Top Quark Mass and Properties at ATLAS

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on behalf of the ATLAS collaboration

The 19th Particle and Nuclei International Conference
(PANIC11)
24-29th July 2011
The Top Quark

- Rich phenomenology
  - Production properties
    - Cross section, kinematics, resonant production, anomalous production \((T \rightarrow tA^0)\), spin polarization, charge asymmetry
  - Top properties and Decay
    - Mass, width, spin, charge, \(W\) polarisation, branching fractions, anomalous couplings, rare/non-SM decays (FCNC)

- Large production cross section at the LHC
  - 165pb\(^{-1}\)@7 TeV
  - 10 ttbar pairs/min @ \(10^{33}\) cm\(^{-2}\)s\(^{-1}\)

Cross section: R. Calkins, this session
Resonant production: J. Abdallah, session 4I
The ATLAS detector

Main detector components

• Muon spectrometer \( \Delta p/p < 10\% \) up to 1 TeV
• Toroid magnet
• Hadronic calorimeter \( \sigma/E \sim 50\%/\sqrt{E} \oplus 3\% \)
• EM calorimeter \( \sigma/E \sim 10\%/\sqrt{E} \oplus 0.7\% \)
• Inner tracker \( \sigma/p_T \sim 0.04\%p_T \oplus 1.5\% \)
• Solenoid magnet

• Analyses presented here with \( L = 35 \text{pb}^{-1} \) 2010 data
• \( \Delta L = 3.4\% \) luminosity uncertainty
• Peak luminosity \( 2.1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \)
• max. 4PV per event on average
General Object and Event Selection

- Analysis mainly in ttbar single lepton channel (BR 30%)
  - Trigger on isolated high-\(p_T\) lepton at efficiency plateau

- Signature and selection
  - Exactly one isolated lepton
    - within tracker acceptance and \(p_T > 20\) GeV
    - calorimeter isolation
    - electron ‘tight’ ID selection
    - muon combined from inner tracker and muon spectrometer, track isolation
  - At least 4 jets, anti-kt (R=0.4), from calorimetric clusters
    - within tracker acceptance, \(p_T > 25\) GeV
  - At least one b-jets
    - reconstruct secondary vertex (SV0) @ 50% eff.

- After selection S/B 3:1-5:1

- Main backgrounds: QCD and W+jets (HF), data driven determination

\(E_T^{\text{miss}}\) from vector sum of jets, electrons, contribution from muons and unassociated calorimeter cells
- \(E_T^{\text{miss}} > 20(35)\) GeV for muon (electron)

Transverse mass \(M_T\) from lepton and neutrino
- \(M_T > 35\) GeV (electron), \(M_T + E_T^{\text{miss}} > 60\) GeV (muon)
Top mass measurement
Top mass measurement

- 1-D template fit on top/W mass ratio $R_{32}$
  
  
  $$R_{32} = \frac{m_{\text{top}}^{\text{reco}}}{m_{W}^{\text{reco}}}$$

- $m_{\text{top}}^{\text{reco}}$ three jets with highest vector sum $p_T$
- $m_{W}$ using the two non $b$-tagged jets with smallest distance in top rest frame,
  select events with $60 < m_{W} < 100$ GeV
- Less sensitive to jet energy scale uncertainties

- $m_{\text{top}}$ dependent signal templates ($tt\bar{t}$+single top): ratio of two Gaussians+Landau function

- Background template (MC and data driven): Landau function

- Unbinned likelihood fit for mass extraction
  
  Combined $e+\mu$ channel
  
  $m_{\text{top}} = 169.3 \pm 4.0\text{(stat.)} \pm 4.9\text{(syst.)}$ GeV

Dominant systematics

<table>
<thead>
<tr>
<th>Uncertainty [GeV]</th>
<th>$e$-channel</th>
<th>$\mu$-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>6.7</td>
<td>5.0</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>2.2</td>
<td>2.6</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.3</td>
<td>1.9</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Total systematic</td>
<td>4.8</td>
<td>5.0</td>
</tr>
</tbody>
</table>
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- Cross check analyses
- Template method
  - $m_{\text{top}}$ distributions from kinematic fit
- **Simultaneous fit to $m_{\text{top}}$ and global JES factor**
  - reduced JES uncertainty, but increased statistical uncertainty
- Similar size of uncertainties in e/µ channel
- Consistent result with all methods and channels
- Smallest uncertainty from 1D template fit:
  - 2.4\%(stat.)
  - 3.7\%(syst.)
• Measure the **pole mass** from cross section
  • Unambiguous definition of top mass
  • Test consistency of QCD cross section calculations

\[ \sigma_{t\bar{t}} = \left( \frac{1}{\mu_{\text{top}}^{\text{pole}}} \right) (a + bx + cx^2 + d^3) \text{pb} \]

with \( x = \mu_{\text{top}}^{\text{pole}} - 170 \text{ GeV} \)

• Using multivariate l+jets b-tag cross section analysis vs. \( m_{\text{top}} \)
• Three theory calculations
• Uncertainty from
  • cross section (13%) 5GeV
  • scales+PDF 3GeV

• With approx. NNLO Langefeld \( m_{\text{top}} = 166.4^{+7.8}_{-7.3} \text{ GeV} \)
FCNC, $T \rightarrow tA^0$, W-helicity,
FCNC \( \text{ttbar} \)

- FCNC vertex \( t \rightarrow Zq \)
- **fully leptonic** to suppress multi-jet background
- Selection on 3 leptons (\( p_T > 25, 20, 15 \text{ GeV} \)), two of them same flavor and OS

\[ \chi^2 \text{ event reconstruction} \]

Only one candidate

**BR (SM) = 10^{-12}**

<table>
<thead>
<tr>
<th>Channel</th>
<th>e-channel</th>
<th>( \mu )-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>W+jets</td>
<td>0.00±0.08</td>
<td>0.00±0.08</td>
</tr>
<tr>
<td>Z+jets</td>
<td>0.10±0.08</td>
<td>0.02±0.01</td>
</tr>
<tr>
<td>Dibosons</td>
<td>0.08±0.01</td>
<td>0.11±0.01</td>
</tr>
<tr>
<td>ttbar</td>
<td>0.05±0.02</td>
<td>0.04±0.02</td>
</tr>
<tr>
<td>Single-top</td>
<td>0.00±0.00</td>
<td>0.00±0.00</td>
</tr>
<tr>
<td>Exp. bkg.</td>
<td>0.23±0.11</td>
<td>0.17±0.08</td>
</tr>
<tr>
<td>Data</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Limits on BR(\( t \rightarrow Zq \)) (mod. frequentist method)

\( \text{BR} < 17\% \) (obs.)

\( \text{BR} < 12^{+4}_{-3}\% \) (exp.)

\( @95\% \text{CL} \)

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FCNC single top

- FCNC vertex gq→t
- Anomalous **single top production**
- Cross section below Wt-channel

- Event selection with exactly one b-tagged jet
- Neural network analysis with 13 input variables

- Limit on \(\sigma(u(c)g→t)\)*BR
  - Upper limit from Bayesian posterior:
    \[
    \sigma(u(c)g→t)\times BR < 17.3 \text{pb (obs.)}
    \]
    \[
    \sigma(u(c)g→t)\times BR < 17.4^{+8.2}_{-5.4} \text{pb (exp.)}
    \]

- Systematics from ISR, JES and W+jets HF fraction

\[
\sigma(u(c)g→t) = 10\text{pb}
\]
Anomalous $E_{T}^{\text{miss}}$

- Large $E_{T}^{\text{miss}}$ in lepton+jets events
  - from exotic top partner $T$ decay into top quark and neutral long lived scalar $A^{0}$
  - use $T \rightarrow tA^{0}$ as benchmark

- Event selection:
  - no b-tag required
  - $E_{T}^{\text{miss}}>80\text{GeV}$, transverse mass $>120\text{GeV}$
  - restrictive dilepton veto $p_{T}>15\text{GeV}$, isolated track, looser electron selection

No disagreement with SM
Exclusion at 95% CL:
- $m_{T}<275\text{GeV}$ ($m_{A^{0}}<50\text{GeV}$)
- $m_{T}<300\text{GeV}$ ($m_{A^{0}}<10\text{GeV}$)

<table>
<thead>
<tr>
<th></th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single lepton</td>
<td>8.4±1.6</td>
</tr>
<tr>
<td>Dilepton</td>
<td>7.6±2.0</td>
</tr>
<tr>
<td>Z+jets</td>
<td>0.4±0.1</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Single-top</td>
<td>0.4±0.1</td>
</tr>
<tr>
<td>QCD</td>
<td>0.2±0.1</td>
</tr>
<tr>
<td>Total Bkg</td>
<td>17.2±2.6</td>
</tr>
<tr>
<td>Data</td>
<td>17</td>
</tr>
</tbody>
</table>
W helicity in top decays

- **W helicity fractions in SM**
  - Sensitive variable $\theta^*_{lb}$ in W rest frame
  - Asymmetry method
    - $\chi^2$ method reconstruct events
    - Unfold $\cos \theta^*_{lb}$ distribution to parton level
    - Compute asymmetry $A_z$ at three $z$ values sensitive to the three helicity fractions

\[ A_z = \frac{N(\cos \theta^* > z) - N(\cos \theta^* < z)}{N(\cos \theta^* > z) + N(\cos \theta^* < z)} \]

- Longitudinal: $F_0 = 0.698$
- Left handed: $F_L = 0.301$
- Right handed: $F_R = 0.00041$

**Combined**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>0.65±0.15</td>
</tr>
<tr>
<td>$F_L$</td>
<td>0.36±0.10</td>
</tr>
<tr>
<td>$F_R$</td>
<td>-0.01±0.07</td>
</tr>
</tbody>
</table>
W helicity in top decays

- Template method
- Using kinematic fitter to reconstruct final state
- Binned likelihood fit to simulated distributions from pure helicity states to data

<table>
<thead>
<tr>
<th></th>
<th>combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>0.59±0.12</td>
</tr>
<tr>
<td>$F_L$</td>
<td>0.41±0.12</td>
</tr>
<tr>
<td>$F_R$</td>
<td>0 fix</td>
</tr>
</tbody>
</table>

- Both compatible result with SM
  - Statistically limited 16%
  - ISR/FSR 7%, JES 5%, background shapes 5%

(e-channel)

combined channel
Charge asymmetry

New result with $\sim 700 \text{pb}^{-1}$
New result with 700pb$^{-1}$

- $\Delta L = 4.5\%$ luminosity uncertainty
- Peak luminosity $1.75 \times 10^{33}$ cm$^{-2}$s$^{-1}$
- max. 10-12PV per event on average
- Lepton trigger thresholds higher, reconstructed $p_T > 25$GeV

- $|q\bar{q} \rightarrow t\bar{t}g + gg \rightarrow t\bar{t}q|^2$ not symmetric under C conjugation (Tevatron)
- symmetric under C conjugation (LHC)

2-3.4$\sigma$ excess @ Tevatron

Phys. Rev. D 83 (2011) 112003
D0 6062-CONF (2010)
Charge asymmetry

- Modification of charge asymmetry in \( \text{ttbar} \) production due to new physics possible
  - Measure rapidity of top and antitop

\[
A_C = \frac{N(\Delta |Y| > 0) - N(\Delta |Y| < 0)}{N(\Delta |Y| > 0) + N(\Delta |Y| < 0)} \Delta |Y| = |Y_t| - |Y_{\bar{t}}|
\]

- Reconstruct final state with kinematic fit
- Unfold to parton level to enable comparison with theory

\[A_C = -0.020 \pm 0.016\text{(stat.)} \pm 0.034\text{(syst.) combined}\]

Theory (MC@NLO) \( A_C = 0.005 \pm 0.001\text{(stat.)}\)

- Largest systematics
  - Theoretical modeling (generator/PS/fragmentation, mass)
  - JES, jet resolution and QCD background uncertainty
Conclusions
Conclusions

- ATLAS measurements of top properties with 35pb\(^{-1}\)
  - **Top mass** from template method: \(m_{\text{top}} = 169.3\text{GeV} \pm 3.7\%
  - **W boson helicity** fractions in agreement with SM predictions
  - No evidence for **FCNC** in ttbar and single top
  - No evidence for **excess of events with large** \(E_T^{\text{miss}}\)
  - **Charge asymmetry** compatible with SM expectation

- Analyses will benefit from 2011 data
  - Already >1fb\(^{-1}\) by now (July 2011)
  - Systematic will be reduced with better understanding of detector

- 2011 will open the door for precision top property measurements at the LHC
References

- Top Mass: ATLAS-CONF-2011-033
- Top Mass from cross section: ATLAS-CONF-2011-054
- W helicity: ATLAS-CONF-2011-037
- FCNC: ATLAS-CONF-2011-061
- Anomalous $E_T^{\text{Miss}}$: ATLAS-CONF-2011-036
- Charge asymmetry: ATLAS-CONF-2011-106
Backup
Top mass measurement

- 1D-template electron channel
- 1D-template, background muon channel, electron channel
Top mass measurement

- Mass distribution 2D-fit muon channel

- Templates 1D-kinfit muon channel
### FCNC NN inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Significance (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T,w$</td>
<td>66</td>
</tr>
<tr>
<td>$\Delta R(\ell, b)$</td>
<td>29</td>
</tr>
<tr>
<td>Lepton charge</td>
<td>22</td>
</tr>
<tr>
<td>$m_t$</td>
<td>20</td>
</tr>
<tr>
<td>$\Delta \phi(W, b)$</td>
<td>18</td>
</tr>
<tr>
<td>$\eta_b$</td>
<td>16</td>
</tr>
<tr>
<td>$W$-boson helicity</td>
<td>10</td>
</tr>
<tr>
<td>$p_T,b$</td>
<td>9.3</td>
</tr>
<tr>
<td>$p_T,t$</td>
<td>6.9</td>
</tr>
<tr>
<td>$\eta_t$</td>
<td>6.6</td>
</tr>
<tr>
<td>$E_T$</td>
<td>3.8</td>
</tr>
<tr>
<td>$m_W$</td>
<td>4.3</td>
</tr>
<tr>
<td>$\Delta \phi(\ell, b)$</td>
<td>4.2</td>
</tr>
</tbody>
</table>
Charge asymmetry

- Electron channel
W helicity in top decays

- Setting limits on possible anomalous couplings:

\[ \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{i g}{\sqrt{2}} \bar{b} \sigma^{\mu\nu} q^\nu \frac{q_L}{M_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{h.c.} \]

- From asymmetry method:
  - \(-0.44 < V_R < 0.48\)
  - \(-0.24 < g_L < 0.21\)
  - \(-0.49 < g_R < 0.15\)

@ 95% CL

Charge asymmetry

- Transfer matrix

(a) Response Matrix (e+jets)  
(b) Response Matrix (μ+jets)
Charge asymmetry

- Rapidity distributions electron (before/after unfolding)
Charge asymmetry

- Rapidity distributions muon (before/after unfolding)