Top quark properties at ATLAS

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On behalf of the ATLAS Collaboration
Top Quark Physics

• The heaviest particle in the Standard Model (SM)
  ➡ decays before hadronisation
    - can be a good probe to check the property of “quark”
  ➡ sensitive to new physics in its production/decay

• LHC is the “top factory”.
  ➡ ~1 million top pairs produced in 2011 (5fb⁻¹)
  ➡ Production cross section has been measured precisely.
  ➡ It’s time to measure its properties.
    - might give us a clue to catch new physics.
What we measured so far.

• Covered in this talk...
  ➡ Top quark charge @ 0.70fb$^{-1}$
  ➡ Inclusive $t\bar{t}+\gamma$ cross section @ 1.04fb$^{-1}$
  ➡ W boson polarisation in top quark decays @ 0.70fb$^{-1}$
  ➡ Spin correlation in the $t\bar{t}$ production @ 2.1fb$^{-1}$ (New!!)
  ➡ Charge asymmetry in the $t\bar{t}$ production @ 1.04fb$^{-1}$ (New!!)

• Not covered in this talk...
  ➡ Inclusive top production cross section (Indico)
  ➡ Top quark mass (Indico)
  ➡ “Searches” related to the top quark production/decay (Indico)
Top Quark Pair Signature

- BR(t→bW) ~ 100%
- Final state of the top pair production → categorised by the number of leptons from W bosons
- Produced in pairs by the strong interaction, the gluon-gluon fusion dominates.
- Decay modes of the W bosons determine the alljet, lepton+jet or dilepton final states classification.
- Top can be also produced singly, via electroweak processes (s and t channels; Wg fusion).
- This talk focuses on results with t¯t pairs.
- Main backgrounds: vector bosons with jets, multijets (fake leptons).
- Signatures: high-pT isolated leptons, (b-)jets, large missing transverse energy.

Top Pair Branching Fractions

- "alljets" 44%
- τ+jets 15%
- μ+jets 15%
- e+jets 15%
- "dileptons"
- "lepton+jets" for analyses
The top quark charge

- **Motivation**
  - Test for a top-like exotic quark with charge -4/3e

- **Signature**
  - lepton+jets final state

- **Top quark charge determination**
  - \[ t^{(2/3)} \rightarrow b^{(-1/3)} + \ell^{(+1)} + \nu_\ell \]
  - \[ \bar{t}^{(-4/3)} \rightarrow b^{(-1/3)} + \ell^{(-1)} + \nu_\ell \]
  - \[ Q_{comb} = Q_{bjet} \cdot Q_\ell \]
    - good discriminant

- **How to determine the charge of b-jet?**
  - \[ Q_{bjet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^\kappa}{\sum_i |\vec{j} \cdot \vec{p}_i|^\kappa} \]
    - (based on the charge of tracks in b-jet)
The top quark charge

- Data and SM agree well.
- Expected $<Q_{\text{comb}}>$ probability distribution for both SM/Exotic scenarios using pseudo-experiments.

“top-like” quark with $-4/3e$ is excluded at more than $5\sigma$
Inclusive $t\bar{t}+\gamma$ cross section

- **Motivation**
  - Direct access to the electroweak coupling of the quark.

- **Signature**
  - “lepton+jets final state” + photon ($p_T \geq 15$ GeV)

- **#Candidate events**:
  - 52 (e+jets), 70 ($\mu$+jets)

**Background estimation**

- Photon from hadron fake
  - ✓ Template fitting

- Photon from electron fake
  - ✓ $Z \rightarrow e^+e^-$

**Figure 3:** $p_{\text{cone}20}^T$ templates derived from data for prompt photons (blue) and fake photons (red), normalised to unity. The left plot shows the respective expectation per bin, as it is used in the template fit. The right plot shows the same templates with the expectation per GeV, i.e., divided by the bin width. Details on the derivation of the templates can be found in Sec. 5 and Sec. 6.

**Figure 4:** Background templates from data highly enriched in hadron fakes in different regions of $|\eta|$ (left) and $p_T$ (right). The $p_T$ spectrum of the hadron fakes is estimated from data by replacing the signal photon requirement with an anti-requirement on the shower shape variables [30].
Inclusive $t\bar{t}+\gamma$ cross section

\[ \sigma_{t\bar{t}\gamma} \cdot \text{BR} = 2.0 \pm 0.5\text{(stat.)} \pm 0.7\text{(syst.)} \pm 0.08\text{(lumi.)}[\text{pb}] \]

(requiring $P_{T\gamma} \geq 8\text{GeV}$ at generator level)

• Consistent with the NLO prediction : $2.1 \pm 0.5$ [pb]
  ➡ Main systematic uncertainty : photon identification
W polarisation in the top quark decay

• Motivation
  ➤ Test if there are new physics contributions in V-A coupling
    \[
    \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) \gamma_\mu t W^- - \frac{g}{\sqrt{2}} b \bar{b} \gamma_\nu \frac{i \sigma^{\mu\nu} q_\nu}{M_W} (g_L P_L + g_R P_R) \gamma_\mu W^- + \text{h.c.}
    \]
  ➤ Helicity fractions \( F_0, F_L, F_R \) (longitudinal, left and right-handed)
    - SM prediction: \( F_0 \sim 0.7, F_L \sim 0.3, F_R \sim 0.0 \)

• Signature
  ➤ Angle \( \theta^* \) (W boson rest frame)
  ➤ Holding the W boson helicity info.
W polarisation in the top quark decay

- Extract $F_0$, $F_L$ by template fitting
  $\implies \cos \theta^*$ as templates
- Result (combined single/di-lepton)
  \[ F_0 = 0.75 \pm 0.08 \text{ (stat.+syst.)} \]
  \[ F_L = 0.25 \pm 0.08 \text{ (stat.+syst.)} \]
  \[(F_R \text{ is fixed to zero.})\]
- Main systematics: $t\bar{t}$ modelling
- Consistent with SM
  - Setting constraints on $g_L$ and $g_R$.

\[ \mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^- \mu 
- \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W^- \mu + \text{h.c.} \]
Spin correlation in t\bar{t} production

• Motivation
  ➞ We have the access to spins of quark (τt is short enough).
  ➞ The strength of the correlation may differ (e.g. H^+ contribution).

• Correlation coefficient

\[ A = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}} = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)} \]

• Signature
  ➞ Dilepton final state
  ➞ Leptons carry the spin information.
    - The distribution of the ΔΦ between two leptons in the lab frame is a good discriminator.
Spin correlation in $t\bar{t}$ production

- Binned likelihood fit for $\Delta\phi$ distribution to extract $f^{\text{SM}}$ and $f^{\text{UC}}$.
  - Constraint with $f^{\text{SM}} + f^{\text{UC}} = 1$
  - Result: $A_{\text{measured}}^{\text{helicity}} = A_{\text{helicity}}^{\text{SM}} \cdot f^{\text{SM}}$ ($A_{\text{helicity}}^{\text{SM}} = 0.31$)

$$= 0.40 \pm 0.04(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$$

“No correlation model” is excluded by 5$\sigma$
Charge asymmetry in $t\bar{t}$ production

• Motivation
  - Indirect search for new heavy particles.
  - Test the interesting result for $A_{FB}$ at the Tevatron.

• Define asymmetry parameter $A_C$
  
  \[
  A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}
  \]

  where $\Delta|y| \equiv |y_t| - |y_{\bar{t}}|$

• Obtaining $\Delta|y|$ distribution
  - Reconstruct a four vector of $t\bar{t}$
    - likelihood based method
  - Unfolding to correct for acceptance and resolution effects.
Charge asymmetry in $t\bar{t}$ production

• Results: Consistent with SM ($A_C = 0.006 \pm 0.002$)
  
  Inclusive: $A_C = -0.018 \pm 0.028$ (stat.) $\pm 0.023$ (syst.)
  
  Exclusive: $A_C = -0.053 \pm 0.070$ (stat.) $\pm 0.054$ (syst.) for $m_{t\bar{t}} < 450$ GeV
  
  $A_C = -0.008 \pm 0.035$ (stat.) $\pm 0.032$ (syst.) for $m_{t\bar{t}} > 450$ GeV

  ➤ Main systematics: $t\bar{t}$ modelling

• Comparing results with some new physics models.
  
  ➤ ATLAS disfavours the models that would best fit the CDF result.
  
  ➤ We still have a large uncertainty. Measurement will profit from more data.
Conclusions

- **Top quark**: Important particle for LHC physics
  - good probe to check the SM predictions
  - to understand as a main background for “searches”.
  - can be used directly to search for BSM physics.

- **Analysis with 2011 datasets**
  - Property measurements of “the top quark”, “its decay” and “its pair production”.
  - No evidence of physics beyond the standard model.

- **Outlook**
  - Measurements with full 2011 dataset are ongoing.
  - Stay tuned to improve the precision.
backup
The top quark charge

- Other method to determine b-jet charge
  - utilise the charge of the soft muon inside the b-jet
  - lepton-bjet pairing: kinematic likelihood for the ttbar events
  - discriminant: \( Q_{\text{comb}}^{\text{soft}} = Q_{\text{soft} \mu} \cdot Q_{\text{lepton}} \)

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

![Graph showing the expected distributions of the top quark and exotic scenarios.](graph.png)

![Graph showing the measured values for the top quark and exotic scenarios.](graph2.png)
### Inclusive $t\bar{t}+\gamma$ cross section

<table>
<thead>
<tr>
<th>Description</th>
<th>Uncertainty on the cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling</td>
<td>± 0.18</td>
</tr>
<tr>
<td>Initial and final state radiation</td>
<td>± 0.31</td>
</tr>
<tr>
<td>Electron related</td>
<td>± 0.05</td>
</tr>
<tr>
<td>Muon related</td>
<td>± 0.08</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>± 0.24</td>
</tr>
<tr>
<td>Jet energy scale (pile-up uncertainty)</td>
<td>± 0.28</td>
</tr>
<tr>
<td>$b$-jet energy scale</td>
<td>± 0.06</td>
</tr>
<tr>
<td>Jet reconstruction and resolution</td>
<td>± 0.06</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ related</td>
<td>± 0.03</td>
</tr>
<tr>
<td>$b$-tagging performance</td>
<td>± 0.18</td>
</tr>
<tr>
<td>Treatment of dead region in LAr calorimeter read-out</td>
<td>± 0.05</td>
</tr>
<tr>
<td>Luminosity</td>
<td>± 0.08</td>
</tr>
<tr>
<td>Photon identification efficiency</td>
<td>± 0.33</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>± 0.02</td>
</tr>
<tr>
<td>Photon resolution</td>
<td>± 0.01</td>
</tr>
<tr>
<td>$t\bar{t}y$ background yield</td>
<td>± 0.03</td>
</tr>
<tr>
<td>non-$t\bar{t}$ background yield</td>
<td>± 0.11</td>
</tr>
<tr>
<td>Electron to photon extrapolation</td>
<td>± 0.22</td>
</tr>
<tr>
<td>Fraction of converted prompt photons</td>
<td>± 0.03</td>
</tr>
<tr>
<td>Fraction of converted hadron fakes</td>
<td>± 0.16</td>
</tr>
<tr>
<td>Reweighting of the background templates ($p_T$)</td>
<td>± 0.11</td>
</tr>
<tr>
<td>Reweighting of the background templates ($\eta$)</td>
<td>± 0.06</td>
</tr>
<tr>
<td>Pile-up dependence of the signal templates</td>
<td>± 0.01</td>
</tr>
<tr>
<td>Pile-up dependence of the background templates</td>
<td>± 0.05</td>
</tr>
<tr>
<td>Sum</td>
<td>± 0.7</td>
</tr>
</tbody>
</table>
Inclusive $\tilde{t}\tilde{t}+\gamma$ cross section

#expected events with BG only assumption. Blue line: observed events (122).

$p$-value is 0.71 (2.7σ).
W polarisation in the top quark decay

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{8} (1 + \cos \theta^*)^2 F_R + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{4} (1 - \cos^2 \theta^*) F_0 \]

![Diagram of W polarisation in the top quark decay](image)
W polarisation in the top quark decay

- How to reconstruct top quark in dilepton channel
  - Need to factorise “MEt → two neutrinos”.
  - Solve these equations. (6 unknowns, 6 equations)

\[
\begin{align*}
p^{\nu_1}_x + p^{\nu_2}_x &= \not{E}_x, \\
p^{\nu_1}_y + p^{\nu_2}_y &= \not{E}_y, \\
(p_{\ell_1} + p_{\nu_1})^2 &= m_W^2, \\
(p_{\ell_2} + p_{\nu_2})^2 &= m_W^2, \\
(p_W + p_{j_1})^2 &= m_t^2, \\
(p_W + p_{j_2})^2 &= m_t^2.
\end{align*}
\]

- lepton-jet pairing
  - utilise sum of invariant masses \( m_{l_1j_1} + m_{l_2j_2} \).
Spin correlation in the $t\bar{t}$ production

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>$\Delta f^{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>±0.14</td>
</tr>
<tr>
<td>MC simulation template statistics</td>
<td>±0.09</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±0.01</td>
</tr>
<tr>
<td>Lepton</td>
<td>±0.01</td>
</tr>
<tr>
<td>Jet energy scale, resolution and efficiency</td>
<td>±0.12</td>
</tr>
<tr>
<td>NLO generator</td>
<td>±0.08</td>
</tr>
<tr>
<td>Parton shower and fragmentation</td>
<td>±0.08</td>
</tr>
<tr>
<td>ISR/FSR</td>
<td>±0.07</td>
</tr>
<tr>
<td>PDF uncertainty</td>
<td>±0.07</td>
</tr>
<tr>
<td>Top quark mass</td>
<td>±0.01</td>
</tr>
<tr>
<td>Fake leptons</td>
<td>+0.16/−0.07</td>
</tr>
<tr>
<td>Calorimeter readout</td>
<td>±0.01</td>
</tr>
<tr>
<td>All systematics</td>
<td>+0.27/−0.22</td>
</tr>
<tr>
<td>Statistical + Systematic</td>
<td>+0.30/−0.26</td>
</tr>
</tbody>
</table>
Charge asymmetry in the $t\bar{t}$ production

The measured charge asymmetry in the $t\bar{t}$ production is presented. The normalisation of the background estimate includes both statistical and systematic uncertainties. The normalisation of the fraction of heavy flavour contributions in simulated events generated with different predictions including uncertainties from parton distribution functions and factorisation scales.

The unfolded response matrix is shown with data and MC@NLO predictions. The unfolding bias and convergence are discussed. The uncertainty in the estimate of the efficiency and resolution of the detector and acceptance unfolded event counting is accounted for by independently varying the bins of the response matrix according to Poisson distributions.

Pseudoexperiments are performed to confirm that the uncertainty of the unfolding procedure is accounted for. The unfolded asymmetries in two regions of the $|y|$ distribution for the electron channel (left) and the muon channel (right) after background subtraction are compared. The uncertainties from unfolding are presented, including those from parton distribution functions and factorisation scales.

The systematic uncertainties on the fraction of heavy flavour contributions in simulated events are discussed. The uncertainties in the response matrix are taken into account in the statistical uncertainty in measurements of the luminosity. The uncertainty in the estimate of the $t\bar{t}$ cross section at the Tevatron lies in the range $0.023 (\text{syst.})$ to $0.028 (\text{syst.})$ for the inclusive electron and muon channels respectively. This uncertainty is $21\%$ and $23\%$ in the four jet bin, for the electron and muon channels respectively.
Charge asymmetry in the $t\bar{t}$ production

<table>
<thead>
<tr>
<th>Source of systematic uncertainty on $A_C$</th>
<th>Electron channel</th>
<th>Muon channel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Detector modelling</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>0.012</td>
<td>0.006</td>
</tr>
<tr>
<td>Jet efficiency and resolution</td>
<td>0.001</td>
<td>0.007</td>
</tr>
<tr>
<td>Muon efficiency and resolution</td>
<td>$&lt;0.001$</td>
<td>0.001</td>
</tr>
<tr>
<td>Electron efficiency and resolution</td>
<td>0.003</td>
<td>0.001</td>
</tr>
<tr>
<td>b-tag scale factors</td>
<td>0.004</td>
<td>0.002</td>
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<tr>
<td>Calorimeter readout</td>
<td>0.001</td>
<td>0.004</td>
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<tr>
<td>Charge mis-ID</td>
<td>$&lt;0.001$</td>
<td>$&lt;0.001$</td>
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<tr>
<td>b-tag charge</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td><strong>Signal and background modelling</strong></td>
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</tr>
<tr>
<td>Parton shower/fragmentation</td>
<td>0.010</td>
<td>0.010</td>
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<tr>
<td>Top mass</td>
<td>0.007</td>
<td>0.007</td>
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<tr>
<td>$t\bar{t}$ modelling</td>
<td>0.011</td>
<td>0.011</td>
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<tr>
<td>ISR and FSR</td>
<td>0.010</td>
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<tr>
<td>PDF</td>
<td>$&lt;0.001$</td>
<td>$&lt;0.001$</td>
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<tr>
<td>W+jets normalization and shape</td>
<td>0.008</td>
<td>0.005</td>
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<tr>
<td>Z+jets normalization and shape</td>
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<td>0.001</td>
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<tr>
<td>Multijet background</td>
<td>0.011</td>
<td>0.001</td>
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<tr>
<td>Single top</td>
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<td>$&lt;0.001$</td>
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<tr>
<td>Diboson</td>
<td>$&lt;0.001$</td>
<td>$&lt;0.001$</td>
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<tr>
<td>MC Statistics</td>
<td>0.006</td>
<td>0.005</td>
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<tr>
<td>Unfolding convergence</td>
<td>0.001</td>
<td>0.001</td>
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<tr>
<td>Unfolding bias</td>
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<td>$&lt;0.001$</td>
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<tr>
<td>Luminosity</td>
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<td>0.001</td>
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<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>0.028</td>
<td>0.023</td>
</tr>
</tbody>
</table>
Charge asymmetry in the $t\bar{t}$ production

Inclusive

- $m_{t\bar{t}} > 450\text{GeV}$

- $A_C$ vs $A_{FB}$

- Models: SM, $W$, $\Omega^4$, $\omega^4$, $Z'$

- ATLAS, CDF, D0, CMS
Charge asymmetry in the tt production

Unfolded data

MC@NLO

ATLAS

$\int L \, dt = 1.04 \, fb^{-1}$

$A_C$

$< 450$

$> 450$

$m_{\bar{t}t}$ [GeV]