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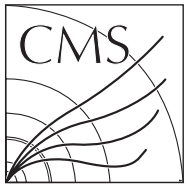

The Compact Muon Solenoid Experiment

Conference Report

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

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Studies of tt+V at CMS

Illia Khvastunov for the CMS Collaboration

Abstract

A measurement of the production cross-section of a pair of top quarks in association with a photon, using 19.7 fb^{-1} of pp collision data collected by CMS detector at $\sqrt{s} = 8$ TeV, and with W and Z boson, using 12.9 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV, is presented. The measurement of $\mathrm{t\bar{t}}\gamma$ is performed in in the fiducial phase space corresponding to the semileptonic decay chain of the top quark pair, and the cross section is measured relative to the inclusive top quark pair production cross section. The fiducial cross section for this process is found to be $\sigma^{fid}_{\mathrm{t\bar{t}}\gamma} = 127 \pm 27$ (stat + syst) fb. The measurement of $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ processes combines three final states with two same-sign, three and four leptons. The $\mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$ production cross sections are measured to be $\sigma(\mathrm{t\bar{t}Z}) = 0.70^{+0.16}_{-0.15}(\mathrm{stat.})^{+0.14}_{-0.12}(\mathrm{sys.})$ pb and$\sigma(\mathrm{t\bar{t}W}) = 0.98\ ^{+0.23}_{-0.22}(\mathrm{stat.})\ ^{+0.22}_{-0.18}(\mathrm{sys.})$ pb with an expected (observed) significance of 2.6 (3.9) and 5.8 (4.6) standard deviations from the background-only hypothesis respectively. The measured cross sections are in agreement with the standard model prediction.

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

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A measurement of the production cross-section of a pair of top quarks in association with a photon, using 19.7 fb^{-1} of pp collision data collected by CMS detector at $\sqrt{s} = 8$ TeV, and with W and Z boson, using 12.9 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV, is presented. The measurement of $t\bar{t}\gamma$ is performed in in the fiducial phase space corresponding to the semileptonic decay chain of the top quark pair, and the cross section is measured relative to the inclusive top quark pair production cross section. The fiducial cross section for this process is found to be $\sigma^{fid}_{t\bar{t}\gamma} = 127 \pm 27$ (stat + syst) fb. The measurement of $t\bar{t}W$ and $t\bar{t}Z$ processes combines three final states with two same-sign, three and four leptons. The $t\bar{t}W$ and $t\bar{t}Z$ production cross sections are measured to be $\sigma(t\bar{t}Z) = 0.70^{+0.16}_{-0.15}(\text{stat.})^{+0.14}_{-0.12}(\text{sys.})$ pb and $\sigma(t\bar{t}W) = 0.98\ ^{+0.23}_{-0.22}(\text{stat.})\ ^{+0.22}_{-0.18}(\text{sys.})$ pb with an expected (observed) significance of 2.6 (3.9) and 5.8 (4.6) standard deviations from the background-only hypothesis respectively. The measured cross sections are in agreement with the standard model prediction.

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1 Introduction

With the integrated luminosity collected at the Large Hadron Collider (LHC) in its first and second runs, rare processes producing top quark pairs in association with electroweak Standard Model (SM) bosons have become experimentally accessible. By measuring the cross section of top quark pairs produced in association with a photon or Z, the strength of the electromagnetic coupling of the top quark and photon or Z boson is probed. The top quark pair produced in association with a W or Z boson consitutes the heaviest set of standard model particles that could be observed in the dataset accumulated so far. Also take note of the fact that all these processes are backgrounds for searches for new physics, and any deviation ofthe meaured cross section value from the SM prediction would be an indication of BSM physics. In this manuscript we discuss the most recent measurements of $t\bar{t}$+V performed by the CMS Collaboration at the LHC [1].

2 The strategies of the analyses

2.1 Measurement of the $t\bar{t}\gamma$ cross-section at $\sqrt{s} = 8$ TeV

The final state of the signal process in the semileptonic decay channel consists of a high transverse momentum of the lepton, missing transverse energy due to the presence of a neutrino, jets originating from both the b quarks and from the decay of the W boson, and an energetic photon. The cross section of the process is measured relative to the $t\bar{t}$ production cross section. In order to measure the ratio of these two cross sections, it is essential to measure how many $t\bar{t}$ and $t\bar{t}\gamma$ events are observed in data. After the photon selection is applied, over half of the events in simulation come from background processes, and not $t\bar{t}\gamma$. The two largest backgrounds are from $t\bar{t}$ events which have a non-prompt photon coming from jets in the event and V+γ events. There is not a single variable which can sufficiently discriminate both of these backgrounds for the signal. The V+γ background can be differentiated from $t\bar{t}\gamma$ events by trying to reconstruct a top quark in the event, however $t\bar{t}$ events are very similar to the signal in this respect. Alternatively, the non-prompt photon from the $t\bar{t}$ background will tend to be less isolated that the photons from the signal, but the photon isolation variable will not be able to distinguish the V+γ background from $t\bar{t}\gamma$ events. In order to be able to distinguish both $t\bar{t}$ and V+γ background events, both of these methods are used and the results are combined to measure the number of the $t\bar{t}\gamma$ events observed in data.

2.2 Measurement of the $t\bar{t}W$ and $t\bar{t}Z$ cross-sections at $\sqrt{s} = 13$ TeV

$t\bar{t}W$ and $t\bar{t}Z$ cross-section measurement is performed using events in which at least one of the W bosons originating from a top quark decays to a lepton and a neutrino, and the associated W boson decays to a lepton and a neutrino, or the Z boson decays to two charged leptons, where electron or muon is only considered as a lepton. Decays to τ leptons are included through their leptonic decays. The $t\bar{t}W$ process is measured in final states containing two leptons with the same charge. Requiring the same charge for the two leptons only the third of the signal produced in the dilepton final state will be selected. However this selection significantly improves the signal over background ratio, because prompt same-charge lepton pairs are only produced in standard model processes with very small cross sections. The main backgrounds to this analysis are due to misreconstruction effects: misidentification of nonprompt leptons from heavy flavour meson decays as prompt leptons and mis-measurement of the charge of the prompt electron in an opposite charge lepton pair. In order to distinguish these backgrounds from the signal, a multivariate analysis (MVA) has been developed. The MVA has been trained using events that pass the following selection: two same-charge leptons with transverse momenta greater than 25 GeV, in case of dielectron pair the leading lepton has to pass 40 GeV requirement; at least 2 jets and 1 b-jet; in order to suppress Z to electron-positron pair events, the invariant mass of the two electrons is required to lie ouside a 15 GeV window around the Z pole mass. In addition, the requirement on transverse missing energy is added to suppress the contribution from Drell-Yan processes. The MVA has been trained with $t\bar{t}W$ and $t\bar{t}$ events as a signal and bacground samples. A Boosted Decision Tree (BDT) classifier with a gradient boost was used and events were equally split for training and testing. The cut on BDT value was used to suppress the background due to nonprompt leptons. The number of jets and b-tagged jets are used to form exclusive event categories to maximize the signal significance.

The $t\bar{t}Z$ proccess is measured in channels with three or four leptons, with a pair of same-flavour leptons of opposite-charge, with an invariant mass close to the Z boson mass. In three leptons channel the leading, sub-leading and trailing transverse momenta has to pass 40, 20 and 10 GeV requirement respectively. Additionally to that the cut on invariant mass of two same-flavour opposite-charge leptons and a cut on at least 2 jets are added. The same as in same-charge dilepton channel the number of jets and b-tagged jets are used to form event categories to maximize the signal significance. In four lepton channel the highest lepton transverse momentum is required to be greater than 20 GeV, while the transverse momenta of all the remaining three leptons is required to be at least greater 10 GeV. The cut on invariant mass of two leptons is exploited, as well as the cut on at least 2 jets. Events are divided into two exclusive categories according to number of b-tagged jets.

3 Results

The number of events passing the photon selection containing top quark pairs can be measured by reconstructing the hadronically decaying top quark in the event. The M3 variable, defined as the invariant mass of the three jet combination that has the highest summed transverse momentum, is used for this purpose. The photon purity variable, defined as the fraction of reconstructed photons in the selection region which come from isolated photons as opposed to fake photons originating from jets, is used to discriminate between the types of real photons expected from signal and the hadronically produced photons from the $t\bar{t}$ background. The fits for extracting the top quark purity and the photon purity are performed sequentially, and then the values are used in a likelihood function, from which a fit is performed to extract the number of events in the selection which originate from the $t\bar{t}\gamma$ signal process. The statistical uncertainty in the number of signal events dominates the determination of the cross section for $t\bar{t}\gamma$. It includes the uncertainties on the measurement of the photon purity, top purity after photon selection and the statistical uncertainty from the number of events in data. The ratio of the fiducial cross section of $t\bar{t}\gamma$ to $t\bar{t}$ production, R, can be found in Table 1 for both electron+jets and muon+jets final state as well as fiducial cross section and the cross section times branching ratio. The measured cross section is in agreement with the theoretical prediction.

A binned maximum likelihood fit [2] is performed over all the signal regions to measure the production cross sections σ_{ttW} and σ_{ttZ}. Systematic uncertainties are treated as nuisance parameters for the fit. In the Table 2 the expected and observed significances could be found, for $t\bar{t}Z$ process with data that collected so far the discovery level is reached. 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. The results of the individual fits are summarized in Figure 1 as well as a simultaneous fit of the cross sections of the two processes using all dilepton, trilepton, and four-lepton channels at the same time. The cross section extracted from this two-dimensional fit for ttZ is identical to those obtained from the two one-dimensional fit, while for ttW the two-dimensional fit is shifted down by approximately 14% towards the theoretical prediction. The two-dimensional fit is in agreement with the theoretical prediction within 1σ band.

References

[1] CMS Collaboration, The CMS experiment at the CERN LHC, JINST 3 (2008) S08004

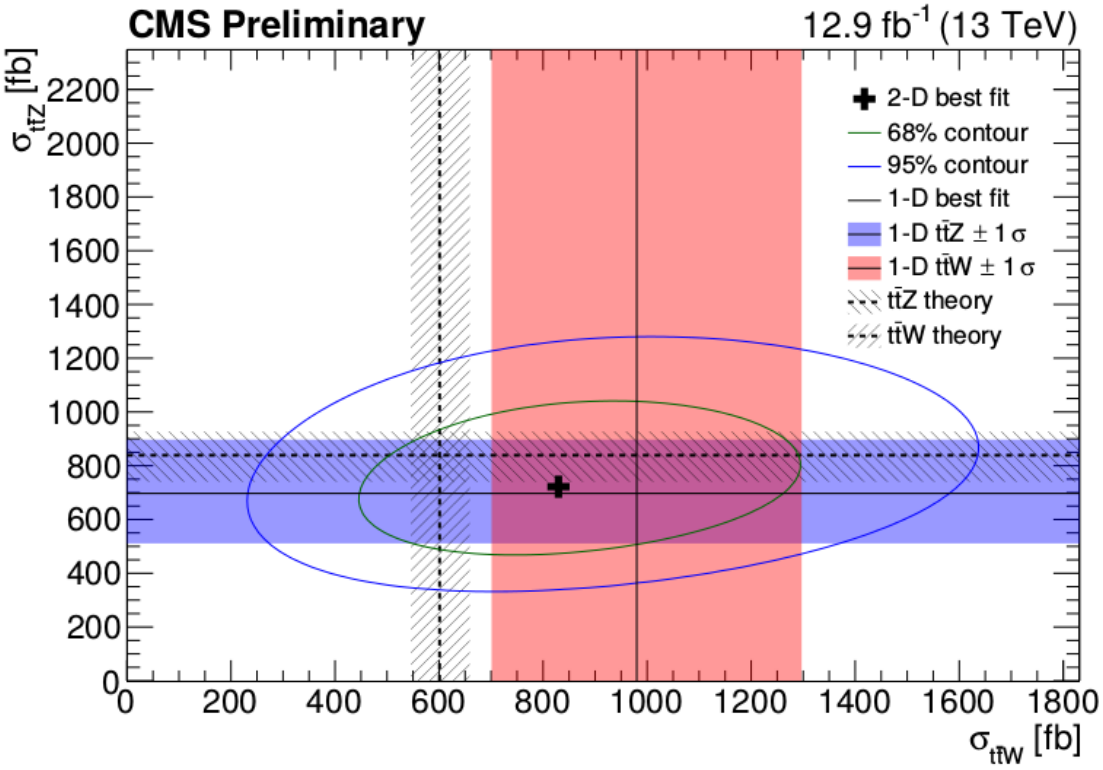

Figure 1: The result of the two-dimensional best fit for $t\bar{t}W$ and $t\bar{t}Z$ cross sections is shown along with its 68 and 95% confidence level contours. The result of this is superimposed with the separate $t\bar{t}W$ and $t\bar{t}Z$ cross section measurements, and the corresponding 1σ bands, obtained from the dilepton, and the trilepton/four-lepton channels, respectively. The figure also shows the predictions from theory and the corresponding uncertainties. Taken from Ref.[4]

Category	R	$\sigma^{\text{fid}}_{\text{t}\bar{\text{t}}+\gamma}$ (fb)	$\sigma_{\text{t}\bar{\text{t}}+\gamma} \times \mathcal{B}$ (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	-	-	$592 \pm 71(\text{scale}) \pm 30(\text{PDF})$

Table 1: Measured values of the cross section ratio as well as fiducial cross sections for $\text{t}\bar{\text{t}}\gamma$ process. Taken from Ref.[3].

Channel	Expected significance	Observed significance
$2\ell ss$ analysis ($\text{t}\bar{\text{t}}\text{W}$)	2.6	3.9
3ℓ analysis ($\text{t}\bar{\text{t}}\text{Z}$)	5.4	3.8
4ℓ analysis ($\text{t}\bar{\text{t}}\text{Z}$)	2.4	2.8
3ℓ and 4ℓ combined ($\text{t}\bar{\text{t}}\text{Z}$)	5.8	4.6

Table 2: Summary of expected and observed significances for $\text{t}\bar{\text{t}}\text{W}$ in the same-charge dilepton channel and for $\text{t}\bar{\text{t}}\text{Z}$ in the 3-lepton and 4-lepton channels and in the two channels combined. Taken from Ref.[4].

[2] G.Cowan et al., Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J.C73,2501(2013), arXiv 1007.1727

[3] CMS Collaboration, Measurement of the $\text{t}\bar{\text{t}}\gamma$ production cross-section in pp collisions at $\sqrt{s} = 8$ TeV, CMS-PAS-TOP-14-008, CDS Record 2216566

[4] CMS Collaboration, Measurement of the top pair production in association with a W or Z boson in pp collisions at 13 TeV, CMS-PAS-TOP-16-017, CDS Record 2205283