Top quark pair property measurements and $\bar{t}t+X$, using the ATLAS detector at the LHC

Nils-Arne Rosien
On behalf of the ATLAS collaboration
II. Physikalisches Institut

GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

25th International Workshop on Deep Inelastic Scattering and Related Topics 2017, University of Birmingham
04.04.2017
Top quark properties at ATLAS

- ~40 millions of $t\bar{t}$ events produced at the ATLAS detector
- Era of precision measurements for top quark physics
- Measurements of top quark properties as tests of Standard Model
- Possibility of probing new observables and extending existing analysis approaches
Publications since last DIS

1) Measurements of **top quark spin observables** in $t\bar{t}$ events using **dilepton** final states in 8 TeV $pp$ collisions with the ATLAS detector: [JHEP 03 (2017) 113]

2) Measurements of the **charge asymmetry** in top-quark pair production in the **dilepton** final state at 8 TeV with the ATLAS detector: [Phys. Rev. D 94, 032006]

3) Measurements of **charge and CP asymmetries in $b$-hadron decays** using top-quark events collected by the ATLAS detector in $pp$ collisions at 8 TeV: [JHEP02(2017)071]

4) Measurement of the **$W$ boson polarisation** in $t\bar{t}$ events from $pp$ collisions at 8 TeV in the **lepton+jets** channel with ATLAS: submitted to EPJC [arXiv:1612.02577]

5) Measurement of the **$t\bar{t}Z$ and $t\bar{t}W$ production cross sections** in multilepton final states using 3.2 fb$^{-1}$ of $pp$ collisions at 13 TeV at the LHC: [Eur. Phys. J. C (2017) 77: 40.]
Top Quark Spin Observables (1)

- 8 TeV, 20.2 fb\(^{-1}\), dilepton channel of \(\bar{t}t\) decays
- Top quark spin is correlated, strength quantified by quantisation axis and production process
- Spin information is transferred to decay products → use angular observables of decay products

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta^a_+ d \cos \theta^b_-} = \frac{1}{4} (1 + B^a_+ \cos \theta^a_+ + B^b_- \cos \theta^b_- - C(a, b) \cos \theta^a_+ \cos \theta^b_-)
\]

- \(B^a = 3 < \cos \theta^a >\) (6 polarisation coefficients)
- \(C(a, b) = -9 < \cos \theta^a_+ \cos \theta^b_- >\) (9 spin correlation coefficients)

10 measured for the first time!

k: helicity axis
n: transverse axis
r: r-axis

\(\bar{t}t\) rest frame

Nils-Arne Rosien
Top Quark Spin Observables (2)

- 2 different analyses:
  - parton level (full phase space)
  - stable particle level (fiducial space)
- $\bar{t}t$ reconstruction using neutrino weighting technique
- Fully Bayesian unfolding to deal with distortions due to cuts and detector resolution
- No significant deviation from SM
- Observation of $C(n,n)$ with 5.1σ
Charge Asymmetry in dilepton (1)

- 8 TeV, 20.3 fb$^{-1}$, dilepton channel of $t\bar{t}$ decays
- Asymmetries expected from valence quark – sea antiquark fusion → antitop more central than top

Leptonic asymmetries:

$$A_{\ell\ell}^C = \frac{N(|\Delta| > 0) - N(|\Delta| < 0)}{N(|\Delta| > 0) + N(|\Delta| < 0)}$$

$t\bar{t}$ asymmetries:

$$A_{t\bar{t}}^C = \frac{N(|\Delta| > 0) - N(|\Delta| < 0)}{N(|\Delta| > 0) + N(|\Delta| < 0)}$$

3 different measurements of both observables:
- inclusive measurements on parton level in the full phase space
- inclusive measurements on particle level in the fiducial region
- differential measurements:
  - inv. mass ($m_{t\bar{t}}$), $p_T$, and longitudinal boost ($P_z$) of $t\bar{t}$ system in the fiducial regions and the full phase space

Nils-Arne Rosien
Charge Asymmetry in dilepton (2)

- Kinematic reconstruction of $t\bar{t}$ system
- Fully Bayesean unfolding
- Result:
  \[ A_C^{\ell\ell} = 0.008 \pm 0.006 \]
  \[ A_C^{\ell\bar{\ell}} = 0.021 \pm 0.016 \]
- SM prediction:
  \[ A_C^{\ell\ell} = 0.0064 \pm 0.0003 \]
  \[ A_C^{\ell\bar{\ell}} = 0.0111 \pm 0.0004 \]
Charge and CP asymmetries in b-decay (1)

- 8 TeV, $\ell$+jets, $b$ decaying semileptonically to a soft muon
- 5 CP asymmetries, 2 charge asymmetries
- charge of lepton from $W$ determines the charge of the produced $b$-quark
- charge of soft lepton determines the charge of $b$-quark at decay

**Charge asymmetries**

$$A_{\text{ass}} = \frac{P(b \to \ell^+)-P(\bar{b} \to \ell^-)}{P(b \to \ell^+)+P(\bar{b} \to \ell^-)}$$

$$A_{\text{cos}} = \frac{P(b \to \ell^-)-P(\bar{b} \to \ell^+)}{P(b \to \ell^-)+P(\bar{b} \to \ell^+)}$$

**CP asymmetries: $B_q$-$\bar{B}_q$ mixing**

$$A_{\text{mix}}^{b\ell} = \frac{\Gamma(b \to \ell^+ X) - \Gamma(\bar{b} \to b \to \ell^- X)}{\Gamma(b \to \ell^+ X) + \Gamma(\bar{b} \to b \to \ell^- X)}$$

$$A_{\text{mix}}^{bc} = \frac{\Gamma(b \to \bar{b} \to \bar{c} X) - \Gamma(\bar{b} \to b \to cX)}{\Gamma(b \to \bar{b} \to \bar{c} X) + \Gamma(\bar{b} \to b \to cX)}$$

**CP asymmetries: direct CP violation**

$$A_{\text{dir}}^{b\ell} = \frac{\Gamma(b \to \ell^- X) - \Gamma(\bar{b} \to \ell^+ X)}{\Gamma(b \to \ell^- X) + \Gamma(\bar{b} \to \ell^+ X)}$$

$$A_{\text{dir}}^{bc} = \frac{\Gamma(b \to \bar{c} X_L) - \Gamma(\bar{b} \to c X_L)}{\Gamma(b \to \bar{c} X_L) + \Gamma(\bar{b} \to c X_L)}$$

Nils-Arne Rosienen
Charge and CP asymmetries in b-decay (2)

- Soft muon heavy flavour tagging (SMT muons)
- Data is unfolded to well defined fiducial space
- CP result cannot disprove DØ deviation in dimuon asymmetry
  → result both compatible with SM and DØ results

<table>
<thead>
<tr>
<th></th>
<th>Data ((10^{-2}))</th>
<th>MC ((10^{-2}))</th>
<th>Existing limits ((2\sigma) \quad (10^{-2}))</th>
<th>SM prediction ((10^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A^{ss})</td>
<td>(-0.7 \pm 0.8)</td>
<td>0.05 \pm 0.23</td>
<td>-</td>
<td>(&lt; 10^{-2}) [19]</td>
</tr>
<tr>
<td>(A^{os})</td>
<td>0.4 \pm 0.5</td>
<td>(-0.03 \pm 0.13)</td>
<td>-</td>
<td>(&lt; 10^{-2}) [19]</td>
</tr>
<tr>
<td>(A^{b}_{\text{mix}})</td>
<td>(-2.5 \pm 2.8)</td>
<td>0.2 \pm 0.7</td>
<td>(&lt; 0.1) [95]</td>
<td>(&lt; 10^{-3}) [96] [95]</td>
</tr>
<tr>
<td>(A^{b}_{\text{dir}})</td>
<td>0.5 \pm 0.5</td>
<td>(-0.03 \pm 0.14)</td>
<td>(&lt; 1.2) [94]</td>
<td>(&lt; 10^{-5}) [19] [94]</td>
</tr>
<tr>
<td>(A^{c\ell}_{\text{dir}})</td>
<td>1.0 \pm 1.0</td>
<td>(-0.06 \pm 0.25)</td>
<td>(&lt; 6.0) [94]</td>
<td>(&lt; 10^{-9}) [19] [94]</td>
</tr>
<tr>
<td>(A^{bc}_{\text{dir}})</td>
<td>(-1.0 \pm 1.1)</td>
<td>0.07 \pm 0.29</td>
<td>-</td>
<td>(&lt; 10^{-7}) [97]</td>
</tr>
</tbody>
</table>

First direct measurements of direct CP violation in this context, improve existing limits of indirect measurements
**W boson polarisation (1)**

- 8 TeV, lepton+jets channel, 20.2 fb\(^{-1}\)
- Most precise W boson polarisation measurement to date
- Use orientation of analyser wrt. the b quark (inv. direction) in the W rest frame of top decay

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

- Take both charged lepton or down-type quark from W decay as analyser
- 3 reweighted \(t\bar{t}\) samples for \(F_L, F_R, F_0 + \text{bkg. samples}\)
W boson polarisation (2)

- KLFitter $t\bar{t}$ reconstruction [Nucl. Instrum. Meth. A 748 (2014) 18–25]
- Perform template fit
- Best fits (=smallest uncertainty):
  - two channel combination (ejets+mujets, $\geq 2b$) for leptonic analyser
  - four channel combination (ejets+mujets, $=1b$ and $\geq 2b$) for hadronic analyser

<table>
<thead>
<tr>
<th>Leptonic analyser (≥2 $b$-tags)</th>
<th>Hadronic analyser (1 $b$-tag + ≥2 $b$-tags)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0 = 0.709 \pm 0.012$ (stat.+bkg. norm.) +0.015$^{+0.015}_{-0.014}$ (syst.)</td>
<td>$F_0 = 0.659 \pm 0.010$ (stat.+bkg. norm.) +0.052$^{+0.052}_{-0.054}$ (syst.)</td>
</tr>
<tr>
<td>$F_L = 0.299 \pm 0.008$ (stat.+bkg. norm.) +0.013$^{+0.013}_{-0.012}$ (syst.)</td>
<td>$F_L = 0.281 \pm 0.021$ (stat.+bkg. norm.) +0.063$^{+0.063}_{-0.067}$ (syst.)</td>
</tr>
<tr>
<td>$F_R = -0.008 \pm 0.006$ (stat.+bkg. norm.) ±0.012 (syst.)</td>
<td>$F_R = 0.061 \pm 0.022$ (stat.+bkg. norm.) +0.101$^{+0.101}_{-0.108}$ (syst.)</td>
</tr>
</tbody>
</table>
W boson polarisation (3)

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

- \( F_L, F_R, F_0 \) can constrain anomalous \( Wtb \) couplings

<table>
<thead>
<tr>
<th>Coupling</th>
<th>95% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_R )</td>
<td>[−0.24, 0.31]</td>
</tr>
<tr>
<td>( g_L )</td>
<td>[−0.14, 0.11]</td>
</tr>
<tr>
<td>( g_R )</td>
<td>[−0.02, 0.06], [0.74, 0.78]</td>
</tr>
</tbody>
</table>
ttZ and ttW cross sections (1)

- Access to the the third component of the weak isospin of the top quark (FSR)
- Access to anomalous ttZ Couplings
- Learn about electroweak symmetry breaking via interactions of $W$ and $Z$
- Indicator for strongly coupled Higgs sector, technicolour, heavy top partners
- Important background process for $t\bar{t}H$ (multilepton channel), SUSY (multilepton, stop pairs) and others
- Possibility to test PDFs via $t\bar{t}W$ because of ISR

\[ \mathcal{L}_{tt\bar{t}Z} \propto \bar{t} \gamma^\mu (c_V^t - c_A^t \gamma^5) t Z_\mu \]
\[ c_V^t = T_t^3 - 2Q_t \sin^2 \theta_W \]
\[ c_A^t = T_t^3 \]
**ttZ and ttW cross sections (2)**

- Separation into 3 different regions:
  1. 2 same sign muons ($2\muSS$) → sensitive to $\bar{t}tW$, dominant bkg: fake leptons
  2. $3\ell$ → sensitive to $\bar{t}tW$ and $ttZ$, dominant bkg: $WZ$ and fake leptons
  3. $4\ell$ → sensitive to $ttZ$, dominant bkg: $ZZ$ and fake leptons

- $2\muSS$ and the $3\ell$ channel: fakes are estimated using fully data driven matrix method

- $4\ell$ channel: fake estimation using FF method using shapes from MC
**ttZ and \( ttW \) cross sections (3)**

- Statistically limited
- First observation (>5σ) of this process for ATLAS (parallel to CMS at 8 TeV)

**1D fit result**

\[
\sigma_{ttW} = 1.5 \pm 0.8 \text{ pb} \\
\sigma_{ttZ} = 0.9 \pm 0.3 \text{ pb}
\]

**NLO QCD**

\[
\sigma_{tt\bar{W}} = 0.60 \pm 0.08 \text{ pb} \\
\sigma_{tt\bar{Z}} = 0.84 \pm 0.09 \text{ pb}
\]
Conclusion

• Top quark properties measurements at ATLAS in spin observables, charge and CP asymmetries, $W$ boson polarisation and $t\bar{t}V$ cross section
• Some spin observables measured for the first time
• $t\bar{t}V$ observed for the first time at 8 TeV (parallel to CMS)
• No disagreements with the SM
• More measurements using 13 TeV data are right around the corner
Thank you very much for your attention!