SUSY Searches in ATLAS and CMS

Caroline Collard (IPHC Strasbourg)
On behalf of the ATLAS and CMS Collaborations
Outline

• Generalities

• New results at 13 TeV based on 2016 data
  • Gluinos
  • Squarks of 1st and 2nd generations
  • Stops
  • Sbottoms
  • EWKinos

• Conclusions

Other experimental talks on SUSY today:
- Marc Besancon (EWKinos@CMS)
- Edoardo Gorini (SUSY@ATLAS)
- Batool Safarzadeh Samani (Stop@CMS)
Generalities
Supersymmetry (SUSY) = new symmetry between forces and matter. 

- Complete spectrum of partners to standard model particles, with same quantum numbers except for the spins which are different by 1/2 unit, and heavier.
Naive Introduction

Supersymmetry (SUSY) = new symmetry between forces and matter.
- Complete spectrum of partners to standard model particles, with same quantum numbers except for the spins which are different by 1/2 unit, and heavier.

Why do people like Susy so much?
- Stabilize the Higgs boson mass,
- Provide a Dark Matter candidate if the R-parity is conserved,
- Realize the grand unification of the gauge couplings
The present situation

• LHC is performing extremely well:
  • Collisions at $\sqrt{s}$ (Run2)$= 13$ TeV
  • Peaks at instantaneous luminosity already exceeding the design value
  • Integrated luminosity already reaching the target value for 2016 (25 fb$^{-1}$)

→ Is SUSY around the corner?

• Challenges for the experiments:
  • Need to keep trigger rates under control
  • Deal with increasing number of Pile-Up events
  • Follow the data-taking conditions with online and offline calibrations
Which SUSY to search for?

• The potential parameter space is enormous:
  cMSSM (4+1), pMSSM (19), MSSM (105), NMSSM, ...

• Some scenarios are privileged in our searches:
  • R-Parity conserved with lightest SUSY particle (LSP) = \tilde{\chi}_1^0
    • Dark Matter candidate
    • Classical SUSY signature with high transverse missing energy (MET)
    • Strong or electroweak production
  • Gauge mediated symmetry breaking (GMSB)
    • Decay chain terminated with low mass and invisible particles
    • Typical signature: MET from \tilde{G}, photons or Z from last decay step
  • R-Parity violating
    • Coupling strongly constrained (proton stability)
    • Loose MET handle for background reduction
    • Alternative signature, like high jet multiplicity
Use of SMS

• SMS (Simplified Models Spectra):
  • Reduce the SUSY spectrum to only particles you are looking at
  • Instead of scanning SUSY model parameters, scan over masses
  • Consider only 1 or 2 decay modes → BR often fixed to a value (100%)

• Very useful to define the signal regions (as closely related to experimental observables) and to interpret the results. Usually the masses of SUSY particles are scanned in 2 dimensions.
What are the associated cross sections?

- Pair production of SUSY particles if R-parity is conserved.
- Cross-sections depending on the mass of the SUSY particles.
- Large increase of the cross-sections of massive particles at 13 TeV:

\[
\sigma(\tilde{g}\tilde{g}) \times 30 \text{ for } m(\tilde{g}) = 1.4 \text{ TeV}
\]
\[
\sigma(\tilde{t}\tilde{t}) \times 8 \text{ for } m(\tilde{t}) = 700 \text{ GeV}
\]
\[
\sigma(\tilde{\chi}\tilde{\chi}) \times 4 \text{ for } m(\tilde{\chi}) = 500 \text{ GeV}
\]

In contrast to SM: \(\sigma(tt) \times 3.3\)  
\[ \Rightarrow \text{S/B boost!} \]
How do we search for susy?

1. Select your preferred signal, with its associated decay. It can be classified as a function of the lepton #: 0l, 1l, 2l, ...

2. Play with the different observables to enrich S/B
   - **Standard SM objects**: isolated leptons, jets, b-jets, MET = |\(-\Sigma\text{ (particle) } p_T\)|
   - **Composite, boosted objects**: topness, boosted W and top taggers, jet substructure
   - **Kinematic variables to reconstruct mass of intermediate states**: $m_T$ of (l, MET) or (b, MET), $m_{T2}$, $m_{CT}$, ...
   - **Hadronic/total energy**: $H_T = \Sigma\text{ (jets) } |p_T|$, $M_{HT} = |\Sigma\text{ (jets) } p_T|$, $m_{\text{eff}} = \Sigma\text{ (jets, leptons) } |p_T| + \text{MET}$, ...
   - **Event kinematics**: hemispheres, razor, recursive jigsaw reconstruction,...
How do we search for susy?

1. Select your **preferred signal**, with its associated **decay**. It can be classified as a function of the lepton #: 0l, 1l, 2l, ...

2. Play with the **different observables** to enrich S/B

3. **Optimize your selection** depending on the parameter space: High $\Delta m$, compressed spectra, ... $\rightarrow$ **several signal regions (SR)**

4. **Different approaches** can be used: multi-variate (with BDT) or cut&count. In Run2 mainly cut&count approach.

**example: the stop pair production**

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C. Collard (IPHC)  
LHC Days in Split 2016
• SUSY analyses can **not rely on** perfect modeling in MC to estimate background yields in SR.

• **Major backgrounds are estimated with data-driven techniques using orthogonal control regions (CR),** typically by varying the lepton multiplicity or the b-jet multiplicity.
  • Otherwise stay as close as possible to the signal regions (~ same binning)
  • If statistically limited, an integration over some variables is done
  • Use of Transfer Factors (Control region $\rightarrow$ Signal region)

• **Yields of Rare backgrounds are taken from simulation**
  • reweighted to the most accurate cross-section and to known mis-modeling of the simulation (ex: PU)
  • all uncertainties (theory – experimental) are taken into account
Interpretation of the results

- **If no excess** is observed in data, **limits** are derived based on the different SR (with the possibility to also have aggregated SR).

Interpretation of the results

- Remember that there are always some assumptions hidden in those limits

Reinterpretation

- SMS limits can be reinterpreted in other models.

Example: Reinterpretation within the pMSSM (MSSM in 19-dim subspace, assuming no CPV couplings, R-Parity conserved, degeneration of 1\textsuperscript{st} and 2\textsuperscript{nd} gen, MFV) of CMS searches (CMS, arXiv:1606.03577): Bayesian analysis including 11 CMS analyses @7 and 8 TeV. Goal: understand the impact of model parameters, limitation of SMS approach and search for "holes" in the experimental searches for MSSM, using scans of pMSSM parameter space.
New results with 13-18/fb at 13 TeV

A lot of new results this summer!
ATLAS : 12 CONF notes for ICHEP + 4 new CONF notes in August
CMS : 14 PAS for ICHEP + (7 PAS or papers on 2015 data only 2.3-2.7/fb)
1. Gluinos

Highest SUSY production cross section $\rightarrow$ Plenty of searches in 2016!

R-Parity conserved, LSP=$\tilde{\chi}_1^0$

R-Parity conserved, LSP=$\tilde{G}$

R-Parity violated
1. Gluinos
R-Parity conserved, LSP=$\tilde{\chi}^0_1$

Similar limits for ATLAS and CMS.

Complementarity of the analyses (Same Sign 2l and 0-lep)
1. Gluinos
R-Parity conserved, LSP=$\tilde{\chi}_1^0$

Hadronic search with $\geq 3$ b-jets among 4 jets, using 2015 +2016 data (14.8/fb).
(ATLAS-CONF-2016-052)

Key variables: $p_T$(jets), #b-jets, MET, $m_{\text{eff}}$, $\Delta \phi(j,\text{MET})$

Improvement by 220 GeV w/respect to 2015 limits
1. Gluinos
R-Parity conserved, LSP=$\tilde{G}$

Search with 2 leptons (Opposite Sign, Same Flavour → on-Z), jets, MET, using 2016 data (12.9/fb). (CMS PAS SUS-16-021)

Key variables: #jets, #b-jets, $H_T$, MET + 1 SR motivated by the ATLAS 3.0 $\sigma$ excess at 8 TeV and 2.2 $\sigma$ at 13 TeV (2015) → no excess in CMS
1. Gluinos

R-Parity violated
(one coupling ≠0)

Search in $\geq 1$ lepton (e/μ) + $\geq 8-10$ jets, 0 or $\geq 3$ b-jets, no MET (RPV) using 2015 +2016 data (14.8/fb).

(ATLAS-CONF-2016-094)
2. Squarks of 1st 2 generations

CMS Preliminary

\[ pp \rightarrow \tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0 \]

ICHEP 2016

13 TeV

ATLAS CONF-2016-054
3. Stops

In Natural SUSY, $m_{\text{Stop}} < 1-1.5$ TeV $\rightarrow$ Plenty of searches in 2016!

R-Parity conserved, LSP=$\tilde{\chi}_1^0$

R-Parity conserved, LSP=$\tilde{G}$

R-Parity violated
3. Stop

R-Parity conserved, LSP=\tilde{\chi}_1^0

Different channels: 0l, 1l, 2l, 2 soft l. **Pushing the limits** to larger m_{Stop} and m_{LSP}.
Start filling the region with Δm = m_{top}.

pp → \tilde{t}\tilde{t}, \tilde{t} → t \tilde{\chi}_1^0

**ICHEP 2016**

**CMS Preliminary**

- SUS-16-014, 0-lep (H_T^{miss}), 12.9 fb^{-1}
- SUS-16-015, 0-lep (M_{T2}), 12.9 fb^{-1}
- SUS-16-016, 0-lep (α_T), 12.9 fb^{-1}
- SUS-16-029, 0-lep stop, 12.9 fb^{-1}
- SUS-16-030, 0-lep (top tag), 12.9 fb^{-1}
- SUS-16-028, 1-lep stop, 12.9 fb^{-1}
- Combination 0-lep and 1-lep stop, 12.9 fb^{-1}

**Status: ICHEP 2016**
Search in 1 lepton (e/µ) + ≥ 4 jets, b-jets, high MET & m_T(l,MET) using 2015 +2016 data (13.2/fb). (ATLAS-CONF-2016-050): largest local excess of 3.3 σ

SR dedicated to t\bar{t} + DM with scalar or pseudo scalar mediator
3. Sbottom

Search with 2 leptons (OS, SF $\rightarrow$ off-Z), $\geq$ 2 jets, MET, using 2016 data (12.9/fb) (CMS PAS SUS-16-021), also known as the dilepton mass edge analysis.

off-Z regions targeting kinematic edge in decay chain. One 3.1 $\sigma$ local excess in one SR.
4. EWkinos

Electroweak production, with low cross section.

5. Summary plots

ATLAS SUSY Searches* - 95% CL Lower Limits

<table>
<thead>
<tr>
<th>Model</th>
<th>$\delta \mu$, $\delta T$, $\Delta T$</th>
<th>Jets</th>
<th>Mass limit</th>
<th>Reference</th>
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<td>$\tilde{g}$</td>
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<td>100-486 GeV</td>
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</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ for theoretical signal cross section uncertainty.
5. Summary plots (NOW)

**ATLAS SUSY Searches** - 95% CL Lower Limits

**Status:** August 2016

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</table>

*Only a selection of the available mass limits on new states or phenomena is shown.*

Run2 Limits (when available) exceed Run1 limits!
Conclusions

• LHC is performing extremely well, allowing considerable increase in sensitivity with only a partial 2016 data set.

• Despite some small excesses, no discovery of SUSY yet. We are pushing the limits higher and higher: 1.9 TeV for the gluino, 900 GeV for the stop, ...

• New challenging scenarios are under study at 13 TeV like electroweak production, compressed mass spectra, ...

• But a question remains: Where is this famous corner behind which SUSY is waiting for us? Let’s hope significant deviations will be at the agenda of the next ”LHC days in Split” conference.
References for ATLAS latest results


<table>
<thead>
<tr>
<th>Topic</th>
<th>Document type</th>
<th>Short title (link to ATLAS Physics Briefing)</th>
<th>Reference and Link</th>
<th>Release conference</th>
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<tr>
<td>SUSY physics</td>
<td>Conference note</td>
<td>Searches for SUSY with two same-sign or three leptons and jets (briefing)</td>
<td>ATLAS-CONF-2016-037</td>
<td>ICHEP</td>
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<td>ICHEP</td>
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<td>SUSY physics</td>
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<tr>
<td>SUSY physics</td>
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<td>ATLAS-CONF-2016-093</td>
<td>SEARCH NEW</td>
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<td>Searches for R-Parity violating SUSY particles in events with one lepton and jets</td>
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References for CMS latest results


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<th>Supersymmetry</th>
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<tr>
<td>Search for SUSY in multiple-jet final states at 13 TeV (2016 data)</td>
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<tr>
<td>Search for SUSY in multiple-jet final states with the $\alpha_T$ variable at 13 TeV (2016 data)</td>
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<td>Search for SUSY in multiple-jet final state with the $M_{T2}$ variable (2016 data)</td>
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<tr>
<td>Search for SUSY in the all-hadronic final state using top quark tagging at 13 TeV (2016 data)</td>
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<td>Search for SUSY in one-lepton and multiple-jet final states at 13 TeV (2016 data)</td>
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<tr>
<td>Search for SUSY in same-sign dilepton final states at 13 TeV (2016 data)</td>
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<td>Search for SUSY in opposite-sign, same-flavor di-lepton final states at 13 TeV (2016 data)</td>
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<td>Search for SUSY in soft opposite-sign leptons in the compressed mass scenario at 13 TeV (2016 data)</td>
</tr>
<tr>
<td>Search for SUSY in opposite-sign, same-flavor di-lepton final states at 13 TeV (2015 data)</td>
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Submitted to JHEP

- Search for SUSY in multi-lepton final states at 13 TeV (2016 data) |
- Search for electroweak SUSY in multi-lepton final states at 13 TeV (2016 data) |
- Search for electroweak SUSY in WH final states at 13 TeV (2016 data) |
- Search for $R$-parity-violating SUSY in 0 or 1-lepton and large jet multiplicity final states at 13 TeV (2015 data) |
- Search for SUSY in photon(s) plus MET final states at 13 TeV (2015 data) |
- Search for SUSY in same-sign dilepton final states at 13 TeV (2015 data) Submitted to EPJC

Search for SUSY in single-lepton final states at 13 TeV (2015 data) Submitted to JHEP

Search for SUSY in all-jet final states with $M_{T2}$ at 13 TeV (2015 data) Submitted to JHEP

Search for SUSY in multi-jet final states at 13 TeV (2015 data) Submitted to PLB

Search for SUSY in Higgs to di-photon final states using the razor variables at 13 TeV (2015 and 2016 data) |

Search for stop pair production in the fully hadronic final state at 13 TeV (2016 data) |
Search for stop pair production in single lepton final states at 13 TeV (2016 data)

- [https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#ICHEP_2016](https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#ICHEP_2016)
Dec 2015 (no update yet): $Z(\ell\ell) + \text{jets} + E_T^{\text{miss}}$: results

Final event yield for 2015 data:

- Expected: $10.3 \pm 2.3$
- Observed: $21$ ($10$ ee, $11$ $\mu\mu$)

$\Rightarrow 2.2\sigma$ excess

CMS observes $12$ with $12^{+4.0}_{-2.8}$ expected (CMS-PAS-SUS-15-011)

No excess from CMS