Searches for third generation squarks with leptonic channels with the ATLAS

Keisuke Yoshihara (University of Pennsylvania) on behalf of ATLAS collaboration

LHCP2017 May17th (Shanghai Jiao Tong University)
**Direct stop and sbottom searches**

- Stop/sbottom searches: a key ingredient to solve hierarchy problem
- Searches benefit from large production cross-section
- Searches consider both R-parity conserving and violating scenarios

**New!**

- Several new results:
  - Stop 1-lepton: ATLAS-CONF-2017-037
  - Stop 2-lepton: ATLAS-CONF-2017-034
  - Stop b-l: ATLAS-CONF-2017-036
  - RPV Stop 1-lepton: arXiv1704.08493
  - Stop via Z/h: ATLAS-CONF-2017-019
**Search strategy: Bino LSP scenarios**

**Pure bino LSP model:**

![Diagram](image)

- New technique: BDT and shape-fit
- Decay phenomenology governed by $\Delta m(t_1, \chi_{10})$.

**m_{\chi^\pm} \sim 2m_{\chi_{01}} model:** motivated by the gauge unification (cMSSM/mSUGRA)

![Diagram](image)

- $b+\chi_{1\pm}$ signature: high $p_T$ $b$-jets, jets, and large MET

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**Search strategy: Higgsino (N)LSP scenarios**

**Light higgsinos model: motivated by Natural SUSY**

- **Higgsino LSP models:**
  a) \( m_{\chi^\pm} = m_{\chi^0} + 5 \text{ GeV} \)
  b) variable \( \Delta m(\chi^0_1, \chi^{\pm}_1) = 0-30 \text{ GeV} \)

  **signature:**
  soft-leptons and large MET

- **Well-tempered model \((M_1 \sim -1\mu l)\): motivated by DM relic density**
  - typical \( \Delta m(\chi^0_1, \chi^{\pm}_1) \sim 20-50 \text{ GeV} \).
  - interpretation only (no event selection optimized)
**Discriminating variables**

- **Had top reconstruction:**
  a key discriminant in stop1-lepton \((t+\chi_1^0)\).

- **Various** \(M_{T2}\) **variables** (\(aM_{T2}\) or \(M_{T2}^{II}\)):
  discriminating signal from \(tt\bar{t}\) events.

**Super-razor variable (\(R_{pT}\))**

- 

**Mass of hadronic top-quark**

  - **Super-razor variables:** [arXiv:13104827]

  kinematic variables defined in super-razor (approximate boost) frame.
**Discriminating variables for BDTs**

- Additional discriminating variables (e.g. RJ Rec: [arXiv:1607.08307]) for the BDTs targeting the compressed t+χ_{1}^{0} region.

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**χ^{2}-based hadronic top rec**

**RJR variable: M_{T}^{S}**

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**Figure 7:** Distributions of discriminating variables: (top left) reconstructed mass of the hadronic top-quark with \( m_{\text{top}} \), (top right) \( M_{ST} \), (bottom left) \( R_{ISR} \), and (bottom right) \( (R_{ISR}, I) \). The \( m_{\text{top}} \) is used in the \( tN_{\text{diag_med}} \) and the others used in the \( tN_{\text{diag_high}} \) signal region, which are defined in Section 7.1.2. In addition to the SM background prediction, signal models are shown, denoted by \( m(\tilde{t}_{1}, \chi_{1}^{0}) \), and scaled by a certain factor for visibility. The lower panels show the ratio of data over total SM background and the signal expectation over total SM background. Others stands for minor SM backgrounds that contribute less than 5% of the total SM background. The hashed area around the total SM prediction and the hashed band in the Data/SM ratio include statistical and experimental uncertainties. The last bin contains overflow.
Background estimate

- Several control regions (CRs) are defined. The background normalizations are determined in a simultaneous fit:
  - Stop1-lepton: ttbar (1L/ 2L), ttbar+V, single-top Wt, W+jets
  - Stop2-lepton: ttbar, ttbar+V, VV, and VZ
- Predicted backgrounds are validated in dedicated validation regions (VRs).

![Dileptonic ttbar CR](image1)
![ttbar+Z CR](image2)
Results: Pure Bino LSP

- Data/SM agreement is good in VRs.
- No significant excess observed in SRs.

\[ R_{\ell\ell} = \frac{E_T^{\text{miss}}}{E_T^{\text{miss}} + p_T(\ell_1) + p_T(\ell_2) + \sum_{i=1,\ldots,N \leq 4} p_T(j_i)}. \]

\[ \bar{\chi}_1^0 \]

\[ \bar{\chi}_2^0 \]

\[ \bar{\chi}_1 \pm \]

\[ \bar{\chi}_2 \pm \]

\[ \bar{\chi}_1^\pm \]

\[ \bar{\chi}_2^\pm \]

\[ \bar{\chi}_1^0 \]

\[ \bar{\chi}_2^0 \]

\[ \bar{\chi}_1 \pm \]

\[ \bar{\chi}_2 \pm \]

\[ \bar{\chi}_1^\pm \]

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\[ \bar{\chi}_1 \pm \]

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\[ \bar{\chi}_1^\pm \]

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\[ \bar{\chi}_1^0 \]

\[ \bar{\chi}_2^0 \]

\[ \bar{\chi}_1 \pm \]

\[ \bar{\chi}_2 \pm \]

\[ \bar{\chi}_1^\pm \]

\[ \bar{\chi}_2^\pm \]
Results: Pure Bino LSP

- 2-body: $m_{t_1} < 900$ GeV is excluded for a massless $\chi_1^0$,
- 2-body diagonal: excluded down to $m_{t_1} \sim 190$ GeV
- 3-/4-body: $m_{t_1} < 450$ GeV / $m_{t_1} < 400$ GeV is excluded,
**Results: Wino NLSP (and Bino LSP)**

- Wino NLSP pMSSM model with the parameters: $M_2 = 2M_1$, $M_3 = 2.2$ TeV, $M_S = 1.2$ TeV, $X_t/M_S \sim \sqrt{6}$, and $\tan \beta = 20$. All other parameters are decoupled. $m_{\tilde{t}_1}$ up to 920 GeV is excluded for $\mu > 0$ (and $\mu < 0$).
Results: Higgsino LSP

- pMSSM-inspired Higgsino models: 1) $t_1 \sim t_L$, 2) $t_1 \sim t_R$, 3) $t_1 \sim t_L$ with large $\tan\beta$. $m_{t_1}$ up to 800 - 880 GeV is excluded for those scenarios.

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

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

- Observed limit
- Expected limit ($\pm 1\sigma_{\text{exp}}$)
- $\tilde{t}_1 \sim \tilde{t}_1$, $\tilde{t}_1 \sim \tilde{t}_R$
- $\tilde{t}_1 \sim \tilde{t}_L$ (large $\tan\beta$)

$\tilde{t}_1 \rightarrow b \tilde{\chi}_1^\pm$, $t \tilde{\chi}_1^0$
$\tilde{\chi}_1^\pm \rightarrow W / Z \tilde{\chi}_1^0$
$\tilde{\chi}_1^0 \rightarrow h \tilde{\chi}_1^0$, $Z \tilde{\chi}_1^0$

BR($t_2^0$, $b\tilde{\chi}_1^0$, $t\tilde{\chi}_1^0$) =
- $\tilde{t}_L$, small $\tan\beta$: (45, 10, 45)%
- $\tilde{t}_L$, large $\tan\beta$: (33, 33, 33)%
- $\tilde{t}_R$: (25, 50, 25)%

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Results: Well-tempered Neutralino

- Exclusion limits are set for the pMSSM model with the MSSM parameters similar to the wino NLSP model, except for $M_1 \sim -|\mu|$ while satisfying dark matter relic density $0.10 < \Omega h^2 < 0.12$.

- Two scenarios are considered in this model: 1) $t_1 \sim t_L$, 2) $t_1 \sim t_R$.
- In $t_1 \sim t_L$, sbottom pair production is also considered doubling the signal acceptance!
- $m_{t_1}$ up to 820 GeV is excluded for $t_1 \sim t_L$ scenario, while no point is excluded for $t_1 \sim t_R$ scenario.
Results: Spin-0 mediator model (DM+ttbar)

- Spin-0 mediator model is studied, exploiting the similarity of the final state: ttbar+MET (1-lepton).
- There *was* mild excess in DM_low(_loose) in 13.2 fb⁻¹
- No longer significant with full 2015+2016 data (1.5σ).

13.2 fb⁻¹

(ATL-CONF-2016-050)
Stop searches with higgs and Z boson

- Signal model (simplified model) targeting intermediate $\chi_2^0$ decaying via either Higgs or Z boson:
  1) $t_1 \rightarrow t + \chi_2^0$ or 2) $t_2 \rightarrow t_1 + h/Z$.

- Final state:
  - 3L+1b (via Z boson)
  - 1L+4b (via Higgs boson)

- Dominant background:
  - ttZ in 3L+1b
  - ttbar in 1L+4b
Stop search in RPV scenario

- Final state: 2L+2b
- Key discriminant: \( m_{bl} \) and \( m_{CT} \)
- Main backgrounds: \( Wt, Z+\text{jets, and ttbar} \) events
- Limits are set on various possible BRs (no \( t_1 \to b\tau \) search)

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

**Figure 1:** Feynman diagram for scalar top pair production, with \( \tilde{t} \) decay to a charged lepton and \( b \) quark.

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 \( b \) quark, as shown in Figure 1. In contrast to RPV-conserving searches for \( \tilde{t} \), there is no significant missing transverse momentum. The \( \tilde{t} \) decay branching fractions to \( e\bar{b}, \mu\bar{b}, \) and \( \bar{\tau}b \) 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 (\( eejj, \mu\mu jj, \bar{\tau}\bar{\tau} bb \) where \( j \) indicates light flavor) and do not focus on final states with \( b \)-jets and electrons and muons (\( eebb, \mu\mu bb \)) 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.
More RPV stop

- Higgsino LSP (with $t_1 \sim t_R$) and Bino LSP scenarios considered.

- $m_{t_1}$ up to 1250 GeV (1100 GeV) is excluded for the bino LSP (higgsino LSP) scenario.

- More in T. Saito’s talk

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

Figure 1

More in T. Saito’s talk

Figure 10

<table>
<thead>
<tr>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. limit ($\pm \sigma_{\text{theory}}$), $\tilde{H}$ LSP</td>
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<tr>
<td>Exp. limit ($\pm \sigma_{\text{theory}}$), $\tilde{H}$ LSP</td>
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<tr>
<td>Obs. limit ($\pm \sigma_{\text{theory}}$), $\tilde{B}$ LSP</td>
</tr>
<tr>
<td>Exp. limit ($\pm \sigma_{\text{theory}}$), $\tilde{B}$ LSP</td>
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</tbody>
</table>

All limits at 95% CL
**Conclusion**

- Many new results from ATLAS for 3rd generation squark searches are presented based on full 2015+2016 data (36 fb$^{-1}$).

- No significant excesses this time around…
- Stringent constraints obtained on various pMSSM and simplified models.

Stay tuned!
Backup
**pMSSM models**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Wino NLSP</th>
<th>Higgsino LSP</th>
<th>Bino/higgsino mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models</td>
<td>pMSSM</td>
<td>simplified</td>
<td>pMSSM</td>
</tr>
<tr>
<td>Mixing parameters</td>
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<td>$X_t/M_S \sim \sqrt{6}$</td>
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<tr>
<td>$\tan \beta$</td>
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<td>20 or 60</td>
<td>20</td>
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<td>$M_S$ [TeV]</td>
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<td>0.7-1.3</td>
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<tr>
<td>$M_3$ [TeV]</td>
<td>2.2</td>
<td>2.2</td>
<td>1.8</td>
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<td>Scanned mass parameters</td>
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<tr>
<td>$(M_1, m_{q3L})$</td>
<td>$(\mu, m_{q3L}/m_{tR})$</td>
<td>$(M_1, m_{q3L}/m_{tR})$</td>
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<td>Electroweakino masses [TeV]</td>
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<td>$\mu = \pm 3.0$</td>
<td>$M_2 = M_1 = 1.5$</td>
<td>$M_2 = 2.0$</td>
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<tr>
<td>$M_2 = 2M_1 \ll</td>
<td>\mu</td>
<td>$</td>
<td>$\mu \ll M_1 = M_2$</td>
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<td>Additional requirements</td>
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<td>0.10 $&lt; \Omega h^2 &lt; 0.12$</td>
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<tr>
<td>$\tilde{t}_1$ decay modes and their BR [%]</td>
<td>$\tilde{t}_1 \sim \tilde{t}_L$</td>
<td>(a) / (b) / (c)</td>
<td>(a) / (b)</td>
</tr>
<tr>
<td>$\tilde{t}_1 \to \tilde{t}_1 \tilde{\chi}_0^0$</td>
<td>&lt; 5</td>
<td>$\sim 25/\sim 45/\sim 33$</td>
<td>&lt; 10/ &lt; 10</td>
</tr>
<tr>
<td>$\tilde{t}_1 \to b\tilde{\chi}_1^+\tilde{\chi}_0^-$</td>
<td>$\sim 65$</td>
<td>$\sim 50/\sim 10/\sim 33$</td>
<td>$\sim 50/\sim 10$</td>
</tr>
<tr>
<td>$\tilde{t}_1 \to \tilde{t}_1 \tilde{\chi}_2^0$</td>
<td>$\sim 30$</td>
<td>$\sim 25/\sim 45/\sim 33$</td>
<td>$\sim 20/\sim 40$</td>
</tr>
<tr>
<td>$\tilde{t}_1 \to \tilde{t}_1 \tilde{\chi}_3^0$</td>
<td>–</td>
<td>–</td>
<td>$\sim 20/\sim 40$</td>
</tr>
</tbody>
</table>
**Results: Pure Bino LSP scenario (Low mass zoom)**

**ATLAS** Preliminary

\[ \sqrt{s} = 13 \text{ TeV}, 36.1 \text{ fb}^{-1} \]

Limit at 95\% CL

Pure Bino LSP model: \( \tilde{t}_1 \tilde{t}_1 \) production, \( \tilde{t}_1 \rightarrow bff' \tilde{\chi}_1^0, \tilde{t}_1 \rightarrow bW \tilde{\chi}_1^0, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \)

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Figure 21: Expected (black dashed) and observed (red solid) 95\% excluded regions in the plane of \( m_{\tilde{t}_1} \) versus \( \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \) for the direct stop pair production assuming either \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \), \( \tilde{t}_1 \rightarrow bW \tilde{\chi}_1^0 \), or \( \tilde{t}_1 \rightarrow bff' \tilde{\chi}_1^0 \) decay with a branching ratio of 100\%. The excluded regions from previous publications [44, 46] are shown with the grey shaded area. In the region of phase-space above the line, only the \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0 \) decay is allowed.
Results: Pure Bino LSP scenario (SR map)
Results: Pure Bino LSP scenario (BDT output)

New!
Results: Higgsino LSP: fixed $\Delta m(\chi_1^\pm, \chi_1^0) = 5\text{GeV}$

**ATLAS** Preliminary

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

Limit at 95% CL

- Observed limit
- Expected limit ($\pm 1\sigma_{\text{exp}}$)

- $\tilde{t}_1 \approx \tilde{t}_L$, $\tilde{t}_1 = \tilde{t}_L$ (large tan$\beta$)
- $\tilde{t}_1 \approx \tilde{t}_R$

Higgsino LSP model: $\tilde{t}_1\tilde{t}_1$ production, $m_{\chi_1^+} = m_{\chi_1^0} + 5$ GeV, $m_{\chi_2^0} = m_{\chi_1^0} + 10$ GeV

$\tilde{t}_1 \to b\tilde{\chi}_1^0$, $t\tilde{\chi}_{1,2}^0$

$\tilde{\chi}_1^\pm \to W\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$, $Z\tilde{\chi}_1^0$

BR($t\tilde{\chi}_2^0$, $b\tilde{\chi}_1^0$, $t\tilde{\chi}_1^0$) =

- $\tilde{t}_L$, small tan$\beta$: (45, 10, 45)%
- $\tilde{t}_L$, large tan$\beta$: (33, 33, 33)%
- $\tilde{t}_R$: (25, 50, 25)%
Results: Higgsino LSP (Diagonal region)

Higgsino LSP model: $\tilde{t}_1\tilde{t}_1$ production, $\text{BR}(\tilde{t}_1 \rightarrow b \tilde{\chi}_1^+) = 100%$

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

Limit at 95% CL

$\chi \sim m_{\tilde{t}_1} \pm 5$ GeV + $m_{\tilde{\chi}_1^0}$
Results: Compressed $b+$chargino

$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$, $\Delta m(\tilde{t}_1\tilde{\chi}_1^\pm) = 10 \text{ GeV}$

ATLAS Preliminary
Figure 9: Exclusion contour for a simplified model assuming $\tilde{t}_1\tilde{t}_1$ pair production, decaying via $\tilde{t}_1\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$ with 100% branching ratio. The lightest chargino mass is assumed to be close to the stop mass, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} + 10 \text{ GeV}$. The dashed grey line and the shaded band are the expected limit and its uncertainty. The thick solid red line is the observed limit for the central value of the signal cross-section. The expected and observed limits do not include the effect of the theoretical uncertainties on the signal cross-section. The dotted lines show the effect on the observed limit when varying the signal cross-section by ±1σ.

Limit at 95% CL

$\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b + \tilde{\chi}_1^\pm$, $m_{\tilde{t}_1} = m_{\tilde{\chi}_1^\pm} + 10 \text{ GeV}$

ATLAS Preliminary
Figure 23: Expected (black dashed) and observed (red solid) 95% excluded regions in the plane of $m_{\tilde{\chi}_1^\pm}$ versus $m_{\tilde{t}_1}$ for direct stop pair production assuming $b\tilde{\chi}_1^\pm$ decay with a branching ratio of 100%. The chargino mass is assumed to be close to the stop mass, $m_{\tilde{\chi}_1^\pm} = m_{\tilde{t}_1} + 10 \text{ GeV}$. All limits at 95% CL.
Results: spin-0 mediator model

Preliminary ATLAS -1 = 36.1 fb

<table>
<thead>
<tr>
<th>Theory unc. on σ(g=1.0)</th>
<th>Expected σ ±1 σ</th>
<th>Expected σ ±2 σ</th>
<th>Observed 95% CL</th>
<th>ATLAS Preliminary</th>
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<tbody>
<tr>
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<td>Expected 95% CL</td>
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<td>Pseudoscalar</td>
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<tr>
<td>γs = 13 TeV, L_{int} = 36.1 fb^{-1}</td>
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<td>Scalar</td>
<td>Pseudoscalar</td>
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Stop $b$-$l$ Results:

$\bar{t}\bar{t}^*$ production, $\bar{t} \to b\ell$

**ATLAS** Preliminary

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

- Observed limit ($\pm 1\sigma_{SUSY}$)
- Expected limit ($\pm 1\sigma_{exp}$)

All limits at 95% CL
Stop search with higgs and Z boson

- Higgs or Z boson can be a key ingredient in various stop searches:
  1) $t_1 \rightarrow t + \chi_2^0$ or 2) $t_2 \rightarrow t_1 + h/Z$.

- 3L+1b (via Z boson) and 1L+4b (via Higgs boson) final states are targeted for the analysis.

![Diagram with particles and reactions](image-url)