Evidence for the standard model production of a Z boson with a single top quark in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

Evidence for the standard model production of a Z boson in association with a single top quark is presented. The study uses a data sample of proton-proton collisions at $\sqrt{s} = 13$ TeV recorded in 2016 by the CMS experiment, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. Final states with three leptons (electrons or muons) and at least two jets are investigated. The corresponding measured $tZq$ measured cross section is $\sigma(p p \to tZq \to Wb\ell^+\ell^-q) = 123^{+44}_{-39}$ fb, where $\ell$ stands for electrons, muons, and taus, with an observed (expected) significance of 3.7 (3.1) standard deviations.

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1 Introduction

At the CERN LHC, top quarks are produced predominantly in pairs (t\bar{t}) via the strong (QCD) interaction [1]. Single top quark production, which happens via the electroweak interaction and at lower rates compared to the pair-production process, proceeds via three different production modes: t-channel, s-channel, and associated tW production. Cross section measurements of single top quark production have been reported at the Tevatron by the DØ and CDF experiments [2, 3], and at the LHC by ATLAS [4–8] and CMS [9–12].

The high centre-of-mass collision energy at the LHC, together with large integrated luminosities, permits the study of processes with very low cross sections that were not accessible at lower energies. One example of such a process is the rare associated production of a single top quark with a Z boson. This production mechanism, leading to a final state with a single top quark, a Z boson, and an additional quark, denoted by tZq, can probe the standard model (SM) in a unique way. The leading order (LO) diagrams that contribute to this final state are shown in Fig. 1. The process is sensitive to the top quark coupling to the Z boson, as illustrated in Fig. 1(d), but also to the triple gauge-boson coupling WWZ, as illustrated in Fig. 1(f).

![Leading order tZq production diagrams.](image)

Figure 1: Leading order tZq production diagrams. The initial- and final-state quarks, denoted q and q', are predominantly first-generation quarks, although there are smaller additional contributions from strange- and charm-initiated diagrams. Diagram (c) represents the non-resonant contribution to the tZq process.

The top quark coupling to the Z boson and triple gauge-bosons couplings are sensitive to new physics effects. In particular, measurements of tZq production are sensitive to processes beyond the SM that have similar experimental signatures, such as flavour-changing neutral currents (FCNC) with the decay of the top quark into a Z boson [13] or the direct production of a top quark and a Z boson from an up or charm quark [14]. Within the SM, FCNC processes are forbidden at tree level and suppressed at higher orders [15]. Therefore, deviations from the expected SM tZq production cross section could be indicative of beyond-SM FCNC processes.

For proton-proton (pp) collisions at a centre-of-mass energy of 13 TeV, and considering only the leptonic decays of the Z boson (to electrons, muons, and taus, generically denoted by \ell), the next-to-leading order (NLO) cross section of the tZq → Wb + \ell^+\ell^- + q process has been calculated with MC@NLO [16] and the parton distribution function (PDF) set NNPDF3.0 [17] in the five-flavour scheme, including lepton pairs from off-shell Z bosons with invariant mass...
The result is $\sigma_{\text{SM}}^{t\ell^+\ell^-q} = 94.2^{+1.9}_{-1.8}$ (scale) $\pm 2.5$ (PDF) fb, with uncertainties estimated by changing the renormalisation and factorisation scales by factors of 0.5 and 2 (scale), and from the 68% confidence level (CL) uncertainty on the NNPDF3.0 PDF set (PDF). This cross section is used as reference in the analysis reported here. Another calculation, including all Z boson decays, gives a compatible cross section when accounting for the branching ratio to charged leptons [18]. Given its very low cross section, $t\ell q$ production has not yet been observed. Previous searches 8 TeV by CMS [19] reported a signal with a significance of only 2.4 standard deviations, while ATLAS [20] Collaboration reported an evidence for $t\ell q$ production at 13 TeV, measuring a cross section of $600 \pm 220$ fb.

This note presents a search for $t\ell q$ production in pp collisions at a centre-of-mass energy of 13 TeV, using a data sample collected by CMS, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The signature of $t\ell q$ production considered in this analysis consists of a single top quark produced in the $t$-channel, a Z boson, and an additional (“recoiling”) jet emitted in the pseudorapidity range $|\eta| < 4.5$. The search targets events where the Z boson decays to $e^+e^-$ or $\mu^+\mu^-$, while the W boson, produced in the decay of the top quark, decays into a neutrino plus an electron or a muon, resulting in four possible final-state leptonic combinations: $e^+e^-\mu\mu$, $e\mu\mu\mu$, and $\tau$ leptons decaying into electrons or muons. The measurement is based on a multivariate analysis, where boosted decision trees (BDT) are used to enhance the signal to background separation. Several control regions are defined for better control of the backgrounds, each containing different amounts of events from signal and other processes.

2 Object online selection, reconstruction, and identification

The analysis reported in this note is based on pp collisions collected with the CMS detector during the 2016 data taking period. The data are selected online using triggers that rely on the presence of either one, two, or three high-$p_T$ leptons. The lowest $p_T$ thresholds of the three-lepton triggers are 16, 12, and 8 GeV for electrons, and 12, 10, and 5 GeV for muons; the corresponding values for the dilepton triggers are 23 and 12 GeV (electrons), and 17 and 8 GeV (muons). The triggers requiring the presence of at least one electron and at least one muon have similar thresholds. A trigger efficiency of nearly 100% is achieved by including single-lepton triggers with thresholds of 32 (24) GeV for electrons (muons).

The events are reconstructed using the particle-flow algorithm [21], which reconstructs and identifies each individual particle with an optimised combination of information from the various elements of the CMS detector. The energy of the photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects, while that of the electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the total energy of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of the muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum, measured in the tracker, and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding ECAL and HCAL corrected energy deposits.

The event selection makes use of the concept of lepton isolation, reflected in the variable $I_{\text{iso}}$, which is computed as the summed energy of all particles in a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.
around the lepton, excluding the lepton itself, and divided by the lepton $p_T$. The sum is then corrected to remove the energy of neutral particles produced in extra pp interactions within the same or neighbouring LHC bunch crossings, known as pileup collisions (PU). For electrons, $R$ is set to 0.3, and the expected PU energy inside the isolation cone is estimated from the median energy density per area of PU contamination. Muon $Iso$ uses $R = 0.4$. The average PU energy inside a cone of $R = 0.4$ has been measured in multijet events and found to be half of the energy coming from charged hadrons. This average PU energy value is used in the Muon $Iso$ PU correction. Electrons (muons) are considered isolated if $Iso$ is smaller than 0.06 (0.15).

The data samples with prompt leptons are contaminated by (real) leptons from hadron decays (often called “nonprompt leptons”) and by hadrons or jets misidentified as leptons (sometimes called “fake leptons”). In addition, nonprompt isolated electrons can arise from the conversion of photons. For simplicity of language, and given that these background sources are evaluated with similar data-driven methods, they will be jointly referred to as “not-prompt” leptons, or simply “NPL”, in this note. Data samples for evaluating the NPL background are constructed using objects that are reconstructed similarly to the prompt leptons, with two important differences. First, while the prompt and not-prompt leptons are identified using the same variables, looser criteria are applied to the NPL sample. Second, leptons are considered not-prompt only if they are non-isolated, requiring not-prompt electrons (muons) to have $Iso > 0.17$ (0.25). Additionally, not-prompt electrons are required to have $Iso < 1$. Tight criteria to reject photon conversions [22] are required for both prompt and not-prompt electrons.

For each event, jets are clustered from the particle-flow candidates with the anti-$k_T$ algorithm [23, 24], with a cone radius of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found in simulation studies to be within 5 to 10% of the true momentum over the whole $p_T$ spectrum and detector acceptance. Jet energy corrections are derived from simulation studies and confirmed with in situ measurements, through the energy balance of dijet and photon plus jet events [25]. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared with 40%, 12%, and 5% when only the calorimeters are used for jet clustering. Jets reconstructed too close to a selected lepton, within an angular distance, in pseudorapidity and azimuthal angle, $\sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.4$, are not considered for further analysis. Events containing jets in the transition region between the ECAL and HCAL, $2.7 < |\eta| < 3.0$, are removed from the sample.

Jets that originate from the hadronisation of a b quark are identified (tagged) using the Combined Secondary Vertex (CSVv2) algorithm [26, 27], which combines various track-based variables with potential secondary vertex variables to construct a discriminating observable in the region $|\eta| < 2.4$. At the working point chosen in this analysis, the CSVv2 algorithm has an efficiency of about 83% to correctly tag b jets and a misidentification probability of 10%, as estimated from QCD multijet simulations.

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particle-flow objects in an event. Its magnitude is denoted by $p_T^{\text{miss}}$. The transverse mass of the $W$ boson is defined as $m_W^T = \sqrt{2 p_T p_T^{\text{miss}} (1 - \cos(\Delta \phi))}$, where $p_T$ is the transverse momentum of the lepton decaying from the $W$ boson and $\Delta \phi$ is the angle in the $x$-$y$ plane between the direction of the lepton and the direction of the $\vec{p}_T^{\text{miss}}$. 
3 Simulated events

Samples of Monte Carlo (MC) simulated events are used extensively in this measurement, to evaluate detector resolution, efficiencies and acceptance effects, and to estimate the contribution from background processes that have similar topologies to the trilepton tZq final state.

Samples simulating signal events, tZq, are generated at NLO precision using the MadGraph 5_AMC@NLO package (version 5.222) [16]. The two main background processes, WZ+jets and top quark pair production in association with vector bosons (ttZ and ttW), are also simulated with MadGraph 5_AMC@NLO, with up to one additional hadronic jet at NLO. Other minor backgrounds are ZZ and ttH production, for which we use the NLO generators MadGraph 5_AMC@NLO and POWHEG [28–33], respectively, and ttWZ production, generated with MadGraph [34] at LO accuracy. The PDF set NNPDF3.0 is used with all generators. The simulated samples are interfaced to PYTHIA8 (v8.205) [35] for parton shower and hadronisation. The full simulation of detector effects and running conditions is provided by the GEANT4 package [36].

The events are simulated in final states including decays to electrons and/or muons, as well as to tau leptons. In all simulated samples involving top quarks, a top quark mass of 172.5 GeV is assumed. Multiple minimum bias events generated with PYTHIA8 are added for each simulated event to mimic the presence of PU. Simulated events are weighted to reproduce the distribution of the number of PU vertices inferred from data.

The samples are normalised to their expected cross sections, obtained from NLO calculations for all processes, except for tWZ, which is estimated at LO accuracy.

The samples are further corrected using scale factors depending on the $p_T$ and $\eta$ of the jets and leptons, so that their resolutions, energy scales, and efficiencies measured in data are well reproduced by the simulation. The corrections include the smearing of the jet energy resolution, which is observed to be smaller in the simulation than in the data, and scale factors that account for the different efficiencies in the lepton identification and reconstruction. The shape of the CSVv2 discriminant is one of the variables used in the multivariate analysis to extract the signal. The simulated shape has been corrected [26, 27] so that the $b$ tagging efficiency and purity reproduce those observed in data.

One of the most abundant background sources in the three lepton final state arises from events with at least one NPL. Unlike all other backgrounds, which are well modelled by MC simulation, the samples used in this analysis to estimate the NPL background contribution are derived from the data, as described in Section 5.2.

4 Event selection: signal and background control regions

In the analysis, we target tZq event candidates where $t \rightarrow Wb$, $W \rightarrow l\nu$, and $Z \rightarrow l'^+l'^-$,

$$tZq \rightarrow (t \rightarrow b + l + \nu) (Z \rightarrow l'^+ + l'^-) q,$$

(1)

where $l$ and $l'$ are either electrons or muons, including those coming from a leptonic tau decay. Therefore, the sample of events including the signal must contain exactly three isolated leptons, one of them arising from the top quark decay and the other two from the Z boson decay. In single top quark production, the associated recoil jet usually goes in the same direction as the incoming proton, being detected in very forward regions of the detector. For this reason, we select jets in the extended pseudorapidity range $|\eta| < 4.5$. Given the tracker acceptance, b-
tagged jets are confined to the $|\eta| < 2.4$ range. Both tagged and untagged jets are required to have $p_T > 30$ GeV.

The baseline selection for the analysis consists in exactly three leptons, two of which have the same flavour, opposite sign, and an invariant mass compatible with the Z boson mass within 15 GeV. The third lepton, assumed to arise from the top quark decay, is referred to as the “additional lepton”. Electrons and muons are both required to have $p_T > 25$ GeV, and to be measured within $|\eta| < 2.5$ and $|\eta| < 2.4$, respectively. In order to reduce backgrounds with four or more leptons in the final state, e.g. from ZZ, ttZ, and ttH, events containing any additional lepton with the same $\eta$ requirements as the signal leptons, but with $p_T > 10$ GeV and looser identification criteria, are removed from the sample.

Several other SM processes, some of them with much higher cross sections than that of the expected tZq signal, contain three reconstructed leptons in the final state. Out of these, the three most important are the WZ+jets and ttZ productions, and those contributing to NPL background. In the first two cases, the three lepton topology is identical to the tZq case: two opposite-sign leptons of the same flavour decaying from the Z boson, and a third high-$p_T$, isolated lepton. In the case of ttZ production, the cross section for the three lepton final state with one of the top quarks decaying hadronically is higher than the four lepton case with both top quarks decaying leptonically, which is also suppressed by the already mentioned veto on the fourth lepton. Although the misidentification rate per lepton, especially for muons, is small, the cross sections for the processes from which not-prompt leptons originate (dominated by Drell–Yan production in association with jets, DY+jets, and tt production) are orders of magnitude larger than the expected tZq cross section, making NPL to one of the most important backgrounds to the three lepton final state.

For the tZq final state, two jets, one of which arises from a b quark, are expected. In the ttZ three lepton final state, two b jets are expected. However, given the inefficiencies of the b tagging algorithm, one of the two b jets may be untagged, leading to an identical final state as the signal. Likewise, one of the b jets produced by gluon splitting in the WZ+jets final states may be tagged, or, most commonly, light flavour jets from WZ+jets production can be mistagged as b jets, again resulting in an identical topology as the signal.

In order to reduce the impact of the background determination uncertainties on the tZq measurement, the following strategy is adopted: the baseline (three lepton) selection is subdivided in three regions of interest, one of them enriched in tZq events, another selected to contain mostly ttZ events, and a third one containing mostly WZ+jets and NPL backgrounds. The final analysis performs a simultaneous fit to these three regions, so that the signal cross section is determined and the normalisations of the main backgrounds are better constrained.

The three regions are defined according to their jet and b-tagged jet multiplicities, as follows.

**1bjet (signal region):** In this region, the target events are those arising from the tZq process with one b jet and one recoiling jet. In order to increase the signal acceptance for the cases where one additional jet is produced by radiation, the 1bjet region is defined as containing events with 2 or 3 jets, of which exactly one is tagged as a b jet.

**2bjets control region (ttZ enriched):** This region is defined by requiring at least two jets, at least two of them b-tagged, enhancing the amount of ttZ events.

**0bjet control region (WZ+jets enriched):** Events with at least one jet, but zero b tagged jets, selected in this region most likely originate from a WZ process. Since the majority of DY+jets events also do not contain b jets in the final state, this region is also rich in NPL background.
events.

5 Shape analysis

The measurement of the tZq cross section is obtained from a simultaneous binned maximum-likelihood fit, considering the rates and shapes of the BDT discriminant distributions in the 2bjets and 1bjet regions, and of the $m_T^W$ distributions in the 0bjet region. Templates are built using these variables in their respective region, for each of the four final states (eee, eeµ, µe, and µµµ), adding up to 12 distributions that are fit simultaneously.

5.1 Input normalisation of the SM predictions

The expected yields of backgrounds taken from simulations are given by the corresponding theoretical cross sections. The contributions from WZ+b, WZ+c, and WZ+light-flavour jets in the WZ+jets MC sample are separated, using the generator-level information, and considered as independent backgrounds in all steps of the shape analysis. This allows a better modelling of the heavy flavour content of the WZ+jets sample, rather than relying on the flavour content given by MC.

5.2 NPL background treatment

In the shape analysis, templates for the NPL background are built from data. The origin of not-prompt leptons depends on the flavour of the lepton. In the case of muons, the dominant source is the semileptonic decay of heavy flavour hadrons. In the case of electrons, the dominant sources are light hadrons misreconstructed as electrons and photon conversions. Therefore, not-prompt electrons and muons are treated as separate background sources in this analysis.

The background events containing not-prompt leptons originate primarily from DY+jets processes, then from t̅t events decaying into two leptons, and to a less extent from WW and tW processes, all containing two prompt and one not-prompt leptons. Given the low probability that a NPL is identified as prompt, the contribution from events with more than one NPL is negligible. Not-prompt electron (muon) templates are obtained from events containing exactly one not-prompt electron (muon), identified as described in Section 3, and two prompt leptons (either electrons or muons). In the NPL sample, the not-prompt leptons can be associated to either the top quark candidate or to the Z boson candidate.

The data sample that is used to obtain the NPL background templates is a high-statistics sample, typically two orders of magnitude larger than the signal sample obtained with the baseline selection. While the shapes of the distributions used in the multivariate analysis are provided by the templates, their normalization is determined with a two-step procedure. In a first step, the $m_T^W$ distribution in the 0bjet control region is used to provide the normalization of all NPL components, independently in the four channels. This first step is used to fix the relative NPL normalization of the templates in the four channels. In a subsequent step the not-prompt electron and muon yields are treated as two free parameters, independent from each other, in a simultaneous fit of the 0bjet/1bjet/2bjets regions. This second step represents the final fit used to provide the results and is described in Section 7.

The use of the 0bjet region to provide the relative NPL yields in the four channels is justified by the dominance of the DY process as source of NPL background events in all three b tagging regions. In order to check the procedure, an independent analysis has been performed where this relative weight of the DY background process compared to t̅t production has been suppressed by means of mild requirements on missing transverse energy and transverse mass. In this cross
check analysis, the relative normalisations of the not-prompt electron and muon backgrounds were left free in the four channels, and results obtained in a single common fit. This alternative procedure gave similar final results.

5.3 Multivariate analysis

The signal extraction relies on a fit to the data, simultaneously in the three different selections defined in Section 4, to better constrain the backgrounds in the signal region.

In order to enhance the separation between signal and background processes, two multivariate discriminators are used, built for the 1bjet and 2bjets regions. The discriminators are based on the BDT algorithm [37] implemented in the toolkit for multivariate analysis TMVA [38]. The samples described in Section 3 are used for the BDT training.

Several observables are used as input variables for the BDT. These include masses, kinematic and angular distributions involving the recoiling jet, the reconstructed top quarks and Z bosons as well as their decay products – leptons and jets. The information related to b tagging is also used through the distributions of the CSVv2 discriminator [26, 27] and of the b-tagged jet multiplicity.

In addition, variables computed with the matrix element method (MEM) [39] are also included in the multivariate analysis. A weight \( w_{i,\alpha} \) is computed for each event \( i \) and hypothesis \( \alpha \) (where \( \alpha \) is either signal, \( t\bar{t}Z \), or \( WZ+jets \)) as

\[
w_{i,\alpha}(\Phi') = \frac{1}{\sigma_\alpha} \int \mathcal{d}\Phi_{\Phi} \cdot \delta^4 \left( p_1^\mu + p_2^\mu - \sum_{k \geq 2} p_k^\mu \right) \cdot \frac{\mathcal{M}_{\alpha}(p_F^\mu)}{x_1 x_2 s} \cdot \frac{\mathcal{M}_{\alpha}(p_F^\mu)}{x_1 x_2 s} \cdot W(\Phi'|\Phi_{\alpha}),
\]

where \( \sigma_\alpha \) is the cross section; \( \Phi' \) are the 4-momenta of the reconstructed particles; \( \mathcal{d}\Phi_{\Phi} \) is the element of phase space corresponding to parton-level variables with momentum conservation enforced; \( f(x, \mu_F) \) are the parton density functions, where \( \mu_F \) is the QCD factorisation scale, computed using NNPDF2.3 LO [40]; \( |\mathcal{M}_{\alpha}|^2 \) is the squared matrix element, computed with MADGRAPH 5_AMC@NLO stand-alone [16] at LO in the narrow-width approximation for \( t \) and \( \bar{t} \); and \( W \) are the transfer functions for jet energy and \( p_T^{miss} \), relating parton-level variables to reconstructed quantities, estimated from simulated events and normalised to unity.

For all of the three processes, the mass of the W boson arising from the top quark decay follows a Breit–Wigner distribution, as specified by the matrix element. The \( Z/\gamma^* \) bosons in the \( t\bar{t}Z/\gamma^* \) hypothesis also follow a Breit–Wigner (interference is included in the matrix element). The matrix element squared provided at LO by MADGRAPH 5_AMC@NLO does not contain additional jets, which are present in the data. To evaluate the matrix element at LO, the total momentum must have a null transverse component. The total momentum is computed as the sum of the momenta of all particles in the final state. An inverse boost corresponding to the opposite of the total transverse momentum is applied to all final state particles, thus correcting for any recoiling jets not present in the matrix element at LO.

In computing the MEM weights, jets with the highest CSVv2 discriminator values are assigned to the b quarks from top decays. Among the remaining jets, up to two jets with the highest \( |\eta| \) (signal hypothesis), with the invariant mass closest to the W boson mass (\( t\bar{t}Z \) hypothesis), or with the highest \( p_T \) (\( WZ+jets \) hypothesis), are assigned to the quarks at parton level. Jets in the 1bjet region may not be matched to all parton-level quarks needed in the \( t\bar{t}Z \) hypothesis (two b-quarks and two non-b quarks). In this case, the \( t\bar{t}Z \) weight can still be computed by leaving the phase space of the missing jets unconstrained in the integral.
The final weight for each hypothesis $\alpha$ is taken as the average of the weights computed for each lepton and jet permutation. The MEM weights are combined in likelihood ratios of signal versus $t\bar{t}Z + WZ +$jets (in the 1bjet region) and $t\bar{t}Z$ (in the 2bjets region), and then used as input variables to the BDT. Additionally, the maximum value of the function being integrated is also included, corresponding to the MEM score associated to the most probable kinematic configuration. The normalised BDT discriminants for signal and backgrounds in the 1bjet and 2bjets regions are shown in Fig. 2 for BDT trainings with and without MEM variables. Including the MEM variables in the BDT training improves the significance by about 10% in the 1bjet region and 20% in 2bjets region.

![Figure 2: Normalised distributions of the BDT output for signal (thick lines) and backgrounds (thin lines). The discriminants including (excluding) MEM variables in the BDT training are shown as dashed (solid) lines for the 1bjet (left) and 2bjets (right) regions. Contributions from all channels are included.](image)

The distributions of some of the most discriminant variables for the BDT in the 1bjet and 2bjets regions are shown in Fig. 3, comparing data to the predictions. These variables are the highest CSVv2 discriminator among all selected jets, the logarithm of the MEM score associated to the most probable $tZq$ kinematic configuration ($-\log(w_{tZq})$), and the separation between the $b$ quark and recoiling jets ($\Delta R(b,j')$). Fig. 4 shows, for events in the 0bjet region, the distributions of pseudorapidity and $p_T$ of the recoiling jet ($\eta(j')$ and $p_T(j')$), and the additional lepton asymmetry, defined as the product of its charge and pseudorapidity, $(q|\eta(l)|)$. The distributions are shown for the combination of the four channels: $\mu\mu\mu$, $eee$, $\mu\mu e$, and $ee\mu$. The sum of the systematic and statistical uncertainties on the predictions is shown as a hatched band. The pulls of the distributions, defined in each bin as the difference between data and prediction, divided by the quadratic sum of total uncertainties in the predictions (systematic and statistical) and the data (statistical), are shown in the bottom plots.

### 6 Systematic uncertainties

Different sources of systematic uncertainty are considered. They can affect the number of events passing the selections or the shape of the variables used in the multivariate analysis.

The sources of systematic uncertainty considered in this analysis are:

- **The scale factors used to correct the signal and simulated background samples:**
  - **Luminosity:** An uncertainty of 2.5% on the sample luminosity [41] is propagated as a normalisation-only uncertainty of the total predicted yields.
Figure 3: Data-to-prediction comparisons in the 1bjet (signal-enriched) region (upper row) and in the 2bjets region (bottom row) for the highest CSVv2 discriminator among all selected jets (left), the negative values of the logarithm of the MEM score associated to the most probable tZq kinematic configuration (center), and the $\Delta R$ separation between the b quark and recoiling jets (right). The distributions include events from all final states. Underflows and overflows are included in the first and last bins, respectively. The predictions correspond to the normalisations obtained after the fit described in Section 7. The hatched bands include the total uncertainty on the background and signal samples.
Figure 4: Data-to-prediction comparisons in the 0bjet region for the $\eta$ (left) and $p_T$ (centre) of the recoiling jet, and the additional lepton asymmetry (right). More details are given in the caption of Fig. 3.

- **Pileup**: The minimum bias cross section used to estimate the PU simulation corrections is varied by 4.6%; only shape effects are considered.
- **Trigger**: The trigger efficiency is estimated to be near 100% both in data and in simulation. A normalisation-only variation of $\pm 1\%$ ($\pm 2\%$) is applied to the predicted yields in the $\mu\mu\mu$ and $ee\mu$ ($\mu\mu\mu$ and $ee\mu$) channels to account for residual differences on the trigger efficiency in data and simulation.
- **Lepton selection**: The scale factors used to correct the simulations for lepton isolation and identification efficiencies are varied within their 1$\sigma$ uncertainty, affecting both the shape and the normalisation of the fitted distributions.
- **Jet energy scale and resolution**: Both the jet energy scale and the jet energy resolution corrections in simulation are varied within their 1$\sigma$ uncertainty. The uncertainty is propagated to the $E_T^{\text{miss}}$. These uncertainties affect both shape and normalisation of the simulated samples.
- **b-tagging**: The scale factors related to b tagging and mistagging efficiencies are varied within 1$\sigma$. Eight independent variations are considered, including two types of statistical uncertainties (linear and quadratic) on the b-, c-, and light-flavour components of the MC samples, light flavour contamination on the b tagging scale factors, and b quark contamination on the mistag scale factors. There is one nuisance parameter for each variation. Both shape and normalisation are affected.

**The normalisation of the simulated backgrounds.** The normalisations of the several background sources are assumed to have an uncertainty of 30%. This value reflects the theoretical uncertainties on the corresponding cross sections, scaled up by a factor of two (or more) to account for possible limitations of the simulated processes, potentially unnoticed given the absence of relevant measurements in the phase space of the analysis.

**The NPL background estimation**: The shape-related uncertainties on the data-driven backgrounds involving NPL are estimated by changing the isolation criteria used to determine the NPL sample. The shape variations of not-prompt muons and electrons are two different nuisance parameters.
• The scale and PDF uncertainties for simulated signal (tZq) and background processes. These uncertainties affect the shape of the signal as well as the shape and normalisation of the simulated background samples, except for tWZ, for which only normalisation uncertainties from scale and PDF were considered.
  - The renormalisation and factorisation scales at the matrix element level are varied by factors of 1/2 and 2.
  - The renormalisation and factorisation scales at the parton shower level are varied by factors of 1/2 and 2; this uncertainty is only estimated for the signal sample.
  - The PDF uncertainties are estimated following the PDF4LHC recommendations, as the RMS of the results from 100 variations of the NNPDF.

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The dominant systematic uncertainties arise from the normalisation of the NPL background, the scale variations at the parton shower level, the b-tagging efficiency, and the normalisation of the tZ background.

7 Results

The tool used for this statistical analysis [42] is based on the ROOSTATS [43] framework. The analysis is performed building a binned likelihood function

\[ L(\text{data}|\mu, \theta) = \sum_i \frac{(\mu s_i(\theta) + b_i(\theta))^N_i}{N_i!} \exp -\mu s_i(\theta) - b_i(\theta), \] (2)

where \( N_i \) is the observed number of events in each bin and \( s_i(\theta) \) and \( b_i(\theta) \) are the expected signal and background yields in each bin, normalised as discussed in the previous sections, and taking into account all systematic uncertainties, represented by \( \theta \), as nuisance parameters. The simultaneous fit to the data templates in the four channels maximises \( L(\text{data}|\mu, \theta) \), from which the measured cross section \( \sigma(t\ell^+\ell^-q) \) is extracted according to its relation to the signal strength

\[ \mu = \frac{\sigma(t\ell^+\ell^-q)}{\sigma^{\text{SM}}(t\ell^+\ell^-q)}. \] (3)

The reference cross section is \( \sigma^{\text{SM}}(t\ell^+\ell^-q) = 94.2 \text{ fb} \), for \( m_{\ell^+\ell^-} > 50 \text{ GeV} \) and with \( \ell \) standing for electrons, muons, or taus. The measurement implies an extrapolation from the considered phase space (Section 4), defined as containing three leptons (\( l'^+l'^-l' \) with \( l \) and \( l' \) denoting muons or electrons) in the final state, with t → lνb, and an additional constraint of \( m_{\ell^+\ell^-} \) being within 15 GeV of the Z boson mass. The acceptance, defined as the fraction of \( t\ell^+\ell^-q \) events fulfilling the event selection criteria, is estimated from the simulated tZq sample as 1.81%, combining the 1bjet, 2bjets, and 0bjet regions. All nuisance parameters are constrained in the fit.

The post-fit distributions of the three variables used as templates in the measurement are shown in Fig. 5. Although the fit is performed using templates for each channel individually, the figure displays the combination of the four channels.

Table 1 shows the post-fit yields, separately for each channel, in the 1bjet region. The last two rows show the total number of predicted (“Total”) and observed (“Data”) events. The last column displays the ratio between the pre- and post-fit predicted yields, accounting for the post-fit systematic uncertainties. The fit constrains the normalisation of the background processes, yielding post-fit normalisations relatively close to the pre-fit values for most of the background sources. The event yields for the WZ + light flavour jets background preferred by
the fit is less than 3 σ away from the SM prediction. This feature, that may be attributed to the somewhat worse description of the data by the simulation for some bins of jet multiplicity \cite{44}, does not affect the measurement, as verified in several checks. First, the predicted shapes of the kinematic variables relevant to the analysis were verified to describe the data well in the WZ+light flavour enriched region. The analysis was also repeated increasing the uncertainty on the WZ+light flavour component to 50%, leaving the results unchanged within about half a percent. Finally the WZ+light flavour yield was fit simultaneously with the NPL background yields using the 0bjet only, and the resulting $N_{\text{obs}}/N_{\text{pred}}$ scale factor was found to be $0.73 \pm 0.11$, in good agreement with the results of Table 1. The expected number of tZq events in the 1bjet region is 32.3. The 0bjet and 2bjets control regions (not shown) also contain tZq events, with predicted yields around 23 and 19 events, respectively.

<table>
<thead>
<tr>
<th>Process</th>
<th>eee</th>
<th>eμ</th>
<th>μμ</th>
<th>μμμ</th>
<th>All channels</th>
<th>$N_{\text{obs}}/N_{\text{pred}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>tZq</td>
<td>5.0±1.5</td>
<td>6.6±1.9</td>
<td>8.5±2.5</td>
<td>12.3±3.6</td>
<td>32.3±5.0</td>
<td>–</td>
</tr>
<tr>
<td>tZ</td>
<td>3.7±0.7</td>
<td>4.7±0.9</td>
<td>6.1±1.2</td>
<td>8.0±1.5</td>
<td>22.4±2.2</td>
<td>0.9±0.2</td>
</tr>
<tr>
<td>tW</td>
<td>0.3±0.1</td>
<td>0.3±0.1</td>
<td>0.7±0.2</td>
<td>0.6±0.2</td>
<td>1.9±0.3</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>Z Z</td>
<td>4.8±1.3</td>
<td>3.2±0.9</td>
<td>9.0±2.5</td>
<td>7.8±2.2</td>
<td>24.7±3.6</td>
<td>1.3±0.3</td>
</tr>
<tr>
<td>WZ+b</td>
<td>3.0±0.9</td>
<td>3.4±1.1</td>
<td>4.6±1.4</td>
<td>5.5±1.7</td>
<td>16.6±2.6</td>
<td>1.0±0.2</td>
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<tr>
<td>WZ+c</td>
<td>9.0±2.4</td>
<td>13.7±3.7</td>
<td>18.0±4.9</td>
<td>24.2±6.5</td>
<td>64.8±9.3</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>WZ+light</td>
<td>12.2±1.6</td>
<td>16.6±2.0</td>
<td>22.4±2.8</td>
<td>29.1±3.4</td>
<td>80.3±5.1</td>
<td>0.7±0.1</td>
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<tr>
<td>tH</td>
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<td>1.0±0.3</td>
<td>1.5±0.4</td>
<td>4.0±0.6</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>tWZ</td>
<td>1.0±0.3</td>
<td>1.3±0.4</td>
<td>1.7±0.5</td>
<td>2.4±0.7</td>
<td>6.5±1.0</td>
<td>1.0±0.2</td>
</tr>
<tr>
<td>NPL: electrons</td>
<td>19.2±3.1</td>
<td>0.6±0.1</td>
<td>17.9±2.8</td>
<td>–</td>
<td>37.7±4.2</td>
<td>–</td>
</tr>
<tr>
<td>NPL: muons</td>
<td>–</td>
<td>7.2±2.3</td>
<td>31.1±9.9</td>
<td>15.3±4.9</td>
<td>53.6±11.3</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>58.8±4.8</td>
<td>58.4±5.5</td>
<td>120.9±12.4</td>
<td>106.6±10.1</td>
<td>344.8±17.6</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>56</td>
<td>58</td>
<td>104</td>
<td>125</td>
<td>343</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Observed and expected (post-fit) yields for each production process in the 1bjet region. The yields of columns 2–5 correspond to each channel, and that of column 6 displays the total for all channels. The last column displays the ratio between post- and pre-fit yields.

The observed tZq signal strength is
\[
\mu = 1.31^{+0.35}_{-0.33} \text{ (stat)}^{+0.31}_{-0.25} \text{ (syst),}
\]
from which, using the reference NLO cross section, the measured cross section is derived to be
\[ \sigma(t\ell^+\ell^-q) = 123^{+33}_{-31} \text{(stat)}^{+29}_{-23} \text{(syst)} \text{ fb}, \]
for \( m_{t\ell^+\ell^-} > 50 \text{ GeV} \), where \( \ell \) stands for electrons, muons, and taus. The precision of the measurement is limited by the statistical uncertainty (stat), which is larger than the sum of all systematic uncertainties (syst). The corresponding observed (expected) significance is 3.7 (3.1), with a p-value of 0.0001. The 68% CL of the expected significance is [1.4,5.9].

The analysis was tested against potential biases coming from the input background yields. Firstly, the analysis was repeated to measure simultaneously the tZq and ttZ cross sections, in addition to the determination of the NPL background normalisation. The tZq signal strength increases by less than 1%, while the observed and expected significances decrease by about 1%. Then, the not-prompt muon and electron normalisations were fixed to their input values, described as the first step in Sec. 5.2, and allowed to vary in the fit as Gaussian uncertainties of 100%. In this case both the tZq signal strength and the significances increase by about 10%, while the uncertainties on the signal strength increase by about 5%. Additionally, the measurement was repeated individually for each channel. The measured signal strengths are 1.32^{+1.14}_{-0.98}, 0.66^{+0.78}_{-0.66}, 0.01^{+0.97}_{-0.01}, and 1.22^{+0.75}_{-0.63} for the eee, e\mu, \mu\mu, and \mu\mu\mu channels, respectively.

The highest observed (expected) significance are 2.07 (1.94) for the \mu\mu\mu channel.

### 8 Summary

The associated production cross section of a top quark and a Z boson is measured using data from pp collisions at 13 TeV collected by the CMS experiment. The measurement uses events containing three charged leptons in the final state. Evidence for tZq production is found with an observed (expected) significance of 3.7 (3.1). The cross section is measured to be \[ \sigma(t\ell^+\ell^-q) = 123^{+33}_{-31} \text{(stat)}^{+29}_{-23} \text{(syst)} \text{ fb}, \]
compatible with the NLO SM prediction of 94.2 ± 3.1 fb.

### References


