Single-top quark studies in ATLAS

Dominic Hirschbühl

On behalf of the ATLAS collaboration

EPSHEP 2011 – Grenoble
21.07.2011
Production of single top quark events

\[ \begin{align*}
\text{t-channel:} & \quad q \rightarrow q' t, \\
\text{Wt:} & \quad g \\ & \quad b \rightarrow W t, \\
\text{s-channel:} & \quad q \rightarrow s \bar{q}' W t, \\
\end{align*} \]

Cross sections @ 7 TeV

<table>
<thead>
<tr>
<th>Channel</th>
<th>Cross Section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>t-channel</td>
<td>$64.6^{+3.2}_{-2.6}$</td>
</tr>
<tr>
<td>Wt</td>
<td>$15.7 \pm 1.3$</td>
</tr>
<tr>
<td>s-channel</td>
<td>$4.6 \pm 0.3$</td>
</tr>
</tbody>
</table>

Kidonakis, approx. NNLO
Motivation

- Test of standard model predictions
  - Cross section $\propto |V_{tb}|^2$
- Test of the unitarity of the CKM Matrix
  - Hints for existence of a 4th generation
- Test of the $b$-quark structure function: DGLAP evolution
- Probe and preparation for searches for new physics
  - Charged heavy Bosons $W'$, $H^+$ etc.
- $Wt$ process not accessible at the Tevatron
- Measure all three processes independently
  - Access to anomalous couplings
Cross sections @ Tevatron and LHC

- Small S/B compared to $t\bar{t}$ analyses, because of low number of jets in final state.
- Need to control backgrounds very well.
  - Precise estimation of the rates
  - Good model
Overview

Common object definitions

Lepton+jets channel
Cut-based
Neural network

Di-lepton channel
Cut based

Cross section measurement

Upper limit

Used luminosity: 0.70 fb⁻¹

Cross section measurement

Used luminosity: 0.70 fb⁻¹

Total Delivered: 1.36 fb⁻¹
Total Recorded: 1.30 fb⁻¹
t-channel analyses
t-channel analyses

Biggest cross section of single top processes
Improved S/B ratio compared to Tevatron

Paper with 36 $\text{pb}^{-1}$ (3.5 $\sigma$)
TOP-10-008

CONF note with 156 $\text{pb}^{-1}$ (6.2 $\sigma$)
ATLAS-CONF-2011-088

Event signature:
- Real W boson & one high-$p_T$ central b-jet (from top quark)
  - Leptonic decay of W:
    1 electron or muon + missing transverse energy ($E_T^{\text{miss}}$)
- 1 or 2 extra forward jet ($2^{\text{nd}}$ b-jet, if visible, is also forward)

ATLAS-CONF-2011-101
Event selection

- Lepton selection (electron / muon):
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - Relative Isolation

- Jets
  - Anti-$k_T$ algorithm $R=0.4$
  - $p_T > 25$ GeV
  - $|\eta| < 4.5$
  - One secondary vertex tag
  - Number of jets
    - NN analysis : 2
    - Cut based: 2 & 3

- Missing transverse energy
  - $E_T^{miss} > 25$ GeV

- QCD multijet veto
  - $M_T(W) > 60$ GeV $- E_T^{miss}$
Background estimation - strategy

**W+jets (only cut based)**

\[ N_{W+jets}^{\text{pretag}} = N_{\text{data}}^{\text{pretag}} - N_{\text{qcd}}^{\text{pretag}} - N_{\text{MC}}^{\text{pretag}} \]

\[ N_{\Phi,n}^{\text{tag}} = N_{\Phi,n}^{\text{pretag}} F_{\Phi,n}^{\text{tag}} \Phi_n. \]

**Top processes, Diboson, Z+jets (W+jets – NN)**

\[ N = \sigma \cdot \varepsilon \cdot \mathcal{L} \]

**QCD background**

\[ E_T^{\text{Miss fit}} \]

QCD model from data

MC processes

Data

Fit in sideband
Extrapolation to signal region

Candidate Events

Discriminant
QCD estimate

- Backgrounds with no real W boson
- Huge cross section combined with small fake rate gives sizeable contribution

Model:
- Jet trigger data
- Choose jet with high em fraction and more than three tracks
Expected event yield for $L_{\text{int}} = 0.70 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th></th>
<th>Muon</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-jet</td>
<td>3-jet</td>
<td>2-jet</td>
<td>3-jet</td>
</tr>
<tr>
<td>single-top $t$-channel</td>
<td>267 ± 27</td>
<td>187 ± 19</td>
<td>288 ± 29</td>
<td>198 ± 20</td>
</tr>
<tr>
<td>single-top $Wt$</td>
<td>83 ± 8</td>
<td>112 ± 11</td>
<td>81 ± 8</td>
<td>110 ± 11</td>
</tr>
<tr>
<td>single-top $s$-channel</td>
<td>24 ± 2</td>
<td>11 ± 1</td>
<td>27 ± 2</td>
<td>12 ± 1</td>
</tr>
<tr>
<td>top pairs</td>
<td>372 ± 31</td>
<td>912 ± 75</td>
<td>388 ± 32</td>
<td>935 ± 77</td>
</tr>
<tr>
<td>$W + \text{light jets}$</td>
<td>278 ± 83</td>
<td>112 ± 55</td>
<td>365 ± 109</td>
<td>148 ± 73</td>
</tr>
<tr>
<td>$Wc + \text{jets}$</td>
<td>990 ± 230</td>
<td>330 ± 120</td>
<td>1190 ± 280</td>
<td>340 ± 130</td>
</tr>
<tr>
<td>$Wbb + \text{jets}$</td>
<td>480 ± 330</td>
<td>270 ± 190</td>
<td>560 ± 380</td>
<td>301 ± 220</td>
</tr>
<tr>
<td>$Wc\bar{c} + \text{jets}$</td>
<td>270 ± 190</td>
<td>150 ± 110</td>
<td>340 ± 240</td>
<td>180 ± 130</td>
</tr>
<tr>
<td>Diboson</td>
<td>35 ± 2</td>
<td>16 ± 1</td>
<td>44 ± 2</td>
<td>18 ± 1</td>
</tr>
<tr>
<td>$Z + \text{jets}$</td>
<td>68 ± 41</td>
<td>51 ± 31</td>
<td>63 ± 38</td>
<td>39 ± 23</td>
</tr>
<tr>
<td>Multijets</td>
<td>310 ± 160</td>
<td>310 ± 150</td>
<td>380 ± 190</td>
<td>103 ± 51</td>
</tr>
<tr>
<td>TOTAL Expected</td>
<td>3180 ± 480</td>
<td>2450 ± 310</td>
<td>3730 ± 580</td>
<td>2380 ± 310</td>
</tr>
<tr>
<td>DATA</td>
<td>3291</td>
<td>2462</td>
<td>3662</td>
<td>2596</td>
</tr>
</tbody>
</table>
Background modeling

Good agreement between data and background model/prediction
Cut based analysis

<table>
<thead>
<tr>
<th>Cut</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_T$</td>
<td>$&gt; 210$ GeV</td>
</tr>
<tr>
<td>$M_{lvb}$</td>
<td>$&gt; 150$ GeV &amp; $&lt; 190$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta(\text{light jet})</td>
</tr>
<tr>
<td>$</td>
<td>\Delta\eta(j_1,j_1)</td>
</tr>
</tbody>
</table>

Cuts are optimized including systematics.
### Cut based analysis - Result

Statistical analysis:
Profile likelihood using 4 bins:
- electron / muon
- + / - charge
2 channels:
- 2 and 3 jets

**Observed cross section:**
\[ \sigma_t = 90 \pm 9 \text{ (stat.)} \pm^{31}_{-20} \text{ (syst.)} \]

**Observed significance** 7.6 \( \sigma \)

**SM:** \( \sigma_t = 64.5 \text{ pb} \)

---

<table>
<thead>
<tr>
<th>Source</th>
<th>2-jet</th>
<th>3-jet</th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \pm 16 )</td>
<td>( \pm 24 )</td>
<td>( \pm 13 )</td>
</tr>
<tr>
<td>Data statistics</td>
<td>( \pm 8 )</td>
<td>( \pm 11 )</td>
<td>( \pm 6 )</td>
</tr>
<tr>
<td>MC statistics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>(+7/-5)</td>
<td>(+10/-1)</td>
<td>(+9/-1)</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>(+6/-4)</td>
<td>(+8/-7)</td>
<td>(+6/-1)</td>
</tr>
<tr>
<td>Jet reconstruction</td>
<td>(+2/-1)</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
</tr>
<tr>
<td>b-tagging scale factor</td>
<td>(+17/-12)</td>
<td>(+21/-14)</td>
<td>(+18/-13)</td>
</tr>
<tr>
<td>Mis-tagging scale factor</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
</tr>
<tr>
<td>Lepton efficiencies</td>
<td>(+6/-5)</td>
<td>(+11/-9)</td>
<td>(+8/-6)</td>
</tr>
<tr>
<td>Lepton energy scale/resolution</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
<td>(+2/-1)</td>
</tr>
<tr>
<td>Generator</td>
<td>(+10/-8)</td>
<td>(+16/-12)</td>
<td>(+11/-9)</td>
</tr>
<tr>
<td>Parton shower</td>
<td>(+9/-7)</td>
<td>(+14/-12)</td>
<td>(+10/-9)</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>(+19/-16)</td>
<td>(\pm 7)</td>
<td>(\pm 14)</td>
</tr>
<tr>
<td>PDF</td>
<td>(+5/-4)</td>
<td>(+6/-5)</td>
<td>(\pm 5)</td>
</tr>
<tr>
<td>W+jets shape modeling</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
</tr>
<tr>
<td>Jet ( \eta ) reweighting</td>
<td>(+12/-10)</td>
<td>(+18/-14)</td>
<td>(+13/-11)</td>
</tr>
<tr>
<td>Background normalization</td>
<td>(\pm 4)</td>
<td>(\pm 8)</td>
<td>(\pm 4)</td>
</tr>
<tr>
<td>QCD normalization</td>
<td>(\pm 2)</td>
<td>(\pm 2)</td>
<td>(\pm 3)</td>
</tr>
<tr>
<td>W+heavy flavour normalization</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
<td>(\pm 1)</td>
</tr>
<tr>
<td>W+light flavour normalization</td>
<td>(\pm 7)</td>
<td>(\pm 13)</td>
<td>(\pm 8)</td>
</tr>
<tr>
<td>Theory cross sections</td>
<td>(+6/-5)</td>
<td>(+11/-8)</td>
<td>(+7/-6)</td>
</tr>
<tr>
<td>Luminosity</td>
<td>(+42/-27)</td>
<td>(+51/-37)</td>
<td>(+41/-27)</td>
</tr>
<tr>
<td>All systematics</td>
<td>(+45/-31)</td>
<td>(+57/-43)</td>
<td>(+44/-30)</td>
</tr>
</tbody>
</table>
Neural network analysis

Idea: Combine many variables including correlations in one discriminate

<table>
<thead>
<tr>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m(\ell v b)$</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$E_T(ji)$</td>
</tr>
<tr>
<td>$\Delta\eta(j_1, j_2)$</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$p_T(\ell)$</td>
</tr>
<tr>
<td>$m(b)$</td>
</tr>
<tr>
<td>$m_T(W)$</td>
</tr>
<tr>
<td>$\eta(\ell)$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$</td>
</tr>
<tr>
<td>polarization</td>
</tr>
<tr>
<td>$q(\ell)$</td>
</tr>
<tr>
<td>$m(j_1, j_2)$</td>
</tr>
<tr>
<td>$H_T$</td>
</tr>
</tbody>
</table>

Training:
- Hidden layer: 33 nodes
- Signal/Background 50:50
- Background weighted to exp. number of events
Neural network analysis - Result

Statistical analysis:
Maximum likelihood fit using the full output distribution

Observed cross section:
\[ \sigma_t = 105 \pm 7 \text{ (stat.)} +^{36}_{-30} \text{ (syst.)} \]
SM: \[ \sigma_t = 64.5 \text{ pb} \]
Event signature:
Two real $W$ bosons & one high-$P_T$ central $b$-jet (from top quark)
• Leptonic decay of $W$s:
  • 2 electrons or 2 muons or 1 electron and 1 muon
  • missing transverse energy ($E_T^{miss}$)
Object selection

- Lepton selection (electron / muon):
  - $p_T > 25$ GeV
  - $|\eta| < 2.5$
  - Relative Isolation
  - Exactly two leptons (ee / $\mu\mu$ / e$\mu$)

- Jets
  - Anti-$k_T$ algorithm $R=0.4$
  - $p_T > 30$ GeV
  - $|\eta| < 4.5$
  - Exactly one jet

- Missing transverse energy
  - $E_T^{\text{miss}} > 50$ GeV

- Z-mass veto (ee/mm –channel)
  - $|M(ll)-M(Z)| > 10$ GeV

- $Z\to\tau\tau$ veto
  - $\Delta\Phi(l_1, E_T^{\text{miss}}) + \Delta\Phi(l_1, E_T^{\text{miss}}) > 2.5$
Background estimation - strategy

Drell-Yan / QCD
ABCD method

Diboson
\[ N = \sigma \cdot \varepsilon \cdot L \]

Top Pair
\[ SF = \text{Data} - \Sigma \text{Bkg} / \text{MC} \]
Preselection for $L_{\text{int}} = 0.70 \text{ fb}^{-1}$

**Signal sample**

**Top quark pair background region**

**ATLAS Preliminary**

$\int L \, dt = 0.70 \text{ fb}^{-1}$

- Data
- $Wt$
- Fake leptons
- $Z(\rightarrow ee/\mu\mu)+\text{jets}$
- $Z(\rightarrow \tau\tau)+\text{jets}$
- Diboson
- $t\bar{t}$

Number of Events / 20 GeV

Number of Jets

$H_T(\text{all jet}) \text{ [GeV]}$

EPSHEP 2011 - Grenoble 21.07.2011 Dominic Hirschbühl Bergische Universität Wuppertal
### Expected event yield for $L_{\text{int}} = 0.70 \text{ fb}^{-1}$

<table>
<thead>
<tr>
<th>Process</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
<th>$e\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Wt$</td>
<td>$8.6 \pm 1.6$</td>
<td>$11.9 \pm 1.7$</td>
<td>$26.6 \pm 2.5$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$31.8 \pm 4.5$</td>
<td>$48.0 \pm 7.0$</td>
<td>$104.7 \pm 15.2$</td>
</tr>
<tr>
<td>$WW$</td>
<td>$6.0 \pm 1.0$</td>
<td>$8.1 \pm 1.2$</td>
<td>$15.2 \pm 1.5$</td>
</tr>
<tr>
<td>$WZ$</td>
<td>$1.6 \pm 0.3$</td>
<td>$3.0 \pm 0.3$</td>
<td>$2.0 \pm 0.3$</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>$0.2 \pm 0.0$</td>
<td>$1.0 \pm 0.1$</td>
<td>$0.1 \pm 0.0$</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$6.2 \pm 1.1$</td>
<td>$0.0 \pm 0.0$</td>
<td>$0.0 \pm 0.0$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$0.0 \pm 0.0$</td>
<td>$8.4 \pm 1.4$</td>
<td>$0.0 \pm 0.0$</td>
</tr>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>$0.5 \pm 0.3$</td>
<td>$0.5 \pm 0.8$</td>
<td>$3.9 \pm 1.0$</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>$2.3 \pm 1.2$</td>
<td>$0.0 \pm 0.6$</td>
<td>$1.5 \pm 0.8$</td>
</tr>
<tr>
<td>Total Expected</td>
<td>$57.2 \pm 5.1$</td>
<td>$82.1 \pm 7.3$</td>
<td>$154.0 \pm 15.4$</td>
</tr>
<tr>
<td>Total observed</td>
<td>$62$</td>
<td>$73$</td>
<td>$152$</td>
</tr>
</tbody>
</table>

Final selection with $n_{\text{jet}} = 1$.
Uncertainties include also systematic uncertainties.
Good agreement between data and background model/prediction
Statistical analysis: Profile likelihood

Observed cross section (significance 1.2\sigma):
$$\sigma_{Wt} = 14.4^{+5.3}_{-5.1} \text{ (stat.)}^{+9.7}_{-9.4} \text{ pb}$$

Observed limit @ 95% C.L.
$$\sigma_{Wt} < 39.1 \text{ pb}$$

SM: $$\sigma_t = 15.7 \text{ pb}$$
Summary / Conclusion

• Measured single top quark t-channel and Wt cross sections with the 2011 dataset of $0.70\,\text{fb}^{-1}$.
• Both measurements are in agreement with the SM expectations.

**t-channel:** Performed two analyses
- Using a neural network
  \[ \sigma_t = 107^{+37}_{-31}\,\text{pb} \]
- Cut based approach
  \[ \sigma_t = 90^{+32}_{-22}\,\text{pb} \]

**Wt-channel:** Performed one analysis
- Cut based approach
  Upper limit: $39\,\text{pb} @ 95\% \text{ C.L.}$

**Future:**
- Start searching for new physics in the single top sector