Search for direct pair production of stops and sbottoms with the ATLAS detector

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Introduction and motivation

• Stop and sbottom key ingredient for solution of hierarchy problem
• Question ATLAS addressed, how much of the pMSSM parameter space for stop sbottoms with masses below ~TeV can we cover with early 13 TeV data?
• Two lines of development:
  – Address large parameter space
  – Address difficult final state kinematics
• Complete set of searches with first 36 fb^-1 collected at 13 TeV now published. Today give broad view with emphasis on recent work
Parameter space for stop/sbottom searches

- **Stop/sbottom sector:**
  - 5 parameters:
    - $m(t_L) = m(b_L), m(t_R), m(b_R)$
    - Mixing angles $\theta_t, \theta_b$
  - Mass eigenstates $t_1, t_2, b_1, b_2$ from mixing of L-R states
  - Concentrate search on lighter states $t_1, b_1$

- **Chargino-neutralino sector:**
  - 4 parameters:
    - $M_1, M_2, \mu, \tan\beta$
  - From mixing obtain 4 neutralinos and 2 charginos
  - From hierarchy of $M_1, M_2, \mu$
  - Characteristic mass patterns for neutralinos/charginos
  - Take $\chi^0_1$ as LSP

For searches parameter space collapsed to two dimensional space $m(t_1, \chi^0_1)$. Choose representative combinations of other parameters to cover the main phenomenologies.

Searches for both stop and sbottom necessary.
Each of these scenarios yields specific decay patterns/final state topologies
Optimise selections for each of these scenarios
Stop final states

Final state $bb \, W(*)\, W(*)$

Classify in terms of number of leptonic decays of $W$: $0L$, $1L$, $2L$ : golden channel

Mass hierarchy determines number of resonant top/$W$ bosons, and analysis strategy

Mass relations and stop decays

If decay through intermediate chi02: $Z$ and $h$ in final state
Difficult kinematics: Run1 coverage for bino LSP

- $m(\text{stop}) - m(\text{chi01}) \sim 0$
- $m(\text{stop}) - m(\text{chi01}) \sim m(W)$
- $m(\text{stop}) - m(\text{chi01}) \sim m(t)$

Compressed spectra: final states invisible or identical to SM background

Focus for Run 2 on covering holes in this plane
All of the decay modes searched for with full 2015-16 statistics (36 fb-1)

<table>
<thead>
<tr>
<th>Channel</th>
<th>ATLAS</th>
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</thead>
<tbody>
<tr>
<td>Stop 0L</td>
<td>JHEP 12 (2017) 085</td>
</tr>
<tr>
<td>Stop 1L</td>
<td>arXiv: 1711.11520, to JHEP (with DM interpretation)</td>
</tr>
<tr>
<td>Stop 2L</td>
<td>EPJC 77 (2017) 898</td>
</tr>
<tr>
<td>Stop with Z/h</td>
<td>JHEP 08 (2017) 006</td>
</tr>
<tr>
<td>Stop to stau</td>
<td>arXiv: 1803.10178, to PRD</td>
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<tr>
<td>Stop to charm</td>
<td>arXiv: 1805.01649, to JHEP NEW</td>
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<tr>
<td>Sbottom</td>
<td>JHEP 11 (2017) 195</td>
</tr>
<tr>
<td>RPV re-interpretation</td>
<td>ATLAS-CONF-2018-003</td>
</tr>
</tbody>
</table>
Stop 1L

Final state: 1 lepton (soft or hard) + b-jets + $E_T^{\text{miss}}$

- Exploit the presence of 1 leptonic ($M_T$) and one hadronic top decay (hadronic mass reco)
- Asymmetric transverse mass to suppress dilepton background
- Angular correlations between jets to enhance signal discrimination

[Graph and data analysis plots]

arXiv:1711.11520
Stop 0L

- Signature: $0L + E_T^{\text{miss}} + \geq 4$ jets with two b-tagged.
- For high mass stop, top reconstruction with large-radius jets ($R=1.2$) in boosted topology.
- For compressed mass spectra, exploit initial state radiation.
Results: Scenario Bino-LSP

- Maximum coverage in stop mass for 0L analysis
- Dedicated searches cover difficult regions based on request of system recoiling against ISR jet

Benchmark scenario:
$\text{BR}(\text{stop1} \rightarrow \text{top chi01}) = 100\%$

Achieve complete coverage for $m(\text{stop}) < \sim 1 \text{ TeV}$ and $m(\text{chi01}) < \sim 300 \text{ GeV}$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
Results: scenario Wino NLSP

Assume \( m(\text{chi02}/\text{chiplus}) = 2 \times m(\text{chi01}) \)

Choice of sign of \( \mu \) (higgsino mass) yields different decay BRs for \( \text{chi02} \)
\( \mu > 0 \) dominantly into \( h \)
\( \mu < 0 \) significant \( Z \) contribution

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
Results: scenario Higgsino LSP

Higgsino LSP Model: $\tilde{t}_1$ production, $m(\tilde{\chi}^0_1) = m(\tilde{\chi}^0_1)+5\text{ GeV}$, $m(\tilde{\chi}^0_2) = m(\tilde{\chi}^0_1)+10\text{ GeV}$, March 2018

Final states with additional Soft leptons from chargino/neutralino2 decay

Assume three different scenarios for left/right composition of stop1 resulting in different BRs

Best limits for $t_1=t_L$

Dominated by neutral decays

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SUSY/
A compressed search: stop to charm

Loop decay competing with tree level ones
Require:
● At least 1 c-tagged jet
● 1 high pt non-c-tagged jet to boost the system
● high Etmiss

No excess found,

Set limits assuming
BR(stop → charm)=100%

Show results in plane:
DM=m(stop)-m(χ01) vs m(stop)

Complementary reach to monojet searches

arXiv:1805.01649
Sbottom searches: 0L

Require two b-tagged jets

Veto leptons

Main discriminant: $m_{CT}$ built with the two b-tagged jets

$$m_{CT}^2(v_1, v_2) = \left[ E_T(v_1) + E_T(v_2) \right]^2 - \left[ p_T(v_1) - p_T(v_2) \right]^2,$$
Conclusions

• Comprehensive ATLAS research program for stop and sbottom carried on first 36 fb$^{-1}$ of 13 TeV data

• Focus on
  – Covering a very broad parameter space in MSSM
  – Addressing difficult signatures, covering kinematic holes

• No excess found, stringent limits on pMSSM models set, yet part of parameter space still uncovered

• Searches go on targeting full LHC Run2 statistics (>120 fb$^{-1}$)
Backup
Stop to stau

Motivated by tau-rich GGM/GMSB models
Two channels: $\tau_{\text{lep}}\tau_{\text{had}}$, $\tau_{\text{had}}\tau_{\text{had}}$ with large $E_T^{\text{miss}}$ and $M_{T2}$

Interpreted as a combination of the two channels

Exclude up to 1.16 TeV stop
Stop to Z/h

Simplified model targeting $\chi_2^0$ decaying via higgs or Z boson

Final states:
- 3l+1b (Z decay)
- 1l+4b (h decay)

Backgrounds:
- ttZ in 3l+1b
- ttbar in 1l+4b
Sbottom searches: 1l

Require one isolated lepton
two b-tagged jets and ETmiss

Lepton transverse mass and asymmetric MT2
To reject ttbar and W+jets backgrounds

Dedicated selections for soft regions near
the diagonal

JHEP 11 (2017) 195
Proton-Proton collisions

$\sqrt{s} = 7$ TeV  \hspace{1em} \text{Int. Lumi} \sim 5 \text{ fb}^{-1} \ (2011)$

$\sqrt{s} = 8$ TeV  \hspace{1em} \text{Int. Lumi} \sim 20 \text{ fb}^{-1} \ (2012)$

$\sqrt{s} = 13$ TeV  \hspace{1em} \text{Int. Lumi} > 40 \text{ fb}^{-1} \ (2015+2016)$

$\sqrt{s} = 13$ TeV  \hspace{1em} \text{Int. Lumi} > 120 \text{ fb}^{-1} \ (by \ 2018)$

$\sqrt{s} = 14$ TeV  \hspace{1em} \text{Int. Lumi} \sim 300 \text{ fb}^{-1} \ (by \ 2022)$

Consistently above the promised luminosity
This year is going extremely well!
The experiments

ATLAS
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
~ 3000 km of cables

Varied signatures for SUSY:
need excellent performance for
- electrons,
- photons,
- muons,
- jets,
- Etmiss,
- tau jets,
- b-jets
**SUSY**

(Still) our favourite template for a BSM theory:

- Theorists like it for a series of good reasons, and the good reasons tell us that some of the SUSY particles should be in the TeV region
- It does provide a great candidate for Dark Matter
- Experimentalists like it because of the rich panoply of signatures, some of them abundantly produced at colliders, and easy to separate from backgrounds
“simplified models”

Simplified models as a tool for analysis optimisation and display:

- Generate pair of particles with a given decay on both legs
- Assume no other contribution to new physics
- 2-d space of masses of involved sparticles

- Optimise selection based on mass hierarchy in different areas of 2-d space: define different Signal Regions

**m(gl)~m(lsp): soft topology:**
Rely on hard jet recoiling against gluino-gluino system

**m(gl)>>m(lsp): hard topology:**
Cut hard on jets and Emiss

- Plot excluded cross-section as a color map in 2-d mass plane (CMS)
- Assume for initial particles SUSY production cross-section and 100% BR in studied channel and define excluded region in 2-d plane
Three case studies

LHC searches only up to ~3 TeV sparticle masses. Approximate upper limit on some sparticle masses from the Requirement of “small” fine-tuning of the Higgs mass.

Gluino <~ a few TeV
Stop <~ 1 TeV
Higgsino <~2-300 GeV

To what extent we can explore this hierarchy?
stop → top NLSP: Run 1 coverage (ATLAS)

- $m(\text{stop}) - m(\chi_0^1) \approx 0$
- $m(\text{stop}) - m(\chi_0^1) \approx m(W)$
- $m(\text{stop}) > \sim 200$ GeV, $m(\text{stop}) - m(\chi_0^1) \approx m(t)$

Why are these areas difficult?

- $m(\text{stop}) < \sim 200-220$ GeV
- $m(\chi_0^1) < 20-30$ GeV

SUMMER 2015
Bino LSP can boost its $\sigma_{\text{ann}}$ through coannihilation with stop. For enhancement to be relevant: $\Delta m = m_{\text{top}} - m_{\text{LSP}}$ small.

$$\Gamma(\tilde{t}_1 \rightarrow cN) = \frac{2g^2 \tan^2 \theta_W \theta_{t_c}^2 \Delta M^2}{9\pi m_{\tilde{t}_1}} = 100 \text{ cm}^{-1} \left( \frac{\theta_{t_c}}{10^{-5}} \right)^2 \left( \frac{\Delta M}{30 \text{ GeV}} \right)^2 \left( \frac{400 \text{ GeV}}{m_{\tilde{t}_1}} \right)$$

$$\Gamma(\tilde{t}_1 \rightarrow Nbl^+\nu_l) = \frac{3g^6 \tan^2 \theta_W \Delta M^8}{70(6\pi)^5 M_W^4 m_l^2 m_{\tilde{t}_1}} = 28 \text{ cm}^{-1} \left( \frac{\Delta M}{30 \text{ GeV}} \right)^8 \left( \frac{400 \text{ GeV}}{m_{\tilde{t}_1}} \right)$$

Region below $\Delta m = 30 \text{ GeV}$ relevant.
Stop RPV (examples)

Lepton number (L) Violation

\[ W_{RPV} = \frac{\lambda_{ijk}}{2} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k \]

\[ + \frac{\lambda''_{ijk}}{2} \bar{U}_i \bar{D}_j D_k + \kappa_i L_i H_u \]

R = \((-1)^{3B+L+2S}\)

LQD - \(\lambda'\)

2L+2 jets

>=1 b-tagged jet

UDD - \(\lambda''\)

4-jet final state

Inclusive or with b-tagging
