs).

- Use of validation regions (VRs) to check CRs independently while keeping data in SRs blinded.

- Unblinding SRs and interpretation of results in predefined signal models.
0 leptons + 2-6 jets

- Very inclusive final state
- Assuming only gluinos (or only squarks) and LSP
- Also consider intermediate light chargino
- Six SRs chosen, depending on number of jets and mass spectrum compression

- Analyses all based on cut on $m_{\text{eff}}$ and on $R_1 = E_T^{\text{miss}}/m_{\text{eff}}$
- Exclusions to 1-1.5 TeV, generally exceed Run-1 limits
1 lepton + 2-6 jets

- Pair-produced gluinos decaying via light charginos

- Signature is one final-state $W^{(*)}$ decaying leptonically, together with $\leq 6$ jets and $E_T^{\text{miss}}$

- $E_T^{\text{miss}}$ cuts (70 GeV in trigger, 200 GeV offline) allow to select very soft leptons (from 6 to 35 GeV)

- Six different SRs based on $E_T^{\text{miss}}$, $m_{\text{eff}}$, $m_T$, jet aplanarity:
  - soft lepton & =2 or =5 jets;
  - hard lepton & =4 (2 variants), 5 or 6 jets

- Dominant background: $t\bar{t}$, W+jets

- Main systematics: JES and JER

- Data/MC agreement <2σ in all SRs

- Interpretation in several simplified models with assumptions about relations between sparticle masses
1 lepton - stop decay

- Two models of stop production considered: direct and gluino-mediated
- Signatures based on $t\bar{t} + E_T^{\text{miss}}$
- 3 SRs defined with cuts on $E_T^{\text{miss}}$, $m_T$, $a_{MT2}$, $\geq 1$ b-jet, topness ($\chi^2$ compatibility with $tt\to ll'X$)
- Main backgrounds: $t\bar{t}$, $Wt$ (or fully leptonic with one non selected lepton), $W+jets$. Data-driven estimate of fake leptons (negligible)
- Larger systematics: JES, JER, b-tagging, $E_T^{\text{miss}}$ due to soft lepton tracks
- Alternative interpretations: 3rd generation leptoquarks, vector-like quarks
2 leptons - stop decay

- Production of stop decaying to $b + \tilde{\chi}_1^\pm$
- Selection requires $b$-jets, leptons from $W$ decay, $E_T^{\text{miss}}$
- Two SRs (Different and Same Flavor leptons) based on third-lepton veto, $m_{ll} > 20$ GeV, $m_{T2} > 145$ GeV, $E_T^{\text{miss}}/m_{\text{eff}} > 0.3$
- Main backgrounds: $WW/ZZ \rightarrow llvv$ and $tt\bar{t}$ normalized to data in CRs and verified in VRs. Also $Z \rightarrow ll$ veto applied
- Minor backgrounds: $Z + \text{jets}, tt+V, Wt$ estimated on MC; fakes from data
- Results investigated in two signal models:
  \[ m_{\tilde{\chi}_1^\pm} = 2 \times m_{\tilde{\chi}_1^0} \]
  \[ m_{\tilde{t}_1} - m_{\tilde{\chi}_1^\pm} = 10 \text{ GeV} \]
Z → ll + Jets & $E_T^{\text{miss}}$

- Targets 1-step gluino decay, with $Z \rightarrow ll$
- SR requires 2 leptons from $Z$, $n_{\text{jets}} \geq 2$, $E_T^{\text{miss}} > 225$ GeV and $H_T > 600$ GeV
- Main backgrounds: $t\bar{t}$, WW, Wt, $Z \rightarrow \tau\tau$
- 21 events observed in SR (10 ee, 11 $\mu\mu$)
- $10.3 \pm 2.3$ expected

- p-value: 0.013
- Significance at 13 TeV, 3.2 fb$^{-1}$: 2.2$\sigma$
- Observed (Expected) S95: 20.0 (10.2$^{+4.4}_{-3.0}$)
2 same sign or 3 leptons

- Aims at same-charge products of gluino decays in low $\Delta m(\tilde{g}, \tilde{\chi}_1^0)$ region
- Also 3 leptons considered arising from final states with multiple Z, W and t decaying leptonically
- Four SRs defined for sensitivity to many SUSY processes (with both direct and two-step decay)
- SM background (mostly $t\bar{t}V$, $VV$, fake) strongly suppressed (for example using Z-veto)
Di-photon & $E_T^{miss}$

- Results interpreted in the context of general gauge mediation (GGM) SUSY model in which the Gravitino $\tilde{G}$ with mass $< 1$ GeV as LSP.

- Di-photon trigger selection ($p_T > 50$ GeV), tighter offline ($75$ GeV), $E_T^{miss} > 175$ GeV, $m_{eff} > 1500$ GeV.

- Main background from QCD (real di-photon+jets and jet-faking), W, Z, $tt$ with electron-faking, irreducible $W\gamma\gamma$ and $Z\gamma\gamma$ CR.

- Two benchmark points considered: $(m_g, m_\chi) = (1500, 1300)$ and $(m_g, m_\chi) = (1500, 100)$ GeV.

- No events observed in SR (SM expectation value of 0.27).

- GGM model limit set to 1650 GeV.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Number of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two photons, $p_T^{\gamma} &gt; 75$</td>
<td>4982</td>
</tr>
<tr>
<td>$\Delta \phi_{min}(jet, p_T^{miss}) &gt; 0.5$</td>
<td>4724</td>
</tr>
<tr>
<td>$m_{eff} &gt; 1500$ GeV</td>
<td>1</td>
</tr>
<tr>
<td>$E_T^{miss} &gt; 175$ GeV</td>
<td>0</td>
</tr>
<tr>
<td>Expected SM background</td>
<td>0.27$^{+0.22}_{-0.10}$</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
</tr>
</tbody>
</table>
RPV stop searches

- R-parity violating term in superpotential $\lambda^u_{ijk} \tilde{U}_i \tilde{D}_j \tilde{D}_k$

- $\tilde{t} \rightarrow b s$ decay expected in minimal flavor-violating SUSY scenarios

- Look for 2 heavy pairs of close-by jets (1 b-jet/pair)

- Dominant uncertainty: multijet production

- Final variable used: $m_{\text{avg}} = (m_{1ji} + m_{2ji})/2$

- Uncertainty limited by CR statistics

- Stop masses from 250 to 345 GeV are excluded at 95% CL (previous ATLAS 8 TeV limit was 320 GeV)
Long-lived ionizing particles (1/2)

- Search for **R-hadrons**: charged massive, low-β Long Lived Particles (LLPs)
  - **Stable** (lifetime >50 ns, escape detector)
  - **Metastable** (lifetime ~ns, detection in Pixels with dE/dx, improved with insertion of IBL)

- Mass determined by assuming the Bethe-Bloch for LLPs’ $\beta\gamma$:
  \[
  (dE/dx)_{MPV}(\beta\gamma) = \frac{p_1}{\beta p_3} \ln(1 + [p_2\beta\gamma]^{p_5}) - p_4
  \]
  with $p_i$ calibration constants from low momentum pions, kaons, protons

- Two SRs for stable / metastable LLPs
  - $E_T^{\text{miss}} > 130$ GeV
  - Track $p > 150$ GeV
  - Muon veto (for metastable)
  - Isolation & ionization requirements

- Data-driven background estimation
Long-lived ionizing particles (2/2)

<table>
<thead>
<tr>
<th>Selection Region</th>
<th>Background expected</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable $R$-hadron</td>
<td>$17.2 \pm 2.6 \pm 1.2$</td>
<td>16</td>
</tr>
<tr>
<td>Metastable $R$-hadron</td>
<td>$11.1 \pm 1.7 \pm 0.7$</td>
<td>11</td>
</tr>
</tbody>
</table>

- (Meta)stable $R$-hadrons excluded below 1.57 TeV

\[
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\]

**Phys. Rev. D 93, 112015 (2016)**
Summary and conclusions

- Run-2 with pp collisions at 13 TeV has been successful, with more than 15 fb$^{-1}$ of data collected the ATLAS detector until July 2016.

- Here results with 3.2 fb$^{-1}$ shown for just few signatures of interest.

- Search strategy for SUSY has been extended with respect to Run-1.

- **No significant excess** of events has been found so far and all results agree well with SM.

- LHC is expected to deliver much more data in 2016 and many unexplored regions will be tested to update limits.

- A very challenging year for SUSY is in front of us!
Backup slides
Abstract

• Despite the absence of experimental evidence, weak scale supersymmetry remains one of the best motivated and studied Standard Model extensions. This talk summarises recent ATLAS results for searches for supersymmetric (SUSY) particles, with focus on those obtained using proton-proton collisions at a centre of mass energy of 13 TeV. Strong production in both R-Parity conserving and R-Parity violating SUSY scenarios are considered. The searches involved final states including jets, missing transverse momentum, light leptons, as well as long-lived particle signatures.
### ATLAS SUSY Searches* - 95% CL Lower Limits

**Status:** March 2016

**$\sqrt{s} = 7, 8, 13$ TeV**

| Model | $\ell, \mu, \tau, \gamma$ | Jets | $E_{\text{miss}}$ | $|\Delta R|$(trk-$l^{-}$) | Mass limit | Reference |
|-------|--------------------------|------|-----------------|-----------------|------------|-----------|
| **Inclusive Searches** | | | | | |
| MSUGRA/CMSSM | $0-3 \phi, \mu / 1-2 \tau$ | 2-16 jets/3 b | Yes | 20.3 | $1.85 \text{TeV}$ | $m(\tilde{g}) < 860 \text{GeV}$ | ATLAS-CONF-2015-062 |
| GMSB (2 NLSP) | $1-2 \phi + 0-1 \ell$ | 0-2 jets | Yes | 20.3 | $1.52 \text{TeV}$ | $m(\tilde{g}) < 860 \text{GeV}$ | ATLAS-CONF-2015-062 |
| GGM (higgsino NLSP) | 2 $\ell$, 1 b | Yes | 20.3 | $1.52 \text{TeV}$ | $m(\tilde{g}) < 860 \text{GeV}$ | ATLAS-CONF-2015-062 |
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| GGM (higgsino NLSP) | 2 $\ell$, 1 b | Yes | 20.3 | $1.52 \text{TeV}$ | $m(\tilde{g}) < 860 \text{GeV}$ | ATLAS-CONF-2015-062 |
| Gravitino LSP | 0 | mono-jet | Yes | 20.3 | $1.52 \text{TeV}$ | $m(\tilde{g}) < 860 \text{GeV}$ | ATLAS-CONF-2015-062 |

**Additional Tables and Figures:**

- **3rd gen. squarks, gluinos, production:**
- **3rd gen. squarks, decays:**
- **EW direct:**
- **Long-lived particles:**
- **RPV:**
- **Other:**

*Only a selection of the available mass limits on new states or phenomena is shown.*
Definition of transverse masses

**Transverse mass** $m_T$

$$m_T^2(p_T^1, p_T^2) = [E_T^1 + E_T^2]^2 - [p_T^1 + p_T^2]^2$$

- $m_T = m_T(\ell, E_T^{\text{miss}}) = \sqrt{2p_T^\ell E_T^{\text{miss}}[1 - \cos\Delta\phi(p_T^\ell, p_T^{\text{miss}})]}$ bounded by $m_W$: reduce $WW, Wt, t\bar{t}$

**Stransverse mass** $m_{T2}$

- generalization of $m_T$ to pair decay with final state consisting of 2 visible objects and $E_T^{\text{miss}}$

$$m_{T2}(p_T^1, p_T^2, q_T) = \min_{q_T^1 + q_T^2 = q_T} \{ \max[m_T(p_T^1, q_T^1), m_T(p_T^2, q_T^2)] \}$$

- $m_{T2} = m_{T2}(p_T^1, p_T^2, p_T^{\text{miss}})$ bounded by $m_W$: reduce $WW, Wt, t\bar{t} \rightarrow 2\ell$

- $am_{T2}$ bounded by $m_t$: reduce $t\bar{t} \rightarrow 2\ell$ with a lost lepton

- $m_{T2}^\tau$ bounded by $m_W$: reduce $t\bar{t} \rightarrow \ell\ell^{\text{had}}$
0 leptons + 7-10 jets

- Two sets of regions using jets with $p_T > 50$ GeV or $p_T > 80$ GeV, using high-multiplicity jet triggers
  - 50 GeV: 8+, 9+ or 10+ jets with 0, 1 or 2+ b-jets and cutting on $E_T^{\text{miss}}/\sqrt{H_T}$
  - 80 GeV: same as above, only with 7+ or 8+ jets

- Interpretation in one- and two-step gluino decay

- Gluino masses up to 1.4 TeV excluded in large regions in these simplified models
Monojet (compressed $\tilde{q}$’s)

- Compressed scenario with ISR topology $\tilde{t} \rightarrow c \tilde{\chi}_1^0$:
  - Small squark-LSP mass difference, with large $E_T^{\text{miss}}$

- Dominant background $Z(\nu\nu)+\text{jets}$ estimated with CRs based on $W(\nu\nu)+\text{jets}$

- Fit to three main background sources:
  - $W(e\nu)$ / $W(\mu\nu)$ / $Z(\nu\nu)$

- Thirteen SRs defined by $E_T^{\text{miss}}$ thresholds/ranges from 250 to 700 GeV

- Results are interpreted in terms of 95% CL exclusion limits of parameters of the ADD model