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Measurement of the $t\bar{t}$ production cross section using events in the eμ final state in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract The cross section of top quark–antiquark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV is measured by the CMS experiment at the LHC, using data corresponding to an integrated luminosity of 2.2 fb^{-1}. The measurement is performed by analyzing events in which the final state includes one electron, one muon, and two or more jets, at least one of which is identified as originating from hadronization of a b quark. The measured cross section is $815 \pm 9\,(\text{stat}) \pm 38\,(\text{syst}) \pm 19\,(\text{lumi})$ pb, in agreement with the expectation from the standard model.

1 Introduction

The measurement of the top quark–antiquark pair ($t\bar{t}$) cross section provides a test of the hadroproduction of top quark pairs as predicted by quantum chromodynamics (QCD). At the CERN LHC, measurements have been performed in many different decay channels and at three different proton–proton collision energies [1–24]. Precision measurements of these cross sections allow for a test of their energy dependence as predicted by QCD; they can also place constrains on the parton distribution functions (PDFs) [25]. In combination with some theory, they also provide unambiguous measurements of interesting quantities, such as the top quark pole mass [13,21], which is difficult to determine by other means. A detailed understanding of the production cross section is also required in searches for evidence of new physics beyond the standard model, as $t\bar{t}$ production is often the dominant background process. This is especially important if the signature for the new physics is similar to that of $t\bar{t}$ production [13,26]. This paper presents a measurement of the $t\bar{t}$ production cross section ($\sigma_{t\bar{t}}$) in the $e^{\pm}\mu^{\mp}$ decay channel using an event-counting method, based on observed yields. The analysis follows closely [12], and uses the full data set recorded by CMS at 13 TeV during 2015, which corresponds to an integrated luminosity of 2.2 fb^{-1}. This represents a factor of 50 increase in the amount of data over the original analysis and allows for more detailed studies of the experimental and theory uncertainties.

2 The CMS detector and Monte Carlo simulation

The CMS detector [27] has a superconducting solenoid in its central region that provides an axial magnetic field of 3.8 T. The silicon pixel and strip trackers cover $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ in pseudorapidity. The lead tungstate crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter are located inside the solenoid. These are used to identify electrons, photons and jets. Muons are measured in gas-ionization detectors 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 selects the most interesting pp collisions for offline 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. [27].

Different Monte Carlo (MC) event generators are used to simulate signal and background events. The next-to-leading-order (NLO) POWHEG (v2) [28,29] generator is used for $t\bar{t}$ events, with the top quark mass (m_t) set to 172.5 GeV. The NNPDF3.0 NLO [30] PDFs are used. For the reference $t\bar{t}$ sample, the events are interfaced with PYTHIA (v8.205) [31,32] with the CUETP8M1 tune [33,34] to simulate parton showering, hadronization, and the underlying event. Additional samples are produced by showering the events in the reference sample with HERWIG++ (v2.7.1) [35] or by generating events using MG5_aMC@NLO (v5_2.2.2) [36] interfaced with MADSPIN [37] to account for spin correlations in the decays of the top quarks, and using PYTHIA for parton showering and hadronization.

The MG5_aMC@NLO generator is also used to simulate W+jets events and Drell–Yan (DY) quark–antiquark anni-

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hilation into lepton-antilepton pairs through a virtual photon or a Z boson exchange; for these backgrounds the event yields are estimated from data. Single top quark events are simulated using POWHEG (v1) [38,39] and PYTHIA, and the event yields are normalized to the approximate next-to-next-to-leading order (NNLO) cross sections from Ref. [40]. The diagram removal approach [41] is used to handle the interference between the $\mathrm{t\bar{t}}$ and tW final states starting at NLO. The contributions from WW, WZ, and ZZ (referred to as "VV") processes are simulated with PYTHIA, and the event rates are normalized to the NLO cross sections from Ref. [42]. Other contributions from W and Z boson production in association with $\mathrm{t\bar{t}}$ events (referred to as "$\mathrm{t\bar{t}V}$") are simulated using MG5_aMC@NLO and PYTHIA. The simulated samples include additional interactions per bunch crossing (pileup), with the distribution matching that observed in data, with an average of about 11 collisions per bunch crossing.

The SM prediction for $\sigma_{\mathrm{t\bar{t}}}$ at 13 TeV is 832^{+20}_{-29} (scales) $\pm$ 35 (PDF+α_s) pb for $m_\mathrm{t} = 172.5$ GeV, as calculated with the TOP++ program [43] at NNLO in perturbative QCD, including soft-gluon resummation at next-to-next-to-leading-log order [44]. The first uncertainty reflects uncertainties in the factorization (μ_F) and renormalization (μ_R) scales. The second one is associated with possible choices of PDFs and the value of the strong coupling constant, following the PDF4LHC prescriptions [45,46], using the MSTW2008 68% confidence level NNLO [47,48], CT10 NNLO [49,50], and NNPDF2.3 5f FFN [51] PDF sets. The expected event yields for signal in all figures and tables are normalized to this cross section.

3 Event selection

In the SM, top quarks in pp collisions are mostly produced as $\mathrm{t\bar{t}}$ pairs, where each top quark decays predominantly to a W boson and a bottom quark. In $\mathrm{t\bar{t}}$ events where both W bosons decay leptonically, the final state contains two leptons of opposite electric charge and at least two jets coming from the hadronization of the bottom quarks.

At the trigger level, a combination of the single lepton and dilepton triggers is used. Events are required to contain either one electron with transverse momentum $p_\mathrm{T} > 12$ GeV and one muon with $p_\mathrm{T} > 17$ GeV or one electron with $p_\mathrm{T} > 17$ GeV and one muon with $p_\mathrm{T} > 8$ GeV. In addition, single-lepton triggers with one electron (muon) with $p_\mathrm{T} > 23$ GeV (20) are used in order to increase the efficiency. The efficiency for the combination of the single lepton and dilepton triggers is measured in data using triggers based on p_T imbalance in the event. The trigger efficiency is measured to be 0.99 ± 0.01 (combined statistical and systematic uncertainties) when the selection on the leptons described below is applied. The trigger in simulation is corrected using a multiplicative data-to-simulation scale factor (SF), given by the trigger efficiency measured in data with independent monitoring triggers.

The particle-flow (PF) event algorithm [52,53] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. Selected dilepton events are required to contain one isolated electron [54] and one isolated muon [55] with opposite electric charge and $p_\mathrm{T} > 20$ GeV and $|\eta| < 2.4$. Isolation requirements are based on the ratio of the scalar sum of the transverse momenta of all PF candidates, reconstructed inside a cone centered on the lepton, excluding the contribution from the lepton candidate. This isolation variable is required to be smaller than 7% (15%) of the electron (muon) p_T.

In events with more than one pair of leptons passing the selection, the two opposite-sign different-flavour leptons with the largest p_T are selected for further study. Events with W bosons decaying into τ leptons contribute to the measurement only if the τ leptons decay into electrons or muons that satisfy the selection requirements.

The efficiency of the lepton selection is measured using a "tag-and-probe" [56] method in a sample of same-flavour dilepton events, which is enriched in Z boson candidates. The measured p_T- and η-dependent values for the combined identification and isolation efficiencies average to about 80% for electrons and 90% for muons. To account for the difference in efficiencies determined using data and simulation, the event yield in simulation is corrected using p_T- and η-dependent SFs based on a comparison of lepton selection efficiencies in data and simulation. These have an average of 0.99 for electrons and 0.98 for muons.

In order to suppress backgrounds from DY production of τ lepton pairs with low invariant dilepton mass, $\mathrm{t\bar{t}}$ candidate events are further required to have a dilepton pair of invariant mass $m_{\mathrm{e}\mu} > 20$ GeV.

Jets are reconstructed from the PF particle candidates using the anti-k_t clustering algorithm [57,58] with a distance parameter of 0.4. The jet momentum is determined from the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole p_T spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from additional proton–proton interactions within the same or nearby bunch crossings. Jet energy corrections are derived from simulation, confirmed with in situ measurements of the energy balance in dijet and photon + jet events, and are applied as a function of the jet p_T and η [59] to both data and simulated events. The $\mathrm{t\bar{t}}$ candidate events are required to have at least two reconstructed jets with $p_\mathrm{T} > 30$ GeV and $|\eta| < 2.4$.

Since $\mathrm{t\bar{t}}$ events decay into final states containing a bottom quark–antiquark pair, requiring the presence of jets identified as originating from b quarks ("b jets") reduces backgrounds from DY and W+jets production. Jets are identified as b jets using the combined secondary vertex algorithm [60,61], with an operating point which yields an identification efficiency of 67% and a misidentification (mistag) probability of about 1% and 15% [61] for light-flavour jets (u, d, s, and gluons) and c jets, respectively. The selection requires the presence of at least one b jet in the event.

4 Background determination

Background events arise primarily from single top quark, DY, and VV events in which at least two prompt leptons are produced by Z or W boson decays. The single top quark and VV contributions are estimated from simulation.

The DY event yield is estimated from data using the "$R_{\mathrm{out/in}}$" method [1,2,6], where events with same-flavour leptons are used to normalize the yield of $e^{\pm}\mu^{\mp}$ pairs from DY production of τ lepton pairs. A data-to-simulation normalization factor is estimated from the number of events in data within a 15 GeV window around the Z boson mass and extrapolated to the number of events outside the Z mass window with corrections applied using control regions enriched in DY events in data. The SF is found to be 0.95 ± 0.05 (statistical uncertainty) after applying the final event selection.

Other background sources, such as $t\bar{t}$ or W+jets events in the lepton+jets final state, can contaminate the signal sample if a jet is incorrectly reconstructed as a lepton, or the lepton is incorrectly identified as being isolated. This is more important for electrons. For muons, the dominant contribution comes from the semileptonic decay of bottom or charm quarks. These events are grouped into the nonprompt leptons category ("non-W/Z leptons") since prompt leptons are defined as originating from decays of W or Z boson, together with contributions that can arise, for example, from decays of mesons or photon conversions.

The contribution of non-W/Z lepton events is estimated from a control region of same-sign (SS) events and propagated in the opposite-sign (OS) signal region. The SS control region is defined using the same criteria as the nominal signal region, except for requiring eμ pairs with the same electric charge. The SS dilepton events are predominantly events containing misidentified leptons. Other SM processes produce prompt SS or charge-misidentified dilepton events with significantly smaller rates; these are estimated using simulation and subtracted from the observed number of events in data.

The scaling from the SS control region in data to the signal region is performed through the ratio of the numbers of OS to SS events with misidentified leptons in simulation. This ratio is calculated using simulated $t\bar{t}$ and W+jets samples, which are rich in nonprompt dilepton events, and is measured to be

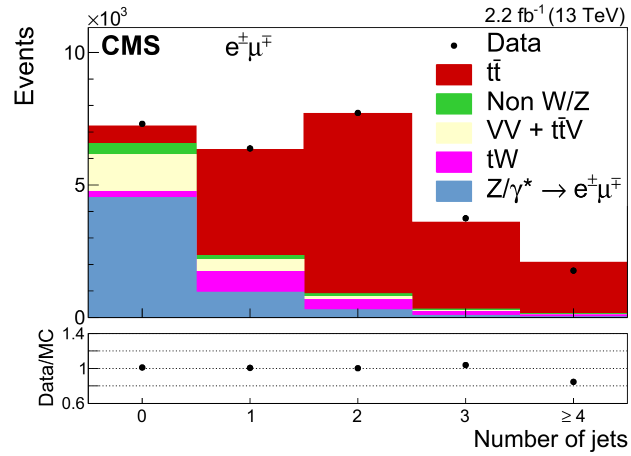

Fig. 1 Distribution of the jet multiplicity in events passing the dilepton selection criteria. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based on control regions in data are applied; the last bin contains the overflow events. The ratio of data to the sum of the expected yields is given at the *bottom* of the figure. The *error bars*, which are within the size of the points, indicate the statistical uncertainties

1.4 ± 0.1 (stat). In data, 152 SS events are observed, with a contribution of 79.8 ± 1.9 (stat) prompt lepton SS events as evaluated from simulation. In total 104 ± 8 (stat + syst) events with misidentified leptons contaminating the signal region are predicted. This agrees within the uncertainties with predictions from the simulation.

Figure 1 shows the multiplicity of jets for events passing the dilepton criteria. The MC simulation does not describe well the data for events with $\geq$4 jets, the region in which parton shower effects are expected to dominate the prediction. After requiring at least two jets, Fig. 2 shows the p_{T} and $|\eta|$ distributions of the selected leptons, and Fig. 3 shows the p_{T} (a, c) and $|\eta|$ (b, d) distributions of the two most energetic jets; Fig. 3(e) shows the scalar sum of the transverse momenta of all jets (H_{T}) and Fig. 3(f) the b jet multiplicity. Good agreement between data and the predictions for signal and background is observed.

5 Sources of systematic uncertainty

Table 1 summarizes the statistical uncertainty and the different sources of systematic uncertainties in the measured $t\bar{t}$ production cross section.

The uncertainty in the trigger efficiency SF applied to simulation to correct for differences with respect to data is 1.1%. The uncertainty in the SF applied to correct the electron (muon) identification efficiency is found to be about 1.8% (1.5%), with some dependence on the lepton p_{T} and η.

The modeling of lepton energy scales was studied using $Z \rightarrow ee/\mu\mu$ events in data and simulation, resulting in

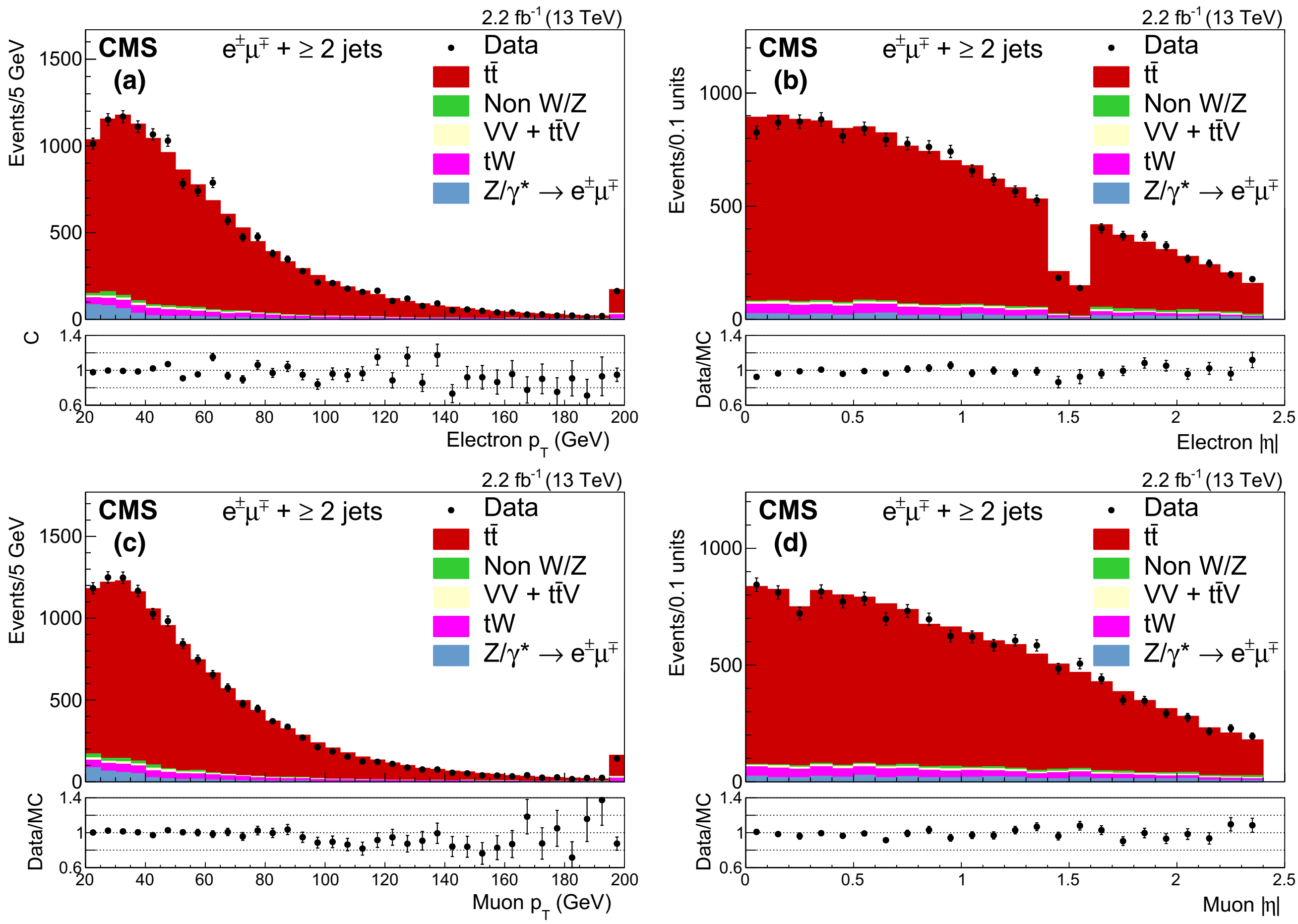

Fig. 2 The distributions of **a** p_T and **b** $|\eta|$ of the electron, and **c** p_T and **d** $|\eta|$ of the muon after the selection of jets and before the b jet requirement. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based on control regions in data are applied; for the *left plots* (**a**, **c**) the last bin contains the overflow events. The ratios of data to the sum of the expected yields are given at the *bottom of each panel*. The *error bars* indicate the statistical uncertainties

an uncertainty for the electron (muon) energy scale of 1.0 (0.5)%. These values are used to obtain the effect on the signal acceptance, which is taken as a systematic uncertainty.

The impact of uncertainties in jet energy scale (JES) and jet energy resolution (JER) is estimated from the change observed in the number of simulated $t\bar{t}$ events selected after changing the jet momenta within the JES uncertainties, and for JER by an $|\eta|$-dependent variation of the JER scale factors within their uncertainties.

The uncertainties resulting from the b tagging efficiency and misidentification rate are determined by varying the b tagging SF of the b jets and the light-flavour jets, respectively. These uncertainties depend on the p_T and η of the jet and amount to approximately 2% for b jets and 10% for mistagged jets [61] in $t\bar{t}$ signal events. They are propagated to the $t\bar{t}$ selection efficiency using simulated events.

The uncertainty assigned to the number of pileup events in simulation is obtained by changing the inelastic proton–proton cross section, which is used to estimate the pileup in data, by ±5% [62].

The systematic uncertainty related to the missing higher-order diagrams in POWHEG is estimated as follows: the uncertainty in the signal acceptance is determined by changing the μ_F and μ_R scales in POWHEG independently up and down by a factor of two, with the uncertainty taken as the maximum observed difference.

The predictions of the NLO generators POWHEG and MG5_aMC@NLO for $t\bar{t}$ production are compared, where both use PYTHIA for hadronization, fragmentation, and additional radiation description. The difference in the signal acceptance between the two is taken as an uncertainty.

The uncertainty arising from the hadronization model mainly affects the JES and the fragmentation of b quark jets. The uncertainty in the JES already contains a contribution from the uncertainty in the hadronization. In addition, we determine a related uncertainty by comparing samples

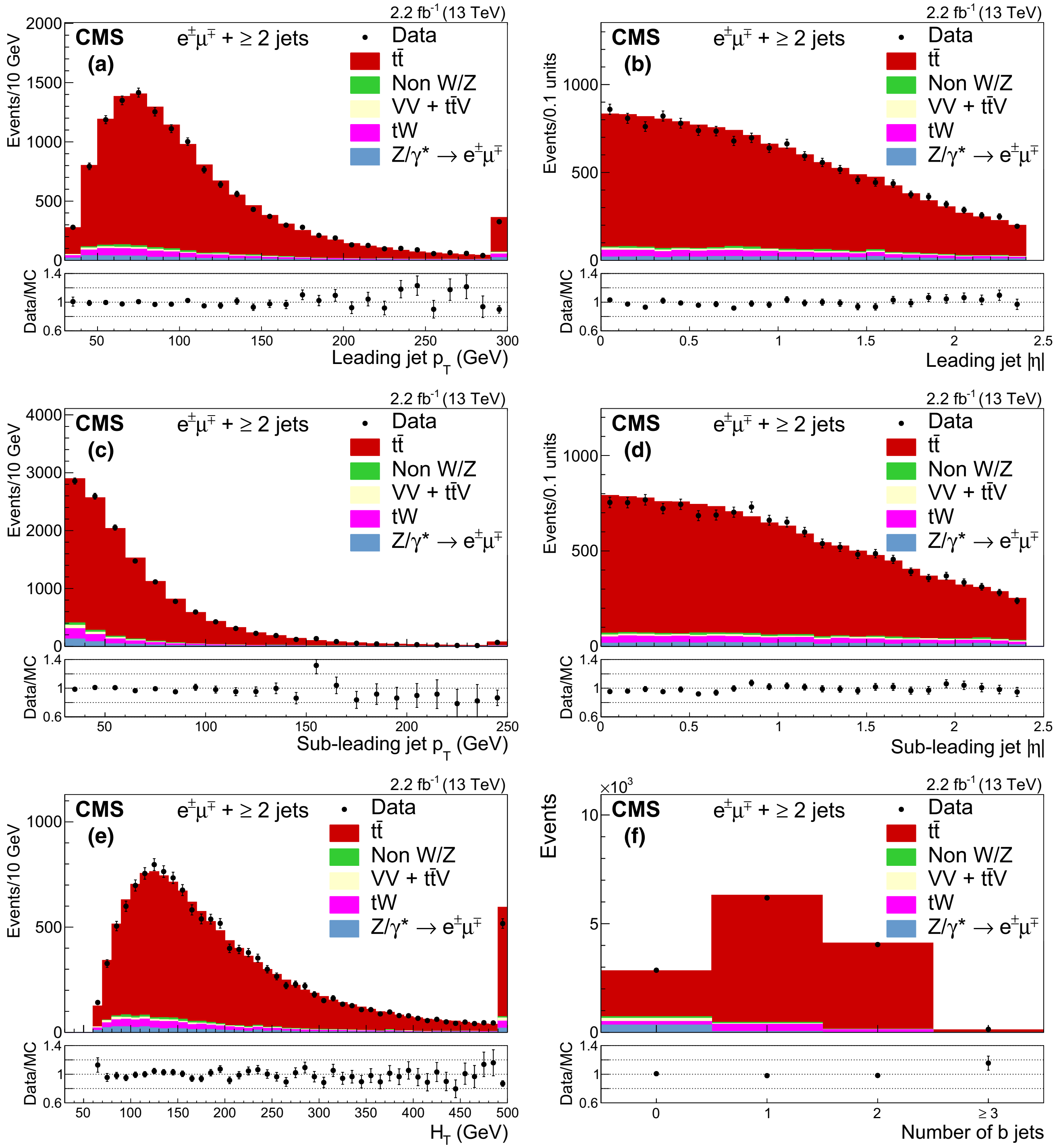

Fig. 3 The distributions of **a** p_T and **b** $|\eta|$ for the leading jet, **c** p_T and **d** $|\eta|$ for the sub-leading jet, **e** H_T, and **f** b jet multiplicity after the jets selection and before the b jet requirement. The expected distributions for $t\bar{t}$ signal and individual backgrounds are shown after corrections based on control regions in data are applied; in each plot the last bin contains the overflow events. The ratios of data to the sum of the expected yields are given at the *bottom of each panel*. The *error bars* indicate the statistical uncertainties

of events generated with POWHEG, where the hadronization is modeled with PYTHIA or HERWIG++. In what follows we refer to this difference as the hadronization uncertainty.

The impact of the choice of the parton shower scale is studied by changing the scale of the parton shower (initial and final state radiation) by a factor of 2 and 1/2 from its

Table 1 Summary of the individual contributions to the uncertainty in the $\sigma_{t\bar{t}}$ measurement. The first and second uncertainty corresponds to the total and relative component, respectively. The total uncertainty in the result, calculated as the quadratic sum of the individual components, is also given

Source	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Experimental		
Trigger efficiencies	9.9	1.2
Lepton efficiencies	18.9	2.3
Lepton energy scale	<1	≤0.1
Jet energy scale	17.4	2.1
Jet energy resolution	0.8	0.1
b tagging	11.0	1.3
Mistagging	<1	≤0.1
Pileup	1.5	0.2
Modeling		
μ_F and μ_R scales	<1	≤0.1
$t\bar{t}$ NLO generator	17.3	2.1
$t\bar{t}$ hadronization	6.0	0.7
Parton shower scale	6.5	0.8
PDF	4.9	0.6
Background		
Single top quark	11.8	1.5
VV	<1	≤0.1
Drell–Yan	<1	≤0.1
Non-W/Z leptons	2.6	0.3
$t\bar{t}V$	<1	≤0.1
Total systematic (no integrated luminosity)	37.8	4.6
Integrated luminosity	18.8	2.3
Statistical	8.5	1.0
Total	43.0	5.3

default value. The maximum variation with respect to the central value of the signal acceptance at particle level [63] for the fiducial volume of the analysis is taken as an uncertainty.

The uncertainty from the choice of PDF is determined by reweighting the sample of simulated $t\bar{t}$ events according to the NNPDF3.0 PDF sets [30]. The root-mean-square of the distribution is taken as an uncertainty.

Based on recent measurements of the production cross section for single top quark [64–66] and VV [67–74] we use an uncertainty of 30% for these background processes. For DY production, an uncertainty of 15%, that covers the difference of the SF at different levels of the selection, is assumed. A 30% systematic uncertainty is estimated for the non-W/Z lepton background derived from the uncertainty in the ratio of the numbers of OS to SS events with misidentified leptons in the MC simulation.

The uncertainty in the integrated luminosity is 2.3% [75].

Table 2 Number of dilepton events obtained after applying the full selection. The results are given for the individual sources of background, $t\bar{t}$ signal with a top quark mass of 172.5 GeV and $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb, and data. The uncertainties correspond to the statistical component

Source	Number of $e^{\pm}\mu^{\mp}$ events
Drell–Yan	$46 \pm 5 \pm 7$
Non-W/Z leptons	$104 \pm 8 \pm 31$
Single top quark	$452 \pm 6 \pm 141$
VV	$14 \pm 2 \pm 5$
$t\bar{t}V$	$30 \pm 1 \pm 9$
Total background	$646 \pm 11 \pm 145$
$t\bar{t}$ signal	$9\,921 \pm 14 \pm 436$
Data	10368

6 Results

The $t\bar{t}$ production cross section is measured by counting events and applying the expression

$$\sigma_{t\bar{t}} = \frac{N - N_B}{\mathcal{A}\,\mathcal{L}},$$

where N is the total number of dilepton events observed in data, N_B is the number of estimated background events, $\mathcal{A}$ is the product of the mean acceptance, the selection efficiency, and the branching fraction into the $e^{\pm}\mu^{\mp}$ final state, and $\mathcal{L}$ is the integrated luminosity.

Table 2 shows the total number of events observed in data together with the total number of signal and background events determined from simulation or estimated from data. The value of $\mathcal{A}$, determined from simulation assuming $m_t = 172.5$ GeV, is $(0.55 \pm 0.03)\%$, including statistical and systematic uncertainties. The measured cross section is

$$\sigma_{t\bar{t}} = 815 \pm 9\,(\text{stat}) \pm 38\,(\text{syst}) \pm 19\,(\text{lumi})\,\text{pb},$$

for a top quark mass of 172.5 GeV.

As a cross-check, analogous measurements have been performed using independent data samples with same-flavour leptons in the final state. The results obtained in the e^+e^- and $\mu^+\mu^-$ channels are consistent with the result in the $e^{\pm}\mu^{\mp}$ channel. Given their larger uncertainties, the results are not combined with the main one in the $e^{\pm}\mu^{\mp}$ channel.

The measured fiducial cross section for $t\bar{t}$ production with two leptons (one electron and one muon) in the range $p_T > 20$ GeV and $|\eta| < 2.4$, at least two jets with $p_T > 30$ GeV and $|\eta| < 2.4$, and at least one b jet is $\sigma^{\text{fid}}_{t\bar{t}} = 12.4 \pm 0.1\,(\text{stat}) \pm 0.5\,(\text{syst}) \pm 0.3\,(\text{lumi})$ pb.

The acceptance has been measured in the range 166.5–178.5 GeV and is parameterized as a linear function of m_t. The cross section varies by 3.7 pb when the top quark mass changes 0.5 GeV.

7 Summary

A measurement of the $t\bar{t}$ production cross section in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ is presented for events containing an oppositely charged electron-muon pair, and two or more jets, of which at least one is tagged as originating from a b quark. The measurement is performed through an event-counting method based on a data sample corresponding to an integrated luminosity of $2.2\,\text{fb}^{-1}$. The measured cross section is

$$\sigma_{t\bar{t}} = 815 \pm 9\,(\text{stat}) \pm 38\,(\text{syst}) \pm 19\,(\text{lumi})\,\text{pb},$$

with a total relative uncertainty of 5.3%. The measurement, that supersedes [12], is consistent with recent measurements from the ATLAS [24] and CMS [12] experiments and with the standard model prediction of $\sigma_{t\bar{t}} = 832^{+40}_{-46}\,\text{pb}$ for a top quark mass of 172.5 GeV.

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