Searches for direct stop pair production with the ATLAS detector

Keisuke Yoshihara (University of Pennsylvania)
**Stop searches**

- A key ingredient to solve hierarchy problem
- In R-parity conserved (RPC) scenario, LSP can be a DM candidate

\[
\Delta m_{h}^2 = -\frac{\lambda_f^2}{8\pi^2} \Lambda^2 + \ldots
\]

\[
\Delta m_{h}^2 = \frac{\lambda_s}{16\pi^2} \Lambda^2 + \ldots
\]

- UV cut-off \(\Lambda\) ~ Planck scale

New results (interpretations) with full run-2 data

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Date</th>
<th>Luminosity</th>
<th>Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft b-hadron ID</td>
<td>JUL-11-2019</td>
<td>139 fb^{-1}</td>
<td>ATLAS-CONF-2019-027</td>
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<tr>
<td>Stop1L</td>
<td>MAY-19-2019</td>
<td>139 fb^{-1}</td>
<td>ATLAS-CONF-2019-017</td>
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<tr>
<td>StopZ/h</td>
<td>MAY-17-2019</td>
<td>139 fb^{-1}</td>
<td>ATLAS-CONF-2019-016</td>
</tr>
<tr>
<td>SS/3L (backup)</td>
<td>MAY-17-2019</td>
<td>139 fb^{-1}</td>
<td>ATLAS-CONF-2019-015</td>
</tr>
</tbody>
</table>
Stop searches (pure Bino LSP)

- All SUSY particles are considered to be heavy except for $\tilde{t}_1$ and $\tilde{\chi}_1^0$
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ regime
Stop searches (pure Bino LSP)

- All SUSY particles are considered to be heavy except for $\tilde{t}_1$ and $\tilde{\chi}_1^0$
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ regime

**On-shell (2-body) regime:**
Top reconstruction (boosting tech.) is crucial

$$\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$$

On-shell top
**Stop searches (pure Bino LSP)**

- All SUSY particles are considered to be heavy except for $\tilde{t}_1$ and $\tilde{\chi}_1^0$
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ regime

Intermediate (3-body) regime:
- Topology similar to SM ttbar -> MVA technique

![Diagram showing the mass region](image)

**Equations**
- $m_{\tilde{\chi}_1^0}$ vs $m_{\tilde{t}_1}$
- $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$
- Off-shell top
- $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$
Stop searches (pure Bino LSP)

- All SUSY particles are considered to be heavy except for $\tilde{t}_1$ and $\tilde{\chi}^0_1$
- Different analysis techniques are required in different $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1)$ regime

**Compressed (4-body) regime:**
Reconstruction of "low-$p_T$" objects is crucial

- $m_{\tilde{t}_1} < m_{\tilde{\chi}^0_1}$
- $m_{\tilde{t}_1} \rightarrow c\tilde{\chi}^0_1$
- $m_{\tilde{t}_1} \rightarrow b\tilde{f}\tilde{f}^*\tilde{\chi}^0_1$
- $m_{\tilde{t}_1} \rightarrow bW\tilde{\chi}^0_1$

LATEX:

\begin{align*}
\Delta m &> m_W \\
\Delta m &< m_W \\
\Delta m &> m_W \\
\Delta m &< m_W \\
\end{align*}
3-body ML analysis

Signal jet collection

Sorted by $p_T$

Jet 1 $(p_T, \eta, \phi, e)$
Jet 2 $(p_T, \eta, \phi, e)$
Jet 3 $(p_T, \eta, \phi, e)$
... 
Jet N $(p_T, \eta, \phi, e)$

Shallow neural network

Additional input variables
(e.g. ETmiss, mT, etc.)

Signal
Background
3-body ML analysis

Recurrent Neural Network (RNN)

- RNN can handle variable length inputs — 4-vector of physics objects can be fed into the RNN.
- In our case, jet property is different between signal and bkg — jet collection (max 8 jets) is fed into the RNN.

Signal jet collection

Sorted by $p_T$

Jet 1 $(p_t, n, \phi, e)$
Jet 2 $(p_t, n, \phi, e)$
Jet 3 $(p_t, n, \phi, e)$
Jet N $(p_t, n, \phi, e)$

Shallow neural network

Additional input variables (e.g. ETmiss, mT, etc.)

Signal

Background

ATLAS-CONF-2019-017
**3-body ML analysis**

**Signal jet collection**

Jet 1: (pt, η, φ, e)

Jet 2: (pt, η, φ, e)

Jet 3: (pt, η, φ, e)

Jet N: (pt, η, φ, e)

Sorted by pt

...  

Shallow neural network

Additional input variables (e.g. ETmiss, mT, etc.)

**Recurrence Neural Network (RNN)**

- RNN can handle variable length inputs — 4-vector of physics objects can be fed into the RNN.
- In our case, jet property is different between signal and bkg — jet collection (max 8 jets) is fed into the RNN.

**Shallow Neural Network**

- Jet sequence is connected to NN together with other high level variables (MT, MET, m(bl), lepton 4-vector, etc.)
Misalignment

**3-body ML analysis (cont’d)**

**Truth assisted ML training**

- **Training statistics was found to be very important!**
- Training performed with particle-level signal events (TRUTH) applying a dedicated smearing procedure. Training statistics enhanced by a factor of 75 (100k -> 7.5M)
- Careful validation for all input variables comparing to “Reco” distributions.

**Figure 3:** Comparison of important kinematic distributions between smeared particle-level signal events (“Smeared-truth”, shown as black dots on a black histogram) and fully reconstructed signal events (“Reco” shown as red dots on a red histogram) after preselection in benchmark signal model used for the ML classifier training: \( E_{\text{miss}} \), \( m_T \), \( m_{b}\text{jet} \) (middle left), leading \( b \)-jet \( p_T \) (middle right) and classifier score (bottom), referred to as \( bWN \). Distributions are normalised to unity in order to investigate the shape of the distributions.

ML classifier, denoted \( bWN \), is also shown in Figure 3. In general, kinematic distributions of all input variables after smearing were found to have fair agreement with the distributions at detector-level within uncertainties.

After applying the preselection on the smeared benchmark signal model, a total of approximately 200 000 signal events were selected to perform the machine learning classification, accompanied by approximately 300 000 SM background events. In order to verify the result of the training procedure, 30% of the total signal and background statistics are reserved as a test set.
Truth assisted ML training

- Training statistics was found to be very important!
- Training performed with particle-level signal events (TRUTH) applying a dedicated smearing procedure. Training statistics enhanced by a factor of 75 (100k -> 7.5M)
- Careful validation for all input variables comparing to "Reco" distributions.
**3-body ML analysis (cont’d)**

- Signal region (SR) defined as the high NN output score ($\text{NN}_{bWN} > 0.9$).
- Dileptonic ttbar events are normalized in control region (CR), and the variable extrapolation tested in validation region (VR).
3-body ML analysis (cont’d)

- Set limits to masses of stop and LSP using multi-bin SR (10 bins).
- The limit significantly extended; $m(\tilde{t}_1) \sim 700$ GeV.
Soft b-hadron ID for 4-body

Low-\(p_T\) b-hadron reconstruction (out of standard b-tag coverage)
provides additional handles to reduce overwhelming V+jets background.

Secondary vertex (SV) tagger developed for soft b-hadron
identification starting from track selection, followed by vertex selection.
Soft $b$-hadron ID for 4-body

**Track selection:**

Impossible to check all track combinatorics for vertexing; $\sim O(500-1k)$ tracks in an event: remove tracks from PV/pileup, and remove tracks in jets

**Vertex reco. and selection:**

Perform 2-track vertexing, followed by N-track vertexing. A set of vertex selections is applied further to reduce fake vertices

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**ATLAS Simulation Preliminary**

Signal: stop, $m(t, \chi^2) = (450, 430)$ GeV, Background: W+jets, b/c-hadron veto

**ATLAS Simulation Preliminary**

Signal: stop, $m(t, \chi^2) = (450, 430)$ GeV, Background: W+jets, b/c-hadron veto

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**d0 sig cut in track selection**

**SV mass cut in vertex selection**
25% efficiency is achieved at b-hadron $p_T \sim 15$ GeV at Loose WP.

- kinematics of SV (including SV mass) is well modeled.
Stop/sbottom decay may have longer decay chain; Wino NLSP or Bino NLSP

- Simplified model: $\tilde{\chi}_2 (\tilde{\chi}_1^\pm)$ decays into LSP in association with $Z/h$ ($W^\pm$) — in MSSM, BR largely depends on sign($\mu$)

- Target signature: multi-jets (including b-jets) + large $E_T^{miss} + 0$-$3$ leptons

- Simplified model with 100% BR — in MSSM, $\tilde{\chi}_2$ decay is roughly $BR(\tilde{\chi}_2 \rightarrow W \tilde{\chi}_1^+) = BR(\tilde{\chi}_2 \rightarrow W \tilde{\chi}_1^-) = BR(\tilde{\chi}_2 \rightarrow h \tilde{\chi}_1)$. $BR(\tilde{\chi}_2 \rightarrow Z \tilde{\chi}_1)$ is suppressed (no TGC in the SM)
Stop decay w/ Z

ATLAS-CONF-2019-016

- OS 2-leptons from Z decay and an additional lepton(s) from top decay leads to multi-leptons final state.
- $t\bar{t}Z$ is dominant (irreducible) background. -- $t\bar{t}Z$ bkg is normalized to data in CR.

**ATLAS Preliminary**

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

- $t\bar{t}$ production, $t\bar{t}\rightarrow t + \tilde{\chi}_{2}^{0}, \tilde{\chi}_{2}^{0} \rightarrow Z h + \tilde{\chi}_{2}^{0}, m(\tilde{\chi}_{2}^{0}) = 0$ GeV

$\chi_{0}^{0}$ mass vs. $m_{\tilde{t}_{1}}$

$m(\tilde{\chi}_{0}^{0}) = 0$ GeV

ARXIV:1706.03986
Light higgsino scenarios

- Light higgsino models (pMSSM-inspired) were developed and studied with 36/fb data.
- Higgsino LSP (natural SUSY):
  - soft-lepton reco. is crucial
- Well-tempered neutralino (DM relic):
  - current analysis turned out to be insensitive due to moderate $\Delta m$

**ATLAS PHYS-PUB-2019-022**

### Light higgsino scenarios

- $\tilde{t}_1$, $\tilde{t}_1, \tilde{b}_1$
- $\tilde{\chi}^0_1, \tilde{\chi}^\pm_1, \tilde{\chi}^0_2$
- $\tilde{\chi}^\pm_1, \tilde{\chi}^0_2, \tilde{\chi}^0_3$
- $\tilde{\chi}^0_1$

#### c) higgsino LSP
d) bino/higgsino mix

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**ATLAS Preliminary**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- All limits at 95% CL

**Higgsino LSP**

- $m(\tilde{\chi}^0_1) = m(\tilde{\chi}^0_2) + 5\,\text{GeV}$, $m(\tilde{\chi}^0_2) = m(\tilde{\chi}^0_3) + 10\,\text{GeV}$, March 2018

**Bino/Higgsino Mix Model**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- All limits at 95% CL

**Well-tempered LSP**

- $\tilde{t}_1 \rightarrow b \tilde{\chi}^0_1, t \tilde{\chi}_2^0, \tilde{b}_1 \rightarrow t \tilde{\chi}^0_2, b \tilde{\chi}^0_3$
- $\tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^\pm$
- $\tilde{\chi}_3^0 \rightarrow W^+ \tilde{\chi}_1^\pm$
- $\tilde{\chi}_2^0 \rightarrow W^+ \tilde{\chi}_1^\pm$,$ Z^0 \tilde{\chi}_1^0$
- $\tilde{\chi}_3^0 \rightarrow Z^0 \tilde{\chi}_1^0$

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**Conclusion**

- Extensive search program developed for 3rd gen SUSY in ATLAS (including RPV searches — see backup).
- **No SUSY (just yet)** but many full Run-2 results are in preparation, some of which hopefully(!) give us a hint for new physics 😊.
Backup
The event selection for the single-bin SR as well as for the shape-fit configuration is listed in Table 3: Discriminating variables applied as inputs to the NN to train the classifier. In addition, the output vector of the jet-RNN to transform the variable length jet collection is also applied as an input to the neural network.

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{\text{miss}}$</td>
<td>Missing transverse energy</td>
</tr>
<tr>
<td>$\phi(p_T^{\text{miss}})$</td>
<td>Azimuthal angle of the $p_T^{\text{miss}}$</td>
</tr>
<tr>
<td>$m_T$</td>
<td>Transverse mass</td>
</tr>
<tr>
<td>$\Delta\phi(l, \vec{p}_T^{\text{miss}})$</td>
<td>Azimuthal angle between $\vec{p}_T^{\text{miss}}$ and lepton</td>
</tr>
<tr>
<td>$m_{bl}$</td>
<td>Invariant mass of leading b-tagged jet and lepton</td>
</tr>
<tr>
<td>$p_T^{b,jet}$</td>
<td>Transverse momentum of the leading b-tagged jet</td>
</tr>
<tr>
<td>$n_{jet}$</td>
<td>Jet multiplicity</td>
</tr>
<tr>
<td>$n_{b-tag}$</td>
<td>Number of $b$-tagged jets @ 77%</td>
</tr>
<tr>
<td>$p_T(l)$</td>
<td>Transverse momentum of lepton</td>
</tr>
<tr>
<td>$\eta(l)$</td>
<td>Pseudorapidity of lepton</td>
</tr>
<tr>
<td>$\phi(l)$</td>
<td>Azimuthal angle of lepton</td>
</tr>
<tr>
<td>$E(l)$</td>
<td>Energy of lepton</td>
</tr>
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</table>

Table 4: Architecture and hyperparameters of the neural network.

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Parameter set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hidden layers</td>
<td>1</td>
</tr>
<tr>
<td>Neurons per hidden layer</td>
<td>128</td>
</tr>
<tr>
<td>Activation function</td>
<td>leaky relu ($\epsilon = 0.1$) [121]</td>
</tr>
<tr>
<td>Learning rate</td>
<td>$10^{-3}$ [120]</td>
</tr>
<tr>
<td>Regularisation</td>
<td>$L2 (\lambda = 10^{-2})$ [116]</td>
</tr>
<tr>
<td>Weight initialisation</td>
<td>Glorot normal [122]</td>
</tr>
<tr>
<td>Batch size</td>
<td>32 [116]</td>
</tr>
<tr>
<td>Batch normalisation [123]</td>
<td>Yes</td>
</tr>
</tbody>
</table>

- NN is trained using Keras framework with TensorFlow (as a backend)
- The Adam optimizer with a learning rate of $10^{-3}$ was used to optimize the error function.
- 12 input variables used for NN training: lepton 4-vector, jet 4-vector (RNN), $E_T^{\text{miss}}$, and their angular variables, etc
- Long-short term memory (LSTM) algorithm allows you to simultaneously train and optimize the consequent NNs.
Track selection

Impossible to check all track combinatorics for vertexing — ~O(500-1k) tracks in an event in \texttt{InDetTrackParticle} container

Remove tracks from PV or pileup

- \( \text{d}0/\sigma(\text{d}0) > 1.7 \)
- \( \text{z}0/\sigma(\text{z}0) > 0.5 \)
- \( |z0\sin\theta| < 1.5\text{mm} \)
- other selections (\texttt{VertSecInclusive code})

Remove tracks in AntiKt4EMTopo jets

- \( \Delta R(\text{track, jet}) > 0.4 \) [*]

[*] Standard b-tagging is used when AntiKt4EM jets \( (p_T > 30\text{GeV}) \) available
**Vertex reconstruction**

### 2-track vertexing
- all possible combinations are tested;
- 2-track seeds retained based on the vertex position
- compatibility check between vertex position and the sum of the momenta of associated tracks

### N-track vertexing
- starting from the list of 2-track seeds, n-track vertexing is performed
- ambiguities arising from track association to multiple vertices resolved
h -> bb decay leads to multi b-jets final state.

- Depending on Δm, b-jets from \( \tilde{b}_1 \) may have different kinematics from ones from \( h \).

- \( \text{ttbar} \) and Z+jets dominant
SS and 3L analysis

SS 2-leptons or 3-lepton final state also sensitive to 3rd generation search.

ttV and fake-lepton are dominant backgrounds — data-driven estimate for the fake-lepton bkg.

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Analysis is extended to heavy stop ($\tilde{t}_2$) search in the same final state.

Two SRs optimized for high mass and compressed region
mediated models \[ \text{(where gluino is given by the running mass parameters) sbottoms (t_1)} \\]

\[ \text{sparticle masses of the top quark and LSP masses, the dominant decay channel is via} \]

A simplified model is considered for the scenario where the only light sparticles are the stop \( \tilde{t} \):

- a) pure bino LSP
- b) wino NLSP
- c) higgsino LSP
- d) bino

\[ m_{\chi_1^0} \]

\[ m_{\tilde{t}_1, \tilde{b}_1} \text{ production, } m(\tilde{\chi}_1^\pm) = 2 m(\tilde{\chi}_1^0), (M_2 = 2 M_1) \text{, March 2018} \]

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV, 36.1 fb}^{-1}, \text{ All limits at } 95\% \text{ CL} \]

- Best Observed limit \( \mu > 0 \) 0L/1L/2L
- Best Observed limit \( \mu < 0 \) 0L/1L/2L
- Expected limit 0L [1709.04183]
- Expected limit 1L [1711.11520]
- Expected limit 2L [1708.03247]

\[ \tilde{t}_1 \rightarrow b \tilde{\chi}_1^0, t \tilde{\chi}_{1,2}^0 \]

\[ \tilde{b}_1 \rightarrow t \tilde{\chi}_1^\pm, b \tilde{\chi}_{1,2}^0 \]

\[ \tilde{\chi}_1^0 \rightarrow W \tilde{\chi}_1^0 \]

\[ \mu > 0; \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0 \text{ (dominant), } Z \tilde{\chi}_1^0 \]

\[ \mu < 0; \tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0, Z \tilde{\chi}_1^0 \]

\[ \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(\tilde{\chi}_1^0) + m(b) \]

\[ m_{\tilde{t}_1} \text{ [GeV]} \]

\[ m_{\tilde{\chi}_1^0} \text{ [GeV]} \]
Higgsino LSP: $\Delta m(\chi_1^\pm, \chi_1^0)$ vs $m(t_1)$

ATLAS
\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]
Limit at 95% CL

- Observed limit
- Expected limit ($\pm 1\sigma_{\text{exp}}$)
- $\tilde{t}_1 \sim \tilde{t}_L$ (large $\tan\beta$)
- $\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm, t \tilde{\chi}_1^0$
- $\tilde{\chi}_1^\pm \rightarrow W \tilde{\chi}_1^0$
- $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0, Z \tilde{\chi}_1^0$

$B(t\tilde{\chi}_2^0, b\tilde{\chi}_1^\pm, t\tilde{\chi}_1^0) =$
- $\tilde{t}_L$: small $\tan\beta$: (45, 10, 45)%
- $\tilde{t}_L$: large $\tan\beta$: (33, 33, 33)%
- $\tilde{t}_R$: (25, 50, 25)%

Higgsino LSP model: $\tilde{t}_1$, production, $m_{\tilde{\chi}_1^0} = 150$ GeV

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Stop search in RPV scenario

- RPV stop decay, while conserving the baryon number (B) to avoid a prompt proton decay.

- Final state: 2L+2b
- Key discriminant: m_{bl} and m_{CT}
- Main backgrounds: Wt, Z+jets, and ttbar events
- Limits are set on various possible BRs (no \( \tilde{t}_1 \rightarrow b\tau \) search)

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Figure 1: Feynman diagram for scalar top pair production, with \( \tilde{t} \) decay to a charged lepton and b-quark.
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This paper presents the first search performed by ATLAS for direct scalar top pair production, with the RPV decay of each \( \tilde{t} \) to a charged lepton and a b-quark, as shown in Figure 1. In contrast to R-parity conserving searches for \( \tilde{t} \), there is no significant missing transverse momentum. The \( \tilde{t} \) decay branching fractions to \( e^b, \mu^b, \) and \( \tau^b \) may be different in a manner related to the neutrino mass hierarchy [16, 17]. Therefore, the experimental signature is two oppositely charged leptons of any flavor and, in principle, two b-jets. For this analysis, only events with electron or muon signatures are selected, and final states are split by flavor into \( ee, e\mu, \) and \( \mu\mu \) selections. To improve the efficiency of the selection of signal events for high values of the \( \tilde{t} \) mass, only one jet is required to be identified as initiated by a b-quark. Events are chosen that reconstruct two b` resonances of roughly equal mass. Previous searches with similar final states have targeted the pair production of first, second, and third generation leptoquarks at ATLAS [18, 19] and at CMS [20]. However, they consider final states within the same generation (\( eejj, \mu\mujj, \tau\taubb \) where \( j \) indicates light flavor) and do not focus on final states with b-jets and electrons and muons (\( e\mu bb, \mu\mu bb \)) nor consider final states with both electrons and muons (\( e\mu bb \)). The results of the Run 1 leptoquark searches were interpreted for the \( \tilde{t} \) mass and its decay branching fractions in the \( B_L \) model [16, 17], setting weaker limits than expected from a dedicated search by up to 300 GeV.

The ATLAS detector and the dataset collected during Run 2 of the LHC are described in Sec. 2, with the corresponding Monte Carlo simulation samples presented in Sec. 3. The identification and reconstruction of jets and leptons is presented in Sec. 4, and the discriminating variables used to construct the signal regions are described in Sec. 5. The method of background estimation is described in Sec. 6, and the systematic uncertainties are detailed in Sec. 7. The results are presented in Sec. 8, and the conclusion given in Sec. 9.
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Stop search in RPV scenario (cont’d)

- Higgsino LSP (with $\tilde{t}_1 \sim \tilde{t}_R$) and Bino LSP scenarios considered.

- $m_{\tilde{t}}$ up to 1250 GeV (1100 GeV) is excluded for the bino LSP (higgsino LSP) scenario.

- In RPV, LSP decays further into quarks, leading to multijets (up to $\geq 12$ jets!) and a lepton (from semi-leptonic top-quark decay) final state.

- In RPV models, LSP decays further into quarks, leading to multijets (up to $\geq 12$ jets!) and a lepton (from semi-leptonic top-quark decay) final state.
$\sqrt{s} = 13$ TeV, 36.1-36.7 fb$^{-1}$

All limits at 95% CL

**ATLAS Preliminary**

July 2018
DM + HF summary

ATLAS

$s = 13$ TeV, $36.1$ fb$^{-1}$

All limits at 95% CL
Scalar $\phi, \phi \rightarrow \chi\bar{\chi}$
$g = g_q = g_{\chi} = 1$
$m_\chi = 1$ GeV, Dirac DM

$\sigma/\sigma(\text{g}=1)$

Observed

Expected

$E_T^{\text{miss}} + b\bar{b}$ 0L [EPJC 78 (2018) 18]
$E_T^{\text{miss}} + t\bar{t}$ 0L [EPJC 78 (2018) 18]
$E_T^{\text{miss}} + t\bar{t}$ 1L [JHEP 06 (2018) 108]
$E_T^{\text{miss}} + t\bar{t}$ 2L [EPJC 78 (2018) 18]

$10^{-3}$
$10^{-2}$
$10^{-1}$
$1$