



Associated Production of $t\bar{t}$ and $t +$ Vector Bosons in ATLAS

Top quark physics at the precision frontier

Serban Protopopescu ([BNL](#))

for ATLAS collaboration

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OUTLINE

- **Introduction**
- **Single top+Z+q cross section measurement**
- **$t\bar{t}$ + vector boson cross section measurements**
 - $t\bar{t} + \gamma$
 - $t\bar{t} + (Z, W)$



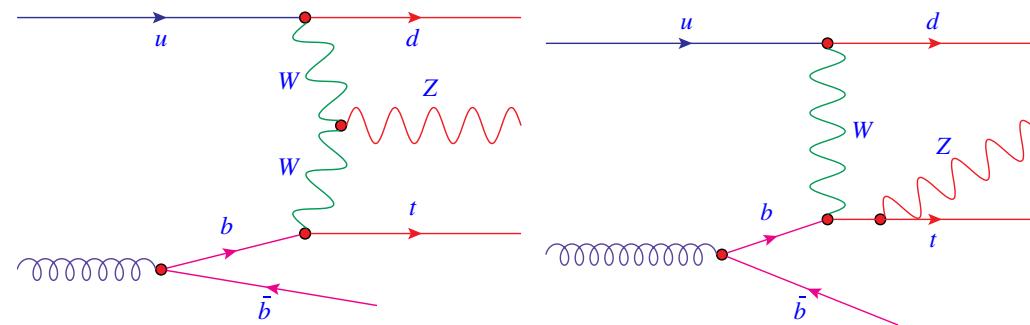
Introduction

- LHC high luminosity and energy \Rightarrow small cross section final states tZq , $t\bar{t}\gamma$, $t\bar{t}W$ and $t\bar{t}Z$ are accessible
- Top quark (t) may play special role in electroweak symmetry breaking (EWSB) due to its large mass
Composite t or excited t (t^*) can be followed by
 $t^* \rightarrow t + V$ (γ, Z)
- Deviations from expected cross sections a signature for physics beyond the SM (BSM).
- Final state $t\bar{t}W$ a source of same sign leptons (SS) with multijets \Rightarrow background to BSM searches using SS as a signature.



tZq Cross Section, 13 TeV

36.1 fb^{-1} : <https://arxiv.org/abs/1710.03659>



- $pp \rightarrow tZq$ process probes the WWZ and tZ couplings
- Important SM background to tH .
- Measurement relies on a three lepton channel: W from t and Z decaying leptonically.



Event Selection

Common selections

Exactly 3 leptons with $|\eta| < 2.5$ and $p_T > 15$ GeV
 $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV
 $p_T(\text{jet}) > 30$ GeV
 $m_T(\ell_W, \nu) > 20$ GeV

SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSSF pair	≥ 1 OSDF pair
$ m_{\ell\ell} - m_Z < 10$ GeV	$ m_{\ell\ell} - m_Z < 10$ GeV	$ m_{\ell\ell} - m_Z > 10$ GeV	No OSSF pair
2 jets, $ \eta < 4.5$	1 jet, $ \eta < 4.5$	2 jets, $ \eta < 4.5$	2 jets, $ \eta < 4.5$
1 b -jet, $ \eta < 2.5$	—	1 b -jet, $ \eta < 2.5$	1 b -jet, $ \eta < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—

SR: signal region, CR: control region, VR: validation region

CR: used to obtain scale factor for WZ background

VR: used to check model

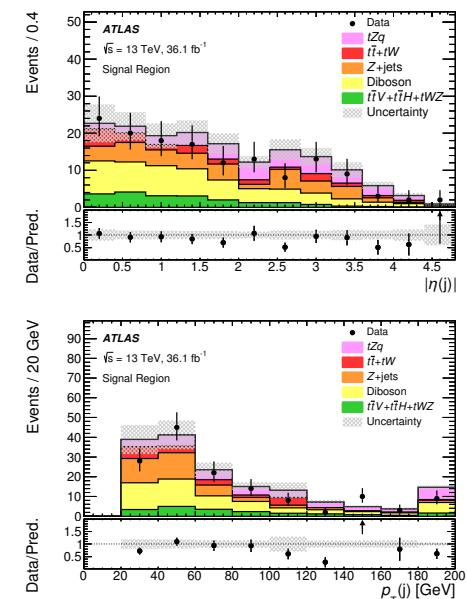


Multivariate analysis

Use NeuroBayes neural-network package with 10 variables.

Training considers all background processes except $t\bar{t}$ (few MC events pass selection criteria). Dominant source of background are WZ events.

Variable	Definition
$ \eta(j) $	Absolute value of untagged jet η
$p_T(j)$	Untagged jet p_T
m_t	Reconstructed top-quark mass
$p_T(\ell^W)$	p_T of the lepton from the W -boson decay
$\Delta R(j, Z)$	ΔR between the untagged jet and the Z boson
$m_T(\ell, E_T^{\text{miss}})$	Transverse mass of W boson
$p_T(t)$	Reconstructed top-quark p_T
$p_T(b)$	Tagged jet p_T
$p_T(Z)$	p_T of the reconstructed Z boson
$ \eta(\ell^W) $	Absolute value of η of the lepton coming from the W -boson decay

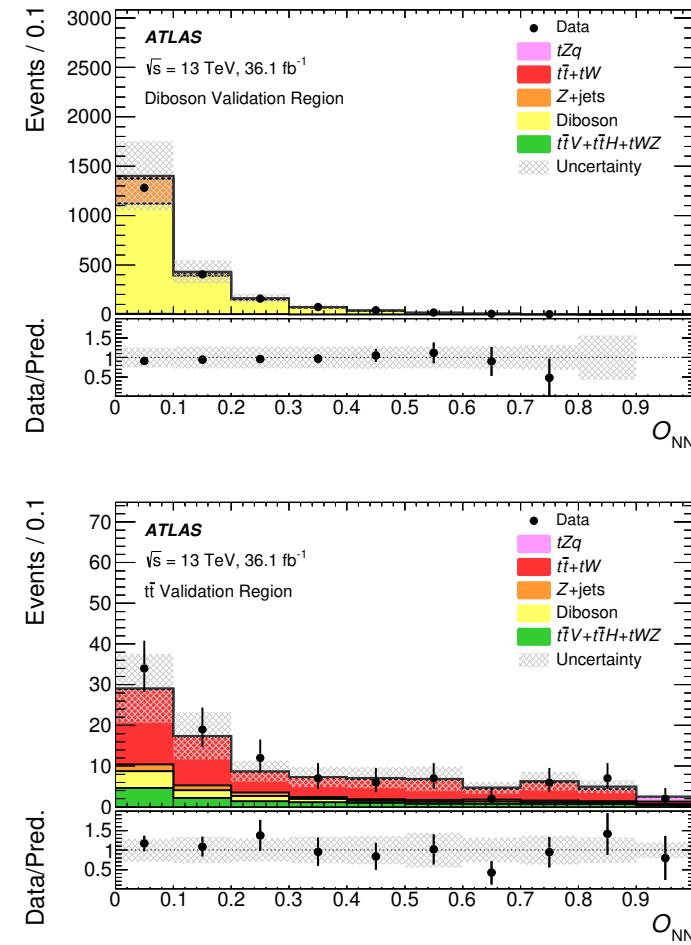




Systematics and Validation



Source	Uncertainty [%]
tZq radiation	± 10.8
Jets	± 4.6
b -tagging	± 2.9
MC statistics	± 2.8
Luminosity	± 2.1
Leptons	± 2.1
tZq PDF	± 1.2
E_T^{miss}	± 0.3

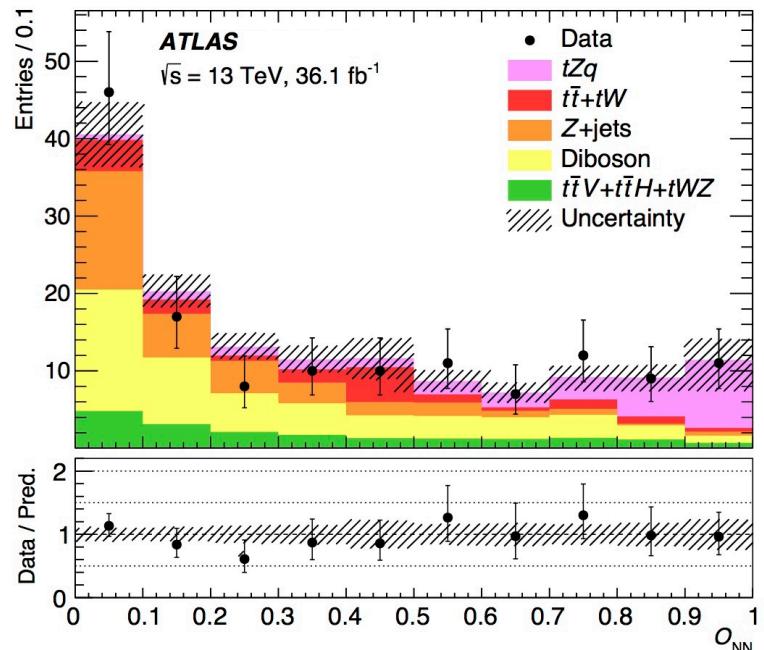




Fit Results



Channel	no. events
tZq	26 ± 8
$t\bar{t}+tW$	17 ± 7
$Z+jets$	34 ± 11
Diboson	48 ± 12
$t\bar{t}V + t\bar{t}H$	
$+tWZ$	19 ± 3
Total	143 ± 11



Data	SM (NLO)
$600 \pm 170 \pm 140 \text{ fb}$	$800^{+49}_{-59} \text{ fb}$



$t\bar{t}\gamma$ Cross Section, 8 TeV

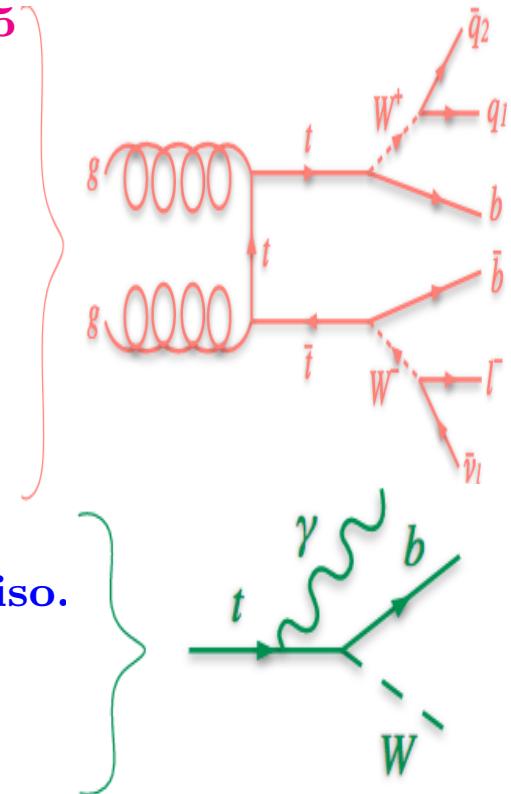
20.2 fb⁻¹: [https://link.springer.com/article/10.1007/JHEP11\(2017\)086](https://link.springer.com/article/10.1007/JHEP11(2017)086)

- Studies of $t\bar{t}\gamma$ production probe the $t\gamma$ EW coupling.
- Deviation from SM predictions of the γ p_T spectrum would indicate an anomalous dipole $t\gamma$ coupling and lead to new physics.
- Event selection optimized to enrich γ radiation from top quarks.
- Production cross section measured using data with one isolated high- p_T lepton, one high- p_T γ and ≥ 4 jets (≥ 1 b-tagged).
- Differential cross section measured as function of γ p_T and η .



Event Selection

- One lepton (e or μ), $p_T > 25 \text{ GeV}, |\eta| < 2.5$
- ≥ 4 jets, $p_T > 25 \text{ GeV}, |\eta| < 2.5$
- ≥ 1 jet tagged as b -jet
- e -channel: $E_T^{miss} > 30 \text{ GeV}$,
 $m_T^W > 30 \text{ GeV}$
- μ -channel: $E_T^{miss} > 20 \text{ GeV}$,
 $E_T^{miss} + m_T^W > 60 \text{ GeV}$
- One photon, $E_T > 15 \text{ GeV}$, $|\eta| < 2.37$, no iso.
- $\Delta R(jet, \gamma) < 0.5$, $\Delta R(\ell, \gamma) < 0.7$
- $|m_{e\gamma} - m_Z| > 5 \text{ GeV}$



Selection yields 1256 e events and 1826 μ events. Expected $t\bar{t}\gamma$ events: 440 ± 90 and 720 ± 140



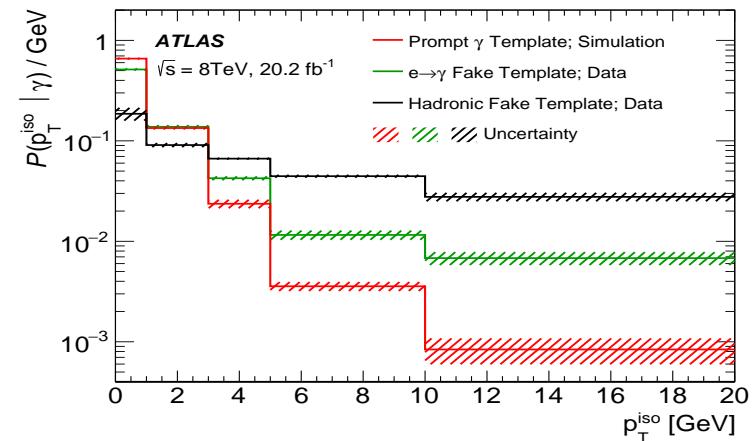
Maximum Likelihood Fit

Signal extracted by max. likelihood fit to p_T^{iso} with 3 templates:

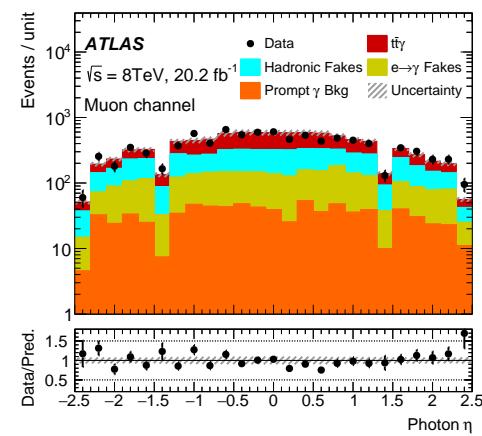
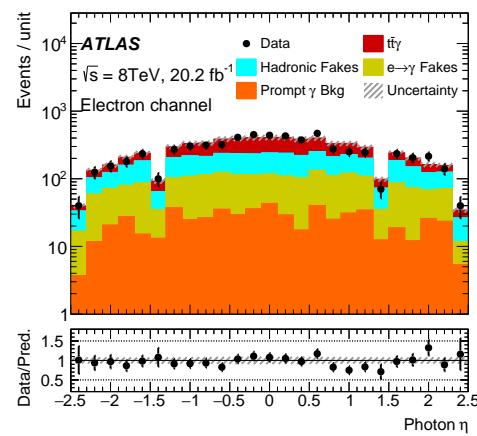
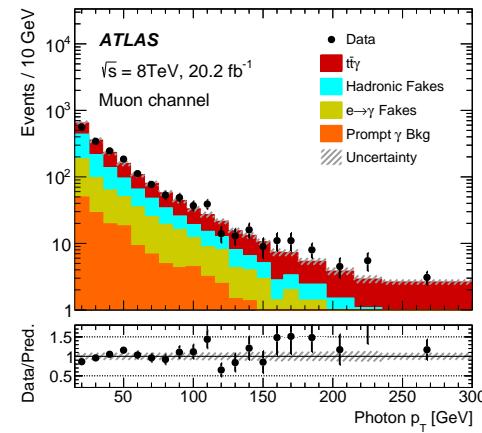
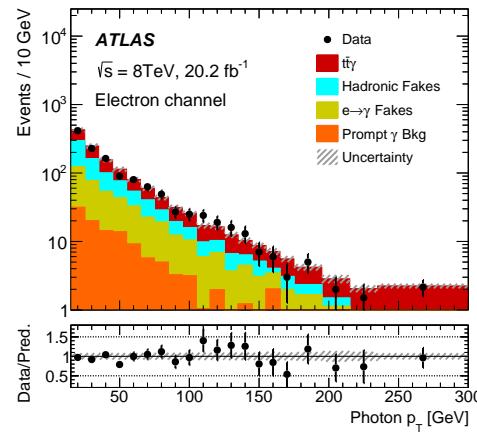
1. prompt γ
2. hadronic fakes
3. e fakes

$p_T^{iso} = \text{sum}(p_T^{tracks})$ within $\Delta R(\gamma, track) < 0.2$

1. from simulated events
2. from control regions with ≥ 4 jets and a γ candidate failing 1 of 4 criteria defining a γ
3. from control sample of $e\gamma$ pairs with $70 < m_{e\gamma} < 110$ GeV



p_T^γ and η_γ distributions



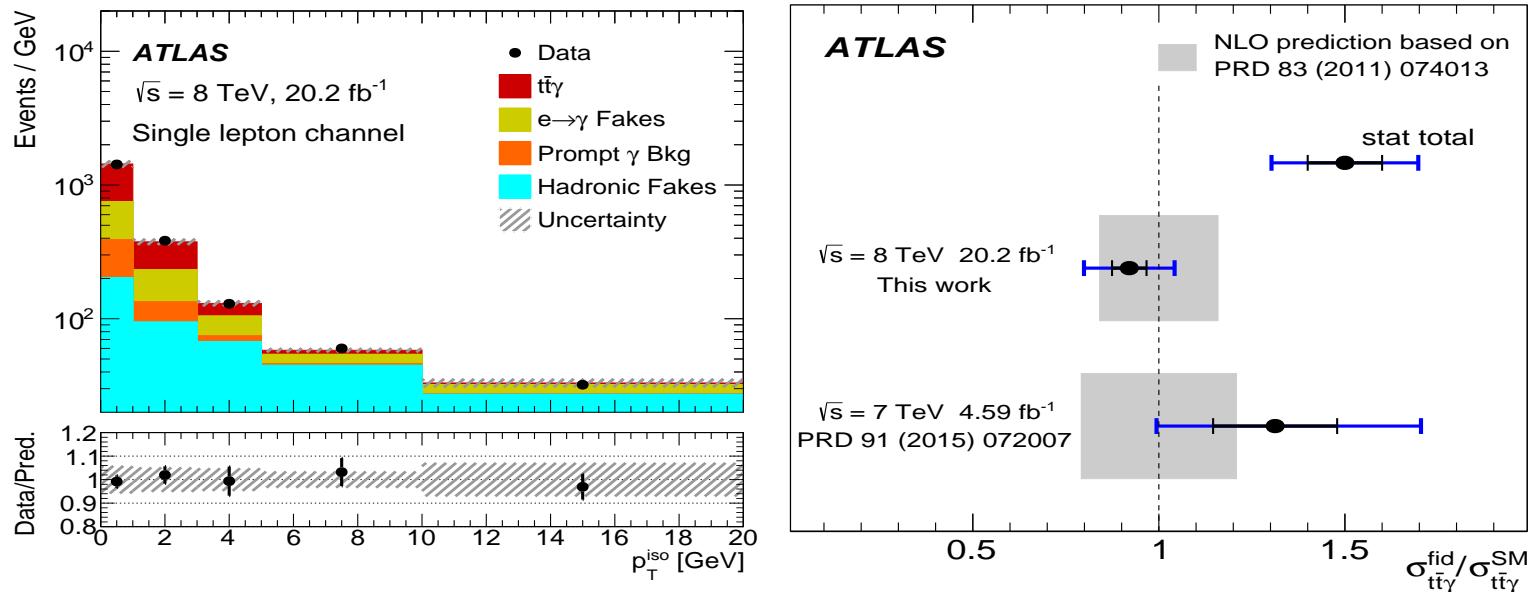


Uncertainties

Source	Relative uncertainty [%]
Hadron-fake template	6.3
$e \rightarrow \gamma$ fake	6.3
Jet energy scale	4.9
$W\gamma + \text{jets}$	4.0
$Z\gamma + \text{jets}$	2.8
Initial- and final-state radiation	2.2
Luminosity	2.1
Photon	1.4
Single top+ γ	1.2
Muon	1.2
Electron	1.0
Scale uncertainty	0.6
Parton shower	0.6
Statistical uncertainty	5.1
Total uncertainty	13



$t\bar{t}\gamma$ fiducial cross section



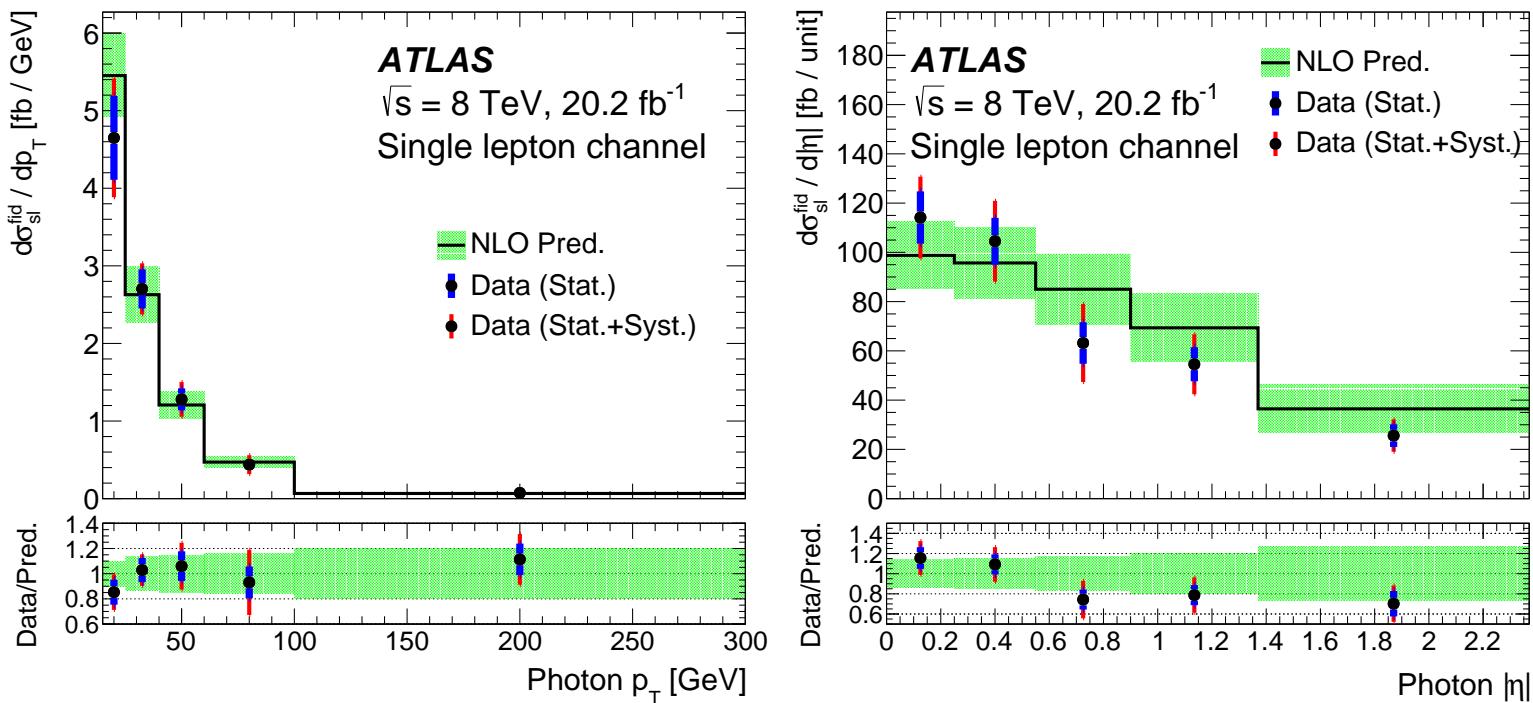
8 TeV: $139 \pm 7 \pm 17 \text{ pb}$

NLO: $151 \pm 24 \text{ pb}$

Fiducial: $p_T^\gamma > 15 \text{ GeV}, \eta_\gamma < 2.37, p_T^\ell > 25 \text{ GeV}, \eta_\ell < 2, 5, \Delta R(\ell, \gamma) > 0.7,$
 $\Delta R(jet, \gamma) > 0.5$



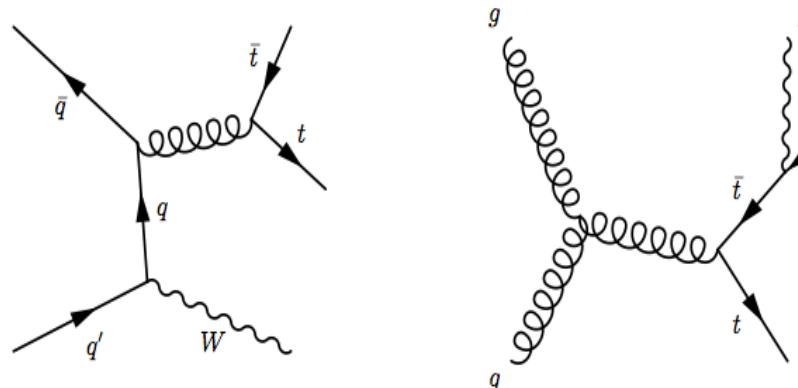
$t\bar{t}\gamma$ differential cross sections



Data well described by simulation within uncertainties.



$t\bar{t}Z$ and $t\bar{t}W$, 8 and 13 TeV



20.3 fb^{-1} , 8 TeV:
<https://link.springer.com/article/10.1140/epjc/s10052-016-4574-y>
3.2 fb^{-1} , 13 TeV:
[https://link.springer.com/article/10.1007/JHEP11\(2015\)172](https://link.springer.com/article/10.1007/JHEP11(2015)172)

Measurements of $t\bar{t}Z$ production give information about t neutral-current coupling

$t\bar{t}W$ a source of SS lepton pairs, important in searches for physics beyond SM.

Channels with only 2 same and opposite sign leptons (2SS, 2OS), 3 and 4 leptons (3L,4L) are used.

At 13 TeV 2OS channel is not included.

$t\bar{t}W$: dominates 2SS, minor contribution to 3L

$t\bar{t}Z$: major contribution to 3L, little non- $t\bar{t}Z$ events in 4L



2OS Analysis (8 TeV only)

2OS sample categorized
in 3×2 regions

2ℓ with =3, =4, $\geq 4(5)$ jets
with and w/o ($|m_{\ell\ell} - m_Z| < 10$ GeV)
 $p_T^\ell > 25$ GeV, $\eta_\ell < 2.5$
 $p_T^{jet} > 25$ GeV, ≥ 1 b-tag

Region	Targeting	Sample fraction [%]
$2\ell\text{-no}Z\text{-4j}$	$t\bar{t}W$ and $t\bar{t}Z$	0.68
$2\ell\text{-no}Z\text{-5j}$		1.2
$2\ell\text{-}Z\text{-5j}$	$t\bar{t}Z$	3.3
$2\ell\text{-no}Z\text{-3j}$	$t\bar{t}$	92
$2\ell\text{-}Z\text{-3j}$	Z	70
$2\ell\text{-}Z\text{-4j}$		66

$2\ell\text{-no}Z\text{-4j}$, $2\ell\text{-no}Z\text{-5j}$ and $2\ell\text{-}Z\text{-5j}$ are signal regions (SR)

$2\ell\text{-no}Z\text{-3j}$, $2\ell\text{-}Z\text{-3j}$ and $2\ell\text{-}Z\text{-4j}$ are control regions (CR)

$2\ell\text{-}Z$ regions require 2 b-tags.

CR used to constrain background norm. uncertainties
by event counting in $2\ell\text{-no}Z\text{-3j}$, fitting H_T^{had} in $2\ell\text{-}Z\text{-3j}$, $2\ell\text{-}Z\text{-4j}$
Separate NN discriminant used for each SR.
Fit SR NN output distributions to extract $t\bar{t}Z$ and $t\bar{t}W$ signals.



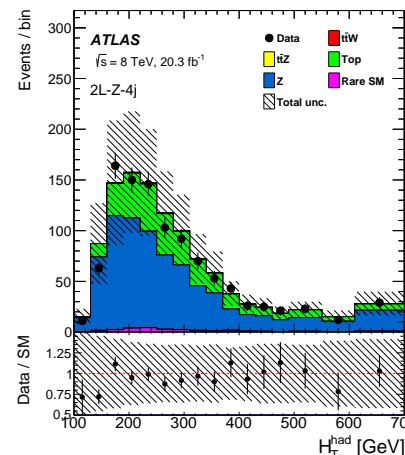
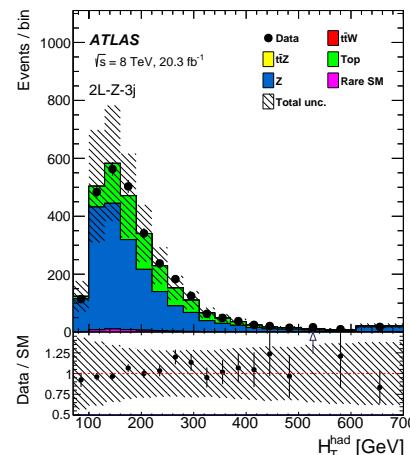
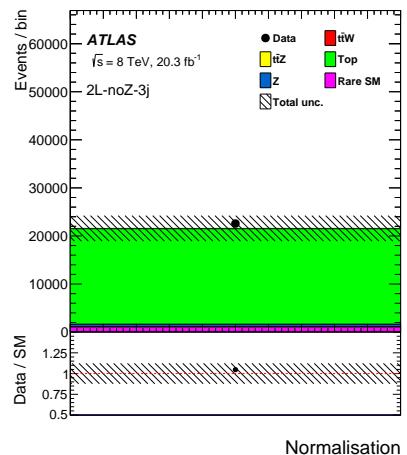
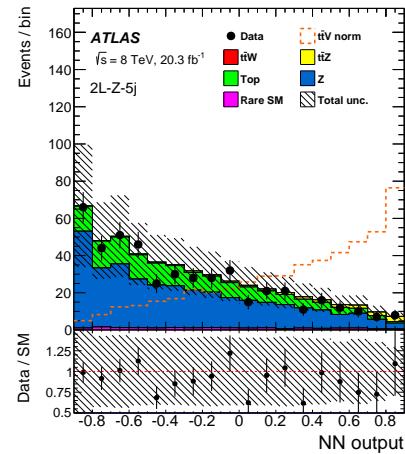
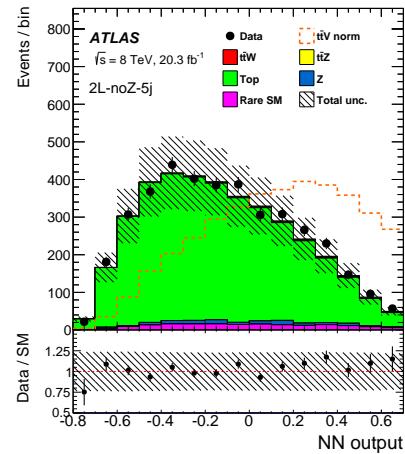
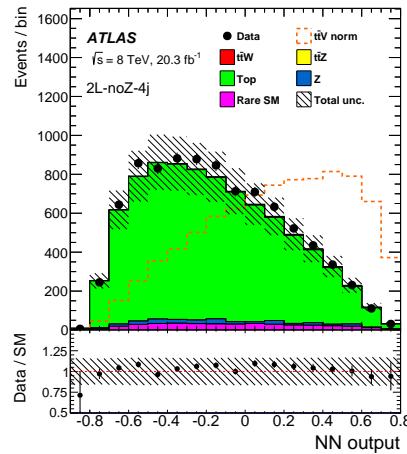
2OS NN variables

Variable	Definition	NN rank		
		a	b	c
$m_{uu}^{p_T, ord}$	m_{jj} of 2 highest untagged p_t^{jet}	1	7	-
Cent_{jet}	$\text{sum}(p_T^{jet})/\text{sum}(E^{jet})$	2	1	6
H_1	2nd Fox-Wolfram moment	3	2	-
$m_{jj}^{\min \Delta R}$	m_{jj} of min ΔR_{jj}	4	6	-
$\max m_{\ell b}^{\min \Delta R}$	max. $m_{\ell, b}$ of min. $(\Delta R(\ell, b))$	5	5	-
p_T^{jet3}	p_T of 3rd jet	6	-	-
p_T^{jet4}	p_T of 4th jet	-	3	-
ΔR_{ave}^{jj}	average ΔR of all jet pairs	7	-	-
$N_{jet}^{ m_{jj} - m_V < 30}$	N_{jj} with $ m_{jj} - m_V < 30$ GeV	-	4	2
N_{40}^{jet}	no of jets with $p_T > 40$ GeV	-	-	1
$m_{bb}^{\max p_T}$	m_{bb} of pair with max. p_T	-	-	3
$\Delta R^{\ell 1 \ell 2}$	ΔR of 2 leptons	-	-	4
$m_{bj}^{\max p_T}$	m_{bj} of pair with max. p_T	-	-	5
H_1^{jet}	H_1 with only jets	-	-	7

a= 2ℓ-noZ-4j, b= 2ℓ-noZ-5j, c=2ℓ-Z-5j



2OS Fits





2SS Analysis, 8 and 13 TeV

This channel targets $t\bar{t}W$ process.

Events split into three regions: **2e-SS**, **$e\mu$ -SS** and **2μ -SS**.

$e\mu$ -SS and **$\mu\mu$ -SS** regions subdivided into 4 sub-regions:

low- N_{jets} ($N_{jets} < 4$), low- E_T^{miss} ($40 < E_T^{miss} < 80$ GeV),
high- N_{jets} ($N_{jets} \geq 4$), high- E_T^{miss} ($E_T^{miss} > 80$ GeV).

Only the **$\mu\mu$ -SS** region is used at 13 TeV.

All regions require $E_T^{miss} > 40$ GeV, $H_T > 240$ GeV and ≥ 2 b-tagged jets.

2e-SS requires $75 < m_{ee} < 105$ GeV

Main Backgrounds: e with misidentified charge (1) or non-iso. ℓ (fakes) (2).

(1) estimated studying events with $75 < m_{ee} < 105$ GeV

(2) estimated from ratios of loose/tight isolation criteria.

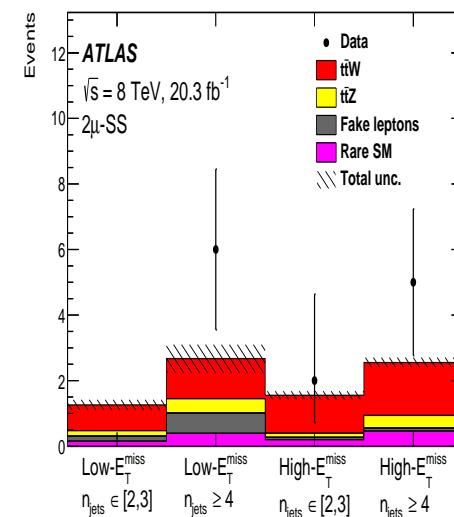
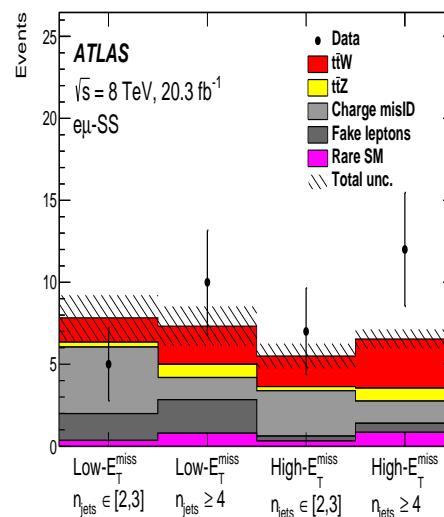
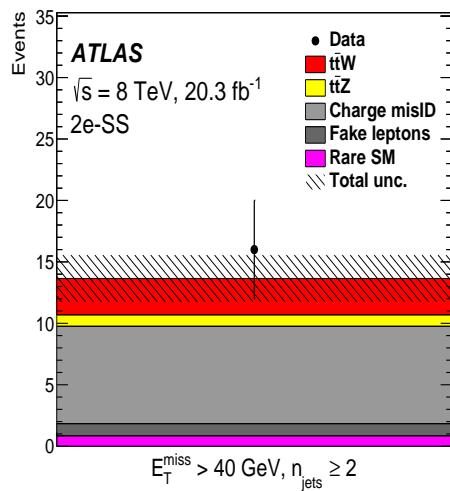
The amount of signal is obtained from event yield



2SS Event yields, 8 and 13 TeV

8 TeV

backg.	$t\bar{t}W$	$t\bar{t}Z$	Data
28.3 ± 5.8	16.4 ± 0.9	4.21 ± 0.62	63



13 TeV

backg.	$t\bar{t}W$	$t\bar{t}Z$	Data
2.6 ± 1.3	2.32 ± 0.33	0.7 ± 0.10	9



3L Analysis

Not all 3 ℓ can have same sign and $p_T^{\ell 3} > 20$ GeV.

Two sets of events pre-selected:

3 ℓ -Z (for $t\bar{t}Z$) and **3 ℓ -noZ** (for $t\bar{t}W$), .

3 ℓ -Z have an opposite sign pair with $|m_{\ell\ell} - m_Z| < 10$ GeV

3 ℓ -noZ do not and require $p_T^{\ell 3} > 25$ GeV.

4 signal regions defined:

3 ℓ -Z-1b4j (≥ 4 jets, $=1$ b-tag), **3 ℓ -Z-2b3j** ($=3$ jets, ≥ 2 b-tags),

3 ℓ -Z-2b4j (≥ 4 jets, ≥ 2 b-tags), **3 ℓ -noZ-2b** (≥ 2 b-tags)

Control region **3 ℓ -Z-0b3j** ($= 3$ jets) to constrain WZ background

Verification region **3 ℓ -noZ-1b3j** to verify backg. model at 13 TeV

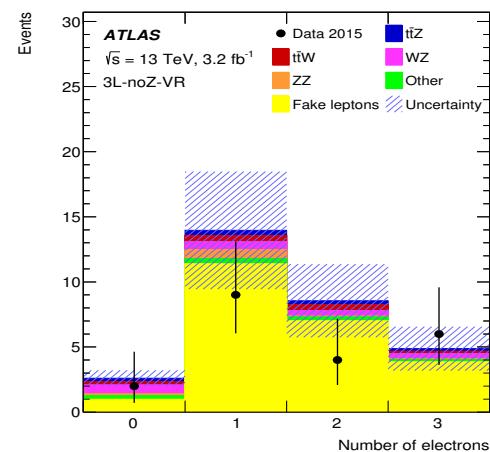
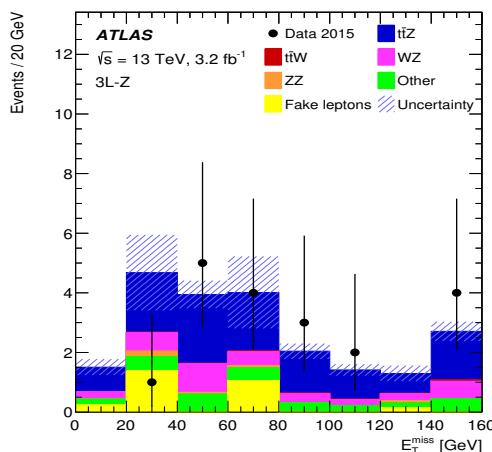
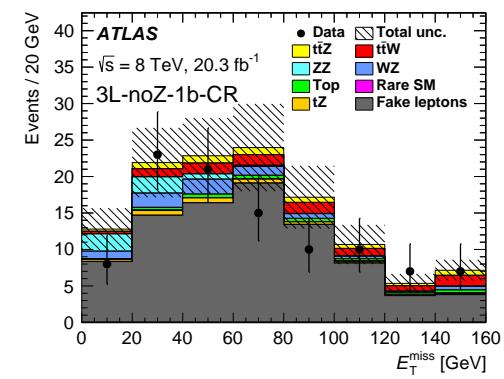
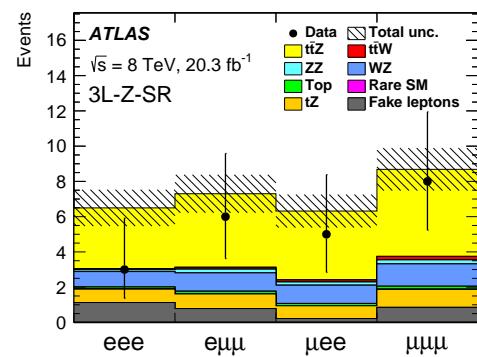
Signals extracted from event yields. Fake ℓ backg. estimated from data.



3L Event yields

Expected yields:

8 TeV	
backg.	14.6 ± 1.9
$t\bar{t}Z$	17.7 ± 2.4
$t\bar{t}W$	4.2 ± 0.9
data	28
13 TeV	
backg.	13.8 ± 3.6
$t\bar{t}Z$	13.2 ± 1.0
$t\bar{t}W$	1.77 ± 0.29
data	29





4L Analysis

This channel targets $t\bar{t}Z$ process with both W 's and Z decaying leptonically.

Z_1 : same flavor opposite sign leptons (OSSF) with $m_{\ell\ell}$ closest to m_Z

Z_2 : the other 2 leptons.

5 signal regions defined:

4 ℓ -DF-0b, 4 ℓ -DF-1b, 4 ℓ -DF-2b, 4 ℓ -SF-1b, 4 ℓ -SF-2b.

DF: Z_2 pair different flavor, SF: same flavor.

4 ℓ -DF-0b not used at 13 TeV.

Signal extracted by event counting

Region	Z_2 leptons	p_{T34}	$ m_{Z_2} - m_Z $	E_T^{miss}	$n_{b\text{-tags}}$
4 ℓ -DF-1b	$e^\pm \mu^\mp$	$> 35 \text{ GeV}$	-	-	1
4 ℓ -DF-2b	$e^\pm \mu^\mp$	-	-	-	≥ 2
4 ℓ -SF-1b	$e^\pm e^\mp, \mu^\pm \mu^\mp$	$> 25 \text{ GeV}$	$\begin{cases} > 10 \text{ GeV} & > 40 \text{ GeV} \\ < 10 \text{ GeV} & > 80 \text{ GeV} \end{cases}$	-	1
4 ℓ -SF-2b	$e^\pm e^\mp, \mu^\pm \mu^\mp$	-	$\begin{cases} > 10 \text{ GeV} & - \\ < 10 \text{ GeV} & > 40 \text{ GeV} \end{cases}$	-	≥ 2

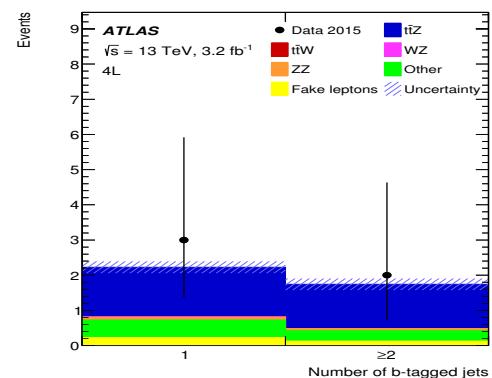
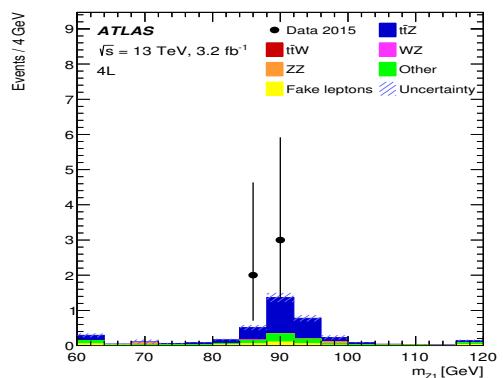
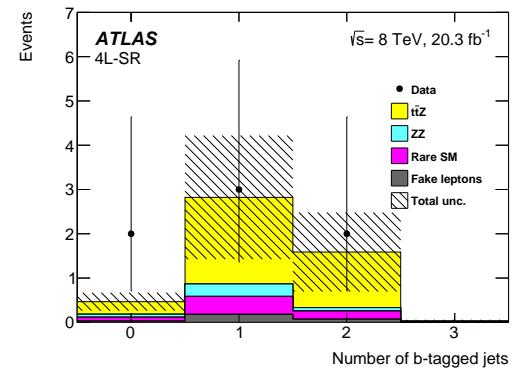
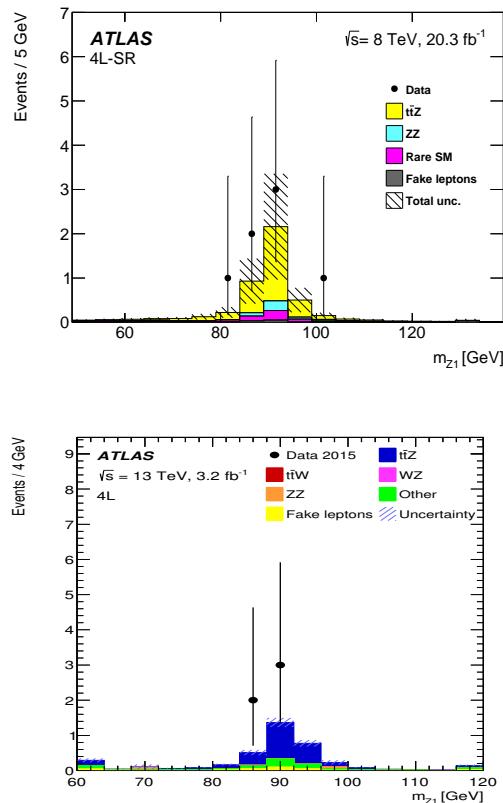


4L Event yields

Expected yields:

8 TeV	
backg.	1.64 ± 0.35
$t\bar{t}Z$	3.52 ± 0.05
data	7

13 TeV	
backg.	1.27 ± 0.12
$t\bar{t}Z$	1.40 ± 0.18
data	5





Systematics and Significance

All regions of 2OS (not in 13 TeV), 2SS, 3L and 4L
fitted simultaneously to extract $t\bar{t}Z$ and $t\bar{t}W$ signal.

8 TeV

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

13 TeV

Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	2.6%	3.1%
Reconstructed objects	8.3%	9.3%
Backgrounds from simulation	5.3%	3.1%
Fake leptons and charge misID	3.0%	19%
Signal modelling	2.3%	4.2%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

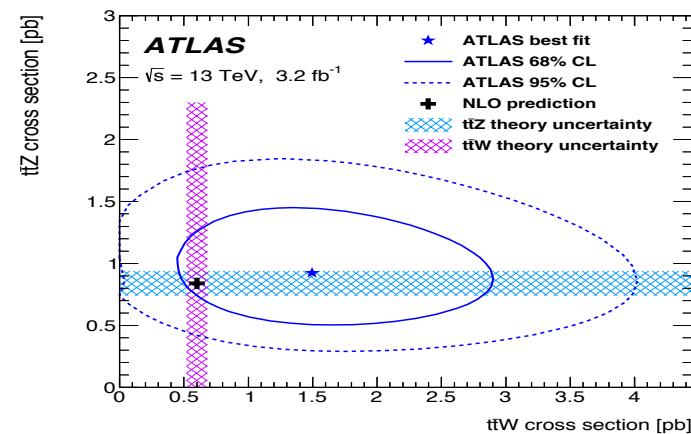
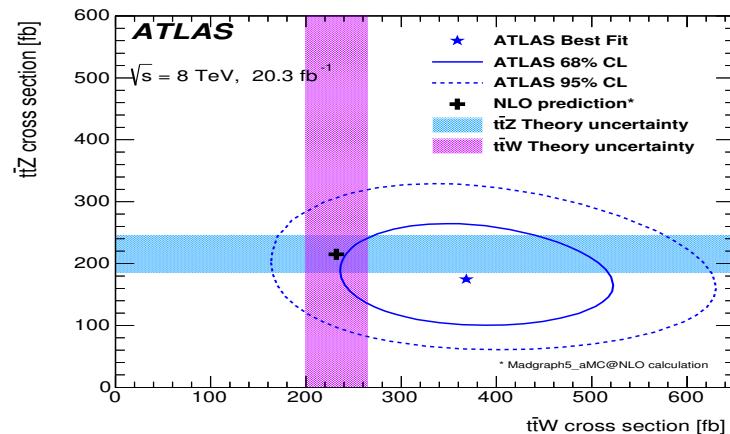
significance (no. of standard dev.):

	$t\bar{t}W$		$t\bar{t}Z$	
	Expected	Observed	Expected	Observed
8 TeV	3.2	5.0	4.5	4.2
13 TeV	1.0	2.2	3.4	3.2

stat. uncertainty
dominates



$t\bar{t}W$ and $t\bar{t}Z$ Cross Sections



8 TeV $\sigma_{t\bar{t}W}$	369^{+100}_{-91} fb
8 TeV $\sigma_{t\bar{t}Z}$	176^{+58}_{-52} fb
13 TeV $\sigma_{t\bar{t}W}$	1500 ± 800 fb
13 TeV $\sigma_{t\bar{t}Z}$	900 ± 300 fb



Summary

Inclusive and differential cross sections of single top and $t\bar{t}$ pairs associated with vector bosons have been measured in 8 and 13 TeV pp collisions with the ATLAS detector.

Other than $t\bar{t}\gamma$ (dominated by fake γ 's) all measurements are statistics limited. All agree with SM expectations.

Measured Cross Sections

	8 TeV 20.3 fb^{-1}	13 TeV 36.3 fb^{-1} (1), 3.2 fb^{-1} (2)
tZq	-	$600 \pm 170 \pm 140 \text{ fb}$ (1)
$t\bar{t}\gamma$	$139 \pm 7 \pm 17 \text{ pb}$	-
$t\bar{t}W$	$369^{+100}_{-91} \text{ fb}$	$1500 \pm 800 \text{ fb}$ (2)
$t\bar{t}Z$	$176^{+58}_{-52} \text{ fb}$	$900 \pm 300 \text{ fb}$ (2)