Searches for jets + $E_T^{\text{miss}}$ + 0 leptons at ATLAS

Tanya Sandoval
on behalf of the ATLAS Collaboration

Workshop on Searches for Supersymmetry at the LHC
LBNL, Oct 19-21 2011
Motivation

- **LHC**’s high sensitivity to SUSY $\rightarrow$ squark & gluino factory
- Final-state of many SUSY models e.g. **R-parity conserving**:
  - Sparticles produced in pairs $\tilde{q}\tilde{q}$, $\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$
  - Decay chains and stable LSP
    - $\tilde{g} \rightarrow q\bar{q}\chi_1^0$
    - $\tilde{q} \rightarrow q\tilde{\chi}_1^0$
    - high-$p_T$ jets + moderate to large $E_T^{miss}$

- Simple & general signature
- High discovery reach

\[ m_0 \quad 0 \quad 200 \quad 400 \quad 600 \quad 800 \quad 1000 \quad 1200 \quad 1400 \]
\[ \frac{1}{2} m_1 \quad 0 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \quad 400 \quad 450 \]
\[ (0.5 \text{ TeV}) \tilde{q}\sim \quad (1.0 \text{ TeV}) \tilde{q}\sim \quad (1.5 \text{ TeV}) \tilde{q}\sim \]
\[ (0.5 \text{ TeV}) \tilde{g}\sim \quad (0.75 \text{ TeV}) \tilde{g}\sim \quad (1.00 \text{ TeV}) \tilde{g}\sim \]
Strategy - in a nutshell

- Signal Regions (SRs) defined to maximise sensitivity to different models
  - 4 jets
  - 3 jets
  - 2 jets
  - larger $E_T^{\text{miss}}$
  - lower jet multiplicity
  - 2-4 jet searches

- Discriminating variables to maximise significance

- Search for non-SM excess in $m_{\text{eff}}$ and $E_T^{\text{miss}}/\sqrt{H_T'}$
  - data-driven methods where possible
  - otherwise from MC

- If no excess, set model-independent limits

$H_T, H_T' = \sum_{\text{jets}} p_T$

$m_{\text{eff}} = E_T^{\text{miss}} + H_T$

lower $E_T^{\text{miss}}$
higher jet multiplicity

6-8 jet searches

$E_T^{\text{miss}}/\sqrt{H_T'}$ tails $\rightarrow$ BG

$\sigma_{\text{SUSY}} \times \epsilon \times A$
Inclusive 2-4 jet searches
@ 1.04 fb$^{-1}$
2-4 jet search details :: SR Event Selection

- **5 different SRs** from \( \geq n \)-jets and \( m_{\text{eff}} \) cut
- After selecting good data-quality events with **no leptons**:

\[
\tilde{q}\tilde{q}, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}
\]

<table>
<thead>
<tr>
<th>Signal Region</th>
<th>( \geq 2)-jet</th>
<th>( \geq 3)-jet</th>
<th>( \geq 4)-jet</th>
<th>High mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_T^{\text{miss}} )</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
</tr>
<tr>
<td>Leading jet ( p_T )</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
<td>&gt; 130</td>
</tr>
<tr>
<td>Second jet ( p_T )</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>Third jet ( p_T )</td>
<td>–</td>
<td>&gt; 40</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>Fourth jet ( p_T )</td>
<td>–</td>
<td>–</td>
<td>&gt; 40</td>
<td>&gt; 80</td>
</tr>
<tr>
<td>( \Delta \phi(\text{jet}, \vec{P_T^{miss}})_{\text{min}} )</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
<td>&gt; 0.4</td>
</tr>
<tr>
<td>( E_T^{\text{miss}}/m_{\text{eff}} )</td>
<td>&gt; 0.3</td>
<td>&gt; 0.25</td>
<td>&gt; 0.25</td>
<td>&gt; 0.2</td>
</tr>
<tr>
<td>( m_{\text{eff}} )</td>
<td>&gt; 1000</td>
<td>&gt; 1000</td>
<td>&gt; 500/1000</td>
<td>&gt; 1100</td>
</tr>
</tbody>
</table>

\( m_{\text{eff}} = E_T^{\text{miss}} + \sum p_T \) SR jets

\( m_{\text{incl eff}} = E_T^{\text{miss}} + \sum p_T \) jets \( p_T > 40 \)

\( \Delta \phi \) cut up to 3rd leading jet

Trigger requirements
Channel definition
QCD rejection
Enhance signal

arXiv:1109.6572[2]
Main backgrounds:

1. $Z/W + \text{jets}$
   $Z \rightarrow \nu\nu, W \rightarrow l\nu$

2. TOP
   $t\bar{t}/t \rightarrow \text{jets}$

3. QCD
   multijets, $b \rightarrow l\nu$

true & fake $E_T^{\text{miss}}$ from $\nu$'s & mismeasured jets

Method:

- $\geq 1$ Control Region (CR) per background per SR, such that:

  \[ \text{Transfer Factor (TF)} = \frac{N(\text{SR, raw, proc})}{N(\text{CR, raw, proc})} \]

  - Data-driven
  - As close as possible to SR to minimize extrapolation with reasonable stats.
  - High purity ($> 50\%$) w.r.t calibration process

- Final result obtained from a **combined** likelihood fit to all CRs - handles mutual CR contamination & correlated uncert's
2 Control Regions:

- **2 Control Regions:**
  - for $p_T > M_Z$, $p_T(\gamma) \propto p_T(Z)$

<table>
<thead>
<tr>
<th>CR</th>
<th>$\gamma$+jets (high-purity)</th>
<th>$Z(\ell\ell, \mu\mu)$ +jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-driven</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Large stats</td>
<td>✔</td>
<td>✗</td>
</tr>
<tr>
<td>Small theory uncert’s</td>
<td>✗</td>
<td>✔</td>
</tr>
</tbody>
</table>

**Definition**
- 1 iso. $\gamma$
  - $p_T(\gamma) \rightarrow E_T^{\text{miss}}$
- 2 iso. leptons
  - $p_T(Z) \rightarrow E_T^{\text{miss}}$
  - looser $m_{\text{eff}}$ cuts

**TF**
- from MC & data
  - main acceptance
  - theory $Z/\gamma$
- from MC
  - stats
  - theory extrapol.
  - JES/JER

**Example Transfer Function:**

$$\gamma+\text{jets} \quad \text{TF}(p_T) = \left[ \frac{(1 - f_{\text{bkg}})}{A_{\gamma}(p_T) \cdot \varepsilon_{\gamma}(p_T)} \cdot R_{Z/\gamma}(p_T) \cdot Br(Z \rightarrow \nu\nu) \right]$$

- photon purity
- theory ratio
- photon eff. and acceptance
2-4 jet search details :: $W$ and Top Backgrounds

**$W$+jets**
- **data-driven CR**
  - 1 iso. lepton ($e, \mu$), treated as jet
  - $30 < m_T < 100$ GeV
  - b-tag veto
  - looser $m_{\text{eff}}$ cuts
- **TF from MC**
  - main uncert’s: stats, theory extrapol, JES/JER, b-tagging

**Top**
- **data-driven CR**
  - as in $W$ + jets except
  - b-tag veto $\rightarrow$ b-tag required
- **TF from MC**
  - main uncert’s: as in $W$ + jets
**2-4 jet search details :: QCD background, Overall results**

### QCD
- **data-driven CR**
  - reversing $\Delta \phi (\text{jet}, E_T^{\text{miss}})_{\text{min}}$ cut
- **TF from Data**
  - pseudo-events with large $E_T^{\text{miss}}$
    obtained by jet-smearing low-$E_T^{\text{miss}}$
    events with 'jet response function'
  - main uncert's: jet response modelling

### Overall Background results
- ✓ Validated: **data-driven** methods agree with the **MC** expectation
- ✓ For each SR, estimate taken from a **combined fit** (to the 5 CRs, TFs and uncert’s)
No significant excess in SRs with respect to SM expectation:

Exclusion limits prescription:

- $\text{CL}_S$ (95% CL) on $\sigma_{\text{SUSY}} \times A \times \varepsilon$ (model-indep)
- statistic: Profile likelihood Ratio
- SR with best expected limit chosen for each point
- 2 different interpretations

<table>
<thead>
<tr>
<th>Process</th>
<th>Signal Region</th>
<th>Data</th>
<th>4-lepton Searches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\geq 2$-jet</td>
<td>$\geq 3$-jet</td>
<td>$m_{\text{eff}} &gt; 500$ GeV</td>
</tr>
<tr>
<td>$Z/\gamma$+jets</td>
<td>32.3±2.6±6.9</td>
<td>25.5±2.6±4.9</td>
<td>209±9±38</td>
</tr>
<tr>
<td>W+jets</td>
<td>26.4±4.0±6.7</td>
<td>22.6±3.5±5.6</td>
<td>349±30±122</td>
</tr>
<tr>
<td>$t\bar{t}$+ single top</td>
<td>3.4±1.6±1.6</td>
<td>5.9±2.0±2.2</td>
<td>425±39±84</td>
</tr>
<tr>
<td>QCD multi-jet</td>
<td>0.22±0.06±0.24</td>
<td>0.92±0.12±0.46</td>
<td>34±2±29</td>
</tr>
<tr>
<td>Total</td>
<td>62.4±4.4±9.3</td>
<td>54.9±3.9±7.1</td>
<td>1015±41±144</td>
</tr>
</tbody>
</table>

Excluded $\sigma A \varepsilon$ (fb) | 24 | 30 | 477 | 32 | 17
1. Simplified Model

- Pheno. MSSM
  - LSP ($m_{\text{LSP}} = 0$)
  - $\tilde{g}$ and $\tilde{q}$ (1$^{\text{st}}$ and 2$^{\text{nd}}$ gen.)
  - $m = 100$ GeV - 2 TeV
  - other sparticles $m = 5$ TeV
- up to 1 TeV exclusion if $m_{\tilde{g}} = m_{\tilde{q}}$
- Limit stable up to $m_{\text{LSP}} \sim 200$ GeV

2. CMSSM/mSUGRA

- $A_0 = 0$, $\mu > 0$, $\tan \beta = 10$
- larger jet multiplicities SRs $\rightarrow$ larger $m_0$ reach
- up to 980 GeV exclusion if $m_{\tilde{g}} = m_{\tilde{q}}$
- $m_{1/2} < 450$ GeV excluded at low $m_0$
Inclusive 6-8 jet searches ("multijet" analysis)
@ 1.34 fb$^{-1}$
Extension of 2-4 jet analysis to \( \uparrow \) sensitivity to larger multiplicities with moderate \( E_T^{\text{miss}} \)

New challenge: multi-jet events poorly modelled in MC
\( \rightarrow \) want variable invariant under jet multiplicity to \( \downarrow \) MC dependence

2-4 jet search
\[
\Delta \phi (E_T^{\text{miss}}, \text{jet})
\]
\[
\frac{E_T^{\text{miss}}}{m_{\text{eff}}}
\]
\[
m_{\text{eff}}
\]

6-8 jet search
\[
\frac{E_T^{\text{miss}}}{\sqrt{H_T}} \quad (H_T = \sum_{\text{jets}} p_T
\]
jet \( p_T > 40 \text{ GeV}, |\eta| < 2.8 \))

since \( E_T^{\text{miss}} \) resolution \( \sim \sqrt{H_T} \)
for these events

Event Selection:

<table>
<thead>
<tr>
<th>Signal region</th>
<th>7j55</th>
<th>8j55</th>
<th>6j80</th>
<th>7j80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet ( p_T )</td>
<td>( &gt; 55 \text{ GeV} )</td>
<td>( &gt; 80 \text{ GeV} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet</td>
<td></td>
<td>(</td>
<td>\eta</td>
<td>&lt; 2.8 )</td>
</tr>
<tr>
<td>( \Delta R_{jj} )</td>
<td>( &gt; 0.6 ) for any pair of jets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of jets</td>
<td>( \geq 7 )</td>
<td>( \geq 8 )</td>
<td>( \geq 6 )</td>
<td>( \geq 7 )</td>
</tr>
<tr>
<td>( E_T^{\text{miss}} / \sqrt{H_T} )</td>
<td></td>
<td></td>
<td>( &gt; 3.5 \text{ GeV}^{1/2} )</td>
<td></td>
</tr>
</tbody>
</table>

6-8 jet search details :: Background Estimation

Main backgrounds:

1. **multijet QCD + fully hadronic** $t\bar{t}$ ($t\bar{t} \rightarrow qq$)
   - requires data-driven methods as MC not good enough
   - $TF = \frac{N(CR_j | E_T^{miss} / \sqrt{H_T} > 3.5)}{N(CR_j | E_T^{miss} / \sqrt{H_T} < 1.5)}$
   - data-driven, using smaller jet mult. than in SRs
   - from 5j/6j events

2. **Semi- and fully leptonic** $t\bar{t}$ ($t\bar{t} \rightarrow q\ell, \ell\ell$)
   - data-driven CR: 1 $\mu$ (treated as jet), 1 $b$-jet
   - TF defined as above but from MC

3. **Z/W+jets** ($Z \rightarrow \nu\nu, W \rightarrow l\nu$)
   - data-driven CR (as in (2) but with $b$-jet veto),
   - TF from MC
No significant excess in SRs with respect to SM expectation:

<table>
<thead>
<tr>
<th>Signal region</th>
<th>7j55</th>
<th>8j55</th>
<th>6j80</th>
<th>7j80</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-jets</td>
<td>26 ± 5.2</td>
<td>2.3 ± 0.7</td>
<td>19 ± 4</td>
<td>1.3 ± 0.4</td>
</tr>
<tr>
<td>t\bar{t} \to q\ell, \ell\ell</td>
<td>10.8 ± 6.7</td>
<td>0.4±0.3</td>
<td>6.0 ± 4.6</td>
<td>0±0.13</td>
</tr>
<tr>
<td>W + jets</td>
<td>0.95 ± 0.45</td>
<td>±0.13</td>
<td>0.34 ± 0.24</td>
<td>0±0.13</td>
</tr>
<tr>
<td>Z + jets</td>
<td>1.5 ± 1.8</td>
<td>0±0.75</td>
<td>0±0.75</td>
<td>0±0.75</td>
</tr>
<tr>
<td>Total Standard Model</td>
<td>39.3 ± 8.7</td>
<td>2.5±4.4</td>
<td>25.8 ± 6.1</td>
<td>1.3±0.9</td>
</tr>
</tbody>
</table>

| Data | 45 | 4 | 26 | 3 |
| N_{BSM, max}^{95%} | 26.0 | 11.2 | 16.3 | 6.0 |
| \sigma_{BSM, max}^{95%} \times \epsilon/fb | 19.4 | 8.4 | 12.2 | 4.5 |
| PSM | 0.30 | 0.36 | 0.49 | 0.16 |

Limit prescription as in 2-4j analysis
-Exclusion less than predicted due to upward fluctuations in two channels
- \( m_{\tilde{g}} > 520 \text{ GeV} \)

Summary & Outlook
2010: 2-4j search @35 pb$^{-1}$

Outlook

Next update planned for Moriond’12 with further improvements:

- **More data** (recorded lumi $> 4 \text{ fb}^{-1}$)
- **Extended $m_{\text{eff}}$-based reach with minimal changes:**
  - re-optimise cuts for higher lumi e.g. harder $m_{\text{eff}}$
  - include 5j and 6j channels
  - optimise $\Delta \phi\left( E_T^{\text{miss}}, m_{\text{eff}} \right)$
- **Use of signal-shape info**
  - ↓ dependence on cut optimisation
  - constrain better backgrounds and uncert’s
- **Refined background estimation**
  - treatment of low background rates
  - decrease MC dependence e.g. in TFs
  - decrease uncertainties (stat. + syst.)
**Summary**

ATLAS searches for $E_T^{\text{miss}} + \text{jets} + 0$-leptons have been updated to $\sim 1 \text{ fb}^{-1}$

- 2-4 jet channels
- 6-8 jet channels

Data agrees with SM prediction in all SRs

No indication of SUSY yet
- in $R$-parity conserving models and CMSSM

Exclusion limits have been set for above models
- Now approaching $\sim 1 \text{ TeV}$

R&D is ongoing for next analysis round
- Aimed to extend reach
References


[2] ATLAS, 2011. 0-lepton EPS results (paper submitted to PLB),

   \(\gamma+\text{jets}\) Production to Calibrate the Standard Model \(Z_{\nu\nu}+\text{jets}\)
   Background to New Physics Processes at the LHC, 2011.

[4] ATLAS, 2011. 0-lepton Multijet search,

[5] ATLAS, 2010. 0-lepton December results,
– Backup –
**JET PRESELECTION:**
- Anti-$k_T$ - $\Delta R = 0.4$
- $P_T > 20$ GeV, $|\eta| < 2.8$

**MISSING $E_T$ (MET):**
- Reconstructed from the vectorial sum of all jets and leptons. Clusters not belonging to any jets are added to the MET

**LEPTON VETO:**
- **Electrons** Identified using shower shape and track matching criteria; $P_T > 20$ GeV, $|\eta| < 2.47$
- **Muons** identified with a track matching between the ID and muon spectrometer; $P_T > 20$ GeV, $|\eta| < 2.4$

• Simultaneous likelihood fit to Signal Region + 5 Control Regions in each channel
  – Six Poisson-distributed variables and PDF to constrain systematic uncertainties

\[ L(n \mid \mu, b, \theta) = P_{SR} \times P_{WR} \times P_{TR} \times P_{ZRa} \times P_{ZRb} \times P_{QR} \times C_{syst} \]

• Correlations between Control Regions taken into account
  – eg jet energy scale and b-tagging efficiency
**Highest $m_{\text{eff}}$ event in EPS’11 dataset**

**Figure:** This event possesses five jets with $p_T > 40$ GeV ($p_T = 528, 418, 233, 171$ and $42$ GeV respectively), $E_T^{\text{miss}} = 460$ GeV and $m_{\text{eff}} = 1810$ GeV (calculated using the leading four jets).