Differential measurements of \( \bar{t}t \) production at ATLAS

Matteo Negrini
INFN Bologna

on behalf of the ATLAS collaboration
Overview

- Differential $t \bar{t}$ production cross-sections allow us to test theories, to possibly observe unexpected effects in the top sector and to provide better background models to other searches.

- Several differential measurements of top quark pair production cross-section observables performed by ATLAS at $\sqrt{s} = 7, 8, 13$ TeV.

- This talk focuses on recent differential measurements:
  - Effect of $t \bar{t}$ differential cross section measurements on the proton PDFs: *ATL-PHYS-PUB-2018-017*
Top quark pair signatures

3 jets or 1 large-R jet (one b-tag)

Hadronic top

Leptonic top

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

- Full hadronic (45%)
- $\mu$+jets (15%)
- $\tau$+jets (15%)
- E$_T$ miss (15%)
- $e$+jets (15%)
- $\nu$+jets (15%)
- di-lepton (10%)

Jet (b-tag)

Lepton
Measured differential cross-sections

Possibility to extract two differential cross-sections:

- **Absolute** measurements provide the actual cross-sections
- **Normalized** measurements to extract shapes with higher precision (cancellation of systematic uncertainties)

and to apply two corrections:

- **Particle-level**: extrapolate measurement in a fiducial region closely following the event selection, defined using “stable” particles ($\tau > 0.3 \times 10^{-10}$ s)
  - Less affected by modeling/extrapolation uncertainties
  - Used for MC comparison/tuning (RIVET)
- **Parton-level**: extrapolate measurement to full top pair production phase space
  - Can be compared with theoretical calculations
Experimental uncertainties arise from an imperfect knowledge of:

- **Detector modeling and calibration:** full analysis repeated after 1σ variations of each source of systematic uncertainty
  - include: Jet and MET calibration, lepton reconstruction, b-tagging
- **Background modeling:** full analysis repeated after variation of the backgrounds by 1σ from their nominal values
- **Signal modeling:** each source of uncertainty is estimated using a different MC sample for the unfolding. The uncertainty is obtained as the difference between the unfolded and the true distributions of the baseline sample
  - include: ME generator, PS+hadronization, ISR/FSR, PDF

More details on tt̅ modeling in ATLAS in the talk by James Monk later in this session
Comparison of MC with measurements

- For each differential cross-section a bin-to-bin covariance matrix is constructed to include the effect of all uncertainties affecting the measurement (statistics, detector modeling/calibration, background estimation, signal modeling).
- Uncertainties on theoretical predictions not included.
- The $\chi^2$ for each measurement and for all tested MC generators is computed as:

$$\chi^2 = V^T \cdot Cov^{-1} \cdot V$$

**Cov**: bin-to-bin covariance matrix. Always provided in recent (and future) analyses.

**V**: vector of differences between measurement and prediction (after discarding one row/column in case of normalized distributions).
Lepton+jets

$s=13$ TeV – $3.2$ fb$^{-1}$
Lepton+jets at 13 TeV - Overview

Analysis strategy:

- Measurement done at particle-level only
- Reconstruction of both resolved and boosted channels
- Measure both absolute and normalized cross-sections
- Also test the effect of radiation on $t\bar{t}$ kinematics measuring distributions as a function of the number of “extra” jets

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resolved</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>$123800 \pm 10600$</td>
</tr>
<tr>
<td>Single top</td>
<td>$6300 \pm 800$</td>
</tr>
<tr>
<td>Multijets</td>
<td>$5700 \pm 3000$</td>
</tr>
<tr>
<td>$W+$jets</td>
<td>$3600 \pm 2000$</td>
</tr>
<tr>
<td>$Z+$jets</td>
<td>$1300 \pm 700$</td>
</tr>
<tr>
<td>$t\bar{t}V$</td>
<td>$400 \pm 100$</td>
</tr>
<tr>
<td>Diboson</td>
<td>$300 \pm 200$</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$142000 \pm 11000$</td>
</tr>
<tr>
<td>Data</td>
<td>$155593$</td>
</tr>
</tbody>
</table>

Approx. 85% signal purity in both channels
Results

Good modeling observed for most observables...

- except for the top $p_T$ (as discussed by Federica Fabbri)
- mis-modeling of $m_{tt}$ observed for HERWIG++

More details on this analysis in the talk by Matteo Scornajenghi in the YSF
Impact of radiation on kinematics

The effect of gluon radiation on the $t\bar{t}$ kinematics is checked by measuring differential cross-sections in for a given number of “extra” jets in the event.

Kinematic variables chosen:

- $p_T^{t\bar{t}}$, $p_T^{t,\text{had}}$: transverse momentum of the top quark pair system and the hadronically decaying top

- $|p_{\text{out}}^{t\bar{t}}|$: out-of-plane transverse momentum (momentum of one top projected on the direction perpendicular to the plane defined by the other top and the beam axis): sensitive to radiation and used in MC tuning

\[ |p_{\text{out}}^{t\bar{t}}| = \left| \vec{p}_T \cdot \frac{\vec{p}_{T,\text{lep}} \times \hat{z}}{|\vec{p}_{T,\text{lep}} \times \hat{z}|} \right| \]
Results

Good modeling of absolute $|p_{\text{out}}^{\text{tt}}|$ differential cross-sections
Results

Mis-modeling of absolute $p_T^{\text{had}}$ differential cross-sections enhanced in events with no extra-jets
Results

Normalized $p_T^{tt}$ differential cross-section

Mismodeling observed in particular for the 6-jet inclusive configuration
All-hadronic boosted

$\sqrt{s}=13$ TeV – 36 fb$^{-1}$
All-hadronic boosted 13 TeV - Overview

Analysis strategy:

- Measurement done at parton- and particle-level
- Reconstruction of boosted channel
- Measure normalized and absolute cross-sections
- Main background from multi-jet production

<table>
<thead>
<tr>
<th>Category</th>
<th>Events ± Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ (all-hadronic)</td>
<td>3250 ± 470</td>
</tr>
<tr>
<td>$t\bar{t}$ (non-all-hadronic)</td>
<td>200 ± 40</td>
</tr>
<tr>
<td>Single-top-quark</td>
<td>24 ± 12</td>
</tr>
<tr>
<td>$t\bar{t}+W/Z/H$</td>
<td>33 ± 10</td>
</tr>
<tr>
<td>Multijet events</td>
<td>810 ± 50</td>
</tr>
<tr>
<td>Prediction</td>
<td>4320 ± 530</td>
</tr>
<tr>
<td>Data (36.1 fb$^{-1}$)</td>
<td>3541</td>
</tr>
</tbody>
</table>

75% signal purity in signal region
Multijet background estimation

- Top candidate:
  - large-R jet with $p_T > 500/350$ GeV for leading/sub-leading top
  - tagging using jet substructure ($m_{\text{jet}} + N$-subjettiness ratio $\tau_{32}$)
  - $b$-tagged small-R jet angularly matched to the large-R jet ($\Delta R < 1.0$)

- Defining set of control regions on the basis of top-tag and $b$-tag of the leading and sub-leading jet

- Size of multijet event contribution in $S$ obtained from ratios of event numbers in these regions

**Definition of signal and control regions and expected proportion of $t\bar{t}$ events**

<table>
<thead>
<tr>
<th>2nd large-$R$ jet</th>
<th>Leading large-$R$ jet</th>
</tr>
</thead>
<tbody>
<tr>
<td>1t1b</td>
<td>J (7.6%)</td>
</tr>
<tr>
<td>0t1b</td>
<td>B (2.2%)</td>
</tr>
<tr>
<td>1t0b</td>
<td>E (0.7%)</td>
</tr>
<tr>
<td>0t0b</td>
<td>A (0.2%)</td>
</tr>
<tr>
<td></td>
<td>0t0b</td>
</tr>
<tr>
<td></td>
<td>1t0b</td>
</tr>
<tr>
<td></td>
<td>0t1b</td>
</tr>
<tr>
<td></td>
<td>1t1b</td>
</tr>
</tbody>
</table>

| 1t0b              | K (21%)               |
| 0t1b              | D (5.8%)              |
| 1t0b              | F (2.4%)              |
| 0t0b              | C (0.8%)              |
|                   |                       |
|                   |                       |

| L (42%)           |                       |
| H (13%)           |                       |
| G (6.4%)          |                       |
| I (2.2%)          |                       |
| O (11%)           |                       |

- **Signal region**
- **Sizable $t\bar{t}$ contribution**
- **Multijet background dominated**
Multijet background: checks

- Good agreement observed in validation (L and N) region
- Slight MC prediction mis-modeling in signal (S) region
Systematic uncertainties

Main contribution from large-R jet (calibration of JES and top-tagging variables $m_{\text{jet}}$, $\tau_{32}$) and signal modeling (hard scattering and PS)
Results

Good agreement observed for $p_{T}^{t1}$ and $p_{T}^{t2}$ (but large uncertainty especially in the TeV region)
Results

- Overall good agreement observed for the $t\bar{t}$ system
- Mis-modeling of $p_T^{t\bar{t}}$ observed for MG5_aMC@NLO+Pythia8
Results

- Differential measurements generally well described by MC generators
- The measured **inclusive fiducial cross-section** at particle-level is below all predictions

$$\sigma_{\text{fid}} = 292 \pm 7\,\text{(stat)} \pm 71\,\text{(syst)} \, \text{fb}$$
Constraining the proton PDF using differential cross-sections
Fit strategy

- Added **top quark data** to a previous fit of ATLAS and HERA data using differential $W$ and $Z/\gamma^*$ cross sections.

- Top quark data are complementary to $W$ and $Z/\gamma^*$ data as they are more sensitive to high-$x$ gluon distribution.

- Distributions most sensitive to the gluon PDF: mass and rapidity of $t\bar{t}$ system ($m_{t\bar{t}}, y_{t\bar{t}}$), average top quark rapidity and transverse momentum ($y_t, p_{T,t}$).

- Better constraints obtained by fitting distributions simultaneously: statistical and systematic correlations necessary.

- Using $t\bar{t}$ differential production results at 8 TeV in the $l+\text{jets}$ and dilepton channels, parton level, full phase-space, to exploit NNLO predictions.

- Systematic uncertainties are fully correlated, both bin-to-bin and between spectra.
Considering separately each variable

Ratio of the PDFs (may have different behavior for different variables)
Using 3 distributions

Fit including 3 \(tt\) data distributions on HERA PDF fit:
- Produce harder \(p_{T,t}\) spectrum
- Sensibly reduces the uncertainty in the large-\(x\) region
Summary

- Differential $t\bar{t}$ production cross-sections measured for several observables, reconstructed in different channels
- Overall good modeling of $t\bar{t}$ production provided by NLO generators
- NLO generators tend to produce $p_T^{\text{top}}$ spectra harder than the measured one
- Signal modeling among the largest sources of systematic uncertainties
- Need to reduce large-R jet calibration uncertainties to improve precision of measurements where high $p_T$ tops are present
- Differential cross-section measurements provide constraints to the PDF
Thank you!
Correction procedure

\[
\frac{d\sigma_{t\bar{t}}}{dp_{T, ptcl}}(p^i_{T, ptcl}) = \frac{1}{\Delta p^i_{T, ptcl} \mathcal{L} f^i_{ptcl!reco}} \cdot \sum_j M^{-1}_{i,j} f^{j}_{reco!ptcl} (N^j_{reco} - N^j_{reco,bgnd})
\]

Input: measured number of events after subtraction of the background contributions
Correction procedure

\[
\frac{d\sigma_{t\bar{t}}}{dp_{T,\text{ptcl}}} \left( p_{T,\text{ptcl}}^i \right) = \frac{1}{\Delta p_{T,\text{ptcl}}^i \mathcal{L} f_{\text{ptcl!reco}}^i} \cdot \sum_j M_{ij}^{-1} f_{\text{reco!ptcl}}^j \left( N_{\text{reco}}^j - N_{\text{reco,bgnd}}^j \right)
\]

**Correct for events in the particle/parton-level fiducial region failing the detector-level cuts**

**Correct for resolution through inversion of the migration matrix (regularized unfolding technique)**

**Correct for events passing RECO selection but outside the particle/parton-level fiducial region**
Results: l+jets at 13 TeV

Measurement of $p_T^{\text{top}}$ in the l+jets analysis

Top $p_T$ (absolute, resolved)

Top $p_T$ (absolute, boosted)
Spin correlations

Spin correlations studied through the angular separation of leptons in the $e\mu$ channel
Results presented in ATLAS-CONF-2018-027

Deviations of all MC predictions observed in the normalized differential cross-section

Fit of SM-like spin correlation $f_{SM}$:

$$n_i = f_{SM} n_{spin} + (1-f_{SM}) n_{nospin}$$

$n_i$ are normalized cross-sections in bin $i$

$n_{spin/nospin}$ obtained under the hypothesis of correlated/uncorrelated spins

<table>
<thead>
<tr>
<th>Region</th>
<th>$f_{SM}$</th>
<th>Significance (incl. theory uncertainties)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{t\bar{t}} &lt; 450$ GeV</td>
<td>$1.11 \pm 0.04 \pm 0.13$</td>
<td>$0.85 (0.84)$</td>
</tr>
<tr>
<td>$450 &lt; m_{t\bar{t}} &lt; 550$ GeV</td>
<td>$1.17 \pm 0.09 \pm 0.14$</td>
<td>$1.00 (0.91)$</td>
</tr>
<tr>
<td>$550 &lt; m_{t\bar{t}} &lt; 800$ GeV</td>
<td>$1.60 \pm 0.24 \pm 0.35$</td>
<td>$1.43 (1.37)$</td>
</tr>
<tr>
<td>$m_{t\bar{t}} &gt; 800$ GeV</td>
<td>$2.2 \pm 1.8 \pm 2.3$</td>
<td>$0.41 (0.40)$</td>
</tr>
<tr>
<td>inclusive</td>
<td>$1.250 \pm 0.026 \pm 0.063$</td>
<td>$3.70 (3.20)$</td>
</tr>
</tbody>
</table>