Searches for squarks and gluinos in 
R-parity conserving models at the LHC

Christina Agapopoulou, on behalf of the ATLAS and CMS collaborations
Supersymmetry in the standard model of particle physics

★ Supersymmetry, or SUSY, is an extension of the Standard model predicting a partner to each SM fundamental particle with spin differing by 1/2

★ a very thorough overview of SUSY and its motivations given yesterday by Dr. Cem Salih Un

- SUSY particles in the Minimum Supersymmetric Standard Model
  - leptons → sleptons ($\tilde{l}$)
  - quarks → squarks ($\tilde{q}$)
  - gluons → gluinos ($\tilde{g}$)
  - $W/Z$ → gauginos
  - Higgs → higgsinos \{mixing to form $\tilde{\chi}_0^i, \tilde{\chi}_j^\pm$\}

SUSY must be a broken symmetry → SUSY particles expected at high masses
Supersymmetry in the standard model of particle physics

Why the persistent interest in SUSY?

- It provides possible solution to many shortcomings of the SM

  - Hierarchy problem of the Higgs boson “lightness”
Supersymmetry in the standard model of particle physics

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- Grand unification
Supersymmetry in the standard model of particle physics

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- In case of R-parity* conservation, it provides a WIMP-like dark matter candidate!

★ R-parity is an ad-hoc symmetry imposing that SUSY particles are produced and decay in pairs.

- Introduced to impose conservation of lepton/baryon number

- Lightest SUSY particle is neutral, stable and weakly interacting → excellent DM candidate
Supersymmetry in the standard model of particle physics

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- In case of R-parity* conservation, it provides a WIMP-like dark matter candidate!

- it’s a benchmark model!
Why search for squarks and gluinos?

- (Why not?)
- At the LHC, for a fixed mass **squarks** and **gluinons** have the highest expected production cross section
Let's simplify things

Even the minimal SUSY model (MSSM) has $\sim O(100)$ free parameters! How can we constrain such a vast phase-space?

★ simplified models!

- most LHC analyses today target SUSY in this simplistic way
- $2/3$ s-particles per model and rest of the SUSY spectrum effectively decoupled
- decay BRs to desired SM signatures often assumed to be 100%

★ Full picture much more complicated

- coupling with extra s-particles + smaller BRs can reduce x-section
- simplified model limits should be taken with a grain of salt!
So many models.. How to group them?
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Inclusive vs targeted
So many models.. How to group them?

- Inclusive vs targeted

- Specific final state:
  - hadronic activity (jets)
  - number of leptons
  - V bosons
  - 3rd generation specifics (b-jets, top id)
  - Higgs boson
  - ...

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The Run2 program of LHC

- both ATLAS and CMS recorded $\sim 140 \text{ fb}^{-1}$ of physics-worthy data
- luminosity and detector performances exceeded expectations
- many SUSY analyses published mid-Run with partial datasets $\rightarrow$ no significant deviations from the SM were observed :(

⭐ Disclaimer: only analyses using the full Run 2 datasets are shown in this presentation
The time for innovation

Taking advantage of the large amount of collected data, new analysis techniques can be tried out!
Inclusive searches
A case study: 0L, jets + $E_T^{\text{miss}}$ from ATLAS

**RPC search for gluinos and squarks (1st + 2nd generation only)**

- neutralino is LSP
- 2-6 jets
- no leptons
- large $E_T^{\text{miss}}$ from the escape of the neutralino

![Diagram of particle interactions involving gluinos and squarks](image)

ATLAS-CONF-2019-040
A case study: 0L, jets + $E_T^{\text{miss}}$ from ATLAS

Key variable

\[ m_{\text{eff}} = |E_T^{\text{miss}}| + \sum_{j=1}^{n} |p_T^j| + \sum_{l=1}^{n} |p_T^l| \]

Analysis strategy: 2 complementary approaches

★ Multi-bin fit based on "traditional" variables
  ▶ takes advantage of signal / bkg shape
  ▶ 3-D binning in $N_j$, $m_{\text{eff}}$, $E_T^{\text{miss}}/\sqrt{H_T} \to O(100)$ bins
  ▶ 3 separate strategies for direct squark, direct gluino and compressed spectrum

★ Boosted Decision Tree (BDT)
  ▶ cut & count approach
  ▶ introduce BDT variable built from $\sim 10$ kinematic variables
  ▶ targeting gluino direct/one-step decays
Main backgrounds: \(Z+\text{jets}, W+\text{jets}, t\bar{t} + \text{single-}t, \text{multi-jet QCD}\)

- For most backgrounds, **MC simulation** is used
  - mismodelling / detector effects can bias MC estimate
  - build dedicated Control Regions (CRs)
    - pure in target SM background + no signal
    - orthogonal to SRs
    - comparison of MC to data in CRs \(\rightarrow\) correction factors

- The extrapolation from CR to SR can be **validated**
  - in "intermediate" regions (VRs)
A case study: 0L, jets + $E_T^{miss}$ from ATLAS

★ Results:

▶ no significant excess from SM prediction :(

![Graph showing the results of the analysis with BDT-GGd1 score and Events/MC ratios.](image)
A case study: 0L, jets + $E_T^{\text{miss}}$ from ATLAS

In many cases, dominant sources of systematic uncertainty are:

- CR/MC sample statistical uncertainty
- modelling of SM backgrounds
- JES/JER

![Graph showing relative error and jet multiplicity](image)

**ATLAS** Preliminary

$s=13$ TeV, 139 fb$^{-1}$

MB-SSd Signal region

N$_{\text{jet}}$=[2,4) and N$_{\text{jet}}$=[4,$\infty$)

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19
A case study: 0L, jets + $E_T^{\text{miss}}$ from ATLAS

No excess in SRs $\rightarrow$ limits on potential models can be placed!

- exclusion limits from best SR per SUSY mass point
- for $\tilde{q}\tilde{q}$ grid, 8-fold $\tilde{q}$ degeneracy is assumed

0L, jets + $E_T^{\text{miss}}$ from CMS: CMS-SUS-19-006
the $M_{T2}$ variable:

$$M_{T2} = \min_{p_T^{\text{miss}}(1) + p_T^{\text{miss}}(2)} \left[ \max(M_T^{(1)}, M_T^{(2)}) \right]$$

- group jets until two stable large-R jets are constructed
- decompose $p_T^{\text{miss}}$ to take into account the 2 neutralinos
- compute transverse mass $M_T^{(i)*}$ from pairing either of the two jets to either of the two $p_T^{\text{miss}}$ components
- $M_{T2} \leq m_{\text{SUSY}}$
- low values for multijet events

$$M_T = \sqrt{2p_T^Jp_T^{\text{miss}}[1 - \cos(\Delta \phi_j, p_T^{\text{miss}})]}$$
0L, MT2 + disappearing tracks CMS

2 searches for $\tilde{g}, \tilde{q}$ (all generations):
- inclusive $0l + \text{jets}$ with $M_{T2}$ variable
- long-lived $\tilde{\chi}^{\pm}_1$ based on disappearing tracks

$M_{T2}$ inclusive:
- SRs binned in $N_j$, $N_b$, $H_T$ and $M_{T2}$ (or $p_T^{\text{jet}}$ for $N_j=1$)
- SM Background
  - lost lepton: estimated from 1L CRs
  - $Z \to \nu\nu$: from $Z \to ll$
  - QCD: data driven technique (rebalance and smear)
2 searches for $\tilde{g}, \tilde{q}$ (all generations):

- inclusive $0l + \text{jets with } M_{T2}$ variable
- long-lived $\tilde{\chi}_1^\pm$ based on disappearing tracks
2 searches for $\tilde{g}, \tilde{q}$ (all generations):

- inclusive $0l + \text{jets with } M_{T2}$ variable
- long-lived $\tilde{\chi}_1^{\pm}$ based on disappearing tracks

**Disappearing tracks:**

- **Event selection**
  - tracks with no outer-layer hits and no calo deposit
  - SRs split to various track lengths to probe different life times

- **SM Background**
  - poorly reconstructed objects
  - incorrect combinatorics
search for $\tilde{g}$ in final states with 1l, $p_T^{\text{miss}}$ and high $N_j$

Analysis strategy: 2 key variables

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

Main background: SM $t\bar{t}$

- $m_T$ and $M_J$ uncorrelated for SM $t\bar{t}$
- correlated for signal
search for $\tilde{g}$ in final states with 1l, $p_T^{\text{miss}}$, and high $N_j$

Signal regions:
- binning of $M_J-m_T$ plane in $N_j$, $N_b$, $p_T^{\text{miss}}$
- background from dedicated CRs
- No significant deviation from SM

CMS Preliminary

137 fb$^{-1}$ (13 TeV)

Data, $m_T > 140$ GeV
$\tilde{g} \tilde{g} \to t\tilde{t} \chi_{1}^{0} (2100,100)$
$\tilde{g} \to t\tilde{t} \chi_{1}^{0} (1900, 1250)$

Weighted data, $m_T \leq 140$ GeV

350 < $p_T^{\text{miss}}$ < 500 GeV, $N_{\text{jets}} \geq 7$, $N_b \geq 1$
search for \( \tilde{g} \) in final states with 1l, \( p_T^{\text{miss}} \) and high \( N_j \)

No significant deviation from SM

★ exclusion limits
★ \( m(\tilde{g}) > 2150 \) GeV
3rd Generation searches
Natural SUSY: scenario with minimum fine-tuning to obtain $m_H$ (hierarchy problem)

- s-particles with significant radiative contributions to Higgs potential should not be too heavy!
- stops, sbottoms, gluinos and higgsinos
- rest of the s-particles effectively decoupled
Why is 3rd generation special - natural SUSY

Assuming lightness of s-top, we get very interesting - and sensitive - phenomenology!

Decay topologies of $\tilde{t}_1$ in the $m(\tilde{\chi}_1^0)$-$m(\tilde{t}_1)$ plane  
(rest of s-particles decoupled)
Search for \(1l(e/\mu) + \text{high missing transverse energy}\)

**Signal selection**
- DNN to identify and categorize hadronically decaying \(t\)
- Standard selection: SRs defined by selections on \(N_j, N_t, E_T^{\text{miss}}, M_{lb}\)
- search regions targeting compressed mass spectra based on ISR
  - Two mass splittings: \(\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m_t, \Delta m(\tilde{\chi}_1^0) \sim m_W\)

**Main backgrounds**
- lost lepton: di-lepton CR
- one lepton: mainly from \(W+\text{jets} \rightarrow 0b\) CR
- \(Z+\text{jets}\): estimated from simulation
stop 1L, CMS

★ No excess from SM → exclusion + interpretation

- $m_{\tilde{t}} < 1.2$ TeV excluded
- exclusion in compressed region of the $\tilde{t} \rightarrow t\tilde{\chi}^0_1$ channel improved by x5

stop+1L from ATLAS, targeting 3-body decay: ATLAS-CONF-2019-017
**unique signature:** high \# (b)-jets, $E_T^{miss}$, 0 leptons + $h \to b\bar{b}$

- Analysis strategy: 3 SR groups to target 3 mass hierarchies
  - each taking advantage of special kinematic properties
  - try to reconstruct higgs boson - low efficiencies

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**moderate/high $\Delta m(\tilde{b}_1, \tilde{\chi}^0_2)$**

- $n_b \geq 4$
- at least one reco $h$
- multi-bin in $m_{eff}$

**SRA Target**

![SRA Target Diagram](image)

**SRB Target**

![SRB Target Diagram](image)

**SRC Target**

![SRC Target Diagram](image)

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**small $\Delta m(\tilde{b}_1, \tilde{\chi}^0_2)$, $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 130$GeV**

- ISR jet
- $n_b \geq 5$
- both $h$

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**small $\Delta m(\tilde{b}_1, \tilde{\chi}^0_2)$, $m(\tilde{\chi}^0_1) = 60$GeV**

- object-based $E_T^{miss}$-significance $S$
- $n_b \geq 4$

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[arXiv:1908.03122]
★ Interpretation in two mass-splitting scenarios:

- \( m(\tilde{\chi}^0_1) = 60 \text{ GeV} \)
- \( \Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) = 130 \text{ GeV} \)

\( \rightarrow m(\tilde{b}) \) excluded up to 1.5 TeV
Summary limits

★ Most partial limits extended by a few 100 GeV with full Run2 data
★ Many analyses targeting challenging regions
Run 2 of the LHC finished at the end of 2018 and was an undeniable success

Most SUSY analyses are now updating their partial results with the full dataset

Systematic use of simplified models

So far, no evidence of squarks and gluinos in RPC SUSY :( 

Most limits increased a few 100 GeV from partial results

Limit highlights:

$\tilde{g}\tilde{g} \rightarrow qqqq\tilde{\chi}_1^0\tilde{\chi}_1^0 : m(\tilde{g})$ excluded up to 2.4 TeV

$\tilde{q}\tilde{q} \rightarrow qq\tilde{\chi}_1^0\tilde{\chi}_1^0 : m(\tilde{q})$ excluded up to 1.9 TeV (assuming 8-fold degeneracy)

$\tilde{t}\tilde{t} \rightarrow tt\tilde{\chi}_1^0\tilde{\chi}_1^0 : m(\tilde{t})$ excluded up to 1.2 TeV

A lot more analyses to come! + reinterpretations, pMSSM scans
Thank you for your attention!
Backup
Search for $\tilde{q}$ and $\tilde{g}$ - signatures with same-sign (SS) or $\geq 3$ leptons

- selection based on $n_l, N_j, E_T^{\text{miss}}, m_{\text{eff}}$
- $+ N_b$ to probe 3rd generation $\tilde{q}$

**SM Background:**
- WZ+jets, $t\bar{t}V, VV$
- Reducible: charge flip, fake/non-prompt leptons

`[arXiv:1909.08457]`

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**ATLAS**

<table>
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<th>Events</th>
<th>Data</th>
<th>WZ</th>
<th>$t\bar{t}Z$</th>
<th>$t\bar{t}W$</th>
<th>WW</th>
<th>ZZ</th>
<th>VV</th>
<th>Charge-flip</th>
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</table>

**ss+3l from CMS:** CMS-SUS-19-008

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search for \( \tilde{t} \) - signatures with \( E_T^{\text{miss}} \), jets + 2 SF-OS l (Z-boson)

★ Event selection:
- 4 SRs for 2 mass splittings of the two models
- cuts on \( E_T^{\text{miss}} \), \( N(b)_{\text{jets}} \), \( p_T^{\text{jet}} \) ...

★ Background:
- main contributions from \( t\bar{t}Z + \text{multi-V} \)
- estimated from dedicated CRs
- fake/non-prompt lepton \( \rightarrow \) data driven

<table>
<thead>
<tr>
<th>Requirement / Region</th>
<th>SR(_{1A})</th>
<th>SR(_{1B})</th>
<th>SR(_{2A})</th>
<th>SR(_{2B})</th>
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<td>Third leading lepton ( p_T ) [GeV]</td>
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<td>&gt; 20</td>
<td>&lt; 20</td>
<td>&lt; 60</td>
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<td>( n_{\text{jets}} ) (( p_T &gt; 30 ) GeV)</td>
<td>≥ 4</td>
<td>≥ 5</td>
<td>≥ 3</td>
<td>≥ 3</td>
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<tr>
<td>( n_{\text{b-tagged jets}} ) (( p_T &gt; 30 ) GeV)</td>
<td>≥ 1</td>
<td>≥ 1</td>
<td>–</td>
<td>≥ 1</td>
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<tr>
<td>Leading jet ( p_T ) [GeV]</td>
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<td>&gt; 150</td>
<td>–</td>
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<tr>
<td>Leading b-tagged jet ( p_T ) [GeV]</td>
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<td>( p_{\ell\ell} ) [GeV]</td>
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<td>&lt; 50</td>
<td>&gt; 150</td>
</tr>
<tr>
<td>( m_{T2}^{3\ell} ) [GeV]</td>
<td>&gt; 100</td>
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</table>
Targeting 3 - body decay with challenging mass splitting

$$m_W + m_b < \Delta m(\tilde{t}, \tilde{\chi}_1^0) < m_t$$

☆ Recurrent Neural network:
- classifier between signal and SM $t\bar{t}$
- analysis binned in NN score

☆ SM Background:
- Main contribution from "lost lepton" $t\bar{t}$
- estimated from dedicated CR / extrapolation validated in VR
- residual backgrounds from MC estimates
★ Results: good SM / data agreement in VR and SRs

★ Interpretation in the full mass spectrum

- $m(\tilde{t})$ excluded up to 720 GeV for $m(\tilde{\chi}_1^0) \sim 580$ GeV