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CMS CR -2018/113

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

29 June 2018 (v2, 05 August 2021)

Rare top quark production in CMS ttW, ttZ, ttgamma, tZ, tgamma, and tttt production

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Abstract

A comprehensive set of measurements of top quark pair and single top quark production in association with EWK bosons (W, Z or photon) is presented. The results are compared to theory predictions and re-interpreted as searches for new physics inducing deviations from the standard model predictions using an effective field theory approach. The status of the search for four top quark production, to which the LHC experiments are starting to be sensitive, and that has important BSM re-interpretations, is also reported.

Presented at *DIS2018 XXVI International Workshop on Deep Inelastic Scattering and Related Subjects*

PROCEEDINGS OF SCIENCE

Rare top quark production in CMS: $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\gamma$, and $t\bar{t}t\bar{t}$

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At the LHC, we can study various production and decay processes involving the top quarks due to its large center-of-mass energy and the amount of data collected. CMS experiment has performed measurements of processes where electro-weak vector bosons are produced in association with either a a single top quark or a top-antitop quark pair. We present some of the recent measurements of these processes. Also, four top quark production search has been performed.

XXVI International Workshop on Deep-Inelastic Scattering and Related Subjects (DIS2018)
16-20 April 2018
Kobe, Japan

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1. Introduction

Due to the large top quark pair production cross section at the LHC, many top quark production processes and its decay properties have been measured with unprecedented precision. In many searches with complicated topology, the $t\bar{t}+X$ and $t+X$ are major irreducible backgrounds. Therefore, it is important to measure the processes where top quarks are produced in association with additional high transverse momentum (p_T) or high mass objects. Some of the recent measurements of $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\gamma$, and $t\bar{t}t\bar{t}$ processes based on the data collected using the CMS detector at various center–of-mass energies are presented.

2. $t\bar{t}+W$ and $t\bar{t}+Z$ Processes

Processes where an electro-weak vector boson is produced in association with a top-antitop quark pair allow us to probe the couplings of top quark and vector bosons. If the vector bosons decay leptonically, these channels can yield same-sign charged lepton pairs. Therefore, these processes are important backgrounds in many analyses involving same-signed lepton pairs and multiple hadronic jets.

A simultaneous measurement of cross sections of $t\bar{t}+W$ and $t\bar{t}+Z$ has been performed in the same-signed di-lepton (SSDL) and tri-lepton channels. $t\bar{t}+W$ process contributes primarily to the SSDL channel, while the $t\bar{t}+Z$ process contributes to the tri-lepton channel. To enhance the sensitivity, the sample is divided into sub-samples with different number of hadronic jets and b-tagged jets. Each sub-sample has different contributions of $t\bar{t}+W$, $t\bar{t}+Z$, and various backgrounds. Significances over 5 are observed each for the $t\bar{t}+W$ and $t\bar{t}+Z$ [1]. The measured cross sections are:

$$\sigma(pp \to t\bar{t}W) = 0.77^{+0.12}_{-0.11}(\text{stat.})^{+0.13}_{-0.12}(\text{syst.})\ \text{pb} \tag{2.1}$$

$$\sigma(pp \to t\bar{t}Z) = 0.99^{+0.09}_{-0.08}(\text{stat.})^{+0.12}_{-0.10}(\text{syst.})\ \text{pb}, \tag{2.2}$$

and shown in Fig. 1. The measured cross sections agree with the SM predictions.

3. $t\bar{t}+\gamma$ Process

The $t\bar{t}+\gamma$ could be a probe of electric charge of the top quark, hence could be used to test some models beyond the standard model (BSM). CMS has searched for the process in the 19.7 fb^{-1} data collected at a center of mass energy $\sqrt{s} = 8$ TeV. A single high p_T isolated photon, a charged lepton, three or more hadronic jets, and one or more b-tagged jets from the top quark decays are required. Significant missing momentum is required as a signature of a neutrino from the leptonically decaying W boson. Three-jet mass (M_3) distribution provides a good discriminating power against backgrounds with vector bosons (Fig. 2). The ratio of cross sections $\sigma_{t\bar{t}+\gamma}/\sigma_{t\bar{t}} = (5.2 \pm 1.1) \times 10^{-4}$ was measured for photons with $p_T > 30$ GeV and $|\eta| < 3.0$, and $\Delta R > 0.3$ separated from all other generated particles [2]. This result is in good agreement with the SM expectation.

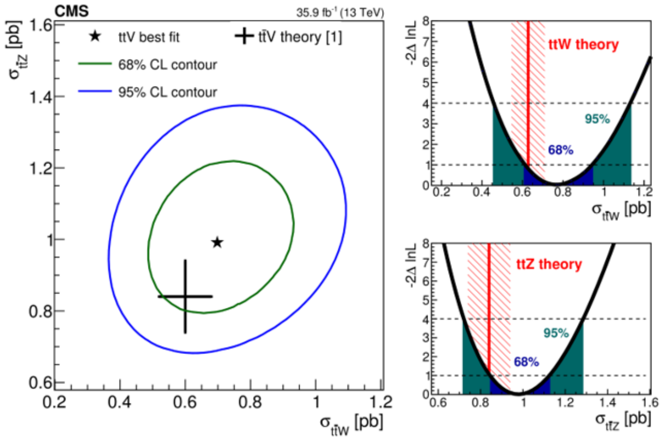

Figure 1: Measurement of the $t\bar{t}W$ and $t\bar{t}Z$ cross sections compared to the SM theory [1].

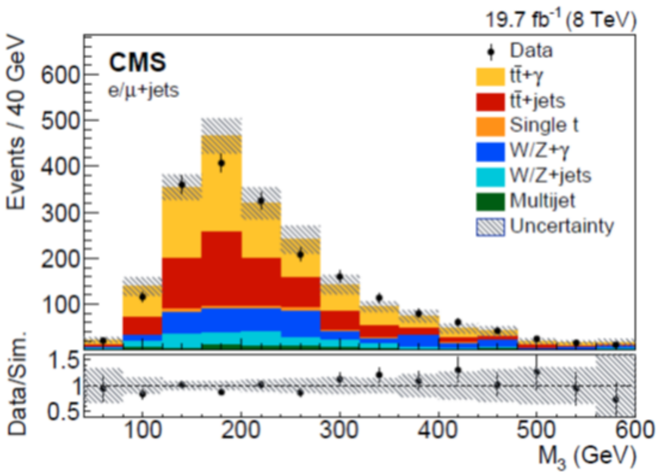

Figure 2: Distribution of the M_3 $t\bar{t}\gamma$ compared to SM prediction [2].

4. Single top quark plus Z boson production

A Z boson can be produced in association with a single top quark. Such a process is a probe of the top quark and the Z boson coupling. Since this process receives contributions from WW vector boson fusion in production, it is also sensitive to the WWZ tri-boson coupling. Deviations from the SM expectations could be due to a beyond-SM flavor-changing neutral current (FCNC) mechanism.

CMS has measured this process using 35.9 fb^{-1} of $\sqrt{s} = 13$ TeV data triggered with 1,2, or 3 high p_T lepton (e or μ) triggers. Events with isolated tri-leptons are required. One of the leptons is from the leptonic decay of the top quark, while the other two are from the decay of the Z boson. Major backgrounds are from $t\bar{t}+Z$, $WZ+jets$, and non-prompt leptons. Different backgrounds dominate events with different number of b-tagged jets (N_{b-jet}). $WZ+jets$ and non-prompt lepton backgrounds are important in the 0 N_{b-jet} sample, while the $t\bar{t}+Z$ is important in 2 N_{b-jet} sample.

A multivariate boosted-decision tree (BDT) analysis provides effective separation between signal and backgrounds. Kinematics of the reconstructed top quark, Z, and their decay products, together with weights of the matrix-element method are used as feature inputs to the BDT. Figure 3 shows good description of the backgrounds and the signal is visible. A simultaneous fit to BDT output distributions for events in different N_{b-jet} bins yields the signal strength and fiducial cross section of

$$\mu = 1.31^{+0.35}_{-0.33}(\text{stat.})^{+0.31}_{-0.25}(\text{syst.}) \tag{4.1}$$

$$\sigma(t\ell^+\ell^-q) = 123^{+33}_{-31}(\text{stat.})^{+29}_{-23}(\text{syst.})\ \text{fb}, \tag{4.2}$$

in agreement with the SM predictions.

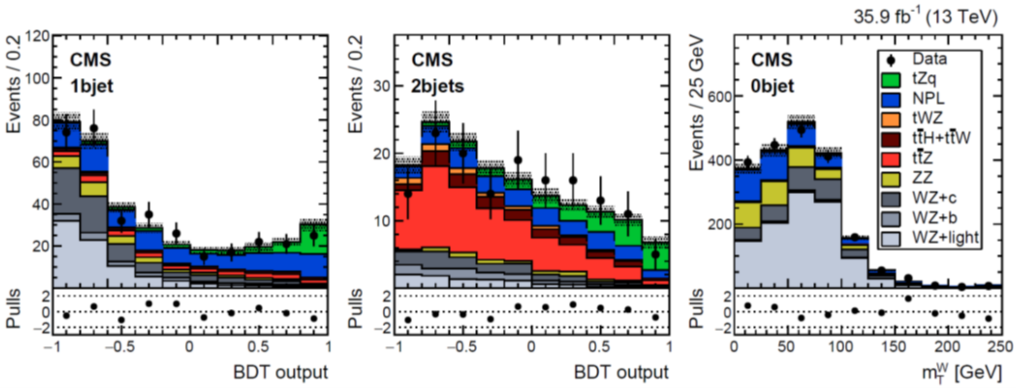

Figure 3: Distributions of BDT discriminator in the 1 b-jet region (left), 2 b-jets region (center), and 0 b-jet control region (right) [3].

5. Search for four top quark production

With greater integrated luminosity, higher-mass states become accessible. And we expect to be sensitive to the four top quark SM production in the very near future. Such a process is expected in the SM through strong interactions. Due to the large mass of the top quark, so far, it has not been seen at the LHC. This process is a probe of the top-Higgs coupling. In some theory models with additional bosons that preferentially couple to top quarks, four top quark production could be enhanced. CMS has performed a search for the four top quark production in the SSDL and tri-lepton channels using the 35.9 fb^{-1} of data collected at a center of mass energy of $\sqrt{s} = 13$ TeV [4].

The events are required to have at least two same-signed charged leptons (e or μ), at least two hadronic jets, at least two b-tagged jets, and significant missing p_T and H_T. The sample is further subdivided according to the number of leptons, number of jets, and number of b-tagged jets, which have different signal-to-background fractions (Fig. 4). Eight signal regions and two background-dominated regions are defined. From the background-dominated regions, we can constrain the backgrounds, $t\bar{t}+W$ and $t\bar{t}+Z$. A simultaneous fit is performed in the signal regions to obtain the signal strength. The observed significance is 1.6σ while 1.0σ is expected, and the best-fit cross section is:

$$\sigma(pp \to t\bar{t}t\bar{t}) = 16.9^{+13.8}_{-11.4}\ \text{fb}. \tag{5.1}$$

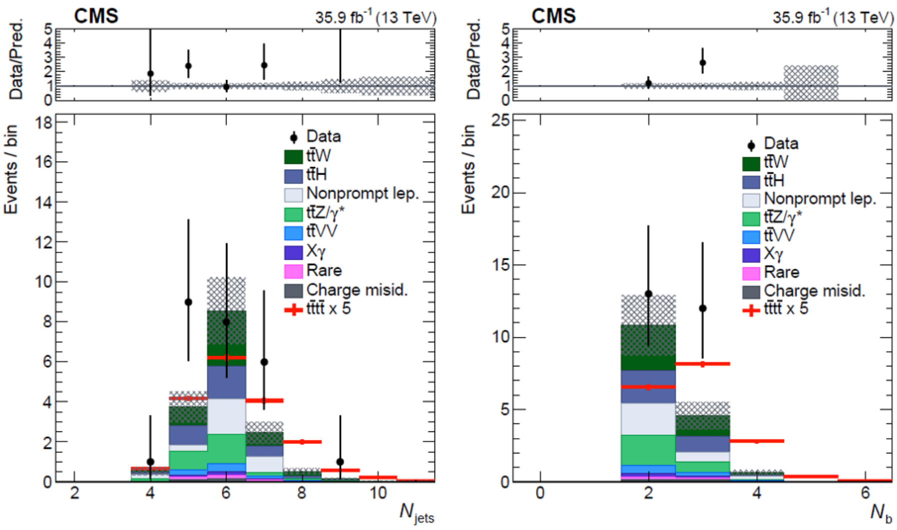

Figure 4: Distribution of the number of jets and b-tagged jets after selection, with the expected four top quark contribution multiplied by 5 [4].

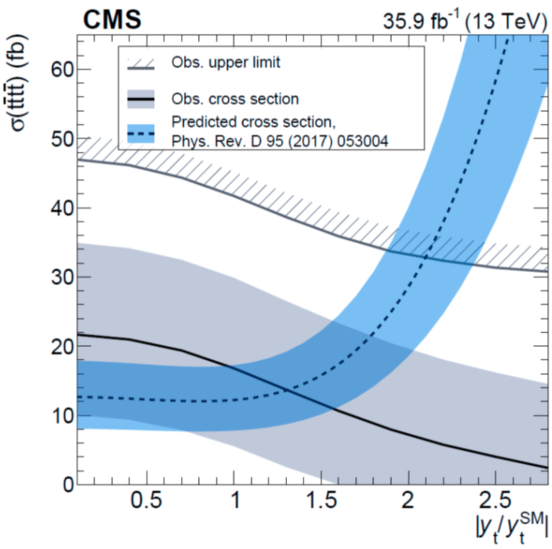

Figure 5: Cross section upper limits and observed cross section as a function of the Yukawa coupling ratio to the SM top-Higgs Yukawa coupling [4].

The four top quark production has some information on the top-Higgs coupling and provides some constraints on y_t (Fig. 5).

6. Summary and Outlook

CMS has probed some of the rarer processes that involve top quarks. Such probes provide information on the electro-weak couplings of the top quark and provide additional information on the top quark sector. So far, the measurements provide confirmation on the SM in the top quark sector. The statistical uncertainties are comparable to the systematic uncertainties in many of these measurements. Therefore, we can expect reduced uncertainties with the full Run 2 data and beyond.

References

[1] CMS Collaboration, *Measurement of the cross section for top quark pair production in association with a W or Z boson in proton-proton collisions at* $\sqrt{s}$*=13 TeV* [arXiv:1711.02547].

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[4] CMS Collaboration, *Search for standard model production of four top quarks with same-sign and multilepton final states in proton-proton collisions at* $\sqrt{s}$*=13 TeV*, *EPJC* **78** (2018) 140.