PROCEEDINGS OF SCIENCE

Top pair production in association with a vector boson

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The latest results for processes with a top-pair and an associated vector boson are presented. Both the ATLAS and the CMS collaborations have improved their previous results such that the observations of $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}\gamma$ are at, or beyond, discovery significances. The cross-sections for these processes are important for constraints on new physics models, in particular for models which go beyond the Standard Model regarding the mechanism for generation of mass.

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Cross-section	ATLAS (fb)	CMS (fb)	CDF (fb)
$\sigma_{t\bar{t}\gamma}$ [2 TeV]			180 ± 80 [1]
$\sigma_{t\bar{t}\gamma}$ [7 TeV]	$2000 \pm 500(stat.) \pm 700(syst.)$ [2]		
$\sigma_{t\bar{t}\gamma}$ [8 TeV]		$2400 \pm 200(stat.) \pm 600(syst.)$ [3]	
$\sigma_{t\bar{t}Z/\gamma^*}$ [7 TeV]	< 700 [4]	$280^{+140}_{-110}(stat.)^{+60}_{-30}(syst.)$ [5]	
$\sigma_{t\bar{t}Z/\gamma^*}$ [8 TeV]	$150^{+55}_{-50}(stat.)^{+21}_{-21}(syst.)$ [6]	$200 \pm 90(total)$ [7]	
$\sigma_{t\bar{t}W}$ [7 TeV]			
$\sigma_{t\bar{t}W}$ [8 TeV]	$300^{+120}_{-100}(stat.)^{+70}_{-40}(syst.)$ [6]	$170^{+110}_{-100}(total)$ [7]	

Table 1: Experimental status of $t\bar{t} + (Z,W,\gamma)$ cross-section measurements as of Top2014.

1. Introduction

Before the LHC era the $t\bar{t}$+boson cross-sections and associated couplings where only weakly and mainly indirectly constrained. The only direct observation was a cross-section measurement of $t\bar{t}\gamma$ at the Tevatron accelerator [1]. With the start of the LHC the situation has improved substantially. A summary of results as of the conference Top2014 is provided in Table 1. These measurements are important since they provide significant input for global constraints on new physics models, for example the top quark couplings in effective theory, strongly coupled Higgs models and composite or excited top quarks. The following sections report on the latest experimental results and improvements made since the Top2014 conference regarding $t\bar{t}Z$, $t\bar{t}W$ and $t\bar{t}\gamma$ production.

2. ATLAS measurement of $t\bar{t}\gamma$

The ATLAS experiment [8] has published a new fiducial measurement of the $t\bar{t}\gamma$ production cross-section [9]. The photon transverse momentum is required to be larger than 20 GeV and is applied to a data sample of $t\bar{t}$ candidates selected using the single lepton final state. The integrated luminosity is 4.59 fb^{-1} using a center-of-mass energy of 7 TeV. The variable which best discriminates between signal and background is the photon track-isolation defined as the sum of the selected tracks transverse momentum in a cone of 0.2 around the photon candidate. The signal is extracted using a template fit to this variable. The different templates used by the fit are constructed with data-driven techniques assisted by Monte Carlo simulation. The templates fitted to data are shown in Figure 2. The measured number of events are 140 and 222 in the electron and muon channels, with a fitted expected background of 79±26 and 120±39 events respectively. This corresponds to a 5.3σ significance to exclude the background only hypothesis. The measured cross-section times the branching ratio is 63 ± 8(stat.) $^{+17}_{-13}$ (syst.) $\pm$ 1(lumi) fb per lepton flavor, in agreement with the theoretical prediction of 48 ± 10 fb.

3. ATLAS measurement of $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$

An updated measurement of the $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ processes has been performed by the ATLAS experiment [10]. To improve the sensitivity compared to the previous measurement [6] which used the same dataset, events from same-signed (SS) dilepton events with electrons and the tetralepton

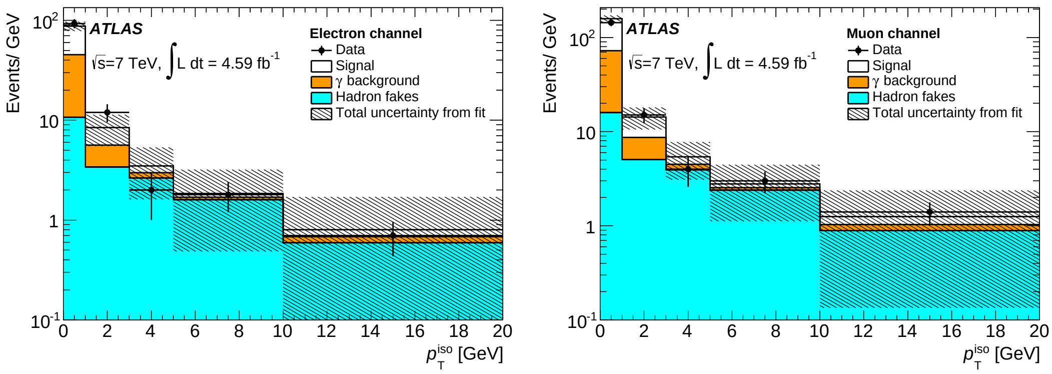

Figure 1: Signal and background template fit of the photon track-isolation to data in the electron channel (left) and the muon channel (right) used in the ATLAS $t\bar{t}\gamma$ cross-section mesurement. Taken from Ref. [9].

Signal region	Main cuts	Main background	Background treatment
OS dilepton	$\geq$ 4jets, $\geq$ 1b-tag	$t\bar{t}$	Neural networks,
		Z	control regions (CR) for $t\bar{t}$, 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

Table 2: Overview of the ATLAS $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ analysis.

channel have been added to the combination. The analysis of the different channels is summarized in Table 2. The yields in the different selected regions are shown after the fit in Figure 2. The $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ cross-sections are fitted simultaneously. This is important since new physics may affect both cross-sections with an unknown ratio. The simultaneously fitted cross-sections are shown in Figure 3. When the processes are fitted one at the time the extracted cross-sections are $\sigma_{t\bar{t}W} = 369^{+86}_{-79}$(stat)$\pm$44(syst.) fb and $\sigma_{t\bar{t}Z/\gamma^*} = 176^{+52}_{-48}$(stat)$\pm$24(syst.) fb.

4. CMS measurement of $t\bar{t}Z$ and $t\bar{t}W$

The CMS experiment presents an updated $t\bar{t}Z$ and $t\bar{t}W$ cross-section measurement [11] compared to to the previous measurement [7]. Both measurements use the same dataset but higher sensitivity in the new measurement has been achieved by multivariate classification using boosted decision trees (BDT). The OS dilepton channel has been added compared to the previous measurement so the full combination consists of OS dilepton, SS dilepton, trilepton and the tetralepton channels. Each final state use a separate BDT, except for the tetralepton channel which only use number of b-tags for classification. After preselection, the events are matched into to the different signal parton configurations using linear discriminants, where the output is called matching score. In a second stage ten dedicated BDTs use the matching score and other variables for final classification. An extra feature of using the parton matching score is that it allows for top quark and W

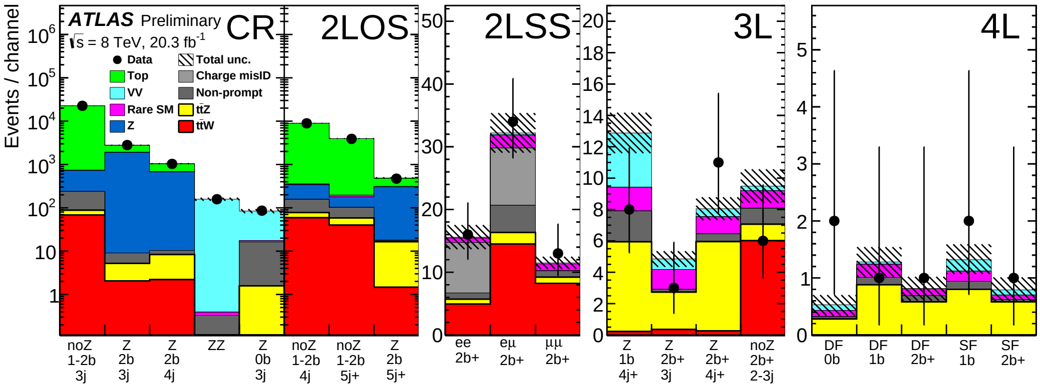

Figure 2: Post-fit yields in the different channels used in the fit for the ATLAS $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ cross-sections. Taken from Ref. [10].

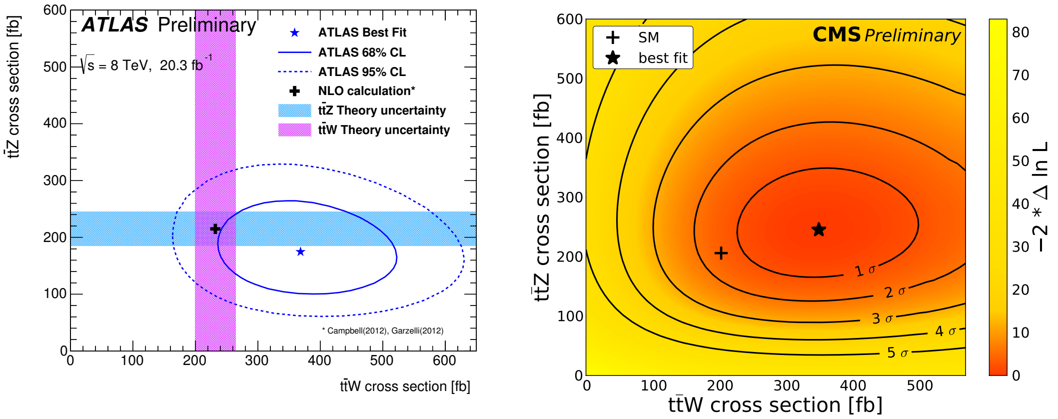

Figure 3: The simultaneously fitted $t\bar{t}Z/\gamma^*$ and $t\bar{t}W$ cross-sections for ATLAS (left) and CMS (right) respectively. Taken from Ref. [10] (left) and [11] (right).

boson reconstruction, see Figure 4 which shows the top quark and W boson candidate masses in the selected events. The simultaneously fitted cross-sections are shown in Figure 3. The separate cross-sections are measured to be $\sigma_{t\bar{t}W} = 382^{+117}_{-102}$ fb and $\sigma_{t\bar{t}Z} = 242^{+65}_{-55}$ fb. Limits are also set on dimension-six effective operators, see Table 3.

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

Table 3: Constraints from the CMS $t\bar{t}Z$ and $t\bar{t}W$ measurement on selected dimension-six operators.

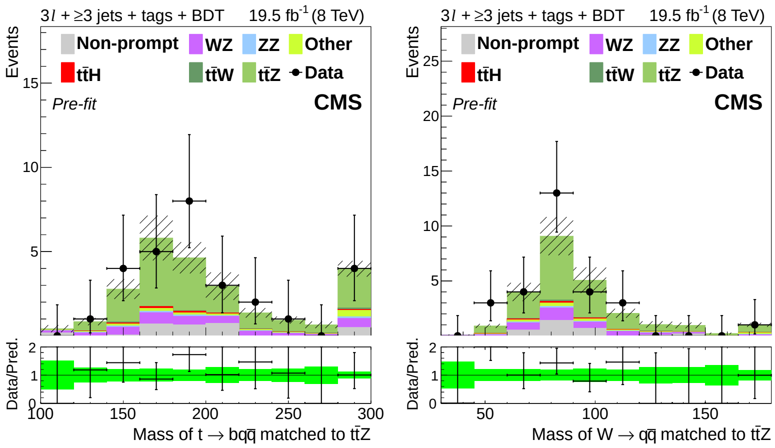

Figure 4: Prefit masses for the top quark (left) and W boson (right) candidates in the trilepton channel, shown from the CMS $t\bar{t}Z$ and $t\bar{t}W$ measurement. Taken from Ref. [11].

5. Conclusions

After revisiting the Run 1 datasets collected at the LHC collider both the ATLAS and the CMS experiments have improved the accuracy and precision of the measured cross-sections of $t\bar{t}$ production is association with a vector boson. For example, both $t\bar{t}Z$ and $t\bar{t}W$ cross-sections are now measured with a relative uncertainty of $O(30\%)$. The improvements have been achieved by adding more final states in the combination and by improving the analyses techniques.

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