Status of SUSY searches at the LHC
(including SUSY Higgs bosons)

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On behalf of the ATLAS and CMS Collaborations
29th Rencontres de Blois
28 May – 2 June 2017
SUSY in One Minute

• Supersymmetry is an additional symmetry of the SM that could solve several problems (Dark Matter, Force Unification, Hierarchy Problem) at the cost of many new particles and parameters.
• **LSP**: Lightest SUSY particle
• **R-Parity**: Postulated symmetry whereby SUSY particles are produced in pairs and the lightest SUSY particle is stable
  – R-Parity means the LSP is a possible WIMP dark matter candidate
• **Gluino / Squark**: SUSY partner of the gluon / quark
• **Gravitino**: SUSY partner of the graviton, popular in General Gauge Mediation scenarios as the LSP
• **Natural SUSY**: With light SUSY (accessible at the LHC), SUSY can solve the hierarchy problem and keep the Higgs mass light. As SUSY particles get heavy, the second-order (log) corrections get larger, and the cancelation that protects the Higgs mass is not as satisfying. Natural SUSY is the name given to SUSY that has particles that are light enough (this is a matter of taste) to satisfactorily solve the hierarchy problem without large log corrections.
• **SUSY Higgses**: SUSY includes two doublets, giving rise to five Standard Model-sector Higgs bosons (h, H, A, H^±). The Higgs found at the LHC with a mass of 125 GeV is generally identified as the h in this characterization.
Organizing the Searches

- SUSY final states are quite **diverse**!
- We tend to search for **simplified models**, not “full” models
- We tend to search from easiest to hardest
  - From **strong** to **electroweak** production, bulk into “corners”
- Most searches shown today use the 2015+2016 LHC datasets
The Other Higgses

- Most SUSY searches these days that involve the Higgs have a Standard Model Higgs in a decay:

- I’ll talk plenty about these today
- Virtually no news on H/A/H± since last year
- CMS and ATLAS released ττ results in the fall
  - CMS-PAS-HIG-16-037
  - ATLAS-CONF-2016-085
- No evidence so far, but that’s no problem (yet?)
  - Decoupling limit (make others very heavy)
  - Alignment limit can force an SM-like SUSY Higgs
  - H precision measurements no problem for SUSY
STRONG PRODUCTION
SEARCHES WITH JETS, MISSING TRANSVERSE MOMENTUM (MET) AND (SOMETIMES) LEPTONS

Xsecs from this TWiki

pp Collisions
$\sqrt{s} = 13$ TeV

<table>
<thead>
<tr>
<th>Mass [GeV]</th>
<th>Cross Section [pb]</th>
</tr>
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<tr>
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<td>2000</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>2500</td>
<td>$10^{-1}$</td>
</tr>
</tbody>
</table>

$\tilde{g} \tilde{g}$
$\tilde{q} \tilde{q}^*$
$\tilde{t}_1 \tilde{t}_1^*$
$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$

$\text{pp Collisions}$
$\sqrt{s} = 13$ TeV

$Xsecs$ from this TWiki

1 June 2017
Status of SUSY Searches at the LHC
ATLAS 0L Strong Production

- Workhorse search vetoing leptons, covering a variety of models
- 24 signal regions in a ‘traditional’ MET+$H_T$-based search
- First search to include the “Recursive Jigsaw” (22 more regions)
ATLAS 0L Strong Production (II)

Limits set on a variety of simplified models like this one:

\[ \tilde{g} \tilde{g} \text{ production, } B(\tilde{g} \rightarrow qq \tilde{\chi}_1^\pm \rightarrow qq W^\pm \tilde{\chi}_1^0) = 100\%, \ m(\tilde{\chi}_1^\pm) = (m(\tilde{g}) + m(\tilde{\chi}_1^0))/2 \]
CMS Boosted-Top

- Search for strongly produced SUSY with boosted top jets
  - Top jet: hadronically decaying top quarks identified in a single jet; combines a low-$p_T$ “resolved” algorithm and a high-$p_T$ fat-jet algorithm
  - Efficiency above 50% for top $p_T > 400$ GeV
- Complex likelihood fit with bins in MET, $N_{b\text{-jet}}$, $N_{t\text{-jet}}$, $M_{T2}$

1 June 2017
Status of SUSY Searches at the LHC
ATLAS Multi-Jet

• Long SUSY decay chains produce many jet final states
• Search in events with 7-11 jets and 0, 1, or 2 b-jets
• Uses a ‘template’ method to estimate QCD background
  – MET significance approximately invariant in jet multiplicity
CMS SS Leptons

- Because of the independent gluino decays, **same-sign leptons** are a common and powerful way to constrain strong production
  - Also can happen in H/A production!
- Main backgrounds from non-prompt leptons, charge mis-ID

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**Graphs and Tables:**

- **Baseline selection:** 2 SS leptons, $N_{jets} > 2$, $E_T^{miss} > 50$ GeV
- **Data/Pred.**
- **Combined fit:** $\sim 100$ bin

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**Additional Information:**

- arXiv:1704.07323
ATLAS SS/3L

- Searching for both R-parity **Conserving** and R-parity **Violating** scenarios with two same-sign or three leptons
  - Targets 12 different SUSY scenarios
- Regions divided according to b-jet/lepton multiplicity and severity of other requirements (e.g. MET, $H_T$)

Large diboson (theory) and non-prompt lepton background uncertainties

Good target for improvement with more data!

1 June 2017

Status of SUSY Searches at the LHC
3RD GENERATION SUSY

SEARCHES WITH HEAVY-FLAVOUR JETS, MET, AND (SOMETIMES) LEPTONS
CMS Sbottom+Higgs

- Search using “Razor” variables for events with Higgs bosons in the decay chain (H→γγ)
- Fitting the diphoton mass spectrum in many bins

Background-only / Signal+Background

CMS Preliminary 35.9 fb⁻¹ (13 TeV)

Events / (1 GeV)

CMS Preliminary 35.9 fb⁻¹ (13 TeV)

pp → ~b~b, ~b → b~χ₂⁺ → bH~χ₁⁺

Observed ± 1σ

Expected ± 1σ

NLO+NLL exclusion

CMS-PAS-SUS-16-045
• Searching for stop in several scenarios (motivated by pMSSM)
  – Includes the first BDT-based SUSY analyses from ATLAS
• Many variables to reduce specific backgrounds
  – $am_{T2}$, $m_T$, $m_{top}^{recl}$, $\Delta R(b,l)$, $m_{T2}^{\tau}$ (tau veto), $MET_\perp$, $\Delta \phi (jet,MET)$, $H_{T,miss}^{\text{sig}}$

NEW!

1 June 2017
Status of SUSY Searches at the LHC
ATLAS Stop 1L

- Searching for stop in several scenarios (motivated by pMSSM)
  - Includes one of the first BDT-based SUSY analyses from ATLAS
- Many variables to reduce specific backgrounds
  - $a m_T$, $m_T$, $m_{\text{top}}^{\text{recl}}$, $\Delta R(b,l)$, $m_{\tau_T}$ (tau veto), MET, $\Delta \phi(jet,\text{MET})$, $H_{T,\text{miss}}^{\text{sig}}$

1 June 2017
Status of SUSY Searches at the LHC
CMS Sbottom/Stop

- Introduces a special “compressed” selection for low-\(p_T\) b-jets
  - Relies on (light flavour) ISR for signal selection, little other jet activity
- 49 total bins in b-tags and c-tags, MET, and jet activity
ATLAS Stop Summary

- Low-mass stop phase space rapidly closing
- Gaps that we used to point to are being closed by clever tricks and new searches
- Several searches “deepen” the exclusion
- Expect more combinations in the near future
CMS Stop Summary

- Low-mass stop phase space rapidly closing
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ATLAS B-L RPV Stop

- One new place to look: B-L R-parity violating stop
  - Theoretically interesting (string+pheno motivations)
  - Look similar to leptoquarks, but with $b+e/\mu/\tau$
- Requires $\sim$symmetric b-jet + lepton pairs
  - Tests the opposite pairing for compatibility with the top mass
- Strong limits covering full decay triangle

ATLAS Preliminary
$$\sqrt{s}=13\text{ TeV}, 36.1\text{ fb}^{-1}$$
SR800

$\tilde{t}_1 \tilde{t}_1$ production, $\tilde{t}_1 \to bl$

ATLAS Preliminary
$$\sqrt{s}=13\text{ TeV}, 36.1\text{ fb}^{-1}$$
Observed 95% CL mass limit

$Br(\tilde{t} \to b \ell)$

$Br(\tilde{t} \to b e)$

Stop mass [GeV]
ELECTROWEAK SUSY
SEARCHES WITH MET, AND (SOMETIMES) LEPTONS, AND USUALLY WITHOUT JETS

pp Collisions
\( \sqrt{s} = 13 \text{ TeV} \)

Mass [GeV]

Cross Section [pb]

Xsecs from this TWiki

- \( \tilde{g} \tilde{g} \)
- \( \tilde{q} \tilde{q}^* \)
- \( \tilde{t}_1 \tilde{t}_1^* \)
- \( \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \)
CMS Photons+MET

- Search for both electroweak (decays to Gravitino) and strong production in final states with a photon and MET
  - Detector-induced backgrounds controlled via template fit

1 June 2017

Status of SUSY Searches at the LHC

CMS-PAS-SUS-16-046
ATLAS 2/3L Electroweak

• Search for a variety of electroweak processes
• Difficult to control detector-induced backgrounds
  – Z+jets with a jet veto and “fake” MET, jets identified as leptons
• Highest limits to date in many simplified models

ATLAS-CONF-2017-039
• Higgsinos are the last (hardest) critical piece of natural SUSY
• Searching in generic compressed scenarios for decays to Higgs+Goldstino for MET and (up to) four b-jets using a deep learning b-tagging algorithm
  – Compressed scenario keeps final state but increases prod. cross section
• Excludes most interesting high-mass Higgsinos space in these scenarios
  – “Bare” Higgsino searches are still a way off, but are in progress
LONG-LIVED SUSY
ATLAS Disappearing Track

- In highly-compressed scenarios, common to have a ‘disappearing track’ type signature
  - Very common in the MSSM

- Small chargino-neutralino mass splitting makes chargino long-lived

- Thanks to the new IBL, able to increase sensitivity to shorter lifetimes

ATLAS-CONF-2017-017
**ATLAS Disappearing Track (II)**

- Strong limits on charginos at moderate lifetimes
  - Basically independent of the rest of the SUSY mass spectrum
- Extended to strong production with the chargino in a cascade

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**Graphical Representation**

- **Graph 1:**
  - $\tan \beta = 5$, $\mu > 0$
  - $\tau_{\chi_1^\pm}$ vs. $m_{\chi_1^\pm}$
  - ATLAS Preliminary
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$

- **Graph 2:**
  - $m_{\tilde{g}}$ vs. $m_{\tilde{\chi}^\pm}$
  - Observed 95% CL limit ($\pm 1 \sigma_{\text{theory}}$)
  - Expected 95% CL limit ($\pm 1 \sigma_{\text{exp}}$)
  - ATLAS (13 TeV, 36.1 fb$^{-1}$, EW prod. Obs.)
  - $m_{\tilde{g}} = m_{\tilde{\chi}^\pm}$
  - ATLAS Preliminary
  - $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
  - $\tau_{\tilde{\chi}^\pm} = 1.0$ ns

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1 June 2017

Status of SUSY Searches at the LHC

ATLAS-CONF-2017-017
Summary

• Lots of searches! But no sign of SUSY yet
  – Should consider SUSY models that only solve most, not all of the many problems that SUSY could help to solve
  – Bulk of region for “natural SUSY” covered, except for Higgsinos
  – But don’t forget our assumptions and watch for false negatives!

Next up:

• Many more manifestations of Supersymmetry to look for
  – Make those simplified models less simple!
  – Push into corners of the models where SUSY is hard to find!
  – Use the Higgs (properties and in our decays) and Higgsinos

• More searches for strange-looking and Electroweak SUSY
  – Displaced vertices (see extras), stopped particles, disappearing tracks…
  – Going after the Higgsino in various scenarios

• Start on search combinations
  – Return to showing multiple decay modes, as at the end of Run 1
  – Find ways to beat the ‘simple’ statistics increases – the time for dataset doubling is getting much longer!
Plenty more on the public results pages:
  CMS Higgs and SUSY, ATLAS Higgs and SUSY, and LHCb news

And plenty more to come!

THANK YOU!
Explicit List of Included Analyses

- ATLAS 0L
- CMS Boosted Top (New)
- ATLAS Multijet (New)
- CMS SS Leptons
- ATLAS SS/3L Strong
- CMS Sbottom+Higgs
- ATLAS Stop 1L (New)
- CMS Sbottom/Stop (Compressed)
- CMS Stop Summary
- ATLAS Stop Summary (New)
- ATLAS B-L Stop (New)
- CMS Photons+MET
- ATLAS 2/3L EWK (New)
- CMS Higgsino (4b)
- ATLAS Disappearing Track

Backups
- ATLAS Multi-b
- ATLAS Displaced Vertex
New Searches since Moriond

- CMS Boosted Top (CMS-PAS-SUS-16-050)
- CMS Stopped particles (CMS-PAS-EXO-16-004)
- ATLAS Multijet (ATLAS-CONF-2017-033)
- ATLAS SS/3L Strong (ATLAS-CONF-2017-030)
- ATLAS Sbottom 2b+MET (ATLAS-CONF-2017-038)
- ATLAS Stop 1L (ATLAS-CONF-2017-037)
- ATLAS Stop 2L (ATLAS-CONF-2017-034)
- ATLAS B-L Stop (ATLAS-CONF-2017-036)
- ATLAS 2/3L EWK (ATLAS-CONF-2017-039)
- ATLAS Di-tau EWK (ATLAS-CONF-2017-035)
- ATLAS Summary Plots (available here)

- CMS MT2 (published since Moriond; arXiv:1705.04650)
- CMS Strong 1L (published since Moriond; arXiv:1705.04673)
- ATLAS RPV 1L (published since Moriond; arXiv:1704.08493)
- ATLAS Strong 1L (published since Moriond; )
Other Talks This Week

• On similar subjects, here at Blois

• Searches with boosted objects in ATLAS and CMS
  – Pekka Sinervo, Tuesday afternoon

• Searches for Supersymmetry in ATLAS
  – Da Xu, Tuesday afternoon

• Searches for Electroweak SUSY production at CMS
  – Constantin Heidegger, Tuesday afternoon

• Searches for BSM Higgs bosons in ATLAS
  – Denys Denysiuk, Wednesday afternoon

• Searches for BSM Higgs bosons in CMS
  – Pietro Vischia, Wednesday afternoon
• Search for gluinos with $3^{\text{rd}}$ generation quarks in decays
• Requires many jets, $\geq 3$ b-tags, and MET ($0$ or $1$ lepton)
  – 10 signal bins targeting a variety of SUSY models, plus a 14-bin fit
• Most background and uncertainty from ttbar (with extra bs)
  – Mostly MC-driven estimates with control regions to constrain modeling
  – Expect more data-driven estimates soon, as in past analyses
ATLAS Displaced Vertex

- Search for R-hadrons (stable, hadronized squarks and gluinos) that decay in the detector
  - Demands excellent understanding of detector material
- Search in decay vertex mass and charged particle multiplicity
- Limits on gluinos up to 2.2 TeV (!!) for lifetimes of 0.05-1 ns
CMS Electroweak Summary

pp → \tilde{\chi}_2^0 \tilde{\chi}_1^\pm

Moriond 2017

35.9 fb^{-1} (13 TeV)

CMS Preliminary

- SUS-16-039, 2l SS + ≥3l (WH)
- SUS-16-043, 1l (WH)
- SUS-16-034, 2l OS (WZ)
- SUS-16-039, 3l (WZ)
- SUS-16-048, soft 2-lep (WZ)

m_{\tilde{\chi}_0} [GeV]

m_{\tilde{\chi}_1} [GeV]

m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} + m_{Z}

m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} + m_{H}

m_{\tilde{\chi}_2} = m_{\tilde{\chi}_1} + m_{H}