RPV + stealth SUSY
(LLP + unconv. signatures)

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On behalf of ATLAS and CMS
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Motivation

• More traditional supersymmetry searches so far have not come up with any new particles.

• Naturally, ask what non-standard signatures have we not covered in standard SUSY searches?

• A wide variety of non-standard SUSY models: R-parity violating, “compressed” spectra, stealth, split, hidden sector, etc...

• Many models have particles that have a longer lifetime.

• Requires clever techniques in analysis to reconstruct these particles and to suppress SM backgrounds.
RPV Supersymmetry

\[
W_{R_{\chi}} = \frac{1}{2} \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \frac{1}{2} \lambda''_{ijk} U^c_i D^c_j D^c_k
\]

\[\tilde{\chi}^\pm \rightarrow l^\pm l^{\mp} l^\pm\]

\[\tilde{\gamma} \rightarrow qqq\]
# RPV Supersymmetry

<table>
<thead>
<tr>
<th></th>
<th>$\lambda L LE$</th>
<th>$\lambda' L Q D$</th>
<th>$\lambda'' U D D$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct RPV decays</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{\nu}$</td>
<td>$Z'$ $\ell^+ \ell^-$</td>
<td>$d\bar{d}$</td>
<td>—</td>
</tr>
<tr>
<td>$\tilde{\ell}^-$</td>
<td>$W'$ $\ell^- \nu$</td>
<td>$\tilde{u}d$</td>
<td>—</td>
</tr>
<tr>
<td>$\tilde{u}$</td>
<td>—</td>
<td>pair prod: leptoquarks $\ell^+ d$, $\ell^- u$</td>
<td>$d\bar{d}$</td>
</tr>
<tr>
<td>$\tilde{d}$</td>
<td>—</td>
<td></td>
<td>$\tilde{u}d$</td>
</tr>
<tr>
<td>$\tilde{\chi}^0$</td>
<td>$\ell^+ \ell^- \nu$</td>
<td>$\ell^+ \tilde{u}d$, $\ell^- u\bar{d}$, $\nu d\bar{d}$</td>
<td>$udd$, $\tilde{u}d\tilde{d}$</td>
</tr>
<tr>
<td>$\tilde{\chi}^+$</td>
<td>$\ell^+ \ell^- \ell^+$, $\ell^+ \nu\nu$</td>
<td>$\ell^+ d\bar{d}$, $\ell^+ u\bar{d}$, $\nu u\bar{d}$</td>
<td>$uud$, $\tilde{u}d\tilde{d}$</td>
</tr>
<tr>
<td><strong>Indirect RPV decays</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{u}_i \rightarrow u_i \tilde{\chi}^0$</td>
<td>$u_i \ell^+ \ell^- \nu$</td>
<td>$u_i \ell^+ \tilde{u}d$, $u_i \ell^- u\bar{d}$, $u_i \nu d\bar{d}$</td>
<td>$u_i u\tilde{d}$, $u_i \tilde{u}d\tilde{d}$</td>
</tr>
<tr>
<td>$\tilde{u}_i \rightarrow d_i \tilde{\chi}^+$</td>
<td>$d_i \ell^+ \ell^+ \ell^-$, $d_i \ell^+ \nu\nu$</td>
<td>$d_i \ell^+ d\bar{d}$, $d_i \ell^+ u\bar{d}$, $d_i \nu u\bar{d}$</td>
<td>$d_i u\tilde{d}$, $d_i \tilde{u}d\tilde{d}$</td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow u_i \tilde{u}_i$</td>
<td>—</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tilde{g} \rightarrow u_i \tilde{u}_i \tilde{\chi}^0$</td>
<td>$u_i \tilde{u}_i \ell^+ \ell^- \nu$</td>
<td>$u_i \tilde{u}_i \ell^+ \tilde{u}d$, $u_i \tilde{u}_i \ell^- u\bar{d}$</td>
<td>$u_i d\tilde{d}$</td>
</tr>
</tbody>
</table>

Table by Ana Ovcharova

- Single sparticle production: dijet resonance, $Z'$, $W'$
- Pair production: paired dijets, excited tops
- Pair production: all-hadronic + resonances

- Inclusive 1ℓ, high jet multiplicity with low or no MET
- 2ℓ OS, 4ℓ, 6ℓ with low or no MET
Many Long-Lived Searches

• **ATLAS**: LLP in displaced jets with muon spectrometer: *Phys. Rev. D 99, 052005*
• **ATLAS**: HIP/monopole
• **ATLAS**: Higgs -> Z + LLP: *Phys. Rev. D 99, 052003*
• **CMS**: Search for new particles decaying to a jet and an emerging jet: [JHEP02(2019)179](https://link.springer.com/article/10.1007%2FJHEP02%282019%29179)
• **CMS**: search for prompt HNL: *Phys. Rev. Lett. 120, 221801*
• **CMS**: long-lived (disappearing track) component of the SUSY MT2 search: [CMS-SUS-19-005](https://cds.cern.ch/record/2657438)
• **CMS**: LLP using delayed jets and missing transverse momentum: [EXO-19-001-PAS](https://cds.cern.ch/record/2657438)
• **LHCb**: dark photon search *Phys Rev. Lett. 120, 061801*
• **LHCb**: Search for a dimuon resonance in the $\Upsilon$ mass region: [JHEP09(2018)147](https://link.springer.com/article/10.1007%2FJHEP09%282018%29147)

Just a subset of long-lived searches – definitely more than can be covered in one talk!

Searches for long-lived particles and other unconventional signatures (Martino Borsato)

Searches for LLP in ATLAS (Sascha Mehlhase) and Searches for LLP in CMS (Malgorzata Kazana)
Search with Displaced Vertex and Muon

ATLAS-CONF-2019-006

• Full Run II Result!! (136 fb\(^{-1}\), 2016 - 2018)
• Pair production of stop LSP, followed by \(\tilde{t} \rightarrow q\mu\) with small \(\lambda'_{23k}\) coupling
• Range of lifetimes \(\sim 0.01\) ns to 100 ns (3 mm to 30 m)

• Large radius tracking – extends number of tracks by relaxing req. for impact parameter and number of shared hits.
• Displaced secondary vertex algorithm – only tracks with transverse impact parameter > 2 mm and \(p_T > 1\) GeV considered

• Dedicated vetoes for three major backgrounds:
  • Cosmic muons
  • Fake muons from random hit combinations
  • Semileptonic decays of SM hadrons

Object Selection:

<table>
<thead>
<tr>
<th>Selection level</th>
<th>Muon selection</th>
<th>Displaced vertex selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>(p_T &gt; 25) GeV, (</td>
<td>\eta</td>
</tr>
<tr>
<td>Full selection</td>
<td>Pass cosmic-muon, fake-muon, and heavy-flavor vetoes</td>
<td>(n_{\text{tracks}}^{DV} \geq 3), (m_{DV} &gt; 20) GeV</td>
</tr>
</tbody>
</table>
Search with Displaced Vertex and Muon

ATLAS-CONF-2019-006

Event Selection:

- **Two Triggers:**
  - missing $E_T$ ($E_{T,miss} > 180$ GeV)
  - muon ($p_T^\mu > 60$ GeV, $E_{T,miss} < 180$ GeV)

- **Background estimation** comes from transfer factors in regions that do not pass the full-selection.

- Limits set for $m_\tilde{t}$ as function of $c\tau$
Two same-sign leptons or at least three leptons and jets

**CMS-SUS-19-008-PAS**

- Full Run II Result!! (137 fb\(^{-1}\), 2016-2018)
- Mostly an RPC SUSY search, but have RPV interpretations:
  - dedicated low missing \( E_T \) search region (\( = 2 \) leptons, \( p_T > 25 \text{ GeV} \) and missing \( E_T < 50 \text{ GeV} \)).
- Pair production of \( \tilde{g} \), followed by one of two decay cascades:
  - T1qqqqL: \( \tilde{g} \rightarrow \tilde{q}q, \tilde{q} \rightarrow q\bar{\chi}^0_1 \rightarrow qq\bar{q}l \)
  - T1tbs: \( \tilde{g} \rightarrow tbs \)

Low missing \( E_T \) search bins:

<table>
<thead>
<tr>
<th>( N_b )</th>
<th>( N_{jets} )</th>
<th>( H_T \in [300, 1125] \text{ GeV} )</th>
<th>( H_T \in [1125, 1300] \text{ GeV} )</th>
<th>( H_T &gt; 1300 \text{ GeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2-4</td>
<td>SR1</td>
<td>SR8 (( N_{jets} &lt; 5 ))</td>
<td>SR10 (( N_{jets} &lt; 5 ))</td>
</tr>
<tr>
<td></td>
<td>5+</td>
<td>SR2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2-4</td>
<td>SR3</td>
<td>SR9 (( N_{jets} \geq 5 ))</td>
<td>SR11 (( N_{jets} \geq 5 ))</td>
</tr>
<tr>
<td></td>
<td>5+</td>
<td>SR4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2-4</td>
<td>SR5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5+</td>
<td>SR6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \geq 3 )</td>
<td>2+</td>
<td>SR7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Triggers:
  - Two isolated leptons
    - \( p_{T,1}^l > 17 - 23 \text{ GeV} \)
    - \( p_{T,2}^l > 8 - 12 \text{ GeV} \)
  - Two non-isolated leptons
    - \( p_{T,1}^l, p_{T,2}^l > 8 \text{ GeV} \)
    - \( H_T > 300 - 350 \text{ GeV} \)
Two same-sign leptons or at least three leptons and jets

- Backgrounds include:
  - Multiple EW bosons production modes (in top quark decays, for example) – estimated using simulation
  - “Non prompt lepton” – misidentified hadron or its decay product. Estimated from “tight-to-loose” method
  - Charge mismeasurement

2.3σ excess in one bin!
Heavy charged long-lived particles


- 2015 -2016 Run II Result (36.1 fb\(^{-1}\))
- Not RPV, but both gluinos and squarks can be long lived (split SUSY)
- Other models include charginos (mAMSB) and stau direct production (GMSB)

\[
- \left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \left[ \frac{1}{\beta^2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\text{max}}}{I^2} - \beta^2 - \frac{\delta(\beta \gamma)}{2} \right]
\]

Two main observables:
- **dE/dx** – R-hadrons and the other SUSY LLP tend to have larger masses and will move slower through the detector, having larger ionization energy losses
  - Corrected for \(\eta\) dependence and run-by-run.
- **Time of Flight** – Since the R-hadrons are moving slower, the time of flight is also longer
  - Measured in the MDTs, the tile calorimeter, and the RPCs and a weighted average using the uncertainties are used.
  - High \(p_T\) muons are used for a series of custom calibrations.
Heavy charged long-lived particles


Divided into 5 mutually exclusive regions

- MS agnostic – do not use information in MS (R hadron-calorimeter interaction agnostic)
- Candidate selection using ID+calo selection, loose, or tight determination ($\eta$ and $p$)
Long-lived particles to displaced jets


- 2016 Result (35.9 fb$^{-1}$)
- RPV SUSY with MFV ($\lambda'_{323}$): $\tilde{g} \rightarrow tbs$
  - $1200 \text{ GeV} < m_{\tilde{g}} < 3000 \text{ GeV}$, $1 \text{ mm} < c\tau < 10 \text{ m}$
- RPV SUSY ($\lambda'_{33k}$): $\tilde{t} \rightarrow bl$
  - $200 \text{ GeV} < m_{\tilde{t}} < 1600 \text{ GeV}$, $1 \text{ mm} < c\tau < 1 \text{ m}$
- Long-lived gluino model (GMSB): $\tilde{g} \rightarrow g\tilde{G}$
  - $800 \text{ GeV} < m_{\tilde{g}} < 2500 \text{ GeV}$, $1 \text{ mm} < c\tau < 10 \text{ m}$
- Simplified jet-jet model (two scalar neutral X particles)
  - $50 \text{ GeV} < m_{X} < 3000 \text{ GeV}$, $1 \text{ mm} < c\tau < 10 \text{ m}$

Selection:

- Derives a likelihood discriminant using vertex track multiplicity, vertex $L_{xy}$ significance, and cluster RMS.
- Contains 9 regions (expanded ABCD method) with 3 selection criteria to cross-check all background estimation methods.
Long-lived particles to displaced jets

\( \tilde{g} \rightarrow tbs \)

ATLAS has a similar displaced jets search, but without a RPV interpretation (covered in Martino’s talk).

\( \tilde{t} \rightarrow bl \)

\[ g \rightarrow t \bar{b} s \]

\[ \tilde{g} \rightarrow g \tilde{G} \]

\[ g \rightarrow g f \]

\[ G \]

ArXiv:1902.03094
Pair produced three jet resonances


- 2016 Data Set (35.9 fb$^{-1}$)
- Pair production of gluinos, followed by $\tilde{g} \rightarrow qqq$ or $qqb$ with $\lambda''_{uud}$ coupling
- $200 \text{ GeV} < m_{\tilde{g}} < 2 \text{ TeV}$

- Dalitz Variables: signal more likely to have uniform jets, QCD more likely to be asymmetric

\[ D_{[3,2]} = \sum_{i>j} \left( \hat{m}(3,2)_{ij} - \frac{1}{\sqrt{3}} \right)^2 \]

\[ D_{[(6,3)+(3,2)]}^2 = \sum_{i<j<k} \left( \sqrt{\hat{m}(6,3)_{ijk}^2 + D_{[3,2]}^2_{ijkl}} - \frac{1}{\sqrt{20}} \right)^2 \]

Triggers:

- High mass ($m_{\tilde{g}} > 700$ GeV):
  - $H_T(p_T,j > 40$ GeV $) \geq 800$ GeV
  - $H_T \geq 750$ GeV, $N_j(p_T > 70$ GeV $) > 4$

- Low mass ($m_{\tilde{g}} \leq 700$ GeV):
  - PF Scouting trigger:
    - $H_T(p_T,j > 20$ GeV $) \geq 410$ GeV

<table>
<thead>
<tr>
<th>Region</th>
<th>Gluino mass range</th>
<th>Jet $p_T$</th>
<th>$H_T$</th>
<th>sixth jet $p_T$</th>
<th>$D_{[(6,3)+(3,2)]}^2$</th>
<th>$A_m$</th>
<th>$\Delta$</th>
<th>$D_{[3,2]}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200–400 GeV</td>
<td>&gt;30 GeV</td>
<td>&gt;650 GeV</td>
<td>&gt;40 GeV</td>
<td>&lt;1.25</td>
<td>&lt;0.25</td>
<td>&lt;250 GeV</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>2</td>
<td>400–700 GeV</td>
<td>&gt;30 GeV</td>
<td>&gt;650 GeV</td>
<td>&gt;50 GeV</td>
<td>&lt;1.00</td>
<td>&lt;0.175</td>
<td>&gt;180 GeV</td>
<td>&lt;0.175</td>
</tr>
<tr>
<td>3</td>
<td>700–1200 GeV</td>
<td>&gt;50 GeV</td>
<td>&gt;900 GeV</td>
<td>&gt;125 GeV</td>
<td>&lt;0.9</td>
<td>&lt;0.15</td>
<td>&gt;20 GeV</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>4</td>
<td>1200–2000 GeV</td>
<td>&gt;50 GeV</td>
<td>&gt;900 GeV</td>
<td>&gt;175 GeV</td>
<td>&lt;0.75</td>
<td>&lt;0.15</td>
<td>&gt;120 GeV</td>
<td>&lt;0.25</td>
</tr>
</tbody>
</table>
Pair produced three jet resonances


- Background Estimation:
  - Region 1:
  - Regions 2 – 4:

*Region 4 sets $p_3 = 0$

Sets limit for gluino masses below 1.5 TeV!

```
\frac{dN}{dx} = \frac{1}{(x+c)^{5+\alpha} \ln \frac{a}{\sqrt{x+c}} - 1}

\frac{dN}{dx} = p_0 \left( \frac{1 - \sqrt{x}}{\sqrt{x}} \right)^{p_1} \left( \frac{\sqrt{x}}{\sqrt{x}} \right)^{p_2 + p_3 \ln \frac{a}{\sqrt{x}}}
```

arXiv:1804.03568

CMS
Summary

• However, full Run 2 results are very much on the way, some of which were presented here!

• Many novel methods are being explored to take advantage of the full dataset!

So far, still no sign of SUSY 😞

ATLAS Public Results

CMS Public Results
Appendix
Pair produced quark pair resonances


- 2016 Data Set (35.9 fb$^{-1}$)
- Pair production of stop LSP, followed by $\tilde{t} \rightarrow q q'$ or $b q'$ through $\lambda''_{312}$ or $\lambda''_{323}$ coupling
- $80 \, \text{GeV} < m_{\tilde{t}} < 1.5 \, \text{TeV}$
- Two search regions: boosted and resolved

<table>
<thead>
<tr>
<th>Selection</th>
<th>Boosted search</th>
<th>Resolved search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>$60 &lt; m_{\tilde{t}} &lt; 450 , \text{GeV}$</td>
<td>$\overline{M} &gt; 350 , \text{GeV}$</td>
</tr>
<tr>
<td>and b-tagged</td>
<td>$(80 \leq m_{\tilde{t}} &lt; 400 , \text{GeV})$</td>
<td>$(m_{\tilde{t}} \geq 400 , \text{GeV})$</td>
</tr>
<tr>
<td>AK8 jets</td>
<td>jet $p_T &gt; 150 , \text{GeV}$</td>
<td>jet $p_T &gt; 80 , \text{GeV}$</td>
</tr>
<tr>
<td></td>
<td>jet $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>Number of jets $\geq 2$</td>
<td>Number of jets $\geq 4$</td>
</tr>
<tr>
<td></td>
<td>$H_T^{AK8} &gt; 900 , \text{GeV}$</td>
<td>$H_T^{AK4} &gt; 900 , \text{GeV}$</td>
</tr>
<tr>
<td></td>
<td>$m_{\text{asymp}} &lt; 0.1$</td>
<td>$M_{\text{asymp}} &lt; 0.1$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{21} &lt; 0.45$</td>
<td>$\Delta \eta_{\text{dijet}} &lt; 1.0$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{32} &gt; 0.57$</td>
<td>$\Delta &gt; 200 , \text{GeV}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \eta &lt; 1.5$</td>
<td></td>
</tr>
<tr>
<td>b-tagged</td>
<td>two loose b-tagged jets</td>
<td>two loose b-tagged jets</td>
</tr>
</tbody>
</table>
Pair produced quark pair resonances
