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Measurement of the  $t(\bar{t})$ -bar production cross section using  
pp events with one lepton and at least one jet in pp

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# Measurement of the $t\bar{t}$ production cross section using events with one lepton and at least one jet in pp collisions at $\sqrt{s} = 13$ TeV

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## The CMS collaboration

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**ABSTRACT:** A measurement of the  $t\bar{t}$  production cross section at  $\sqrt{s} = 13$  TeV is presented using proton-proton collisions, corresponding to an integrated luminosity of  $2.2 \text{ fb}^{-1}$ , collected with the CMS detector at the LHC. Final states with one isolated charged lepton (electron or muon) and at least one jet are selected and categorized according to the accompanying jet multiplicity. From a likelihood fit to the invariant mass distribution of the isolated lepton and a jet identified as coming from the hadronization of a bottom quark, the cross section is measured to be  $\sigma_{t\bar{t}} = 888 \pm 2, (\text{stat})_{-28}^{+26} (\text{syst}) \pm 20 (\text{lumi}) \text{ pb}$ , in agreement with the standard model prediction. Using the expected dependence of the cross section on the pole mass of the top quark ( $m_t$ ), the value of  $m_t$  is found to be  $170.6 \pm 2.7 \text{ GeV}$ .

**KEYWORDS:** Hadron-Hadron scattering (experiments), Top physics

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## 1 Introduction

The rate at which top quark-antiquark ( $t\bar{t}$ ) pairs are produced in proton-proton (pp) collisions at LHC has been measured at center-of-mass energies of 7 [1–14], 8 [15–23], and 13 TeV [24–26]. The latter has been determined experimentally with a 4.4% uncertainty. In addition, several analyses have explored the expected dependence of the  $t\bar{t}$  production cross section ( $\sigma_{t\bar{t}}$ ) on the mass of the top quark ( $m_t$ ) to extract the latter. Recent examples of this can be found in ref. [23], where  $m_t$  is determined with a total uncertainty of  $\approx 1\%$ . Alternatively, the strong coupling strength ( $\alpha_S$ ) can be extracted from the  $t\bar{t}$  cross section, assuming  $m_t$  is known [27]. Knowledge of the parton distribution function (PDF) of the proton can be improved as well from a precise measurement of  $\sigma_{t\bar{t}}$  [28, 29]. In addition, the production of final states via processes beyond the standard model that mimic the ones produced by  $t\bar{t}$  decay can be revealed by a precise measurement of  $\sigma_{t\bar{t}}$  [30]. The above-mentioned interpretations of the measured  $\sigma_{t\bar{t}}$  provide a few examples, among others existing in the literature, that can benefit from such precision comparisons.

In this paper, a measurement of  $\sigma_{t\bar{t}}$  using final states with an isolated charged lepton  $\ell$  (electron or muon) and at least one jet is presented. This selection is chosen in order to minimize the uncertainty in the extrapolation of the cross section to the fully inclusive phase space, and is expected to keep the impact of the dependence of the acceptance on the theoretical uncertainties in the PDFs and quantum chromodynamics (QCD) scale choice to a minimum. The selected events are split into categories according to the total number of jets in the event and the number of jets identified as coming from the hadronization of a b quark. Each category uses observables that can discriminate the main backgrounds (multijet and W+jets production) from the  $t\bar{t}$  signal. A combined fit to the distributions

in data of these observables is used to minimize the main systematic uncertainties, while measuring  $\sigma_{t\bar{t}}$  and  $m_t$ .

The paper is organized as follows: section 2 details the experimental setup, including the CMS detector, the data and simulation used in the analysis, the event selection, and the background estimations, section 3 describes the observables used in the analysis and the associated systematic uncertainties, while section 4 discusses the fit procedure and results. A summary is given in section 5.

## 2 Experimental setup

### 2.1 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. Forward calorimeters extend the pseudorapidity ( $\eta$ ) 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. 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. [31].

### 2.2 Data and simulation

The analysis is based on pp collision data collected by the CMS experiment at the CERN LHC at  $\sqrt{s} = 13$  TeV in 2015, corresponding to an integrated luminosity of  $2.21 \pm 0.05 \text{ fb}^{-1}$  [32].

The analysis is complemented using simulated event samples that are used to estimate the main backgrounds and the signal distributions. The  $t\bar{t}$  signal is modeled with the POWHEG v2 [33–36] generator, matched to PYTHIA v8.205 [37, 38] for shower evolution and hadronization. The NNPDF3.0 next-to-leading-order (NLO) PDFs [39] and the CUETP8M1 [40, 41] underlying-event tune are used in the simulation. To evaluate the systematic uncertainties associated with the QCD renormalization ( $\mu_R$ ) and factorization ( $\mu_F$ ) scales at the matrix-element level, we make use of a weighting scheme implemented in POWHEG v2 to vary the scales by a factor of 2 or 1/2 relative to its nominal value  $\mu_R = \mu_F = m_T$ , where  $m_T = \sqrt{m_t^2 + p_{T,t}^2}$  is the transverse mass of the top quark, with  $p_{T,t}$  being the top quark transverse momentum.

Furthermore, additional simulations in which the QCD renormalization and factorization scales at the parton shower level are changed by a factor of 2 or 1/2 relative to their nominal value are used. In the CUETP8M1 tune, the nominal QCD scale choice at the parton shower level is determined by  $\alpha_S^{\text{ISR}} = 0.1365$ , the value of the strong coupling strength at  $m_Z$  used for the initial-state shower. A different matrix-element generator is also used, for comparison: MG5\_aMC@NLO v5.2.2.2 [42] with MADSPIN [43], and is matched to either PYTHIA 8 or HERWIG++ v2.7.1 [44].

In this analysis, we measure the  $t\bar{t}$  cross section in a fiducial region of the phase space using as reference the theoretical cross section for  $m_t = 172.5$  GeV, computed at next-to-next-to-leading order (NNLO) with next-to-next-to-leading-log (NNLL) soft-gluon resummations,  $\sigma_{t\bar{t}} = 832^{+20}_{-29}$  (scale)  $\pm 35$  (PDF +  $\alpha_S$ ) pb, from TOP++ v2.0 [45]. Single top quark processes are simulated with POWHEG v1 [46, 47] and normalized to the approximate NNLO prediction [48]. The W+jets process is simulated at NLO with MG5\_aMC@NLO. To reach higher statistical accuracy, a larger Born-level MADGRAPH v5.1.3.30 [42] simulated sample, including up to four extra partons in the matrix-element calculations, is used for the derivation of the W+jets background shape. The Drell-Yan (DY) contribution is simulated with MADGRAPH. Both W+jets and DY cross sections are normalized to their NNLO predictions, computed using FEWZ (v3.1.b2) [49]. Diboson production (WW, ZZ, WZ) is simulated either with PYTHIA 8 (ZZ, WZ) or POWHEG v1 [50] (WW). Each diboson process is normalized to the NLO prediction for the cross section, computed with MCFM (v7.0) [51, 52]. The associated production of W or Z boson with  $t\bar{t}$  ( $t\bar{t} + V$ ) is simulated at NLO with MG5\_aMC@NLO.

All simulated events include an emulation of the response of the CMS detector using GEANT4 v9.4p03 [53, 54]. The effect due to multiple pp collisions in the same and neighboring beam crossings (pileup) is measured and added to the simulated  $t\bar{t}$  interactions according to the pileup multiplicity observed in the data.

### 2.3 Event selection

The data are recorded using single-lepton triggers with a minimum transverse momentum ( $p_T$ ) of 22 GeV and 20 GeV for electrons and muons, respectively. Identification and isolation criteria are applied at the trigger level, and the efficiency of these requirements is measured in a control data sample that is dominated by  $Z \rightarrow \ell\ell$  decays. The results obtained from the control data sample are compared with the simulated predictions using a tag-and-probe method [55], and data-to-simulation scale correction factors are derived as function of the  $p_T$  and  $\eta$  of the lepton. The scale factors are observed to be  $\leq 5\%$ .

The events are reconstructed offline using a particle-flow (PF) algorithm that optimally combines the information from subdetectors to reconstruct and identify all individual particles in the event [56]. In addition, reconstruction, identification, and calibration algorithms are employed for electrons and muons, as described in refs. [57, 58]. The lepton candidates are required to have  $p_T > 30$  GeV and  $|\eta| < 2.1$ . Identification and isolation requirements are imposed to reject misidentified muons from punchthrough hadrons, photon conversion, and other objects misreconstructed as lepton candidates. These criteria are tighter than the ones imposed at trigger level. The tag-and-probe method measures the efficiency of these requirements, yielding typical efficiencies of 70% and 92% for electrons and muons, respectively. Nonprompt leptons that come from the decays of long-lived hadrons are rejected by requiring that the significance of the three-dimensional (3D) impact parameter of the lepton track, relative to the primary event vertex, is less than four standard deviations. This requirement effectively reduces the contamination from multijet events, while keeping a high efficiency for the signal. The expected efficiency of this requirement is cross-checked using  $Z \rightarrow \ell\ell$  candidate events. The primary event vertex used as reference is required to

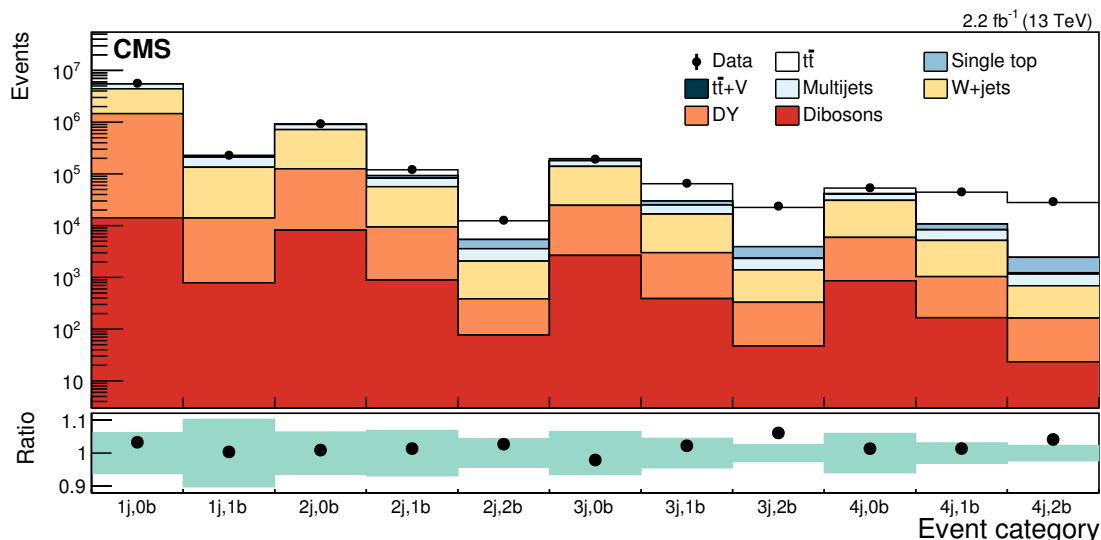
be reconstructed from at least four tracks, and have a longitudinal distance of less than 24 cm from the center of the detector. Among all the pp collision vertices in the event, the one with the largest scalar sum of associated particle transverse momenta is selected as the primary vertex. The event is rejected if an additional electron or muon is found within  $|\eta| \leq 2.5$ , passing looser identification and isolation criteria, and with  $p_T > 15$  or 10 GeV, respectively.

Jets are reconstructed using all PF candidates as inputs to the anti- $k_T$  algorithm with a distance parameter of 0.4, utilizing the FASTJET 3.1 software package [59, 60]. The jet momentum is defined as the vectorial sum of all particle momenta inside the jet cone, and is found from the simulation to be within 5–10% of the generated jet momentum at particle level over the whole  $p_T$  range and detector acceptance. Since pileup collisions result in unwanted calorimetric energy depositions and extra tracks, part of this contribution is reduced by performing a charged-hadron subtraction that removes tracks identified as originating from pileup vertices [61]. In addition, an offset correction is applied to remove the additional energy included in the jets that come from pileup [62, 63]. The energy scale corrections, derived from simulation, are cross-checked with in situ measurements of the energy balance in dijet and photon+jet events [61].

We require at least one jet with  $p_T > 30$  GeV and  $|\eta| \leq 2.5$  in the accepted events. The jets are required to not overlap with the isolated lepton within a cone of angular radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ , where  $\Delta\eta$  and  $\Delta\phi$ , represent the difference in pseudorapidity and azimuthal angle (in radians), between the directions of each jet and the lepton. Jets coming from the fragmentation and hadronization of b quarks (b jets) are identified by a combined secondary vertex (CSV) algorithm [64]. A b jet is identified with a CSV threshold efficiency  $>65\%$  and a misidentification rate  $\approx 1\%$ . This b tagging efficiency is measured using a  $b\bar{b}$  enriched data sample from a method similar to that described in ref. [64].

In the analysis, events with one, two, three, or four or more jets are considered as separate event categories. We expect the low-multiplicity categories to be dominated by W+jets processes, and the high jet multiplicities by  $t\bar{t}$  events. An additional separation of the signal is achieved by counting the number of b-tagged jets in each category, since two b jets in the event are expected, given that each top quark decays to a Wb pair. Therefore, we further subdivide the four jet-multiplicity categories according to the number of reconstructed b-tagged jets, considering events with none, one, or at least two b-tagged jets, for a total of 11 orthogonal categories. Since the collision particles are protons, an asymmetric production of W bosons, with more  $W^+$  produced than  $W^-$ , is expected [65]. Given the charge-symmetric decays of the W bosons in  $t\bar{t}$  decays,  $t\bar{t}$  final states are expected to have the same number of  $W^+$  and  $W^-$  bosons. We use this property to further categorize the events according to the lepton charge (+−) and flavor (electron or muon). Hence, our analysis makes use of a total of  $2 \times 2 \times 11 = 44$  categories.

All backgrounds are estimated using simulation except for that from multijet events, which is difficult to model correctly from simulation in the  $t\bar{t}$  phase-space region. The contribution from the multijet background is estimated using an independent data control sample where the prompt-lepton candidate passes the loose trigger-isolation requirements, but fails the tighter isolation required offline. The expected residual contamination from



**Figure 1.** Event yields from data and the expected  $t\bar{t}$  signal and backgrounds for each of the 11 independent categories. Distributions are combined for the two lepton charges and flavors. The bins represent the measured number of jets (j) and b-tagged jets (b), with the 4j and 2b categories being inclusive. The bottom panel shows the ratio between the data and the expectations. The relative uncertainty owing to the statistical uncertainty in the simulation, the uncertainty in the normalization of the multijet contribution, and the systematic uncertainty in the total integrated luminosity is represented as a shaded band.

background processes other than multijets is estimated from simulation and subtracted from the control sample. The resulting distributions are used to model the multijet background contribution. The initial multijet normalization is obtained from events containing one isolated lepton and having the measured absolute value of the imbalance in the  $p_T$  of all PF candidates in the event less than 20 GeV. The contributions from backgrounds other than multijets are subtracted in the referred to isolated-lepton region, and the ratio of events observed in data in this region with respect to the number of events found in the nonisolated-lepton control region is assigned as the renormalization scale factor. Given the tight requirements on leptons, we expect  $b\bar{b}$  +jets events to dominate the multijet contamination. An isolated, prompt lepton coming from such a process is likely to arise from the decay of a bottom hadron. We can therefore expect a jet in the event to be b-tagged. This motivates the initial normalization for the multijet process through the one-b-tagged-jet category. However, for events with at least three jets, the  $t\bar{t}$  contribution is expected to be nonnegligible, so the multijet process is estimated from events without any b-tagged jets.

Figure 1 compares the numbers of selected events in data with the signal and expected backgrounds from simulation in each category. For simplicity, the contributions from the electron and muon final states, as well as from the two lepton charges, are summed. Within the uncertainties, we observe agreement between the data and the expectations. Although not shown explicitly, agreement is also found separately for each lepton flavor and charge.

### 3 Observables and related uncertainties

For each event category, we select a variable that discriminates the signal from the backgrounds. Categories without b-tagged jets are likely to be dominated by backgrounds and thus are counted without analyzing any distribution. For events with b-tagged jets, we exploit the distinct kinematic character of  $t \rightarrow Wb$  decays, and use the following mass variables: (i) for events with only one b-tagged jet, we use the invariant mass of the system formed by the lepton and the b-tagged jet ( $M(\ell, b)$ ); and (ii) for events with at least two b-tagged jets, the invariant masses of all the lepton and b-tagged jet combinations in the event are calculated, and the minimum mass ( $\min M(\ell, b)$ ) is chosen as a discriminant. The  $M(\ell, b)$ -related variables are expected to be sensitive to  $t\bar{t}$  production, as well as to  $m_t$ , defined by the endpoint in the invariant mass spectrum expected at leading order (LO). The endpoint is determined by the values of the top quark and W boson masses [66].

Figure 2 shows the  $M(\ell, b)$  and  $\min M(\ell, b)$  distributions for data, and the expected contributions from signal and backgrounds in the various event categories. When normalized by the reference cross sections described in section 2.2 there is an overall good agreement between data and expectations. The most noticeable differences are related to the initial multijet background normalization and the uncertainty in the W+jets normalization which is improved by the fitting procedure (see section 4).

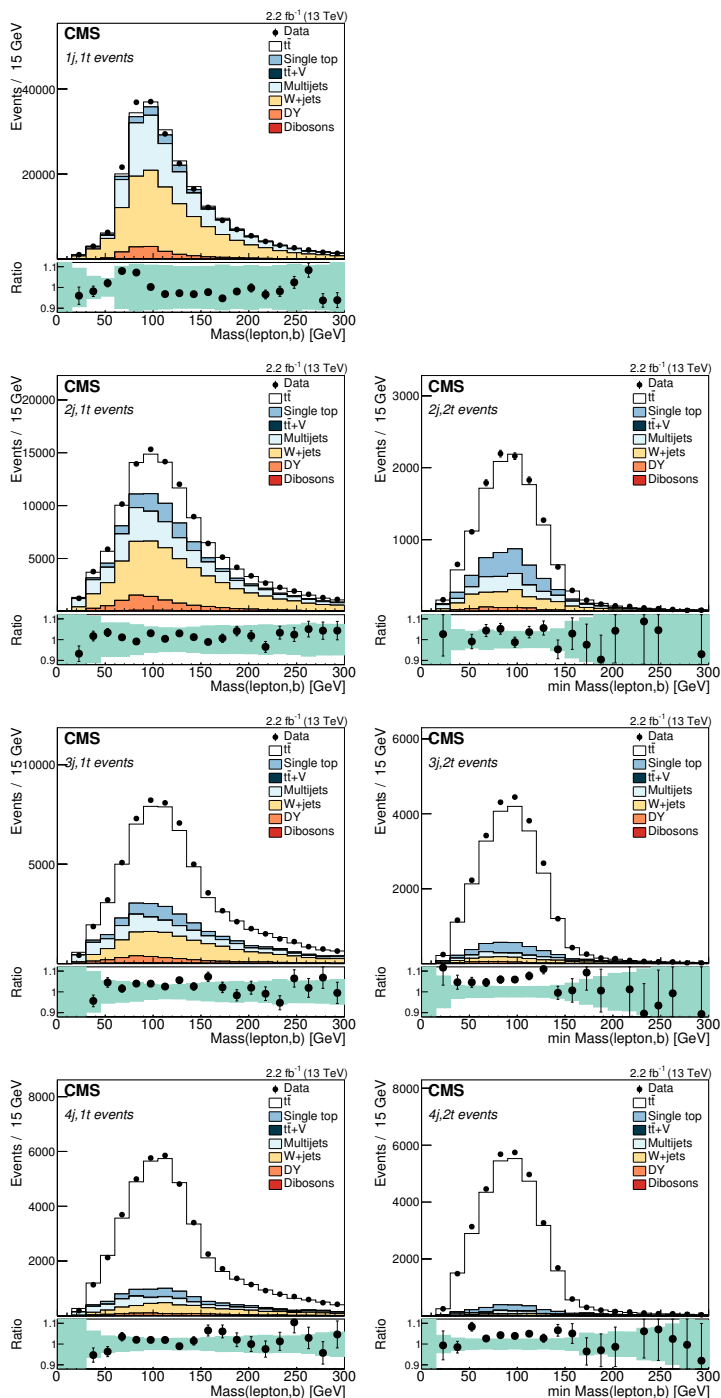
In the signal region, the agreement is good for the simulation using the reference value  $m_t = 172.5$  GeV.

The expectations for the rates and distributions considered in the analysis are affected by different sources of systematic uncertainties. For each source, an induced variation can be parametrized, and treated as a nuisance parameter in the fit that is described in the next section.

Experimental uncertainties pertain mostly to the calibration of the detector and to our assessment of its performance in the simulation. The uncertainty in the efficiency of the trigger and the offline selection is estimated by applying different scale factors as a function of the  $p_T$  and  $\eta$  of the isolated lepton. The scale factors and their uncertainties are obtained using  $Z \rightarrow \ell\ell$  data, based on a tag-and-probe method [55]. The one standard deviation changes applied to the parameters of the simulated events are typically on the order of 1–3%.

The energy scales of the objects used in the analysis (leptons and jets) are varied according to their estimated uncertainties. This can lead to a migration of events to different categories because of the thresholds applied in the preselection and the categorization of the events, as well as to changes in the expected distributions of the observables. When the energy scale of the leptons or jets changes, it affects other variables (e.g., the missing momentum), which are recomputed to reflect the new scales. The uncertainty in the jet energy scale is subdivided into independent sources. A total of 29 nuisance parameters related to the jet energy scale are included in the fit described in the next section. The parameters refer to the effect of uncertainties related to pileup, relative ( $\eta$ -dependent) calibration, high- and low- $p_T$  extrapolation, absolute-scale determination, and flavor-specific differences, amongst others. The categories used for the jet energy scale are similar to those used in the  $\sqrt{s} = 8$  TeV analyses [61, 67].





**Figure 2.** Distributions in the observables used to fit the data with the contributions from all leptons and charges combined. Panels on the left show the distributions in  $M(\ell, b)$ , and on the right in  $\min M(\ell, b)$ , for events with one and two b-tagged jets, respectively. From top to bottom, the events correspond to those with 1, 2, 3, or at least 4 jets. The lower plot in each panel shows the ratio between the data and expectations. The relative uncertainty owing to the statistical uncertainty in the simulations, to the uncertainty in the normalization of the contribution from multijet events and to the systematic uncertainty in the total integrated luminosity is represented as a shaded band.

The jet energy resolution is also affected by an uncertainty that is estimated in our analysis by changing the simulated resolution by one standard deviation as a function of the  $\eta$  of the jet. The corrections applied to the simulated b jet, c jet, and light-flavor jet tagging efficiencies of the CSV algorithm are changed according to their uncertainties [64]. This also causes a migration of events across the different b tagging categories within the same jet multiplicity. The uncertainty from the model used for the average pileup in the simulation is estimated by implementing a 5% change to the assumed inelastic pp cross section [68]. Finally, a 2.3% uncertainty is assigned to the estimated integrated luminosity [32].

For the estimate of the contribution from QCD multijet events we determine an uncertainty owing to the normalization method of the nonisolated-lepton sideband in data through an alternative scale factor obtained from events with  $M_T < 50$  GeV, where  $M_T$  is the transverse mass computed from the lepton candidate and the missing momentum of the event. This yields an intrinsic uncertainty of  $\approx 30$ –60%, depending on the category. Furthermore, uncertainties in the distributions of events caused by the normalizations of other than multijet contributions are obtained by changing the individual sources in the control regions by  $\pm 30\%$ . These uncertainties are considered uncorrelated across all categories of the analysis.

Theoretical uncertainties affect the predictions for the acceptance and the distributions in the signal and nonmultijet background processes. We consider independent changes in  $\mu_R$  or  $\mu_F$  in the  $t\bar{t}$ , W+jets, and tW processes by factors of 2 and 1/2. For the signal, we estimate the parton shower uncertainty by using alternative POWHEG +PYTHIA 8 samples, with the parton shower scale value changed by factors of 2 and 1/2. This affects the fragmentation and hadronization of the jets initiated by the matrix-element calculation, as well as the emission of extra jets. The variation in the acceptance and distributions obtained by using HERWIG++ instead of PYTHIA 8 to interface the POWHEG generator is included as a systematic uncertainty in the modeling of  $t\bar{t}$  in the fit. An additional uncertainty is assigned based on the difference found between the POWHEG and MG5\_aMC@NLO simulations.

For the signal, we also consider an uncertainty in the  $p_T$  distribution of the top quark, based on the CMS measurements at  $\sqrt{s} = 8$  [69] and 13 TeV [66]. The simulation is reweighted using a data-to-simulation scale factor that is verified to be consistent with the measurements performed in both data sets, and the difference is used to assign the uncertainty in the modeling of the top quark  $p_T$ .

Uncertainties in the modeling of the single top quark background include changes of  $\mu_R/\mu_F$  for the t and t W channels. At NLO QCD, t W production is expected to interfere with  $t\bar{t}$  production, owing to the similar initial and final states of some diagrams [70–72]. Two schemes for defining the t W signal that distinguish it from  $t\bar{t}$  production have therefore been compared in this analysis: the “diagram removal” method [70], in which all doubly-resonant NLO t W diagrams are removed, and the “diagram subtraction” scheme [70, 73], where a gauge-invariant subtraction term modifies the NLO t W cross section to locally cancel the contribution from  $t\bar{t}$ . In addition to the theoretical uncertainties described above, all background processes are assigned their corresponding theoretical uncertainties in their normalization.

## 4 Fitting procedure and results

The  $t\bar{t}$  production cross section is measured by performing a maximum-likelihood fit to the number of events counted in the different categories. The likelihood function takes into account the expectations for contributions from different background processes as well as signal. The expectations for signal and backgrounds depend on: (i) the simulation- or data-based expectations ( $\hat{S}$  or  $\hat{B}$  for signal and background, respectively), and (ii) nuisance parameters ( $\theta_i$ ) that reflect the uninteresting variables used to control the effect of the systematic variations described in the previous section. The effect of each source of uncertainty is separated in a rate-changing and shape-changing nuisance parameter. In the fit, the nuisance parameters are assumed to be distributed according to log-normal probability distribution functions (pdfs) if affecting the rate, or Gaussian pdfs if affecting the shapes. We denote generally the pdfs associated with a nuisance parameter as  $\rho(\theta_i)$ . The signal expectation is also modulated by a multiplicative factor, which is defined by the ratio of the measured cross section to the reference theoretical value, i.e., the signal strength  $\mu = \sigma/\sigma_{\text{th}}$  for  $m_t = 172.5$  GeV. For each category ( $k$ ), we write the total number of expected events as:

$$\hat{N}_k(\mu, \Theta) = \mu \hat{S}_k \prod_i (1 + \delta_i^S \theta_i) + \hat{B}_k \prod_i (1 + \delta_i^B \theta_i), \quad (4.1)$$

where  $\Theta$  is the set of all nuisance parameters, the index  $k$  runs over the bins of the distributions (or the counts in different event categories for the cross-check analysis), and  $\delta_i^S$  and  $\delta_i^B$  are changes in yields induced through one-standard-deviation changes in the  $i^{\text{th}}$  sources of uncertainty in the signal and backgrounds, respectively. The likelihood function is defined as:

$$\mathcal{L}(\mu, \Theta) = \prod_k \mathcal{P} \left[ N_k | \hat{N}_k(\mu, \theta_i) \right] \prod_i \rho(\theta_i), \quad (4.2)$$

where  $\mathcal{P}$  is a Poisson distribution and  $N_k$  is the number of events observed in the  $k$ th category. The cross section is measured by maximizing the profile likelihood ratio (PLR) test statistic:

$$\lambda(\mu) = \frac{\mathcal{L}(\mu, \hat{\Theta})}{\mathcal{L}(\hat{\mu}, \hat{\Theta})}, \quad (4.3)$$

where the quantities  $\hat{\Theta}$  correspond to the set of nuisance parameter values  $\theta_i$  that maximize the likelihood for the specified signal strength (also known as the conditional likelihood), and  $\hat{\mu}$ ,  $\hat{\Theta}$  are respectively the values of  $\mu$  and the set of  $\theta_i$  that maximize the likelihood. In the presence of nuisance parameters, the resulting PLR as a function of  $\mu$  tends to be broader relative to the one obtained when the values are well known and fixed. This reflects the loss of information in  $\mu$  because of the presence of systematic uncertainties [74].

Although  $m_t$  does not contribute an intrinsic uncertainty in the measurement of the cross section, since the  $M(\ell, b)$  distribution is used in the fit, its shape has a direct dependence on  $m_t$  that needs to be taken into account. We thus include in the fit a parameterization of the effect of varying  $m_t$  by  $\pm 3$  GeV while measuring the cross section as the parameter of interest. This parameterization is performed for both the signal and

the single top quark simulations. With this procedure, the fit accommodates for a possibly different value of  $m_t$  than that assumed by default in the simulation but without correlating this with the pole mass to be extracted from the inclusive  $t\bar{t}$  production rate, as originally proposed in ref. [75].

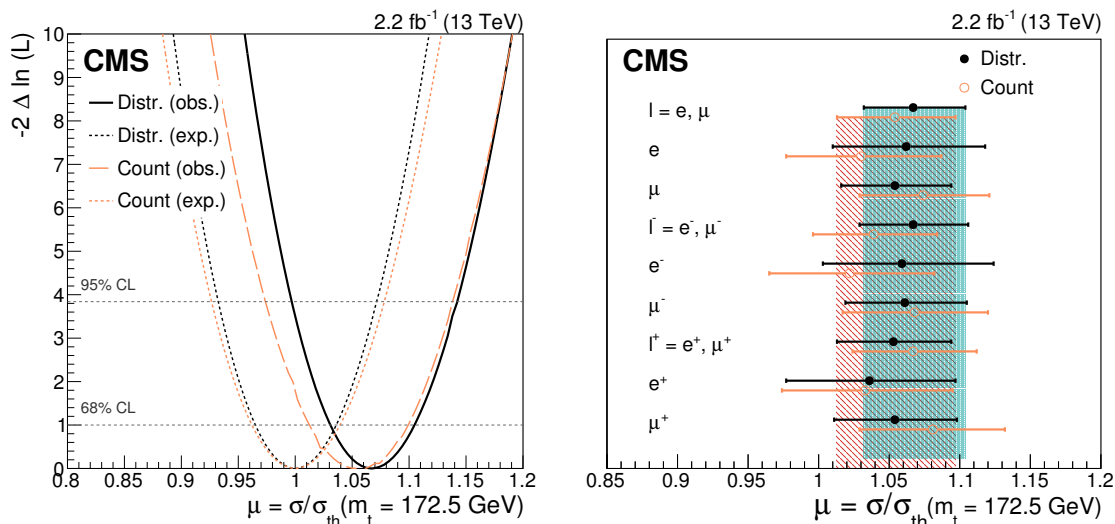
Figure 3 (left) shows the variation of the likelihood as a function of the signal strength from the data and the expected variation from the simulation. From the fit, we measure  $\mu = 1.067 \pm 0.002$  (stat)  $^{+0.037}_{-0.035}$  (syst). The  $t\bar{t}$  cross section in the visible phase space is thus measured with a total uncertainty of 3.4%. As a check, the Monte Carlo simulated signal and background events corresponding to the same integrated luminosity as the data are used as pseudo-data with  $m_t = 172.5$  GeV in the fit. The resulting value of the signal strength is  $\mu = 1.000 \pm 0.002$  (stat)  $^{+0.035}_{-0.034}$  (syst). This is the expected value of  $\mu$ , and the agreement of the statistical and systematic uncertainties with those from the fit to the data is a good check on the fitting procedure.

The default analysis using the shapes of the distributions (labeled “Distr.”) is also compared with a simpler cross-check analysis (labeled “Count”). The cross-check analysis does not use kinematic information, but uses the number of events in the different jet and b-tagged jet categories, and the expected yields. The two results are in agreement with each other, with the cross-check analysis having a larger uncertainty:  $\mu = 1.054 \pm 0.002$  (stat)  $^{+0.043}_{-0.041}$  (syst).

The post-fit normalizations for the main backgrounds (W+jets and multijets) tend to be higher by 1–6% in the main analysis with respect to those from the cross-check analysis. This results in a different signal strength between the two analyses.

Figure 3 (right) compares the inclusive  $\mu$  result for both the default and cross-check analyses (top set of points) with the corresponding values for the different lepton charges and flavors. The results are found to be consistent with each other in the different combinations.

The impact of the sources of uncertainty in the fit is evaluated by making use of the set of post-fit values of the nuisance parameters, and computing the shift induced in the signal strength as each nuisance parameter is fixed at its  $\pm 1$  standard deviation post-fit value, with all other parameters profiled as normal. By repeating the fits, the effect of some nuisance parameters being fixed may be reabsorbed by a variation of the ones being profiled, owing to correlations. Figure 4 summarizes the values obtained for the leading sources of uncertainty in the fit. The dominant sources of uncertainty in both analyses are related to the integrated luminosity, trigger and selection efficiencies, and the model of the W+jets background. These are expected to impact the signal strength at the level of 1–2.5%. The analysis of the distributions is effectively able to mitigate most uncertainties related to the modeling of  $t\bar{t}$ . The modeling of the top quark  $p_T$  and the choice of the hadronizer are the dominant signal modeling uncertainties but their impact in the fit is observed to be  $< 1\%$ . Uncertainties related to the modeling of the multijets background are observed to impact the fit at the level of  $< 0.5\%$ . None of the nuisance parameters used in the fit is observed to be significantly pulled from its initial value and its behavior is similar to that expected by performing the fit using simulated events with  $m_t = 172.5$  GeV. Nuisance parameters related to the integrated luminosity and the trigger and selection efficiencies are observed not to be constrained in the fit procedure.



**Figure 3.** (Left) The observed (solid curve) and expected (dashed curve) variation of the likelihood as a function of the signal strength  $\mu$  for the distribution-based analysis. The expected curve is obtained by performing the fit using simulated events with  $m_t = 172.5 \text{ GeV}$ . For comparison, the corresponding curves for the counting cross-check analysis are also shown. The two horizontal lines represent the values in the PLR that are used to determine the 68% and 95% confidence level (CL) intervals for the signal strength. (right) Comparison of the values of the signal strength extracted for different combinations of events for the distribution-based default analysis (solid circles) and the cross-check counting analysis (open circles). The horizontal bars represent the total uncertainties, except the beam energy uncertainty. The shaded bands represent the uncertainty in the final combined signal strength obtained from the distribution-based and cross-check analyses.

The signal strength is measured in a region of phase space where the lepton has  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.1$ , and at least one jet has  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.5$ . The resulting visible  $t\bar{t}$  cross section in this phase-space region is determined to be

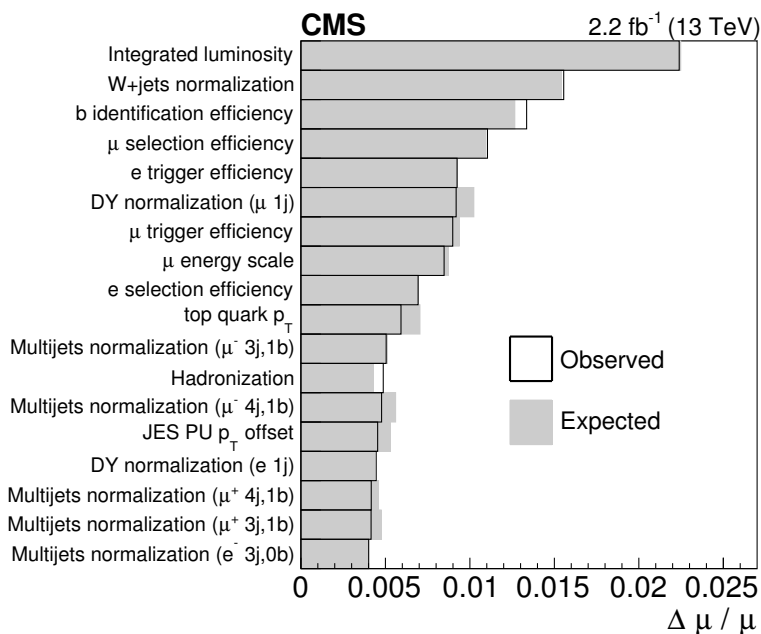
$$\sigma_{t\bar{t}}^{\text{vis}} = 208.2 \pm 0.4 (\text{stat}) \begin{matrix} +5.5 \\ -4.9 \end{matrix} (\text{syst}) \pm 4.8 (\text{lumi}) \text{ pb},$$

where the last uncertainty is from the integrated luminosity.

The extrapolation to the full phase space is performed by using the acceptance estimated from the  $t\bar{t}$  simulation. Using POWHEG, we determine the acceptance to be  $0.2345 \pm 0.0001 (\text{stat}) \begin{matrix} +0.0044 \\ -0.0043 \end{matrix} (\text{syst})$ , where the systematic uncertainty comes from changing  $\mu_R/\mu_F$  ( $\pm 0.0017$ ), considering the CT14 PDF and  $\alpha_S$  uncertainties ( $\begin{matrix} +0.0009 \\ -0.0007 \end{matrix}$ ) [76], and changing the parton shower algorithm used to interface with the matrix-element generator, i.e., PYTHIA 8 vs. HERWIG++, ( $\pm 0.0039$ ). The total uncertainty associated with the extrapolation is estimated to be 1.6%. This uncertainty is added in quadrature to the systematic uncertainty obtained in the fitted fiducial region when extrapolating the measurement to the full phase space.

Summing the statistical (0.2%), systematic (3.0%), and integrated luminosity (2.3%) uncertainties in quadrature, we obtain a total relative uncertainty in the  $t\bar{t}$  cross section of 3.9%. The final result is:

$$\sigma_{t\bar{t}} = 888 \pm 2 (\text{stat}) \begin{matrix} +28 \\ -26 \end{matrix} (\text{syst}) \pm 20 (\text{lumi}) \text{ pb},$$



**Figure 4.** Estimated change  $\Delta\mu$  in the measured signal strength  $\mu$ , coming from the listed experimental and theoretical sources of uncertainties in the main analysis. The open bars represent the values of the observed impact relative to the fitted signal strength. The values are compared to the expectations (shaded bars) by performing the fit using simulated events with  $m_t = 172.5$  GeV. The various contributions are shown from the largest to the smallest observed impact.

in agreement with the NNLO+NNLL prediction [45] and the measurement derived from analyzing events in the electron + muon final state from the same data set [26].

The result can be reinterpreted to extract the pole mass  $m_t$  of the top quark by using the dependence of the cross section on this parameter. We make use of the TOP++ program [45] and the CT14 NNLO PDF [76] to parametrize the dependence of the cross section on the top quark mass. The parametrization used is:

$$\sigma(m_t) = \sigma(m_{\text{ref}}) \left( \frac{m_{\text{ref}}}{m_t} \right)^4 \left[ 1 + a_1 \left( \frac{m_t}{m_{\text{ref}}} - 1 \right) + a_2 \left( \frac{m_t}{m_{\text{ref}}} - 1 \right)^2 \right], \quad (4.4)$$

where  $m_{\text{ref}} = 172.5$  GeV is the reference mass value, and  $a_1$  and  $a_2$  are coefficients determined after performing the calculations with various  $m_t$  hypotheses. The effects induced by the choice of  $\mu_R/\mu_F$ , the uncertainty in the PDF+ $\alpha_S$ , and uncertainties in the beam energy, are evaluated by recomputing the cross section after changing these parameters within their uncertainties. The resulting typical uncertainties in  $\sigma(m_t)$  amount to  $^{+2.5\%}_{-3.7\%}$ ,  $^{+2.7\%}_{-2.6\%}$ , and  $\pm 0.23\%$ , respectively. The latter reflects a  $\pm 0.1\%$  uncertainty in the beam energy at which the data have been collected [77].

To measure the pole mass, the likelihood function (eq. (4.2)) is reparametrized, transforming  $\mu$  into a functional form that depends on the top quark mass

$$\mu(m_t) = \frac{\sigma(m_t)}{\sigma_{\text{th}}} \frac{A}{A(m_t)}, \quad (4.5)$$

Source	$\Delta m_t$ [GeV]
Uncertainties from the fit in the fiducial region	-2.2 / +2.5
Extrapolation to the full phase space	-0.7 / +1.1
Beam energy	-0.08 / +0.12
$\mu_R/\mu_F$ and PDF+ $\alpha_S$	-0.9 / +1.1
Total	$\pm 2.7$

**Table 1.** The source and value of the systematic uncertainties in the measurement of  $m_t$ .

where the last factor ( $A/A(m_t)$ ), is a mass-dependent correction to the acceptance. Using simulated  $t\bar{t}$  samples with different  $m_t$ , we find that the acceptance changes by 0.08% per  $\Delta m_t = 1$  GeV.

The uncertainty in the extrapolation, as well as the theoretical uncertainties that affect the parameterization as a function of  $m_t$  coming from the choices of  $\mu_R/\mu_F$ , PDF,  $\alpha_S$ , and beam energy, are added as extra nuisance parameters in the fit for the pole mass. With the exception of  $\mu_R/\mu_F$ , which is defined through a log-uniform probability distribution consistent with the procedure adopted in ref. [27], the remaining uncertainties are assigned a log-normal function. After repeating the maximum-likelihood fit, we obtain

$$m_t = 170.6 \pm 2.7 \text{ GeV},$$

where the quoted uncertainty contains both statistical and systematic contributions. The result agrees with that obtained using the NNPDF3.0 NNLO PDF [28]:  $m_t = 170.3^{+2.6}_{-2.7}$  GeV. The latter is only used as a cross-check as the NNPDF3.0 PDF includes top-quark-related data in the determination of the proton PDFs. In both cases, the best-fit value is determined by fixing the nuisance parameter associated with the choice of the  $\mu_R$  and  $\mu_F$  ratio to its post-fit value, and repeating the scan of the likelihood. This procedure is adopted to resolve the almost degenerate behavior of the likelihood, induced through the use of a log-uniform pdf assigned to the choice of the  $\mu_R$  and  $\mu_F$  ratio.

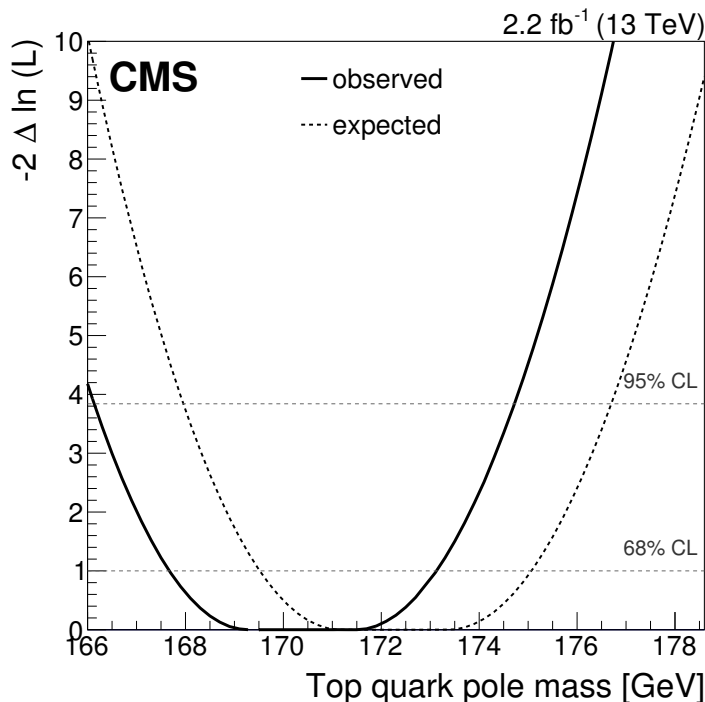
Figure 5 shows the variation of the likelihood as a function of the top quark pole mass. For comparison, the expected likelihood from the Asimov set of nuisance parameters at  $m_t = 172.5$  GeV is shown.

The impact of each source of systematic uncertainty in the values corresponding to the fit is estimated using a similar procedure to the one described above for the cross section measurement. Table 1 summarizes the estimated uncertainties in the determination of  $m_t$  from the measured cross section.

## 5 Summary

A measurement of the  $t\bar{t}$  production cross section at  $\sqrt{s} = 13$  TeV has been presented by CMS in final states containing one isolated lepton and at least one jet. The acceptance in the fiducial part of the phase space is estimated with an uncertainty of 1.6% and has a negligible dependence on  $m_t$ . By performing a simultaneous fit to event distributions in 44 independent categories, we measure the strength of the  $t\bar{t}$  signal relative to the





**Figure 5.** Dependence of the likelihood on the top quark pole mass (solid curve). The expected dependence from the simulation, using the a priori set of nuisance parameters with their expected values at  $m_t = 172.5$  GeV, is shown for comparison as the dotted curve. The changes in the likelihood corresponding to the 68% and 95% confidence levels (CL) are shown by the dashed lines.

NNLO+NNLL [45] computation with an uncertainty of 3.9%. We obtain an inclusive  $t\bar{t}$  production cross section  $\sigma_{t\bar{t}} = 888 \pm 2$  (stat)  $^{+28}_{-26}$  (syst)  $\pm 20$  (lumi) pb, which is compatible with the standard model prediction, competing in precision with it [45] and with similar measurements of this quantity at the same  $\sqrt{s}$  [24–26]. In addition, the top quark pole mass,  $m_t$ , is extracted at NNLO using the same data and the CT14 PDF set and found to be  $m_t = 170.6 \pm 2.7$  GeV. This value is in good agreement with measurements using other techniques.

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