Top quark pair production in ATLAS

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Outline

- inclusive cross-section in dilepton channel [arXiv:1406.5375]
- production cross-section as a function of jet multiplicity and jet transverse momentum [arXiv:1407.0891]
ATLAS dataset

Integrated luminosity of good quality data recorded by ATLAS:

- 2011: $\mathcal{L}_{\text{int}} = 4.6$ fb$^{-1}$, $\sigma_{t\bar{t}} = 177.3^{+10.1}_{-10.8}$ pb, $N_{t\bar{t}} \sim 0.8$ M
- 2012: $\mathcal{L}_{\text{int}} = 20.3$ fb$^{-1}$, $\sigma_{t\bar{t}} = 252.9^{+13.3}_{-14.5}$ pb, $N_{t\bar{t}} \sim 5$ M
Inclusive cross-section in dilepton channel

Signal events:
- opposite-sign $e\mu$ pair with $p_T > 25$ GeV, $|\eta| < 2.5$
- at least one $b$-tagged jet

Simultaneously determine:
- $\sigma_{t\bar{t}}$: cross-section
- $\epsilon_b$: efficiency to reconstruct and tag $b$-jet

Count events with exactly two ($N_2$) and one ($N_1$) $b$-jets:

\[
N_2 = \mathcal{L}_{\text{int}} \sigma_{t\bar{t}} \epsilon_{e\mu} \epsilon_b \epsilon_b^2 + N_{2\text{bkg}} \\
N_1 = \mathcal{L}_{\text{int}} \sigma_{t\bar{t}} \epsilon_{e\mu} 2\epsilon_b (1 - C_b \epsilon_b) + N_{1\text{bkg}}
\]

where
- $\epsilon_{e\mu}$: efficiency to pass the opposite-sign $e\mu$ preselection
- $C_b$: tagging correlation coefficient
Inclusive cross-section: results

\[ \sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3 \text{ pb} \left( \sqrt{s} = 7 \text{ TeV} \right) \]
\[ \sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2 \text{ pb} \left( \sqrt{s} = 8 \text{ TeV} \right) \]

with stat., experimental and theory syst., luminosity and beam energy uncertainty.

- Total measurement unc.: 3.9\% (\sqrt{s} = 7 \text{ TeV}) and 4.3\% (\sqrt{s} = 8 \text{ TeV})
- NNLO+NNLL theo. unc.: 5.7\% (\sqrt{s} = 7 \text{ TeV}) and 5.3\% (\sqrt{s} = 8 \text{ TeV})
Modelling uncertainties not dominant for inclusive $\sigma_{t\bar{t}}$, but notably reduced in fiducial measurement

- $\epsilon_{e\mu} = \text{acceptance} \cdot \text{reconstruction efficiency}$
- acceptance: fraction of events with $e, \mu$: $p_T > 25$ GeV, $|\eta| < 2.5$
- $\sigma_{t\bar{t}} = \text{acceptance} \cdot \sigma_{t\bar{t}}^{\text{fid}} \Rightarrow$ dependence on PDF significantly reduced

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>7 TeV</th>
<th>8 TeV</th>
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<tbody>
<tr>
<td>$\Delta \epsilon_{e\mu} / \epsilon_{e\mu}$ (%)</td>
<td>$\Delta \sigma_{t\bar{t}} / \sigma_{t\bar{t}}$ (%)</td>
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<tr>
<td>$t\bar{t}$ modelling</td>
<td>0.71</td>
<td>1.43</td>
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<tr>
<td>Parton distribution functions</td>
<td>1.03</td>
<td>1.04</td>
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<tr>
<td>Total uncertainty ($\sigma_{t\bar{t}}$)</td>
<td>1.56</td>
<td>3.89</td>
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<tr>
<td>$t\bar{t}$ modelling</td>
<td>0.84</td>
<td>1.56</td>
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<tr>
<td>Parton distribution functions</td>
<td>0.35</td>
<td>0.38</td>
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<tr>
<td>Total uncertainty ($\sigma_{t\bar{t}}^{\text{fid}}$)</td>
<td>1.27</td>
<td>3.81</td>
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Differential measurements

Performed in single lepton channel, at $\sqrt{s} = 7$ TeV

Signal events:

- exactly one $e$ or $\mu$ with $p_T > 25$ GeV, $|\eta| < 2.5$
- $\geq 4$ jets with $p_T > 25$ GeV, $|\eta| < 2.5$
- $\geq 1$ $b$-tagged jet @ 70%
- $E_T > 30$ GeV
- $m_W > 35$ GeV
  
  $$m_W^m = \sqrt{2p_T^\ell p_T^\nu(1 - \cos(\phi^\ell - \phi^\nu))}$$

- cut on quality of $t\bar{t}$ system reconstruction:
  
  $$\log(L) > -50$$
Hadronically decaying top $p_T$

- pass MC predictions through detector simulation
- pass data and simulation through (the same) reconstruction and analysis
- figures: data vs simulation for hadronically decaying top $p_T$. Left: $e$-channel, right: $\mu$-channel

For MC prediction: **Alpgen + Herwig**: simulation prediction overshoots the data for high $p_T$ ($p_T > 200$ GeV).
Invariant mass of the $t\bar{t}$ system

- pass MC predictions through detector simulation
- pass data and simulation through (same) reconstruction and analysis
- figures: data vs simulation for invariant mass of the $t\bar{t}$ system $m_{t\bar{t}}$. Left: $e$-channel, right: $\mu$-channel

For MC prediction: **Alpgen +Herwig**: agreement of data and simulation predictions (within uncertainties).
Unfolding

- background-subtracted measurements are corrected for detector effects
- regularized matrix inversion (Singular Value Decomposition method) used
- left: migration matrix for hadronically decaying top $p_T (\mu\text{-chan.})$
- right: migration matrix for $m_{\tau\bar{\tau}} (\mu\text{-chan.})$

e and $\mu$ channel combination is performed using BLUE (best linear unbiased estimator) method.
Hadronically decaying top $p_T$

After unfolding and channel combination:

- left: data vs various MC generator predictions
- right: top $p_T$ compared to NLO+NNLL prediction, Phys. Rev. D 82 (2010) 114030. Uncertainties: MSTW2008NNLO PDF + error sets, $\mu_r, \mu_f$ varied by factor of 1/2 and 2, scale choices: $\mu = m_{t\bar{t}}$ and $\mu = \sqrt{m_{t\bar{t}}^2 + p_T^2}$.

$p$-values: ALPGEN: 0.00, MC@NLO: 0.24, POWHEG-hvq +HERWIG: 0.57, POWHEG-hvq +PYTHIA: 0.00, NLO+NNLL: 0.27
Invariant mass of the $t\bar{t}$ system

After unfolding and channel combination:

- left: data vs various MC generator predictions
- right: $m_{t\bar{t}}$ compared to NLO+NNLL prediction, JHEP 09 (2010) 097.

Uncertainties: MSTW2008NNLO PDF + error sets, $\mu_r, \mu_f$ varied by factor of 1/2 and 2, scale choices: $\mu = m_{t\bar{t}}$ and $\mu = \sqrt{m_t^2 + p_T^2}$.

$p$-values: ALPGEN: 0.63, MC@NLO: 0.14, POWHEG-hvq +HERWIG: 0.24, POWHEG-hvq +PYTHIA: 0.01, NLO+NNLL: 0.20
MC generator $p$-values affected by several steerable modelling aspects:

- **Parton Distribution Functions**: PDF choice can increase/decrease data-simulation agreement. Top pair production differential distributions should thus soon be relevant for constraining PDF models (e.g. $g$ PDF at high $x$ values).

- **Parton shower and hadronization details**: e.g. $p$-values of POWHEG-hvq + *Herwig* differ notably from POWHEG-hvq + *Pythia* ones. (Partly) explained by momentum rescaling during parton shower. See e.g. P. Nason’s talk @ May 2014 TOPLHCWG mtg.

- **Renormalization and Factorization scale choice**

- **Generator-specific parameters/assumptions**: e.g. details of hardest emission in NLO generators. See e.g. K. Hamilton’s talk @ Top2012.

- ...  

Data-simulation agreement and understanding can be improved by generator tuning and extension of models taken into account.
Jet multiplicity and $p_T$

Differential cross-section as a function of jet multiplicity and jet transverse momentum:

- 7TeV, single lepton channel
- jet multiplicity: using a number of $p_T$ threshold cuts: 25, 40, 60, 80 GeV
- transverse momentum: up to including the fifth jet
- measurements corrected for detector effects using Bayesian Iterative unfolding

![Graph showing differential cross-section as a function of jet multiplicity and leading jet $p_T$.](image)

\[ \text{Expected/Data} \]

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Measure fraction of events with no extra jet in a central rapidity region of the detector ($f_{\text{gap}}$).

- 7 TeV, dileptonic events with 2 $b$-tagged jets (enables flagging extra jets not from $t\bar{t}$ decay)

- measurement done as a function of $p_T$-threshold ($Q_0$) and scalar sum of extra jet activity ($Q_{\text{sum}}$)

- both jet multiplicity and $p_T$ (prev. slide) and gap fraction measured in fiducial phase-space and (being) implemented in Rivet framework; valuable information for improving the description of extra jet activity in $t\bar{t}$ events
Data vs theory for Njet and $f_{gap}(Q_0)$, $f_{gap}(Q_{sum})$

General trend:
if a model prediction of $f(Q_0)$ too low,
then Njet too high. Consistent with expectations.

**NLO generators:**
- in general yield satisfactory agreement with the data for $f_{gap}(Q_0)$
- the observable has some sensitivity also to parton shower activity, deficiencies or bugs in which can spoil the data-MC agreement (e.g. dead regions in fortran HERWIG, buggy MPI activity in old versions of HERWIG++ ≤ 2.6.1)
- not expected to do well for Njet (out of the box) and mostly don’t

**LO Multi-leg generators:**
- both of $f_{gap}(Q_0)$, $f_{gap}(Q_{sum})$ and Njet prove to be challenging to describe within current experimental uncertainties
- measurements useful (and used) for generator tuning (fiducial, Rivet)
- sensitive parameters: factorization scale, renormalization scale, parameters controlling initial and final state radiation
$t\bar{t}$ charge asymmetry

$t\bar{t}$ production via $qg$ or $q\bar{q}$: $t$ emitted in direction of $q$, $\bar{t}$ in direction of $\bar{q}$

**Tevatron:**

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$\Delta y = y_t - y_{\bar{t}}$$

**LHC:**

$$A_C = \frac{N(\Delta |y| > 0) - N(\Delta |y| < 0)}{N(\Delta |y| > 0) + N(\Delta |y| < 0)}$$

$t\bar{t}$ asymmetry: $\Delta |y| = |y_t| - |y_{\bar{t}}|$ (lepton asymmetry: $\Delta |\eta| = |\eta^+| - |\eta^-|$)

- $t\bar{t}$-based $A_{FB}$: $\sim 8.8\%$ in SM*
- $t\bar{t}$-based $A_C$: $\sim 1.2\%$ in SM*

*SM reference values: NLO QCD+EW corrections, Phys. Rev. D 86, 034026
$A_C$ in single lepton channel (7 TeV)

Measure top quark based asymmetry

- use kinematic fit based on a likelihood approach to reconstruct $t$ and $\bar{t}$ 4-momenta
- correct for detector effects using Fully Bayesian unfolding

Inclusive result:

$A_C^{t\bar{t}} = 0.006 \pm 0.010 \text{ (stat.} + \text{ syst.)}$,

SM: $A_C^{t\bar{t}} = 0.0123 \pm 0.0005$

Differential measurements:

- $m(t\bar{t}), p_T(t\bar{t}), y(t\bar{t})$
- $z$-component of $t\bar{t}$ velocity: $\beta$
- measure differential asymmetries at $\beta > 0.6$

**ATLAS + CMS combination:**

$A_C^{t\bar{t}} = 0.005 \pm 0.007 \text{ stat.} \pm 0.006 \text{ syst.}$

All measurements consistent with SM.
Measure lepton and top quark based asymmetry

- $A_{C}^{ll}$: no reconstruction needed
- $A_{C}^{t\bar{t}}$: use ME method to reconstruct $t$ and $\bar{t}$ 4-momenta
- correct for detector effects using calibration

Inclusive asymmetry results:

- $A_{C}^{ll} = 0.023 \pm 0.012$ stat. $\pm 0.008$ syst.  
  SM : $A_{C}^{ll} = 0.0049 \pm 0.0001$

- $A_{C}^{t\bar{t}} = 0.057 \pm 0.024$ stat. $\pm 0.015$ syst.  
  SM : $A_{C}^{t\bar{t}} = 0.0123 \pm 0.0005$

- for both single lepton and dilepton results: stat. $>$ syst.
Conclusions

- inclusive and differential $t\bar{t}$ cross-section measurements are precise enough to challenge state-of-the-art theory predictions
- differential measurements effective in highlighting a number of observables sensitive to details of MC generator modelling/theory assumptions:
  - top $p_T$
  - invariant mass and $p_T$ of the $t\bar{t}$ system
  - differential cross-section as a function of jet multiplicity
  - ...
- a number of recent Run I measurements done in fiducial region. This reduces dependence on assumptions made for the simulated predictions.
- Together with implementation in Rivet framework, fiducial measurements also ease comparisons to theory predictions.
- A recently particularly interesting and debated $t\bar{t}$ observable, charge asymmetry, is so far found to be consistent with the SM in inclusive and differential ATLAS measurements.
- A number of other measurements done/in progress with Run I data; https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults.