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

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

CMS Collaboration

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 $815 \pm 9$ (stat) $\pm 38$ (syst) $\pm 19$ (lumi) pb, in agreement with the expectation from the standard model.

1 Introduction

The measurement of the top quark–antiquark ($t\bar{t}$) 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. 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-
hililation 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 tℓ 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 tℓ events (referred to as “tℓV”) 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 σ_T at 13 TeV is 832^{+20}_{-25} (scales) ± 35 (PDF+α_s) pb for m_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 tℓ pairs, where each top quark decays predominantly to a W boson and a bottom quark. In tℓ 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 quark.

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_T > 12 GeV and one muon with p_T > 17 GeV or one electron with p_T > 17 GeV and one muon with p_T > 8 GeV. In addition, single-lepton triggers with one electron (muon) with p_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_T > 20 GeV and |η| < 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 measure-
t 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, tℓ candidate events are further required to have a dilepton pair of invariant mass m_{ττ} > 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 tℓ candidate events are required to have at least two reconstructed jets with p_T > 30 GeV and |η| < 2.4.

Since tℓ 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 \( R_{\text{out/in}} \) method [1,2,6], where events with same-flavour leptons are used to normalize the yield of \( e^\pm \mu^\pm \) pairs from DY production of \( \tau \) 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 lepton 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 e or \( \mu \) 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 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 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.

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 \( \eta \).

The modeling of lepton energy scales was studied using \( Z \rightarrow e\mu/\mu\mu \) events in data and simulation, resulting in
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 $\eta$ 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 $\pm 5\%$ [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 $\mu_F$ and $\mu_R$ 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
The measured fiducial cross section for $t\bar{t}$ production with a top quark mass of 172.5 GeV and is parameterized as a linear function of $m_t$: 

$$m_t = 172.5 \text{ GeV},$$

where $N$ is the total number of dilepton events observed in data, $N_B$ is the number of estimated background events, $A$ is the product of the mean acceptance, the selection efficiency, and the branching fraction into the $e^\pm \mu^\mp$ final state, and $L$ 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 $A$, determined from simulation assuming $m_t = 172.5$ GeV, is (0.55±0.03)%, including statistical and systematic uncertainties. The measured cross section is

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

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 $\sigma_{t\bar{t}} = 12.4 \pm 0.1$ (stat) $\pm 0.5$ (syst) $\pm 0.3$ (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 $\sqrt{s} = 13$ 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 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 $\sigma_{t\bar{t}} = 832^{+40}_{-46}$ pb for a top quark mass of 172.5 GeV.

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39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
40: Also at University of Florida, Gainesville, USA
41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
42: Also at California Institute of Technology, Pasadena, USA
43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
45: Also at INFN Sezione di Roma; Università di Roma, Rome, Italy
46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
47: Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy
48: Also at National and Kapodistrian University of Athens, Athens, Greece
49: Also at Riga Technical University, Riga, Latvia
50: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
51: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
52: Also at Gaziosmanpasa University, Tokat, Turkey
53: Also at Adiyaman University, Adiyaman, Turkey
54: Also at Mersin University, Mersin, Turkey
55: Also at Cag University, Mersin, Turkey
56: Also at Piri Reis University, Istanbul, Turkey
57: Also at Ozyegin University, Istanbul, Turkey
58: Also at Izmir Institute of Technology, Izmir, Turkey
59: Also at Marmara University, Istanbul, Turkey
60: Also at Kafkas University, Kars, Turkey
61: Also at Istanbul Bilgi University, Istanbul, Turkey
62: Also at Yildiz Technical University, Istanbul, Turkey
63: Also at Hacettepe University, Ankara, Turkey
64: Also at Rutherford Appleton Laboratory, Didcot, UK
65: Also at School of Physics and Astronomy, University of Southampton, Southampton, UK
66: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
67: Also at Utah Valley University, Orem, USA
68: Also at Facoltà Ingegneria, Università di Roma, Rome, Italy
69: Also at Argonne National Laboratory, Argonne, USA
70: Also at Erzincan University, Erzincan, Turkey
71: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
72: Also at Texas A&M University at Qatar, Doha, Qatar
73: Also at Kyungpook National University, Daegu, Korea