Associated Top Quark Production Cross Sections at ATLAS and CMS Experiments: $t\bar{t} + X$

Javier Brochero on behalf of the ATLAS and CMS Collaborations

CIEMAT
May 29, 2018

Heavy Quarks and Leptons
May 27 - June 1, 2018, Yamagata Terrsa, Yamagata, Japan
Outline

- CMS and ATLAS Detectors
- $t\bar{t}$ process
- $t\bar{t}+X$ production
  - $t\bar{t} + W/Z$
  - $t\bar{t} + \gamma$
  - $t\bar{t}+$jets
  - $t\bar{t}t\bar{t}$
- Event identification
- Cross section measurements
- Results
- Conclusions

ATLAS and CMS Results:
- atlas.cern/tags/results
- cms-results.web.cern.ch

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**CMS Detector**

- Event reconstruction based on the Particle Flow algorithm

**CMS Integrated Luminosity, pp**

Data included from 2010-03-30 11:22 to 2018-05-17 05:05 UTC

- 2010, 7 TeV, 45.0 fb⁻¹
- 2011, 7 TeV, 6.1 fb⁻¹
- 2012, 8 TeV, 23.3 fb⁻¹
- 2015, 13 TeV, 4.2 fb⁻¹
- 2016, 13 TeV, 40.8 fb⁻¹
- 2017, 13 TeV, 49.8 fb⁻¹
- 2018, 13 TeV, 10.6 fb⁻¹
Introduction

ATLAS Detector

- Jets identification using 3D topological clusters

Delivered Luminosity [fb]

ATLAS Online Luminosity
- 2011 pp (5 TeV)
- 2012 pp (5 TeV)
- 2013 pp (5 TeV)
- 2014 pp (5 TeV)
- 2015 pp (5 TeV)
- 2016 pp (5 TeV)
- 2017 pp (5 TeV)
- 2018 pp (5 TeV)

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**tt Production @ LHC**

**tt production**

- **tt** mainly dominated by gg fusion (90%)
- The top quark decays predominantly into a b quark and a W boson

**tt detection**

- One of the keys in the identification of a tt process is the b-jet identification
- Dilepton (\(\ell\ell\)) and single lepton (\(\ell + \text{jets}\)) are the preferred decay channels:
  - Low background contamination from other SM processes
  - Low branching ratios (\(\ell\ell \rightarrow 5\%\) and \(\ell + \text{jets} \rightarrow 44\%\))

Final states with 2 b-jets, one (two) lepton(s) and 2 jets.
**t\bar{t} + Z/W Production**

### t\bar{t} + Z production

1. Strong test of QCD predictions
2. Direct probe of the tZ coupling via final state radiation (FSR)
3. Sensitive to new physics (deviations from SM expectations)
4. Multilepton final states are irreducible background in:
   - t\bar{t}H
   - New physics searches
### tt + Z/W Signature

<table>
<thead>
<tr>
<th>Process</th>
<th>Decay</th>
<th>Channel</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttW</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[eνb][qqb]</td>
<td>eν</td>
<td>SS</td>
<td>CMS</td>
</tr>
<tr>
<td>[μνb][qqb]</td>
<td>eν</td>
<td>SS</td>
<td>CMS</td>
</tr>
<tr>
<td>[eνb][qqb]</td>
<td>μν</td>
<td>SS</td>
<td>CMS</td>
</tr>
<tr>
<td>[μνb][qqb]</td>
<td>μν</td>
<td>SS</td>
<td>CMS/ATLAS</td>
</tr>
<tr>
<td>[lνb][lνb]</td>
<td>lν</td>
<td>3l</td>
<td>ATLAS</td>
</tr>
<tr>
<td>ttZ</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[lνb][qqb]</td>
<td>ll</td>
<td>3l</td>
<td>CMS/ATLAS</td>
</tr>
<tr>
<td>[lνb][lνb]</td>
<td>ll</td>
<td>4l</td>
<td>CMS/ATLAS</td>
</tr>
</tbody>
</table>

- For ttW same electric-charged leptons (SS) and 3 leptons are the selected final states.
- For ttZ 3 and 4 leptons are the selected signatures.

**Leptonic decay for the additional bosons**

1. W → ℓ + ν
2. Z → ℓℓ

**Ingredients**

1. Final state selection
2. Identification of the main backgrounds
3. Cross section extraction
Main backgrounds coming from

- Non prompt leptons: Extracted from control regions

Multivariate analysis: signal/bkg

- Inputs: $H_T$, $p_T^\ell$, $E_T$, $\Delta R(\ell, \text{jet})$

Maximum Likelihood (ML) fit for signal and control regions (BDT and $N_b$ categories)
**$t\bar{t}Z$ Cross section**

- 3 leptons:
  - $N_{jets}$ and $N_{b}$-jets categories
  - $WZ$ background from MC
- 4 leptons:
  - Only 2 $N_{b}$-jets bins
  - $ZZ$ also from simulation. Rejected requiring only one $\ell\ell$ compatible with $M_Z$
- $t\bar{t}Z$ extracted by a Maximum Likelihood (ML) fit over the $N_{Jets}$, $N_{b}$ distribution

Control regions (CR) show a good DATA/MC agreement for $WZ$ and $ZZ$ processes.
Simultaneous $t\bar{t}W/Z$ Cross Section

$t\bar{t}W$

- Two signatures: 2 muons and 3 leptons
- 3 leptons
  - Two leptons with opposite electric charge (OS)
  - Veto in the $Z$ mass region
- Control regions for background (fake leptons) validation

$t\bar{t}Z$

- Signal region with 3 and 4 leptons
  - Share the 3 leptons final state with $t\bar{t}W$
- 3 leptons final state
  - Specific $Z$ mass window
  - Requires a pair of same flavor leptons (SF) with OS
- 4 leptons
  - 2 OS pairs with at least one SF
  - Only one $\ell\ell$ compatible with $M_Z$

Simultaneous $t\bar{t}W/Z$

- ATLAS approach involves a simultaneous extraction of the $t\bar{t}W/Z$ cross sections.
- Several control (CR) and signal regions (SR) are fitted in order to constrain also $\sigma_WZ$ and $\sigma_{ZZ}$
Simultaneous $t\bar{t}W/Z$ Cross Section

- **$t\bar{t}W$**
  - Two signatures: 2 muons and 3 leptons
  - 3 leptons
    - Two leptons with opposite electric charge (OS)
    - Veto in the $Z$ mass region
  - Control regions (fake leptons validation)

- **Simultaneous $t\bar{t}W/Z$ cross section extraction**

  - ATLAS approach involves a simultaneous extraction of the $t\bar{t}W/Z$ cross sections.
  - Several control (CR) and signal regions (SR) are fitted in order to constrain also $\sigma_{WZ}$ and $\sigma_{ZZ}$

11 different regions: 9 for signal and 2 for bkg control
**ttW/Z Cross section Results**

<table>
<thead>
<tr>
<th>Process</th>
<th>Detector</th>
<th>Central $\sigma$ [pb]</th>
<th>stat [pb]</th>
<th>syst [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ttW</td>
<td>ATLAS</td>
<td>1.50</td>
<td>0.72</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>0.77</td>
<td>0.12</td>
<td>0.13</td>
</tr>
<tr>
<td>ttZ</td>
<td>ATLAS</td>
<td>0.92</td>
<td>0.29</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>CMS</td>
<td>0.99</td>
<td>0.09</td>
<td>0.12</td>
</tr>
</tbody>
</table>

### ATLAS Results

- $\sqrt{s} = 13$ TeV, 3.2 fb$^{-1}$
- ATLAS best fit
- ATLAS 68% CL
- ATLAS 95% CL
- NLO prediction
- ttZ theory uncertainty
- ttW theory uncertainty

### CMS Results

- 35.9 fb$^{-1}$ (13 TeV)
- ttV best fit
- ttV theory [1]
- 68% CL contour
- 95% CL contour

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**tt + X Cross Section: CMS and ATLAS**  
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11 / 19
probe of electroweak $t\gamma$ coupling

Measurements performed with the full 8 TeV dataset

Single lepton channel for $t\bar{t}$ process

Backgrounds from:
- Prompt photons: $W\gamma$ and $Z\gamma$
- $t\bar{t}$ process with fake photons (from $e$)

$\sigma_{t\bar{t}\gamma}$ measured in the fiducial phase space

ATLAS: $\ell + N_{\text{Jets}} \geq 4 + N_{b} \geq 1 + p_{T}^{\gamma} > 15$ GeV

CMS: $\ell + N_{\text{Jets}} \geq 3 + p_{T}^{\gamma} > 20$ GeV, $p_{T}^{\gamma} > 25$ GeV

ATLAS includes differential $\sigma_{t\bar{t}\gamma}$ measurement
Cross Section Results

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{t\bar{t}\gamma}$ / $\sigma_{t\bar{t}}$ [$10^{-4}$]</th>
<th>$\sigma_{t\bar{t}\gamma}$ [fb]</th>
<th>$\sigma_{\text{Fid-A}}$ [fb]</th>
<th>$\sigma_{\text{Fid-B}}$ [fb]</th>
<th>$\sigma_{t\bar{t}\gamma}$ [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>5.2 ± 1.1</td>
<td>127 ± 27</td>
<td>—</td>
<td>—</td>
<td>515 ± 108</td>
</tr>
<tr>
<td>ATLAS</td>
<td>—</td>
<td>—</td>
<td>139 ± 18</td>
<td>151 ± 24</td>
<td>592 ± 77</td>
</tr>
<tr>
<td>Theory*</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

* Theory uncertainty: Scale + PDF

- Two different fiducial regions
- Fid-A = CMS; Fid-B = ATLAS

- Differential $\sigma_{t\bar{t}\gamma}$ at particle level
- Good agreement with NLO prediction*
- Uncertainties dominated by background predictions.

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1. Sensitive to initial/final state radiation
2. Helps to improve the MC modeling
3. Special relevance for $t\bar{t}b\bar{b}$

\[ \frac{d\sigma}{dX} \] as a function of additional jets

- Measurements
- Cross Section

**Data**

**Theory**

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**Observation**

**Prediction**

**Event Distribution**

**Measurement of the** $\sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj}$

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**Additional Jets**

- ATLAS
- CMS

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**Third Jet**

**Single $t$**

**$Wt$**

**$Z+jets$**

**MisID leptons**

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**$p_T^{b jet}$**

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$p_T$ observed is softer in events with zero additional jets while the agreement is improved at higher jet multiplicities.

$d\sigma /dX$ as a function of additional jets

$p_T$ Vs Number of jets

Measurement of the $\sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj}$

Events

Number of additional jets

Measurement of the $\sigma_{t\bar{t}jj}$
\( p_T^t \) observed is softer in events with zero additional jets while the agreement is improved at higher jet multiplicities.

\[
\frac{d\sigma}{dX} \text{ as a function of additional jets}
\]

\( p_T^t \) Vs Number of jets

Measurement of the \( \sigma_{t\bar{t}b\bar{b}} / \sigma_{t\bar{t}jj} \)

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\( t\bar{t} + X \) Cross Section: CMS and ATLAS

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Differential cross section as a function:
- $N_{\text{Jets}}$ and $p_T$ of additional jets
- $p_T$ top

Comparison with:
- available MC generators as MG5_aMC@NLO, POWHEG, Sherpa
- various ME and PS models

Dominated by jet energy scale and modelling uncertainties
**Results**

**Cross Section Results**

<table>
<thead>
<tr>
<th>σ (pb)</th>
<th>t¯ttj</th>
<th>σ (pb)</th>
</tr>
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<tbody>
<tr>
<td>0.05</td>
<td></td>
<td>0.1</td>
</tr>
<tr>
<td>0.15</td>
<td></td>
<td></td>
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<table>
<thead>
<tr>
<th>jjtptt</th>
<th>σ (%)</th>
<th>jjtptt</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>7</td>
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</tbody>
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<table>
<thead>
<tr>
<th>jjtptt</th>
<th>σ/bjtptt</th>
<th>jjtptt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>0.03</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
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**CMS Unpublished**

\( \sqrt{s} = 13 \text{ TeV}, 2.3 \text{ fb}^{-1} \)

Visible phase space

- Measurement
- Stat
- Total

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

- 4-jet exclusive
- 5-jet exclusive
- 6-jet inclusive
- Stat.+Syst. unc.

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 2.3 \text{ fb}^{-1} \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

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\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

**ATLAS**

\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)
• $j_1$, $j_2$ and $j_3$ are additional jets
• The measurement is softer for the $p_T(j_2)$ and $p_T(j_3)$ distributions

\[ p_T(j_i) \]
Search for $t\bar{t}t\bar{t}$


- **Strong test of the top-Higgs Yukawa coupling**
- $\sigma_{t\bar{t}t\bar{t}}(\text{NLO})@13\,\text{TeV} = 9.2 \pm 2.9\,\text{fb}$
- **CMS**: At least a SS pair $\rightarrow$ low background/low stat
- **ATLAS**: One lepton $\rightarrow$ high background/high stat
- Really complex signal regions!

Search for $t\bar{t}t\bar{t}$

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ATLAS(2015): $3\,\text{fb}^{-1}$  CMS(2016): $36\,\text{fb}^{-1}$

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**t+tt Results**

1. $\sigma_{t+ttt}(CMS)@13$ TeV = 16.9 ± 13.8 fb corresponds to a observed significance of 1.6$\sigma$ (expected 1.0$\sigma$)

2. ATLAS found an observed upper limit of $21 \times \sigma_{SM}^{ttt}$ (expected $16 \times \sigma_{SM}^{ttt}$)

3. Limits in the coupling constant $|C_{4t}|$ and the production $\sigma_{t+ttt}$ in specific BSM models.
• ATLAS and CMS experiments have a very strong program in the measurement of the $t\bar{t} + X$ processes.
• All the results presented are in agreement with the Standard Model (SM) predictions.
• Monte Carlo modeling is/will be optimized with the results from $t\bar{t} + X$ measurements.
• In general, precision in $t\bar{t} + X$ measurements will be improve with the full amount of data expected @ 13 TeV (2016+2017+2018).