Measurements of $t\bar{t}$+boson (except Higgs) results at the LHC

Top2015

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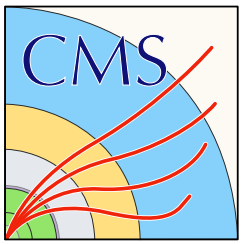
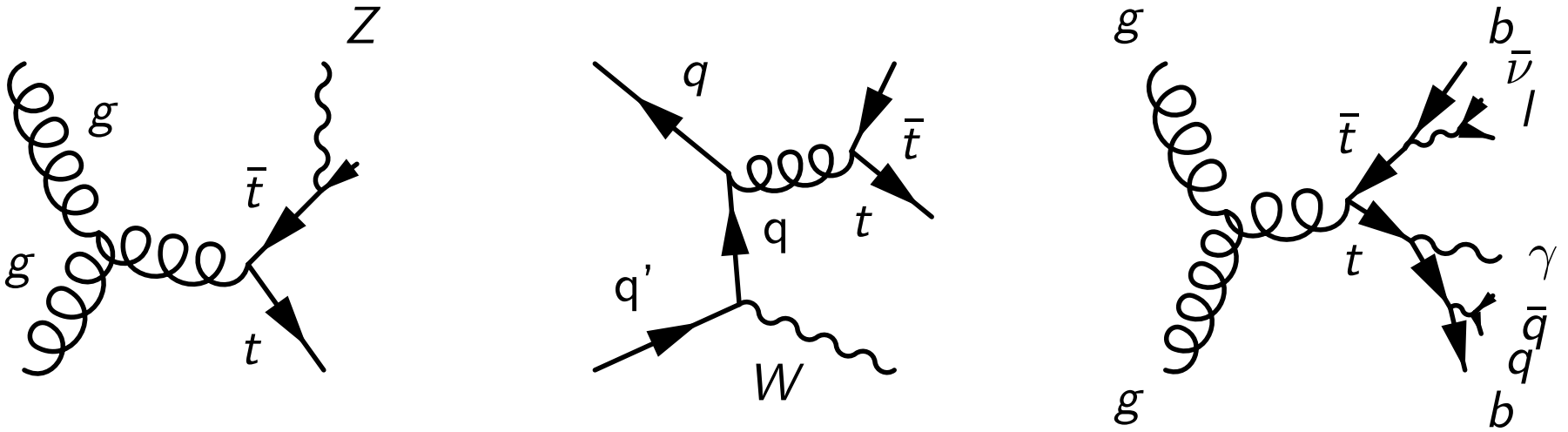


Overview

- Introduction and experimental status of the $t\bar{t}Z$, $t\bar{t}W$, and $t\bar{t}\gamma$ processes.
- (New) "Observation of top-quark pair production in association with a photon and measurement of the $t\bar{t}\gamma$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector". Phys. Rev. D 91, 072007.
- (New) "Measurement of the $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector": ATLAS-CONF-2015-032.
- (New) "Measurement of top quark pair production in association with a W or Z boson using event reconstruction techniques": CMS-PAS-TOP-14-021.

Introduction to $t\bar{t} + (Z, W, \gamma)$



- Direct measurements of $t\bar{t}\gamma$ only had low sensitivity at the Tevatron ($O(3\sigma)$), and $t\bar{t}+(Z, W)$ was not possible before the LHC era.
- The main interest stems from the fact that the observed yields and measured cross-sections could be altered by new physics, e.g. strongly coupled higgs models for $t\bar{t}+(Z, W)$ and composite or excited tops for $t\bar{t}\gamma$.
- Inclusive cross-sections are a first systematic step to constrain the new physics models, providing input to e.g. effective theory modeling.

Experimental status of $t\bar{t} + (Z, W, \gamma)$ as of Top2014

Cross-section	ATLAS (fb)	CMS (fb)	CDF (fb)
$\sigma_{t\bar{t}\gamma}$ [2 TeV]			180 ± 80
$\sigma_{t\bar{t}\gamma}$ [7 TeV]	$2000 \pm 500(stat.) \pm 700(syst.)$		
$\sigma_{t\bar{t}\gamma}$ [8 TeV]		$2400 \pm 200(stat.) \pm 600(syst.)$	
$\sigma_{t\bar{t}Z/\gamma^*}$ [7 TeV]	< 700	$280^{+140}_{-110}(stat.)^{+60}_{-30}(syst.)$	
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV]	$150^{+55}_{-50}(stat.)^{+21}_{-21}(syst.)$	$200 \pm 90(total)$	
$\sigma_{t\bar{t}W}$ [7 TeV]			
$\sigma_{t\bar{t}W}$ [8 TeV]	$300^{+120}_{-100}(stat.)^{+70}_{-40}(syst.)$	$170^{+110}_{-100}(total)$	

Relative uncertainties were: $\sigma_{t\bar{t}Z/\gamma^*} = O(40\%)$, $\sigma_{t\bar{t}W} = O(50\%)$
(The situation will look different at the end of this talk!)

SM prediction 8 TeV

- $\sigma_{t\bar{t}\gamma} = 1800 \pm 500$ fb (Phys.Rev.D83:074013,2011)
- $\sigma_{t\bar{t}Z/\gamma^*} = 215 \pm 30$ fb (aMC@NLO), rel. unc. $= O(10\%)$
- $\sigma_{t\bar{t}W} = 232 \pm 32$ fb (aMC@NLO), rel. unc. $= O(10\%)$

ATLAS - updated $t\bar{t}\gamma$ measurement

Main ingredients

- Fiducial measurement, $E_T(\gamma) > 20$ GeV using single lepton $t\bar{t}$ selection.
- Prompt and non-prompt gamma contributions estimated from data-driven template fit using the track isolation as discriminating variable.
- Signal simulated with MadGraph and Whizard.
- The dataset is 7 TeV from 2011, $\int L\mathrm{d}t = 4.59\,\mathrm{fb}^{-1}$.

Documented in

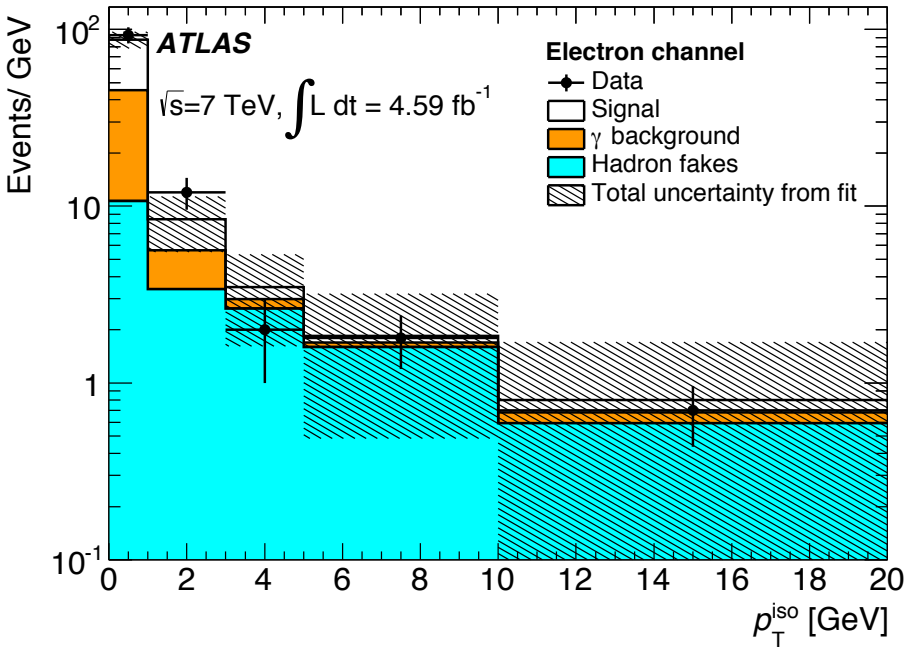
Phys. Rev. D 91, 072007: " Observation of top-quark pair production in association with a photon and measurement of the $t\bar{t}\gamma$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector".

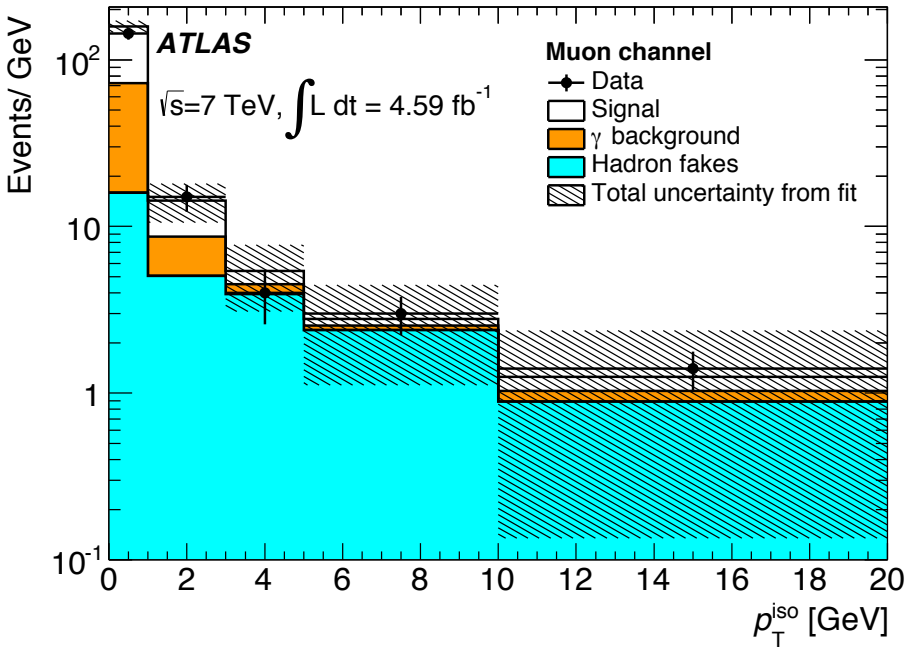
ATLAS - $t\bar{t}\gamma$ selected events and uncertainties

Contribution	Electron chan.	Muon chan.	Total
Signal	52 ± 14	100 ± 28	152 ± 31
Hadrons	38 ± 26	55 ± 38	93 ± 46
Prompt photons	41 ± 5	65 ± 9	106 ± 10
Total background	79 ± 26	120 ± 39	199 ± 47
Total	131 ± 30	220 ± 48	351 ± 59
Data candidates	140	222	362

Uncertainty source	Uncertainty [%]
Background template shapes	3.7
Signal template shapes	6.6
Signal modeling	8.4
Photon modeling	8.8
Lepton modeling	2.5
Jet modeling	16.6
b-tagging	8.2
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	0.9
Luminosity	1.8
Background contributions	7.7

ATLAS - $t\bar{t}\gamma$ results





- $\sigma^{fid}_{t\bar{t}\gamma} \times BR = 63 \pm 8(\text{stat})^{+17}_{-13}(\text{syst}) \pm 1(\text{lumi})$ fb per lepton flavor.
- Consistent with NLO calculation: 48 ± 10 fb.
- Background hypothesis excluded with 5.3σ.

ATLAS - updated $t\bar{t}W$ and $t\bar{t}Z/\gamma^*$ measurement

Main ingredients

- More signal regions added, same sign (SS) dilepton (ee,$e\mu$) and tetralepton, to previous public result ATLAS-CONF-2014-038.
- The dataset is the same 8 TeV from 2012, $\int L\mathrm{d}t = 20.3\,\mathrm{fb}^{-1}$.

Documented in

ATLAS-CONF-2015-032: "Measurement of the $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector".

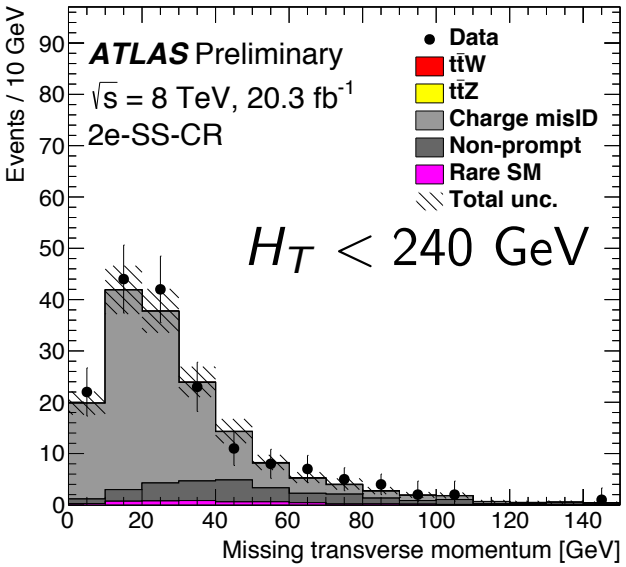
ATLAS - $t\bar{t}W$ and $t\bar{t}Z/\gamma^*$ measurement overview

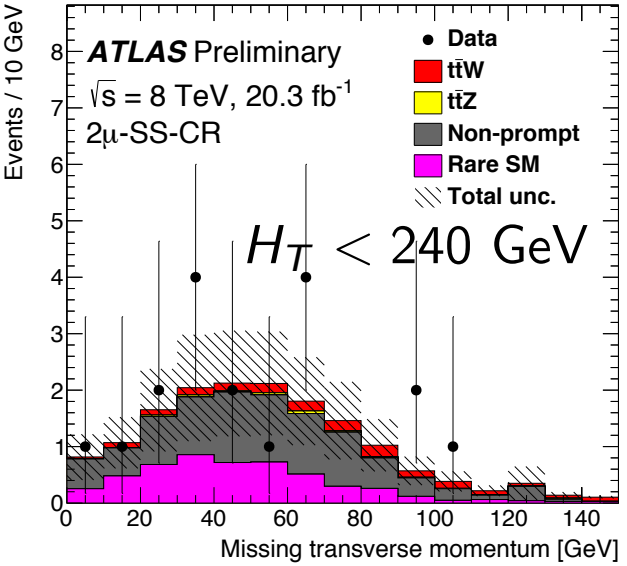
Main updates compared to Top2014

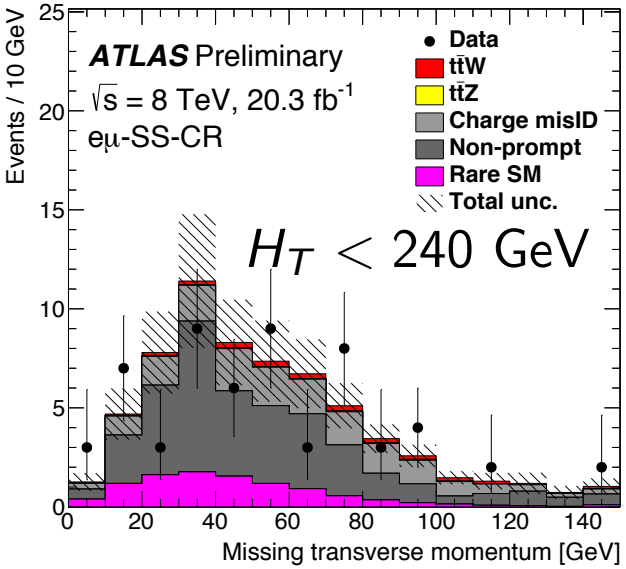
- Same sign (SS) dilepton (ee,$e\mu$) final states added, all SS channels use tighter requirements on the impact parameters to reject fake leptons.
- Tetralepton final states added.
- Consistent use of uncertainty treatment across all channels, in particular the b-tagging systematic uncertainties.

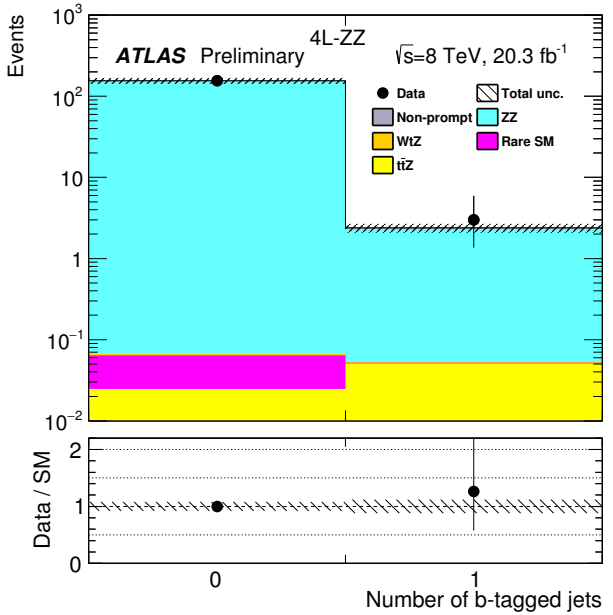
Signal region	Main cuts	Main background	Background treatment
OS dilepton	$\geq$ 4jets, $\geq$ 1b-tag	$t\bar{t}$	Neural networks, control regions (CR) for $t\bar{t}$, Z
		Z	
SS dilepton	$\geq$ 2b-tags	Fake leptons	Fake factor method
		Charge misID	Likelihood fit
Trilepton	$\geq$ 3jets,$\geq$ 1 b-tag	Fake leptons	Matrix method
		WZ	Fit WZ in CR
Tetralepton	$\geq$ 1b-tag	ZZ	Fit ZZ in CR

ATLAS - background CR distributions for SS and 4L

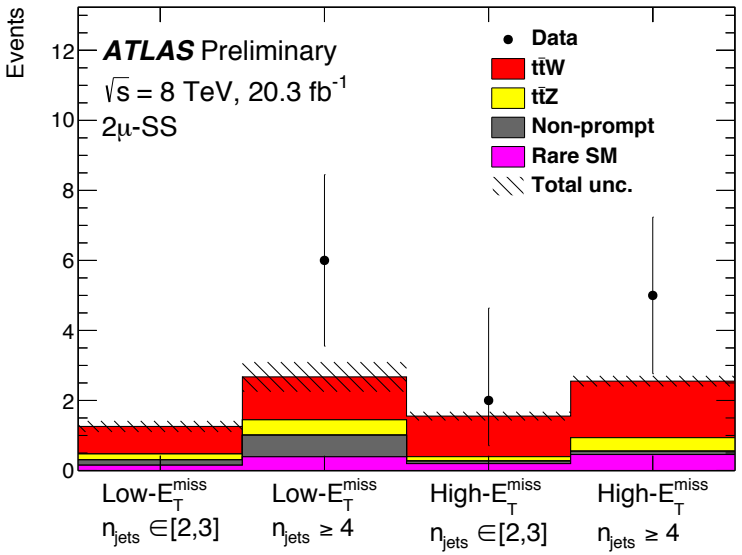


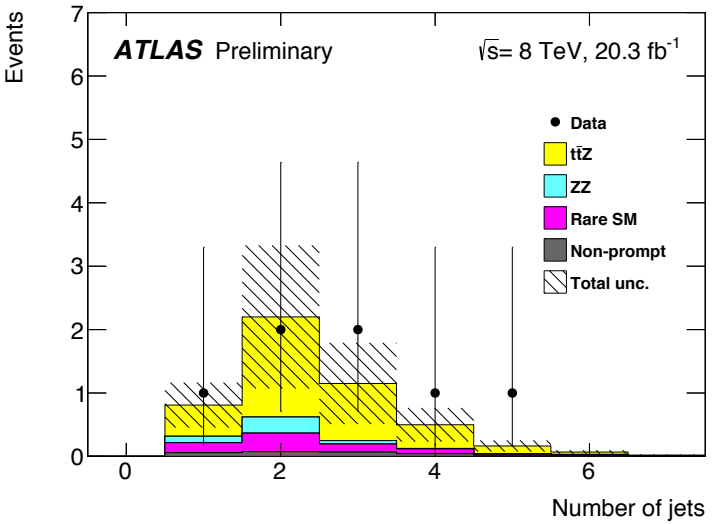


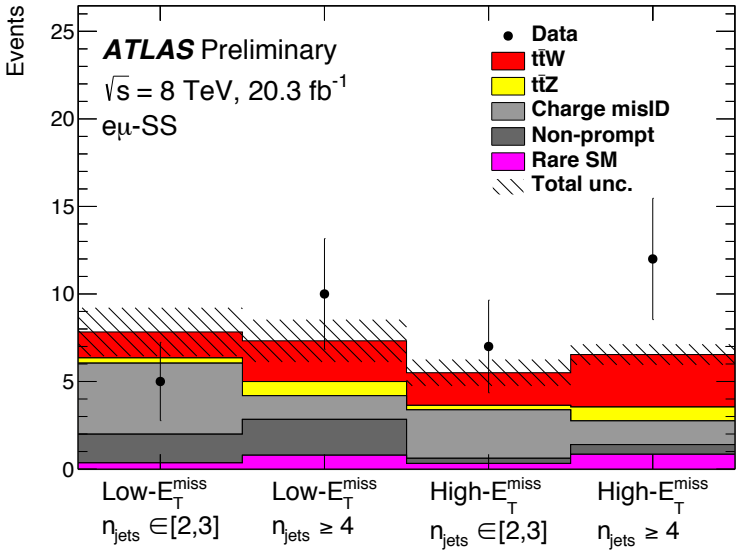


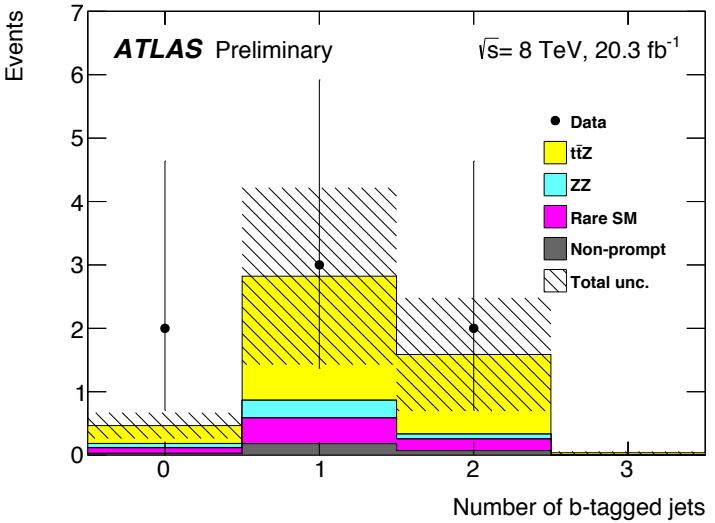


ATLAS - signal region prefit for SS and 4L (right)



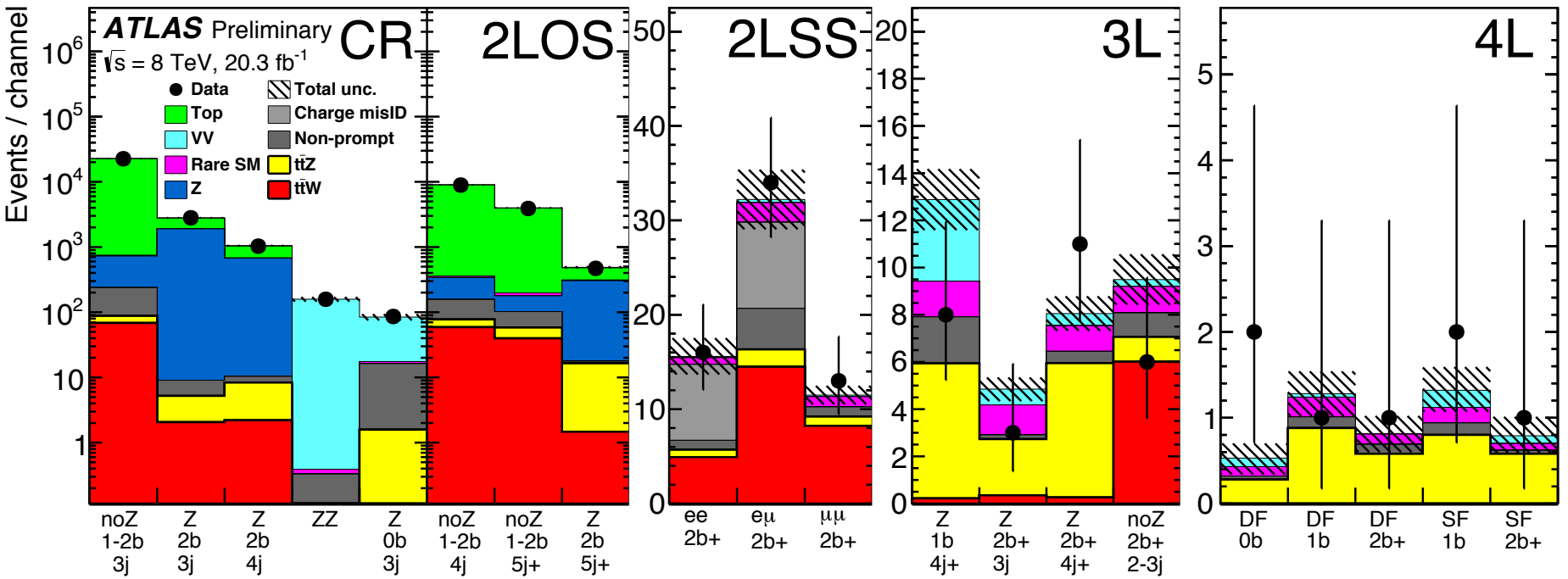






ATLAS - final states combination

- All 15 SR and 5 CR are combined in a profile likelihood fit where $\sigma_{t\bar{t}W}$ and $\sigma_{t\bar{t}Z/\gamma^*}$ are free parameters. The systematic uncertainties are included as nuisance parameters and correlated across channels as appropriate. Postfit result per region is shown below:



ATLAS - results viewed in 1D

Cross-section

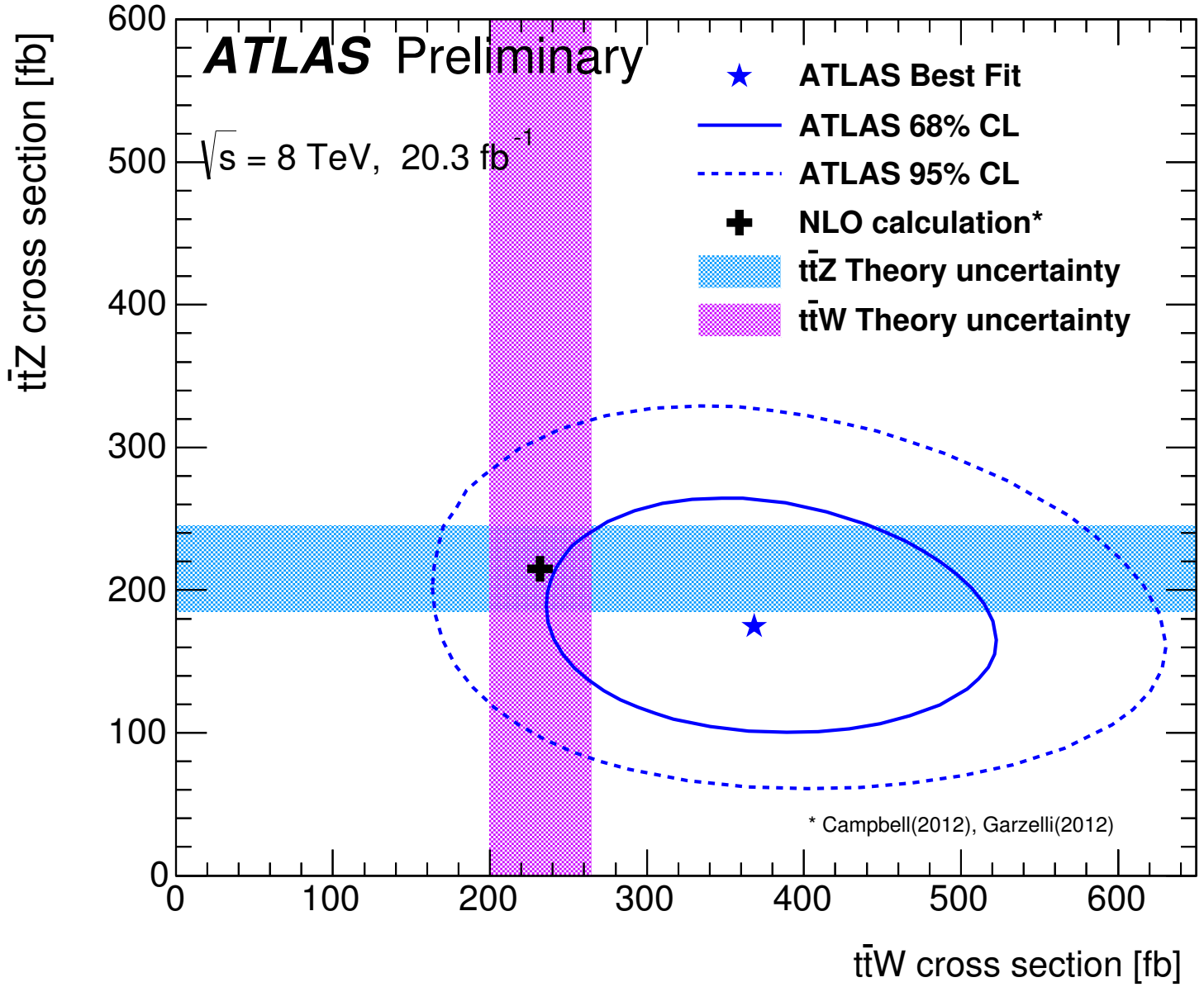
$\sigma_{t\bar{t}W} = 369^{+86}_{-79}(\text{stat})\pm 44(\text{syst.})$ fb $\quad \sigma_{t\bar{t}Z} = 176^{+52}_{-48}(\text{stat})\pm 24(\text{syst.})$ fb

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 systematic	12%	13%
Statistical	+24% / −21%	+30% / −27%
Total	+27% / −24%	+33% / −29%

	$t\bar{t}W$ significance		$t\bar{t}Z$ significance	
Channel	Expected	Observed	Expected	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

Notice the decrease in uncertainty with the update:
$O(40\%) \rightarrow O(30\%)$ for $t\bar{t}Z/\gamma^*$ and $O(50\%) \rightarrow O(30\%)$ for $t\bar{t}W$

ATLAS - results viewed in 2D



CMS - updated $t\bar{t}W$ and $t\bar{t}Z/\gamma^*$ measurement

Main updates compared to Top2014

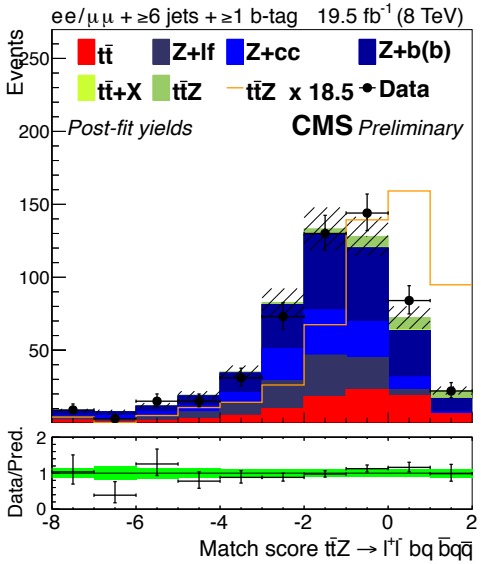
- Parton matching to the signal process (also partial) and BDT classification per final state (10 BDTs) used for all channels, except tetralepton which uses number of b-tags.
- OS dilepton final state added.
- Limits on couplings and operators in dim. 6 EFT.
- The dataset is the same 8 TeV from 2012, $\int L\mathrm{d}t = 19.5\,\mathrm{fb}^{-1}$.

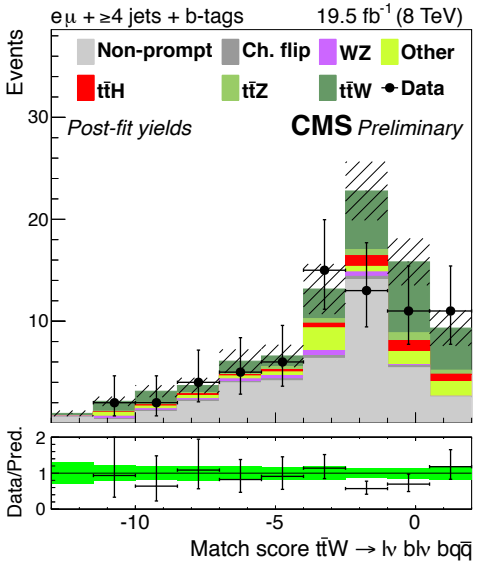
Documented in

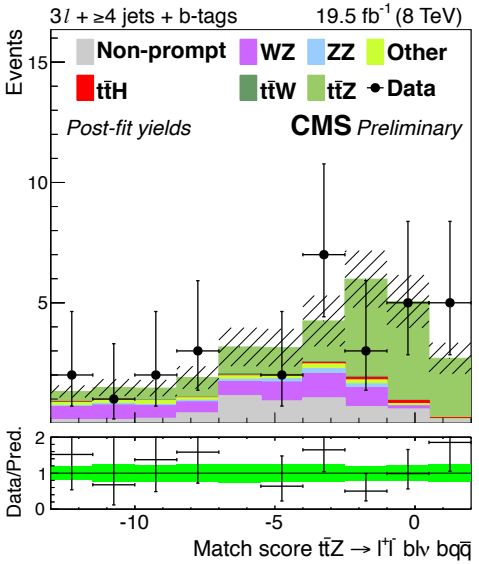
CMS-PAS-TOP-14-021: "Measurement of top quark pair production in association with a W or Z boson using event reconstruction techniques".

CMS - analysis strategy

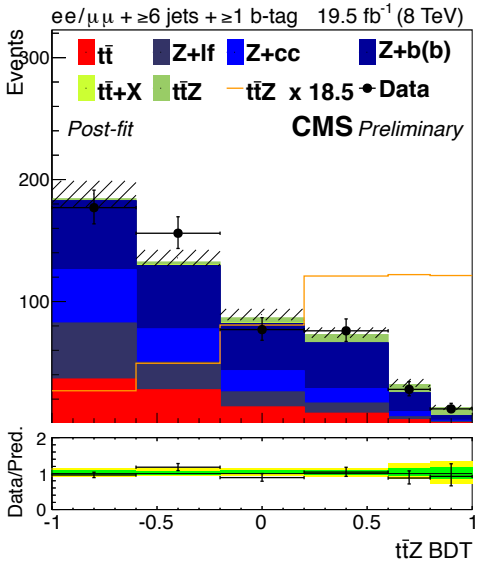
First preselect and do parton matching of $t\bar{t}$ and book score:

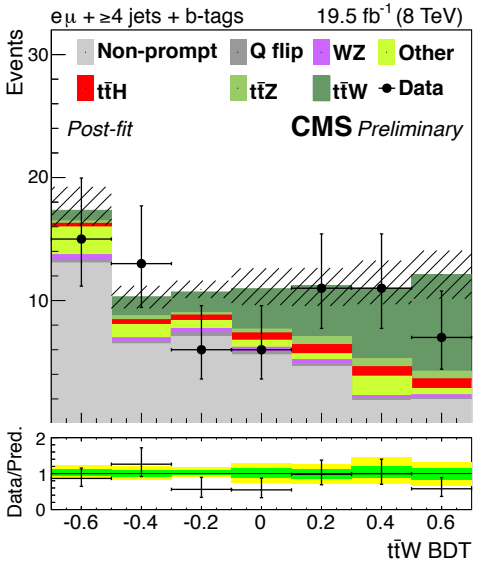


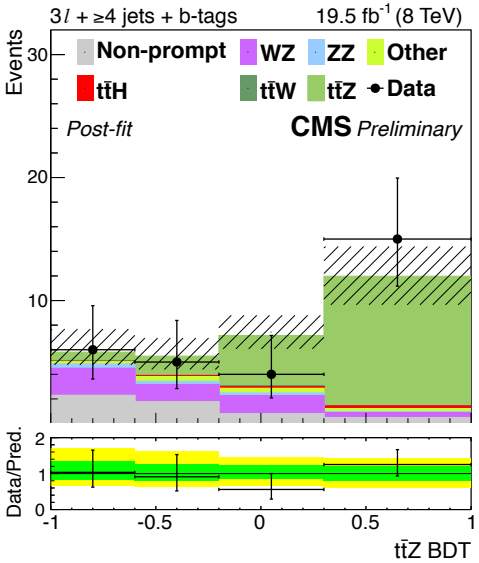




Then add BDT classification using score and other variables as input:

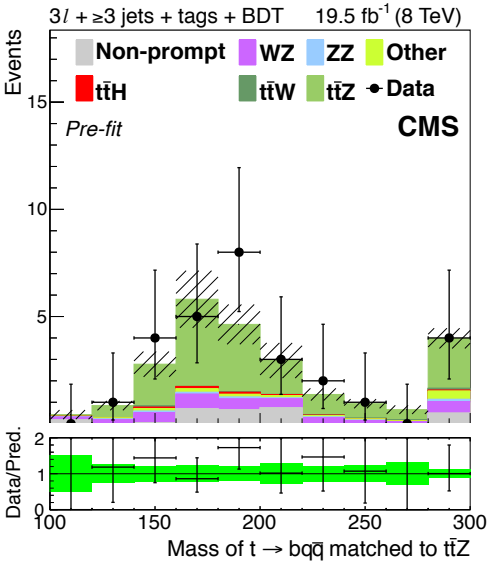


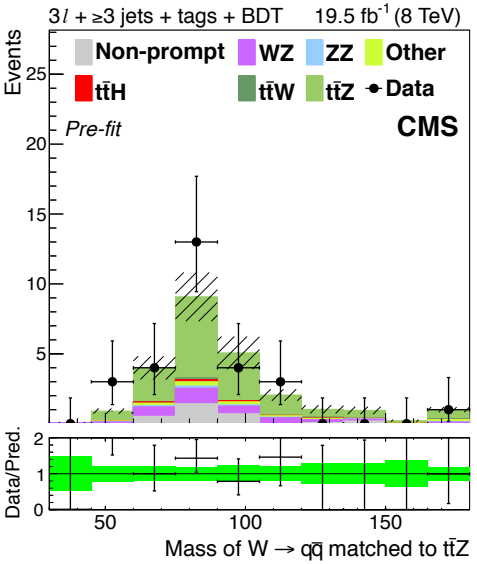


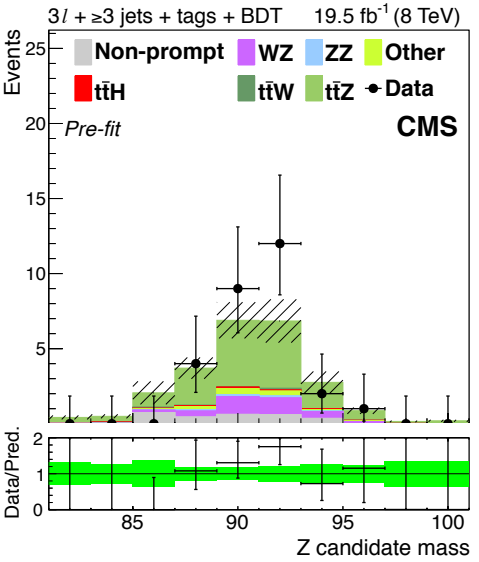


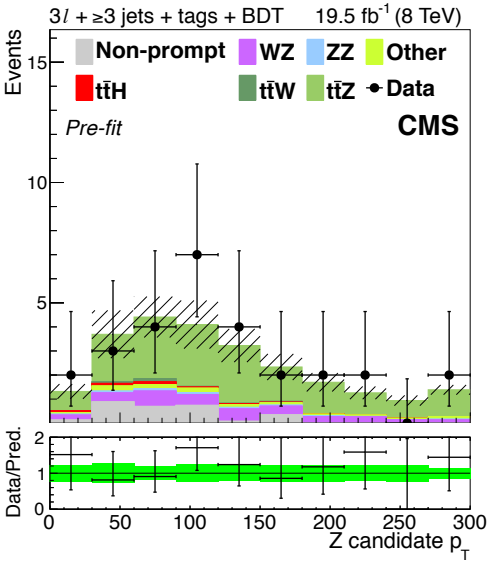
CMS - prefit distributions

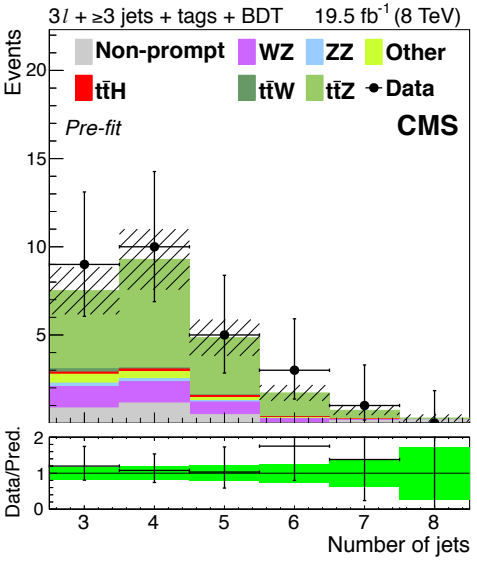
Note that the matching allows for top and W mass reconstruction

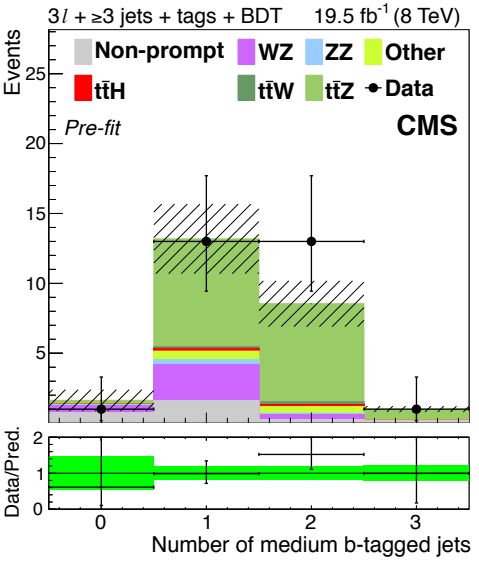












CMS - cross-section results

$t\bar{t}Z$

	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
OS	206^{+142}_{-118}	257^{+158}_{-129}	$1.0^{+0.72}_{-0.57}$	$1.25^{+0.76}_{-0.62}$	1.8	2.1
3ℓ	206^{+79}_{-63}	257^{+85}_{-67}	$1.0^{+0.42}_{-0.32}$	$1.25^{+0.45}_{-0.36}$	4.6	5.1
4ℓ	206^{+153}_{-109}	228^{+150}_{-107}	$1.0^{+0.77}_{-0.53}$	$1.11^{+0.76}_{-0.52}$	2.7	3.4
OS + 3ℓ + 4ℓ	206^{+62}_{-52}	242^{+65}_{-55}	$1.0^{+0.34}_{-0.27}$	$1.18^{+0.35}_{-0.29}$	5.7	6.4

$t\bar{t}W$

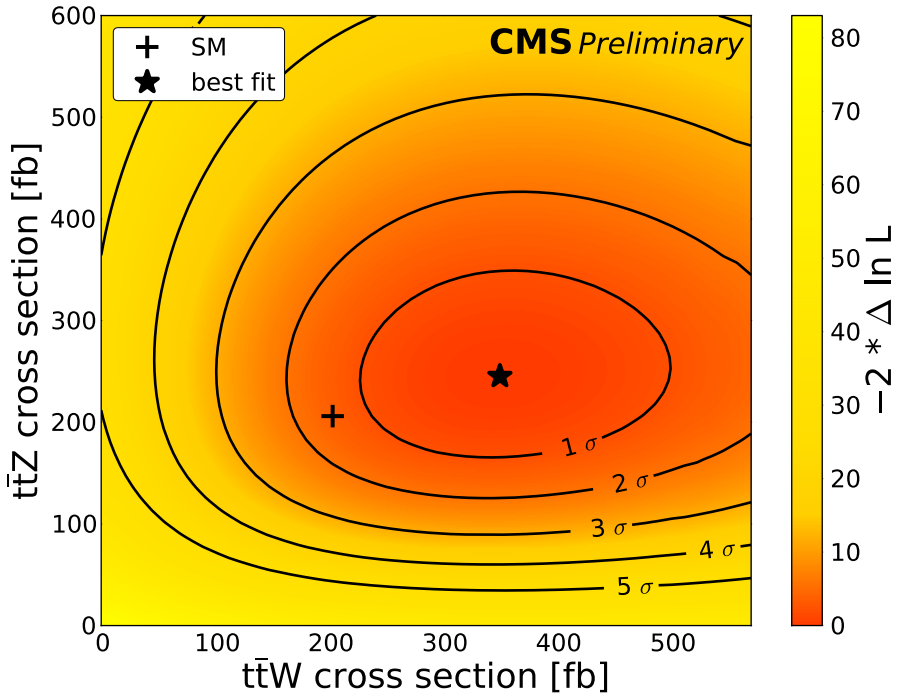
	Cross section (fb)		Signal strength (μ)		Significance	
Channels	Expected	Observed	Expected	Observed	Expected	Observed
SS	203^{+88}_{-73}	414^{+135}_{-112}	$1.0^{+0.45}_{-0.36}$	$2.04^{+0.74}_{-0.61}$	3.4	4.9
3ℓ	203^{+215}_{-194}	210^{+225}_{-203}	$1.0^{+1.09}_{-0.96}$	$1.03^{+1.07}_{-0.99}$	1.0	1.0
SS + 3ℓ	203^{+84}_{-71}	382^{+117}_{-102}	$1.0^{+0.43}_{-0.35}$	$1.88^{+0.66}_{-0.56}$	3.5	4.8

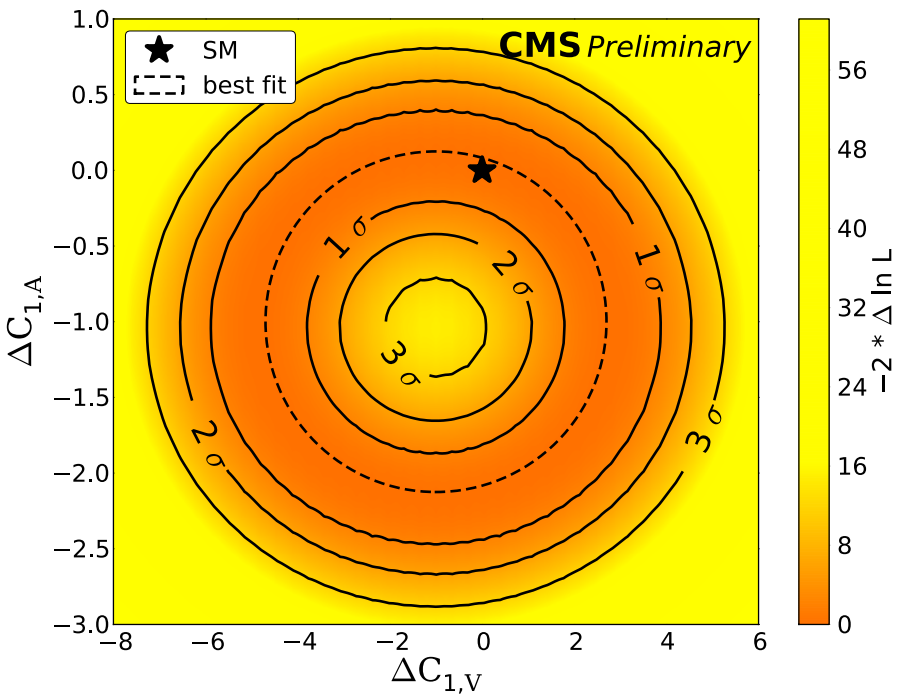
Also here the updated uncertainty is reduced to $O(30\%)$ for $t\bar{t}Z$ and $O(30\%)$ for $t\bar{t}W$.

CMS - uncertainties on the results

Reduction in signal strength uncertainty		
Systematic uncertainties removed	$t\bar{t}W$	$t\bar{t}Z$
Signal modeling	5.2%	7.1%
Nonprompt backgrounds	12.5%	0.5%
Inclusive prompt backgrounds	0.7%	2.6%
Prompt backgrounds with extra jets	0.2%	3.4%
Prompt backgrounds with extra heavy flavor jets	0.0%	1.1%
b tagging efficiency	6.1%	7.3%
Jet energy scale	1.4%	$< 0.1\%$
Lepton ID and trigger efficiency	0.3%	0.5%
Luminosity and pileup	0.7%	0.5%
Bin-by-bin statistical uncertainty	4.4%	1.2%
All systematic uncertainties	31%	29%

CMS - 2D results and couplings





CMS - effective dim. 6 EFT operators

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 $\{0.18, 0.36\}$	$\{-0.43, 0.43\}$

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

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

$$\Delta L = \frac{i\bar{c}_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu q_L\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}'_{Hq}}{v^2}\left(\bar{q}_L\gamma^\mu\sigma^i q_L\right)\left(H^\dagger\sigma^i \overleftrightarrow{D}_\mu H\right) + \frac{i\bar{c}_{Hu}}{v^2}\left(\bar{u}_R\gamma^\mu u_R\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) +$$

$$\frac{\bar{c}_{uB}\,g'}{m_W^2}\,y_u\,\bar{q}_L H^c\sigma^{\mu\nu}u_R\,B_{\mu\nu} + \frac{\bar{c}_{3W}\,g^3}{m_W^2}\,\epsilon^{ijk}W_\mu^{i\,\nu}W_\nu^{j\,\rho}W_\rho^{k\,\mu}$$

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

Conclusions

- By improving the analysis techniques and by adding more final states both CMS and ATLAS have managed to improve the inclusive cross-section uncertainties down to $O(30\%)$ for both $t\bar{t}Z$ and $t\bar{t}W$.
- Significances for both processes are now at the discovery level. Future measurements will likely optimize for accuracy and precision instead of significance.
- CMS has also presented limits on couplings and operators using the inclusive cross-sections as input, highlighting one of the main aims of these measurements.

References

Channel	Experiment	Reference
$\sigma_{t\bar{t}\gamma}$ [2 TeV]	CDF	Phys. Rev. D 84, 031104
$\sigma_{t\bar{t}\gamma}$ [7 TeV]	ATLAS	ATLAS-CONF-2011-153
$\sigma_{t\bar{t}\gamma}$ [7 TeV] (New)	ATLAS	Phys. Rev. D 91, 072007
$\sigma_{t\bar{t}\gamma}$ [8 TeV]	CMS	CMS-PAS-TOP-13-011
$\sigma_{t\bar{t}Z/\gamma^*}$ [7 TeV]	ATLAS	ATLAS-CONF-2012-126
$\sigma_{t\bar{t}Z/\gamma^*}$ [7 TeV]	CMS	Phys. Rev. Lett. 110, 172002
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV]	ATLAS	ATLAS-CONF-2014-038
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV] (New)	ATLAS	ATLAS-CONF-2015-032
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV]	CMS	Eur. Phys. J. C (2014) 74:3060
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV] (New)	CMS	CMS-PAS-TOP-14-021
$\sigma_{t\bar{t}W}$ [8 TeV]	ATLAS	ATLAS-CONF-2014-038
$\sigma_{t\bar{t}W}$ [8 TeV] (New)	ATLAS	ATLAS-CONF-2015-032
$\sigma_{t\bar{t}W}$ [8 TeV]	CMS	Eur. Phys. J. C (2014) 74:3060
$\sigma_{t\bar{t}W}$ [8 TeV] (New)	CMS	CMS-PAS-TOP-14-021

Backup

ATLAS - yield table

Region	$t + X$	Bosons	Fake leptons charge misID	Total expected background	$t\bar{t}W$	$t\bar{t}Z$	Data
2ℓ-noZ-3j*	20800 ± 2600	600 ± 200	160 ± 80	21600 ± 2700	42.0 ± 2.8	23.2 ± 1.5	22585
2ℓ-noZ-4j	8200 ± 1400	240 ± 90	80 ± 40	8600 ± 1400	36.6 ± 1.8	22.4 ± 1.1	8909
2ℓ-noZ-5j	3700 ± 850	100 ± 40	47 ± 23	3810 ± 870	24.9 ± 2.2	22.4 ± 2.0	3901
2ℓ-Z-3j*	800 ± 140	1960 ± 880	4.1 ± 2.1	2760 ± 890	1.24 ± 0.13	3.71 ± 0.38	2806
2ℓ-Z-4j*	330 ± 70	740 ± 390	2.2 ± 1.1	1100 ± 400	1.31 ± 0.11	7.21 ± 0.58	1031
2ℓ-Z-5j	170 ± 40	340 ± 200	1.4 ± 0.7	510 ± 210	0.89 ± 0.07	17.7 ± 1.4	471
$2e$-SS	0.66 ± 0.13	0.17 ± 0.10	8.9 ± 2.4	9.8 ± 2.6	2.97 ± 0.30	0.93 ± 0.23	16
$e\mu$-SS	1.9 ± 0.35	0.39 ± 0.28	14.1 ± 4.5	16.4 ± 5.1	8.67 ± 0.76	2.16 ± 0.51	34
2μ-SS	0.94 ± 0.17	0.25 ± 0.14	0.93 ± 0.55	2.12 ± 0.86	4.79 ± 0.40	1.12 ± 0.27	13
3ℓ-Z-0b3j*	1.11 ± 0.32	67 ± 16	15.2 ± 6.0	83 ± 15	0.05 ± 0.03	1.86 ± 0.47	86
3ℓ-Z-1b4j	1.58 ± 0.42	3.8 ± 1.3	2.4 ± 1.1	7.8 ± 1.6	0.14 ± 0.05	7.1 ± 1.6	8
3ℓ-Z-2b3j	1.29 ± 0.34	0.68 ± 0.33	0.19 ± 0.13	2.16 ± 0.42	0.21 ± 0.07	2.76 ± 0.69	3
3ℓ-Z-2b4j	1.00 ± 0.29	0.48 ± 0.24	0.42 ± 0.37	1.93 ± 0.49	0.14 ± 0.07	6.6 ± 1.6	11
3ℓ-noZ-2b	1.06 ± 0.25	0.27 ± 0.17	1.31 ± 0.90	2.7 ± 0.9	3.7 ± 0.9	1.23 ± 0.32	6
4ℓ-DF-0b	0.06 ± 0.01	0.11 ± 0.04	0.03 ± 0.17	0.21 ± 0.22	-	0.28 ± 0.01	2
4ℓ-DF-1b	0.22 ± 0.03	0.05 ± 0.03	0.13 ± 0.22	0.39 ± 0.27	-	1.05 ± 0.03	1
4ℓ-DF-2b	0.11 ± 0.02	<0.01	0.11 ± 0.19	0.22 ± 0.21	-	0.64 ± 0.02	1
4ℓ-ZZ*	0.01 ± 0.00	134.2 ± 1.2	0.27 ± 0.18	134.5 ± 1.3	-	0.07 ± 0.01	158
4ℓ-SF-1b	0.16 ± 0.02	0.29 ± 0.06	0.14 ± 0.19	0.61 ± 0.27	-	0.91 ± 0.02	2
4ℓ-SF-2b	0.08 ± 0.01	0.09 ± 0.03	0.04 ± 0.18	0.21 ± 0.23	-	0.64 ± 0.02	1

ATLAS - 4L selection

Region	Z_2 leptons	p_{T4}	p_{T34}	$\lvert m_{\ell\ell} - m_{Z_2}\rvert$	$E_{\mathrm{T}}^{\mathrm{miss}}$	N_{jets}	$N_{b\text{-jets}}$
4ℓ-DF-0b	$e^{\pm}\mu^{\mp}$	> 10 GeV	> 45 GeV	-	-	≥ 2	0
4ℓ-DF-1b	$e^{\pm}\mu^{\mp}$	> 7 GeV	> 35 GeV	-	-	-	1
4ℓ-DF-2b	$e^{\pm}\mu^{\mp}$	> 7 GeV	-	-	-	-	≥ 2
4ℓ-SF-1b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 7 GeV	> 25 GeV	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	$\begin{cases} > 40 \text{ GeV} \\ > 80 \text{ GeV} \end{cases}$	-	1
4ℓ-SF-2b	$e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}$	> 7 GeV	-	$\begin{cases} > 10 \text{ GeV} \\ < 10 \text{ GeV} \end{cases}$	$\begin{cases} - \\ > 40 \text{ GeV} \end{cases}$	-	≥ 2

CMS - SS yield table

	$\mu\mu$		eμ		ee	
Process	3 jets	$\geq$4 jets	3 jets	$\geq$4 jets	3 jets	$\geq$4 jets
Nonprompt	29.0 ± 4.7	26.0 ± 4.4	57.0 ± 5.4	40.5 ± 4.2	16.0 ± 3.7	12.9 ± 3.1
Charge misID	-	-	2.9 ± 0.7	1.6 ± 0.4	3.3 ± 1.6	1.7 ± 0.8
WZ	3.1 ± 1.0	1.3 ± 0.5	4.5 ± 1.4	2.2 ± 0.8	1.6 ± 0.5	0.9 ± 0.3
ZZ	0.2 ± 0.1	0.1 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1
Multiboson	1.2 ± 0.5	1.1 ± 0.4	1.5 ± 0.5	1.2 ± 0.4	0.8 ± 0.3	0.5 ± 0.2
tbZ/t$\bar{t}$+X	0.8 ± 0.3	1.0 ± 0.4	4.1 ± 1.4	5.4 ± 2.2	1.4 ± 0.4	2.4 ± 1.3
t$\bar{t}$H	0.7 ± 0.1	3.0 ± 0.5	1.1 ± 0.1	4.0 ± 0.5	0.3 ± 0.1	1.4 ± 0.2
Background	35.1 ± 4.8	32.6 ± 4.5	71.3 ± 5.8	55.1 ± 4.9	23.7 ± 4.1	19.9 ± 3.5
t$\bar{t}$W	10.4 ± 2.8	17.7 ± 4.0	13.9 ± 3.7	25.2 ± 5.5	5.5 ± 1.4	8.1 ± 1.9
t$\bar{t}$Z	0.7 ± 0.1	2.1 ± 0.4	1.1 ± 0.2	3.0 ± 0.6	0.4 ± 0.1	1.3 ± 0.3
Expected	46.2 ± 5.6	52.6 ± 6.0	86.4 ± 6.9	83.6 ± 7.3	29.6 ± 4.4	29.4 ± 4.0
Data	47	61	89	69	31	32

CMS - OS yield table

	$\mu\mu$/ee		eμ	
Process	5 jets	$\geq$6 jets	5 jets	$\geq$6 jets
Z+lf jets	264.7 ± 57.0	92.6 ± 19.7	< 0.1	< 0.1
Z+c$\bar{c}$ jets	341.0 ± 74.4	105.9 ± 22.8	< 0.1	< 0.1
Z+b jet	235.7 ± 59.4	68.4 ± 18.1	< 0.1	< 0.1
Z+b$\bar{b}$ jets	378.0 ± 72.0	135.6 ± 25.2	< 0.1	< 0.1
t$\bar{t}$+lf jets	188.4 ± 18.9	58.4 ± 7.3	180.3 ± 15.6	57.8 ± 6.4
t$\bar{t}$+hf jets	56.7 ± 15.8	30.6 ± 8.3	52.0 ± 14.5	27.3 ± 7.3
tbZ/t$\bar{t}$WW	4.2 ± 1.8	1.8 ± 0.7	< 0.1	< 0.1
t$\bar{t}$H	1.4 ± 0.1	1.0 ± 0.2	1.0 ± 0.1	0.6 ± 0.1
Background	1470.2 ± 134.6	494.4 ± 44.7	233.4 ± 21.3	85.8 ± 9.7
t$\bar{t}$Z	24.0 ± 5.5	28.2 ± 6.8	1.3 ± 0.3	0.8 ± 0.2
t$\bar{t}$W	1.1 ± 0.2	0.5 ± 0.1	1.2 ± 0.2	0.8 ± 0.2
Expected	1495.3 ± 134.7	523.1 ± 45.2	235.8 ± 21.3	87.4 ± 9.7
Data	1493	526	251	78

CMS - 3L and 4L yield table

	3ℓ $t\bar{t}W$		3ℓ $t\bar{t}Z$		4ℓ	
Process	1 jet	$\geq$2 jets	3 jets	$\geq$4 jets	$\geq$1 jet + Z	$\geq$1 jet + Z-veto
Nonprompt	44.6 ± 5.3	54.8 ± 6.4	8.2 ± 2.8	5.4 ± 2.1	-	-
Nonprompt WZ/Z	-	-	-	-	< 0.1	< 0.1
Nonprompt $t\bar{t}$	-	-	-	-	< 0.1	0.2 ± 0.2
WZ	3.2 ± 0.8	8.0 ± 1.7	11.7 ± 2.9	5.4 ± 1.6	-	-
ZZ	1.0 ± 0.2	1.5 ± 0.3	1.6 ± 0.4	0.9 ± 0.3	3.3 ± 0.5	1.8 ± 0.3
Multiboson	0.1 ± 0.1	0.4 ± 0.2	0.5 ± 0.2	0.5 ± 0.2	< 0.1	0.3 ± 0.1
tbZ/$t\bar{t}$+X	0.4 ± 0.1	3.4 ± 1.1	1.6 ± 0.6	0.7 ± 0.3	< 0.1	< 0.1
$t\bar{t}H$	0.2 ± 0.1	4.7 ± 0.4	0.3 ± 0.1	0.4 ± 0.1	< 0.1	0.2 ± 0.1
Background	49.5 ± 5.4	72.7 ± 6.7	23.9 ± 4.1	13.3 ± 2.7	3.3 ± 0.5	2.4 ± 0.4
$t\bar{t}W$	2.5 ± 0.8	18.8 ± 4.7	0.5 ± 0.1	0.2 ± 0.1	-	-
$t\bar{t}Z$	0.3 ± 0.1	7.5 ± 1.2	8.8 ± 1.9	16.9 ± 3.6	0.4 ± 0.1	4.3 ± 1.0
Expected	52.3 ± 5.4	99.4 ± 8.3	33.2 ± 4.5	30.4 ± 4.5	3.7 ± 0.5	6.7 ± 1.1
Data	51	97	32	30	3	6

CMS - SS and 3L $t\bar{t}W$ BDT variables

BDT inputs: same-sign $t\bar{t}W$ vs. $t\bar{t}$	3 jet	$\geq$4 jets
M_T of $\vec{E}_T^{miss}$and $\vec{p}_T$ of leptons and jets	1	1
E_T^{miss}	4	2
2nd highest lepton p_T	6	3
Match score for $t\bar{t} \to \ell_b q\bar{q}\, \bar{b}\ell\nu$	2	4
Highest lepton p_T	5	5
2nd highest CSV value of a jet	8	6
$t\bar{t}$ matched top M_T from $b\ell\nu$	7	7
Match score for $t\bar{t}W \to b\ell\nu\, \bar{b}q$	9	8
Match score for $t\bar{t}W \to b\ell\nu\, \bar{b}q\bar{q}$	-	9
$t\bar{t}$ matched top mass from $\ell_b q\bar{q}$	3	-

BDT inputs: 3ℓ $t\bar{t}W$ vs. $t\bar{t}$	1 jet	$\geq$2 jets
2nd highest CSV value of a jet	-	1
M_T of $\vec{E}_T^{miss}$and $\vec{p}_T$ of leptons and jets	1	2
Match score for $t\bar{t}W \to \ell\nu\, b\ell\nu\, \bar{b}\ell\nu$	-	3
2nd highest same-sign lepton p_T	4	4
$t\bar{t}$ matched top mass from ℓ_W and ℓ_b	-	5
Highest same-sign lepton p_T	3	6
Match score for $t\bar{t}W \to \ell\nu\, b\ell\nu\, \ell\nu$	2	-
E_T^{miss}	5	-
Highest jet p_T	6	-

CMS - OS and 3L $t\bar{t}Z$ BDT variables

BDT inputs: 3ℓ $t\bar{t}Z$ vs. WZ and $t\bar{t}$	3 jet	$\geq$4 jets
Match score for $t\bar{t}Z \to \ell\ell\, b\ell\nu\, \bar{b}q$	1	1
Match score for $t\bar{t}Z \to \ell\ell\, b\ell\nu\, \bar{b}q\bar{q}$	-	2
Match score for $t\bar{t}Z \to \ell\ell\, \ell\nu\, \bar{b}q\bar{q}$	8	3
Match score for $t\bar{t}Z \to \ell\ell\, b\ell\nu\, q\bar{q}$	9	4
Number of medium b-tagged jets	3	5
Mass of lepton pair matched to Z boson	7	6
M_T of $\vec{E}_T^{miss}$and $\vec{p}_T$ of leptons and jets	4	7
Match score for $t\bar{t}Z \to \ell\ell\, b\ell\nu\, \bar{b}$	2	-
Match score for $t\bar{t}Z \to \ell\ell\, \ell\nu\, \bar{b}q$	5	-
Match score for $t\bar{t}Z \to \ell\ell\, b\ell\nu\, q$	6	-

BDT inputs: OS $t\bar{t}Z$ vs. $t\bar{t}$	5 jet	$\geq$6 jets
ΔR between leptons	1	1
p_T of dilepton system	2	2
Dilepton invariant mass	3	3
H_T^{miss}	4	4
Match score for $t\bar{t} \to b\ell\nu\, \bar{b}\ell\nu$	5	5
Number of jets with $p_T > 40$ GeV	9	6
Match score for $t\bar{t}Z \to \ell\ell\, bq\bar{q}\, \bar{b}q\bar{q}$	-	7
Match score for $t\bar{t}Z \to \ell\ell\, bq\, \bar{b}q\bar{q}$	8	8
Match score for $t\bar{t}Z \to \ell\ell\, bq\bar{q}\, \bar{b}q\bar{q}$	7	9
Ratio of M_T to mass of jets	6	10
CSV of jet matched to b from $t\bar{t}$	10	12
CSV of jet matched to $\bar{b}$ from $t\bar{t}$	11	11

BDT inputs: OS $t\bar{t}Z$ vs. Z and $t\bar{t}$	5 jet	$\geq$6 jets
OS $t\bar{t}Z$ vs. $t\bar{t}$ BDT	1	1
Match score for $t\bar{t}Z \to \ell\ell\, bq\, \bar{b}q\bar{q}$	3	2
Match score for $t\bar{t}Z \to \ell\ell\, bq\bar{q}\, \bar{b}q$	4	3
Match score for $t\bar{t}Z \to \ell\ell\, bq\bar{q}\, \bar{b}q\bar{q}$	-	4
Minimum χ^2 for $t\bar{t}Z \to \ell\ell\, bq\bar{q}\, \bar{b}q\bar{q}$	-	5
Number of jets with $p_T > 40$ GeV	6	6
5^{th} highest jet p_T	5	7
Ratio of M_T to mass of jets and leptons	2	8
2^{nd} highest jet CSV	7	9
Highest jet CSV	8	10