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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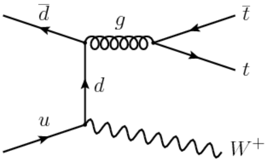
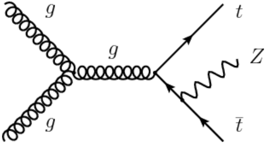
Introduction

- 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

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



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



Introduction

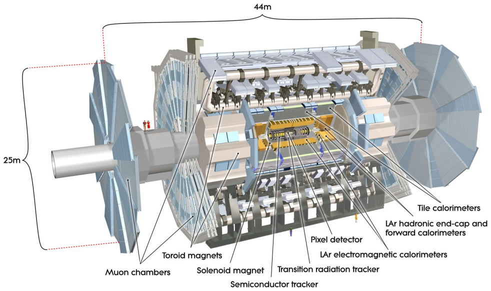
- Measure $t\bar{t}W/Z$ cross sections using proton-proton collisions at $\sqrt{s} = 8\ TeV$ with the ATLAS detector, corresponding to an integrated luminosity of 20.3 fb^{-1}
- Four final states are considered: two opposite-sign leptons, two same-sign leptons, three leptons, four leptons

Process	$t\bar{t}$ decay	Boson decay	Signature
$t\bar{t}W^{\pm}$	$(\ell^{\mp}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	2OSL
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{\pm}\nu$	2SSL
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	3L
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$q\bar{q}$	2OSL
	$(q\bar{q}b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	2OSL
	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	3L
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	4L

- $\sigma_{t\bar{t}W}$ 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→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

	2ℓ-noZ	2ℓ-Z
|m($\ell\ell$) - m(Z)|	> 10 GeV	< 10 GeV
Lepton Flavour	ee, eμ, μμ	ee, μμ
Dominant Signal	$t\bar{t}Z$ and $t\bar{t}W$	$t\bar{t}Z$
Main Background	$t\bar{t}$ + light jets	Z + HF jets
Fit regions (signal, control regions)	2ℓ-noZ-3j 2ℓ-noZ-4j 2ℓ-noZ-5j	2ℓ-Z-3j 2ℓ-Z-4j 2ℓ-Z-5j

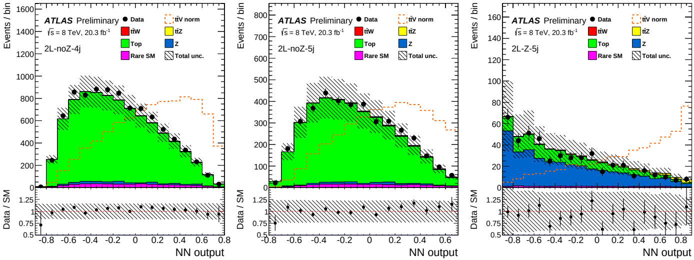
Event selection and background estimation: 2OSL

- 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+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

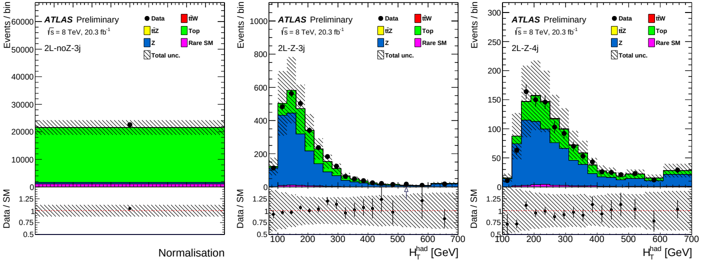
	1 b + 2 b (2ℓ-noZ)	2 b (2ℓ-Z)
3 j	normalisation	H_T(jets)
4 j	NN	H_T(jets)
≥ 5 j	NN	NN

control region signal region

Event selection and background estimation: 2OSL



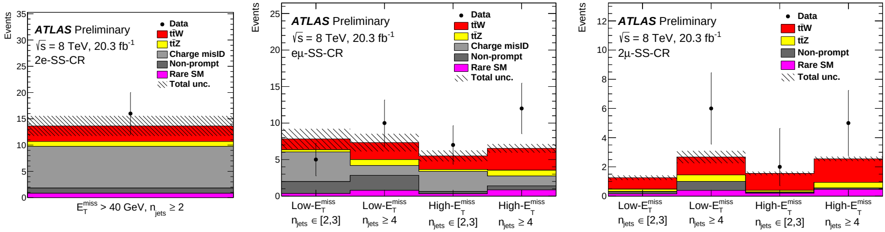
2OSL SR, from ATLAS-CONF-2015-032



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
- $N_{\mathrm{bjets}} >= 2$, $HT > 240$ 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+) $\otimes$ $E_{\mathrm{T}}^{\mathrm{miss}}$ (40-80 GeV, 80 GeV+) in 2D



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

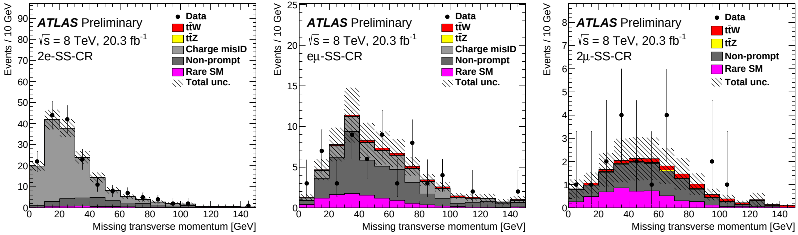
Event selection and background estimation: 2SSL

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

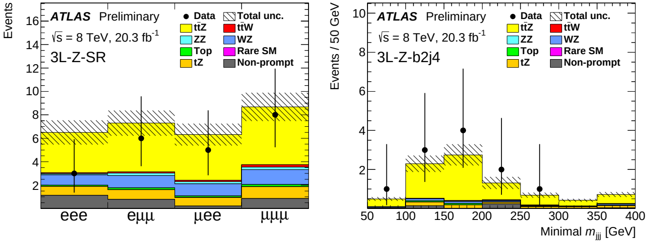


2SSL CR, from ATLAS-CONF-2015-032

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

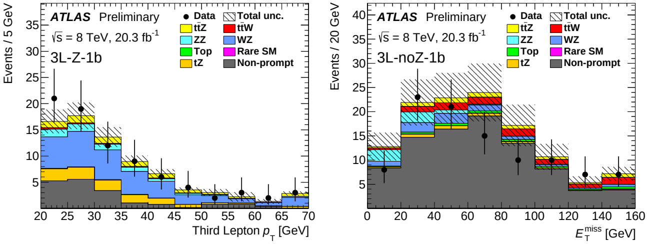
	3ℓ-Z	3ℓ-noZ
$\|m(\ell\ell_{SF,OS})$ - m(Z)$\|$	< 10 GeV	remaining 3L events but NOT all 3L with same-sign
Dominant Signal	$t\bar{t}Z$	$t\bar{t}W$
Main Background	WZ	misID/non-prompt leptons
Fit regions (signal, control regions)	3ℓ-Z-0b3j 3ℓ-Z-1b4j 3ℓ-Z-2b3j 3ℓ-Z-2b4j	3ℓ-noZ-2b



3L SR, from ATLAS-CONF-2015-032

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

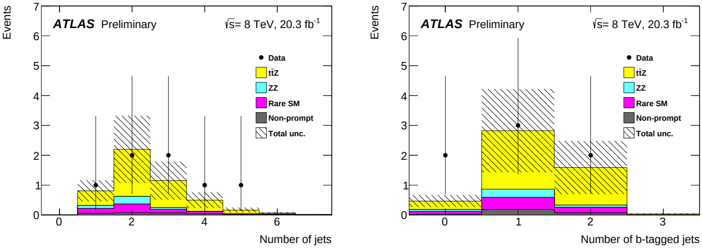


3L VR, from ATLAS-CONF-2015-032

Event selection and background estimation: 4L

- Sensitive to $t\bar{t}Z$
- Choose the best Z candidate $\rightarrow$ l1, l2 (Z1)
- Split signal regions by N_{bjets} and relative flavor of l3, l4 (Z2)

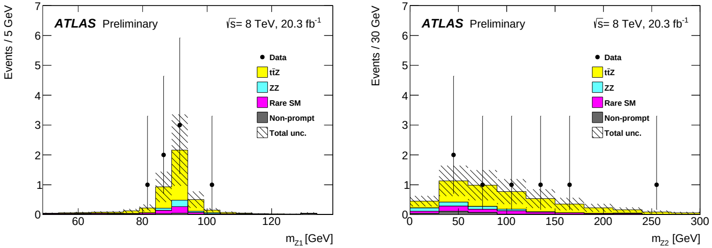
Region	l3, l4	N_{bjets}
4l-DF-0b	$e^{\pm}\mu^{\mp}$	0
4l-DF-1b	$e^{\pm}\mu^{\mp}$	1
4l-DF-2b	$e^{\pm}\mu^{\mp}$	$>= 2$
4l-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	1
4l-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	$>= 2$



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
- $\sigma_{t\bar{t}W} = 369^{+86}_{-79}\,(\mathrm{stat.}) \pm 44(\mathrm{syst.})\,\mathrm{fb} = 369^{+100}_{-91}\,\mathrm{fb}$
- $\sigma_{t\bar{t}Z} = 176^{+52}_{-48}\,(\mathrm{stat.}) \pm 24(\mathrm{syst.})\,\mathrm{fb} = 176^{+58}_{-52}\,\mathrm{fb}$

- Breakdown of the total uncertainties:

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

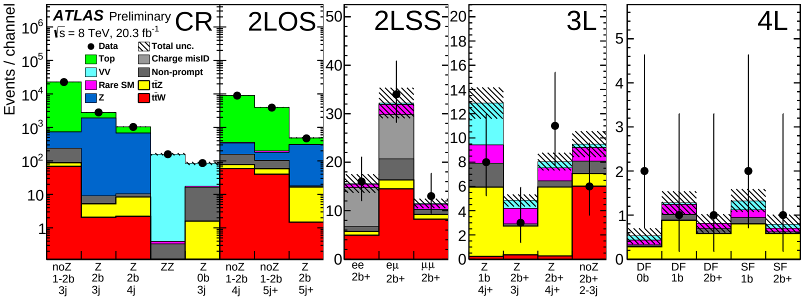
- Expected and observed signal significances:

	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
Channel	Expected	Observed	Expected	Observed
2ℓOS	0.4σ	0.1σ	1.4σ	1.1σ
2ℓSS	2.8σ	5.0σ	-	-
3ℓ	1.4σ	1.0σ	3.7σ	3.3σ
4ℓ	-	-	2.0σ	2.4σ
Combined	3.2σ	5.0σ	4.5σ	4.2σ

from ATLAS-CONF-2015-032

Results

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

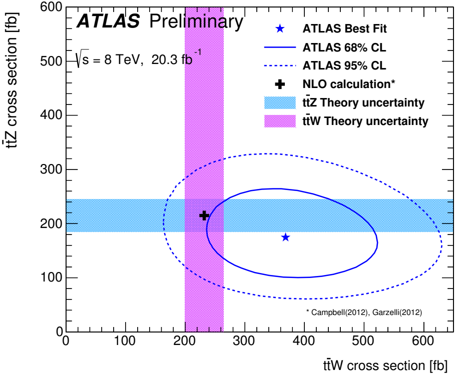


from ATLAS-CONF-2015-032

- 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
- $\sigma_{t\bar{t}W} = 369^{+100}_{-91}\,\mathrm{fb}$, $\sigma_{t\bar{t}Z} = 176^{+58}_{-52}\,\mathrm{fb}$
- The signal significances are 5.0σ for $t\bar{t}W$, and 4.2σ for $t\bar{t}Z$
- The measurements are consistent with the NLO calculations