Associated Production of Top Quarks with Heavy Vector Bosons

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On Behalf of the ATLAS and the CMS Collaborations

Precision Theory for Precise measurements at the LHC and Future Colliders

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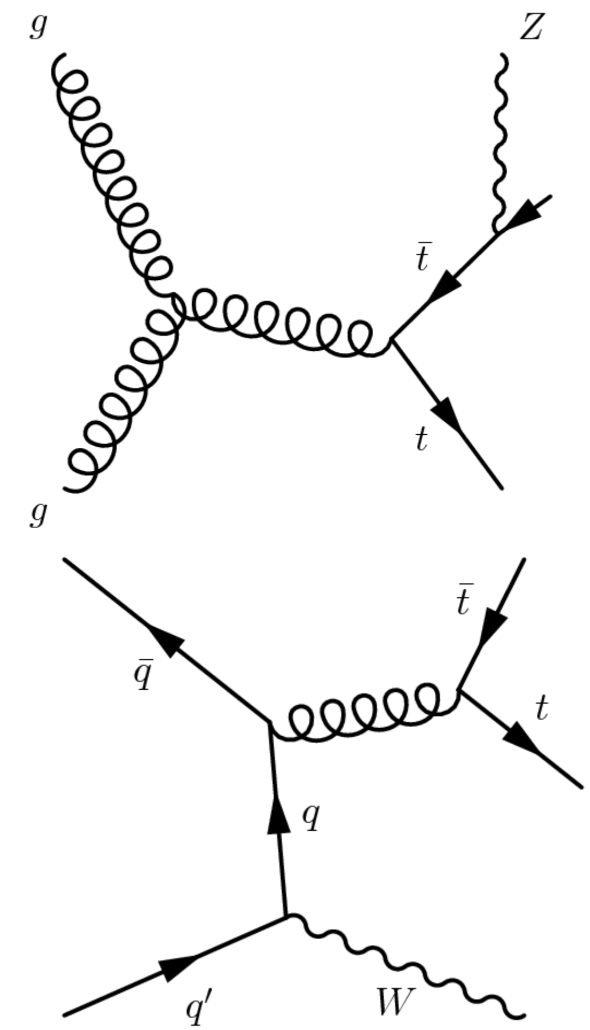
$t\bar{t}Z/W$: Introduction

- $t\bar{t}Z$ helps to test Standard Model predictions:
    - probe tZ coupling directly
- Sensitive to physics BSM like vector-like quarks, technicolor and little Higgs
- $t\bar{t}W$ and $t\bar{t}Z$ are backgrounds in multilepton $t\bar{t}H$ and SUSY searches (SS 2l, >=3l)



- $t\bar{t}$ can decay to 0-2 leptons, W can decay to 0-1 leptons and Z boson can decay to 0 or 2 leptons
- Expected 0-4 leptons in the final state
- Each channel can be split according to lepton flavours

$t\bar{t}Z/W$ @ 8 TeV in ATLAS Using 20.3 fb^{-1}

JHEP11(2015)172

Opposite-sign dilepton (2L OS)		Same-sign dilepton (2L SS)			Trilepton (3L)		Tetralepton (4L)	
different flavor (DF)	same flavor (SF)	ee	$e\mu$	$\mu\mu$	W enriched	Z enriched	DF	SF
$t\bar{t} \to \ell^{\pm}$ & $W \to \ell^{\mp}$	$t\bar{t} \to \ell^{+}\ell^{-}$ or $Z \to \ell^{+}\ell^{-}$	$t\bar{t} \to \ell^{\pm}$ & $W \to \ell^{\pm}$			$t\bar{t} \to \ell^{+}\ell^{-}$ $W \to \ell$	$t\bar{t} \to \ell$ $Z \to \ell^{+}\ell^{-}$	$Z \to \ell^{+}\ell^{-}$ $t\bar{t} \to$ DF	$Z \to \ell^{+}\ell^{-}$ $t\bar{t} \to$ SF

- The opposite-sign dilepton, trilepton and tetralepton are sensitive to $t\bar{t}Z$
- Same-sign dilepton channel targets $t\bar{t}W$ production

$t\bar{t}Z/W$ @ 8 TeV in ATLAS: Background

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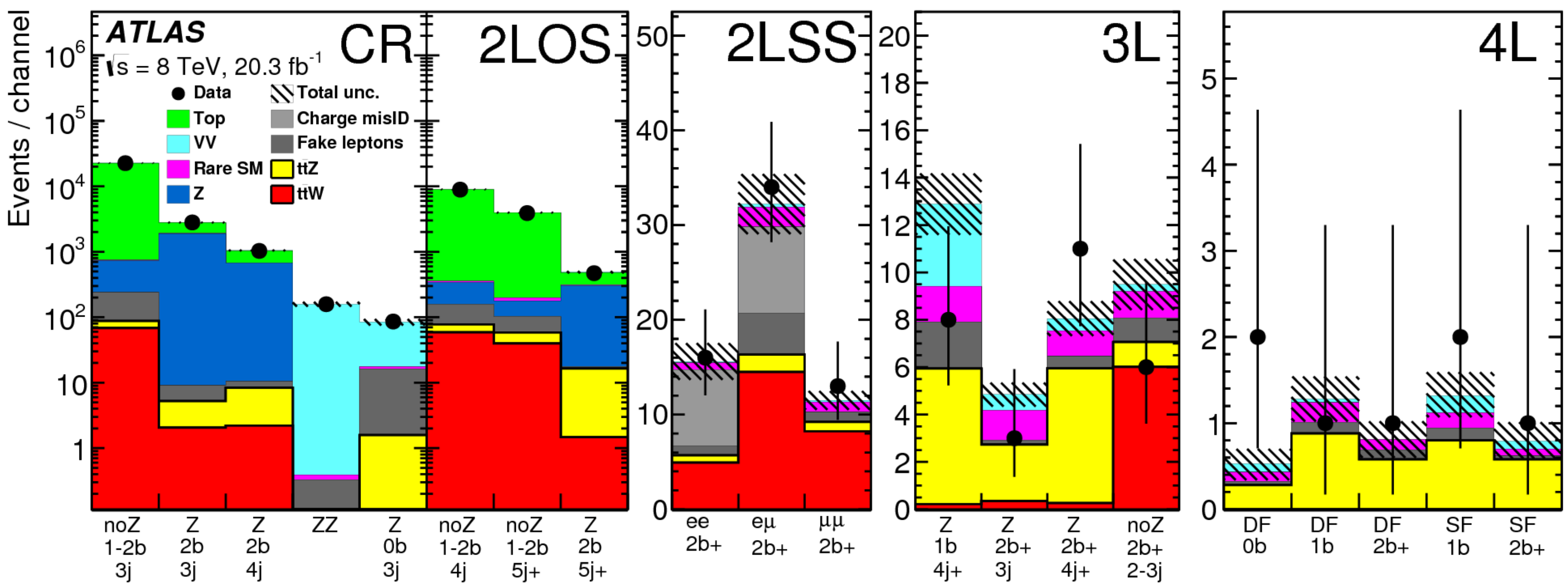
- 19 regions considered defined according to number of leptons, jets and b-tagged jets
- Background (bkg) compositions vary across different regions



- Backgrounds estimated via MC or data: main bkgs normalised by control regions, instrumental bkg by data, others small bkgs by MC

$t\bar{t}Z/W$ @ 8 TeV in ATLAS: Signal Extraction

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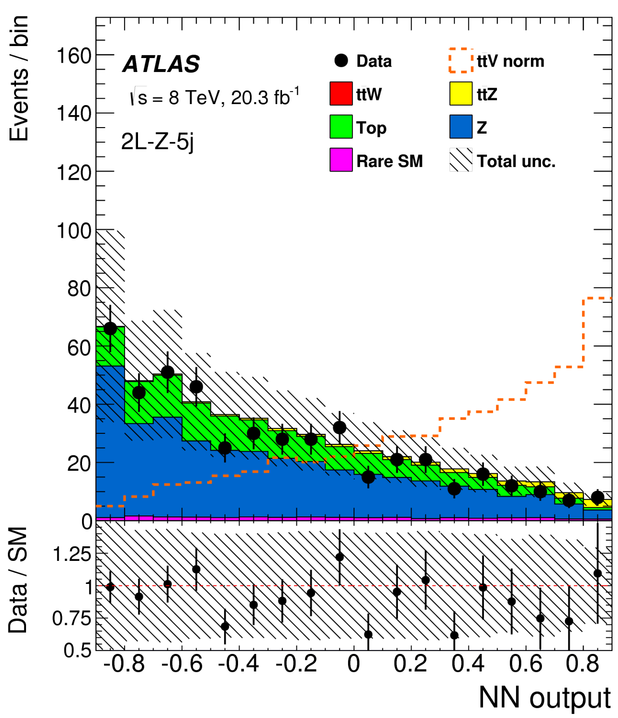
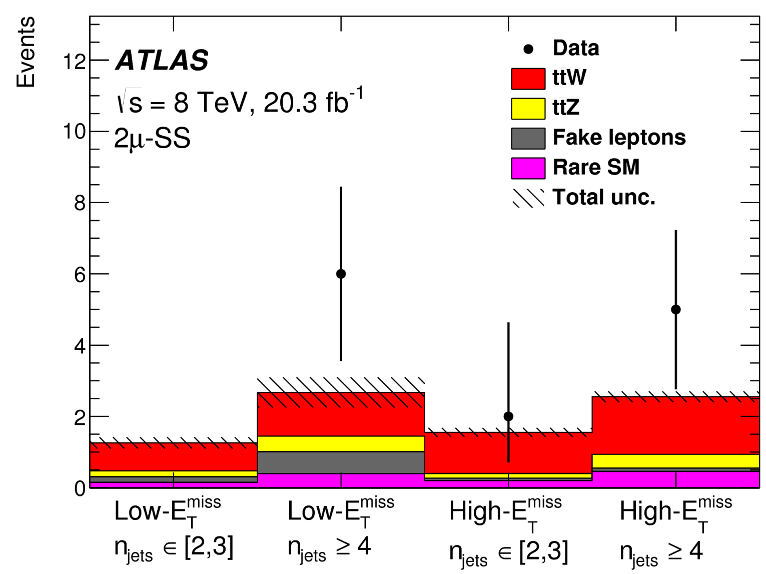
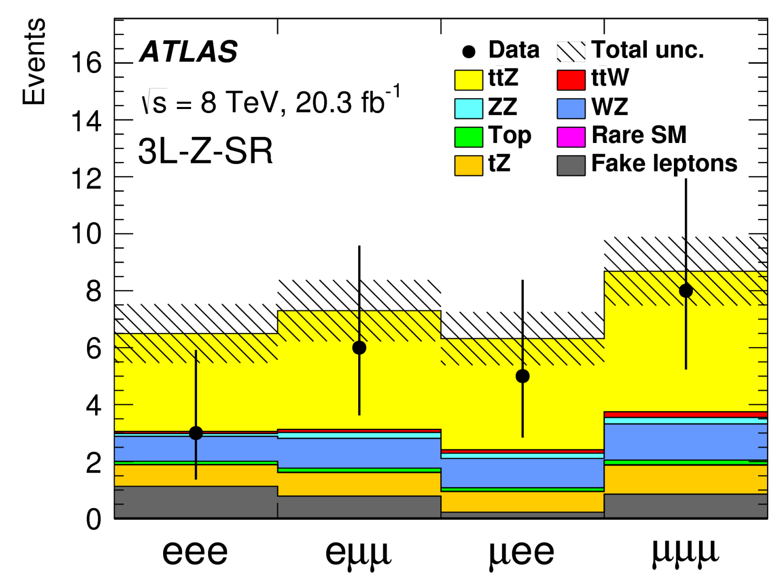
- 3 separate neural networks are utilised to enrich the signal in the 2l-noZ-4j, 2l-noZ-5j and 2l-Z-5j regions
- H_T distributions are used in 2l-Z-3j and 2l-Z4j







- The $t\bar{t}Z$ and $t\bar{t}W$ production cross sections are extracted with simultaneous fit using binned likelihood over all regions

$t\bar{t}Z/W$ @ 8 TeV in ATLAS: Results

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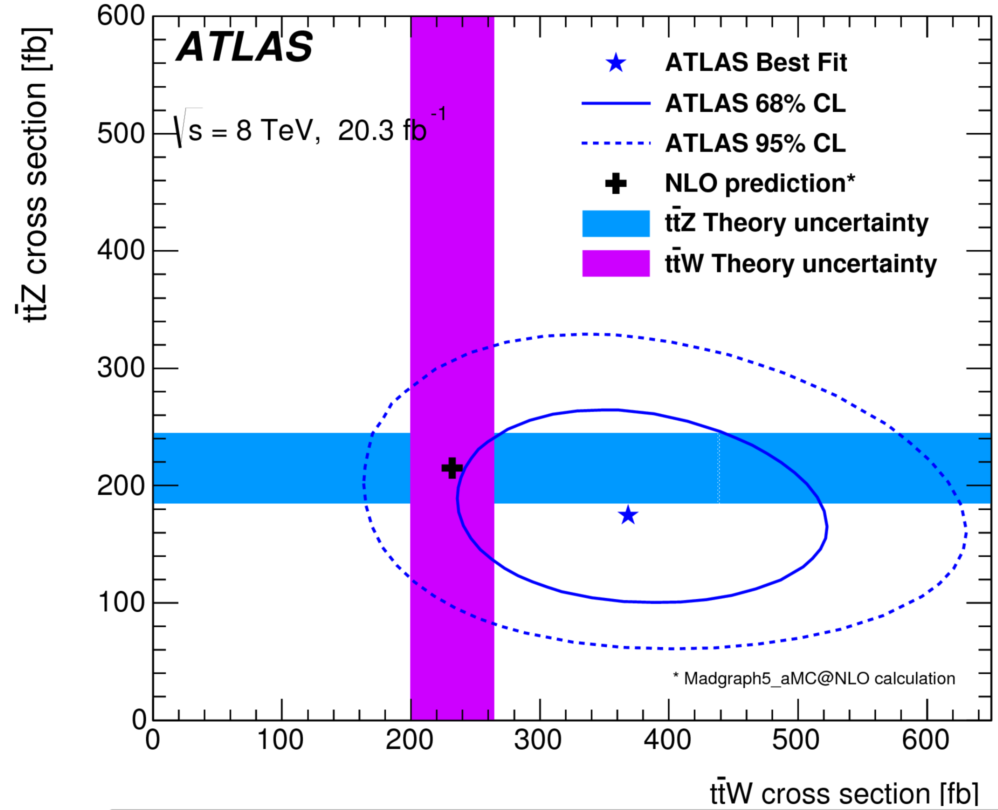
- Measured total cross section

$$\sigma_{t\bar{t}W} = 369^{+86}_{-79}(\text{stat.}) \pm 44(\text{syst.})\ \text{fb}$$

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

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%

- Statistical uncertainty dominates
- Systematical uncertainty mainly from background estimation



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

The background-only hypothesis is excluded with 7.1 σ

$t\bar{t}Z/W$ @ 13 TeV in ATLAS Using 3.2 fb^{-1}

arXiv:1609.01599

- Test SM at new energy scale
- Similar to 8 TeV analysis but only the most sensitive channels used

- $t\bar{t}W$ sensitive regions:
  - 2mu-SS
  - 3L-noZ-2b

- 7 regions sensitive to $t\bar{t}Z$

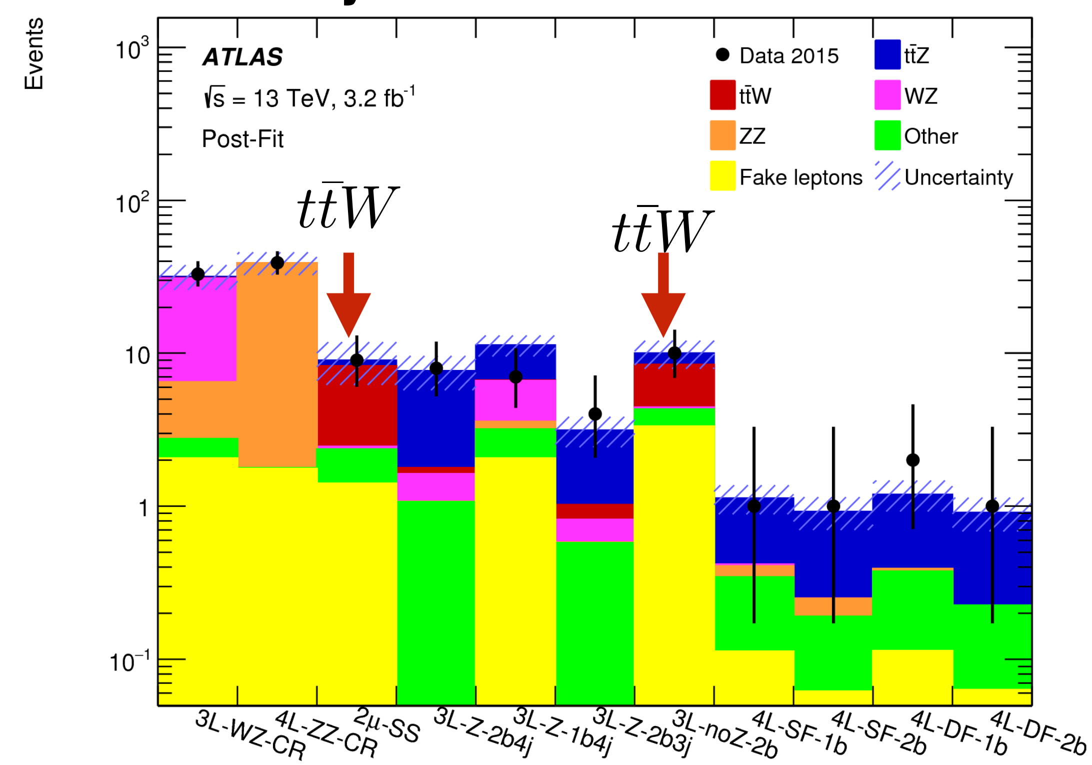
- 2 more control regions to control the background

List decay modes considered in the analysis

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

Electrons have larger charge misidentification

Event yields for the 11 channels



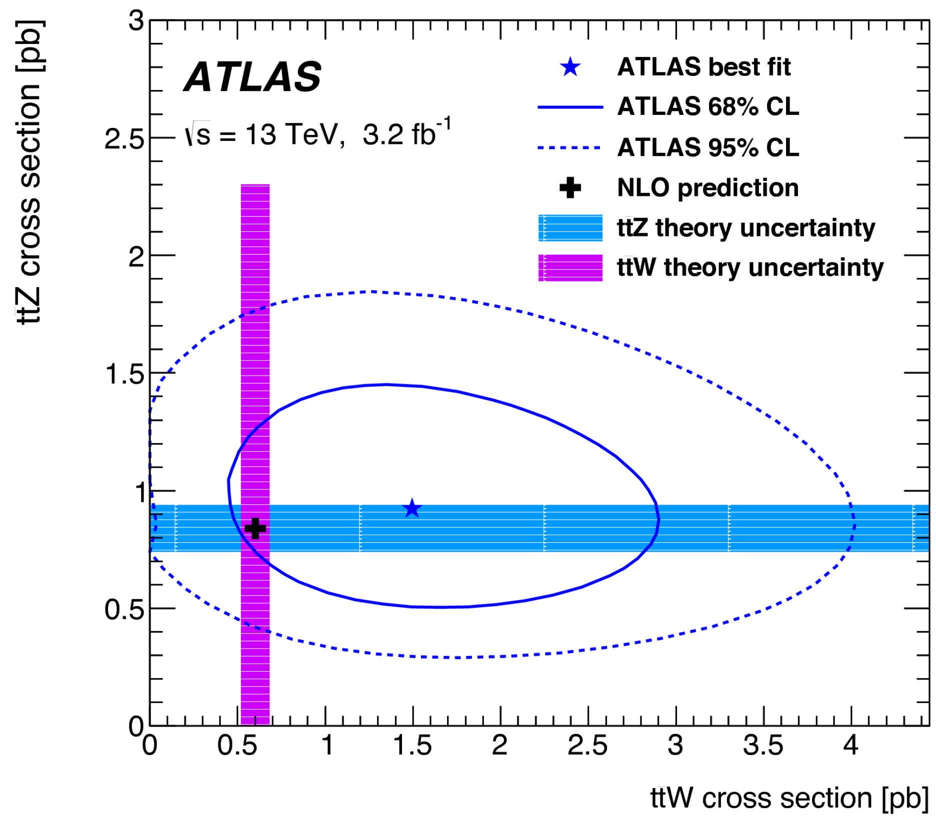
$t\bar{t}Z/W$ @ 13 TeV in ATLAS: Results

arXiv:1609.01599

- Simultaneous binned likelihood fit performed to extract the cross sections

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%	21%
Total systematic	11%	22%
Statistical	31%	48%
Total	32%	53%

- Statistical uncertainty dominates
- Systematical uncertainty mainly from:
  - reconstructed objects and bakg. in $t\bar{t}Z$
  - reconstructed objects $t\bar{t}W$



$$\sigma_{t\bar{t}Z} = 0.92 \pm 0.29(\text{stat.}) \pm 0.10(\text{syst.})\ \text{pb}$$

with significance **3.9 σ**

$$\sigma_{t\bar{t}W} = 1.50 \pm 0.72(\text{stat.}) \pm 0.33(\text{syst.})\ \text{pb}$$

with significance **2.2 σ**

$t\bar{t}Z/W$@ 8 TeV in CMS Using 19.5 fb^{-1}

JHEP 01 (2016) 096

- 5 exclusive channels targeting different decay modes

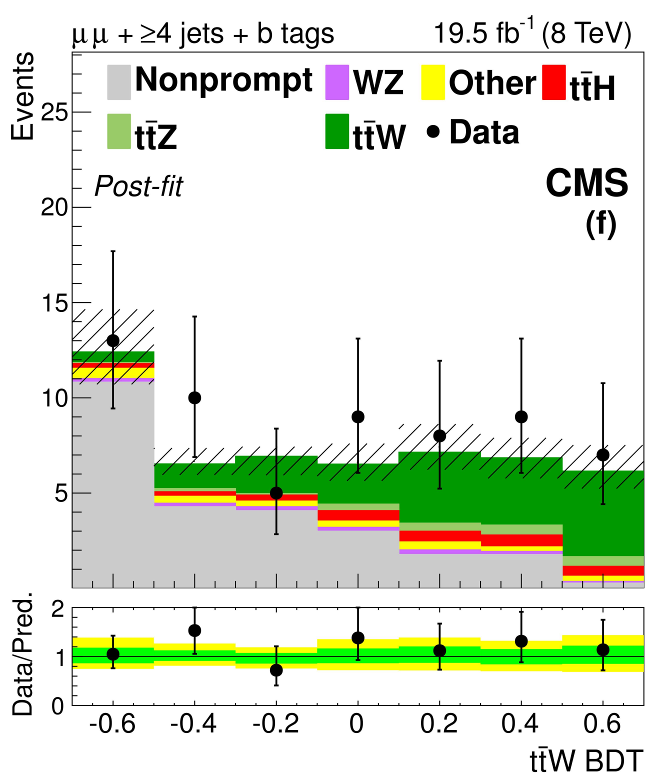
Channel	OS $t\bar{t}Z$		SS $t\bar{t}W$			3ℓ $t\bar{t}W$		3ℓ $t\bar{t}Z$		4ℓ $t\bar{t}Z$	
Lepton flavor	$ee/\mu\mu$	$e\mu$	ee	$e\mu$	$\mu\mu$	Any		Any		Any	
Lepton ID	2 loose		2 tight			SS tight		SS tight		4 loose	
Lepton charge ID	$\geq$0 pass		2 pass			SS pass		SS pass		4 pass	
$Z \to \ell\ell$ candidates	1		0			0		$\geq$1		2	1
Number of jets	5	$\geq$6	3	$\geq$4		1	$\geq$2	3	$\geq$4	$\geq$1	
Number of b tags	$\geq$1 medium		$\geq$2 loose or $\geq$1 medium							$\geq$1 loose	
Other			$Z \to ee$ veto							$H_T^{miss} > 30$ GeV	
Subchannels	4		6			2		2		2	

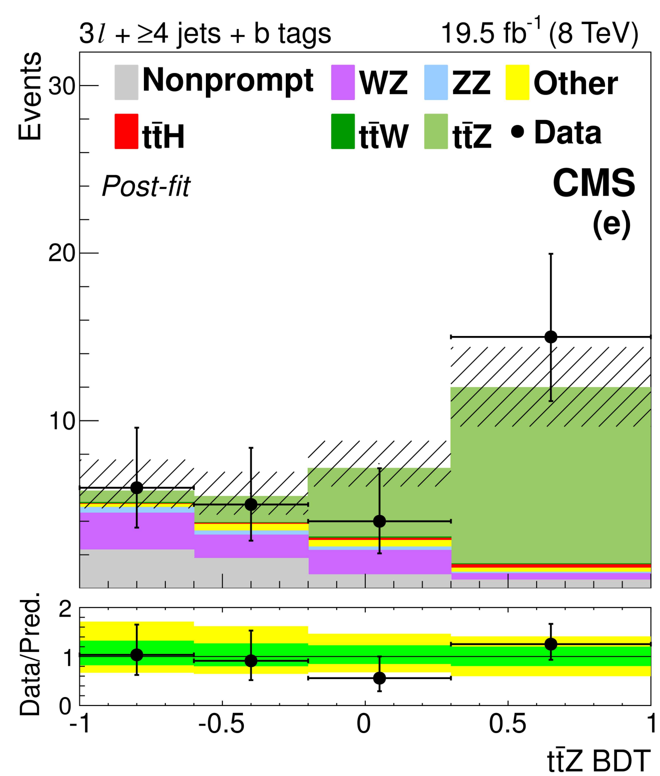
- Channels are divided into sub-channels according to the lepton flavour and jet multiplicity, 16 channels in total

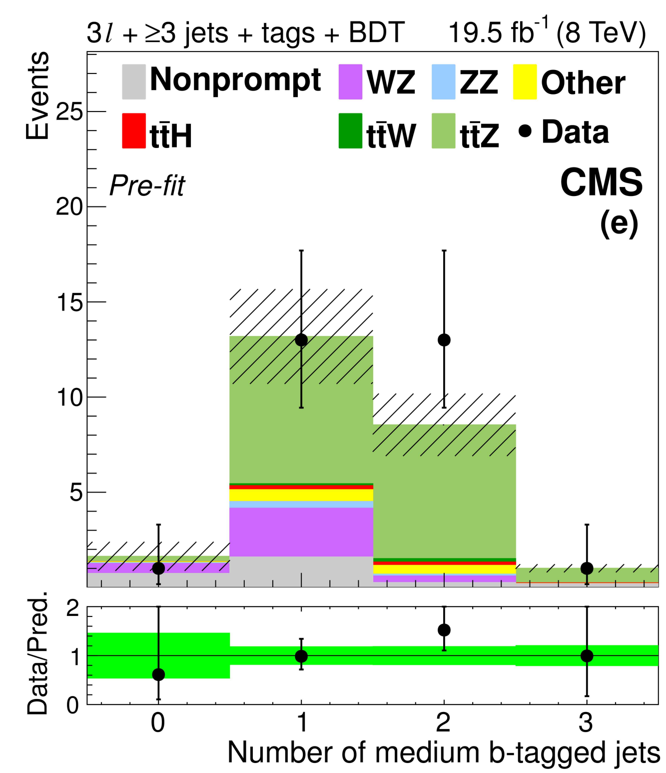
$t\bar{t}Z/W$ @ 8 TeV in CMS: Signal Extraction

JHEP 01 (2016) 096

- BDTs are used to enhance the S/B
- A separate BDT is trained in each category for each jet multiplicity
- BDTs are trained against the dominant background in that region







- In the 4 lepton channel the number of b-tagged jets is used instead BDT

$t\bar{t}Z/W$ @ 8 TeV in CMS: Results

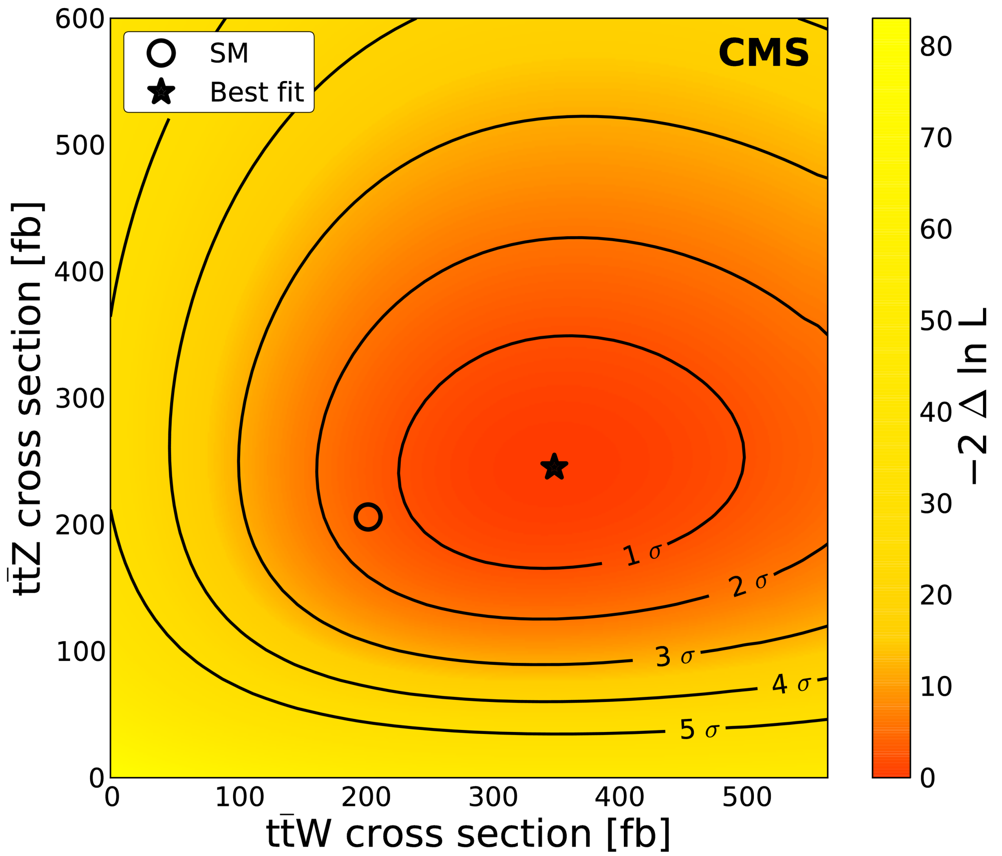
JHEP 01 (2016) 096

- $t\bar{t}Z$ and $t\bar{t}W$ cross sections extracted in a separate 1-dimensional binned likelihood fit using relevant channels for each process

$$\sigma_{t\bar{t}Z} = 242^{+65}_{-55} \text{ fb}$$
$$\text{signal strength} = 6.4\sigma$$

$$\sigma_{t\bar{t}W} = 282^{+117}_{-102} \text{ fb}$$
$$\text{signal strength} = 4.8\sigma$$

Simultaneous fit



- Dominant uncertainties:
  - b tagging efficiency
  - signal modeling
  - background rates

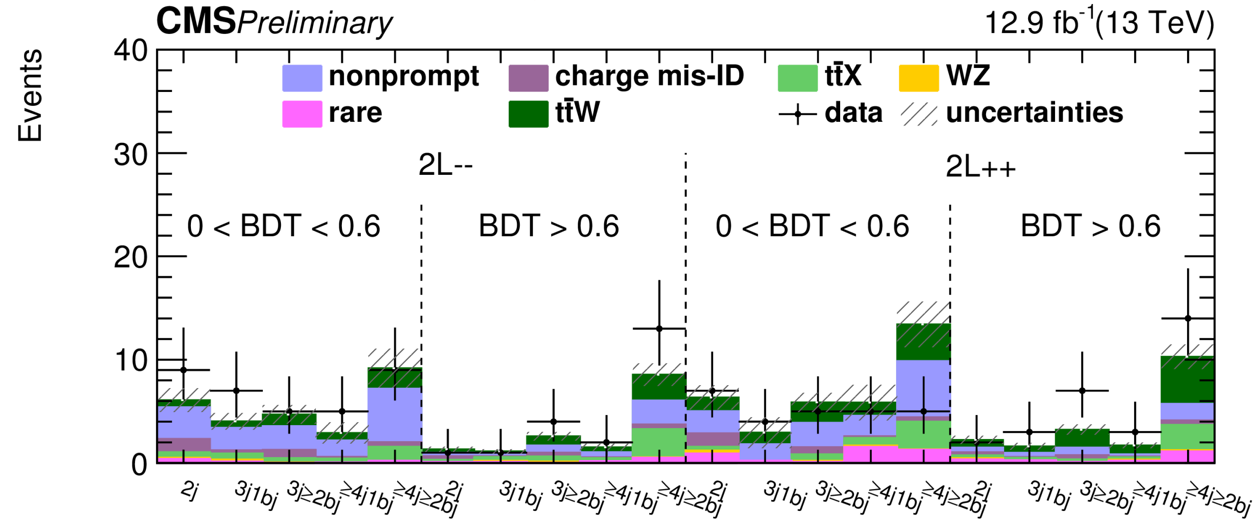
$t\bar{t}Z/W$ @ 13 TeV in CMS Using 12.9 fb^{-1}

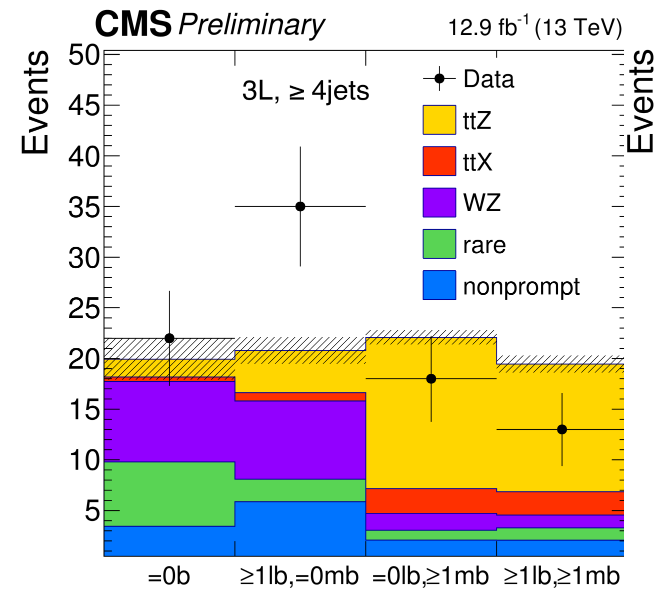
2016 data

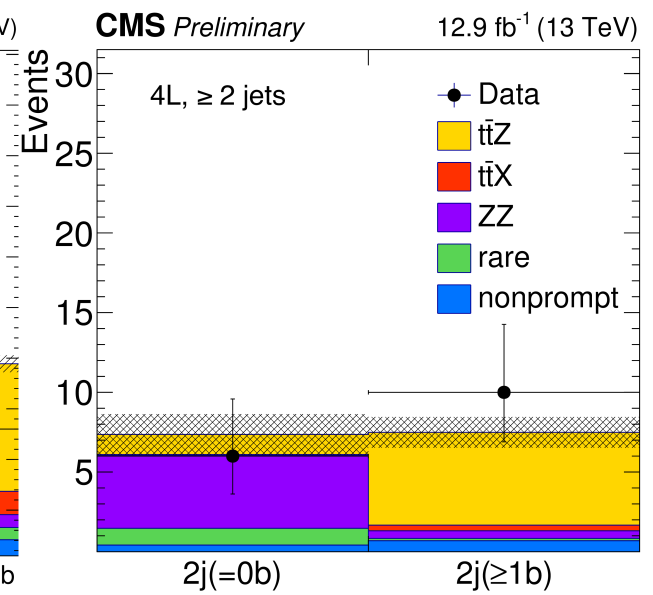
CMS-PAS-TOP-16-017

- Similar to 8 TeV analysis
- Dilepton channel:
  - only events with SS considered
  - BDTG used to improve S/B, divided into two sub regions
  - 5 exclusive channels for each region according to number of jets and b-jets
- Trilepton channel: 12 exclusive regions built from the number of jets and number of b-jets
- Tetralepton channel: 2 regions according to the existence of b-jets or not

BDTG > 0 is considered







$t\bar{t}Z/W$ @ 13 TeV in CMS: Results

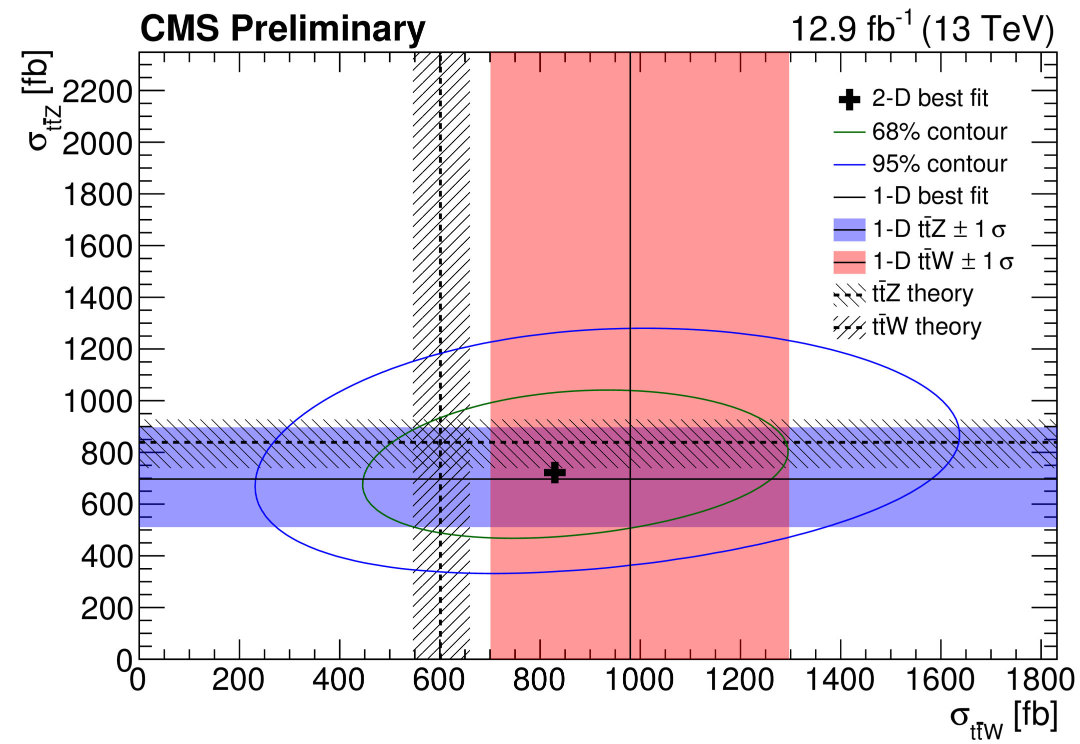
2016 data

CMS-PAS-TOP-16-017

- Measured total cross sections from individual fits

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}Z}) = 0.70^{+0.16}_{-0.15}(\mathrm{stat.})\ ^{+0.14}_{-0.12}(\mathrm{sys.})\ \mathrm{pb}$$

$$\sigma(\mathrm{pp} \to \mathrm{t\bar{t}W}) = 0.98\ ^{+0.23}_{-0.22}(\mathrm{stat.})\ ^{+0.22}_{-0.18}(\mathrm{sys.})\ \mathrm{pb}$$



- Dominant uncertainties:
  - statistical uncertainty
  - 6.2% from luminosity
  - 2% from the pileup

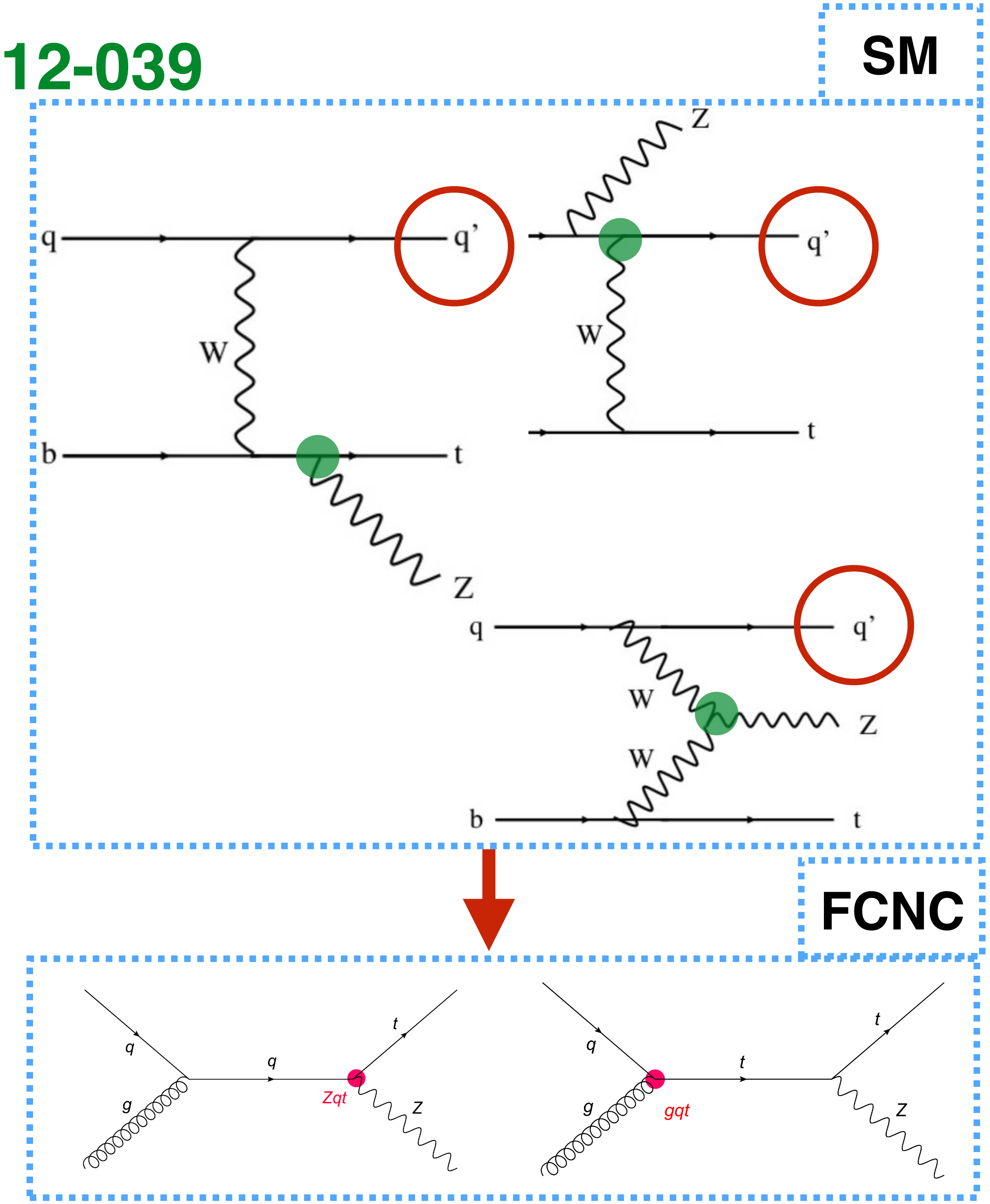
Channel	Expected significance	Observed significance
$2\ell ss$ analysis ($t\bar{t}W$)	2.6	3.9
3ℓ analysis ($t\bar{t}Z$)	5.4	3.8
4ℓ analysis ($t\bar{t}Z$)	2.4	2.8
3ℓ and 4ℓ combined ($t\bar{t}Z$)	5.8	4.6

tZq @ 8 TeV in CMS: Introduction

CMS-PAS-TOP-12-039

Motivation

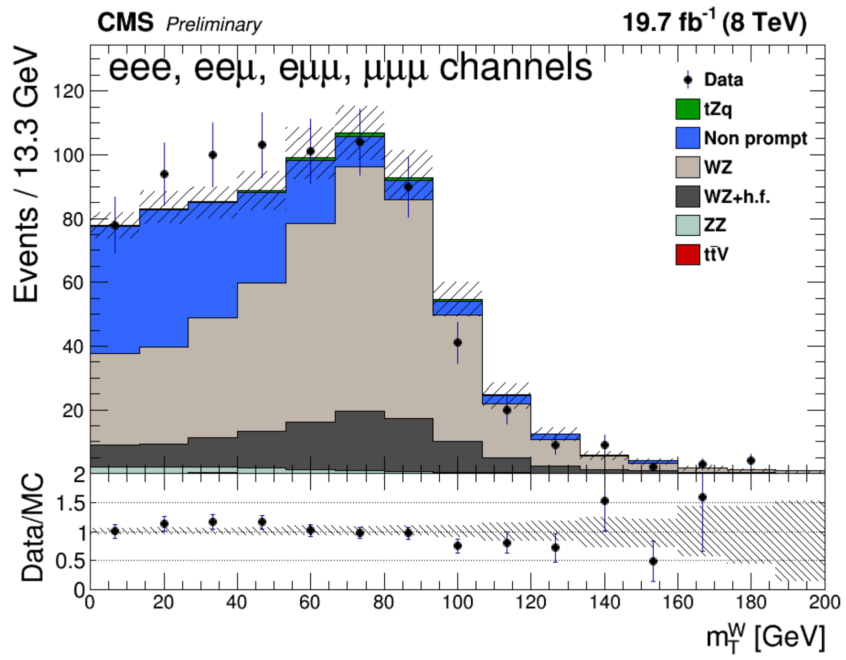
- Important test of the SM predictions
- Sensitive to the coupling of the top quark to the Z boson
- Helps to measure the WWZ coupling directly
- Background of Ht channel
- Same final state as in FCNC-tZ analysis, with the additional quark missing

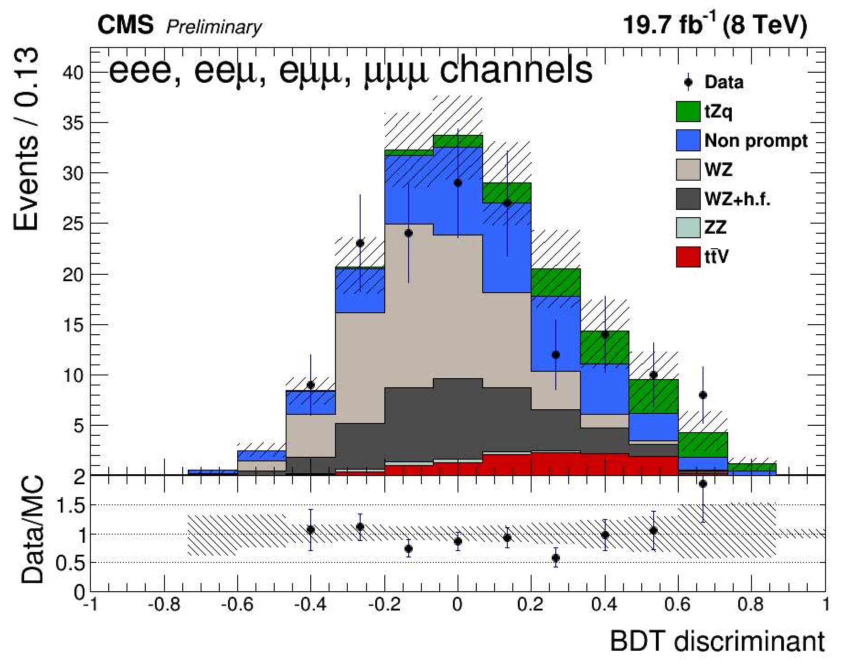


tZq @ 8 TeV in CMS: Procedure

CMS-PAS-TOP-12-039

- Selected events with 3 leptons
- Used BDT to enhance S/B and trained with signal against $t\bar{t}Z$ and WZ backgrounds
- m_T^W distribution is used to control the non prompt leptons and WZ
    - templates are created by inverting the isolation cuts
- A similar BTD is trained for FCNC-tZ signal against all SM backgrounds





tZq @ 8 TeV in CMS: Results

CMS-PAS-TOP-12-039

- The significance of the measured cross section is **2.4 σ**

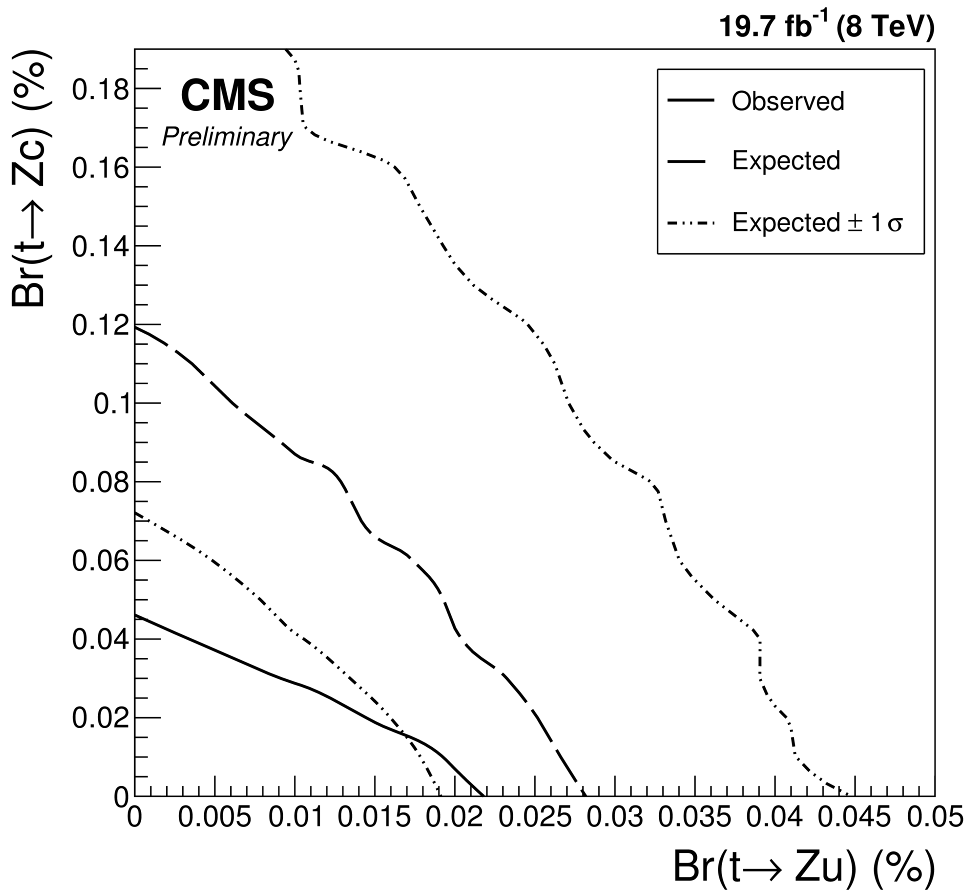
$$\sigma_{tZq} = 10^{+8}_{-7}\ \text{fb}$$

- The predicted cross section is

$$\sigma_{tZq} = 8.2^{+0.59}_{-0.03}\ \text{fb}$$

- The observed upper limit on the cross section is **21 fb** at 95%CL

- Dominant uncertainties:
  - statistical uncertainties
  - luminosity around 2.6%
  - pileup around 5%



Results from FCNC search:

- No excess over SM background observed
- Upper limits at 95% CL

$$Br(t \rightarrow Zu) = 0.022\%$$
$$Br(t \rightarrow Zc) = 0.049\%$$

Summary

- Associated production of top quarks with heavy vector boson is measured at different CME by both ATLAS and CMS Collaborations; good agreement with the SM predictions

- With the13 TeV incoming data, these measurements will be improved

- The search for single top quark associated to the Z boson is conducted by CMS Collaboration at 8 TeV, good agreement with the SM

- The search for tZ is being performed by ATLAS Collaboration using data collected at 13 TeV

Backup

ATLAS 8 TeV

Process	$t\bar{t}$ decay	Boson decay	Channel	$Z \to \ell^+\ell^-$
$t\bar{t}W^\pm$	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^\mp \nu$	OS dilepton	no
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$q\bar{q}$	OS dilepton	no
	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^\pm \nu$	SS dilepton	no
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^\pm \nu$	Trilepton	no
$t\bar{t}Z$	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$q\bar{q}$	OS dilepton	no
	$(q\bar{q}b)(q\bar{q}b)$	$\ell^+\ell^-$	OS dilepton	yes
	$(\ell^\pm \nu b)(q\bar{q}b)$	$\ell^+\ell^-$	Trilepton	yes
	$(\ell^\pm \nu b)(\ell^\mp \nu b)$	$\ell^+\ell^-$	Tetralepton	yes

Table 1: List of $t\bar{t}W$ and $t\bar{t}Z$ decay modes and analysis channels targeting them. The last column indicates whether a final state lepton pair is expected from a Z boson decay.

ATLAS 13 TeV

Table 4: Expected event yields for signal and backgrounds, and the observed data in all control and signal regions used in the fit to extract the $t\bar{t}Z$ and $t\bar{t}W$ cross sections. The quoted uncertainties in expected event yields represent systematic uncertainties including MC statistical uncertainties. The tZ, tWZ, $t\bar{t}H$, three- and four-top-quark processes are denoted $t+X$. The WZ, ZZ, $H \rightarrow ZZ$ (ggF and VBF), HW and HZ and VBS processes are denoted 'Bosons'.

Region	$t+X$	Bosons	Fake leptons	Total bkg.	$t\bar{t}W$	$t\bar{t}Z$	Data
3ℓ-WZ-CR	0.52 ± 0.13	26.9 ± 2.2	2.2 ± 1.8	29.5 ± 2.8	0.015 ± 0.004	0.80 ± 0.13	33
4ℓ-ZZ-CR	< 0.001	39.5 ± 2.6	1.8 ± 0.6	41.2 ± 2.7	< 0.001	0.026 ± 0.007	39
2μ-SS	0.94 ± 0.08	0.12 ± 0.05	1.5 ± 1.3	2.5 ± 1.3	2.32 ± 0.33	0.70 ± 0.10	9
3ℓ-Z-2b4j	1.08 ± 0.25	0.5 ± 0.4	< 0.001	1.6 ± 0.5	0.065 ± 0.013	5.5 ± 0.7	8
3ℓ-Z-1b4j	1.14 ± 0.24	3.3 ± 2.2	2.2 ± 1.7	6.7 ± 2.8	0.036 ± 0.011	4.3 ± 0.6	7
3ℓ-Z-2b3j	0.58 ± 0.19	0.22 ± 0.18	< 0.001	0.80 ± 0.26	0.083 ± 0.014	1.93 ± 0.28	4
3ℓ-noZ-2b	0.95 ± 0.11	0.14 ± 0.12	3.6 ± 2.2	4.7 ± 2.2	1.59 ± 0.28	1.45 ± 0.20	10
4ℓ-SF-1b	0.212 ± 0.032	0.09 ± 0.07	0.113 ± 0.022	0.42 ± 0.08	< 0.001	0.66 ± 0.09	1
4ℓ-SF-2b	0.121 ± 0.021	0.07 ± 0.06	0.062 ± 0.012	0.25 ± 0.07	< 0.001	0.63 ± 0.09	1
4ℓ-DF-2b	0.25 ± 0.04	0.0131 ± 0.0032	0.114 ± 0.019	0.37 ± 0.04	< 0.001	0.75 ± 0.10	2
4ℓ-DF-1b	0.16 ± 0.05	< 0.001	0.063 ± 0.013	0.23 ± 0.05	< 0.001	0.64 ± 0.09	1

CMS – 8 TeV

> Constraints on the axial and vector components of the tZ coupling

$$C_{1,V} = C_V^{\mathrm{SM}} + \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\mathrm{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} - \bar{c}_{Hu}],$$
$$C_{1,A} = C_A^{\mathrm{SM}} - \frac{1}{4\sin\theta_w\cos\theta_w}\frac{v^2}{\Lambda^2}\mathrm{Re}[\bar{c}'_{HQ} - \bar{c}_{HQ} + \bar{c}_{Hu}].$$

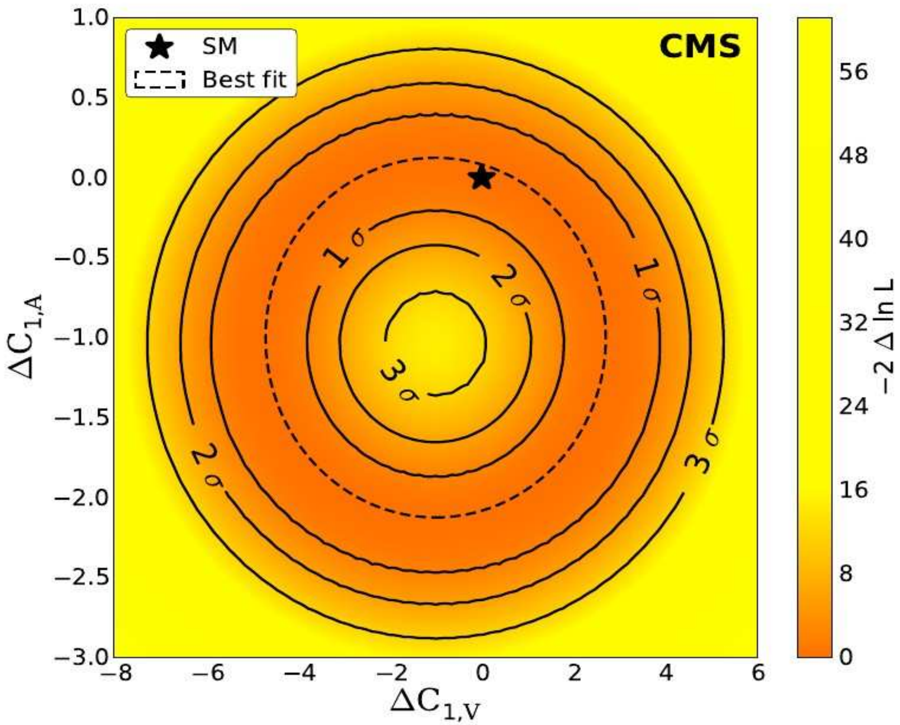


Figure 9: Difference between the profile likelihood and the best fit profile likelihood functions for the relative vector and axial components of the tZ coupling. Contours corresponding to the best fit and the 1, 2, and 3 standard deviation (σ) CLs are shown in lines.

CMS – 8 TeV

> Constraints on dimension 6 operators

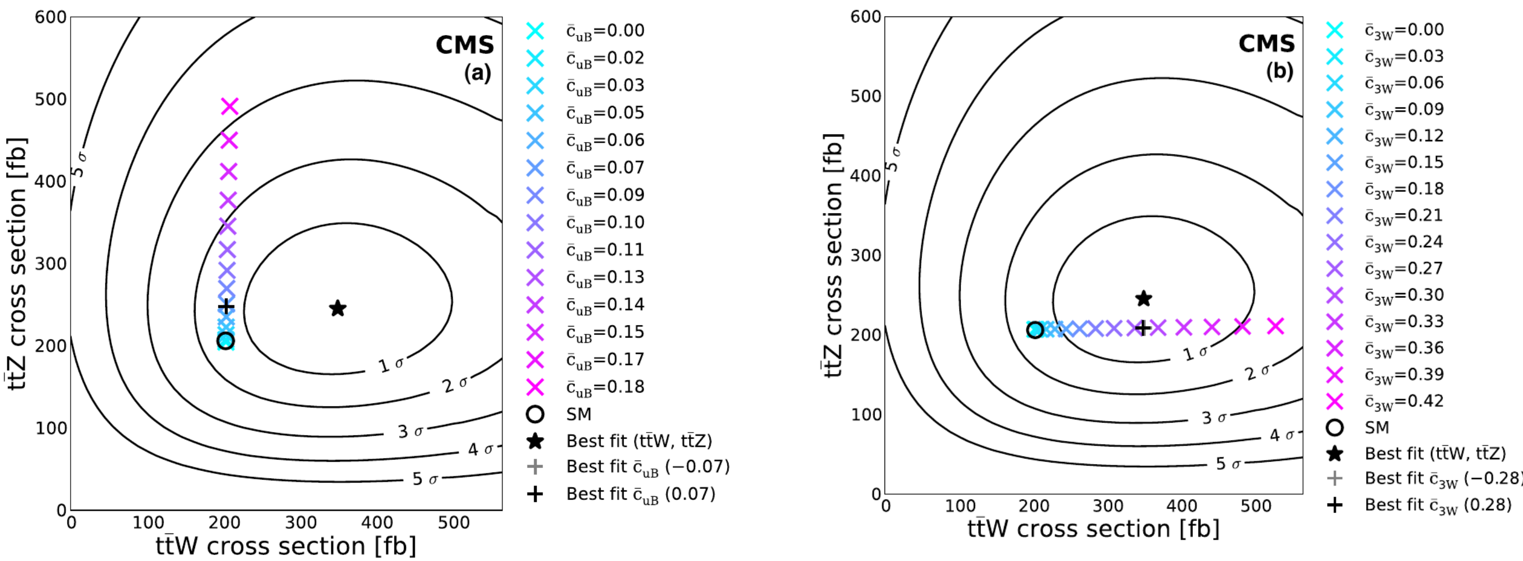


Table 9: Constraints from this $t\bar{t}Z$ and $t\bar{t}W$ measurement on selected dimension-six operators.

Operator	Best fit point(s)	1 standard deviation CL	2 standard deviation CL
$\bar{c}_{uB}$	−0.07 and 0.07	[−0.11, 0.11]	[−0.14, 0.14]
$\bar{c}_{3W}$	−0.28 and 0.28	[−0.36, −0.18] and [0.18, 0.36]	[−0.43, 0.43]
$\bar{c}'_{HQ}$	0.12	[−0.07, 0.18]	[−0.33, −0.24] and [−0.02, 0.23]
$\bar{c}_{Hu}$	−0.47 and 0.13	[−0.60, −0.23] and [−0.11, 0.26]	[−0.71, 0.37]
$\bar{c}_{HQ}$	−0.09 and 0.41	[−0.22, 0.08] and [0.24, 0.54]	[−0.31, 0.63]

CMS tZ-FCNC search

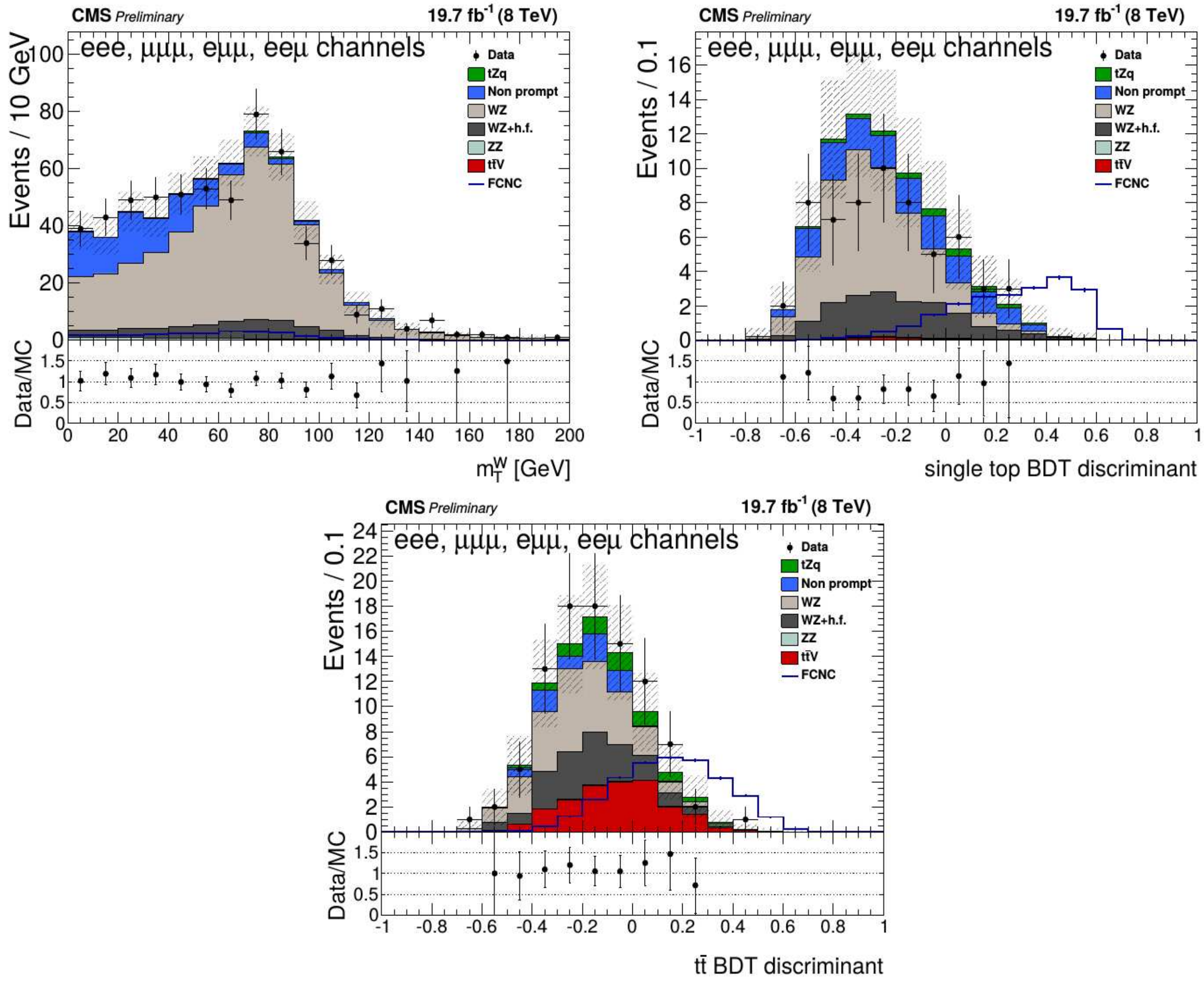


Figure 7: Data to prediction comparisons for the tZ-FCNC search after performing the fit for m_T^W distribution in the control region (top left), and for the BDT responses in the single top (top right) and $t\bar{t}$ (bottom) signal regions. The four channels are combined. An example of the predicted signal contribution for a $\mathcal{BR}(t \to Zu) = 0.1$ % is shown for illustration.

Searches for FCNC