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Measurement of the top quark pair production cross section in dilepton final states containing one τ lepton in pp collisions at $\sqrt{s} = 13$ TeV



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Abstract: The cross section of top quark pair production is measured in the $\mathrm{t\bar{t}} \to (\ell\nu_\ell)(\tau_\mathrm{h}\nu_\tau)\mathrm{b\bar{b}}$ final state, where τ_h refers to the hadronic decays of the τ lepton, and ℓ is either an electron or a muon. The data sample corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ collected in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ with the CMS detector. The measured cross section is $\sigma_{\mathrm{t\bar{t}}} = 781 \pm 7\,(\mathrm{stat}) \pm 62\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}$, and the ratio of the partial width $\Gamma(\mathrm{t} \to \tau\nu_\tau\mathrm{b})$ to the total decay width of the top quark is measured to be $0.1050 \pm 0.0009\,(\mathrm{stat}) \pm 0.0071\,(\mathrm{syst})$. This is the first measurement of the $\mathrm{t\bar{t}}$ production cross section in proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ that explicitly includes τ leptons. The ratio of the cross sections in the $\ell\tau_\mathrm{h}$ and $\ell\ell$ final states yields a value $R_{\ell\tau_\mathrm{h}/\ell\ell} = 0.973 \pm 0.009\,(\mathrm{stat}) \pm 0.066\,(\mathrm{syst})$, consistent with lepton universality.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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JHEP02(2020)191

Contents

1 Introduction 1

2 The CMS detector 2

3 Event simulation 2

4 Event reconstruction and selection 3

5 Event categories and fit procedure 5

6 Background estimate 7

7 Systematic uncertainties 8

8 Results 10

9 Summary 14

The CMS collaboration 21

JHEP02(2020)191

1 Introduction

In proton-proton (pp) collisions at the CERN LHC, top quarks are produced mainly in pairs ($\mathrm{t\bar{t}}$) and subsequently decay to b quarks and W bosons: $\mathrm{pp} \to \mathrm{t\bar{t}} \to \mathrm{W^{+}bW^{-}\bar{b}}$. The decay modes of the two W bosons determine the observed event signature. The dilepton decay channel denotes the case where both W bosons decay leptonically. In this paper, we consider the process $\mathrm{t\bar{t}} \to (\ell\nu_{\ell})(\tau\nu_{\tau})\mathrm{b\bar{b}}$, where one W boson decays into $\ell\nu_{\ell}$ where ℓ is either an electron (e) or a muon (μ), and the other into a tau lepton and a neutrino ($\tau\nu_{\tau}$). The expected fraction of events in this final state corresponds to $\approx$4/81 ($\approx$5%) of all $\mathrm{t\bar{t}}$ decays, i.e. equivalent to the fraction of all light dilepton channels (ee, $\mu\mu$, eμ).

Recent checks of lepton flavour universality violation [1–8] sparked a renewed interest towards measurements involving τ leptons, owing to a potential disagreement with standard model (SM) predictions. The $\mathrm{t} \to (\tau\nu_{\tau})\mathrm{b}$ decay exclusively involves third-generation leptons and quarks which, owing to their large masses, may be particularly sensitive to beyond SM contributions. For example, the existence of a charged Higgs boson [9–12] may give rise to anomalous τ lepton production that could be observed in this decay channel.

This is the first measurement of the $\mathrm{t\bar{t}}$ production cross section in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ that explicitly includes τ leptons. The data sample was collected in 2016 with the CMS detector at the LHC and corresponds to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$. The τ lepton is identified through its visible decay products, either hadrons (τ_{h}) or leptons

(τ_ℓ), with the corresponding branching fractions $\mathcal{B}(\tau_h \to \text{hadrons} + \nu_\tau) \approx 65\%$ and $\mathcal{B}(\tau_\ell \to \ell\,\nu_\ell\nu_\tau) \approx 35\%$. In the first case, the τ_h decays into a narrow jet with a distinct signature, whereas the leptonic decays are difficult to distinguish from prompt electron or muon production. In this measurement, the signal includes only τ leptons that decay hadronically, and ℓ does not include leptons from τ decays. The dominant background contribution comes from events where a jet is misidentified as a τ_h, mostly from $t\bar{t}$ lepton+jets events, i.e. $t\bar{t} \to (\ell\nu_\ell)(q\bar{q}')b\bar{b}$. The cross section is measured by performing a profile likelihood ratio (PLR) fit [13] to the transverse mass of the system containing the lepton (e or μ) and the missing transverse momentum, in two kinematic categories of the selected events for each of the $e\tau_h$ and $\mu\tau_h$ final states. The cross section is measured in the fiducial phase space of the detector and also extrapolated to the full phase space. The ratio of the cross sections in the $\ell\tau$ and light dilepton [14] final states $\sigma_{t\bar{t}}(\ell\tau)/\sigma_{t\bar{t}}(\ell\ell)$, and the ratio of the partial to the total decay width of the top quark $\Gamma(t \to \tau\nu_\tau b)/\Gamma_{\text{total}}$ are evaluated.

This paper is organized as follows: the CMS detector layout is briefly described in section 2; details about the simulated event samples used in the data analysis are provided in section 3; section 4 covers the event reconstruction and the event selection; the event categorization and the fit procedures are described in section 5; the background determination procedure is given in section 6; the description of the systematic uncertainties is presented in section 7; measurements of the cross sections, and the ratio of the partial to the total $t\bar{t}$ decay width are discussed in section 8; and the results are summarized in section 9.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections, covering $0 < \varphi < 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, providing reliable measurement of the momentum imbalance in the plane transverse to the beams. A two-level trigger system [15] selects the most interesting pp collision events for use in physics analysis. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [16].

3 Event simulation

The analysis makes use of simulated samples of $t\bar{t}$ events, as well as other processes that result in reconstructed τ leptons in the final state. These samples are used to design the event selection, to calculate the acceptance for $t\bar{t}$ events, and to estimate most of the backgrounds in the analysis.

JHEP02(2020)191

Signal $\mathrm{t\bar{t}}$ events are simulated with the POWHEG event generator (v2) [17–21] at next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD). The parton showers are modelled using PYTHIA (v8.2) [22] with the CUETP8M2T4 underlying event (UE) tune [23]. The background samples used in the measurement of the cross section are simulated with POWHEG and MADGRAPH5_aMC@NLO (v2.2.2) [24]. The MADGRAPH5_aMC@NLO generator with MLM matching [25] is used for the simulation of W boson production in association with jets (W+jets), and Drell-Yan (DY) production in association with jets at leading-order (LO) accuracy. Here, only the leptonic decays of DY events and W bosons are simulated, and up to four additional jets are included. The diboson processes are produced with NLO accuracy: WW with POWHEG, WZ and ZZ with MADGRAPH5_aMC@NLO with FxFx matching [26]. The POWHEG generator is used for the simulation of t-channel single top quark production and single top quark production associated with a W boson (tW) [27, 28]. The single top quark s-channel sample is produced with MADGRAPH5_aMC@NLO at NLO accuracy with FxFx matching scheme. The simulated events are produced with a top quark mass of $m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$. The generated events are subsequently processed with PYTHIA using the underlying event tune CUETP8M1 to provide the showering of the partons, and to perform the matching of the soft radiation with the contributions from direct emissions included in the matrix-element (ME) calculations. The default parton distribution functions (PDFs) are the NNPDF3.0 [29]. The τ decays are simulated with PYTHIA, which correctly accounts for the τ lepton polarization in describing the kinematic properties of the decay. The CMS detector response is simulated with GEANT4 [30]. Additional pp interactions in the same or nearby bunch crossings (pileup, PU) are superimposed on the hard collision. Simulated events are reweighted to match the distribution of the number of pileup collisions per event in data. This distribution is derived from the instantaneous luminosity and the inelastic cross section [31].

The next-to-next-to-leading-order (NNLO) expected SM $\mathrm{t\bar{t}}$ pair production cross section of $832^{+20}_{-29}\,(\mathrm{scale}) \pm 35\,(\mathrm{PDF}+\alpha_S)\,\mathrm{pb}$ [32] ($m_{\mathrm{t}} = 172.5\,\mathrm{GeV}$) is used for the normalization of the number of $\mathrm{t\bar{t}}$ events in the simulation. The first uncertainty includes the uncertainties in the factorization and renormalization scales, while the second is associated with possible choices of PDFs and the value of the strong coupling constant (α_S). The proton structure is described by the CT14 (NNLO) PDF set with the corresponding PDF and α_S uncertainties [33]. The W+jets and DY+jets backgrounds are normalized to their NNLO cross sections calculated with FEWZ (v3.1) [34]. The t-channel and the s-channel single top quark production are normalized to the NLO calculations obtained from HATHOR (v2.1) [35, 36]. The production of tW is normalized to the NNLO calculation [37, 38]. Finally, the production of diboson pairs is normalized to the NLO cross section prediction calculated with MCFM [39, 40] (v7.0).

4 Event reconstruction and selection

The signal event topology is defined by the presence of two b quark jets from the top quark decays, one W boson decaying leptonically into $\mathrm{e\nu}$ or $\mu\nu$, and a second W boson decaying into $\tau_{\mathrm{h}}\nu$. In each event, all objects are reconstructed with a particle-flow (PF)

JHEP02(2020)191

algorithm [41]. This algorithm combines the information from all subdetectors to identify and reconstruct all types of particles in the event, namely charged and neutral hadrons, photons, muons, and electrons, together referred to as PF objects. These objects are used to construct a variety of higher-level objects and observables, including jets and missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$), which is the negative vector sum of transverse momenta of all reconstructed PF objects. Parameters of jets and the tracks associated with jets provide input variables for b tagging discriminators. The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is taken to be the primary pp interaction vertex. Jets are reconstructed by clustering PF objects with the anti-k_{T} [42] jet algorithm with a distance parameter $R = 0.4$.

Electron or muon candidates are required to originate from the primary vertex, pass quality selection criteria, and be isolated relative to other activity in the event. The relative isolation is based on PF objects within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.4$ around the electron or muon track, and defined as $I_{\mathrm{rel}} = (E_{\mathrm{ch}} + E_{\mathrm{nh}} + E_{\mathrm{ph}} - 0.5\,E_{\mathrm{ch}}^{\mathrm{PU}})/p_{\mathrm{T}}$, where E_{ch} is the transverse energy deposited by charged hadrons from the primary vertex, E_{nh} and E_{ph} are the respective transverse energies of the neutral hadrons and photons, and $0.5\,E_{\mathrm{ch}}^{\mathrm{PU}}$ is the estimation of the contribution of neutral particles from pileup vertices, calculated as half of the energy of the charged particles from pileup; p_{T} is the electron or muon transverse momentum. Electron candidates with $I_{\mathrm{rel}} < 0.0588$ in the barrel or $I_{\mathrm{rel}} < 0.0571$ in the endcaps are considered isolated. The muon candidate is isolated if $I_{\mathrm{rel}} < 0.15$ in either the barrel or the endcaps. The lepton isolation requirements are used to suppress backgrounds from multijet production. The charge misidentification probability for electrons and muons is less than 0.5% and 0.1%, respectively, and is measured from Z boson decays and simulation [43–45].

Hadronic τ lepton decays are reconstructed with the hadron-plus-strips (HPS) algorithm [46], which starts from reconstructed jets. In each jet, a charged hadron is combined with other nearby charged hadrons or photons to identify the decay modes. The identification of π^0 mesons is enhanced by clustering electrons and photons in "strips" along the track bending direction to take into account possible broadening of calorimeter signatures by early showering photons. The τ_{h} candidates are selected from the following combinations of charged hadrons and strips that correspond to the τ decay modes: single hadron, hadron plus a strip, hadron plus two strips, and three hadrons. A multivariate analysis of these HPS τ_{h} candidates is used to reduce the contamination from quark and gluon jets. A boosted decision tree is trained using a sample of DY events with τ_{h} decays as signal and a sample of QCD multijet events as background, both from simulation. Input variables include the multiplicity and the transverse momenta of electron and photon candidates in the vicinity of the τ_{h}, the kinematic properties of hadrons and strips, and the τ_{h} lifetime information, such as the impact parameter of the leading track and the significance of the length of flight to the secondary vertex of the τ_{h} candidates with three charged hadrons. Additional requirements are applied to discriminate genuine τ_{h} leptons from prompt electrons and muons. The τ_{h} charge is taken as the sum of the charges of the corresponding charged hadrons. The misidentification probability for the charge is less than 1% and it is estimated from $\mathrm{Z} \to \tau\tau \to \mu\tau_{\mathrm{h}}$ data events with same-charge μ and τ_{h}. The τ_{h} identification

JHEP02(2020)191

efficiency of this algorithm is estimated to be approximately 60% for $p_T > 20$ GeV, and it is measured in a sample enriched in $Z \to \tau\tau \to \mu\tau_h$ data events with a "tag-and-probe" technique [46]. The corresponding probability for generic hadronic jets to be misidentified as τ_h is less than 1% [46].

For the $e\tau_h$ ($\mu\tau_h$) final state, data are collected with a trigger requiring at least one isolated electron (muon) with a threshold of $p_T > 27$ (24) GeV.

Events are selected by requiring one isolated electron (muon) with transverse momentum $p_T > 30$ (26) GeV and $|\eta| < 2.4$, at least two jets with $p_T > 30$ GeV and $|\eta| < 2.5$, and exactly one τ_h candidate with $p_T > 30$ GeV and $|\eta| < 2.4$. The τ_h candidate and the selected lepton are required to have opposite electric charges (OC). Electrons or muons are required to be separated from any jet and from the τ_h candidate in the η-φ plane by a distance $\Delta R > 0.4$. Events with any additional loosely isolated electron (muon) of $p_T > 15$ (10) GeV are rejected. An electron is considered loosely isolated if $I_{rel} < 0.0994$ in the barrel or $I_{rel} < 0.107$ in the endcaps. A muon is loosely isolated if $I_{rel} < 0.25$ in either the barrel or the endcaps. At least one jet is required to be identified as originating from b quark hadronization ("b tagged"). The b tagging algorithm used ("CSVv2" in ref. [47]) combines the information of displaced tracks and secondary vertices associated with the jet in a multivariate technique. The working point selected provides a b tagging efficiency of about 66% with a corresponding light-flavour misidentification rate of 1%. The selected events exhibit good agreement between the observed data and the expectation, as shown in figure 1 for the p_T distribution of the τ_h candidate. The dominant background contribution comes from other $t\bar{t}$ decays, mostly from lepton+jets final states where a jet is misidentified as a τ_h candidate.

5 Event categories and fit procedure

The $t\bar{t}$ production cross section is extracted from a PLR fit of the binned distribution of the transverse mass of the lepton and p_T^{miss} in two kinematic event categories, for each of the $e\tau_h$ and $\mu\tau_h$ final states. The transverse mass is defined as $m_T = \sqrt{2|\vec{p}_T^{\,\ell}||\vec{p}_T^{\,miss}|(1 - \cos\Delta\varphi)}$, where $\Delta\varphi$ is the azimuthal angle difference between the lepton transverse momentum vector, $\vec{p}_T^{\,\ell}$, and $\vec{p}_T^{\,miss}$. The m_T distribution provides separation between signal and background processes (as shown in figure 2) and does not significantly depend on p_T and η of the τ candidate, or other jet characteristics in the kinematic ranges of this study. Two event categories are defined according to the kinematic properties of jets in the event. In order to discriminate against the main background of misidentified τ_h from the $t\bar{t}$ lepton+jets process, the constraints from top quark and W boson masses in the decay $t \to bW \to b(q\bar{q}')$ are used. Jet triplets are constructed for each combination of one b-tagged jet and two untagged jets, chosen from all jets in the event, including the τ_h candidate. The distance parameter for each triplet is calculated as $D_{jjb} = \sqrt{(m_W - m_{jj})^2 + (m_t - m_{jjb})^2}$, where $m_t = 172.5$ GeV and $m_W = 80.385$ GeV are, respectively, the masses of the top quark and of the W boson [48], m_{jj} is the invariant mass of the two untagged jets, and m_{jjb} is the invariant mass of the jet triplet. The event is assigned to the "signal-like" category if there is only one untagged jet, or if the minimum parameter value D_{jjb}^{min} is larger than 60 GeV.

JHEP02(2020)191

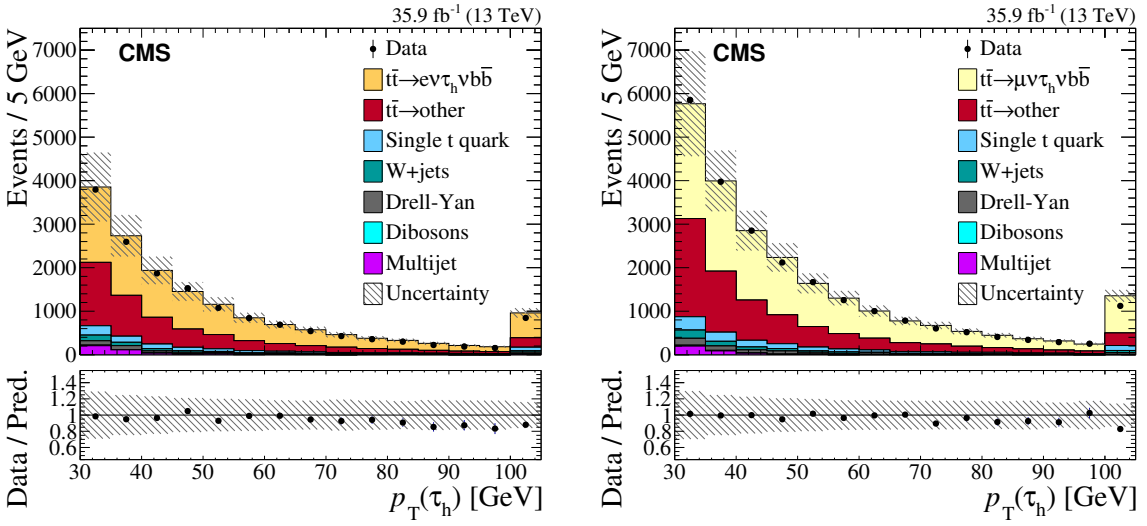


Figure 1. The τ_h p_T distributions for events of the $e\tau_h$ (left) and $\mu\tau_h$ (right) final states observed prior to fitting. Distributions obtained from data (filled circles) are compared with simulation (shaded histograms). The last bin includes overflow events. The simulated contributions are normalized to the cross section values predicted in the SM. The main processes are shown: the signal, the other $t\bar{t}$ processes grouped together, single top quark production, W+jets, DY processes, diboson, and multijet production. The ratio of the data to the total SM prediction is shown in the lower panel. The hatched bands indicate the systematic uncertainties and the statistical uncertainties of all simulated samples. Statistical uncertainties on the data points are not visible because of the scale of the figure.

Otherwise, it is assigned to the "background-like" event category. The threshold of 60 GeV provides an optimal separation of signal and background event categories, together with a maximization of the yields in each of the two categories in order to reduce the statistical uncertainties. In the fit, the two event categories provide an additional constraint on the background processes independent from the details of the m_T distribution.

The cross section is derived from the signal strength measured in the fit, i.e. its ratio to the value expected in the SM. It is estimated for both event categories, in each of the $e\tau_h$ and $\mu\tau_h$ final states. The expected number of events in a given bin of the m_T distribution is parametrized as a function of signal strength and nuisance parameters. The nuisance parameters encode the effects of systematic uncertainties. The signal strength is a free parameter in the fit. The fitted variables do not significantly depend on the kinematic properties of the τ lepton in the specific $t\bar{t}$ signal model considered here, i.e. $t\bar{t} \to (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$. The likelihood function is defined as a product of Poisson distributions of the expected number of events in bins of the m_T distribution and nuisance constraints. Based on the likelihood function, the PLR test statistic is defined as the ratio between the maximum of the likelihood for a given value of signal strength and the global maximum of the likelihood function. The effect of the systematic uncertainties on the signal strength is determined with this approach.

JHEP02(2020)191

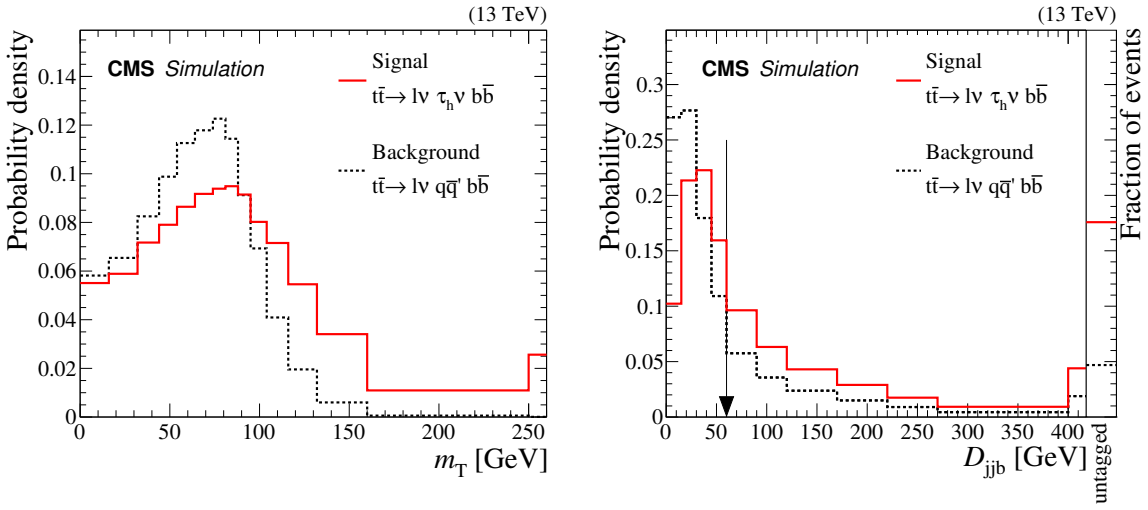


Figure 2. Comparison of the signal ($t\bar{t} \to \ell\nu_\ell\tau_h\nu_\tau b\bar{b}$) and the main background of misidentified τ_h ($t\bar{t} \to \ell\nu_\ell q\bar{q}'b\bar{b}$) in the shapes of the normalized distributions of the transverse mass m_T between the lepton and p_T^{miss} (left), and the D_{jjb}^{min} parameter (see text) of the event categories (right). In the m_T distribution, the signal may extend beyond the W boson mass endpoint because of the two-neutrino final state, whereas the background process cannot. The last bin in both distributions includes overflow events. In the D_{jjb}^{min} distribution, the downward arrow points at the threshold of the cut used (D_{jjb}^{min} >60 GeV), and the panel on the right shows the fraction of events in the "signal-like" category where there is only one untagged jet, which amounts to approximately 5% of all background events and 17% of all signal events.

6 Background estimate

The main background contribution comes from events with one lepton, significant p_T^{miss}, and three or more jets, dominated by the lepton+jets $t\bar{t}$ process, where one of the jets is falsely identified as a τ_h. Misidentified τ_h candidates also come from multijet and W+jet background processes. There is a small contribution from processes with genuine hadronic τ_h: tW single top quark production, $\tau_\ell\tau_h$ from DY decays, $t\bar{t} \to \tau_\ell\tau_h b\bar{b}$, and diboson processes. All processes, except multijet, are estimated from simulation after applying appropriate corrections. The pileup, trigger efficiencies, lepton identification, jet energy corrections, and b tagging efficiencies in the simulation are corrected with scale factors measured in separate publications [43, 45, 49], as described in section 7.

The τ_h misidentification contribution is determined by constraining the falsely identified τ_h in the overall fit to the data in the m_T distribution. In the fit, the event yields of the background processes with a misidentified τ_h are determined by adjusting the normalization of the shapes of the m_T distributions. The normalization factors are introduced as nuisance parameters with constraints determined from studies in other processes [46]. The corresponding uncertainties are discussed in section 7.

The background from the multijet processes is determined from data as it provides a more accurate description with a smaller statistical uncertainty. The shape of the m_T distribution is obtained from a sample of events containing lepton and τ_h candidates of

JHEP02(2020)191

the same charge (SC). It is estimated by subtracting from the data all other processes taken from simulation, including the fully hadronic final states in $\mathrm{t\bar{t}}$, single top quark, and dibosons. The m_{T} shapes for SC and OC events are the same within the uncertainties in a control region with a relaxed τ_{h} identification requirement, and in agreement with the simulation. The normalization is corrected by multiplying the SC m_{T} distribution by the OC-to-SC ratio, $f_{\mathrm{OC/SC}}$, as determined in a control region from events with a relaxed τ_{h} identification and an inverted lepton isolation requirement, where the multijet contribution is dominant. All other event selection requirements remain the same as in the main selection. The ratio is measured to be $f_{\mathrm{OC/SC}} = 1.05 \pm 0.05\,(\mathrm{stat} + \mathrm{syst})$, in agreement with simulation. As one of the processes with misidentified τ_{h}, the normalization of the multijet contribution is varied in the fit as a separate nuisance parameter, as described in section 7.

7 Systematic uncertainties

The main sources of systematic uncertainty are from τ_{h} identification and misidentification, b tagging, estimation of pileup in the pp collisions, jet energy scale (JES), and jet energy resolution (JER). Other sources of uncertainty are from lepton identification, trigger efficiency, and the calibration of the integrated luminosity. Theoretical uncertainties are also included in the event simulation. Uncertainties are applied in a coherent way to signal and background processes. The corresponding corrections and their uncertainties are measured in dedicated studies, which are described below.

The uncertainty in the efficiency of τ_{h} identification is 5% for all τ_{h} with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and is applied to all processes with a genuine τ_{h}. It is measured with a tag-and-probe technique in samples enriched in $\mathrm{Z} \to \tau_{\ell}\tau_{\mathrm{h}}$ events [46]. The τ_{h} charge confusion probability, estimated to be less than 1%, is considered a part of the τ_{h} identification efficiency uncertainty. The correction to the reconstructed energy of the τ_{h} jet (τ energy scale) and the corresponding uncertainty is estimated in a fit of the data in distributions sensitive to the τ energy, such as the τ_{h} visible mass [46]. The dominant background contribution arises from processes where a jet is misidentified as τ_{h}, mainly lepton+jets $\mathrm{t\bar{t}}$, W+jets, and multijet production. The τ_{h} misidentification probability and its uncertainty in these processes are directly measured in the fit. The misidentification probability is varied within $\pm 50\%$ of the expected values in all processes with a jet falsely identified as the τ_{h} candidate. The variation covers the differences between expected and observed misidentification probabilities and the possible dependence on other kinematic properties of the τ_{h} candidate [46]. The misidentification probability is significantly constrained in the fit and is not the dominant source of the uncertainty in the final result.

The uncertainties related to b tagging (mistagging) efficiencies are estimated from a variety of control samples enriched in b quarks (c and light-flavour quarks) [47]; the data-to-simulation scale factors for b, c, and light-flavour jets are applied to the simulation and the corresponding uncertainties are included in the fit.

The uncertainties in the JES, JER, and $p_{\mathrm{T}}^{\mathrm{miss}}$ scales are estimated according to the prescription described in ref. [50]. The uncertainty in the JES is evaluated as a function of jet p_{T} and η. The JES and JER uncertainties are propagated to the $p_{\mathrm{T}}^{\mathrm{miss}}$ scale.

JHEP02(2020)191

The lepton trigger, identification, and isolation efficiencies are measured in data and simulation with a tag-and-probe method in $\mathrm{Z} \to \ell^+\ell^-$ events [43–45]. The simulated events are corrected with the corresponding data-to-simulation scale factors. The uncertainties in the scale factors are included as systematic uncertainties in the measurement.

The uncertainty in the integrated luminosity is estimated to be 2.5% [51].

The pileup distribution is estimated from the measured luminosity in each bunch crossing multiplied by the average total inelastic cross section. It is used to model the pileup in simulation with an uncertainty obtained by varying the inelastic pp cross section extracted from a control region by its uncertainty of ±4.6% [49].

The measurement includes the uncertainty in the modelling of the b quark fragmentation, which covers $\mathrm{e^+e^-}$ data [52–55] at the Z pole with the Bowler-Lund [56] and Peterson [57] parametrizations, and the uncertainties in the semileptonic b-flavoured hadron branching fractions according to their measured values [48]. An uncertainty in the modelling of the p_T distribution of the top quark in $\mathrm{t\bar{t}}$ processes is included to cover the difference between the predicted and observed spectra [58–61]. The fit is sensitive to the top quark p_T as it affects the shape of the m_T distribution. The top quark p_T variation also covers the slight trend of the τ_h p_T distribution.

The cross section is measured by the fit in the fiducial phase space of the detector. The fiducial cross section is extrapolated to the full phase space by correcting for the acceptance of the $\mathrm{t\bar{t}}$ signal process. The fit and the acceptance include the following modelling uncertainties: the renormalization and factorization scales, and PDFs including α_S. The uncertainty in the PDF is estimated by using the CT14 (NNLO) set as alternative PDFs. The renormalization and factorization scales in the ME calculations are varied independently by factors of 0.5 and 2.0 from their nominal values, and the envelope of the variations is included in the measurement. The scale is varied by factors of 0.5 and 2.0 in the parton shower (PS) simulation of final-state and initial-state radiation, FSR and ISR. The h_damp parameter regulating the real emissions in POWHEG (ME-PS matching) is varied from its central value of $1.58\,m_\mathrm{t}$ using samples with h_damp set to $0.99\,m_\mathrm{t}$ and $2.24\,m_\mathrm{t}$ ($m_\mathrm{t} = 172.5\,\mathrm{GeV}$), as obtained from tuning this parameter to $\mathrm{t\bar{t}}$ data at $\sqrt{s} = 8\,\mathrm{TeV}$ [62]. The underlying event tune is varied within its uncertainties [23, 62]. The effect of these uncertainties on the final state objects is included in the fit in the fiducial phase space by adding the corresponding systematic variations normalized to the nominal acceptance. Therefore, the measurement in the fiducial phase space is performed with the nominal acceptance and its uncertainties are only included in the extrapolation to the full phase space. The uncertainties in the fit are not correlated with the acceptance uncertainty in the extrapolation to the full phase space.

The theoretical uncertainties are implemented by reweighting the simulated events with corresponding scale factors. The differences between weighted and unweighted distributions are taken as the uncertainties in the modelling. Separate data sets with varied parameters are used for determining FSR, ISR, ME-PS matching, and underlying event uncertainties.

The impact of the systematic uncertainties on the measurement is given in table 2.

JHEP02(2020)191

	Number of events ($\pm$stat $\pm$ syst)			
	$e\tau_h$		$\mu\tau_h$	
Process	Background-like	Signal-like	Background-like	Signal-like
Signal				
$t\bar{t} \to (\ell\nu_\ell)(\tau_h\nu_\tau)b\bar{b}$	$3440 \pm 40 \pm 210$	$5320 \pm 40 \pm 360$	$5140 \pm 40 \pm 130$	$7890 \pm 50 \pm 280$
$t\bar{t}$ backgrounds				
$t\bar{t} \to (\ell\nu_\ell)(q\bar{q}')b\bar{b}$	$2450 \pm 30 \pm 1210$	$1610 \pm 20 \pm 830$	$3670 \pm 40 \pm 1810$	$2440 \pm 30 \pm 1260$
$t\bar{t} \to$ other	$390 \pm 10 \pm 70$	$510 \pm 10 \pm 80$	$580 \pm 10 \pm 110$	$760 \pm 20 \pm 120$
Other backgrounds				
Single t quark	$370 \pm 10 \pm 90$	$540 \pm 10 \pm 100$	$500 \pm 10 \pm 110$	$790 \pm 10 \pm 150$
Drell-Yan	$150 \pm 20 \pm 20$	$310 \pm 20 \pm 20$	$200 \pm 20 \pm 10$	$410 \pm 30 \pm 40$
Total	$7090 \pm 80 \pm 1230$	$8930 \pm 80 \pm 920$	$10\,490 \pm 90 \pm 1820$	$12\,970 \pm 90 \pm 1310$
Data	6787	8633	9931	13 085

Table 1. Expected and observed event yields in the $\ell\tau_h$ ($\ell = e, \mu$) final state for signal and background processes for an integrated luminosity of 35.9 fb^{-1}. Statistical and systematic uncertainties are shown. The expected prefit contributions of all processes are presented separately for background-like and signal-like event categories. The statistical uncertainties of the modelling are shown for the processes estimated from the simulation. The multijet contribution and the corresponding statistical uncertainties are estimated using data, as described in section 6.

8 Results

The event yields expected from the signal and background processes, as well as the observed event yields are summarized in table 1, for the signal-like and the background-like event categories (described in section 5) in each of the $e\tau_h$ and $\mu\tau_h$ final states. The observed event yields in data show good agreement with the prediction. The m_T distributions in the two categories of the selected events are shown in figure 3, for both the $e\tau_h$ and $\mu\tau_h$ final states. A good shape agreement is observed between the data and the expected sum of signal and background distributions.

Table 2 lists the systematic uncertainties in the signal strength after the fit. The effect of the uncertainties on the signal strength is estimated by a likelihood scan where only one nuisance parameter (or a group of them) is varied at once while the others are fixed to their nominal postfit values. The largest experimental uncertainties are from τ_h identification and misidentification, and pileup estimation. The largest theoretical uncertainties are due to the modelling of top quark p_T in $t\bar{t}$ processes, b quark fragmentation, and PS modelling (ISR and FSR).

JHEP02(2020)191

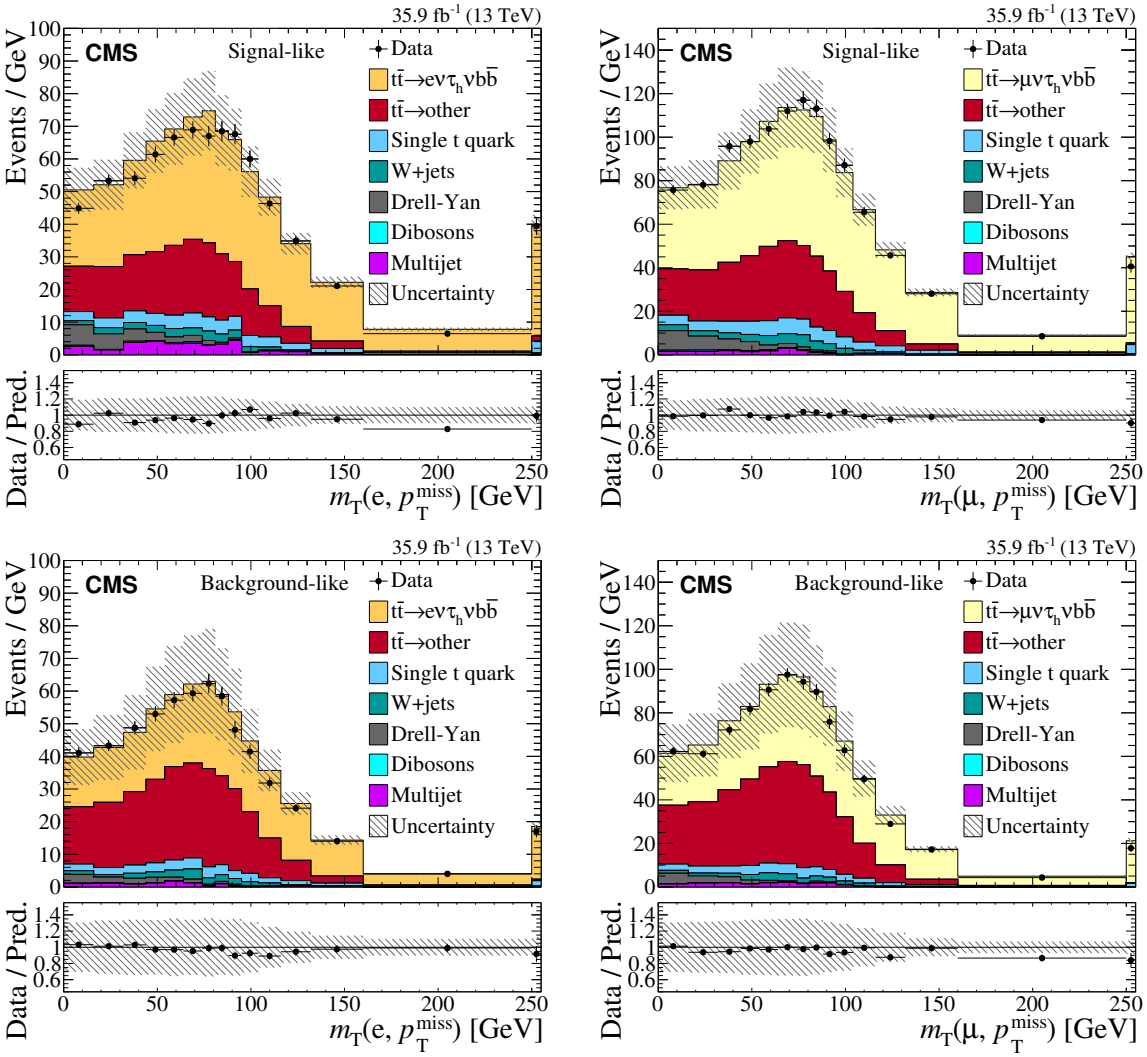


Figure 3. The transverse mass distributions between lepton (e or μ) and $p_{\mathrm{T}}^{\mathrm{miss}}$, m_{T}, in the signal-like (upper) and background-like (lower) event categories for the $\mathrm{e}\tau_{\mathrm{h}}$ (left) and $\mu\tau_{\mathrm{h}}$ (right) final states observed prior to fitting. Distributions obtained from data (filled circles) are compared with simulation (shaded histograms). The last bin includes overflow events. The simulated contributions are normalized to the cross section values predicted in the SM. The main processes are shown: the signal, the other $\mathrm{t\bar{t}}$ processes grouped together, single top quark production, W+jets, DY processes, diboson, and multijet production. The ratio of the data to the total SM prediction is shown in the lower panel. The vertical bars on the data points indicate the statistical uncertainties, the hatched band indicates the systematic uncertainties and the statistical uncertainties in all simulated samples.

JHEP02(2020)191

Source	Uncertainty [%]				
	$e\tau_h$	$\mu\tau_h$	Combined	Dileptons	Correlation
Experimental uncertainties					
τ_h jet identification	4.7	4.5	4.5	—	0
τ_h jet misidentification	2.2	2.3	2.3	—	0
Pileup	2.5	2.2	2.3	0.1	1
Lepton identification and isolation	1.8	1.1	1.2	2.0	1
b tagging efficiency	1.1	1.2	0.9	0.4	1
τ_h energy scale	0.7	0.8	0.8	—	0
Trigger efficiency	2.3	0.6	0.7	0.3	0
Drell-Yan background	0.4	0.4	0.6	0.9	1
$t\bar{t}$ background	1.0	0.8	0.6	0.2	0
tW background	0.6	0.5	0.5	1.1	1
W+jets background	0.1	0.4	0.5	0.2	0
Multijet background	0.1	0.5	0.4	<0.1	0
Jet energy scale	0.1	0.2	0.4	0.4	1
Jet energy resolution	0.6	0.3	0.1	0.4	1
Electron momentum scale	0.1	0.1	0.1	0.1	1
Muon momentum scale	0.1	0.1	0.1	0.1	1
Diboson background	<0.1	<0.1	<0.1	0.2	1
Theoretical uncertainties					
b fragmentation	2.3	2.0	2.4	0.7	1
Top quark p_T modelling	2.7	2.3	2.2	0.5	1
$t\bar{t}$ FSR scale	1.7	1.9	1.7	0.8	1
tW FSR scale	<0.1	<0.1	<0.1	0.1	1
$t\bar{t}$ ISR scale	1.7	1.6	1.5	0.4	1
tW ISR scale	<0.1	<0.1	<0.1	0.1	1
$t\bar{t}$ ME scale	1.1	1.2	1.1	0.2	1
tW ME scale	<0.1	<0.1	<0.1	0.2	1
Drell-Yan ME scale	<0.1	<0.1	<0.1	0.1	1
Semileptonic b hadron branching fraction	0.8	0.6	0.7	0.1	1
Underlying event	0.5	0.5	0.6	0.3	1
ME-PS matching	0.4	0.4	0.5	0.2	1
Colour reconnection	<0.1	<0.1	<0.1	0.3	1
PDFs	1.5	1.5	1.6	1.1	1
Normalization uncertainties					
Statistical	1.4	1.1	0.9	0.2	0
MC statistical	2.0	1.6	1.6	1.1	0
Integrated luminosity	2.5	2.5	2.5	2.5	1

JHEP02(2020)191

Source	Uncertainty [%]				
	$e\tau_h$	$\mu\tau_h$	Combined	Dileptons	Correlation
Extrapolation uncertainties					
$t\bar{t}$ ME scale	0.3	0.4	0.3	0.3	0
PDFs	1.2	1.4	1.3	1.0	0
Top quark p_T modelling	1.0	1.1	1.1	0.5	0
$t\bar{t}$ ISR scale	0.5	0.3	0.3	0.1	0
$t\bar{t}$ FSR scale	1.9	2.0	1.9	0.1	0
Underlying event	0.3	0.2	0.2	<0.1	0

Table 2. Systematic and statistical uncertainties determined from the fit to the data in the $e\tau_h$ and $\mu\tau_h$ final states, and their combination. Uncertainties are grouped by their origin: experimental, theoretical, normalization, and extrapolation. The uncertainties in the measurement in the dilepton final state [14] used in the partial width ratio estimate are also quoted (column "dileptons"), where the asymmetric extrapolation uncertainties are symmetrized by adding them in quadrature. As both measurements use the same data, some uncertainties in the $\ell\tau_h$ and light dilepton final states are correlated, as shown in the last column.

The fiducial cross section for the production of $t\bar{t}$ events is extracted from the acceptance region of kinematic phase space defined by the selection criteria described earlier. The estimate of the fiducial cross section includes the branching fractions of the final states, trigger, lepton identification and isolation, and the overall reconstruction efficiency. The cross sections in the fiducial phase space for the individual $e\tau_h$ and $\mu\tau_h$ final states, as well as the $\ell\tau_h$ combined final state, are measured from the PLR fit to be:

$$\sigma^{\text{fid}}_{t\bar{t}}(e\tau_h) = 133.2 \pm 1.9\,(\text{stat}) \pm 10.9\,(\text{syst}) \pm 3.3\,(\text{lumi})\,\text{pb}, \tag{8.1}$$

$$\sigma^{\text{fid}}_{t\bar{t}}(\mu\tau_h) = 135.2 \pm 1.5\,(\text{stat}) \pm 9.9\,(\text{syst}) \pm 3.4\,(\text{lumi})\,\text{pb}, \tag{8.2}$$

$$\sigma^{\text{fid}}_{t\bar{t}}(\ell\tau_h) = 134.5 \pm 1.2\,(\text{stat}) \pm 9.5\,(\text{syst}) \pm 3.4\,(\text{lumi})\,\text{pb}. \tag{8.3}$$

The acceptance $A_{t\bar{t}}$ is the fraction of signal events in the fiducial phase space, and it is determined with respect to all signal events in the nominal $t\bar{t}$ simulation. It includes kinematic selection cuts and is evaluated for the different signal final states as:

$$A_{t\bar{t}}(e\tau_h) = 0.1687 \pm 0.0004\,(\text{stat}) \pm 0.0060\,(\text{syst}), \tag{8.4}$$

$$A_{t\bar{t}}(\mu\tau_h) = 0.1756 \pm 0.0004\,(\text{stat}) \pm 0.0065\,(\text{syst}), \tag{8.5}$$

$$A_{t\bar{t}}(\ell\tau_h) = 0.1722 \pm 0.0003\,(\text{stat}) \pm 0.0062\,(\text{syst}), \tag{8.6}$$

where the systematic uncertainties include the uncertainties of the modelling as described in section 7 and listed as "Extrapolation uncertainties" in table 2.

JHEP02(2020)191

The cross section values in the full phase space are obtained from the extrapolation of the fiducial cross sections using the acceptances $A_{\mathrm{t\bar{t}}}$ estimated from the simulation:

$$\sigma_{\mathrm{t\bar{t}}}(\mathrm{e}\tau_{\mathrm{h}}) = 789 \pm 11\,(\mathrm{stat}) \pm 71\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}, \tag{8.7}$$

$$\sigma_{\mathrm{t\bar{t}}}(\mu\tau_{\mathrm{h}}) = 770 \pm 8\,(\mathrm{stat}) \pm 63\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}, \tag{8.8}$$

$$\sigma_{\mathrm{t\bar{t}}}(\ell\tau_{\mathrm{h}}) = 781 \pm 7\,(\mathrm{stat}) \pm 62\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})\,\mathrm{pb}. \tag{8.9}$$

The expected and observed dependence of the likelihood on the cross section in the full phase space in the $\ell\tau_{\mathrm{h}}$ combined final state are shown in figure 4. The result of the fit is consistent with the predicted SM $\mathrm{t\bar{t}}$ production cross section of $832^{+20}_{-29}\,(\mathrm{scale}) \pm 35\,(\mathrm{PDF}{+}\alpha_S)\,\mathrm{pb}$ [32]. Using simulated $\mathrm{t\bar{t}}$ samples with different m_{t} values, we find that the cross section changes by 1.5% per $\Delta m_{\mathrm{t}} = 1\,\mathrm{GeV}$.

The ratio of the cross section in the $\ell\tau_{\mathrm{h}}$ final state divided by the cross section measured in the dilepton final state in the same data-taking period [14] yields a value of $R_{\ell\tau_{\mathrm{h}}/\ell\ell} = 0.973 \pm 0.009\,(\mathrm{stat}) \pm 0.066\,(\mathrm{syst})$, consistent with unity as expected from lepton flavour universality. The relative systematic uncertainty in the ratio is 6.8%. About 5% comes from the uncertainties in the τ_{h} identification (4.5%) and misidentification probability in $\mathrm{t\bar{t}}$ events (2.3%). The rest comes from the other uncorrelated uncertainties in the ratio and the treatment of the correlated uncertainties in the calculation of the ratio. In particular, a small contribution comes from the uncertainties in the extrapolation to the full phase space that are considered uncorrelated because the two measurements extrapolate from different fiducial phase spaces. Also, the triggers are not the same.

The measurement also provides an estimate of the ratio of the partial to the total width of the top quark decay, $R_\Gamma = \Gamma(\mathrm{t} \to \tau\nu_\tau\mathrm{b})/\Gamma_{\mathrm{total}}$. The ratio is calculated as $R_\Gamma = \sigma_{\mathrm{t\bar{t}}}(\ell\tau_{\mathrm{h}})\mathcal{B}(\mathrm{W} \to \tau\nu_\tau)/\sigma_{\mathrm{t\bar{t}}}(\ell\ell)$, where the cross section measured in the $\ell\tau_{\mathrm{h}}$ final state is multiplied by the branching fraction $\mathcal{B}(\mathrm{W} \to \tau\nu_\tau)$ and divided by the inclusive $\mathrm{t\bar{t}}$ cross section measured in the dilepton final state [14]. The W boson branching fraction $\mathcal{B}(\mathrm{W} \to \tau\nu_\tau)$ that is included in the signal acceptance is cancelled out in the multiplication. Since both measurements are performed in the same data-taking period with the same reconstruction algorithms, the uncertainty in the ratio includes the correlations between common sources of uncertainties as indicated in table 2. The estimate yields the value $R_\Gamma = 0.1050 \pm 0.0009\,(\mathrm{stat}) \pm 0.0071\,(\mathrm{syst})$, improving over the previous measurements [48, 63, 64]. The result is dominated by the systematic uncertainty and it is consistent with the SM value of 0.1083 ± 0.0002 [48]. While in ref. [63] the partial width is evaluated for hadronic decays of τ leptons, here R_Γ is measured for all τ decays by using the $\mathcal{B}(\tau \to \tau_{\mathrm{h}}\nu_\tau) = 64.8 \pm 0.1\%$ branching fraction [48].

9 Summary

A measurement of the top quark pair production cross section in the $\mathrm{t\bar{t}} \to (\ell\nu_\ell)(\tau_{\mathrm{h}}\nu_\tau)\mathrm{b\bar{b}}$ channel, where ℓ is either an electron or a muon, is performed by CMS in proton-proton collisions at LHC, using a data sample corresponding to an integrated luminosity of $35.9\,\mathrm{fb}^{-1}$ obtained at $\sqrt{s} = 13\,\mathrm{TeV}$. Events are selected by requiring the presence of an electron

JHEP02(2020)191

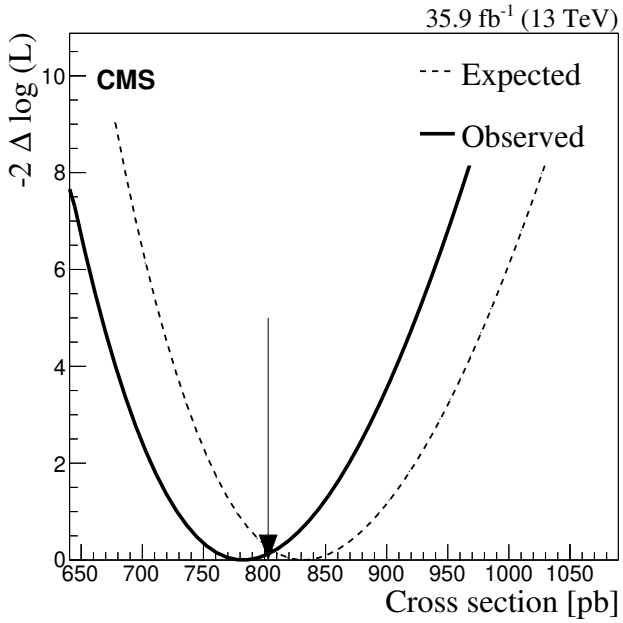


Figure 4. The expected and observed dependence of the likelihood on the total $\mathrm{t\bar{t}}$ cross section $\sigma_{\mathrm{t\bar{t}}}$. It is derived from the fiducial phase space by a simple extrapolation. The arrow points at the cross section measured in the light dilepton final state. The goodness of the fit determined with a Kolmogorov-Smirnov method yields a p value of 0.24.

or a muon, and at least three jets, of which at least one is b tagged and one is identified as a τ lepton decaying to hadrons (τ_{h}). The largest background contribution arises from $\mathrm{t\bar{t}}$ lepton+jets events, $\mathrm{t\bar{t}} \to (\ell\nu_\ell)(\mathrm{q\bar{q}}')\mathrm{b\bar{b}}$, where one jet is misidentified as the τ_{h}. The background contribution is constrained in a fit to the distribution of the transverse mass of the light lepton and missing transverse momentum system in two event categories, constructed according to the kinematic properties of the jets in the $\mathrm{t\bar{t}}$ lepton+jets final state. The signal enters as a free parameter without constraining the kinematic properties of the τ lepton. Assuming a top quark mass of 172.5 GeV, the measured total $\mathrm{t\bar{t}}$ cross section $\sigma_{\mathrm{t\bar{t}}}(\ell\tau_{\mathrm{h}}) = 781 \pm 7\,(\mathrm{stat}) \pm 62\,(\mathrm{syst}) \pm 20\,(\mathrm{lumi})$ pb is in agreement with the standard model expectation. This is the first measurement of the $\mathrm{t\bar{t}}$ production cross section in proton-proton collisions at $\sqrt{s} = 13$ TeV that explicitly includes hadronically decaying τ leptons, and it improves the relative precision with respect to the 7 and 8 TeV results [65, 66]. The higher precision is achieved through a shape fit to the kinematic distributions of the events, thus better constraining the backgrounds. The measurement of the ratio of the cross section in the $\ell\tau_{\mathrm{h}}$ final state to the light dilepton cross section [14] yields a value of $R_{\ell\tau_{\mathrm{h}}/\ell\ell} = 0.973 \pm 0.009\,(\mathrm{stat}) \pm 0.066\,(\mathrm{syst})$, consistent with lepton universality. The ratio of the partial to the total width of the top quark $\Gamma(\mathrm{t} \to \tau\nu_\tau\mathrm{b})/\Gamma_{\mathrm{total}} = 0.1050 \pm 0.0009\,(\mathrm{stat}) \pm 0.0071\,(\mathrm{syst})$ is measured with respect to the $\mathrm{t\bar{t}}$ inclusive cross section extrapolated from the light dilepton final state, improving the precision over the previous measurements [63, 64].

JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

References

[1] LHCb collaboration, *Test of lepton flavor universality by the measurement of the $B^0 \to D^{*-}\tau^+\nu_\tau$ branching fraction using three-prong τ decays*, *Phys. Rev.* **D 97** (2018) 072013 [arXiv:1711.02505] [INSPIRE].

[2] LHCb collaboration, *Search for lepton-universality violation in $B^+ \to K^+\ell^+\ell^-$ decays*, *Phys. Rev. Lett.* **122** (2019) 191801 [arXiv:1903.09252] [INSPIRE].

[3] BaBar collaboration, *Evidence for an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays*, *Phys. Rev. Lett.* **109** (2012) 101802 [arXiv:1205.5442] [INSPIRE].

[4] BaBar collaboration, *Measurement of an excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ decays and implications for charged Higgs bosons*, *Phys. Rev.* **D 88** (2013) 072012 [arXiv:1303.0571] [INSPIRE].

[5] S. Bifani, S. Descotes-Genon, A. Romero Vidal and M.-H. Schune, *Review of lepton universality tests in B decays*, *J. Phys.* **G 46** (2019) 023001 [arXiv:1809.06229] [INSPIRE].

[6] Belle collaboration, *Measurement of the branching ratio of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ relative to $\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell$ decays with hadronic tagging at Belle*, *Phys. Rev.* **D 92** (2015) 072014 [arXiv:1507.03233] [INSPIRE].

[7] Belle collaboration, *Measurement of the branching ratio of $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ relative to $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays with a semileptonic tagging method*, *Phys. Rev.* **D 94** (2016) 072007 [arXiv:1607.07923] [INSPIRE].

[8] Belle collaboration, *Measurement of the τ lepton polarization and $R(D^*)$ in the decay $\bar{B} \to D^*\tau^-\bar{\nu}_\tau$*, *Phys. Rev. Lett.* **118** (2017) 211801 [arXiv:1612.00529] [INSPIRE].

[9] A. Djouadi, *The anatomy of electro-weak symmetry breaking. II. The Higgs bosons in the minimal supersymmetric model*, *Phys. Rept.* **459** (2008) 1 [hep-ph/0503173] [INSPIRE].

[10] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [arXiv:1106.0034] [INSPIRE].

[11] CMS collaboration, *Search for charged Higgs bosons in the $H^\pm \to \tau^\pm\nu_\tau$ decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **07** (2019) 142 [arXiv:1903.04560] [INSPIRE].

[12] ATLAS collaboration, *Search for charged Higgs bosons decaying via $H^\pm \to \tau^\pm\nu_\tau$ in the τ+jets and τ+lepton final states with 36 fb^{-1} of pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS experiment*, *JHEP* **09** (2018) 139 [arXiv:1807.07915] [INSPIRE].

[13] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J.* **C 71** (2011) 1554 [*Erratum ibid.* **C 73** (2013) 2501] [arXiv:1007.1727] [INSPIRE].

[14] CMS collaboration, *Measurement of the $t\bar{t}$ production cross section, the top quark mass and the strong coupling constant using dilepton events in pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J.* **C 79** (2019) 368 [arXiv:1812.10505] [INSPIRE].

[15] CMS collaboration, *The CMS trigger system*, 2017 *JINST* **12** P01020 [arXiv:1609.02366] [INSPIRE].

[16] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

[17] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [hep-ph/0409146] [INSPIRE].

[18] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [arXiv:0709.2092] [INSPIRE].

[19] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [arXiv:1002.2581] [INSPIRE].

[20] J.M. Campbell, R.K. Ellis, P. Nason and E. Re, *Top-pair production and decay at NLO matched with parton showers*, *JHEP* **04** (2015) 114 [arXiv:1412.1828] [INSPIRE].

[21] S. Frixione, P. Nason and G. Ridolfi, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, *JHEP* **09** (2007) 126 [arXiv:0707.3088] [INSPIRE].

[22] T. Sjöstrand et al., *An introduction to PYTHIA* 8.2, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[23] P. Skands, S. Carrazza and J. Rojo, *Tuning PYTHIA* 8.1*: the Monash* 2013 *tune*, *Eur. Phys. J.* **C 74** (2014) 3024 [arXiv:1404.5630] [INSPIRE].

[24] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[25] J. Alwall et al., *Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions*, *Eur. Phys. J.* **C 53** (2008) 473 [arXiv:0706.2569] [INSPIRE].

[26] R. Frederix and S. Frixione, *Merging meets matching in MC@NLO*, *JHEP* **12** (2012) 061 [arXiv:1209.6215] [INSPIRE].

[27] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J.* **C 71** (2011) 1547 [arXiv:1009.2450] [INSPIRE].

[28] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO single-top production matched with shower in POWHEG: s- and t-channel contributions*, *JHEP* **09** (2009) 111 [*Erratum ibid.* **02** (2010) 011] [arXiv:0907.4076] [INSPIRE].

[29] NNPDF collaboration, *Parton distributions for the LHC run II*, *JHEP* **04** (2015) 040 [arXiv:1410.8849] [INSPIRE].

[30] GEANT4 collaboration, *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth.* **A 506** (2003) 250 [INSPIRE].

[31] CMS collaboration, *Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV*, *JHEP* **07** (2018) 161 [arXiv:1802.02613] [INSPIRE].

JHEP02(2020)191

[32] M. Czakon and A. Mitov, *Top++: a program for the calculation of the top-pair cross-section at hadron colliders*, *Comput. Phys. Commun.* **185** (2014) 2930 [arXiv:1112.5675] [INSPIRE].

[33] S. Dulat et al., *New parton distribution functions from a global analysis of quantum chromodynamics*, *Phys. Rev.* **D 93** (2016) 033006 [arXiv:1506.07443] [INSPIRE].

[34] Y. Li and F. Petriello, *Combining QCD and electroweak corrections to dilepton production in FEWZ*, *Phys. Rev.* **D 86** (2012) 094034 [arXiv:1208.5967] [INSPIRE].

[35] M. Aliev, H. Lacker, U. Langenfeld, S. Moch, P. Uwer and M. Wiedermann, *HATHOR: HAdronic Top and Heavy quarks crOss section calculatoR*, *Comput. Phys. Commun.* **182** (2011) 1034 [arXiv:1007.1327] [INSPIRE].

[36] P. Kant et al., *HatHor for single top-quark production: updated predictions and uncertainty estimates for single top-quark production in hadronic collisions*, *Comput. Phys. Commun.* **191** (2015) 74 [arXiv:1406.4403] [INSPIRE].

[37] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-*, *Phys. Rev.* **D 82** (2010) 054018 [arXiv:1005.4451] [INSPIRE].

[38] N. Kidonakis, *NNLL threshold resummation for top-pair and single-top production*, *Phys. Part. Nucl.* **45** (2014) 714 [arXiv:1210.7813] [INSPIRE].

[39] J.M. Campbell and R.K. Ellis, *MCFM for the Tevatron and the LHC*, *Nucl. Phys. Proc. Suppl.* **205-206** (2010) 10 [arXiv:1007.3492] [INSPIRE].

[40] J.M. Campbell, R.K. Ellis and C. Williams, *Vector boson pair production at the LHC*, *JHEP* **07** (2011) 018 [arXiv:1105.0020] [INSPIRE].

[41] CMS collaboration, *Particle-flow reconstruction and global event description with the CMS detector*, 2017 *JINST* **12** P10003 [arXiv:1706.04965] [INSPIRE].

[42] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [arXiv:0802.1189] [INSPIRE].

[43] CMS collaboration, *Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV*, 2015 *JINST* **10** P06005 [arXiv:1502.02701] [INSPIRE].

[44] CMS collaboration, *Electron and photon performance in CMS with the full* 2016 *data sample*, CMS-DP-2017-004, CERN, Geneva, Switzerland (2017).

[45] CMS collaboration, *Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P06015 [arXiv:1804.04528] [INSPIRE].

[46] CMS collaboration, *Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV*, 2018 *JINST* **13** P10005 [arXiv:1809.02816] [INSPIRE].

[47] CMS collaboration, *Identification of heavy-flavour jets with the CMS detector in pp collisions at* 13 *TeV*, 2018 *JINST* **13** P05011 [arXiv:1712.07158] [INSPIRE].

[48] Particle Data Group collaboration, *Review of particle physics*, *Phys. Rev.* **D 98** (2018) 030001 [INSPIRE].

[49] ATLAS collaboration, *Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV with the ATLAS detector at the LHC*, *Phys. Rev. Lett.* **117** (2016) 182002 [arXiv:1606.02625] [INSPIRE].

[50] CMS collaboration, *Jet energy scale and resolution in the CMS experiment in pp collisions at* 8 *TeV*, 2017 *JINST* **12** P02014 [arXiv:1607.03663] [INSPIRE].

JHEP02(2020)191

[51] CMS collaboration, *CMS luminosity measurements for the* 2016 *data taking period*, CMS-PAS-LUM-17-001, CERN, Geneva, Switzerland (2017).

[52] OPAL collaboration, *Inclusive analysis of the b quark fragmentation function in Z decays at LEP*, *Eur. Phys. J.* **C 29** (2003) 463 [hep-ex/0210031] [INSPIRE].

[53] ALEPH collaboration, *Study of the fragmentation of b quarks into B mesons at the Z peak*, *Phys. Lett.* **B 512** (2001) 30 [hep-ex/0106051] [INSPIRE].

[54] SLD collaboration, *Measurement of the b quark fragmentation function in Z^0 decays*, *Phys. Rev.* **D 65** (2002) 092006 [*Erratum ibid.* **D 66** (2002) 079905] [hep-ex/0202031] [INSPIRE].

[55] DELPHI collaboration, *A study of the b-quark fragmentation function with the DELPHI detector at LEP I and an averaged distribution obtained at the Z pole*, *Eur. Phys. J.* **C 71** (2011) 1557 [arXiv:1102.4748] [INSPIRE].

[56] M.G. Bowler, *e^+e^- production of heavy quarks in the string model*, *Z. Phys.* **C 11** (1981) 169 [INSPIRE].

[57] C. Peterson, D. Schlatter, I. Schmitt and P.M. Zerwas, *Scaling violations in inclusive e^+e^- annihilation spectra*, *Phys. Rev.* **D 27** (1983) 105 [INSPIRE].

[58] CMS collaboration, *Measurement of normalized differential $t\bar{t}$ cross sections in the dilepton channel from pp collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **04** (2018) 060 [arXiv:1708.07638] [INSPIRE].

[59] CMS collaboration, *Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at* 13 *TeV*, *Phys. Rev.* **D 95** (2017) 092001 [arXiv:1610.04191] [INSPIRE].

[60] CMS collaboration, *Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C 75** (2015) 542 [arXiv:1505.04480] [INSPIRE].

[61] CMS collaboration, *Measurement of the $t\bar{t}$ production cross section in the all-jets final state in pp collisions at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J.* **C 76** (2016) 128 [arXiv:1509.06076] [INSPIRE].

[62] CMS collaboration, *Investigations of the impact of the parton shower tuning in PYTHIA* 8 *in the modelling of $t\bar{t}$ at $\sqrt{s} = 8$ and* 13 *TeV*, CMS-PAS-TOP-16-021, CERN, Geneva, Switzerland (2016).

[63] ATLAS collaboration, *Measurements of the top quark branching ratios into channels with leptons and quarks with the ATLAS detector*, *Phys. Rev.* **D 92** (2015) 072005 [arXiv:1506.05074] [INSPIRE].

[64] CDF collaboration, *Study of top-quark production and decays involving a tau lepton at CDF and limits on a charged-Higgs boson contribution*, *Phys. Rev.* **D 89** (2014) 091101 [arXiv:1402.6728] [INSPIRE].

[65] CMS collaboration, *Measurement of the top quark pair production cross section in pp collisions at $\sqrt{s} = 7$ TeV in dilepton final states containing a τ*, *Phys. Rev.* **D 85** (2012) 112007 [arXiv:1203.6810] [INSPIRE].

[66] CMS collaboration, *Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV in dilepton final states containing one τ lepton*, *Phys. Lett.* **B 739** (2014) 23 [arXiv:1407.6643] [INSPIRE].

JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191

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JHEP02(2020)191