SEARCHES FOR SQUARKS AND GLUINOS AT THE LHC

Maria Giulia Ratti (ETHZ)

on behalf of the CMS & ATLAS Collaborations

DIS 2019

Torino - April 10th 2019
Super-symmetry provides elegant solutions to theoretical and experimental open questions of the Standard Model

- stabilises higgs mass at the EWK scale
- provides a Dark Matter candidate
- provides unification of gauge couplings
**Strong SUSY at the LHC**

Squarks and gluinos produced via **strong-interaction**

=> largest cross-sections => highest mass reach

If R-parity is conserved (RPC) and lightest SUSY particle (LSP) is neutral

=> get large **missing transverse momentum (MET)** and large event activity, with hard jets and/or leptons

![Diagram of SUSY processes](image)
**Situation after 36 fb⁻¹**

- extremely rich and varied set of SUSY searches from CMS & ATLAS (inclusive & targeted)
- but no sign of SUSY so far!

### ATLAS SUSY Searches - 95% CL Lower Limits

**July 2018**

<table>
<thead>
<tr>
<th>Model</th>
<th>Jets</th>
<th>$E_{\text{miss}}^T$</th>
<th>$\mathcal{L} , \text{fb}^{-1}$</th>
<th>Mass limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q}, \tilde{q} \rightarrow W^0 \tilde{\chi}^0_1$</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>36.1</td>
<td>0.43</td>
</tr>
<tr>
<td>$\tilde{q}, \tilde{q} \rightarrow QW^0 \tilde{\chi}^0_1$</td>
<td>0</td>
<td>mono-jet</td>
<td>36.1</td>
<td>0.71</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{g} \rightarrow WW(\ell\nu)$</td>
<td>3 jets</td>
<td>-</td>
<td>36.1</td>
<td>Forbiden</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{g} \rightarrow WWZ \tilde{\chi}^0_1$</td>
<td>4 jets</td>
<td>-</td>
<td>36.1</td>
<td>1.2</td>
</tr>
<tr>
<td>$\tilde{g}, \tilde{g} \rightarrow ZTT \tilde{\chi}^0_1$</td>
<td>4 jets</td>
<td>-</td>
<td>36.1</td>
<td>0.98</td>
</tr>
</tbody>
</table>

**For strong RPC SUSY, similar maximal reach on sparticle masses between CMS & ATLAS:**

- gluino ~ 2 TeV
- stop ~ 1 TeV
- light squarks ~1.55 TeV

Maria Giulia Ratti - ETH Zürich
The path towards the Summit...

CMS Integrated Luminosity, pp, $\sqrt{s} = 7, 8, 13$ TeV

Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC

- LHC Delivered: 192.29 fb$^{-1}$
- CMS Recorded: 177.65 fb$^{-1}$

Now getting to the (local) summit!

We were here...

up to $\times$ 4 statistics => $\sim \times$ 2 signal significance

In this talk: **personal selection** of first **full Run-2** ($\sim 140$ fb$^{-1}$) and **partial Run-2** results
Overview of Recent Results

Very latest results on gluino and squark production

CMS

- MT2 + jets 137 fb⁻¹ SUS-19-005
- SS leptons + jets / 3 leptons 137 fb⁻¹ SUS-19-008
- GGM combination 36 fb⁻¹ SUS-18-005
- Diphoton + MET 36 fb⁻¹ SUS-17-011
- Delayed jets + MET 137 fb⁻¹ EXO-19-001

ATLAS

- b-jets + H + MET 139 fb⁻¹ CONF-2019-011
- DV + displaced muon 136 fb⁻¹ CONF-2019-006
- Pixel ionisation, calorimeter and muon timing 32 fb⁻¹ arXiv:1902.01636
- ttbar spin correlations 36 fb⁻¹ arXiv:1903.07570

Check out all CMS & ATLAS SUSY public results
**MT2 Analysis Strategy**

**Inclusive** search in final states with 0-lepton + MET + jets

Targets gluinos and squarks pair production, including 3rd generation

Search variable **MT2**

- generalisation of transverse mass $M_T$ to case of two decay chains with an invisible particle each
- MET-like, enhanced S/B discrimination in the tails

**Event topologies**

- High $H_T$
- At least one jet
- $\mu/e$ veto
- Isolated track veto
- Trigger on MET, $H_T$, or $H_T+$MET

Phase space binned in “topological regions”

$= (H_T, N_j, N_{bj})$ bins

Each topological region further binned in MT2

**O(300) search regions!**

Predicted background fitted to the data in all topological regions simultaneously to extract the signal
MT2 analysis Backgrounds

Main backgrounds:

- **Z(vv)+jets** and **lost lepton** (W+jets & top)
- transfer factors from 2-lepton and 1-lepton CRs to SR, in each (H_T, N_j, N_bj) bin
- shape of MT2 taken from data in the CR until stats are too low, then MC is used to distribute events

- For Z(vv)+jets, use Z(ll)+jets with leptons added vectorially to MET
- top contamination in Z(ll) CR estimated via ABCD method
Background estimation compared to data observed in signal regions, integrated in MT2 in all (HT, Nj, Nb) bins

=> No significant excess over the SM predictions
No significant excess over the SM predictions

=> exclusion limits on simplified models, gluino pair production

Maximal excluded gluino masses ~ 2.3 TeV
Results Squarks

No significant excess over the SM predictions

=> exclusion limits on simplified models, squark pair production

Light flavour squarks

assuming 8-fold, max. limit on light flavour squark $\sim 1.8$ TeV

Bottom squarks

max. limit on sbottom $\sim 1.3$ TeV

Top squarks

max. limit on stop $\sim 1.2$ TeV
MT2 + Disappearing Track

Targets:
- strong susy with long-lived charginos
- chargino decays to pion and neutralino with $\Delta m(\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_1) \sim 100 \text{ MeV}$

Signature:
- pion too soft to be detected
- disappearing track + jets + MET

Analysis strategy:
- bins in $N_j$, $H_T$, dis. track length and $p_T$
- background: fake tracks and poorly reconstructed tracks from pions/leptons
- fake rate estimated from data in low MT2 sideband and validated at intermediate MT2

No significant excesses over predictions
Can probe gluino up to 2460 GeV, neutralino up to 2000 GeV

higher sensitivity to large $\Delta m(\tilde{g}, \tilde{\chi}^0_1)$ for short tracks

higher sensitivity to small $\Delta m(\tilde{g}, \tilde{\chi}^0_1)$ for long tracks
Signature: **two SS or three or more light leptons** (electrons and muons) and at \( \geq 3 \) jets  
very rare signature in SM \( \Rightarrow \) low-background search

Targets:
- RPC strong production **with W/Z in the decay**
- low lepton \( p_T \) & MET categories suitable to probe **RPV** scenarios

Categorisation based on \( N\text{-lep}, \text{lep} p_T, N_j, N_{bj}, \text{MET}, H_T \)

Backgrounds:
- rare SM processes leading to 2L-SS estimated via data/MC ratios
- fake leptons (data-driven) with “tight-to-loose” ratio method

Largest deviation from SM predictions \( 2.6 \sigma \), but adjacent bin in \( H_T \) shows \(-1.6\sigma\)
$\Delta m(\tilde{\chi}^\pm_1, \tilde{\chi}^0_1) = 20 \text{ GeV}$

on-shell 3rd gen. squarks

$\Delta m(\tilde{t}, \tilde{\chi}^0_1) = m_t$

RPV w/ non-zero coupling in the baryonic sector
Targets \textbf{sbottom} pair production with \textbf{Higgs} in the decay chain:

- fixed $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1)=130$ GeV, sufficient to produce on-shell $h$
- fixed LSP mass, $m(\tilde{\chi}^0_1)=60$ GeV, motivated by relic density

Signature: \textbf{up to 6 jets, multiple b-tags, MET, 0-leptons}

Signal regions \textbf{target three topologies:}

- SRA moderate-high $\Delta m(b\tilde{\chi}^0_2)$
- SRB small $\Delta m(b\tilde{\chi}^0_2)$, fixed $\Delta m(b\tilde{\chi}^0_2)$
- SRC small $\Delta m(b\tilde{\chi}^0_2)$, fixed $\tilde{\chi}^0_1$

Dominant backgrounds:

- top in SRA and SRB
- Z+jets in SRC

Bkg estimation via \textit{simultaneous fit} in 1-lep, 2-lep control regions

No significant deviation over the SM predictions
**MET + B-JETS + H(BB)**

Significant improvement wrt Run-1 search

Complementarity to other sbottom searches

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**ATLAS Preliminary**

\[ m(\tilde{\chi}_1^0) = 60 \text{ GeV} \]

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

maximal excluded sbottom mass ~ 1.5 TeV

maximal excluded sbottom mass ~ 1.35 TeV

loss in sensitivity due to stringent offline MET cut
**Delayed Jets + MET**

Signature is **delayed jets + large MET**, using ECAL timing

Targets **long-lived neutral hadronic** particles decaying to **jets + invisible**

Benchmark model: (one) long-lived gluino ($\tilde{g} \rightarrow \tilde{G}g$) in GMSB

Event selection:
- MET>300 GeV, barrel jets, $p_t>30$ GeV, $t_{\text{jet}}>3$ns, $t_{\text{jet}}<20$ns
- **Jet cleaning** aims to kill various sources of instrumental background:
  - ECAL noise, beam halo, cosmics, oot pile-up, satellite bunches

Residual backgrounds estimated from data control regions with inverted cuts, e.g. invert $E_{\text{CSC,ECAL}}/E_{\text{ECAL}} < 0.8$, $E_{\text{HCAL}}/E_{\text{total}} > 0.2$

<table>
<thead>
<tr>
<th>Background</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam halo</td>
<td>$0.02^{+0.06}<em>{-0.02}$ (stat) $^{+0.05}</em>{-0.03}$ (syst)</td>
</tr>
<tr>
<td>Core and satellite bunches</td>
<td>$0.11^{+0.09}<em>{-0.05}$ (stat) $^{+0.02}</em>{-0.02}$ (syst)</td>
</tr>
<tr>
<td>Cosmics</td>
<td>$1.0^{+1.8}<em>{-1.0}$ (stat) $^{+1.8}</em>{-1.0}$ (syst)</td>
</tr>
</tbody>
</table>

0 observed events consistent with prediction
Gluino excluded up to 
\( m = 2100, 2500 \) and \( 2150 \) GeV 
for \( c\tau_0 = 0.3, 1.0, \) and \( 30 \) m
Challenging region: **stop and top stop nearly degenerate in mass**

=> \( \tilde{t}\tilde{t} \) production looks like ttbar production

=> Tackle with precise estimate of ttbar using clean channel (OS emu pair)

**ATLAS** [arXiv:1903.07570]

**CMS** [arXiv:1901.01288]
Signature:
- stop pair production would produce different spin correlation compared to SM ttbar

Observables:
- $\Delta \phi$ and $\Delta \eta$ of OS emu pair (leptons carry spin information of the parent top)

Strategy:
- Simultaneous fit of the SM $\Delta \phi$ prediction (Powheg+Pythia) to observed data in three differential $\Delta \eta$ regions

> top corridor region largely excluded compared to generator prediction
An **extensive program of searches** for strongly produced SUSY particles
- complementarity of *inclusive* and *targeted* searches
- both standard and exotic / rare decay channels being explored

**No significant excesses** of events have been found so far

=> **Many more results upcoming with full Run-2 dataset**
BACK-UP SLIDES
CMS Limits after 36 fb⁻¹ @ 13 TeV

Overview of SUSY results: gluino pair production
36 fb⁻¹ (13 TeV)

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Expected Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP → gg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → tt [χ₁⁻]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → tt [χ₀]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → tt [χ₁⁺]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → qql [χ₁⁻/χ₂⁻/χ₂]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → qql [χ₁⁺]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>g → qql [χ₁⁻]</td>
<td></td>
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</tr>
</tbody>
</table>

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probe up to the quoted mass limit for light LSPs unless stated otherwise. The quantities ΔM and x represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to ΔM, respectively, unless indicated otherwise.

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10/04/2019
CMS LIMITS AFTER 36 fb$^{-1}$ @ 13 TeV

Overview of SUSY results: squark pair production

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

**CMS**

**July 2018**

- **pp → t̅t̅**
  - $0/t$: arXiv:1705.04650, 1704.07783, 1802.02110, 1707.03316, 1710.11188
  - $1/t$: arXiv:1706.04462
  - $2^{nd}$ opposite-sign: arXiv:1711.00752

- **$t̅ → b_s^+ → bW^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1707.03316
  - $1/t$: arXiv:1706.04462
  - $x = 0.5$

- **$t̅ → b_s^+ → bW^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1707.03316
  - $1/t$: arXiv:1706.04462
  - $x = 0.5$

- **$t̅ → (t̅_1^0/t̅_1^1) → bW^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1707.03316
  - $1/t$: arXiv:1706.04462
  - $\Delta M_{bW^+_3} = 5$ GeV, BF=50%

- **$t̅ → b^+_3 t̅_1^-$**
  - $0/t$: arXiv:1707.03316
  - $\Delta M < 80$ GeV (max. exclusion)

- **$t̅ → b^+_3 t̅_2^-$**
  - $0/t$: arXiv:1707.03316
  - $\Delta M < 80$ GeV (max. exclusion), $x = 0.5$

- **$t̅ → t^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1707.03316
  - $1/t$: arXiv:1711.00752
  - $x = 0.5$

- **$t̅ → b^+_3 t̅_2^-$**
  - $0/t$: arXiv:1707.03316
  - $\Delta M < 80$ GeV (max. exclusion), $x = 0.5$

- **$t̅ → c^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1707.03316
  - $1/t$: arXiv:1711.00752
  - $\Delta M < 80$ GeV (max. exclusion)

- **$t̅ → (t̅_1^0/t̅_1^1) → bW^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1704.07783, 1705.04650, 1802.02110
  - $1/t$: arXiv:1709.00384
  - $\Delta M_{bW^+_3} = 130$ GeV

- **$b → t^+_3 t̅_1^-$**
  - $0/t$: arXiv:1704.07783, 1705.04650, 1802.02110
  - $1/t$: arXiv:1709.00384
  - $\Delta M_{bW^+_3} = 130$ GeV

- **$b → t^+_3 t̅_1^-$**
  - $0/t$: arXiv:1704.07783, 1705.04650, 1802.02110
  - $1/t$: arXiv:1709.00384
  - $\Delta M_{bW^+_3} = 50$ GeV

- **$b → t^+_3 t̅_1^-$**
  - $0/t$: arXiv:1704.07783, 1705.04650, 1802.02110
  - $1/t$: arXiv:1709.00384
  - $\Delta M_{bW^+_3} = 50$ GeV

- **$b → b^+_3 t̅_1^-$**
  - $0/t$: arXiv:1705.04650, 1704.07783, 1705.04650, 1802.02110
  - $1/t$: arXiv:1709.00384
  - $\Delta M_{bW^+_3} = 130$ GeV

Selection of observed limits at 95% C.L. (theory uncertainties are not included). Probes up to the quoted mass limit for light LSPs unless stated otherwise.

The quantities $\Delta M$ and $x$ represent the absolute mass difference between the primary sparticle and the LSP, and the difference between the intermediate sparticle and the LSP relative to $\Delta M$, respectively, unless indicated otherwise.
**MET + B-jets + H(bb)**

"bulk" region
moderate-high $\Delta m(b, \tilde{\chi}_2^0)$
all b-jets resolved

SRA Target
- $b$-jets from $\tilde{b}_1$ decays
- $b$-jets from $h$ decays
- $E_T^{miss}$

SRB Target
- ISR jet
- $b$-jets from $\tilde{b}_1$ decays
- $b$-jets from $h$ decays
- $E_T^{miss}$

SRC Target
- $b$-jets from $\tilde{b}_1$ decays
- $b$-jets from $h$ decays
- $E_T^{miss}$

$m(\tilde{\chi}^0_{11}) = 60$ GeV (relic density)
small $\Delta m(b, \tilde{\chi}_2^0)$
low pT b-jets

$m(\tilde{\chi}^0_{11}) = 60$ GeV (relic density)
small $\Delta m(b, \tilde{\chi}_2^0)$
low pT b-jets