Supersymmetry searches in ATLAS and CMS in hadronic final states

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This presentation

Searches for SUSY

Knowledge of QCD

Multijet topologies,
Boosted objects,
High mass, non-back-to-back topologies, Initial state radiation

Multijet topologies, parton shower and resummations.
Outline

• Part 1: **Concept** of hadronic SUSY searches
• Part 2: Recent analysis as an **example**
• Part 3: **Overview** of hadronic SUSY searches and limits
• Part 4: A quick look at 13 TeV...
• Part 5: Summary for **discussion**
Production rate

If R-Parity is conserved then SUSY particles are pair produced.
Where are we going?

Followed prescriptions in 1206.2892 [hep-ph]

- $\sqrt{s} = 14\,\text{TeV}$
- $pp \to \tilde{g}\tilde{g}$
- $pp \to \tilde{q}\tilde{q}^*$
- $pp \to \tilde{t}\tilde{t}^*$
- $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0$

Goal for 30 fb-1
Goal for 300 fb-1
Goal for HL-LHC
Analysis model - control regions

- Measure number of events in control selections
- Predict number of events in signal region via a fit to control regions
- Important: Test model and transfer functions (e.g. by alternative control regions or methods)
Analysis model - control regions

**Experimental uncertainties:**
- Trigger efficiency
- Jet energy scale and resolution
- Lepton energy scale and efficiency
- $E_T^{\text{miss}}$ soft component
- b-tagging
- Luminosity
- pileup modelling

**Theory uncertainties:**
- Generator modelling ($\mu_F, \mu_R$, ME/PS matching, $\alpha_s$ scale choice when possible - otherwise compare generators)
- PS uncertainties (typically compare Pythia and Herwig)
- PDF choice

- Measure number of events in control selections
- Predict number of events in signal region via a fit to control regions
- Important: Test model and transfer functions (e.g. by alternative control regions or methods)
Large range of jet multiplicities needed
Large range of jet multiplicities needed

Compressed “Monojets”:

Anti-tag on low 30 GeV $P_T$ jets

$\Rightarrow$ Needs description of low Jet multiplicities and missing transverse momentum object, relying on Initial state radiation

Typical decay: 2-6 jets

Typical signals

Long decay 7-10 jets
Large range of jet multiplicities needed

Compressed “Monojets”:

Anti-tag on low 30 GeV $P_T$ jets

$\Rightarrow$ Needs description of low Jet multiplicities
and missing transverse momentum object, relying on Initial state radiation

Typical decay: 2-6 jets

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T^{miss}$ [GeV] &gt;</td>
<td>2j</td>
</tr>
<tr>
<td>$P_T^{jet1}$ [GeV] &gt;</td>
<td>160</td>
</tr>
<tr>
<td>$P_T^{jet2}$ [GeV] &gt;</td>
<td>130</td>
</tr>
<tr>
<td>$P_T^{jet3}$ [GeV] &gt;</td>
<td>60</td>
</tr>
<tr>
<td>$P_T^{jet4}$ [GeV] &gt;</td>
<td>40</td>
</tr>
<tr>
<td>$\Delta\phi(jet_{1,2,3}, E_T^{miss})_{min}$ &gt;</td>
<td>0.4</td>
</tr>
<tr>
<td>$\Delta\phi(jet_{1,2,3}, E_T^{miss})_{min}$ &gt;</td>
<td>0.2</td>
</tr>
<tr>
<td>$W$ candidates</td>
<td>–</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] &gt;</td>
<td>8</td>
</tr>
<tr>
<td>$E_T^{miss}/m_N^{jj}$ &gt;</td>
<td>–</td>
</tr>
<tr>
<td>$m_{eff}^{incl}$ [GeV] &gt;</td>
<td>800</td>
</tr>
</tbody>
</table>

Long decay 7-10 jets

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Signal region</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$P_T^{jet}$ [GeV] &gt;</td>
<td>50</td>
</tr>
<tr>
<td>$N_{jet}$</td>
<td>= 8</td>
</tr>
<tr>
<td>$N_{b-jet}$</td>
<td>$0 \ 1 \ \geq 2$</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] &gt;</td>
<td>4</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$P_T^{jet}$ [GeV] &gt;</td>
<td>50</td>
</tr>
<tr>
<td>$N_{jet}$</td>
<td>$\geq 8$</td>
</tr>
<tr>
<td>$M_T^{jj}$ [GeV] &gt;</td>
<td>&gt; 340 and &gt; 420 for each case</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] &gt;</td>
<td>4</td>
</tr>
</tbody>
</table>
Part 2: Example analysis

Let’s have a detailed look at a recent search for coloured SUSY by CMS to illustrate the background determination.
Recent searches with M_T2

Two signal regions:

a) Jets, high pt, high M_T2

b) Search for mass peak with Higgs \( \rightarrow b\bar{b} \)

\[ M_{T2}(m_X) = \min_{\not{p}_T^{X(1)} + \not{p}_T^{X(2)} = \not{p}_T^{\text{miss}}} \left[ \max \left( M_{T1}^{(1)}, M_{T1}^{(2)} \right) \right]. \]

M_T2 is generalization of transverse mass concept for 2 invisible particles

Definition of signal regions and their backgrounds and subsequent division in HT and Etmiss
Recent searches with M_T2

• Each of these regions is examined in M_T2 (Model-dependent test)

• Example M_T2 distributions for medium and high sum of jet pt (H_t)
Recent searches with M_T2

Example of background determination QCD multijets:
- QCD dominated region at low minimal delta phi between jet and MET
- Assumption is that transfer factor $r$ (from control to signal region) is described by this parameterization:

$$r(M_{T2}) \equiv \frac{N(\Delta\phi_{\text{min}}>0.3)}{N(\Delta\phi_{\text{min}}<0.2)} = \exp(a - b M_{T2}) + c \quad \text{for } M_{T2} > 50 \text{ GeV}.$$ 

The parameters $a$ and $b$ are obtained from a fit to data in the region $50 < M_{T2} < 80$ GeV, see next slide, procedure validated with simulated QCD multijet events
Recent searches with $M_{T2}$

$r$ is fixed to a constant (conservatively) for high $M_{T2}$.

Various uncertainties on method considered

Note that QCD multijet background is small at high $M_{T2}$
Recent searches with \( M_{T2} \)

**W+ jets background and top background** Mainly stemming from “lost” lepton events, 40% are taus

1. Determined for each signal region by re-versing the zero lepton requirement and asking 1 lepton and small transverse mass \( < 100 \text{ GeV} \)

2. A “lost lepton” factor is applied to determine the expected number of background events in signal region taking into account the lepton efficiencies/acceptance “per signal region”. *Uncertainties e.g. by tag-and-probe method.*

**Z (\( \nu \nu \)) + jets background** is estimated by selecting a control sample of \( \gamma + \text{jets} \) events and then subtracting the photon momentum in the computation of all the relevant event quantities, e.g. \( M_{T2} \). *Z and gamma coupling expected to behave constant for \( p_{T}\_Z > M\_Z \) (difference modeled with MC simulation)*
Recent search with M_T2

Results: Many many signal regions (6 plots from many):

- N_f=2, N_B=0
  - Low H_T
  - Multijet
  - Lost lepton
  - Z(\nu\bar{\nu})+jets
  - Data

- N_f=2, N_B=0
  - Medium H_T
  - Multijet
  - Lost lepton
  - Z(\nu\bar{\nu})+jets
  - Data

- N_f\geq 6, N_B=0
  - Low H_T
  - Multijet
  - Lost lepton
  - Z(\nu\bar{\nu})+jets
  - Data

- N_f\geq 6, N_B=0
  - Medium H_T
  - Multijet
  - Lost lepton
  - Z(\nu\bar{\nu})+jets
  - Data

- N_f\geq 6, N_B=0
  - High H_T
  - Multijet
  - Lost lepton
  - Z(\nu\bar{\nu})+jets
  - Data
Recent searches with M_T2

• Higgs searches requires two b-tags close in delta R in mass(bb) bins
• Shape of mass(bb) is taken from low M_T2 regions since no correlation between M_T2 and mass(bb) is expected from simulation
Recent search with M_T2

Here is an example from Higgs signal region
Signal is gluino with Higgs decays..

Interpretation: >40 signal regions considered
and tested against SUSY predictions.

Regions are combined into a likelihood
function and exclusion limits are calculated
for various different models...
Limits and Signal Regions

Examples: Limits on gluino pair production for different gluino decays.

Longer decay chain limits problematic, first limit on gluinos with Higgs decays.
Run-1 data Overview

• Recent result from ATLAS 2015 summary papers
• Goals: **Combination, complementarity, coverage** in the landscape of minimal SUSY (MSSM)

- Summary of ATLAS constraints in the pMSSM, 1508.06608, Accepted by JHEP
- Inclusive squark/gluino searches, 1507.05525, Accepted by JHEP
- Third generation squarks (direct production), 1506.08616, Submitted to EPJC
Complementarity: 1\textsuperscript{st} and 2\textsuperscript{nd} generation squarks

- Let's start with a result:

Note 400 GeV limits for non-degenerated Squarks even in simplest decay chain

Sensitivity of different methods and search channels needed already for simplest decay scenario!
Background and signal regions

“Monojets”: Z→neutrinos and W→lepton neutrino dominant

Medium (2-6) jets: 
Z+jets and top pairs

Many (7-10) jets: 
QCD, top pairs

Signal regions in ATLAS are typically cut-and-count and limits derived by “best signal region” only (CMS usually combines signal regions)
Coverage beyond simplified models

- Coverage studies by running >20 run-1 analyses over >300000 MSSM points
- All MSSM points selected to fulfill all worldwide constraints (e.g. on Dark Matter)
Coverage beyond simplified models

Fraction models in gluino-neutralino space (well covered by simplified models)

Most constraining search is 2-6 jets + MET

Fraction of models in $\text{min}(\text{squark})$ vs neutralino space
- Less well covered by simplified models
- Different decays $q_L$ and $q_R$, different Masses?
- Low mass squarks not excluded yet!
R_p violation multijets

no MET and a huge background from QCD.

2 recent results on this:
(RPV gluino decays -> jets)
(RPV stop -> jets)
R_p violation multijets

no MET and a huge background from QCD.

2 recent results on this:

Interesting searches
- Using large R jets (reclustering of anti-kt jets)
- Using data-driven QCD estimation
R_p violation multijets

no MET and a huge background from QCD.

2 recent results on this:
(RPV gluino decays -> jets)
(RPV stop -> jets)
Run-2

• Various control distribution from ATLAS and CMS well described...even for 7 jets

ETmiss/VHT template (exactly 6 jets) applied to data with exactly 7 jets.

0-lepton 2 jet selection control region
All-hadronic search using $M_{T2}$

Inclusive search with $M_{T2}$ in bins of $H_T$, $N_j$ and $N_b$.

$M_{T2} =$ sTransverse mass, designed for final states with 2 missing particles.

An important background is W or top with missed leptons or taus.

Measure $M_{T2}$ shape in single lepton control sample.

The $M_{T2}$ distribution in the single-lepton control region is compared to (normalized) MC for events passing the baseline selection and having exactly zero (left) or two or more (right) b-tags.
Material for discussion

Run-2 provides 13 TeV center-of-mass:

• If DM particle is at 100 GeV still, likely to expect multiple decay steps (squarks to heavy neutralinos/charginos)
  ➔ Possibly boosted multi-boson decays
  ➔ High jet multiplicities become even more important
  ➔ High boson multiplicities become even more important (maybe 2-3 W/Z/h bosons per event)

• On the other side we should not forget the low mass squarks.... Low jet pt, low MET ➔ precision physics!? 
Summary

• Final analyses of 8 TeV data with “highly developed techniques” also for background determination

• Still relying on MCs for **signal** and **background**
  *(note that Pdf uncertainties will become important at high susy masses)*

• First 13 TeV data

• High jet and boson multiplicities becoming more important for SUSY searches
**ATLAS Simulation Preliminary**

\[ \int L dt = 300, 3000 \text{ fb}^{-1}, \sqrt{s} = 14 \text{ TeV} \]

0-lepton combined

- **ATLAS 20.3 fb^{-1}, \sqrt{s} = 8 \text{ TeV}, 95\% \text{ CL}**
- 95\% CL limit, 3000 fb^{-1}, \langle \mu \rangle = 140
- 95\% CL limit, 300 fb^{-1}, \langle \mu \rangle = 60
- 5\sigma \text{ disc., } 3000 \text{ fb}^{-1}, \langle \mu \rangle = 140
- 5\sigma \text{ disc., } 300 \text{ fb}^{-1}, \langle \mu \rangle = 60

\[ \sigma_{\text{bkg}} = 10\% \]
Additional material
All-hadronic search using $M_{T2}$

Inclusive search with $M_{T2}$ in bins of $H_T$, $N_j$ and $N_b$.

$M_{T2}$ = sTransverse mass, designed for final states with 2 missing particles

Another important background is $Z \rightarrow \nu\nu$. Estimate with photon sample, multiplied by $Z/\gamma$ ratio. Validate this by measuring the $Z \rightarrow \ell\ell$ to $\gamma$ ratio & validating photon purity measurement.

Left: Ratio between the yields in the $Z \rightarrow \ell^+\ell^-$ control region and the photon control region as a function of $M_{T2}$. Right: Prompt photon purity in the photon control region as a function of $M_{T2}$, comparing the results of the template fit to the shower shape and the MC prediction.
Figure 5: Distribution of the $M_{T2}$ variable for data and simulation after requiring the presence of one photon, $N_b = 0$, and the remainder of the inclusive-$M_{T2}$ selection criteria. Events satisfying the low-$H_T$ selection (left), and the medium- and high-$H_T$ selections (right) are shown. For these results, $M_{T2}$ is calculated after adding the photon $p_T$ to the $E_T^{miss}$ vector.
### MT_2 systematics

On the search region, and the typical ranges of effect are shown. Sources of uncertainty that change the shape of the \( M_{T2} \) distributions in the inclusive-\( M_{T2} \) analysis or the shape of the \( M_{bb} \) distributions in the \( M_{T2} \)-Higgs search are marked with a cross in the last column.

<table>
<thead>
<tr>
<th>Process</th>
<th>Source/Region</th>
<th>Effect</th>
<th>Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multijet</td>
<td>( M_{T2} &lt; 200 \text{ GeV} )</td>
<td>10–50%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>( M_{T2} \geq 200 \text{ GeV} )</td>
<td>50–100%</td>
<td>—</td>
</tr>
<tr>
<td>Lost-lepton method (sys ( \oplus ) stat)</td>
<td></td>
<td>10–65%</td>
<td>—</td>
</tr>
<tr>
<td>b-tagging scale factor</td>
<td></td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td></td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>Matching scale</td>
<td></td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>Renormalization and factorization scales</td>
<td></td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>System recoil modelling</td>
<td></td>
<td>—</td>
<td>x</td>
</tr>
<tr>
<td>( Z(\nu\bar{\nu}) ) + jets and Top</td>
<td>Systematics on ( Z(\nu\bar{\nu})/\gamma ) ratio (( N_b = 0\text{–1} ))</td>
<td>20–30%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Systematics on ( 1b/0b ) ratio from ( Z_{\ell\ell} ) (( N_b = 1 ))</td>
<td>10–75%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Statistics from ( \gamma ) + jets data (( N_b = 0\text{–1} ))</td>
<td>5–100%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Simulation (( N_b \geq 2 ))</td>
<td>100%</td>
<td>—</td>
</tr>
<tr>
<td>( Z(\nu\bar{\nu}) ) + jets</td>
<td>Integrated luminosity</td>
<td>2.6%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Trigger efficiency</td>
<td>1%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>Parton distribution functions</td>
<td>5–15%</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>b-tagging scale factor</td>
<td>5–40%</td>
<td>—</td>
</tr>
</tbody>
</table>
Overview plots
<table>
<thead>
<tr>
<th>Model</th>
<th>(\ell^-, \mu^-, \tau^- )</th>
<th>Jets</th>
<th>(E_{\text{miss}}^\gamma)</th>
<th>(L_{\text{int}})</th>
<th>Mass limit</th>
<th>(\sqrt{s} = 7) TeV</th>
<th>(\sqrt{s} = 8) TeV</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSUGRA/CMSSM</td>
<td>0-3 (e^-, \mu^-, \tau^-)</td>
<td>2-10 jets</td>
<td>3/3</td>
<td>Yes</td>
<td>20.3</td>
<td>(q, \bar{q}) 850 GeV</td>
<td>(q, \bar{q}) 850 GeV</td>
<td>1.8 TeV</td>
</tr>
<tr>
<td>(\tilde{g}, \tilde{l})</td>
<td>0</td>
<td>2-6 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>100-440 GeV</td>
<td>780 GeV</td>
<td>1.33 TeV</td>
<td>1507.05520</td>
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<tr>
<td>(\tilde{g}, \tilde{l}) (compressed)</td>
<td>mono-jet</td>
<td>1-3 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.26 TeV</td>
<td>1507.05520</td>
</tr>
<tr>
<td>(\tilde{g}, \tilde{l})</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.32 TeV</td>
<td>1.6 TeV</td>
<td>1507.05520</td>
</tr>
<tr>
<td>GMSB (I NLS)</td>
<td>1-2 (\tau) + 0-1 (\ell) - 0-2 (\ell)</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.29 TeV</td>
<td>1.6 TeV</td>
</tr>
<tr>
<td>GGM (bino NLS)</td>
<td>2 (\gamma)</td>
<td>-</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.34 TeV</td>
</tr>
<tr>
<td>GGM (higgsino-bino NLS)</td>
<td>2 (\gamma)</td>
<td>-</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.29 TeV</td>
</tr>
<tr>
<td>GGM (higgsino NLS)</td>
<td>2 (\gamma)</td>
<td>2 jets</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.29 TeV</td>
</tr>
<tr>
<td>Gravitino LSP</td>
<td>0 (\mu, \tau) mono-jet</td>
<td>Yes</td>
<td>20.3</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>2 (e, \mu) ((\ell^-, \ell^+))</td>
<td>1.34 TeV</td>
<td>1.7 TeV</td>
</tr>
</tbody>
</table>

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1\(\sigma\) theoretical signal cross section uncertainty.
Summary of CMS SUSY Results* in SMS framework

For decays with intermediate mass,

\[ m_{\text{intermediate}} = x \cdot m_{\text{mother}} + (1-x) \cdot m_{\text{LSP}} \]

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe "up to" the quoted mass limit