Studies of $t\bar{t}$+V at CMS

Illia Khvastunov
University of Ghent, CEA Saclay

on behalf of the CMS Collaboration

TOP2016

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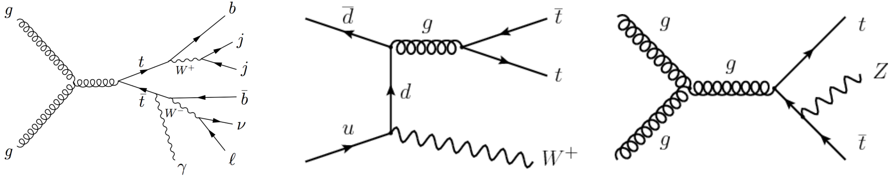
Overview

- Introduction and experimental status of $t\bar{t}\gamma$, $t\bar{t}W$ and $t\bar{t}Z$ processes.
- (NEW) Measurement of the ttγ production cross section at 8 TeV (19.7 fb^{-1}) (CMS-PAS-TOP-14-008)
- (NEW) Measurement of the top pair-production in association with a Z boson in pp collisions at 13 TeV using 2015 data (2.7 fb^{-1}) (CMS-PAS-TOP-16-009)
- (NEW) Measurement of the top pair-production in association with a W or Z boson in pp collisions at 13 TeV using 2016 data (12.9 fb^{-1}) (CMS-PAS-TOP-16-017)

Introduction



- The observed yields and measured cross-sections could be altered by new physics, these processes are the main background for ttH and for BSM processes
- Strength of the electromagnetic coupling of top quark and γ can be probed
- Direct measurement of coupling of the heaviest quark with Z boson

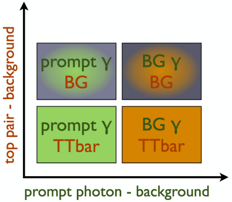
$t\bar{t}\gamma$ measurement: strategy

Old 8 TeV measurement (CMS-TOP-13-011)

$\sigma_{t\bar{t}\gamma} = 2400 \pm 200 \text{ (stat.)} \pm 600 \text{ (syst.) fb}$

New 8 TeV measurement (TOP-14-008)

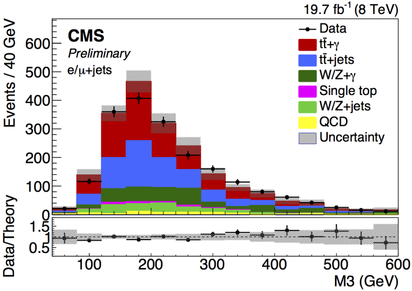
- Measure $t\bar{t}\gamma$ cross-section relative to the $t\bar{t}$ cross section
- Two categories of background:
  - Top events with fake photon ($t\bar{t}$)
  - Non-top events with real photon ($W\gamma$, $Z\gamma$)



- Measure the **number of top quark pair events** after the top quark selection and photon selection using a to invariant mass of three jets with highest p_T
- Measure the **photon purity** using a fit to the photon charged hadron isolation, separates real photon events from other backgrounds (data-driven approach)
- Use likelihood fit to the **photon purity, number of top quark events, and total number of events** to extract number of $t\bar{t}\gamma$ events

$t\bar{t}\gamma$ measurement: systematics and results

Source	Ratio Change (%)
Statistical likelihood fit	15.5
Top quark mass	7.9
Jet energy scale	6.9
Fact. and renorm. scale	6.7
ME/PS matching thresh.	3.9
Photon energy scale	2.4
Jet energy resolution	2.3
Multijet estimate	2.0
Electron fake rate	1.3
Z+jets scale factor	0.8
Pileup	0.6
Background normalization	0.6
Top p_T reweighting	0.4
b-tagging scale factor	0.3
Muon efficiency	0.3
Electron efficiency	0.1
Parton Distribution Function	0.1
Muon energy scale	0.1
Electron energy scale	0.1
Total	20.7



Category	R	$\sigma^{\text{fid}}_{t\bar{t}+\gamma}$ (fb)	$\sigma_{t\bar{t}+\gamma} \times \mathcal{B}$ (fb)
e+jets	$(5.7 \pm 1.8) \times 10^{-4}$	139 ± 45	582 ± 187
μ+jets	$(4.7 \pm 1.3) \times 10^{-4}$	115 ± 32	453 ± 124
Combination	$(5.2 \pm 1.1) \times 10^{-4}$	127 ± 27	515 ± 108
Theory	-	-	$592 \pm 71\text{(scale)} \pm 30\text{(PDF)}$

Experimental status of $t\bar{t}$ + (W,Z) as of Top2015

Documented in

10.1007/JHEP01(2016)096: "Observation of top quark pairs produced in association with a vector boson in pp collisions at $\sqrt{s} = 8$ TeV"

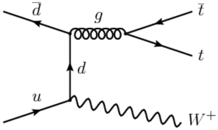
$t\bar{t}W$	Cross section (fb)		Signal strength (μ)		Significance (σ)	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
SS + 3ℓ	203^{+84}_{-71}	382^{+117}_{-102}	$1.00^{+0.43}_{-0.35}$	$1.88^{+0.66}_{-0.56}$	3.5	4.8

$t\bar{t}Z$	Cross section (fb)		Signal strength (μ)		Significance (σ)	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
OS + 3ℓ + 4ℓ	206^{+62}_{-52}	242^{+65}_{-55}	$1.00^{+0.34}_{-0.27}$	$1.18^{+0.35}_{-0.29}$	5.7	6.4

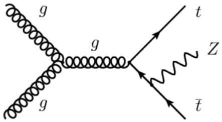
- Relative uncertainties were O(30%) for both $t\bar{t}W$ and $t\bar{t}Z$

Towards 13 TeV analysis for $t\bar{t}V$

- Measurement is done in most sensitive channels: same-sign dilepton for $t\bar{t}W$ and 3-lepton and 4-lepton channels for $t\bar{t}Z$:



$t\bar{t}W \to (bjj)(bjj)(jj)$
$t\bar{t}W \to (bjj)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bjj)(l\nu)$
$t\bar{t}W \to (bl\nu)(bl\nu)(l\nu)$



$t\bar{t}Z \to (bjj)(bjj)(jj)$
$t\bar{t}Z \to (bjj)(bjj)(ll)$
$t\bar{t}Z \to (bl\nu)(bjj)(ll)$
$t\bar{t}Z \to (bl\nu)(bl\nu)(ll)$

Process	$\sigma_{8\text{TeV}}$, pb	$\sigma_{13\text{TeV}}$, pb	$\sigma_{13\text{TeV}}/\sigma_{8\text{TeV}}$
ttZ(inclusive)	0.206	0.760	3.69
ttW(inclusive)	0.232	0.57	2.46
tt(inclusive)	234	831	3.55
WZ (to 3l)	1.058	2.165	2.05
ZZ (to 4l)	0.078	0.157	2.03

- Signal/background is better for $t\bar{t}Z$ in 13 TeV than 8 TeV, while for $t\bar{t}W$ it's worse

13 TeV analysis: strategy and event selection

$t\bar{t}W$, SS2ℓ

- 2 same-sign leptons
- $p_T > 40, 20\mathrm{GeV}$
- veto 3rd lepton
- at least 2 jets, 1 b-tag jet
- BDT analysis

$t\bar{t}Z$, 3ℓ

- 3 leptons
- $p_T >$ 40, 20, 10 GeV
- at least 2 jets
- $|m_{\ell\ell} - M_Z| <$ 10 GeV
- C&C analysis

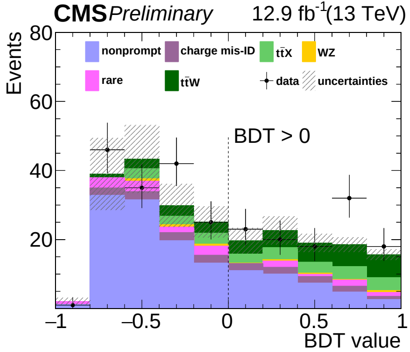
$t\bar{t}Z$, 4ℓ

- 3 leptons
- $p_T >$ 20, 10, 10, 10 GeV
- Sum of charges $= 0$
- at least 2 jets
- $|m_{\ell\ell} - M_Z| <$ 20 GeV
- C&C analysis

- To maximise significance the number of jets and b-tagged jets are used to form signal regions

13 TeV analysis: $t\bar{t}W$ in SS 2ℓ

- For $t\bar{t}W$ in same-sign dilepton channel BDT analysis was developed
- BDT input:
  - Number of jets; number of medium b-tagged jets; the sum of p_T of the jets
  - Leading and trailing lepton p_T, transverse invariant mass of both leptons
  - Leading and subleading jet p_T, missing transverse energy
  - ΔR between the trailing lepton and the nearest selected jet



Event selection

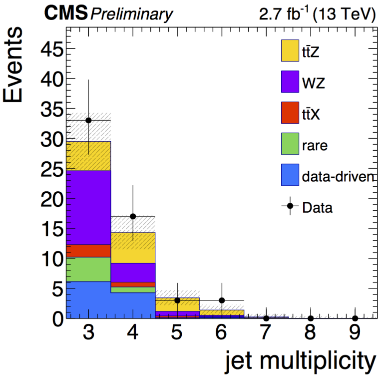
- BDT > 0
- Further split in number of jets, b-tag jets
- Split in $++$ and $--$

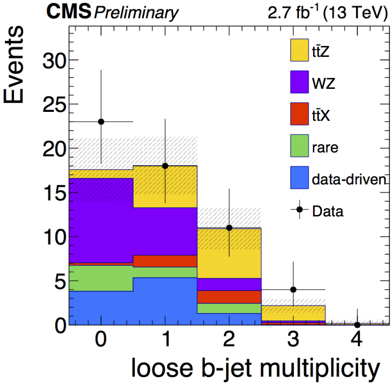
Backgrounds

- misidentified leptons, $t\bar{t}$
- $t\bar{t}Z$, rare SM processes

13 TeV analysis: $t\bar{t}Z$ in 3ℓ and 4ℓ

3ℓ channel after selection cuts



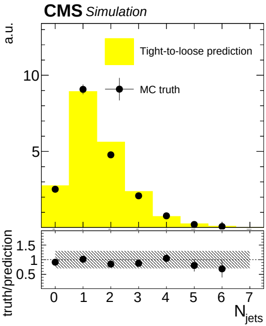


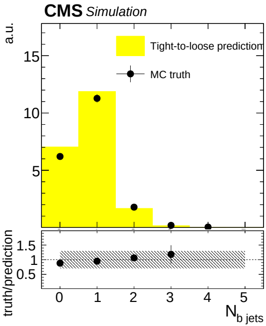
Main backgrounds:

- $t\bar{t}$ and WZ is relevant for 3ℓ
- ZZ for 4ℓ

Nonprompt lepton background

- Nonprompt background are expected to occur mostly in $t\bar{t}$ and Drell-Yan production: an additional nonprompt lepton from the semi-leptonic decays of a b-hadron, or additional jets misidentified as lepton
- Data-driven approach is used for nonprompt background estimation
- The probability of loosely identified lepton to pass the full set of identification/isolation requirements is calculated in respective enriched region and validated in Monte-Carlo simulation

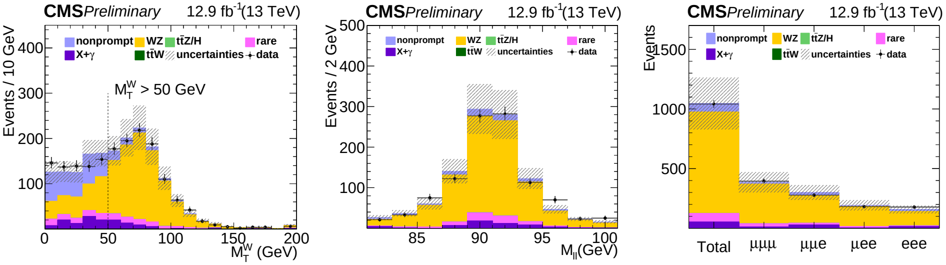




- 30% uncertainty covers the discrepancy between predicted and observed

WZ background

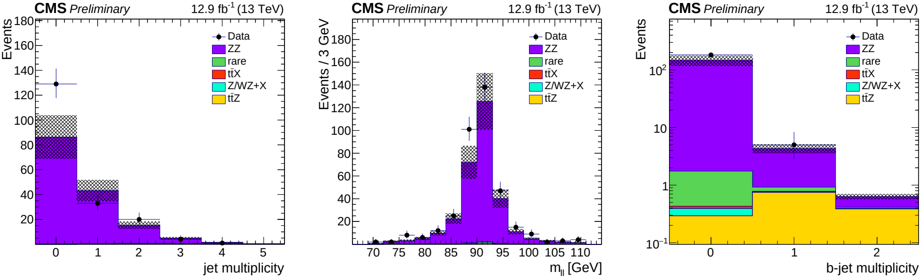
- MC is used for estimation
- Validate WZ in enriched control region with 85% purity:
  - 3 leptons, 2 of the form an opposite-sign same-flavour pair close to Z peak mass
  - 3rd lepton is used to form transverse mass with transverse component of missing energy
  - Cuts on low number of jets and the cut that excludes b-tag jets are used



- Overall 20% systematic uncertainty is assigned that covers uncertainty on:
  - normalization in enriched control region
  - theoretical and experimental uncertainties
  - uncertainty on extrapolation from low b-tag jet region to high b-tag jet regions

ZZ background

- MC is used for estimation
- Validated in enriched region with $> 95\%$ purity: requirement on two opposite-sign same-flavour pairs close to Z peak mass



- Excess in 0-jet bin, similar observation in SUSY searches (CMS-SUS-16-024)
- Inclusive yields within uncertainties; good agreement for njets$\geq$1 (i.e. the signal region)
- 20% uncertainty is assigned that covers the discrepancy

Charge misID background, rare SM processes and signal

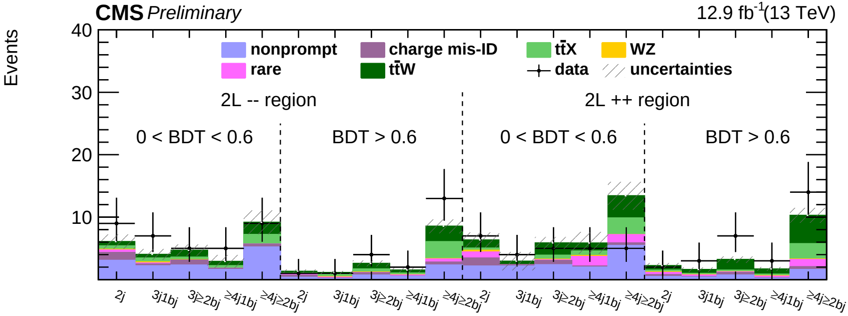
- Charge misidentified background is estimated using opposite-sign events and multiplied by the charge misID ratio
- The charge misID ratio is measured in MC simulation and validated in $Z \rightarrow ee$ events in data
- Rare SM processes is estimated from simulation:
    - WZ, WWW,WWZ, WZZ, ZZZ, $t\bar{t}t\bar{t}$, $t\bar{t}\gamma$, tZq and $Z\gamma$ are generated with MADGRAPH at NLO, $W\gamma$ LO MADGRAPH
    - $t\bar{t}$H and ZZ are produced with POWHEG at NLO
- $t\bar{t}$Z and $t\bar{t}$W are simulated at LO with MADGRAPH

Systematic uncertainties

Source	Syst. uncertainties	Effect on x-section measurement ttW	Effect on x-section measurement ttZ
Luminosity	6.2%	7-10%	8-14%
Jet Energy Scale/Resolution	1-6%	$\leq$ 1%	< 1%
Trigger	2-5%	4-7%	3-6%
BTagging	1-8%	2-6%	3-6%
PU modeling	1%	<1%	<1%
Lepton Id., Eff.	7-10%	5-9%	7-16%
μ_R/μ_F scale choice	2%	<1%	<1%
PDF choice	1%	<1%	< 1%
Non-prompt background	30%,100%	12%	7-10%
WZ background cross section	20%	<1%	5-6%
ZZ background cross section	20%	-	4%
Charge mis-identification	20%	2%	-
Rare SM bkg	50%	5%	1-2%
ttH/tZq bkg	25%	2%	0-6%
Stat nonprompt	5-50%	8%	5%
Stat rare SM processes	20-100%	5%	3%
Total	-	23%	20%

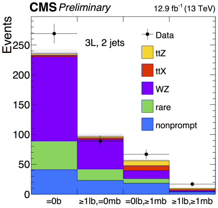
- Uncertainties on the integrated luminosity, lepton reconstruction and nonprompt background have the greatest effect both on the $t\bar{t}W$ and $t\bar{t}Z$ cross-section measurement.
- Uncertainty on WZ and ZZ background gives a significant contribution to the systematic uncertainty of $t\bar{t}Z$ cross section measurement.

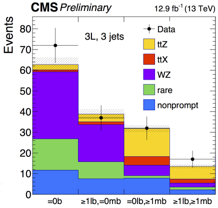
Results: CMS-TOP-16-017, $t\bar{t}W$ SS 2ℓ

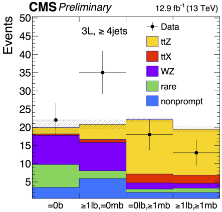


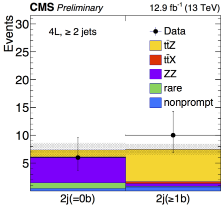
- $\sigma_{\text{measured}}(t\bar{t}W) = 0.98^{+0.23}_{-0.22}(\text{stat.})\ ^{+0.22}_{-0.18}(\text{sys.})$ pb
- $\sigma_{\text{theoretical}}(t\bar{t}W) = 0.6^{+0.06}_{-0.05}(\text{scale})\ ^{+0.01}_{-0.01}(\text{pdf})\ ^{+0.01}_{-0.01}(\alpha_s)$ pb (NLO in QCD and EW)
- Exptected significance - 2.6, observed 3.9

Results: CMS-TOP-16-017 $t\bar{t}Z$ 3ℓ and 4ℓ



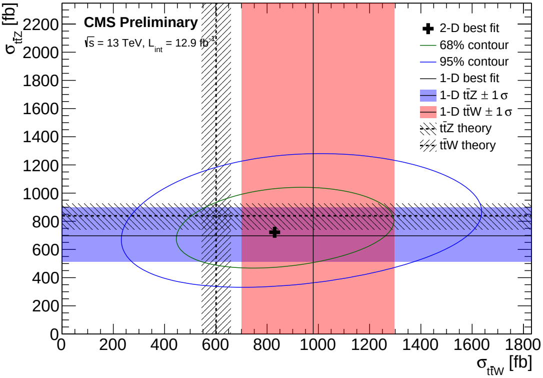






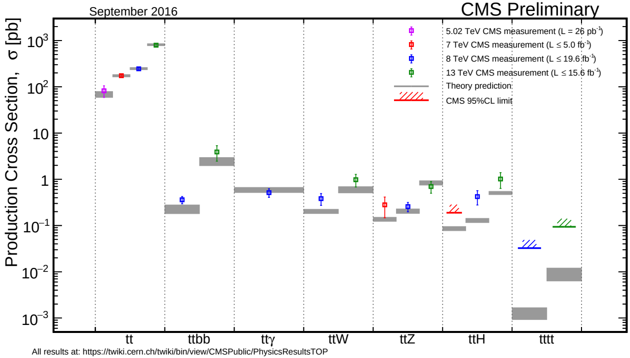
- $\sigma_{\text{measured}}(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}(\text{stat.})\ ^{+0.14}_{-0.12}(\text{sys.})$ pb
- $\sigma_{\text{theoretical}}(t\bar{t}Z) = 0.84^{+0.08}_{-0.09}(\text{scale})\ ^{+0.03}_{-0.03}(\text{pdf})\ ^{+0.03}_{-0.03}(\alpha_s)$ pb (NLO in QCD and EW)
- Combined significance: 5.8 expected and 4.6 observed

Results: fit in 2D



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

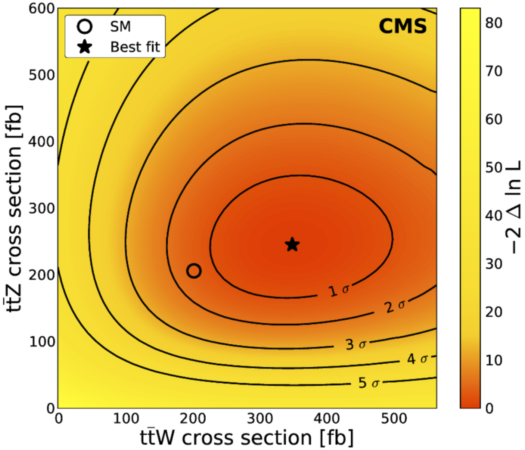
Conclusions



- New $t\bar{t}\gamma$ measurement: app. 21% uncertainty (stats limited)
- Measurement of $t\bar{t}$ + V cross-section is done at 13 TeV with statistical uncertainty O(20%) and systematic uncertainty O(20%)
- Significance for $t\bar{t}Z$ process is at the discovery level
- We are excited to have more data already in 2016 (app. 3 times more)!

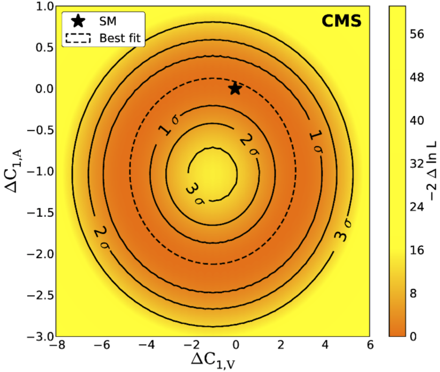
Back-up

8 TeV analysis: 2D Fit



- Profile likelihood as a function of $\sigma(t\bar{t}W)$ and $\sigma(t\bar{t}Z)$, measured cross section is in agreement with theoretical prediction within 2 σs

8 TeV analysis: tZ coupling interpretation in EFT



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

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

- The measured tZ interaction was interpreted in terms of effective field theory approach
- Difference between the profile likelihood and the best fit profile likelihood functions for the relative vector and axial components for the tZ coupling
- Constrain on dimension-six operators that have small effect on inclusive Higgs boson and $t\bar{t}$ production, and a large effect on $t\bar{t}W$ and $t\bar{t}Z$

8 TeV analysis: constrain on dimension-six operators

- Constrain on dimension-six operators that have small effect on inclusive Higgs boson and $t\bar{t}$ production, and a large effect on $t\bar{t}W$ and $t\bar{t}Z$

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

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

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

$$\Delta L = \frac{i\bar{c}_{Hq}}{v^2}(\bar{q}_L\gamma^\mu q_L)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}'_{Hq}}{v^2}(\bar{q}_L\gamma^\mu\sigma^i q_L)(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H) + \frac{i\bar{c}_{Hu}}{v^2}(\bar{u}_R\gamma^\mu u_R)(H^\dagger \overleftrightarrow{D}_\mu H) + \frac{\bar{c}_{uB}\,g'}{m_W^2} y_u\,\bar{q}_L H^c \sigma^{\mu\nu} u_R\, B_{\mu\nu} + \frac{\bar{c}_{3W}\,g^3}{m_W^2}\epsilon^{ijk} W_\mu^{i\,\nu} W_\nu^{j\,\rho} W_\rho^{k\,\mu}$$

- From the cross-section scan it's observed that $\bar{c}_{uB}$, $\bar{c}_{Hu}$ and $\bar{c}_{HQ}$ affect only $t\bar{t}Z$, $\bar{c}_{3W}$ only $t\bar{t}W$, $\bar{c}'_{HQ}$ both

Results: TOP-16-009, 3ℓ channel

	$N_{\text{jets}} = 2$	
Process	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} \geq 1$
WZ	34.06 ± 0.71±6.81	12.88 ± 0.44±2.58
ttX	0.64 ± 0.06±0.16	2.78 ± 0.13±0.70
Non-prompt	17.94 ± 2.64±5.38	10.63 ± 1.66±3.19
Rare	12.52 ± 1.48±6.26	4.44 ± 1.03±2.22
Background	65.16 ± 3.11±10.70	30.74 ± 2.01±4.71
ttZ	0.63 ± 0.10±0.08	2.65 ± 0.19±0.17
Predicted	65.79 ± 3.12±10.70	33.38 ± 2.02±4.72
Data	64	35

Results: TOP-16-009, 3ℓ channel

	$N_{\text{jets}} = 3$		
Process	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} = 1$	$N_{\text{bjets}} \geq 2$
WZ	7.67 $\pm$ 0.32$\pm$1.53	3.88 $\pm$ 0.24$\pm$0.78	0.73 $\pm$ 0.10$\pm$0.15
ttX	0.23 $\pm$ 0.04$\pm$0.06	0.95 $\pm$ 0.07$\pm$0.24$\pm$	0.94 $\pm$ 0.08$\pm$0.24
Non-prompt	1.82 $\pm$ 0.72$\pm$0.55	3.80 $\pm$ 1.04$\pm$1.14	0.21 $\pm$ 0.19$\pm$0.06
Rare	2.16 $\pm$ 0.56$\pm$1.08	0.88 $\pm$ 0.13$\pm$0.44	1.03 $\pm$ 0.67$\pm$0.52
Background	11.89 $\pm$ 0.97$\pm$1.96	9.51 $\pm$ 1.08$\pm$1.47	2.91 $\pm$ 0.71$\pm$0.59
ttZ	0.41 $\pm$ 0.10$\pm$0.07	2.50 $\pm$ 0.19$\pm$0.13	1.99 $\pm$ 0.18$\pm$0.17
Predicted	12.30 $\pm$ 0.97$\pm$1.96	12.01 $\pm$ 1.10$\pm$1.47	4.91 $\pm$ 0.73$\pm$0.61
Data	17	9	5

Results: TOP-16-009, 3ℓ channel

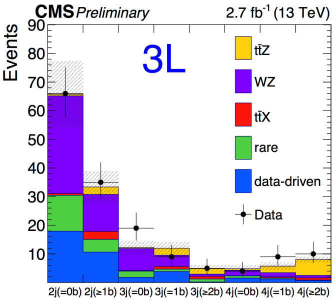
	$N_{\text{jets}} \geq 4$		
Process	$N_{\text{bjets}} = 0$	$N_{\text{bjets}} = 1$	$N_{\text{bjets}} \geq 2$
WZ	$1.88 \pm 0.16 \pm 0.38$	$1.48 \pm 0.15 \pm 0.30$	$0.82 \pm 0.12 \pm 0.16$
ttX	$0.06 \pm 0.02 \pm 0.01$	$0.40 \pm 0.07 \pm 0.10$	$0.78 \pm 0.08 \pm 0.19$
Non-prompt	$1.56 \pm 0.62 \pm 0.47$	$1.26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

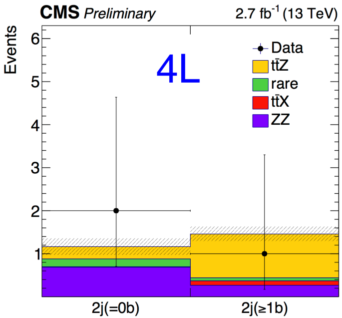
Results: TOP-16-009, 4ℓ channel

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

Results: TOP-16-009, significancies

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





- $\sigma_{\text{measured}}(t\bar{t}Z) = 1.07^{+0.35}_{-0.31}(\text{stat.})\ ^{+0.17}_{-0.14}(\text{sys.})$ pb
- $\sigma_{\text{theoretical}}(t\bar{t}Z) = 0.84^{+0.08}_{-0.09}(\text{scale})\ ^{+0.03}_{-0.03}(\text{pdf})\ ^{+0.03}_{-0.03}(\alpha_s)$ pb (NLO in QCD and EW)
- Combined significance: 3.1 expected and 3.6 observed

Results: TOP-16-017, same-sign dilepton channel

	SS 2L, $0 < \text{BDT} < 0.6$, minus-minus				
Process	2 jets	3 jets 1 bjet	3 jets $\geq$ 2 bjets	$\geq$ 4 jets 1 bjet	$\geq$ 4 jets $\geq$ 2 bjets
total background	5.39 ± 1.14	3.42 ± 0.81	3.57 ± 0.88	2.20 ± 1.02	7.21 ± 1.86
ttW	0.70 ± 0.09	0.61 ± 0.08	1.12 ± 0.14	0.71 ± 0.09	1.97 ± 0.24
total	6.08 ± 1.15	4.03 ± 0.81	4.69 ± 0.90	2.91 ± 1.03	9.18 ± 1.88
observed	9	7	5	5	9
	SS 2L, $0.6 < \text{BDT}$, minus-minus				
Process	2 jets	3 jets 1 bjet	3 jets $\geq$ 2 bjets	$\geq$ 4 jets 1 bjet	$\geq$ 4 jets $\geq$ 2 bjets
total background	1.00 ± 0.25	0.82 ± 0.19	1.70 ± 0.39	1.04 ± 0.32	6.05 ± 1.05
ttW	0.32 ± 0.04	0.32 ± 0.04	0.90 ± 0.11	0.48 ± 0.06	2.51 ± 0.30
total	1.33 ± 0.26	1.13 ± 0.20	2.59 ± 0.40	1.52 ± 0.33	8.55 ± 1.09
observed	1	1	4	2	13

Results: TOP-16-017, same-sign dilepton channel

	SS 2L, $0 < \mathrm{BDT} < 0.6$, plus-plus				
Process	2 jets	3 jets 1 bjet	3 jets $\geq$ 2 bjets	4 jets 1 bjet	$\geq$ 4 jets $\geq$ 2 bjets
total background	5.02 ± 1.14	1.83 ± 1.47	3.88 ± 0.89	4.57 ± 1.71	9.86 ± 2.15
ttW	1.33 ± 0.16	1.12 ± 0.14	1.99 ± 0.24	1.29 ± 0.16	3.56 ± 0.43
total	6.35 ± 1.15	2.94 ± 1.48	5.87 ± 0.92	5.85 ± 1.72	13.42 ± 2.19
observed	7	4	5	5	5

	SS 2L, $0.6 < \mathrm{BDT}$, plus-plus				
Process	2 jets	3 jets 1 bjet	3 jets $\geq$ 2 bjets	$\geq$ 4 jets 1 bjet	$\geq$ 4 jets $\geq$ 2 bjets
total background	1.50 ± 0.37	0.98 ± 0.30	1.49 ± 0.44	0.84 ± 0.24	5.72 ± 1.05
ttW	0.74 ± 0.09	0.63 ± 0.08	1.74 ± 0.21	0.86 ± 0.11	4.56 ± 0.55
total	2.24 ± 0.38	1.61 ± 0.32	3.22 ± 0.49	1.70 ± 0.27	10.29 ± 1.18
observed	2	3	7	3	14

Results: TOP-16-017, three-lepton channel

	3L, 2 jets		
Process	0 bjet	1 bjet	$\geq$ 2 bjet
Background	333.30 $\pm$ 55.56	49.60 $\pm$ 8.36	4.54 $\pm$ 1.19
ttZ	5.74 $\pm$ 0.83	8.26 $\pm$ 1.15	2.18 $\pm$ 0.33
Predicted	339.04 $\pm$ 55.57	57.85 $\pm$ 8.44	6.72 $\pm$ 1.23
Data	358	78	6

	3L, 3 jets		
Process	=0 bjet	=1 bjet	$\geq$ 2 bjet
Background	95.36 $\pm$ 17.08	20.70 $\pm$ 3.68	3.90 $\pm$ 0.91
ttZ	6.26 $\pm$ 0.93	13.03 $\pm$ 1.78	6.66 $\pm$ 1.00
Predicted	101.62 $\pm$ 17.10	33.73 $\pm$ 4.09	10.55 $\pm$ 1.35
Data	109	41	8

	3L, $\geq$ 4 jets		
Process	0 bjet	1 bjet	$\geq$ 2 bjet
Background	34.72 $\pm$ 6.48	9.85 $\pm$ 1.78	3.70 $\pm$ 0.82
ttZ	5.95 $\pm$ 0.92	15.50 $\pm$ 2.15	12.03 $\pm$ 1.80
Predicted	40.67 $\pm$ 6.54	25.35 $\pm$ 2.79	15.73 $\pm$ 1.98
Data	57	20	11

Results: TOP-16-017, four-lepton channel

	4L, $\geq$ 2 jets	
Process	0 bjet	$\geq$ 1 bjet
Background	6.10 ± 1.27	1.67 ± 0.81
ttZ	1.27 ± 0.17	5.83 ± 0.73
Predicted	7.37 ± 1.28	7.50 ± 1.09
Observed	6	10