PROCEEDINGS OF SCIENCE

Rare top quark production at the LHC: $t\bar{t}Z$, $t\bar{t}W$, $t\bar{t}\gamma$, tZq, $t\gamma q$, and $t\bar{t}t\bar{t}$

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A comprehensive set of measurements of top quark pair and single top quark production in association with electroweak bosons (W, Z, or γ) is presented. The results are compared to standard model (SM) predictions and used to set limits on new physics effects that would induce deviations from the SM. Searches for four top quark production, to which the ATLAS and CMS experiments at the CERN LHC are starting to be sensitive and which has important beyond-the-SM interpretations, are also discussed.

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1. Introduction

In proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$, recorded by the ATLAS and CMS experiments at the CERN LHC [1] between 2015 and 2018, top quarks have been produced plentifully. While the dominant top quark production channels of pair production ($\sigma \approx 830\,\text{fb}$) and t-channel single production ($\sigma \approx 220\,\text{fb}$) have been measured with high precision [2], many rare top quark production modes become fully accessible as well.

This contribution presents recent results of the ATLAS and CMS Collaborations on measurements of top quark pair production in association with a W boson ($\text{t}\bar{\text{t}}\text{W}$), a Z boson ($\text{t}\bar{\text{t}}\text{Z}$), or a photon ($\text{t}\bar{\text{t}}\gamma$), and of t-channel single top quark production with a Z boson (tZq) or a photon (tγq). A summary of the measured cross sections is given in Tab. 1. Furthermore, search results for four top quark production ($\text{t}\bar{\text{t}}\text{t}\bar{\text{t}}$) are discussed.

process	measured cross section [fb]		SM prediction [fb]
$\text{t}\bar{\text{t}}\text{W}$	ATLAS [3]	$870 \pm 130 \pm 140$	628 ± 82
	CMS [4]	$770\,^{+120}_{-110}\,^{+130}_{-120}$	
$\text{t}\bar{\text{t}}\text{Z}$	ATLAS [3]	$950 \pm 80 \pm 100$	839 ± 101
	CMS [5]	$1000\,^{+60}_{-50}\,^{+70}_{-60}$	
tZq	ATLAS [7]	$600 \pm 170 \pm 140$	$800\,^{+49}_{-59}$
tZq ($\text{Z} \to 2\ell$)	CMS [8]	$111 \pm 13\,^{+11}_{-9}$	94 ± 3
fiducial $\text{t}\bar{\text{t}}\gamma$ ($\text{t}\bar{\text{t}} \to 1\ell$)	ATLAS [9]	$521 \pm 9 \pm 41$	495 ± 99
fiducial $\text{t}\bar{\text{t}}\gamma$ ($\text{t}\bar{\text{t}} \to 2\ell$)		$69 \pm 3 \pm 4$	63 ± 9
fiducial tγq	CMS [10]	$115 \pm 17 \pm 30$	81 ± 4

Table 1: Summary of measured cross sections for associated top quark production with vector bosons, and corresponding standard model (SM) predictions.

2. Top quark production in association with heavy vector bosons

The measurement of associated production of top quarks with heavy electroweak vector bosons allows for a direct test of electroweak couplings. Especially the top quark–Z boson coupling can be tested both in $\text{t}\bar{\text{t}}\text{Z}$ and tZq production, whereas tZq production is additionally sensitive to the WWZ triboson coupling. In addition, many measurements and searches in final states with leptons and b quarks have large backgrounds from $\text{t}\bar{\text{t}}\text{Z}$ and $\text{t}\bar{\text{t}}\text{W}$ production, like Higgs boson production in association with a top quark pair ($\text{t}\bar{\text{t}}\text{H}$) [11], thus providing additional motivation for their study.

The ATLAS Collaboration performed a simultaneous measurement of the $\text{t}\bar{\text{t}}\text{W}$ and $\text{t}\bar{\text{t}}\text{Z}$ production cross sections, using data collected in 2015 & 2016 [3]. Events are selected with two, three or four leptons (electrons and muons), and are further categorised to increase the separation between the signal processes and backgrounds. A template fit is performed to extract the two cross sections, which are found to be in good agreement with the SM prediction.

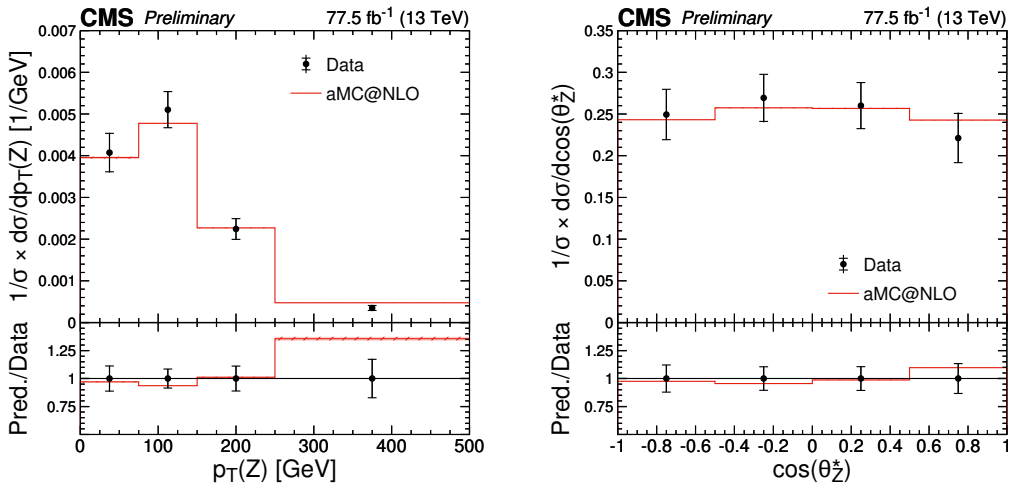

Figure 1: Differential $t\bar{t}Z$ production cross section as function of the transverse momentum of the Z boson (left), and of the angle of the negatively charged lepton with respect to the Z boson, boosted to the Z boson's rest frame (right), as measured by the CMS Collaboration [5].

A similar measurement of $t\bar{t}W$ and $t\bar{t}Z$ production has been performed by the CMS Collaboration, using data collected in 2016 [4]. Recently, the $t\bar{t}Z$ production measurement has been updated with the data collected in 2016 & 2017 [5][1]. Events are selected with three or four leptons, and categorised according to number of jets and b-tagged jets. The measured cross section, extracted with a template fit, exceeds the precision of the next-to-leading order (NLO) SM prediction.

Additionally, a first differential measurement of the $t\bar{t}Z$ production cross section has been performed, using the unfitted event counts from the three-lepton selection, subtracting predicted backgrounds and applying an unfolding procedure to correct for detector acceptance and resolution effects. The measured distributions at parton-level are shown in Fig. 1.

A measurement of tZq production has been performed by the ATLAS Collaboration using data collected in 2015 & 2016 [7]. Events with three leptons and at least two jets are evaluated with a neural network (NN), trained to separate tZq signal events from the dominant background processes (single and diboson production, $t\bar{t}$ production). From a template fit to the NN output distribution, evidence for tZq production is found at an observed (expected) significance of 4.2 (5.4) standard deviations.

The CMS Collaboration reported the first observation of tZq production, using data collected in 2016 & 2017 [8]. Events with three leptons are further categorised according to number of jets and b-tagged jets, and in each category a boosted decision tree (BDT) is trained to separate tZq signal events from the dominant $t\bar{t}Z$ (diboson) production background in the high-multiplicity (low-multiplicity) categories. The measured cross section, extracted with a template fit to the BDT output distributions, is in good agreement with the SM prediction.

3. Associated top quark production with a photon

While the study of photons radiated off a top quark provides a direct test of the electroweak

[1]The presented result has been superseded by Ref. [6].

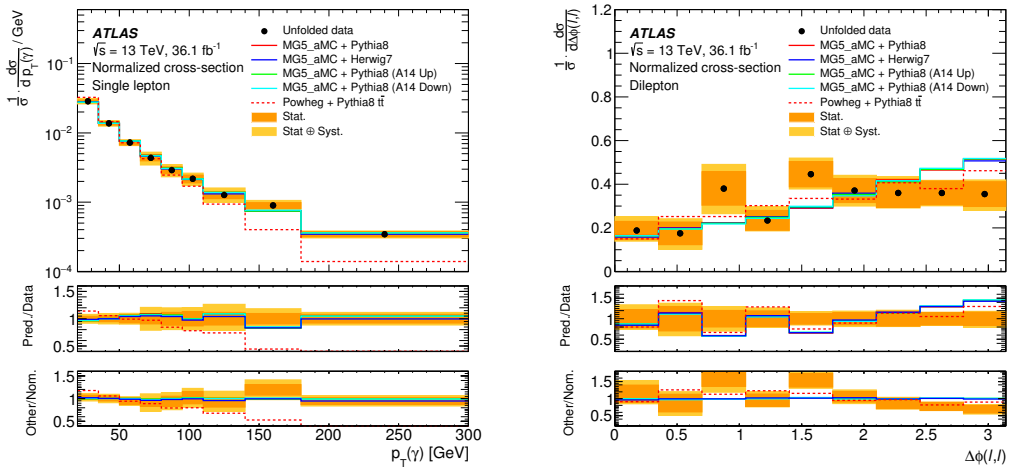

Figure 2: Fiducial differential $t\bar{t}\gamma$ production cross section as function of the photon momentum for the single-leptonic $t\bar{t}$ decay (left), and as function of the angle between the two leptons for the dileptonic $t\bar{t}$ decay (right), as measured by the ATLAS Collaboration [9].

top quark–photon coupling, associated top quark production with a photon receives also large contributions from photon radiation off charged initial or final state particles. To increase sensitivity to the former, fiducial volumes are defined requiring tightly isolated photons with large transverse momentum.

A fiducial cross section measurement of $t\bar{t}\gamma$ production, separately for the single-leptonic and dileptonic decay channel of the $t\bar{t}$ system, was performed by the ATLAS Collaboration, using data collected in 2015 & 2016 [9]. NNs are trained to separate $t\bar{t}\gamma$ signal events from the dominant background processes. Inclusive cross sections are measured with a template fit, and found to be in agreement with the NLO SM prediction, exceeding the prediction's precision.

Differential cross section measurements were performed as well, using the unfitted event counts and applying an unfolding procedure. Good agreement with the SM prediction is found in all distributions, two of which are shown in Fig.2.

First evidence for $t\gamma q$ production has been reported by the CMS experiment, using data collected in 2016 [10]. Events are selected with one muon, one isolated photon and at least two jets. A BDT is trained to discriminate between $t\gamma q$ signal events and the dominant $t\bar{t}\gamma$ production background. A template fit yields a fiducial cross section in good agreement with the SM prediction, at an observed (expected) significance of 4.4 (3.0) standard deviations.

4. Production of four top quarks

Four top quark production is predicted by the SM at NLO precision with a cross section of 12 fb, and is thus the rarest top quark production mode considered here. It receives contributions from diagrams with a virtual Higgs boson, and provides therefore the possibility to constrain the top quark Yukawa coupling from its cross section measurements. Furthermore, many beyond-the-SM models predict a significantly enhanced $t\bar{t}t\bar{t}$ production cross section.

The ATLAS Collaboration performed a search for $t\bar{t}t\bar{t}$ production in events with one lepton or two opposite-sign (OS) leptons, using data collected in 2015 & 2016 [12]. To identify hadronically

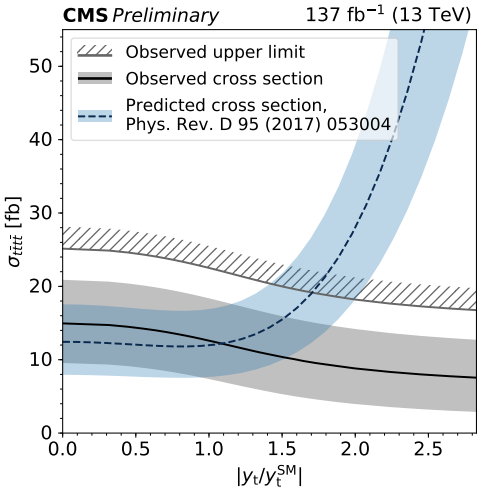

Figure 3: Exclusion limits on the top quark Yukawa coupling from the $t\bar{t}t\bar{t}$ production cross section measurement performed by the CMS Collaboration [17].

decaying top quarks, the selected jets are reclustered into mass-tagged large-R jets, using a larger radius parameter $R = 1.0$ in the clustering algorithm. A template fit is then performed to the hadronic activity distribution in several categories of jet, b-tagged jet and mass-tagged large-R jet multiplicity. In combination with results from a search for new physics in events with two same-sign (SS) or three leptons [13], the observed (expected) significance of $t\bar{t}t\bar{t}$ production is 2.8 (1.0) standard deviations.

A search for $t\bar{t}t\bar{t}$ production in the same signature (1ℓ or 2ℓ OS) was performed by the CMS Collaboration, using data collected in 2016 [14][2]. A BDT is trained to separate $t\bar{t}t\bar{t}$ signal events from the dominant $t\bar{t}$ production background, and a template fit is performed to the BDT output distribution in different categories of jet and b-tagged jet multiplicity. Combined with the results from a $t\bar{t}t\bar{t}$ production search in the 2ℓ SS and 3ℓ final states on the same dataset [16], the observed (expected) significance of $t\bar{t}t\bar{t}$ production is 1.4 (1.1) standard deviations.

The CMS Collaboration has recently updated the $t\bar{t}t\bar{t}$ search in the 2ℓ SS and 3ℓ final states with 137 fb^{-1} of data collected in 2016, 2017, and 2018 [17][3]. Similarly, events are evaluated with a BDT to separate $t\bar{t}t\bar{t}$ signal events from the dominant $t\bar{t}W$ and $t\bar{t}Z$ production backgrounds. A template fit results in an observed (expected) significance of 2.6 (2.7) standard deviations.

The measured cross section is used to put constraints on the top quark Yukawa coupling, resulting in a 95% confidence level exclusion limit on the Yukawa coupling of 1.7 times the SM prediction. The full limits are shown in Fig. 3.

5. Conclusions

The large amount of data collected at the LHC between 2015 and 2018 as well as refined analysis techniques allowed the ATLAS and CMS Collaborations to measure many rare top quark

[2]The presented result has been superseded by Ref. [15].

[3]The presented result has been superseded by Ref. [18].

production processes: For the associated production of top quark pairs with a Z boson or a photon, inclusive cross section results have a precision competing with current theoretical calculations, and first differential measurements have been performed. Single top quark production in association with a Z boson has been observed for the first time, and first evidence was found for single top quark production in association with a photon. In the search for four top quark production, first results have been obtained with the full 2016–2018 dataset, coming close to first evidence.

In all analyses, the measured results are found to be in agreement with the SM predictions. The results are also used to constrain deviations from the SM, either by precise measurements of SM parameters that have not been tested directly before, or in terms of limits on EFT operators (described in more detail in Ref. [19]).

For most processes, not all available datasets have been analysed yet, and measurements of additional decay channels are possible. Therefore, more precise results on rare top quark production from the ATLAS and CMS Collaborations can be expected soon.

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PoS(DIS2019)157