$t\bar{t}V$ $V = W, Z$ measurements from ATLAS and CMS

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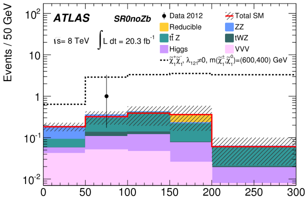
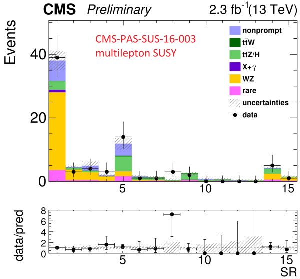
Introduction

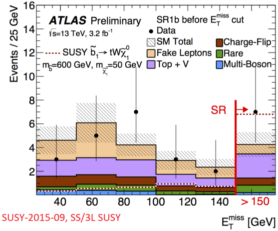
Top pair production in association with a Z or W:

- Heaviest final states produced and measured at the LHC thus far
- Rare SM processes - provide an important test of the SM
- $t\bar{t}Z$ measurements provide a window to the coupling of the top to the Z (but also $t\bar{t}W$ through tW scattering - Dror et al, arXiv:1511.03674)
- Important backgrounds to BSM physics searches in various final states: stop pair production ($t\bar{t}$+MET final state), EWK SUSY production giving 3/4 real leptons in the final state, SS dilepton searches, and others
- Also important backgrounds to $t\bar{t}H$ measurements in multilepton final states



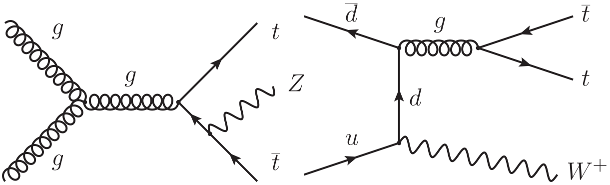
arXiv:1405.5086 SUSY 4l+MET





SUSY-2015-09, SS/3L SUSY

$t\bar{t}V$ production at the LHC



Cross sections computed to NLO in α_s (=$\mathcal{O}(\alpha_s^3\alpha)$).

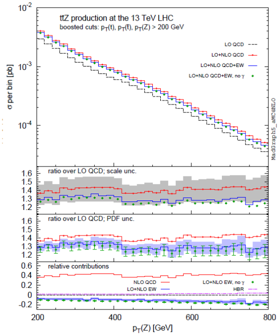
- $\mathcal{O}(\alpha_s\alpha^2), \mathcal{O}(\alpha_s^2\alpha^2)$ electroweak corrections also computed (Frixione et al, arXiv:1504.03446)
- few % corrections to inclusive cross-sections, but can be important in tails of observables (e.g. $p_T(Z)$)

$t\bar{t}V$ production at the LHC: cross sections

Process		Syntax	Cross section (pb)	
Heavy quarks+vector bosons			LO 13 TeV	NLO 13 TeV
e.7	$pp \to t\bar{t}W^{\pm}$	`p p > t t~ wpm`	$3.777 \pm 0.003 \cdot 10^{-1}$ ${}^{+23.9\%}_{-18.0\%}$ ${}^{+2.1\%}_{-1.6\%}$	$5.662 \pm 0.021 \cdot 10^{-1}$ ${}^{+11.2\%}_{-10.6\%}$ ${}^{+1.7\%}_{-1.3\%}$
e.8	$pp \to t\bar{t}Z$	`p p > t t~ z`	$5.273 \pm 0.004 \cdot 10^{-1}$ ${}^{+30.5\%}_{-21.8\%}$ ${}^{+1.8\%}_{-2.1\%}$	$7.598 \pm 0.026 \cdot 10^{-1}$ ${}^{+9.7\%}_{-11.1\%}$ ${}^{+1.9\%}_{-2.2\%}$
e.9	$pp \to t\bar{t}\gamma$	`p p > t t~ a`	$1.204 \pm 0.001 \cdot 10^{0}$ ${}^{+29.6\%}_{-21.3\%}$ ${}^{+1.6\%}_{-1.8\%}$	$1.744 \pm 0.005 \cdot 10^{0}$ ${}^{+9.8\%}_{-11.0\%}$ ${}^{+1.7\%}_{-2.0\%}$

Alwall et al, arXiv:1405.0301

$t\bar{t}Z$: σ(pb)	8 TeV	13 TeV
LO QCD	$1.379 \cdot 10^{-1}$	$5.282 \cdot 10^{-1}$ $(1.955 \cdot 10^{-2})$
NLO QCD	$5.956 \cdot 10^{-2}$	$2.426 \cdot 10^{-1}$ $(7.856 \cdot 10^{-3})$
LO EW	$6.552 \cdot 10^{-4}$	$-2.172 \cdot 10^{-4}$ $(4.039 \cdot 10^{-4})$
LO EW no γ	$-1.105 \cdot 10^{-3}$	$-5.771 \cdot 10^{-3}$ $(-6.179 \cdot 10^{-5})$
NLO EW	$-4.540 \cdot 10^{-3}$	$-2.017 \cdot 10^{-2}$ $(-2.172 \cdot 10^{-3})$
NLO EW no γ	$-5.069 \cdot 10^{-3}$	$-2.158 \cdot 10^{-2}$ $(-2.252 \cdot 10^{-3})$
HBR	$1.316 \cdot 10^{-3}$	$5.056 \cdot 10^{-3}$ $(4.162 \cdot 10^{-4})$



Frixione et al, arXiv:1504.03446

NB: 13 TeV SM value used in CMS $\sigma(t\bar{t}Z) = 839\ {}^{+80}_{-92}(\text{scale})\ {}^{+25}_{-25}(\text{PDF})\ {}^{+25}_{-25}(\alpha_s)$ fb slightly higher than ATLAS value of $\sigma(t\bar{t}Z) = 760$ fb, due to different scale choices.

$t\bar{t}V$ measurements at the LHC

Can be attempted in many different final states.

$t\bar{t}Z$

- Dilepton: $(t \to bjj)(t \to bjj)(Z \to l^{\pm}l^{\mp})$, $(t \to bl^{+}\nu)(\bar{t} \to \bar{b}l^{-}\bar{\nu})(Z \to jj)$
- Trilepton: $(t \to bl^{\pm}\nu)(t \to bjj)(Z \to l^{\pm}l^{\mp})$
- Four lepton: $(t \to bl^{+}\nu)(\bar{t} \to \bar{b}l^{-}\bar{\nu})(Z \to l^{\pm}l^{\mp})$
- Others (e.g. $Z \to$invisible), not explored yet

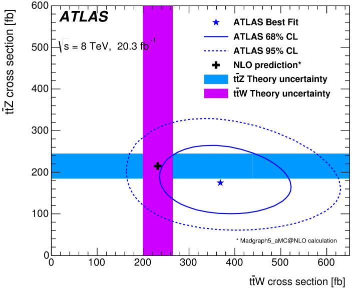
Sample statistics, S/B and dominant backgrounds very different for different final states.

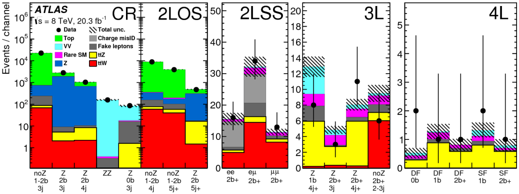
- $t\bar{t}Z$ and $t\bar{t}W$ studied at both ATLAS (arXiv:1509.05276) and CMS (arXiv:1510.01131) in Run 1
- Preliminary Run 2 results for $t\bar{t}Z$ by CMS and for $t\bar{t}Z$ and $t\bar{t}W$ by ATLAS
- ATLAS and CMS strategies broadly similar

ATLAS 8 TeV results

Simultaneous fit to extract $t\bar{t}Z$ and $t\bar{t}W$ cross sections in $2l$ (OS and SS), $3l$ and $4l$ signal regions.

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

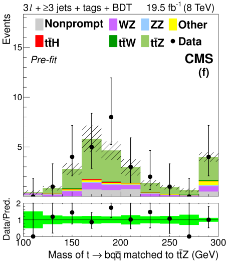


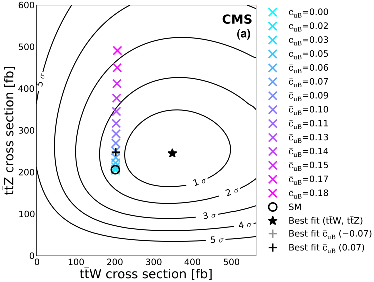


CMS 8 TeV results

Like ATLAS, uses $2l$ (OS and SS), $3l$ and $4l$ signal regions.

- Also attempts full event reconstruction, feeding outputs (match scores) into BDTs
- Limits set on vector/axial couplings and dim-6 EFT operators, based on implemetation from Fuks et al. JHEP **1404** (2014) 110





Significances 6.4σ for $t\bar{t}Z$ and 4.8σ for $t\bar{t}W$ (5.7 and 3.5 expected).

- Mild excesses seen by both ATLAS and CMS in SS $2l$ channels

ATLAS+CMS 8 TeV combination

ATLAS measurement

$$\sigma_{t\bar{t}Z} = 176\ ^{+52}_{-48}(\text{stat.}) \pm 24(\text{syst.})\ \text{fb}$$
$$\sigma_{t\bar{t}W} = 369\ ^{+80}_{-92}(\text{stat.}) \pm 44(\text{syst.})\ \text{fb}$$

CMS measurement

$$\sigma_{t\bar{t}Z} = 245\ ^{+65}_{-55}\ \text{fb}$$
$$\sigma_{t\bar{t}W} = 382\ ^{+117}_{-102}\ \text{fb}$$

The SM predictions at 8 TeV are $\sigma_{t\bar{t}Z} = 206^{+19}_{-24}$ fb and $\sigma_{t\bar{t}W} = 203^{+20}_{-22}$ fb.

A statistical combination of the results is in progress.

$t\bar{t}Z$ @ CMS with 13 TeV data

Preliminary result shown at Moriond 2016: CMS-PAS-TOP-16-009.

- Considers $3l$ and $4l$ channels.

Monte Carlo

- $t\bar{t}V$ (including $V = H, \gamma$), triboson and tZq from MG5_AMC@NLO+Pythia8
- Powheg used for WZ/ZZ simulation

Dataset and object definitions

- Uses data collected with single lepton triggers with thresholds at 23 (20) GeV for e (μ)
- Integrated lumi 2.7 fb^{-1}
- Isolated leptons with $p_T > 10$ GeV used, $|\eta| < 2.4$ (< 2.5) for μ (e)
- Jets with $p_T > 30$ GeV, $|\eta| < 2.4$; b-tagging efficiency 75%-85% depending on p_T and η

$t\bar{t}Z$ @ CMS @ 13 TeV: signal regions

$3l$ signal regions

Separated by jet and b-jet multiplicity.

- one OSSF pair of leptons with $|m_{ll} - M_Z| < 10$ GeV
- lepton p_Ts at least $30, 20, 10$ GeV
- $N_{\mathrm{jets}} = 2$ and $N_{\mathrm{b-jets}} = 0, \geq 1$
- $N_{\mathrm{jets}} = 3$ and $N_{\mathrm{b-jets}} = 0, = 1, \geq 2$
- $N_{\mathrm{jets}} \geq 4$ and $N_{\mathrm{b-jets}} = 0, = 1, \geq 2$

$4l$ signal regions

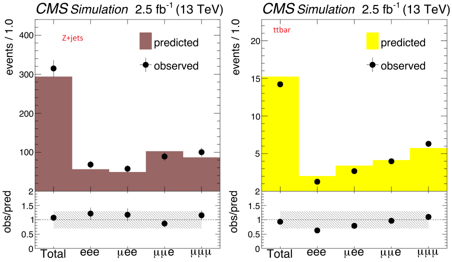
- lepton p_Ts at least $20, 10, 10, 10$ GeV
- one OSSF pair of leptons with $|m_{ll} - M_Z| < 20$ GeV
- Sum of lepton charges $= 0$
- $m_{ll} > 12$ GeV for all OSSF lepton pairs
- reject 2nd OSSF pair in $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$ events
- $N_{\mathrm{jets}} \geq 2$ and $N_{\mathrm{b-jets}} = 0, \geq 1$

$t\bar{t}Z$ @ CMS @ 13 TeV: estimate of non-prompt lepton background

$3l$ channel dominated by WZ and non-prompt lepton backgrounds.

- Non-prompt leptons arise from heavy flavour hadron decays, photon conversions, mis-ID hadrons
- Estimated from data using a sideband containing events which pass a loose lepton selection and fail the tight one
- Weights applied to events in sideband based on **tight to loose** ratio measured in dijet events with loose leptons

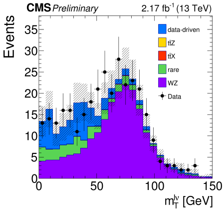
$\sim$30% systematic from closure test in MC: rates from QCD events applied in $t\bar{t}$ and Z+jets.



$t\bar{t}Z$ @ CMS @ 13 TeV: estimate of WZ background

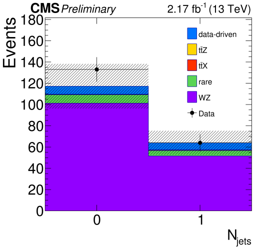
To determine the WZ background in the $3l$ regions, a low jet multiplicity $3l$ region is used.

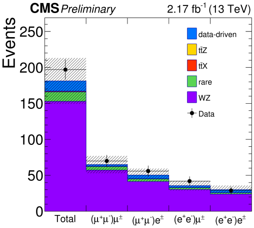
- OSSF lepton pair; $N_{\rm jets} = 0, 1$ and $N_{\rm b-jets} = 0$
- $E_T^{\rm miss} > 30$ GeV, $M_T^{l\nu} > 50$ GeV to suppress non-prompt background



$N_{\rm obs}/N_{\rm exp} = 1.1 \pm 0.1 \implies$ used as a systematic uncertainty.

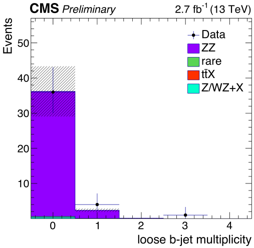
- heavy flavour modelling assessed in Z+jets events; additional 20% systematic from here (also includes extrapolation to higher $N_{\rm jet}, N_{b-jet}$)

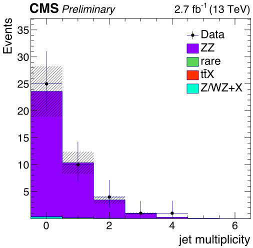




$t\bar{t}Z$ @ CMS @ 13 TeV: ZZ and other backgrounds

- $4l$ validation region considered for ZZ.
- 2 SFOS pairs required
- orthogonal to $4l$ SR
- 20% resulting uncertainty





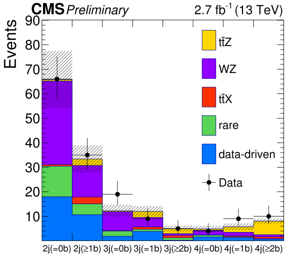
Rare processes all estimated from MC (to NLO accuracy).

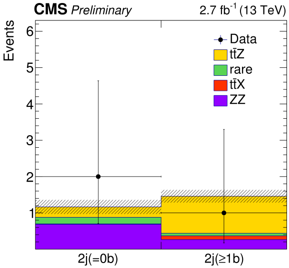
- scale + PDF uncertainties on $t\bar{t}X \sim 25\%$
- others (triboson etc) assigned a 50% uncertainty

In $4l$ SR, non-prompt lepton backgrounds from MC $\longrightarrow$ found to be negligible.

$t\bar{t}Z$ @ CMS @ 13 TeV: results

Profile likelihood fit used to extract signal cross section.



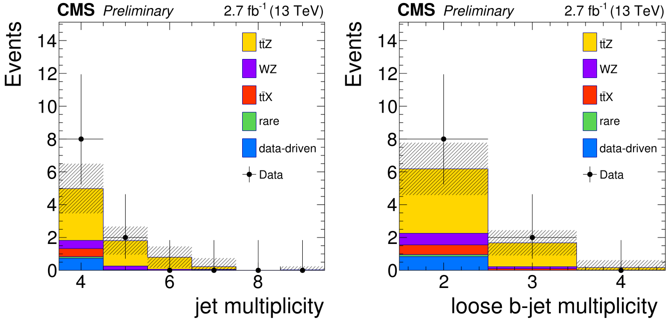


	$N_{\text{jets}} \geq 4$		
Process	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} = 1$	$N_{\text{bjets}} \geq 2$
WZ	1.88 ± 0.16±0.38	1.48 ± 0.15±0.30	0.82 ± 0.12±0.16
ttX	0.06 ± 0.02±0.01	0.40 ± 0.07±0.10	0.78 ± 0.08±0.19
Non-prompt	1.56 ± 0.62±0.47	1.26 ± 0.85±0.38	0.72 ± 0.53±0.22
Rare	0.78 ± 0.24±0.39	0.33 ± 0.03±0.16	0.16 ± 0.02±0.08
Background	4.27 ± 0.69±0.72	3.46 ± 0.87±0.52	2.48 ± 0.55±0.34
ttZ	0.59 ± 0.10±0.10	2.29 ± 0.22±0.23	5.58 ± 0.32±0.45
Predicted	4.87 ± 0.69±0.72	5.74 ± 0.89±0.57	8.06 ± 0.64±0.57
Data	4	9	10

	$N_{\text{jets}} \geq 2$	
Process	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} \geq 1$
ZZ	0.68 ± 0.03 ± 0.15	0.27 ± 0.01 ± 0.06
$t\bar{t}X$	0.01 ± 0.01 ± 0.01	0.10 ± 0.03 ± 0.03
Rare	0.18 ± 0.02 ± 0.09	0.07 ± 0.01 ± 0.04
Background	0.87 ± 0.04 ± 0.17	0.44 ± 0.03 ± 0.08
$t\bar{t}Z$	0.29 ± 0.06 ± 0.04	1.02 ± 0.13 ± 0.08
Predicted	1.16 ± 0.07 ± 0.17	1.46 ± 0.13 ± 0.13
Data	2	1

$t\bar{t}Z$ @ CMS @ 13 TeV: results

Measured value $\sigma(pp \to t\bar{t}Z) = 1065\ ^{+352}_{-313}(\text{stat.})\ ^{+168}_{-142}(\text{syst.})$ fb, consistent with the SM prediction of $839\ ^{+80}_{-92}(\text{scale})\ ^{+25}_{-25}(\text{PDF})\ ^{+25}_{-25}(\alpha_s)$ fb.



Channel	Expected significance	Observed significance
3ℓ analysis	2.9	3.5
4ℓ analysis	1.2	0.9
3ℓ and 4ℓ combined	3.1	3.6

$t\bar{t}Z$ and $t\bar{t}W$ @ ATLAS @ 13TeV

Preliminary result shown at Moriond 2016: ATLAS-CONF-2016-003.

ATLAS strategy similar to that of CMS, and essentially identical to 8 TeV ATLAS approach.

- $3l$ and $4l$ SRs targeting $t\bar{t}Z$
- Two SRs: SS2μ and $3l$ with no Z candidate target $t\bar{t}W$

Process	$t\bar{t}$ decay	Boson decay	Channel
$t\bar{t}W^{\pm}$	$(\mu^{\pm}\nu b)(q\bar{q}b)$	$\mu^{\pm}\nu$	SS dimuon
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{\pm}\nu$	Trilepton
$t\bar{t}Z$	$(\ell^{\pm}\nu b)(q\bar{q}b)$	$\ell^{+}\ell^{-}$	Trilepton
	$(\ell^{\pm}\nu b)(\ell^{\mp}\nu b)$	$\ell^{+}\ell^{-}$	Tetralepton

$t\bar{t}V$ @ ATLAS @ 13 TeV

Monte Carlo

Somewhat more diverse than the tools used in CMS:

- $t\bar{t}V$ signal and tZ from MadGraph+Pythia
- tWZ from MG5_AMC@NLO+Pythia8; $t\bar{t}H$ uses MG5_AMC@NLO+Herwig++
- Sherpa 2.1 for WZ/ZZ as well as tribosons
- Other rare processes (3top, 4top, $t\bar{t}WW$) simulated with MadGraph+Pythia

Dataset and object definitions

- Single lepton triggers used; integrated lumi 3.2 fb^{-1}
- Isolated leptons with $p_T > 7$ GeV considered, $|\eta| < 2.4$ (< 2.47) for μ (e)
- Jets with $p_T > 25$ GeV, $|\eta| < 2.5$; average b-tagging efficiency 77%

$t\bar{t}V$ @ ATLAS @ 13 TeV: signal regions

2μ-SS SR

Two SS muons with $p_T > 25$ GeV, $E_T^{\text{miss}} > 40$ GeV, $H_T > 240$ GeV and $N_{\text{b-jets}} \geq 2$.

Variable	3ℓ-Z-1b4j	3ℓ-Z-2b3j	3ℓ-Z-2b4j	3ℓ-noZ-2b
Leading lepton p_{T}	> 25 GeV			
Other leptons' p_{T}	> 20 GeV			
Sum of lepton charges	± 1			
Z-like OSSF pair	$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV			$\lvert m_{\ell\ell} - m_Z \rvert > 10$ GeV
n_{jets}	≥ 4	3	≥ 4	≥ 2 and ≤ 4
$n_{b\text{-jets}}$	1	≥ 2	≥ 2	≥ 2

Region	Z_2 leptons	p_{T34}	$\lvert m_{Z_2} - m_Z \rvert$	$E_{\text{T}}^{\text{miss}}$	$N_{b\text{-jets}}$
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	> 35 GeV	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 25 GeV	$\{ > 10$ GeV < 10 GeV	> 40 GeV $\}$ > 80 GeV	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	-	$\{ > 10$ GeV < 10 GeV	- $\}$ > 40 GeV	≥ 2

Background estimation

Non-prompt lepton background dominates in the 2μ-SS SR and is important in the $3l$ SRs.

- Estimated from data using the matrix method technique
- Similar to CMS approach, except that the prompt and non-prompt loose$\rightarrow$tight efficiencies are derived from data, in OS/SS dilepton events

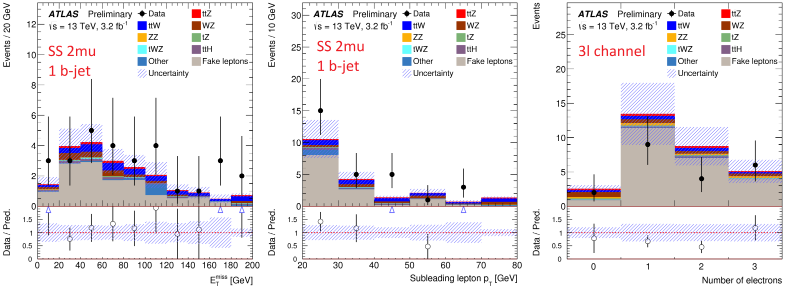
Dedicated control regions used for the WZ and ZZ backgrounds.

- Included in the fit

The remaining backgrounds typically small (apart from tWZ/tZ) and taken from Monte Carlo.

$t\bar{t}V$ @ ATLAS @ 13 TeV: non-prompt lepton background

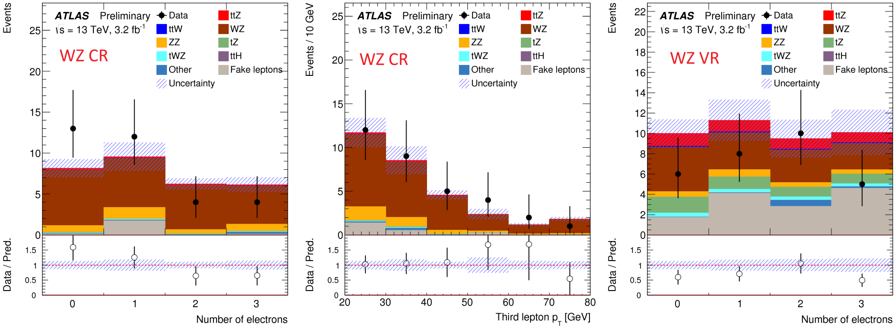
Validated in a SS 2μ region with $N_{\mathrm{b-jets}} = 1$.



- Separate validation for the $3l$ channel in a region with no OSSF pair with $|m_{ll} - m_Z| < 10$ GeV.
- Systematic uncertainty on non-prompt background $\sim 25-50\%$, from limited control region statistics and subtraction of charge-flip in SS $2l$ regions where the loose$\rightarrow$tight rates are derived

$t\bar{t}V$ @ ATLAS @ 13 TeV: WZ background

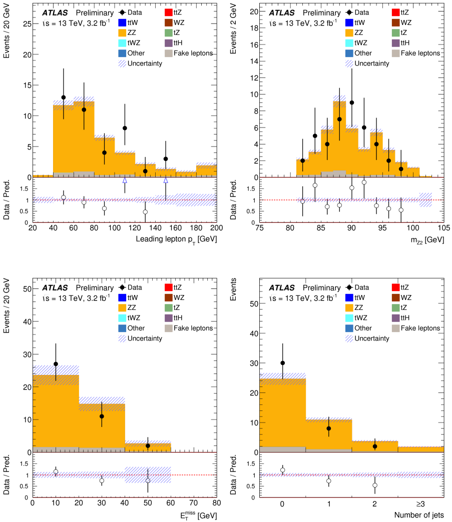
Control region with $3l$, an OSSF pair $|m_{ll} - m_Z| < 10$ GeV, $N_{\text{jets}} = 3$ and $N_{\text{b-jets}} = 0$ used.



Further validated in a region with $1 \leq N_{\text{jets}} \leq 3, N_{\text{b-jets}} = 1$ or $N_{\text{b-jets}} = N_{\text{jets}} = 2$.

$t\bar{t}V$ @ ATLAS @ 13 TeV: ZZ background

Control region with two OSSF pairs with $|m_{ll} - m_Z| < 10$ GeV and $E_T^{\text{miss}} < 50$ GeV.



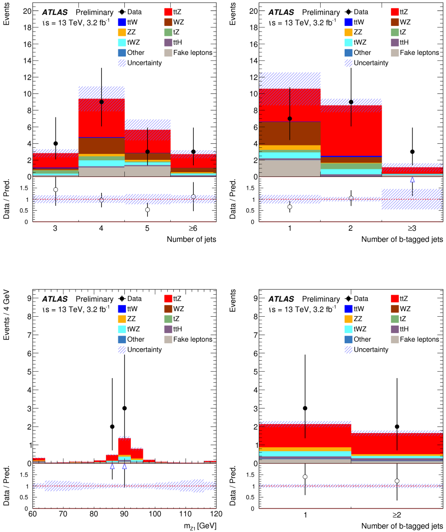
$t\bar{t}V$ @ ATLAS @ 13 TeV: uncertainties and fitting procedure

- Conservative 50-100% uncertainty on WZ background from limited CR statistics and extrapolation to higher b-jet multiplicity $\Longrightarrow$ important in $3l$ signal regions.
- Signal systematics from scale variations, Pythia A14 tune variations and comparisons of Madgraph with Sherpa
- tWZ background: uncertainty from interference with $t\bar{t}Z$ also considered; $+$10%-22%
- Typically consider 50% for small backgrounds such as tribosons or VBS $WWjj$

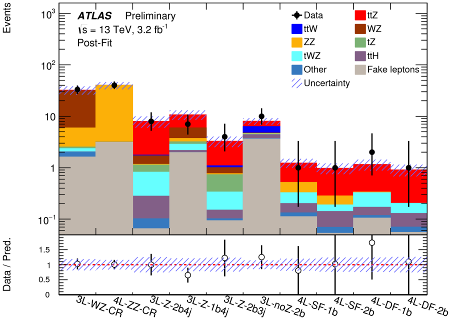
Two fits are performed:

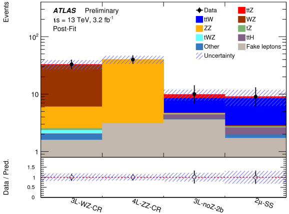
- Fix $t\bar{t}W$, consider normalisation uncertainty of $\sim 11\%$, and fit for $t\bar{t}Z$
- ...or vice versa

$t\bar{t}V$ @ ATLAS @ 13 TeV: results



$t\bar{t}V$ @ ATLAS @ 13 TeV: results





Uncertainty	$\sigma_{t\bar{t}Z}$	$\sigma_{t\bar{t}W}$
Luminosity	6.4%	7.0%
Reconstructed objects	7.0%	7.3%
Backgrounds from simulation	5.5%	3.7%
Fake leptons and charge misID	3.9%	21%
Total systematic	12%	24%
Statistical	32%	51%
Total	34%	56%

$t\bar{t}V$ @ ATLAS @ 13 TeV: results

Region	$t+X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3ℓ-WZ-CR	0.51 ± 0.13	26.9 ± 2.5	1.6 ± 1.7	29.0 ± 3.0	0.017 ± 0.005	0.71 ± 0.08	33
4ℓ-ZZ-CR	0.007 ± 0.006	37.9 ± 2.5	3.1 ± 0.9	41.0 ± 2.7	< 0.001	0.031 ± 0.006	40
2μ-SS	1.00 ± 0.19	0.14 ± 0.06	1.7 ± 1.5	2.9 ± 1.5	2.28 ± 0.34	0.65 ± 0.07	9
3ℓ-Z-2b4j	1.06 ± 0.25	0.5 ± 0.4	0.1 ± 0.6	1.7 ± 0.8	0.061 ± 0.013	5.1 ± 0.5	8
3ℓ-Z-1b4j	1.23 ± 0.26	3.4 ± 2.2	2.0 ± 1.7	6.6 ± 2.8	0.037 ± 0.010	4.0 ± 0.4	7
3ℓ-Z-2b3j	0.64 ± 0.23	0.25 ± 0.18	0.1 ± 0.4	1.0 ± 0.5	0.082 ± 0.015	1.75 ± 0.20	4
3ℓ-noZ-2b	0.95 ± 0.15	0.18 ± 0.09	3.6 ± 2.2	4.7 ± 2.2	1.55 ± 0.24	1.35 ± 0.16	10
4ℓ-SF-1b	0.198 ± 0.035	0.22 ± 0.08	0.112 ± 0.032	0.53 ± 0.09	< 0.001	0.59 ± 0.05	1
4ℓ-SF-2b	0.130 ± 0.035	0.11 ± 0.05	0.053 ± 0.016	0.29 ± 0.07	< 0.001	0.57 ± 0.05	1
4ℓ-DF-1b	0.21 ± 0.04	0.022 ± 0.011	0.105 ± 0.027	0.34 ± 0.05	< 0.001	0.67 ± 0.05	2
4ℓ-DF-2b	0.15 ± 0.05	< 0.001	0.055 ± 0.017	0.20 ± 0.05	< 0.001	0.58 ± 0.05	1

Fitted cross sections:

$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.30(\text{stat.}) \pm 0.11(\text{syst.})\ \text{pb}$$
$$\sigma_{t\bar{t}W} = 1.38 \pm 0.70(\text{stat.}) \pm 0.30(\text{syst.})\ \text{pb}$$

Consistent with SM predictions of $\sigma_{t\bar{t}Z} = 0.76$ pb and $\sigma_{t\bar{t}W} = 0.57$ pb.

Conclusions

- Exciting new measurements of $t\bar{t}V$ processes by ATLAS and CMS at 13 TeV
- $t\bar{t}Z$ precision already becoming competitive with 8 TeV results, thanks to the large increase of cross section 8→13 TeV
- The two experiments have comparable results and sensitivity for the $t\bar{t}Z$ cross section
- Looking forward to more data
- **The era of systematics-dominated, precision measurements of $t\bar{t}V$ is about to begin!**