PROCEEDINGS OF SCIENCE

$t\bar{t}$+X and t+X production in CMS: $t\bar{t}$Z, $t\bar{t}$Z, $t\bar{t}$W, $t\bar{t}\gamma$, tZq, tγq in CMS

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The most recent measurements of top quark pair and single top quark production in association with electroweak bosons (W, Z, or γ) are presented. Data collected with the CMS experiment in proton-proton collisions at the LHC at different centre-of-mass energies are used and the results are compared to the standard model predictions.

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1. Introduction

Top quarks are produced at an incredibly high rate the CERN LHC. While the dominant top quark production channels of pair production ($t\bar{t}$, $\sigma \approx 830$ fb) and t-channel single production ($\sigma \approx 220$ fb) have been measured with high precision, other more rare production modes are becoming fully accessible. This document provides a review of the current experimental studies of measurements of $t\bar{t}$ production in association with a W boson ($t\bar{t}W$), a Z boson ($t\bar{t}Z$), or a photon ($t\bar{t}\gamma$), and of t-channel single top quark production with a Z boson (tZq) or a photon ($t\gamma q$) with the CMS detector [1] at the LHC proton-proton (pp) collider at different centre-of-mass energies. The results are compared to the standard model (SM) predictions.

2. Top quark pair production in association with a Z boson

A measurement of $t\bar{t}Z$ production using a data sample of pp collisions at $\sqrt{s}$ = 13 TeV, with an integrated luminosity ($\mathcal{L}$) of 77.5 fb^{-1}, is presented [2]. Three- and four-lepton final states using categories defined with jet (N_j) and b jet (N_b) multiplicities (see Fig. 1) are used.

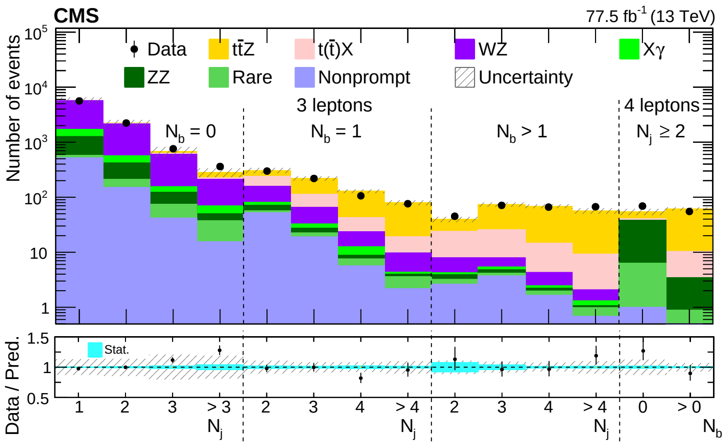

Figure 1: Observed event yields in data for different values of N_j and N_b for events with 3 and 4 leptons, compared with the signal and background yields, as obtained from the fit. The lower panel displays the ratio of the data to the predictions of the signal and background from simulation. The inner and outer bands show the statistical and total uncertainties, respectively [2].

Data samples enriched in background processes are used to validate predictions, as well as to constrain their uncertainties. The larger data set and reduced systematic uncertainties such as those associated with the lepton identification, helped to substantially improve the precision on the measured cross section with respect to previous measurements. The measured inclusive cross section $\sigma(t\bar{t}Z) = 0.95 \pm 0.05$ (stat) $\pm$ 0.06 (syst) pb is in good agreement with the SM prediction of 0.84 ± 0.10 pb. This is the most precise measurement of the $t\bar{t}Z$ cross section to date, and the first measurement with a precision competing with current theoretical calculations.

Absolute and normalized differential cross sections for the transverse momentum of the Z boson, $p_T(Z)$, and for the angle between the direction of the Z boson and the direction of the negatively charged lepton in the rest frame of the Z boson, θ^*_Z, are measured for the first time (Fig. 2) and are found to be in good agreement with the SM predictions at next-to-leading order (NLO).

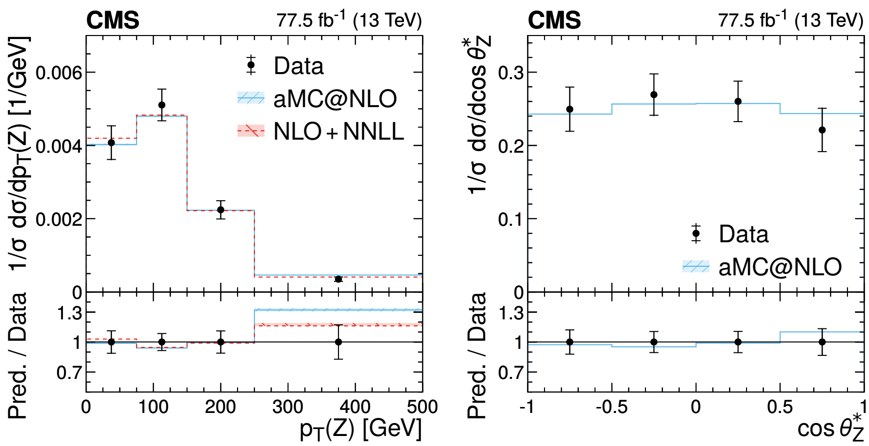

Figure 2: Differential $t\bar{t}Z$ production normalized cross sections as a function of $p_T(Z)$ (left) and cos θ^*_Z (right). The data are represented by the points. The inner (outer) vertical lines indicate the statistical (total) uncertainties. The solid histogram shows the prediction from the MadGraph5_aMC@NLO MC simulation, and the dashed histogram shows the theory prediction at NLO+NNLL accuracy. The hatched bands indicate the theoretical uncertainties in the predictions, as defined in the text. The lower panel displays the ratios of the predictions to the measurement [2].

3. Top quark pair production in association with a W boson

A measurement of $t\bar{t}W$ production using pp collisions at 13 TeV with $\mathcal{L}$ = 35.9 fb^{-1} is presented [3]. To distinguish backgrounds from the signal, a multivariate analysis (MVA) has been developed. A boosted decision tree (BDT) classifier is used as the MVA discriminant. Figure 3 (left) shows its output (D) for background and signal. Events with D > 0 are selected to suppress the background from nonprompt leptons, and further split into two categories: 0 < D < 0.6 and D > 0.6. Furthermore, N_j and N_b are also used to form five exclusive event categories that maximize signal significance. (N_j = 2, 3, and > 3, the latter two are further split according to N_b = 1 and N_b > 1). Events with D < 0 are also used in the signal extraction procedure to constrain the uncertainties in the nonprompt lepton background. Each of these categories is further split into two sets according to the total charge of the leptons. The predicted SM background and signal yields, and the observed data are shown in Fig.3 (right) for each of the above categories.

The expected (observed) signal significance is found to be 4.5 (5.3) standard deviations. The measured cross section is $\sigma(t\bar{t}W) = 0.77^{+0.12}_{-0.11}$ (stat) $^{+0.13}_{-0.12}$ (syst) pb, in agreement with the NLO SM prediction of 0.628 ± 0.082 pb.

4. Single top quark production in association with a Z boson and a quark

We report the observation of tZq production using the leptonic decay mode [4]. The data used correspond to $\mathcal{L}$ = 77.4 fb^{-1}. The increased integrated luminosity, a MVA lepton identification, and a redesigned strategy improve significantly the sensitivity compared to previous searches.

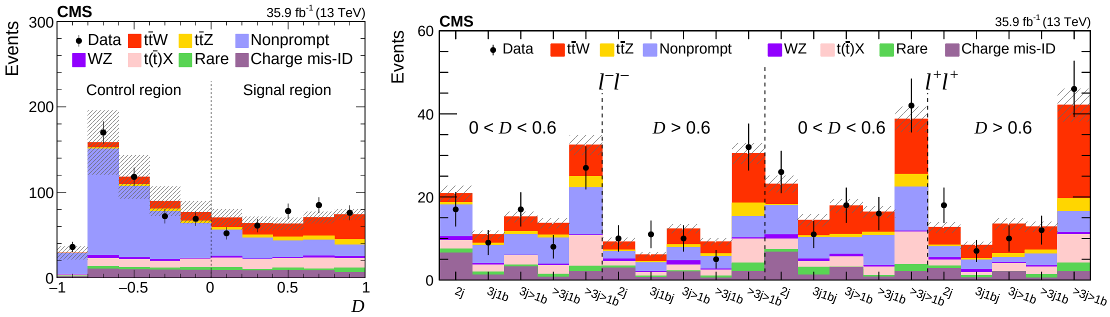

Figure 3: Left: BDT classifier D for background and signal in the SS dilepton analysis. Right: Predicted and observed yields in N_j= 2, 3, and > 3 categories in the three-lepton analysis. The hatched bands show the total uncertainty associated with the signal and background predictions, as obtained from the fit [3].

Events with three charged leptons (either electrons or muons) and at least two jets are divided into three categories, referred to as signal regions (SRs), based on the number of jets they contain. Events with a total of two or three jets, exactly one of which is b tagged, make up SR-2/3j-1b, which contains most tZq events. Events with four or more jets, exactly one of which is b tagged, form SR-4j-1b, while SR-2b contains events with two or more b-tagged jets. Events without b-tagged jets, or with one b-tagged jet and no additional jets, have a very low signal-to-background ratio and are rejected. In each of these categories, a dedicated BDT is trained to extract the tZq signal from the total background on several discriminating variables. The observed and expected BDT distributions in the most sensitive region, SR-2/3j-1b, are shown in Fig.4 (left). The distribution in SR-2/3j-1b of the reconstructed Z boson p_T (variable highly sensitiveto the presence of new physics phenomena) in events with a BDT discriminant value greater than 0.5 can be found in Fig.4 (right).

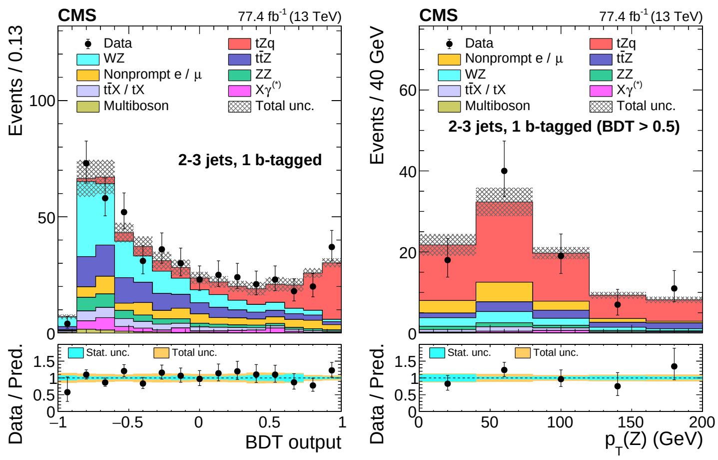

Figure 4: Left: observed and post-fit expected BDT distributions for events in SR-2/3j-1b. Right: p_T of the Z boson for events with BDT discriminant larger than 0.5 in SR-2/3j-1b. The vertical bars on the points give the statistical uncertainty in data, and the hatched regions display the total uncertainty in the prediction. The lower panels display the ratio of the observed data to the predictions, including the tZq signal, with inner and outer shaded bands, respectively, representing the statistical and total uncertainties in the predictions [4].

The tZq signal is observed with a significance of well over five standard deviations. The tZq production cross section is measured to be $\sigma(\mathrm{pp} \to \mathrm{tZq} \to \mathrm{t}\ell^+\ell^-\mathrm{q}) = 111 \pm 13\ (\mathrm{stat})\ ^{+11}_{-9}\ (\mathrm{syst})$ fb, where ℓ refers to an electron, muon, or τ lepton, for dilepton invariant masses in excess of 30 GeV, in agreement with the SM prediction.

5. Single top quark production in association with a photon and a quark

The first evidence of events consistent with $\mathrm{t}\gamma\mathrm{q}$ production is reported [5]. The analysis is based on pp collisions at $\sqrt{s}$ = 13 TeV, corresponding to $\mathcal{L}$ = 35.9 fb^{-1}. Events are selected by requiring the presence of a muon (μ), a photon (γ), an imbalance in transverse momentum from an undetected neutrino (ν), and at least two jets (j) of which exactly one is identified as associated to the hadronization of a b quark. A MVA discriminant, shown in Fig. 5 (right), based on topological and kinematic event properties is used to separate signal from background processes.

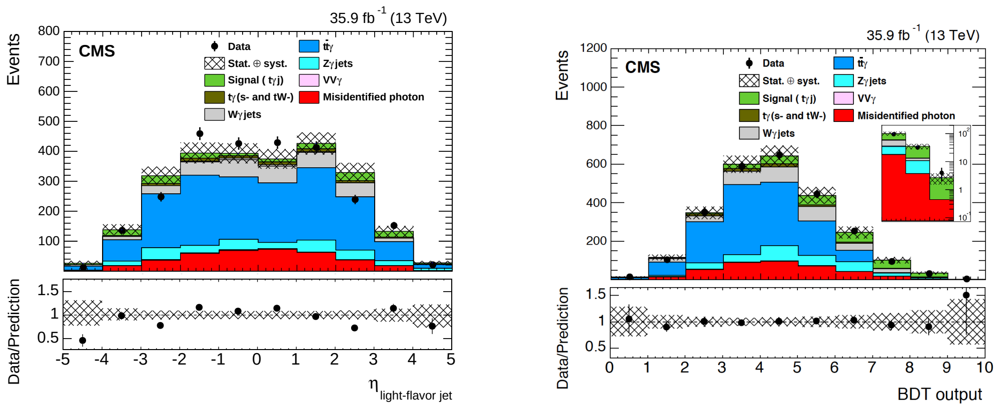

Figure 5: Left: Distribution of η of the light-flavor jet for data and the SM prediction. Right: The BDT output distribution for data and SM predictions after performing the fit. The hatched bands show the statistical and systematic uncertainties, and the vertical bars on the points represent the statistical uncertainties of the data. The ratio of the data to the SM prediction is shown in the bottom panel [5].

An excess above the background-only hypothesis is observed, with a significance of 4.4 standard deviations. The median expected significance is 3.0. A fiducial cross section is measured for isolated photons with transverse momentum greater than 25 GeV in the central region of the detector. The measured product of the cross section and branching fraction is $\sigma(\mathrm{pp} \to \mathrm{t}\gamma\mathrm{j})\mathrm{B}(\mathrm{t} \to \mu\nu\mathrm{b})$= 115 $\pm$ 17 (stat) $\pm$ 30 (syst) fb, which is consistent with the SM prediction of 81 $\pm$ 4 fb.

6. Top quark pair production in association with a photon

A measurement of the cross section for $\mathrm{t\bar{t}}\gamma$ production in pp collisions at $\sqrt{s}$ = 8 TeV is presented [6]. The analysis uses $\mathcal{L}$ = 19.7 fb^{-1} of data. The analysis is performed in the semileptonic e+jets and μ+jets decay channels. The signal is defined as the production of a $\mathrm{t\bar{t}}$ pair in association with a photon having a transverse energy larger than 25 GeV and $|\eta|$<1.44. The measurement is performed in the fiducial phase space corresponding to the semileptonic decay chain of the $\mathrm{t\bar{t}}$ pair, and the cross section is measured relative to the inclusive $\mathrm{t\bar{t}}$ pair production cross section. The ratio of the $\mathrm{t\bar{t}}\gamma$ to $\mathrm{t\bar{t}}$ production cross sections has been measured to be R = $(5.2 \pm 1.1)\times10^{-4}$. By multiplying the measured ratio by the previously measured value of the $\mathrm{t\bar{t}}$ cross section, the fiducial cross section for $\mathrm{t\bar{t}}\gamma$ production of 127 ± 27 fb has been found for events in the e+jets and μ+jets final states. The measured values are in agreement with the theoretical predictions.

7. Summary

The large amount of data collected at the LHC between 2015 and 2018 as well as refined analysis techniques allowed the CMS Collaboration to measure many rare top quark 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 is found for single top quark production in association with a photon. In all analyses, the measured results are found to be in agreement with the SM predictions. 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 CMS Collaboration can be expected soon.

References

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