Using direct stop searches at ATLAS to constrain the parameter space of supersymmetric models

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LBNL Seminar

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The Standard Model

- The Standard Model (SM) is great
  - Describes most of nature’s interactions and particles
  - Many accurate predictions verified by experiment
  - Last piece of the puzzle discovered: Higgs

We’re done! We discovered all the SM particles!
There are problems with the SM

- **Hierarchy problem**: higgs mass calculation is sensitive to extremely high energy contribution
  - To achieve measured value, absurdly exact cancellation is needed
  - Top quark contribution to correction most important
- The SM has no explanation for **dark matter**
  - Overwhelming evidence from: bullet cluster, rotational curves, CMB
- And more...
  - Anti-matter/matter asymmetry
  - Dark energy
  - Neutrino masses

[Diagram of mass eigenstates]

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Supersymmetry (SUSY) has solutions!

- Introduce SUSY partners to SM particles
  - Fermions partners for SM gauge bosons
  - Scalars partners for SM fermions
- Hierarchy problem solution: Additional loops with opposite sign cancels large contributions
- Dark matter solution: Neutral Lightest Supersymmetric Particle (LSP or $\tilde{\chi}^0$) is stable dark matter candidate

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SUSY parameter space

- SUSY is very broad and describes many models
- Masses and scales of SUSY are not specified!

NMSSM = Next-to-Minimal Supersymmetric Standard Model
MSSM = Minimal Supersymmetric Standard Model
pMSSM = phenomenological Minimal Supersymmetric Standard Model
Simplified models

- SUSY has many tunable parameters $\Rightarrow$ need to reduce
  - Even with experimental constraints (as in pMSSM with 19 free parameters)

**Solution: simplified models**

- Assume only select SUSY particle can be produced at LHC
  - Remainder is too massive (4-7 TeV)
  - Production cross section depends on mass
- Make simplified assumption of decay chain
  - Only 1 or 2 decay modes for stops ($\tilde{t}$)
Stop quark production

- Top/stop quark are important for hierarchy problem solution
  - Preference for stop masses below $\sim 1$ TeV
- Searching for **direct stop pair production**
  - QCD production $\Rightarrow$ calculable
- Highest production cross section after gluinos and light squarks

![Diagram of SUSY production](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections)

**LPCC SUSY $\sigma$ WG**

<table>
<thead>
<tr>
<th>SUSY sparticle mass [GeV]</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{q}, \tilde{g}$</td>
<td>$\tilde{q}, \tilde{g}$</td>
</tr>
<tr>
<td>$\tilde{l}^+, \tilde{l}^-, \tilde{\chi}^+, \tilde{\chi}^-, \tilde{\chi}^0$</td>
<td></td>
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</tbody>
</table>


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Stop decay mode

\[ \tilde{t}_1 \rightarrow t + \tilde{\chi}^0 \]

where \( \tilde{\chi}^0 = \) Lightest Supersymmetric Particle (LSP)

- LSP doesn’t interact with detector: missing energy
- Final states contains 2 tops and missing energy
  - Top pair decay with 0, 1, or 2 leptons
  - **Highlight 0-lepton (all hadronic) search as example**

Simplified model parameters:

\[ m_{\tilde{t}}, m_{\tilde{\chi}^0} \]
LHC

- ATLAS: general purpose
- CMS: general purpose
- LHCb: b-quark physics
- ALICE: Heavy-ion (lead-lead)

- 27 km circumference in Geneva-land
- 7 and 8 TeV proton-proton collisions finished in 2012
  - Early 13 TeV collisions are happening now!
• Subdetectors used in analysis:
  • **Calorimeters**: jets
  • Inner tracker: b quark identification
Jets

- Quarks/gluons hadronize and form showers of particles in the detector
  - Usually within a certain spatial extent
- Group together energy deposit from common source: **Jet algorithms!**
  - Recursive algorithm
  - Energy weighted
  - Spatial extent determined by \( R \) parameter
Identifying jets containing b-quarks (b-jets)

- Charged particles arc in 2T field
  - Inner tracker used to reconstruct arc parameters
- B mesons are long lived \((c\tau \sim \gamma \times 450 \, \mu m)\) resulting in:
  - Secondary vertex from decay away from primary interaction
  - Tracks from decay have high impact parameter
  - Unique decay topology due decay to charm mesons
- Information is combined (with MVA) to discriminate jets containing b-quarks from light jets
General outline of a SUSY search at ATLAS

- Divide the signal “grid” into regions with similar final state kinematics
  - Identify backgrounds which fake your signal signature
  - Find handles to reject background

- Estimate background from Monte Carlo (MC) simulations
  - Control regions (CR): Normalize the MC for specific background
  - Validation regions (VR): closer to SR and check normalization and shape

- Unblind and look for excesses
  - If nothing is found, set limits on models

Signal region aims

\[ m_{\tilde{\chi}^0} \]

\[ m_{\tilde{t}} \]

observables 1, 2

SR3
CR2
VR2
SR2
CR1
VR1
SR1
Signal signature

- Direct stop production with each $\tilde{t} \rightarrow t + \tilde{\chi}^0$
- Tops decay to $W$-boson + $b$-quark
- 2 LSP’s results in large missing energy ($E_T^{\text{miss}}$)
- 2 $b$-jets from top decay
- More jets from $W$ decay
- **Ideally: 6 jets (2 of which are $b$-jets) and missing energy**
  - 2 Top masses can be reconstructed
Possible backgrounds

Semi-leptonic $t\bar{t}$

- Dominated by $\tau$ decays
- Only 1 reconstructed top mass
- $\tau$’s mimic jets but have less tracks associated with jet
- $E_T^{\text{miss}}$ near $\tau$ jet

Other backgrounds

- $Z/W + b\bar{b}, c\bar{c}$
  - $Z \rightarrow \nu\nu$
  - $W \rightarrow \ell\nu$
- Irreducible hadronic $t\bar{t} + Z \rightarrow \nu\nu$
  - Has 2 b-jets, 2 top masses, and $E_T^{\text{miss}}$
• Strongest discriminator is $E_{\text{T}}^{\text{miss}}$
• $E_{\text{T}}^{\text{miss}}$ details
  • Infer invisible component from $p_{\text{T}} = 0$ requirement: $E_{\text{T}}^{\text{miss}} = |p_{\text{T}}^{\text{miss}}|$  
• Amount of $E_{\text{T}}^{\text{miss}}$ in signal depends on $m_{\tilde{t}}$ and $m_{\tilde{\chi}^0}$
Semi-leptonic $t\bar{t}$ rejection: $\tau$-veto

- Semi-leptonic $t\bar{t}$ background mainly from $t \to b + W(\to \tau + \nu)$
- Hadronic $\tau$ decay is dominant source of background
  - Most commonly decay into 1 and 3 pions
- Identified by:
  - Jet with $\leq 4$ tracks
  - $\Delta\phi$ between jet and $E_T^{\text{miss}}$ small ($\Delta\phi < \pi/5$)
- Events with such a $\tau$ jet are vetoed
Signal region example: high $m_{\tilde{t}}$

At higher $m_{\tilde{t}}$, tops can have high $p_T$ (boosted)
  - Jets from top become collimated
  - Can reconstruct top mass from jets with a certain cone
    - Same algorithm (anti-$k_t$) used in jet reconstruction is used to form “top jets” but with different parameters ($R = 1.2$)
  - Top masses reject background: 2 top masses should be present in signal
    - Semi-leptonic $t\bar{t}$ should only have 1 top
    - $Z/W+$jets should not have any tops
Control region example: $t\bar{t}$

- Require 1 lepton $\Rightarrow$ orthogonal to signal region
- Similar definition to signal region
  - 2 b-jets,
  - $E_{\text{miss}}^{\text{T}} > 150$ GeV
- Some modification to enhance $t\bar{t}$ purity

Good agreement between MC and data
**Final background composition (highlight)**

**Low $E_T^{\text{miss}}$, loose top reco**

- $t\bar{t} = 10.64 \pm 1.90$
- $t\bar{t}V = 1.80 \pm 0.59$
- $Z = 1.42 \pm 0.53$
- $W = 0.95 \pm 0.45$
- Other = 1.00 ± 0.35

Total: 15.8 ± 1.9

Other contains: single top, dibosons, and multijet (negligible)

**High $E_T^{\text{miss}}$, tight top reco**

- $t\bar{t} = 0.49 \pm 0.34$
- $t\bar{t}V = 0.50 \pm 0.17$
- $Z = 0.68 \pm 0.27$
- $W = 0.06 \pm 0.08$
- Other = 0.63 ± 0.34

Total: 2.4 ± 0.7

Background contribution changes drastically for different kinematic regions
Unblinding example: $E_T^{\text{miss}}$ after all other requirements

**Data 2012**

<table>
<thead>
<tr>
<th>Number of events</th>
<th>SRA1</th>
<th>SRA2</th>
<th>SRA3</th>
<th>SRA4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>11</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Expected background</td>
<td>$15.8 \pm 1.9$</td>
<td>$4.1 \pm 0.8$</td>
<td>$4.1 \pm 0.9$</td>
<td>$2.4 \pm 0.7$</td>
</tr>
</tbody>
</table>

No significant excess over background...
In any of the stop searches (0, 1, 2-lepton, and more final states)
Data event with 5 jets

$E_T^{\text{miss}} = 896$ GeV

Top candidate masses: 167 GeV and 170 GeV
Interpretation of stop searches in terms of simplified models
Stop 0-lepton limits: $\text{BF}(\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1) = 100\%$

- Limit considering only 0-lepton stop search
- Limits assume 100% decay to $t + \tilde{\chi}^0$
- At high $\tilde{t}_1$, low $\tilde{\chi}^0$ mass:
  - Expected limit of $275 < m_{\tilde{t}} < 700$ GeV
  - Observed limit of $270 < m_{\tilde{t}} < 645$ GeV

\textbf{ATLAS}

\[ \int \text{Ldt} = 20.1 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \]

All-hadronic

All limits at 95 % CL
Considered additional BH(t + \tilde{\chi}^0)

- 100%, 75%, 50%, 25%, 0%
- Only other decay: b+\tilde{\chi}_1^\pm
- Designed SR’s for kinematics of this channel
- At BH(t + \tilde{\chi}^0)=50% and \m_{\tilde{\chi}_1^0}<60 \text{ GeV}: exclude 250 < m_{\tilde{t}} < 550 \text{ GeV}

**Set tight bounds, even at BF=50%**

\int L_{dt} = 20.1 \text{ fb}^{-1}, \sqrt{s}=8 \text{ TeV}

All-hadronic

Excluded Limit at 95% CL

\begin{align*}
\tilde{t}_1 \tilde{t}_1 \text{ production, } \tilde{t}_1 \rightarrow t\tilde{\chi}_1^0 \text{ or } \tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm (m_{\tilde{t}} = 2 \times m_{\tilde{\chi}_1})
\end{align*}
0 and 1 lepton combination

- Combination of 0 and 1-lepton stop results
  - For BF=0, 25, 50, 75, and 100%
  - No excess over background
  - Sets stringent limits: $m_{\tilde{t}} < 700$ ($m_{\tilde{t}} < 570$) GeV at BF=100% (BF=50%)

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### ATLAS

$t\tilde{t}$ production, $t\rightarrow t\tilde{\chi}_1^0$

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

All limits at 95% CL

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Combining all Run 1 stop searches

- Includes searches with different kinematics
  - Off-shell top and W
- Additional decay modes: \( \tilde{t}_1 \rightarrow \text{charm} + \text{LSP} \)
- Spin correlations measurement: enhanced sensitivity when \( m_{\tilde{t}} \sim m_t + m_{\tilde{\chi}_0} \)

Many kinematic regions covered!
ATLAS is not alone!

- CMS performs similar searches
- Similar results: $250 < m_{\tilde{t}} < 750$ GeV excluded (at 100% BF)

**Observed limits**
**Expected limits**
**All limits at 95% CL**

Superseded by SUS-13-023-PAS

Strong limits from both ATLAS and CMS
Sensitivity to other production modes

- There are 2 stops: light stop = ℓt1, heavy stop = ℓt2
  - Searches are aimed ℓt1 production
- If mℓt1 ≈ mt: difficult direct ℓt1 detection
  - Similar to top production with low E_\text{miss}^\text{T}
- Sensitivity to ℓt2 → t + χ^0 becomes dominant ⇒ similar signature as ℓt1 search
- 3 decays of ℓt2 considered
  - BF limits can be shown in triangle

\[ m_{\tilde{t}_2} = 500 \text{ GeV} \]
\[ m_{\chi_1^0} = 120 \text{ GeV} \]
Interpretation SUSY searches in terms of pMSSM models
- Minimal extension of the Standard Model
  - R-parity conserving and $\tilde{\chi}^0$ is LSP $\Rightarrow$ causes signatures with $E_T^{\text{miss}}$
- $p =$ phenomenological $\Rightarrow$ constrained by experimental observations
- Results in 19 parameters
  - $X^{19}$ possible model points, $X = \text{grid spacing}$. Need more reduction!

Use many analyses Run 1 searches + more to further constrain pMSSM
Scope of pMSSM scan

- Total of 22 analyses used, each with many signal regions
- Initial pMSSM models considered with random sampling of parameter space
  - 500 million model points
- Apply more experimental constraints:
  - Pre-LHC direct searches, precision measurements, dark matter
- 300K remaining model points
  - 30 billion events generated
- 45K models went through detector simulation
  - 600 million events

Massive effort to understand pMSSM parameter space constraints
• Gluinos (partner of gluon) have highest production cross section
• White line: searched aimed at finding gluinos
  • Dedicated search excludes nearly all pMSSM points within mass limit
• Additional searches extend reach
  • High gluino mass/low $\tilde{\chi}^0$ mass
  • Compressed region

Compressed and high gluino mass sensitivity extended by addition of analyses
• Limits from 3rd generation (stop and sbottom) searches cover the $m_{\tilde{t}}$ region well
• Additional searches significantly help constrain high $m_{\tilde{t}}$ region
New neutralino constraints

- Dedicated searches require multiple leptons
  - Assumes $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z$
- pMSSM allows many cases with low $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + Z$ BF
  - Reduction of sensitivity
- Greatest sensitivity at high $\tilde{\chi}_2^0$ mass due to disappearing track analysis

Strongest bounds are not from dedicated search!
Dark matter relic density

- $\Omega_{\tilde{\chi}^0} h$ (Dark matter relic density) = current amount of dark matter
- Project pMSSM model points onto $m_{\tilde{\chi}^0} - \Omega_{\tilde{\chi}^0} h$ plane
- $\tilde{\chi}^0$ is a mix of various SUSY fermions (gauginos)
  - Which gaugino is dominant has strong effect on DM production
- 3 cases considered:
  - $\tilde{\chi}^0$ is mostly Wino-like, Bino-like, Higgsino-like

Before ATLAS

After ATLAS
What’s left?

- How does a pMSSM model that isn’t excluded look?
- Consider the most “natural”:
  - “natural” = lowest stop mass so that top/stop loop cancels maximally
- Most “natural” that evades all bounds: $m_{\tilde{t}} \sim 800 \text{ GeV}$
  - Stop exclusion reminder: $m_{\tilde{t}} < 750 \text{ GeV}$

This model seems to have just escaped our reach!

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Summary of sparticle mass bounds

Black areas are robustly excluded

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For Run 2
- $\sqrt{s} = 13$ TeV
- $\sim 100$ pb$^{-1}$ of 13 TeV 50 ns data collected
- $\sim 2 - 4$ fb$^{-1}$ by the end of 2015
- $\sim 100$ fb$^{-1}$ by end of Run 2

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<td>Q1</td>
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<td>Q3</td>
<td>Q4</td>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
</tr>
</tbody>
</table>

- Run 2
- LS 2

- Physics
- Shutdown
- Beam commissioning
- Technical stop
Run 2 considerations

- Increase in $\sqrt{s}$
  - Factor of $\sim 10$ increase of cross section for $m_\tilde{t} = 800$ GeV
  - More boosted topologies
- Background cross section increases:
  - $t\bar{t} \sim 3\times$
  - $W/Z+\text{jets} \sim 2\times$
  - $t\bar{t}+Z \sim 4\times$
- Run 2 comes with challenges
  - Higher trigger thresholds
    - Run 1: $E_T^{\text{miss}} > 150$ GeV
    - Run 2: $E_T^{\text{miss}} > 250$ GeV
  - Different background makeup
Run 2 has started!

- 13 TeV data taking started in May/June
  - With 50 ns proton bunch spacing
  - With 6 pb$^{-1}$: first $E_{T}^{\text{miss}}$ studies
  - Data/MC comparisons in $W \rightarrow e\nu$ events

Reasonable MC/data agreement!

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, $\int L dt \sim 6 \text{ pb}^{-1}$
Run 2 and beyond

- Run 2 should yield \( \sim 100 \text{ fb}^{-1} \) by 2018
- High Luminosity LHC planned: total data \( \sim 3000 \text{ fb}^{-1} \)
  - What if early data shows no signs of SUSY?
  - Will more data yield insight?

Due to small cross sections at high stop mass more luminosity is important for search
Searched for direct stop production

Found nothing!

Set limits on $m_{\tilde{t}}$, $m_{\tilde{\chi}^0}$
  - $m_{\tilde{t}} > 750$ GeV for low $m_{\tilde{\chi}^0}$

Constrained pMSSM parameters space

Run 2 is happening!