Measurements of the $t\bar{t}W/Z$ production cross-sections using proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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Introduction

- Measurement of $t\bar{t}Z$ is a direct test of the top-EWK couplings
- Understanding $t\bar{t}W/Z$ processes is important for $t\bar{t}H$ measurement and new physics searches

$t\bar{t}W$, $\sigma(\text{NLO}) = 232 \text{ fb}$

$t\bar{t}Z/\gamma^*$, $\sigma(\text{NLO}) = 215 \text{ fb}$
Introduction

- Measure $t\bar{t}W/Z$ cross sections using proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, corresponding to an integrated luminosity of $20.3 \text{ fb}^{-1}$
- Four final states are considered: two opposite-sign leptons, two same-sign leptons, three leptons, four leptons

<table>
<thead>
<tr>
<th>Process</th>
<th>$t\bar{t}$ decay</th>
<th>Boson decay</th>
<th>Signature</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}W^{\pm}$</td>
<td>$(\ell^{\mp}\nu b)(q\bar{q}b)$, $(\ell^{\pm}\nu b)(q\bar{q}b)$, $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$</td>
<td>$\ell^{\pm}\nu$, $\ell^{\pm}\nu$, $\ell^{\pm}\nu$</td>
<td>2OSL, 2SSL, 3L</td>
</tr>
<tr>
<td>$t\bar{t}Z$</td>
<td>$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$, $(q\bar{q}b)(q\bar{q}b)$, $(\ell^{\pm}\nu b)(q\bar{q}b)$, $(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$</td>
<td>$q\bar{q}$, $\ell^{+}\ell^{-}$, $\ell^{+}\ell^{-}$</td>
<td>2OSL, 2OSL, 3L, 4L</td>
</tr>
</tbody>
</table>

- $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ are simultaneously extracted using a maximum likelihood fit over all channels
ATLAS detector

- Collect collision data at the LHC
- Three layers:
  - Inner detector, measure charged particle tracks
  - Calorimeters, measure particle energies
  - Muon detectors, measure muon tracks
Simulation samples

- $t\bar{t}W/Z$: MadGraph+Pythia
- $W/Z$ production: Alpgen+Pythia
- $WZ, ZZ, W^+W^-, W^\pm W^\pm$: Sherpa
- $t\bar{t}$, single top: Powheg+Pythia
- $tZ, WtZ$, Tri-boson, $t\bar{t}t\bar{t}$: MadGraph+Pythia
- $t\bar{t}H, gg\rightarrow H$: Powheg+Pythia
- The generated events are processed through a detector simulation based on GEANT4
Object definitions

- Electrons: $|\eta| < 2.47$ (veto $1.37 < |\eta| < 1.52$)
- Muons: $|\eta| < 2.5$
- Channel-dependent $p_T$, isolation and impact parameter cuts on electrons and muons
- Jets: $p_T > 25$ GeV, $|\eta| < 2.5$
- b-tagging: 70% efficiency working point
Event selection and background estimation

Event selection

▶ Standard data quality criteria
▶ Single electron or muon trigger with $p_T > 24$ GeV
  ▶ At least one trigger-matched lepton with $p_T > 25$ GeV

Background estimation

▶ Physics backgrounds: simulation
▶ Instrumental backgrounds: data-driven (except 2OSL channel)
Event selection and background estimation: 2OSL

- Two opposite-sign leptons with $p_T > 15$ GeV
- Split into 2l-Z and 2l-noZ
- Further define signal regions and control regions by jet and bjet multiplicity

<table>
<thead>
<tr>
<th></th>
<th>2l-noZ</th>
<th>2l-Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>m(\ell\ell) - m(Z)</td>
<td>$</td>
</tr>
<tr>
<td>Lepton Flavour</td>
<td>ee, e\mu, \mu\mu</td>
<td>ee, \mu\mu</td>
</tr>
<tr>
<td>Dominant Signal</td>
<td>ttZ and ttW</td>
<td>ttZ</td>
</tr>
<tr>
<td>Main Background</td>
<td>tt + light jets</td>
<td>Z + HF jets</td>
</tr>
</tbody>
</table>

Fit regions
(signal, control regions)
- 2l-noZ-3j
- 2l-noZ-4j
- 2l-noZ-5j
- 2l-Z-3j
- 2l-Z-4j
- 2l-Z-5j
Event selection and background estimation: 2OSL

- All backgrounds are estimated from simulation
- \(t\bar{t}\) events are reweighted to correct top quark \(p_T\) and \(t\bar{t}\) \(p_T\)
- \(Z\) events are reweighed to correct \(Z\) \(p_T\) and \(Z+\text{LF/HF}\) rates
- Train neural network (NN) for each signal region
- Include control regions in the likelihood fit to constrain the \(t\bar{t}\) and \(Z\) backgrounds
Event selection and background estimation: 2OSL

2OSL SR, from ATLAS-CONF-2015-032

2OSL CR, from ATLAS-CONF-2015-032
Event selection and background estimation: 2SSL

- Sensitive to $t\bar{t}W$
- Main background: instrumental backgrounds
- Two same-sign leptons with $p_T > 25$ GeV
- Split into $ee$, $e\mu$, $\mu\mu$ regions
- $N_{bjets} \geq 2$, $HT > 240$ GeV
- For $ee$ region, veto events if $75$ GeV < $m_{ee}$ < 105 GeV
- For $e\mu$ and $\mu\mu$ regions, further bin by $N_{jets}$ (2-3, 4+) $\otimes E_T^{miss}$ (40-80 GeV, 80 GeV+) in 2D

2SSL SR, from ATLAS-CONF-2015-032
Event selection and background estimation: 2SSL

Charge mis-identification:
- Apply charge mis-ID rates to data events with two opposite-sign leptons
- Measure charge mis-ID rates in opposite-sign and same-sign Z peaks

Fake/non-prompt lepton:
- Fake lepton events are estimated with events with loose leptons, as well as corresponding scale factors
- Scale factors are measured in regions of two same-sign leptons and $HT < 240$ GeV
Event selection and background estimation: 3L

- Three leptons with $p_T > 15$ GeV
- Define three 3l-Z signal regions and one 3l-noZ signal region
- Also define control region 3l-Z-0b3j to constrain the WZ background
Event selection and background estimation: 3L

- The fake/non-prompt lepton background is estimated with orthogonal regions with loose leptons as well as corresponding efficiencies
- Define validation region 3l-Z-1b and 3l-noZ-1b to check background estimation

3L VR, from ATLAS-CONF-2015-032
Event selection and background estimation: 4L

- Sensitive to $t\bar{t}Z$
- Choose the best $Z$ candidate $\rightarrow l_1, l_2$ (Z1)
- Split signal regions by $N_{bjets}$ and relative flavor of $l_3, l_4$ (Z2)

<table>
<thead>
<tr>
<th>Region</th>
<th>$l_3, l_4$</th>
<th>$N_{bjets}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4l-DF-0b</td>
<td>$e^\pm \mu^\mp$</td>
<td>0</td>
</tr>
<tr>
<td>4l-DF-1b</td>
<td>$e^\pm \mu^\mp$</td>
<td>1</td>
</tr>
<tr>
<td>4l-DF-2b</td>
<td>$e^\pm \mu^\mp$</td>
<td>$\geq 2$</td>
</tr>
<tr>
<td>4l-SF-1b</td>
<td>$e^\pm e^\mp, \mu^\pm \mu^\mp$</td>
<td>1</td>
</tr>
<tr>
<td>4l-SF-2b</td>
<td>$e^\pm e^\mp, \mu^\pm \mu^\mp$</td>
<td>$\geq 2$</td>
</tr>
</tbody>
</table>

4L-SR, from ATLAS-CONF-2015-032
Event selection and background estimation: 4L

- Also define control region 4l-ZZ to constrain the ZZ background
- The fake or non-prompt lepton background is estimated using simulation, where the normalizations are corrected with data-driven constant factors

4L-SR, from ATLAS-CONF-2015-032
Systematic uncertainties

- Luminosity
- Reconstructed objects
  - lepton selection
  - jet selection
  - flavor tagging
- Signal modelling
  - factorisation and renormalisation scale
  - ISR, FSR
  - jet matching
  - PDF

- Uncertainties on $WZ$ and $ZZ$ backgrounds:
  - $WZ$ and $ZZ$ normalizations are floated in the fit
  - $WZ$ and $ZZ$ shape uncertainties

- Uncertainties on other backgrounds
  - $Z$ production, $t\bar{t}$, single top, $t\bar{t}H$, $tZ$, small backgrounds
  - charge mis-identification, fake/non-prompt lepton
Results

- $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z}$ are simultaneously extracted using a maximum likelihood fit over all channels.
  
  - $\sigma_{t\bar{t}W} = 369_{-79}^{+86} \text{ (stat.)} \pm 44 \text{ (syst.) fb} = 369_{-91}^{+100} \text{ fb}$
  
  - $\sigma_{t\bar{t}Z} = 176_{-48}^{+52} \text{ (stat.)} \pm 24 \text{ (syst.) fb} = 176_{-52}^{+58} \text{ fb}$

- Breakdown of the total uncertainties:

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\sigma_{t\bar{t}W}$</th>
<th>$\sigma_{t\bar{t}Z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.2%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Reconstructed objects</td>
<td>3.7%</td>
<td>7.4%</td>
</tr>
<tr>
<td>Background from simulation</td>
<td>5.8%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Fake leptons and charge misID</td>
<td>7.5%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Signal modelling</td>
<td>1.8%</td>
<td>4.5%</td>
</tr>
<tr>
<td>Total systematics</td>
<td>12%</td>
<td>13%</td>
</tr>
<tr>
<td>Statistical</td>
<td>+24% / −21%</td>
<td>+30% / −27%</td>
</tr>
<tr>
<td>Total</td>
<td>+27% / −24%</td>
<td>+33% / −29%</td>
</tr>
</tbody>
</table>

- Expected and observed signal significances:

<table>
<thead>
<tr>
<th>Channel</th>
<th>$t\bar{t}W$ significance</th>
<th>$t\bar{t}Z$ significance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Expected</td>
<td>Observed</td>
</tr>
<tr>
<td>2\ell OS</td>
<td>0.4$\sigma$</td>
<td>0.1$\sigma$</td>
</tr>
<tr>
<td>2\ell SS</td>
<td>2.8$\sigma$</td>
<td>5.0$\sigma$</td>
</tr>
<tr>
<td>3\ell</td>
<td>1.4$\sigma$</td>
<td>1.0$\sigma$</td>
</tr>
<tr>
<td>4\ell</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Combined</td>
<td>3.2$\sigma$</td>
<td>5.0$\sigma$</td>
</tr>
</tbody>
</table>

from ATLAS-CONF-2015-032
Results

- Expected yields after the fit compared to observed yields in the 5 control regions and 15 signal regions:

from ATLAS-CONF-2015-032

- Good agreement between expectation and data
- $t\bar{t}W$ significance is mainly from the 2SSL regions while $t\bar{t}Z$ significance is mainly from the 3L and 4L regions
Results

- Compare the measured results with the NLO calculations
- Consistency between measurements and calculations

from ATLAS-CONF-2015-032
Conclusion

- Measurements of the $t\bar{t}W$ and $t\bar{t}Z$ cross sections using 8 TeV proton-proton collisions at ATLAS are presented.
- $\sigma_{t\bar{t}W} = 369^{+100}_{-91}$ fb, $\sigma_{t\bar{t}Z} = 176^{+58}_{-52}$ fb.
- The signal significances are 5.0$\sigma$ for $t\bar{t}W$, and 4.2$\sigma$ for $t\bar{t}Z$.
- The measurements are consistent with the NLO calculations.