Top Pair Production and Top Properties at ATLAS

Ulrich Husemann, DESY on behalf of the ATLAS Collaboration
**Large Hadron Collider**
- Proton-proton collisions at 7 TeV center-of-mass energy
- 2010: delivered about 50 pb$^{-1}$ of integrated luminosity
- 2011: breaking luminosity records daily, more than 1 fb$^{-1}$ already delivered

**ATLAS**
- Multi-purpose HEP detector: tracking/vertexing, calorimetry, muon detectors
- Excellent performance 2010/2011
Top Quarks Physics

- Top – a heavy-weight among the quarks:
  - The only “bare” quark
  - Role in electroweak symmetry breaking?

- Tevatron: almost 20 years of impressive top physics program

- LHC = top factory
  - LHC $t\bar{t}$ cross section at 7 TeV $> 20 \times$ Tevatron
  - Today: top as a signal
  - Very soon: top as a background and calibration source

- Today’s talk: ATLAS top results with full 2010 dataset, one new result using 2011 data

“Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier”
(G. F. Lichtenberg)
Analyzing Top Quark Events

- Top decay in the standard model: \( B(t \rightarrow Wb) \approx 100\% \)
- Challenging signature: multiple leptons & jets, missing \( E_T\) (MET)
- \( t\bar{t} \) decay signatures characterized by \( W \) decays:
  - **All-Hadronic**: 45% of all decays, large QCD background
  - **Lepton+Jets**: 30% of all decays, moderate backgrounds
  - **Dilepton**: 5% of all decays, very clean, but small branching fraction
- Dominant backgrounds for leptonic channels
  - **W/Z bosons + jets** (similar signature)
  - **QCD jets** (misidentified as leptons)
ATLAS Event Display: e + Jets + MET
Outline

Top Pair Production Cross Section
- Lepton+jets and dilepton channel, with and without b-tagging
- Cross section combination
- First look at the all-hadronic channel

Top Mass and further Properties
- Direct mass measurement
- Indirect mass determination via the cross section
- W polarization in top decays
- Search for FCNC in top production and decay
- Search for high-mass phenomena decaying into top

Most results based on full 2010 dataset: 35 pb$^{-1}$
Top Quark Pair Production
Cross Section
Analysis I: without b-tagging

- Lepton+jets selection: high-$p_T$ $e/\mu$, $\geq3$ jets, missing $E_T$, transverse mass
- Template fit to projective likelihood discriminant based on well-modeled event kinematics
- Lepton charge: $t\bar{t}$ symmetric, $W$ asymmetric
- Pseudorapidity: $t\bar{t}$ more central
- Aplanarity: $t\bar{t}$ more spherical
- Four-channel fit: $e, \mu + 3, \geq4$ jets

Lepton Charge

Lepton Pseudorapidity
Top Cross Section: Lepton + Jets

- Analysis II: “continuous” b-tagging (same event selection as before)
  - Input variables (as before): lepton pseudorapidity, aplanarity
  - New variable: $H_{T,3p} = \frac{\sum_{i=3}^{N_{\text{jets}}} |p_{T,i}|^2}{\sum_{j=1}^{N_{\text{objects}}} |p_{z,j}|}$
  - New variable: average b-tagging weight for two most b-like jets (“JetProb” tagger)
  - Six-channel fit (e, $\mu$ + 3, 4, ≥5 jets) using sophisticated profile likelihood technique: systematic uncertainties included as nuisance parameters → constrained by data
Top Cross Section: Lepton + Jets

Without b-tagging:

\[ \sigma_{\bar{t}t} = 171 \pm 17 \text{(stat.)}^{+20}_{-17} \text{(syst.)} \pm 6 \text{(lumi.) \, pb} \]

Continuous b-tagging:

\[ \sigma_{\bar{t}t} = 186 \pm 10 \text{(stat.)}^{+21}_{-20} \text{(syst.)} \pm 6 \text{(lumi.) \, pb} \]

- Comparison with state-of-the-art theory prediction: \( \sigma_{\bar{t}t} = 165^{+11}_{-16} \text{ pb} \)
  (using Hathor, approx. NNLO, CTEQ6.6) \( \rightarrow \) consistent

- Various cross check analyses (cut & count, multivariate) \( \rightarrow \) consistent
Top Cross Section: Lepton + Jets

- Already with 2010 dataset: measurements precision limited by systematic uncertainties, dominant sources:
  - Both analyses: jet energy scale & resolution, ISR/FSR
  - Additionally for analysis with b-tag: b-tagging calibration, W+jets heavy flavor content

- Expect improvements of systematic uncertainties
  - Data-driven backgrounds and profile likelihood technique: improve with more data
  - Working on improved MC-based and theory-based uncertainties

<table>
<thead>
<tr>
<th>Uncertainty (%)</th>
<th>No b-tag</th>
<th>b-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>9.7</td>
<td>–5.2 / +5.3</td>
</tr>
<tr>
<td>Jet energy scale &amp; reconstruction</td>
<td>–6.1 / +5.7</td>
<td>–5.0 / +5.7</td>
</tr>
<tr>
<td>QCD normalization &amp; shape</td>
<td>5.2</td>
<td>1.0</td>
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<tr>
<td>Initial/final state radiation</td>
<td>–2.1 / +6.1</td>
<td>4.0</td>
</tr>
<tr>
<td>b-tagging calibration</td>
<td>–</td>
<td>–6.3 / +7.2</td>
</tr>
<tr>
<td>W+jets heavy flavor content</td>
<td>–</td>
<td>–6.3 / +7.5</td>
</tr>
</tbody>
</table>
Top Cross Section: Dilepton

- Two cut-based analysis: without & with b-tag
  - 2 high-$p_T$ leptons (ee/μμ/eμ), ≥2 jets
  - ee/μμ + jets: large missing $E_T$ and $Z\rightarrow ll$ veto
  - eμ + jets: large $H_T$ (sum of jet and lepton $p_T$)
  - Major backgrounds: $Z/\gamma^*+$jets, “fake” leptons → (MC-assisted) data-driven estimates

**Additional Measurements**
- $\sigma_{t\bar{t}}$ normalized to $\sigma_Z$
- Inclusive dilepton analysis (extract $\sigma_{t\bar{t}}$, $\sigma_{WW}$, and $\sigma_{Z\rightarrow\tau\tau}$)
- $\sigma_{t\bar{t}}$ and b-tagging efficiency

**Stransverse mass:** $m_{T2}^2 = \min_{\vec{p}_{T,1} + \vec{p}_{T,2} = \vec{p}_T} \left\{ \max \left[ m_T^2(\vec{p}_T, \ell^+, \vec{p}_{T,1}, ...), m_T^2(\vec{p}_T, \ell^-, \vec{p}_{T,2}, ...) \right] \right\}$

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**No b-tag: Jet Multiplicity**

<table>
<thead>
<tr>
<th>Number of jets</th>
<th>Events</th>
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<tr>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>1</td>
<td>140</td>
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<tr>
<td>2</td>
<td>120</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>≥4</td>
<td>80</td>
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</table>

**No b-tag: Stransverse Mass**

<table>
<thead>
<tr>
<th>$m_{T2}$ [GeV]</th>
<th>Events / 10 GeV</th>
</tr>
</thead>
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<tr>
<td>0</td>
<td>160</td>
</tr>
<tr>
<td>10</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
</tr>
<tr>
<td>30</td>
<td>100</td>
</tr>
</tbody>
</table>

**b-tag: $H_T$**

<table>
<thead>
<tr>
<th>$H_T$ [GeV]</th>
<th>Events / 40 GeV</th>
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<tr>
<td>0</td>
<td>160</td>
</tr>
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<td>10</td>
<td>140</td>
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very clean!
Combination of all dilepton channels: profile likelihood

Results:

No b-tagging:
\[ \sigma_{\bar{t}t} = 173 \pm 22\text{(stat.)} +^{18}_{-16}\text{(syst.)} +^{8}_{-7}\text{(lumi.)} \text{ pb} \]

b-tagging:
\[ \sigma_{\bar{t}t} = 171 \pm 22\text{(stat.)} +^{21}_{-16}\text{(syst.)} +^{7}_{-6}\text{(lumi.)} \text{ pb} \]

Dominant uncertainties

- Jet energy scale: 5%
- Parton shower model: −5%/+4%
- Fake leptons: −4%/+3%

Simultaneous measurement of b-tagging efficiency: fit to number of b-tags → consistent results
Combination of lepton+jets and dilepton analyses on the level of likelihood functions

Uncertainty of combined result: 10% \rightarrow \text{competitive with Tevatron}
Top Cross Section: All-Hadronic

- Measure cross section in all possible channels $\rightarrow$ important cross check

- All-hadronic channel:
  - Signature: ≥6 jets, 2 b-tags
  - Very challenging: QCD overwhelming
  - Construct mass $\chi^2$ discriminant:
    \[
    \chi^2 = \sum_{i=1}^{2} \left( \frac{m_{ijb} - m_t}{\sigma_t} \right)^2 + \left( \frac{m_{ij} - m_W}{\sigma_W} \right)^2
    \]
    $\rightarrow$ 6 combinations, take lowest $\chi^2$

- Results with limited 2010 dataset:
  - Fitted $t\bar{t}$ production cross section:
    \[
    \sigma_{t\bar{t}} = 118 \pm 73\text{(stat.)} \pm 48\text{(syst.)} \pm 4\text{(lumi.) pb}
    \]
    $\rightarrow$ 1.6σ significance (2.2σ expected)
  - 95% C.L. upper limit: $\sigma_{t\bar{t}} < 261\text{ pb}$
Top Mass and Properties
Top Mass: Direct Measurements

Top quark mass:
- Standard model: key parameter (relation to W and Higgs mass)
- Known to high precision from Tevatron: uncertainty only 1.1 GeV (=0.6%) from single experiment (CDF Note 10444)

2010 data: template-based analyses
- Lepton+jets selection
- 1D “stabilized mass” $R_{32} = m_t^{\text{reco}} / m_W^{\text{reco}}$
- 1D kinematic fit
- 2D: mass vs. jet energy scale factor (JSF)

Main result (stabilized mass, e/µ combined)
$$m_t = 169.3 \pm 4.0(\text{stat.}) \pm 4.9(\text{syst.}) \text{ GeV}$$
(3.7% total uncertainty)
Guiding idea: experimental dependence on MC mass parameter (acceptance) weaker than theoretical dependence on pole mass \(1/m_t^4\)

Analysis technique:
- Lepton+jets cross section with b-tagging: repeat for nine mass hypotheses between 140 and 210 GeV
- Assumption: relative systematic uncertainties independent of mass (verified for 140 GeV and 210 GeV)
- Pole mass value and uncertainty extracted from overlap of experimental and theoretical likelihoods

Result (for approx. NNLO calculation, Langenfeld, Moch, Uwer):

\[ m_t = 166.4^{+7.8}_{-7.3} \text{ (stat. + syst.) GeV} \]
W Polarization in Top Decays

Probe \( V-A \) structure of Wtb vertex:
- SM expectation for polarization fractions:
  - left-handed \( F_L \approx 0.3 \) – longitudinal
  - \( F_0 \approx 0.7 \) – right-handed \( F_R \approx 0 \)
- Observable \( \cos \theta^* \): decay angle of charged lepton w.r.t. top boost direction in W rest frame

Two analysis techniques:
- Fit left-handed, longitudinal, right-handed templates to measured \( \cos \theta^* \)
- Extract asymmetries (e.g. \( A_{FB} \)) from \( \cos \theta^* \) → correct back to parton level

Interpretation: limits on anomalous couplings \( g_L, g_R \)

\[ F_0 = 0.59 \pm 0.12 \] (\( F_R \) fixed to 0)

\[ \text{Entries } 11449 \]

\[ \text{Mean } -0.02788 \]

\[ \text{RMS } 0.5719 \]

\[ \text{ATLAS Preliminary} \]

[ATLAS-CONF-2011-037]
Flavor-Changing Neutral Currents

- Top flavor-changing neutral currents (FCNC)
  - Extremely rare in standard model (BR < $10^{-12}$)
  - Current experimental limits much weaker, e.g. $B(t \rightarrow Zq) < 3.2\%$ at 95% C.L. (DØ, arXiv:1103.4574 [hep-ex])

Single top: $qg \rightarrow t \rightarrow Wb$
Signature: $W + b$-jet + MET
→ Limit: $\sigma(qg \rightarrow t) \times B(t \rightarrow Wb) < 17$ pb (95% C.L.)

Decay $tt \rightarrow Zq Wb$
Signature: three leptons + jets + missing $E_T$
→ Limit: $B(t \rightarrow Zq) < 17\%$ (95% C.L.)
High-Mass Phenomena Producing Top

- Anomalous missing $E_T$ in top events
  - Benchmark: heavy $T T \rightarrow tA^0 \bar{t} \bar{A}^0$ ($A^0$ dark matter candidate)
  - Signature: lepton+jets with MET $> 80$ GeV and $m_T > 120$ GeV
  - Exclude $T$ with 300 GeV (275 GeV) for $A^0$ mass $< 10$ GeV (50 GeV) at 95% C.L.

- Search for high-mass “resonances”
  - Reconstruct $t\bar{t}$ mass with $dR_{\text{min}}$ method (remove jets “far away” from rest of activity in event)
  - Interpretation in leptophobic $Z'$ model: $\sigma(Z') \times B(Z' \rightarrow t\bar{t}) < 38$ pb (3.2 pb) for $M_{Z'} = 500$ GeV (1300 GeV) at 95% C.L.
  - Exclude Kaluza-Klein gluons with $m < 650$ GeV at 95% C.L.
• Analysis of 2010 LHC data: many ATLAS top results, some already competitive with Tevatron
  • Pair production cross section
  • Top mass & properties

• LHC and ATLAS performing extremely well in 2011
  • ATLAS has recorded 1 fb$^{-1}$ of data in 2010/2011
  • Expect more sensitive searches
  • Expect precision measurements

Top: The New Standard Candle at the LHC
Topics for Discussion

- Making top the new standard candle
  - Cross section measurements with fiducial cuts? → reduce extrapolation uncertainty
  - Which differential cross sections are the most interesting?
  - Next step in precision: reduce systematic uncertainties

- Precision measurements: improve uncertainties related to theory
  - Vector boson + jets production: rates, kinematic shapes, heavy flavor content?
  - Additional jets in top production: hard process at (N)NLO? ISR and FSR?
  - MC generator uncertainties: LO $2 \rightarrow n$ vs. NLO (vs. MENLOPS)? $Q^2$ scales? $\alpha_S$?
  - Current PDF uncertainty prescription extremely heavy for all but the simplest analysis technique
  - … and experimenters will do their homework, too
Backup Slides
<table>
<thead>
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<tbody>
<tr>
<td>Top Quark Pair Production Cross-Section Measurement in ATLAS in the Single Lepton+Jets Channel without b-tagging</td>
<td>ATLAS-CONF-2011-023</td>
</tr>
<tr>
<td>Measurement of the Top Quark Pair Cross-Section with ATLAS in pp Collisions at $\sqrt{s} = 7$ TeV in the Single-Lepton Channel using b-tagging</td>
<td>ATLAS-CONF-2011-035</td>
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<td>Measurement of the Top Quark Pair Production Cross Section with ATLAS in pp Collisions at $\sqrt{s} = 7$ TeV in Dilepton Final States</td>
<td>ATLAS-CONF-2011-034</td>
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<tr>
<td>A Combined Measurement of the Top Quark Pair Production Cross-Section using Dilepton and Single-Lepton Final States</td>
<td>ATLAS-CONF-2011-040</td>
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<td>Search for tt Production in the All-Hadronic in ATLAS with $\sqrt{s} = 7$ TeV Data</td>
<td>ATLAS-CONF-2011-066</td>
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[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults]
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<td>ATLAS-CONF-2011-033</td>
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<tr>
<td>Determination of the Top-Quark Mass from the $t\bar{t}$ Cross Section Measurement at $\sqrt{s} = 7$ TeV with the ATLAS Detector</td>
<td>ATLAS-CONF-2011-054</td>
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<td>Measurement of the W-boson Polarisation in Top-Quark Decays in pp Collision Data at $\sqrt{s} = 7$ TeV using the ATLAS Detector</td>
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<td>Search for Anomalous Missing $E_T$ in $t\bar{t}$ Events</td>
<td>ATLAS-CONF-2011-036</td>
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<td>Search for FCNC Top Quark Processes at $\sqrt{s} = 7$ TeV with the ATLAS Detector</td>
<td>ATLAS-CONF-2011-061</td>
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<td>A Search for New High-Mass Phenomena Producing Top Quarks with the ATLAS Experiment</td>
<td>ATLAS-CONF-2011-070</td>
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<td>A Search for $t\bar{t}$ Resonances in the Lepton Plus Jets Channel using 200 pb$^{-1}$ of $pp$ Collisions at $\sqrt{s} = 7$ TeV</td>
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