Highlights of top-quark measurements in hadronic final states at ATLAS

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XLVII International Symposium on Multiparticle Dynamics
Tlaxcala, Mexico
September 12, 2017
Physics motivations

Top-quark pair production mechanisms and decays

Recent measurements:

**Top-quark inclusive cross section**
- Measurements of the $t\bar{t}$ production cross-section in the $\tau +$ jets channel at $\sqrt{s} = 7$ TeV \[\text{Eur.Phys.J.C(2013)73:2328}\]
- Measurements of the $t\bar{t}$ production cross-section with hadronically decaying $\tau$ lepton at $\sqrt{s} = 8$ TeV \[\text{Phys. Rev. D 95, 072003 (2017)}\]
- Measurements of the $t\bar{t}$ production cross-section with the $\tau +$ lepton at $\sqrt{s} = 7$ TeV \[\text{CERN-PH-EP-2012-102}\]
- Measurements of the $t\bar{t}$ production cross-section in the all-hadronic channel at $\sqrt{s} = 7$ TeV \[\text{ATLAS-CONF-2012-031}\]

**Top-quark differential cross-sections**
- Measurements of the $t\bar{t}$ differential cross-sections in the all-hadronic channel at $\sqrt{s} = 13$ TeV \[\text{ATLAS-CONF-2016-100}\]

Summary
Physics motivations

Why top-quark physics?

✈️ It is the heaviest elementary particle known;

\[ m_t = 173.34 \pm 0.27 \text{(stat)} \pm 0.71 \text{(syst)} \text{ GeV} \]

✈️ its large mass is a fundamental parameter in the Standard Model ⇒ highest coupling to the Higgs boson;

✈️ due its very short lifetime, the top-quark decays before hadronizing:

\[ t \rightarrow Wb \sim 10^{-24} \text{s vs hadronization } \sim 10^{-23} \text{s} \] ⇒ allows to study the properties of a bare quark;

✈️ its cross-section is large

♦ \( \sim 15 \text{ } t\bar{t} \text{ pairs/min}, \sim 5 \text{ milions } t\bar{t} \text{ at 8 TeV with } 20fb^{-1} \)

♦ \( \sim 500 \text{ } t\bar{t} \text{ pairs/min}, \sim 30 \text{ milions } t\bar{t} \text{ at 13 TeV with } 36fb^{-1} \)
Top-quark pair production

- Top-quark pairs production via strong interactions;
- the LO dominant process at $\sqrt{s} = 13$ TeV at LHC is the gluon-gluon fusion;

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gluon-gluon fusion $\sim 87\%$
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q\bar{q} \text{ annihilation } \sim 13\%
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Why top pair studies?
- Stringent tests of pQCD;
- high sensitivity to gluon PDF;
- important background to Higgs and BSM processes;
- improvement in MC generators of the $t\bar{t}$ samples.
Top pair decay

- In the Standard Model, top quarks decay to $Wb$ about 99.8% of the time;

- decay signatures are categorized according to the decay of the two $W$’s, semi-leptonically or hadronically:
  - **All-hadronic**: both $W$’s decay via $W \rightarrow qq$ (46%);
  - **$\ell+Jets$**: one $W$ decays via $W \rightarrow \ell\nu$ (30%);
  - **dilepton**: both $W$’s decay via $W \rightarrow \ell\nu$ (4%).
Inclusive measurements \( \tau + \text{jets} \)

**\( \tau + \text{jets} \) cross-section in the \( \tau + \text{jets} \) channel**

\[
\begin{align*}
\tau + \text{jets} &: \sqrt{s} = 7\text{ TeV} \quad \mathcal{L} = 1.67\text{ fb}^{-1} \quad \text{Eur.Phys.J.C(2013)73:2328} \\
\tau + \text{jets} &: \sqrt{s} = 8\text{ TeV} \quad \mathcal{L} = 20.2\text{ fb}^{-1} \quad \text{arXiv:1702.08839v2}
\end{align*}
\]

- Final state with a **hadronically decaying** \( \tau \) lepton and jets;
- such an event topology correspond to \( \sim 10\% \) of \( t\bar{t} \) decays;
- this measurement is particularly important for charged Higgs boson production in top-quark decays
  - the existence of a \( H^{\pm} \) would lead to an enhancement in the cross-section for the considered \( t\bar{t} \) final state.
$t\bar{t}$ cross-section in the $\tau +$ jets channel at $\sqrt{s} = 7$ TeV
**Inclusive measurements**  

**τ +jet \( \sqrt{s} = 7 \) TeV: Event selection & τ decays**

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**Event selection**

- Require at least 5 jets with \( p_T > 20 \) GeV and \( |\eta| < 2.5 \):
  - 2 jets having originated from \( b - quark \);
  - 2 jets from the hadronic decay of one of the top quarks;
  - 1 \( \tau_{had} \) candidate (\( p_T > 40 \) GeV) from the other top-quark.

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**τ decays**

- Hadronically decaying τ in:
  - 1 or 3 charged hadrons in the final state charged hadrons (+ other neutrals);
Inclusive measurements $\tau + \text{jets}$

$\tau + \text{jet} \sqrt{s} = 7 \text{ TeV}: \text{Data analysis}$

- Charged hadrons in the final state can be reconstructed as charged particle tracks in the inner-detector;
- number of tracks ($n_{\text{tracks}}$) associated to a $\tau_{\text{had}}$ used to separate $\tau_{\text{had}}$ contribution from misidentified jet background;
- Signal extraction from the $n_{\text{track}}$ distribution $\Rightarrow$ data sample fitted with 3 probability density functions (templates).

![Graph showing $n_{\text{track}}$ distribution](image)

- **tau/electron template** (simulated $t\bar{t}$ events);
- **gluon-jet template** (Jet fakes from QCD multijet);
- **quark-jet template** (Jet fakes from $t\bar{t}$, $W+$jets, single-top-quark).
$\tau + \text{jet } \sqrt{s} = 7 \text{ TeV}: \text{ Fit results}$

- Binned-likelihood fit to $n_{\text{tracks}}$ distribution with three templates.

\[
\sigma_{t\bar{t}} = \frac{N_T}{L \cdot \epsilon} \Rightarrow \sigma_{t\bar{t}} = 194 \pm 18 \text{ (stat.)} \pm 46 \text{ (syst.) pb}
\]

Leading uncertainties:
- QCD (ISR/FSR) (15%);
- event generator (11%).

Total systematic uncertainty on the cross-section is 24%.
$t\bar{t}$ cross-section in the $\tau +$ jets channel at $\sqrt{s} = 8$ TeV
Inclusive measurements \( \tau + \text{jets} \)

\( \tau + \text{jet} \sqrt{s} = 8 \text{ TeV}: \) Reconstructed object selection

**Event selection**

- Require 4 jets:
  - \( \geq 2 \) jets with \( E_T > 25 \text{GeV} \) and \( |\eta| < 2.5 \);
  - \( 2 \) jets having originated from \( b - \text{quark} \), b-tagging efficiency \( 70\% \);
- \( 1 \) \( \tau_{\text{had}} \) candidate (\( E_T > 20 \text{GeV} \) and \( |\eta| < 2.5 \)) \( \Rightarrow \) decays into 1 or 3 charged particles:
  - single prong (\( \tau_{1-prong} \)) \( \Rightarrow \) decays to a single charged particle;
  - three prong (\( \tau_{3-prong} \)) \( \Rightarrow \) decays to a 3 charged particle.

**Background estimation**

- Events where the \( \tau_{\text{had}} \) in the final state is real;
- includes single top, W/Z+jets, diboson.

- Events where the \( \tau \) lepton in the final state is fake (misidentified);
- dominated by multi-jet processes.
Cross-section extraction for each $\tau_{\text{had}}$ and then combined:

$$\sigma_{t\bar{t}} = 239 \pm 4(\text{stat.}) \pm 28(\text{syst}) \pm 5(\text{lumi})\text{pb}$$

Data prediction agreement in the signal region;

total uncertainty 12%, agreement with the SM prediction.
$t\bar{t}$ cross-section in the $\tau +$ lepton channel at $\sqrt{s} = 7$ TeV

Phys. Lett. B717 (2012) 89-108
Inclusive measurements \( t\bar{t} \) cross-section in the \( \tau + \text{lepton} \) channel with \( \sqrt{s} = 7 \text{ TeV} \)

\[ \tau + \text{lepton} : \, \sqrt{s} = 7 \text{ TeV} \, \mathcal{L} = 2.05 \text{fb}^{-1} \]

- Final states with an electron or a muon and a hadronically decaying \( \tau \) lepton;
- Searches for top-quark decays to b-quarks + charged Higgs, decaying to \( \tau + \) neutrino.

**Event Selection**

- A primary vertex with \( \geq 5 \) tracks (each with \( p_T > 4 \text{GeV} \));
- \( \geq 1 \) \( \tau \) candidate;
- One isolated high-\( p_T \) \( \mu \) or \( e \);
- \( \geq 2 \) jets with \( p_T > 25 \text{ GeV} \) and \( |\eta| < 2.5 \);
- \( E_T^{\text{miss}} > 30 \text{GeV} \) to reduce the multi-jet background.
Signal extraction

- discriminants employed which outputs are used to separate hadronic tau from jets;
  - use **boosted decision tree** (BDT) discriminants.
- Same sign (SS) and opposite sign (OS) $BDT_j$ distributions.

**Background methods**

- Fit BDT shape with background and signal template (template fitting).
- Matrix method to extract background after a cut on BDT $> 0.7$.

|          | Background template 0 b-tag | W + 1 jet | MC | Signal | $\bar{\nu}$ |
|----------|-----------------------------|-----------|----|--------|-------------|
| $\mu + \tau$ |
| $\tau_1$   | 490 ± 40                    | 456 ± 32  | 432 | 388    |             |
| $\tau_3$   | 135 ± 33                    | 130 ± 50  | 126 | 116    |             |
| $e + \tau$ |
| $\tau_1$   | 440 ± 50                    | 430 ± 50  | 388 | 338    |             |
| $\tau_3$   | 116 ± 32                    | 120 ± 28  | 114 | 101    |             |
| Combined   |
| $\tau_1$   | 930 ± 70                    | 860 ± 50  | 820 | 726    |             |
| $\tau_3$   | 260 ± 60                    | 260 ± 40  | 239 | 217    |             |

|          | Background template 0 b-tag | W + 1 jet |
|----------|-----------------------------|-----------|
| $\mu + \tau$ |
| $\tau_1$   | 460 ± 50                    | 440 ± 50  |
| $\tau_3$   | 130 ± 40                    | 105 ± 35  |
| $e + \tau$ |
| $\tau_1$   | 420 ± 60                    | 350 ± 50  |
| $\tau_3$   | 140 ± 40                    | 160 ± 40  |
| Combined   |
| $\tau_1$   | 880 ± 70                    | 800 ± 70  |
| $\tau_3$   | 270 ± 60                    | 260 ± 60  |

Good agreement with the numbers obtained by the two methods.
Measuring the $t\bar{t}$ cross-section

- The cross-section is derived from the number of observed OS–SS signal events in the $\geq 1$ b-tag data sample;
- the results are given separately for $\tau_1$ (one track candidate) and $\tau_3$ (> one tracks candidate) and then combined.

$$\sigma_{t\bar{t}} = 186 \pm 13\,(\text{stat.}) \pm 20\,(\text{syst.}) \pm 7\,(\text{lumi})\,\text{pb}$$
$t\bar{t}$ cross-section in the all-hadronic channel at $\sqrt{s} = 7 \text{ TeV}$
$t\bar{t}$ cross-section in the all-hadronic channel with $\sqrt{s} = 7 \, \text{TeV}$

all-hadronic channel : $\sqrt{s} = 7 \, \text{TeV}$ $\mathcal{L} = 4.7 \, \text{fb}^{-1}$

- Final state with both $W$’s decaying hadronically, six jets topology;
- such an event topology correspond to $\sim 46\%$ of $t\bar{t}$ decays, large BR but large multi-jet background;
- important test of pQCD, major background to many new physics scenarios.
Event Selection

Event selection

⇒ ≥ 1 reconstructed primary vertex with 5 or more associated tracks;
⇒ all jets reconstructed with $|JVF| < 0.75$;
  ♦ ≥ 5 jets with $p_T > 55\text{GeV}$ and $|\eta| < 2.5$;
  ♦ ≥ 1 additional jet with $p_T > 30\text{GeV}$ and $|\eta| < 2.5$;
  ♦ ≥ 2 of the jets should be b-tagged and have $p_T > 55\text{GeV}$ and $|\eta| < 2.5$.

Systematic uncertainties

| Source of uncertainty                  | Contribution (%) |
|----------------------------------------|------------------|
| Jet energy scale (JES)                 | +20/−11 |
| b-tagging                              | ± 17 |
| ISR, FSR                               | ± 17 |
| Parton shower and Hadronisation        | ± 13 |
| Multi-jet trigger                      | ± 10 |
| Generator                              | ± 7 |
| PDF                                    | +7/−4 |
| Pile-up                                | +5/−7 |
| Background model                       | ± 4 |
| Luminosity                             | ± 4 |
| Jet energy resolution                  | ± 3 |
| Jet reconstruction efficiency          | < 1 |
| Total                                  | +36/−34 |

Dominant systematics

JES, b-tagging, ISR, FSR
Kinematic fit and cross-section extraction

- Kinematic fit performed to compute the top-quark mass ($m_{t\bar{t}}$) reconstruction of $t\bar{t}$ events;
- Kinematic fit based on a likelihood approach to find the correct association of jets with the final-state partons of the all-hadronic channel;
- $m_t$ used to perform an unbinned likelihood fit and extract the cross-section;
- Measured cross-section compatible with the SM prediction.

$$\sigma_{t\bar{t}} = 168 \pm 12\,(\text{stat.})^{60}_{-57}\,(\text{syst.}) \pm 7\,(\text{lumi})\text{pb}$$
$t\bar{t}$ differential cross-section in the all-hadronic channel at $\sqrt{s} = 13$ TeV
$t\bar{t}$ differential cross-section in the all-hadronic channel with $\sqrt{s} = 13\,\text{TeV}$

all-hadronic channel: $\sqrt{s} = 13\,\text{TeV}$ $\mathcal{L} = 14.7\,\text{fb}^{-1}$

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- Boosted all-hadronic $t\bar{t}$ decay mode $\Rightarrow$ only top-quark candidates with high $p_T$ selected;
- detailed studies of high-$p_T$ SM processes;
- searches of anomalies that could be signals for new physics.
Event selection

- Primary vertex with five or more charged tracks;
- No reconstructed electron/µon with $p_T > 25$ GeV;
- At least 2 large-R jets with $p_T > 350$ GeV and $|\eta| < 2.0 \Rightarrow$ leading jet $p_T > 500$ GeV;
- $\geq 2$ small-R jets with $p_T > 25$ GeV and $|\eta| < 2.5$;
- $\geq 2$ small-R b-tagged jets $\Rightarrow$ each associated with just one of the top-tagged large-R jets;

|            | $t\bar{t}$ (all-hadronic) | $t\bar{t}$ (non all-hadronic) | Single top quark | Multijet events | Prediction | Data (14.7 fb$^{-1}$) |
|------------|-----------------------------|--------------------------------|-----------------|----------------|-----------|-------------------|
| 0 $t$      | 1190 $\pm$ 240             | 60 $\pm$ 15                    | 9 $\pm$ 5       | 300 $\pm$ 20   | 1570 $\pm$ 260 | 1512            |

Large background $\Rightarrow$ multi-jet events $S_{bg} = \frac{1}{2}(\frac{G}{A} + \frac{H}{B}) \times C$

S: signal region;
G,A,H,B: regions multi-jet dominated;
Fiducial phase-space differential cross-section

Variables: $p_{T}^{1,1}, p_{T}^{1,2}, |y^{1,1}, |y^{1,2}, p_{T}^{t\bar{t}}, m^{t\bar{t}}, |y^{t\bar{t}}, \cos \theta \ast, |H_{T}^{t\bar{t}}, y_{B}^{t\bar{t}}, \Delta \phi(t_{1}, t_{2}), \chi^{t\bar{t}}, |p_{out}^{t\bar{t}}$

Hadronic top-quark variables

Dominant uncertainties: Large R-jets, signal modelling, b-tagging
Fiducial phase-space differential cross-section

**tt system variables**

| Dominant uncertainties |
|-------------------------|
| Large R-jets            |
| signal modelling        |
| b-tagging               |

\[ \sigma_{\text{fid}} = 374 \pm 13 \text{ (stat.)}^{+111}_{-92} \text{ (syst.) fb} \]
Conclusions

- Results agree well with latest SM theory predictions;
- ATLAS is testing the SM at high precision with cross section measurements;
- shown a small set of the Top-quark ATLAS results;
- full set of top-quark measurements available at: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults.

All the measurements will benefit with the incoming data allowing to do more precision measurements.

Thank you for the attention!
BACKUP
$\tau + \text{jets } \sqrt{s} = 7 \text{ TeV}: \text{systematics uncertainties}$

| Source of uncertainty                      | Relative uncertainty |
|--------------------------------------------|----------------------|
| ISR/FSR                                    | 15%                  |
| Event generator                            | 11%                  |
| Hadronisation model                        | 6%                   |
| PDFs                                       | 2%                   |
| Pile-up                                    | 1%                   |
| $b$-jet tagging efficiency                 | 9%                   |
| Jet energy scale                           | 5%                   |
| $E_T^{\text{miss}}$ significance mismodelling | 5%               |
| $b$-jet trigger efficiency                 | 3%                   |
| Jet energy resolution                      | 2%                   |
| Fit systematic uncertainties               | 4%                   |
| Luminosity                                 | 4%                   |
| **Total uncertainty**                      | **24%**              |
$\tau + \text{jets}$ $\sqrt{s} = 8\text{ TeV}$: number of events yield

| Event counts          | $\tau_{1\text{-prong}}$ | $\tau_{3\text{-prong}}$ | $\tau_{\text{had}}$ |
|----------------------|--------------------------|--------------------------|----------------------|
| $t\bar{t} \rightarrow e/\mu + \text{jets}$ | $21.8 \pm 4.7$           | $6.8 \pm 2.5$            | $28.3 \pm 5.3$       |
| Single top           | $107 \pm 10$             | $33.9 \pm 5.8$           | $141 \pm 12$         |
| $W + \text{jets}$    | $71.7 \pm 8.5$           | $27.1 \pm 5.2$           | $99 \pm 10$          |
| $Z + \text{jets}$    | $7.2 \pm 2.7$            | $1.6 \pm 1.3$            | $8.7 \pm 3.0$        |
| Diboson              | $1.0 \pm 1.0$            | $0.4 \pm 0.6$            | $1.5 \pm 1.2$        |
| Misidentified-$\tau_{\text{had}}$ | $46.6 \pm 6.8$           | $24.9 \pm 5.0$           | $74.9 \pm 8.7$       |
| Expected $t\bar{t} \rightarrow \tau + \text{jets}$ | $1084 \pm 33$            | $312 \pm 18$             | $1398 \pm 37$        |
| Total Expected       | $1339 \pm 37$            | $407 \pm 20$             | $1751 \pm 42$        |
| Data                 | $1278$                   | $395$                    | $1678$               |
### \( \tau + \text{jets} \sqrt{s} = 8 \text{ TeV}: \text{systematic uncertainties} \)

| Uncertainty                        | \( \tau_{1\text{-prong}} \) | \( \tau_{3\text{-prong}} \) | \( \tau_{\text{had}} \) |
|------------------------------------|------------------------------|------------------------------|--------------------------|
| Total Systematic                   | -11/+11                      | -16/+14                      | -12/+12                  |
| Jet energy scale                   | -4.0/+/+4.2                  | -8.4/+/+5.7                  | -5.0/+/+4.5              |
| \( b \)-tag efficiency             | -4.7/+/+5.0                  | -4.8/+/+5.0                  | -4.7/+/+5.0              |
| \( c \)-mistag efficiency          | -1.6/+/+1.6                  | -1.5/+/+1.5                  | -1.6/+/+1.6              |
| Light-jet mistag efficiency        | -0.3/+/+0.3                  | -0.5/+/+0.5                  | -0.4/+/+0.4              |
| \( E_T^{\text{miss}} \)           | -0.3/+/+0.5                  | -1.7/+/+0.5                  | -0.6/+/+0.4              |
| \( \tau_{\text{had}} \) identification | -3.5/+/+3.4                  | -6.0/+/+5.6                  | -4.1/+/+3.9              |
| \( \tau_{\text{had}} \) energy scale | -2.1/+/+2.0                  | -1.2/+/+1.4                  | -1.9/+/+1.9              |
| Jet vertex fraction                | -0.1/+/+0.3                  | -0.3/+/+0.3                  | -0.2/+/+0.3              |
| Jet energy resolution              | -1.4/+/+1.4                  | -0.2/+/+0.2                  | -1.1/+/+1.1              |
| Generator                          | -1.5/+/+1.5                  | -2.5/+/+2.5                  | -2.1/+/+2.1              |
| Parton Shower                      | -2.0/+/+2.0                  | -2.6/+/+2.6                  | -2.1/+/+2.1              |
| ISR/FSR                            | -6.2/+/+6.2                  | -8.5/+/+8.5                  | -6.7/+/+6.7              |
| Misidentified-\( \tau_{\text{had}} \) background | -1.3/+/+1.4                  | -2.0/+/+2.2                  | -1.6/+/+1.6              |
| \( W + \text{jets} \) background  | -2.9/+/+2.9                  | -3.6/+/+3.6                  | -3.0/+/+3.0              |
| Statistics                         | -2.2/+/+2.2                  | -5.6/+/+5.6                  | -1.7/+/+1.7              |
| Luminosity                         | -2.3/+/+2.3                  | -2.3/+/+2.3                  | -2.3/+/+2.3              |
$\tau + \text{lepton} \sqrt{s} = 7\;\text{TeV}: \text{systematic uncertainties}$

| Source              | $\mu + \tau$   | $e + \tau$   |
|---------------------|----------------|--------------|
| $\mu$ (ID/Trigger) | $-1.1^{+1.5}_{-1.1}$ | $-1.9^{+2.8}_{-1.9}$ |
| $e$ (ID/Trigger)   | $-2.0^{+2.2}_{-2.0}$ | $-1.9^{+2.8}_{-1.9}$ |
| JES                 | $+2.0^{+5.0}_{-2.0}$ | $+2.1^{+7.1}_{-1.0}$ |
| JER                 | $+4.8^{+4.8}_{-4.8}$ | $+3.5^{+3.5}_{-3.5}$ |
| ISR/FSR             | $+0.7^{+0.7}_{-0.7}$ | $+0.7^{+0.7}_{-0.7}$ |
| Generator           | $+2.0^{+2.0}_{-2.0}$ | $+2.1^{+2.1}_{-2.1}$ |
| $b$-tag             | $-7.7^{+9.0}_{-7.7}$ | $-7.5^{+8.9}_{-7.5}$ |
| $\tau_1$ ID        | $-3.0^{+3.2}_{-3.0}$ | $-2.7^{+3.0}_{-2.7}$ |
| $\tau_3$ ID        | $-3.1^{+3.4}_{-3.1}$ | $-2.9^{+3.2}_{-2.9}$ |
τ + lepton $\sqrt{s} = 7$ TeV: BDT fit
$\tau + \text{lepton} \sqrt{s} = 7 \text{ TeV}: \text{matrix method}$
$t\bar{t}$ differential cross-section $\sqrt{s} = 13$ TeV: fiducial phase-space distributions