Top quark properties and mass measurements with the ATLAS detector

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on behalf of the ATLAS collaboration
Motivations

- Top quark physics is now in the “precision era” thanks to the huge top quark samples collected at the LHC (production rate ~ 10 Hz at peak luminosity)
- The top quark decays before hadronization ($\tau_{\text{dec}} \sim 10^{-25}$ s, $\tau_{\text{had}} \sim 10^{-24}$ s) giving the possibility to study a “bare” quark
- Precision measurements of top properties sensitive to possible new physics effects
Top quark pair signatures

Hadronic top

Leptonic top

Jet (b-tag)

Jet (b-tag)

Jet

Jet

Lepton

$W^+$

$W^-$

$\mu^+$

$\nu$

$E_T^{\text{miss}}$

Branching fractions for $t\bar{t}$ events

- Full hadronic (45%)
- Di-lepton (10%)
- $\tau+$jets (15%)
- $\mu+$jets (15%)
- $e+$jets (15%)

M. Negrini - QCD 17 Montpellier - 3-7 July 2017
Overview: event selection strategies

**Dilepton**
- two isolated leptons
  - jets ($\geq 2$)
- $m_\ll$ cuts to suppress quarkonia and $Z$
- missing $E_T$
- b-tagging
- kinematic assumptions for top reconstruction

**Lepton+jets**
- one isolated lepton
  - jets ($\geq 4$)
  - missing $E_T$
  - b-tagging
  - kinematic fit

**All-hadronic**
- jets ($\geq 6$)
- no missing $E_T$
- b-tagging
- top reconstructed testing possible jet combinations ($\chi^2$ minimization)

**Main backgrounds**
- $Z/\gamma +$ jets
- diboson
- single top

**Main backgrounds**
- $W+$jets
  - multijet QCD
  - single top

**Main background**
- multi-jet QCD
Top quark spin observables in $t\bar{t}$ events

- Top quarks are mostly unpolarised in the SM but $t\bar{t}$ spins are correlated
  - Top quarks decay before spin decorrelation
- New physics phenomena can modify the polarization and spin correlation wrt SM predictions because of a different $t\bar{t}$ production mechanism

- Measure angles between the lepton and 3 spin quantization axes:
  - Helicity axis $k$: top quark direction in $t\bar{t}$ rest frame
  - Transverse axis $n$: transverse to production plane
  - $r$ axis: orthogonal to $k$ and $n$

- Measurements corrected at stable-particle (fiducial phase-space) or at parton (full phase-space) levels

$\sqrt{s}=8$ TeV - 20 fb$^{-1}$ - dilepton

JHEP 03 (2017) 113
Angular observables

Normalized double-differential cross-section:

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

6 angles defined: \( a/b \rightarrow k,n,r \) axes; \(+/- \rightarrow t/\bar{t}\)

\( B^a = 3 \) <cos \( \theta^a \) > : 6 polarization coefficients

\( C(a,b) = -9 \) <cos \( \theta^a_+ \cos \theta^b_- \) > : 9 spin correlation coefficients
Polarization and spin correlation coefficients

Results at parton-level in agreement with SM prediction computed at NLO in QCD

\[ \text{JHEP 03 (2017) 113} \]

\[ \text{JHEP 12 (2015) 026} \]

Contributions to the systematic uncertainty:
- Detector modeling: \( \sim 20\% \) of the total uncertainty
- Background modeling: negligible
- \( \bar{t}t \) signal modeling: \( \sim 80\% \) of the total uncertainty
  - MC generator, parton shower and hadronization, ISR/FSR, color reconnection and underlying event
W-boson polarization in $t\bar{t}$ events

- Three W boson helicity fractions $F_i$ ($i = 0, L, R$) for longitudinal, left- and right-handed

- Kinematic likelihood fit with extension to discriminate up/down quark types in W hadronic decay, based on b-tagging (60% correct matching)

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

$F_0 = 0.687 \pm 0.005$

$F_L = 0.311 \pm 0.005$

$F_R = 0.0017 \pm 0.0001$

$\theta^*$: Angle between the reversed direction of flight of the b-quark and the lepton or d-type quark in the W rest frame

Fit of the $\cos \theta^*$ distributions using templates
Extraction of W helicity fractions from \( \cos \theta^* \)

- Leptonic side is the most sensitive to helicity fractions
- Hadronic side has worse separation power and is affected by larger systematic uncertainties

**Dominant uncertainties in the leptonic side**
- Jet energy scale and resolution
- Statistical uncertainty in MC templates

**Results:**
- \( F_0 = 0.709 \pm 0.019 \)
- \( F_L = 0.299 \pm 0.015 \)
- \( F_R = -0.008 \pm 0.014 \)
Wtb vertex anomalous couplings

Reinterpretation of the W helicity fractions measurements in terms of anomalous couplings of the Wtb vertex:

- $V_{L/R}$: left- and right-handed vector couplings
- $g_{L/R}$: left- and right-handed tensor couplings

all vanish in the SM, except $V_L = V_{tb}$

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} b \gamma^\mu (V_LP_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} b \frac{i\sigma^{\mu\nu} q_\nu}{m_W} (g_LP_L + g_R P_R) t W^-_\mu + \text{h. c.}$$

### W helicity fractions

<table>
<thead>
<tr>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ATLAS+CMS Preliminary LHCtopWG May 2017</strong></td>
</tr>
</tbody>
</table>

- **Theory (NNLO QCD)**
  
  PRD 81 (2010) 111503 (R)

- **Data (F_R/F_L/F_0)**

#### ATLAS

- **2010 single lepton, \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 35 \text{ pb}^{-1} \)**
  - ATLAS-CONF-2011-037

- **2011 single lepton and dilepton, \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 1.04 \text{ fb}^{-1} \)**
  - JHEP 1206 (2012) 088

- **2011 single lepton, \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 2.2 \text{ fb}^{-1} \)***
  - CMS-PAS-TOP-11-020

- **2012 single lepton, \( \sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 20.2 \text{ fb}^{-1} \)**
  - EPJC 77 (2017) 264

#### CMS

- **2011 single lepton, \( \sqrt{s} = 7 \text{ TeV}, L_{\text{int}} = 5.0 \text{ fb}^{-1} \)**
  - JHEP 10 (2013) 167

- **2012 single top, \( \sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 19.7 \text{ fb}^{-1} \)**
  - JHEP 01 (2015) 053

- **2012 single lepton, \( \sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 19.8 \text{ fb}^{-1} \)**
  - PLB 762 (2016) 512

- **2012 dilepton, \( \sqrt{s} = 8 \text{ TeV}, L_{\text{int}} = 19.7 \text{ fb}^{-1} \)**
  - CMS-PAS-TOP-14-017

* superseded by published result
Measurements of $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ are important checks of the SM.

New physics mechanisms could alter the $t\bar{t}+W/Z$ production cross sections.

3 channels defined based on the number of leptons: di-muon same sign (2$\mu$-SS), tri-lepton (3L), four-lepton (4L).

Main background contributions from di-boson production and fake leptons, checked in control regions.
**t\bar{t} production in association with a W/Z boson**

Simultaneous fit of 9 signal and 2 control regions to extract $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$

- **2\mu-SS** region particularly sensitive to $t\bar{t}W$
- **3L-noZ-2b** region sensitive to both $t\bar{t}W$ and $t\bar{t}Z$
- all other regions to determine $t\bar{t}Z$

Results:

$\sigma_{t\bar{t}Z} = 0.92 \pm 0.29 \pm 0.10$ pb (uncertainty: 32%)

$\sigma_{t\bar{t}W} = 1.50 \pm 0.72 \pm 0.33$ pb (uncertainty: 53%)

Measurements limited by statistical uncertainty, expected to significantly improve with the analysis of the full dataset (36 fb$^{-1}$ available)

**NLO predictions:** (JHEP 06 (2015) 084)

- $\sigma_{t\bar{t}Z} = 0.84 \pm 0.09$ pb
- $\sigma_{t\bar{t}W} = 0.60 \pm 0.08$ pb
Probe the $t\bar{t}\gamma$ electroweak coupling

Anomalies in the $\gamma p_T$ spectrum could point to new physics effects (anomalous dipole moments of the top quark)

Require an additional isolated $\gamma$ with $p_T > 15$ GeV

Signal/background discrimination based on $p_T^{\text{iso}}$
- $p_T^{\text{iso}}$: sum of the $p_T$ of all tracks in a cone around the $\gamma$ with opening angle 0.2 rad

$\sqrt{s} = 8$ TeV - 20 fb$^{-1}$ - $l+jets$

$\sigma_{tt\gamma}^{\text{fid}} = 139 \pm 7 \pm 17$ fb (uncertainty: 13%) in agreement with NLO predictions: $151 \pm 24$ fb

Main systematic uncertainties:
- shapes of templates for fake hadrons and e/$\gamma$ mis-id (6.3% each)
- JES (4.9%)
Agreement with NLO predictions observed also for differential cross sections
Top quark mass

- Is a fundamental parameter of the SM
- Precision measurements needed to check internal consistency of the SM
- Top, Higgs and W masses are related through radiative corrections

arXiv:1407.3792
Top quark mass: recent ATLAS measurements

Two recent measurements using the template technique:
2) all-hadronic channel : arXiv:1702.07546

$m_{lb}^{reco}$ : reconstructed lepton-$b$-jet invariant mass

$R_{3/2}$ : ratio of 3-jets to 2-jets (W candidate) masses

$\sqrt{s}=8$ TeV - 20 fb$^{-1}$
Top quark mass: recent ATLAS measurements

**Dilepton**


Negligible background contribution

Main uncertainties: JES (0.54 GeV), b-jet JES (0.30 GeV), hadronization and IFSR modeling (0.22 GeV and 0.23 GeV)

\[ m_t = 172.99 \pm 0.41 \pm 0.74 \text{ GeV} \]

(0.49% uncertainty)

**All-hadronic**

- arXiv:1702.07546

Fit of \( R_{3/2} \) using templates for signal and multi-jet background (derived from control regions)

Main uncertainties: JES (0.60 GeV), b-jet JES (0.34 GeV), hadronization and IFSR modeling (0.22 GeV and 0.23 GeV)

\[ m_t = 173.72 \pm 0.55 \pm 1.01 \text{ GeV} \]

(0.66% uncertainty)

Possible reduction of systematic uncertainties profiting from the large samples that will be collected in Run2
# Top quark mass - ATLAS summary

![ATLAS+CMS Preliminary LHCtopWG m_{top} summary, \sqrt{s} = 7-8 TeV May 2017](image)

<table>
<thead>
<tr>
<th>Source</th>
<th>m_{top} [GeV]</th>
<th>\sqrt{s} [TeV]</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, l+jets (*)</td>
<td>172.31 ± 1.55 (0.75 ± 1.35)</td>
<td>7 TeV [1]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>173.09 ± 1.63 (0.64 ± 1.50)</td>
<td>7 TeV [2]</td>
<td></td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td>173.49 ± 1.06 (0.43 ± 0.97)</td>
<td>7 TeV [3]</td>
<td></td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.50 ± 1.52 (0.43 ± 1.46)</td>
<td>7 TeV [4]</td>
<td></td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>173.49 ± 1.41 (0.69 ± 1.23)</td>
<td>7 TeV [5]</td>
<td></td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>173.29 ± 0.95 (0.35 ± 0.88)</td>
<td>7 TeV [6]</td>
<td></td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>173.34 ± 0.76 (0.36 ± 0.67)</td>
<td>1.96-7 TeV [7]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, l+jets</td>
<td>172.33 ± 1.27 (0.75 ± 1.02)</td>
<td>7 TeV [8]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>173.79 ± 1.41 (0.54 ± 1.30)</td>
<td>7 TeV [9]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>175.1 ± 1.8 (1.4 ± 1.2)</td>
<td>7 TeV [9]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, single top</td>
<td>172.2 ± 2.1 (0.7 ± 2.0)</td>
<td>8 TeV [10]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, dilepton</td>
<td>172.99 ± 0.85 (0.41 ± 0.74)</td>
<td>8 TeV [11]</td>
<td></td>
</tr>
<tr>
<td>ATLAS, all jets</td>
<td>173.72 ± 1.15 (0.55 ± 1.01)</td>
<td>8 TeV [12]</td>
<td></td>
</tr>
<tr>
<td>ATLAS comb. (June 2016)</td>
<td>172.84 ± 0.70 (0.34 ± 0.61)</td>
<td>7+8 TeV [11]</td>
<td></td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td>172.35 ± 0.51 (0.16 ± 0.48)</td>
<td>8 TeV [13]</td>
<td></td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.82 ± 1.23 (0.19 ± 1.22)</td>
<td>8 TeV [13]</td>
<td></td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>172.32 ± 0.64 (0.25 ± 0.59)</td>
<td>8 TeV [13]</td>
<td></td>
</tr>
<tr>
<td>CMS, single top</td>
<td>172.95 ± 1.22 (0.77 ± 0.95)</td>
<td>8 TeV [14]</td>
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<tr>
<td>CMS comb. (Sep 2015)</td>
<td>172.44 ± 0.48 (0.13 ± 0.47)</td>
<td>7+8 TeV [13]</td>
<td></td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line.
Summary

• The top quark provides the unique opportunity to study a “bare” quark

• Its mass is a fundamental parameter of the SM and can be measured at the sub-GeV level
  – Aiming at total uncertainty ~200-300 MeV at the end of Run2

• Precision tests of the properties of the top quark are needed to test the SM, improve the modeling of $t\bar{t}$ events, and may reveal physics effects beyond the SM

• LHC Run1 and first round of Run2 measurements in agreement with SM predictions

• With a large increase of the available samples, that can also be exploited to reduce systematic uncertainties, LHC Run2 offers unprecedented possibilities in top quark physics
Thank you!
References

- Top quark spin observables in $t\bar{t}$ events: JHEP 03 (2017) 113
- $W$ boson polarization in $t\bar{t}$ events: Eur. Phys. J. C 77 (2017) 264
- $t\bar{t}+W/Z$ associated production: Eur. Phys. J. C 77 (2017) 40
- $t\bar{t}+\gamma$ associated production: arXiv:1706.03046
- $m_t$ measurement in the dilepton channel: Phys. Lett. B 761 (2016) 350
- $m_t$ measurement in the all-hadronic channel: arXiv:1702.07546

- ATLAS results in top physics: link
Polarization and spin correlation coefficients

Results at parton-level in agreement with SM prediction computed at NLO in QCD

\[ \text{JHEP 12 (2015) 026} \]

\[ \text{JHEP 03 (2017) 113} \]

\[ \text{ATLAS} \quad s = 8 \text{ TeV} - 20.2 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Polarisation</th>
<th>JHEP 12 (2015) 026</th>
<th>Result ± (stat+det) ± (mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_x^t )</td>
<td></td>
<td>-0.044 ± (0.027) ± (0.026)</td>
</tr>
<tr>
<td>( B_t^c )</td>
<td></td>
<td>-0.064 ± (0.030) ± (0.023)</td>
</tr>
<tr>
<td>( B_x^c )</td>
<td></td>
<td>-0.018 ± (0.023) ± (0.024)</td>
</tr>
<tr>
<td>( B_t^p )</td>
<td></td>
<td>0.023 ± (0.024) ± (0.034)</td>
</tr>
<tr>
<td>( B_x^p )</td>
<td></td>
<td>0.039 ± (0.030) ± (0.029)</td>
</tr>
<tr>
<td>( B_t^q )</td>
<td></td>
<td>0.033 ± (0.029) ± (0.045)</td>
</tr>
</tbody>
</table>

\[ \text{Spin correlations} \quad s = 8 \text{ TeV} - 20.2 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>JHEP 12 (2015) 026</th>
<th>Result ± (stat+det) ± (mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C(k,k) )</td>
<td></td>
<td>0.296 ± (0.072) ± (0.057)</td>
</tr>
<tr>
<td>( C(n,n) )</td>
<td></td>
<td>0.304 ± (0.038) ± (0.047)</td>
</tr>
<tr>
<td>( C(r,r) )</td>
<td></td>
<td>0.086 ± (0.075) ± (0.122)</td>
</tr>
</tbody>
</table>

\[ \text{Cross correlations} \quad s = 8 \text{ TeV} - 20.2 \text{ fb}^{-1} \]

<table>
<thead>
<tr>
<th>Correlation</th>
<th>JHEP 12 (2015) 026</th>
<th>Result ± (stat+det) ± (mod)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C(n,k)+C(k,n) )</td>
<td></td>
<td>-0.012 ± (0.089) ± (0.067)</td>
</tr>
<tr>
<td>( C(n,k)-C(k,n) )</td>
<td></td>
<td>-0.040 ± (0.065) ± (0.056)</td>
</tr>
<tr>
<td>( C(n,r)+C(r,n) )</td>
<td></td>
<td>0.117 ± (0.082) ± (0.102)</td>
</tr>
<tr>
<td>( C(n,r)-C(r,n) )</td>
<td></td>
<td>-0.006 ± (0.082) ± (0.070)</td>
</tr>
<tr>
<td>( C(r,k)+C(k,r) )</td>
<td></td>
<td>-0.261 ± (0.112) ± (0.135)</td>
</tr>
<tr>
<td>( C(r,k)-C(k,r) )</td>
<td></td>
<td>0.073 ± (0.122) ± (0.148)</td>
</tr>
</tbody>
</table>