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Measurement of the t -channel single top quark cross section in proton-proton collisions at $\sqrt{s} = 5.02$ TeV

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Abstract

The single top quark t -channel production cross section is measured in proton-proton collisions at the CERN LHC at $\sqrt{s} = 5.02$ TeV, using data recorded with the CMS detector in 2017, corresponding to an integrated luminosity of 302 pb^{-1} , and resulting in the first CMS measurement of the process at that energy. Events with one electron or muon and two or more jets, among which at least one is identified as originating from a b quark fragmentation, are analyzed. The combined cross section of single top quark (tq) and single top antiquark ($\bar{t}q$) production is $\sigma(tq + \bar{t}q) = 25.5^{+3.6}_{-3.5}(\text{stat})^{+4.2}_{-3.9}(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb}$. The individual cross sections are measured to be $\sigma(tq) = 17.7^{+2.9}_{-2.7}(\text{stat})^{+2.6}_{-2.4}(\text{syst}) \pm 0.3(\text{lumi}) \text{ pb}$ and $\sigma(\bar{t}q) = 6.7^{+2.4}_{-1.6}(\text{stat})^{+2.1}_{-2.5}(\text{syst}) \pm 0.1(\text{lumi}) \text{ pb}$. Their ratio is measured to be $\mathcal{R}_{t\text{-ch}} = 2.7^{+1.5}_{-0.8}(\text{stat})^{+1.2}_{-0.3}(\text{syst})$. The absolute value of the Cabibbo–Kobayashi–Maskawa matrix element is found to be $|f_{LV} V_{tb}| = 0.92 \pm 0.09(\text{exp}) \pm 0.01(\text{theo})$. The measurements are in good agreement with the standard model predictions at next-to-next-to-leading order accuracy in quantum chromodynamics.

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1 Introduction

The top quark is the heaviest fundamental particle discovered so far. Because of its large mass and decay width, it has a very short lifetime of about 10^{-25} s [1], an order of magnitude shorter than the characteristic timescale on which hadron bound states form. As a consequence, it is the only quark that can be studied as an asymptotically free particle. At the LHC, single top quark production in proton-proton (pp) collisions proceeds dominantly via the t -channel process, yielding polarized top quarks. Single top quarks in the t channel are produced with the exchange of a W boson through an initial-state bottom (b) quark. This results in sensitivity to the b quark parton distribution function (PDF), in particular in the top quark to antiquark cross section ratio. The t channel has a characteristic final-state topology with the presence of a light quark recoiling against the top quark. Figure 1 shows representative Feynman diagrams of t -channel single top quark and antiquark production. The single top quark production cross section is proportional to the squared Cabibbo–Kobayashi–Maskawa matrix element $|V_{tb}|$, allowing for a direct measurement of this quantity to further test the standard model (SM), including the assumption that only three quark families exist [2, 3].

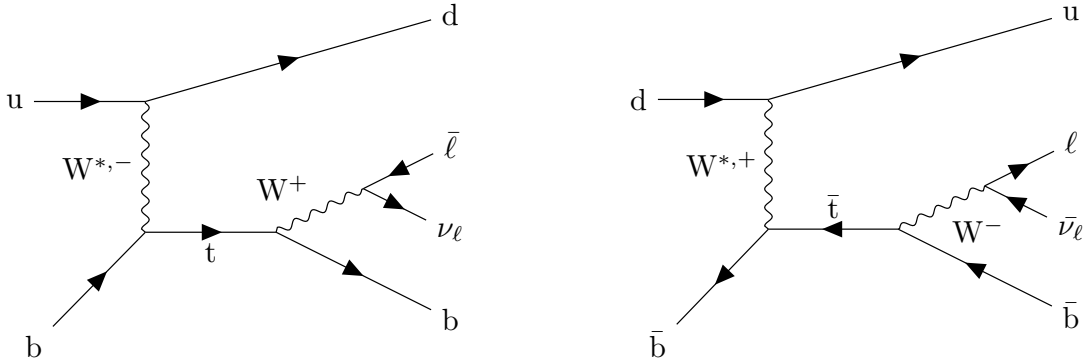


Figure 1: Representative leading-order Feynman diagrams for single top quark (left) and antiquark (right) production via the t channel.

A measurement of single top quark production in the t channel was performed for the first time at the Tevatron collider at Fermilab [4]. More recently, both the ATLAS and CMS Collaborations have reported measurements of the cross section for single top quark production in the t channel using LHC data collected at $\sqrt{s} = 7, 8$, and 13 TeV [5–13], both inclusively and differentially, and with increased precision. The ATLAS Collaboration has measured the process at $\sqrt{s} = 5.02$ TeV using data corresponding to an integrated luminosity of 255 pb^{-1} , obtaining a cross section of $\sigma(tq + \bar{t}q) = 27.1^{+6.2}_{-5.5} \text{ pb}$, in agreement with the SM prediction [14].

This paper presents the first CMS measurement of the single top quark production cross section at $\sqrt{s} = 5.02$ TeV, using data collected by CMS during a special LHC run in 2017, corresponding to an integrated luminosity of 302 pb^{-1} . Data recorded in the same run have been analyzed by CMS to perform several measurements, including cross sections of diboson [15] and top quark pair ($t\bar{t}$) [16, 17] production. Performing measurements at various beam energies provides interesting stress tests for the theory, probing whether current calculations correctly describe the energy dependence of the measured processes. Moreover, in the study of the b quark PDF in the proton, complementary insight can be gained by probing different regions of the proton momentum fraction. A distinct feature of this data sample is the low number of interactions per bunch crossing (pileup) with respect to the standard operating conditions of the LHC, yielding a cleaner detector environment, and improved detection and reconstruction. In this measurement, the top quark is reconstructed via the leptonic decay channel of the

W boson, $W \rightarrow \ell \nu$ (with $\ell = e, \mu$), since it provides a cleaner experimental signature when compared to the fully hadronic W boson decay channel. The measured cross sections are obtained by performing binned maximum likelihood (ML) fits of histogram templates to the data in several event categories.

This paper is organized as follows. A brief description of the CMS detector is given in Section 2. Section 3 describes the data used for the measurement, as well as the Monte Carlo (MC) simulation samples, followed by the object reconstruction and event selection in Section 4. Background estimation methods are covered in Section 5, while systematic uncertainties are described in Section 6. Results are discussed in Section 7, and the summary is given in Section 8. Tabulated results from this analysis are provided in the HEPData record [18].

2 The CMS detector and object reconstruction

The CMS apparatus [19, 20] is a multipurpose, nearly hermetic detector, designed to trigger on [21–23] and identify electrons, muons, photons, charged and neutral hadrons [24–26]. Its central feature 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 (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are reconstructed using gas-ionization detectors interleaved with the layers of the steel flux-return yoke outside the solenoid. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Refs. [19, 20].

Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μ s [21]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 30 kHz in this special run before data storage [22, 23]. We consider in the analysis those events in which the trigger detected at least one electron (muon) with transverse momentum $p_T > 20$ (17) GeV.

The particle-flow (PF) algorithm [27] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex (PV) as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the associated energy deposits in the ECAL and HCAL, corrected for the calorimeter response to hadronic showers. In addition, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Finally, the missing transverse momentum $\vec{p}_T^{\text{miss}}$ is defined as the negative vector p_T sum of all PF candidates [28].

Jets are clustered from all objects reconstructed by the PF algorithm using the anti- k_T algorithm [29, 30] with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average,

within 5–10% of the true momentum over the whole p_T spectrum and detector acceptance. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. Simulated particle-level jets are obtained by clustering stable particles originating from the hadronization of final-state partons. To determine any residual differences between the jet energy scale (JES) in data and in simulation, measurements of the momentum balance are used, leading to appropriate correction factors. Additional selection criteria are applied to each jet to remove jets potentially dominated by instrumental effects or reconstruction failures. This is done by rederiving the corrections for this specific run with the methods used in Refs. [31, 32]. Jets are identified as coming from the fragmentation of bottom quarks using the medium working point of the DEEPCSV b tagging algorithm [33], calibrated at 13 TeV, as differences with the 5.02 TeV data set are negligible. Nevertheless, the corresponding efficiencies are derived for the latter dataset. For jets with $p_T > 20$ GeV in $t\bar{t}$ events we obtain a b tagging efficiency of 68%, and mistag rates of 12% and 1.1% for c quark and light-flavour quark or gluon jets, respectively. We will refer to jets in general as “j”, to b-tagged jets as “b”, and to untagged (non-b-tagged) jets as “u”.

A gradient boosted decision tree (BDT) based on the shower shape and the track quality of the electron candidates [24] is used to identify electrons. Electron candidates are required to satisfy $|\eta| < 2.4$ (excluding the region $1.48 < |\eta| < 1.57$, the transition region between the barrel and endcaps, where the electron reconstruction is suboptimal) and $p_T > 20$ GeV. A veto is applied on candidates that are matched to a secondary vertex consistent with a photon conversion, or have a missing hit in the inner layer of the tracker. Reconstructed muon candidates are required to have $|\eta| < 2.4$ and $p_T > 20$ GeV. They must also fulfil criteria on the geometrical matching between the tracks reconstructed by the silicon tracker and the muon system, as well as on the quality of the global muon track fit combining information from both subdetectors [25]. Both electron and muon energy scales and resolution are corrected according to measurements using Drell–Yan (DY) events in simulation and low-pileup pp collision data at 5.02 TeV [24, 25].

Pileup collisions may cause events to contain multiple interaction vertices. The PV is taken to be the vertex corresponding to the hardest scattering in the event, which is evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [34].

Lepton candidates must be consistent with originating from the PV. This is guaranteed by requiring the longitudinal impact parameter to be smaller or equal to 0.1 cm and the transverse impact parameter smaller than 0.02 (0.05) cm for electrons (muons). Electrons and muons must also satisfy a requirement on their relative isolation (I_{rel}), defined as the scalar p_T sum of all the particles inside a cone around the lepton direction, excluding the lepton itself, divided by the lepton p_T . The cone size, defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where ϕ is the azimuthal angle, changes as a function of the lepton p_T as $\Delta R(p_T) = 10 \text{ GeV}/p_T$ if $50 < p_T < 200$ GeV, $\Delta R = 0.2$ if $p_T < 50$ GeV, and $\Delta R = 0.05$ for $p_T > 200$ GeV. Electrons (muons) must have isolation $I_{\text{rel}} < 0.085$ (0.325).

A BDT is used to distinguish leptons coming from hadron decays and misidentified leptons, collectively denoted “nonprompt” leptons, from those produced in the decays of W, Z, or Higgs bosons (“prompt”). The BDT is trained using MC simulated events and exploits the properties of the jet which contains the lepton, as well as properties of the lepton itself, irrespective of the isolation requirement described above. It is specifically calibrated for this run, following the same methods as in Refs. [35, 36]: the chosen working point for the BDT score yields more than 99% prompt lepton efficiency and a nonprompt rejection factor higher than 55%. Leptons clustered inside a jet satisfying the loose working point of the DEEPCSV b tagging algorithm [33] are rejected to further suppress nonprompt leptons originating from b

hadron decays. Using this working point with $t\bar{t}$ events, we obtain a b tagging efficiency of 84%, and mistag rates of 41% and 11% for c and light jets with $p_T > 20$ GeV.

3 Data and simulated samples

The measurement is performed using pp collision data collected during a low-energy (5.02 TeV) and low-intensity LHC run. The maximum instantaneous luminosity delivered by the LHC during this period was $\mathcal{L} = 1.37 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, and the mean of the pileup distribution was 2, to be compared with the standard conditions in the 13 TeV run in 2017, where $\mathcal{L} = 2.07 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, and the mean pileup was 32.

This analysis considers the t -channel process as signal, and the following processes as sources of background: single top quark production in the s channel, and in association with a W boson (tW); $t\bar{t}$ production; quark-antiquark annihilation into lepton-antilepton pairs through Z boson or a virtual photon exchange with additional jets (DY +jets); W boson production with additional jets (W +jets) and SM events composed uniquely of jets produced through the strong interaction (QCD multijet). Signal and background contributions are simulated using several MC event generators, but for the QCD multijet background. This contribution is estimated using both MC event generators and control data samples, as further explained in Section 5. The propagation of the generated particles through the CMS detector and the modelling of the detector response in simulations are performed with the GEANT4 [37] package. The pileup distribution in the simulated samples roughly matches that observed in data.

The simulated t - and s -channel events are generated at next-to-leading order (NLO) in perturbative QCD (pQCD) using POWHEG (v2) [38–41]. A nominal top quark mass (m_{top}) of 172.5 GeV and the five-flavour scheme is used. The NNPDF3.1 [42] NNLO set is used as the default PDF set. A similar setup is used for the simulation of tW and $t\bar{t}$ production. In the case of tW , the diagram removal scheme [43] is employed to treat the interference with $t\bar{t}$ events, using a fixed scale scheme.

The MADGRAPH5_aMC@NLO (v2.4.2) generator [44] is used to simulate DY +jets and W +jets processes. The simulation is performed at NLO in pQCD and includes up to two extra partons at the matrix element (ME) level. The FxFx matching scheme [45] is used to match jets from the ME calculations to the parton shower (PS). For all processes, simulated events are interfaced with PYTHIA (v8.230) [46], using the CP5 tune [47] for PS, hadronization, and the underlying event description.

The individual predictions of the cross sections of single top quark (tq) and single top antiquark ($\bar{t}q$) production in the t channel are $\sigma(tq) = 20.3^{+0.5}_{-0.4} \text{ pb}$ and $\sigma(\bar{t}q) = 10.0^{+0.2}_{-0.3} \text{ pb}$, respectively. The cross sections were calculated with the MCFM program (v10.1) [48] and next-to-next-to-leading order (NNLO) in quantum chromodynamics (QCD), using m_{top} as 172.5 GeV and the five-flavour scheme, in which the bottom quark is treated as a massless parton constituent of the proton. The quoted uncertainties include the ones due to the choice of the renormalization (μ_R) and the factorization (μ_F) scales (their nominal values being $\mu_R = \mu_F = 175 \text{ GeV}$), and the ones in the proton PDFs, and in the value of the strong coupling constant $\alpha_s(m_Z)$, where m_Z is the mass of the Z boson. The combined PDF and α_s uncertainties were determined at 68% confidence level (CL) according to the Hessian representation of the PDF4LHC21 PDF set [49].

The cross section prediction used for the normalization of $t\bar{t}$ events is calculated with the TOP++ program [50] at NNLO in pQCD including soft-gluon resummation at next-to-next-to-leading logarithmic (NNLL) accuracy [51]. The SM prediction for tW events is calculated at

approximate NNLO accuracy, meaning an NLO calculation for QCD order of approximation, matched with soft gluon resummation [52] at NNLL, where a logarithmic expansion of soft and collinear gluon radiation is used. For W+jets and DY+jets, the calculation is performed at NNLO in QCD and NLO in electroweak (EW) orders of approximation [53]. Finally, the calculation for s -channel events is done at the same order of approximation as for the t -channel signal, described in Section 1. The signal and background simulated samples used in the analysis are summarized in Table 1, as well as their predicted cross sections, reported in the best available fixed-order calculations and used to normalize the simulated events.

Table 1: Summary of simulated samples used to model the signal and background processes. The last column corresponds to the pQCD and EW order of approximation used to normalize the distributions provided by the generators.

Process	Generator + PS	Cross section, σ_{norm} (pb)	Order of σ_{norm} approximation
t channel	POWHEG + PYTHIA8	30.3 ± 0.6	NNLO [48]
$t\bar{t}$	POWHEG + PYTHIA8	69.5 ± 3.6	NNLO + NNLL [50, 51]
tW	POWHEG + PYTHIA8	6.54 ± 0.36	Approximate NNLO [52]
s channel	POWHEG + PYTHIA8	2.74 ± 0.07	NNLO [54]
W+jets	MADGRAPH5_aMC@NLO + PYTHIA8	$21\,160 \pm 330$	NNLO [QCD] + NLO [EW] [53]
DY+jets	MADGRAPH5_aMC@NLO + PYTHIA8	$3\,647 \pm 63$	NNLO [QCD] + NLO [EW] [53]

4 Event selection and background discrimination

The final state targeted by this analysis consists of a lepton (electron or muon) and a neutrino from the W boson decay, a jet from the b quark hadronization, and an additional forward jet from the hadronization of a light quark. Candidate events are, consequently, required to contain exactly one selected electron or muon, and at least two jets. Only jets with $p_T > 25$ GeV, $|\eta| < 4.7$, and whose ΔR distance from any lepton is greater than 0.4 are considered. In order to reduce the background contamination from QCD multijet events, the magnitude of $\vec{p}_T^{\text{miss}}$ must be greater than 30 GeV, and the transverse mass of the lepton and missing transverse momentum (m_T^W) must be greater than 50 GeV. It is defined as:

$$m_T^W = \sqrt{2p_T^\ell p_T^{\text{miss}}(1 - \cos \Delta\phi)}, \quad (1)$$

where p_T^ℓ is the p_T of the selected lepton and $\Delta\phi$ is the azimuthal angle between the lepton and $\vec{p}_T^{\text{miss}}$. To further increase the purity of the signal, events are required to have $H_T' > 170$ GeV, where H_T' is defined as the scalar sum of p_T^{miss} and the p_T of the jets and of the lepton. The region defined by these criteria is known as the signal region (SR). Events are classified according to their jet and b-tagged jet multiplicities: those considered for the measurement have exactly two reconstructed jets, only one of which is b tagged, or exactly three reconstructed jets, with either one or two of them that are b tagged. These categories are denoted as 2j1b, 3j1b, and 3j2b, respectively. The two latter categories are intended to improve constraints on the $t\bar{t}$ background. All the categories are further split according to the flavour and the electric charge of the selected lepton in the event, resulting in twelve mutually exclusive analysis categories.

The resulting observed number of events in data and the expected number of events for signal and background in each of the twelve categories of the analysis are shown in Fig. 2. Figure 3

shows the leading jet (in p_T) transverse momentum and pseudorapidity inclusively in lepton charge and flavour for the 2j1b jet category, which contains the majority of the signal events.

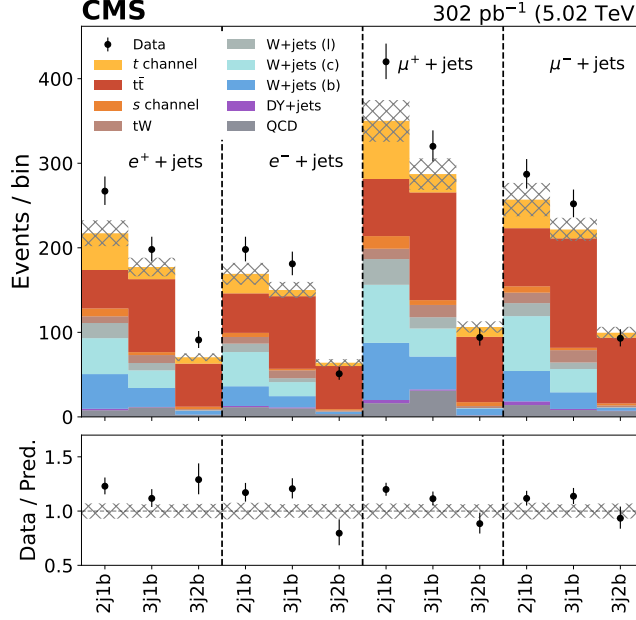


Figure 2: Observed and predicted number of events in each of the twelve categories considered in the analysis, before the ML fit. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty in the prediction. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the data-to-prediction ratio. The normalizations of the processes are those of the SM predictions except for QCD, which is estimated from data. The W+jets background is split as explained in Section 5.

4.1 Top quark reconstruction

Top quarks (antiquarks) give rise to positively (negatively) charged leptons. The four-momentum of a top quark or antiquark is reconstructed from its decay products: the charged lepton, the b jet, and the unobserved neutrino (ν); following the procedure that has already been used in previous CMS analyses [10, 11]. The reconstruction is done in two steps: first a W boson is reconstructed and then it is associated with a b-tagged jet.

To reconstruct the W boson, we first reconstruct the unobserved neutrino. We assign the x and y components of the $\vec{p}_T^{\text{miss}}$ to the momentum of the neutrino, and infer its z component by applying the following constraint on the W boson mass, m_W :

$$m_W^2 = \left(E^\ell + \sqrt{(p_T^{\text{miss}})^2 + (p_z^\nu)^2} \right)^2 - \left(p_x^\ell + p_{T,x}^{\text{miss}} \right)^2 - \left(p_y^\ell + p_{T,y}^{\text{miss}} \right)^2 - \left(p_z^\ell + p_z^\nu \right)^2. \quad (2)$$

This equation leads to the following two solutions:

$$p_z^\nu = \frac{\Lambda p_z^\ell}{(p_T^\ell)^2} \pm \sqrt{\frac{(\Lambda p_z^\ell)^2}{(p_T^\ell)^4} - \frac{(E^\ell p_T^{\text{miss}})^2 - \Lambda^2}{(p_T^\ell)^2}}, \quad (3)$$

where

$$\Lambda = \frac{m_W^2}{2} + p_x^\ell p_{T,x}^{\text{miss}} + p_y^\ell p_{T,y}^{\text{miss}}. \quad (4)$$

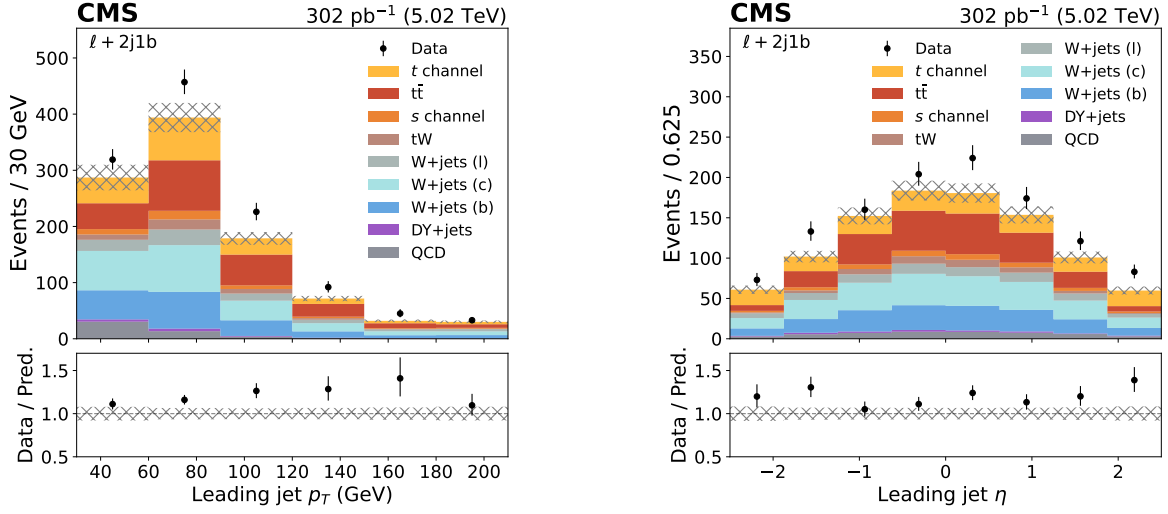


Figure 3: Observed and predicted distributions of the leading jet p_T (left) and η (right), in the 2j1b category, before the ML fit. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty in the prediction. The lower panels show the data-to-prediction ratio. The first and last bins in each distribution include underflow and overflow events, respectively. The normalizations of the processes are those of the SM predictions except for QCD, which is estimated from data. The W+jets background is split as explained in Section 5.

There can either be two real solutions for p_z^ν , or the solutions have an imaginary component. In the first case, the solution with the smallest absolute value is chosen. In the second, an extra constraint is adopted: the imaginary component is eliminated by replacing $p_{T,x}^{\text{miss}}$ and $p_{T,y}^{\text{miss}}$ with modified values p_x^ν and p_y^ν such that $m_T^W = m_W$, but still respecting the constraint from Eq. (2). This is achieved by setting the discriminant in Eq. (3) to zero. This leads to a quadratic relation between p_x^ν and p_y^ν with two possible solutions: the one with the smallest difference between p_T^ν and p_T^{miss} is chosen.

The W boson is reconstructed from the neutrino candidate and the selected lepton. In the 2j1b and 3j1b regions, the b-tagged jet is associated with the b quark from the top quark decay and the non-b-tagged jet with the highest p_T is associated with the recoiling light quark. In the 3j2b region, the b-tagged jet with the larger b tag discriminator value is associated with the b quark from the top quark decay. Finally, the top quark is reconstructed from the W boson candidate and the selected b-tagged jet. Its mass is then used as an input variable to the multivariate analysis (MVA) described in Section 4.2.

4.2 Multivariate analysis discriminator

In the 2j1b categories, which contain most of the signal events, W+jets events constitute the largest source of background, while $t\bar{t}$ dominates in the other categories. A dedicated MVA binary classifier has been developed for these categories in order to better discriminate signal from these backgrounds, while for the other categories a single observable, the absolute value of η of the untagged jet ($|\eta_{u_0}|$), is used. Figure 4 shows the distribution of the latter variable in those categories.

As for the MVA, a random forest [55] has been trained inclusively in lepton charge and flavour, using a mix of $t\bar{t}$ and W+jets events as background sample and t -channel events as signal.

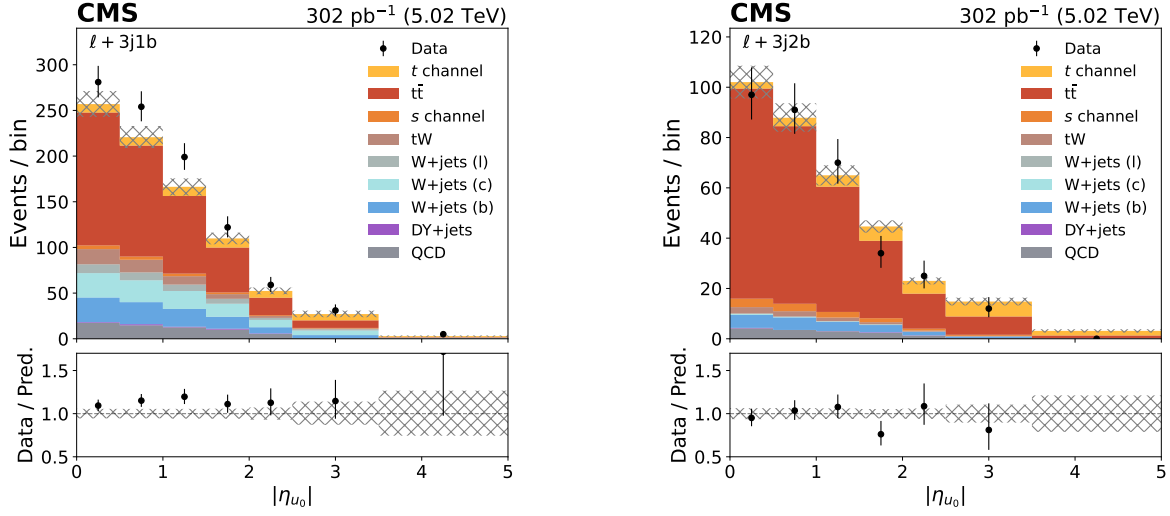


Figure 4: Observed and predicted distributions of $|\eta_{u_0}|$ in the 3j1b (left) and 3j2b (right) categories, before the ML fit. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty in the prediction. The lower panels show the data-to-prediction ratio. The normalizations of the processes are those of the SM predictions except for QCD, which is estimated from data. The W+jets background is split as explained in Section 5.

Subsets of the simulated samples, orthogonal to those used in the rest of the analysis have been employed for this purpose: 70% of these events are used for the training and the remaining ones for the testing. The variables used in the classifier are described in Table 2, ordered by their discriminating power.

Figure 5 shows the comparison of data and prediction for the most discriminating input variable of the MVA, the absolute value of the η of the leading untagged jet ($|\eta_{u_0}|$), and the output MVA discriminator in the 2j1b category. A reasonable agreement is observed between data and predictions for all variables used in the classifier before the fit.

5 Background estimation

The event selection is designed to maximize the signal contribution over the expected background contamination. The background contributions come from the following processes: $t\bar{t}$, tW , W+jets production in the single-lepton final state, QCD multijet events when a jet is misidentified as a lepton, and DY+jets events. The estimation of these background contributions is based on MC simulation, except for the QCD multijet contribution, which is determined in a hybrid approach, exploiting control samples in data as described later. The W+jets background is split according to the generator level flavour of the additional jets into W+b jets if at least one b jet is found in the analyzed event, W+c jets if there are no b jets but there is at least one c jet, and W+light jets (including light quark or gluon jets) otherwise. The split is included to handle better flavour dependent tagging efficiencies and production uncertainties. As a further check of this process, a validation region has been defined by inverting the $H_T' > 170$ GeV requirement, thus enhancing the contribution of W+jets events. In this region, good agreement between data and prediction is found.

In order to estimate the QCD multijet contribution, a two-step procedure is applied, using a

Table 2: Summary of the variables used for training the MVA classifier in the 2j1b categories. The variables are ordered according to their discriminating power, assessed via the mean decrease in impurity method [55]. “Leading” jet refers to the jet with the highest p_T in the event.

Variable	Definition
$ \eta_{u_0} $	The absolute value of η of the untagged jet
$ \Delta\eta(u, b) $	The absolute value of the difference in η between the tagged and untagged jets
m_T^W	The transverse mass of ℓ and p_T^{miss}
$m_{\text{top}}^{\text{reco}}$	The invariant mass of the reconstructed top quark
$\Delta R(j, j')$	The ΔR between the two jets
$m(j, j')$	The invariant mass of the two jets
$m(\ell, b)$	The invariant mass of the lepton and the b-tagged jet
$H_T(j, \ell)$	The scalar sum of the p_T of all jets and the lepton in the event
H_T'	The scalar sum of p_T^{miss} and the p_T of the jets and of the lepton in the event
$ \Delta\eta(\ell, u) $	The absolute value of the difference in η between the lepton and the untagged jet
$ \Delta\phi(W, ub) $	The absolute value of the difference in ϕ between the reconstructed W boson and the jet pair
$ \Delta p_T(W, ub) $	The absolute value of the difference in p_T between the reconstructed W boson and the jet pair

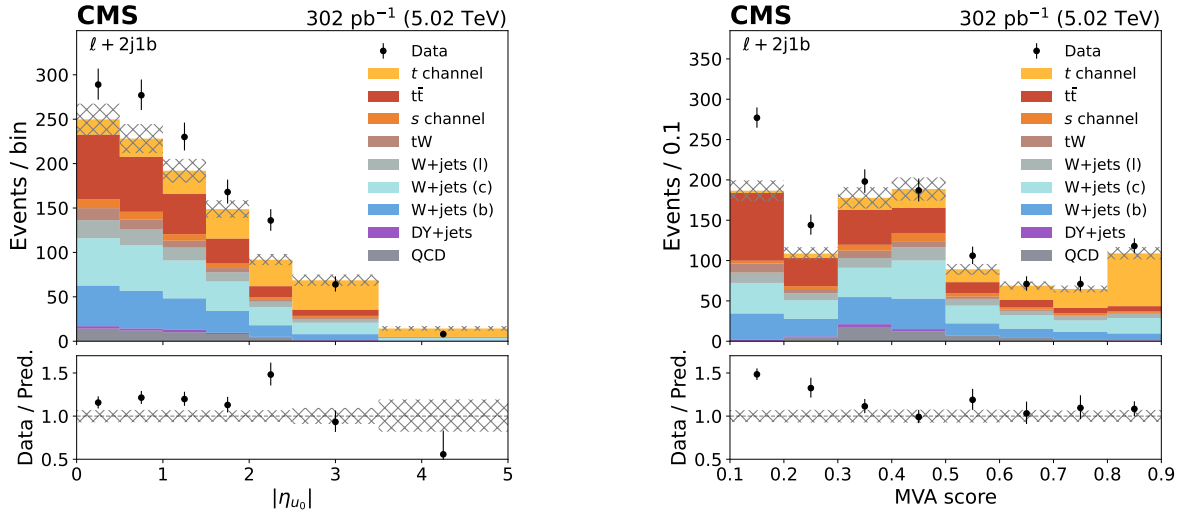


Figure 5: Observed and predicted distributions of the most discriminating input variable used in the random forest training, $|\eta_{u_0}|$ (left), and the output MVA discriminator (right), in the 2j1b category, before the ML fit. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty in the prediction. The lower panels show the data-to-prediction ratio. The first and last bins in the MVA output distribution include underflow and overflow events, respectively. The normalizations of the processes are those of the SM predictions except for QCD, which is estimated from data. The W +jets background is split as explained in Section 5.

control region (CR) defined following the same criteria as the SR, but with the lepton failing either the I_{rel} or prompt lepton BDT requirements described in Section 2. In the first step, the number of QCD background events in the SR ($N_{\text{QCD}}^{\text{SR}}$) is estimated for each of the twelve event categories. To do so, extrapolation factors from the CR to SR are obtained from a sample of events with $p_{\text{T}}^{\text{miss}} < 25 \text{ GeV}$, where a large contribution of QCD background and low signal contamination is observed. The values for $N_{\text{QCD}}^{\text{SR}}$ are calculated as

$$N_{\text{QCD}}^{\text{SR}} = \left(N_{\text{obs}}^{\text{CR}} - N_{\text{MC}}^{\text{CR}} \right)_{\text{yields}} \frac{N_{\text{obs, low } p_{\text{T}}^{\text{miss}}}^{\text{SR}} - N_{\text{MC, low } p_{\text{T}}^{\text{miss}}}^{\text{SR}}}{N_{\text{obs, low } p_{\text{T}}^{\text{miss}}}^{\text{CR}} - N_{\text{MC, low } p_{\text{T}}^{\text{miss}}}^{\text{CR}}}, \quad (5)$$

where the total normalization is expressed as the product of two components: an extrapolation factor (second term on the right-hand side), which accounts for the transfer from the CR to SR, and a category-specific normalization factor, estimated from events in the CR that satisfy the nominal $p_{\text{T}}^{\text{miss}}$ requirement (first term on the right-hand side). Both factors are determined after subtracting the contributions, derived from the simulated samples, of the signal and the other background sources considered ($N_{\text{MC}}^{\text{SR}}$), from the observed numbers of events in data ($N_{\text{obs}}^{\text{SR}}$).

In a second step, the shapes of variable distributions are determined from QCD multijet simulated samples. For each distribution, a template used in all categories is obtained by summing all the contributions to all the regions. Here, the selection requirements in $p_{\text{T}}^{\text{miss}}$, m_{T}^{W} , and H_{T}' described in Section 4 are removed in order to reduce the statistical uncertainty on the prediction having checked that no significant bias is introduced. Individual distributions (per category) are then obtained by normalizing these shapes to the yields obtained in the previous step. The whole procedure is an improved alternative of the one followed in other analysis using this data set [17].

To estimate the normalization uncertainty in the QCD multijet background, the normalization factor is re-evaluated after shifting the $p_{\text{T}}^{\text{miss}}$ requirement by $\pm 5 \text{ GeV}$ in both the SR and CR, and calculating the difference in acceptance, similarly to other analysis using this data set [17]. This leads to a flat normalization uncertainty of 30 (40)% in the μ +jets (e+jets) channel, covering the observed variation. A shape uncertainty is assessed by recalculating the QCD contribution using alternative extrapolation factors, determined independently in bins of the leading lepton p_{T} and $|\eta|$. The QCD multijet background accounts for approximately 7% of the total event yield.

6 Systematic uncertainties

The measurement of $\sigma(tq+\bar{t}q)$ is affected by sources of systematic uncertainty related to the detector effects, background estimation, and theoretical assumptions. The statistical uncertainty coming from the limited size of the simulated samples is incorporated into the ML fit using the Barlow–Beeston “light” method [56]. The experimental uncertainties (considered for all processes) and modelling uncertainties (considered only for the t -channel signal and $t\bar{t}$ background processes) affect both the acceptance and efficiency. The modelling uncertainties account for the choice of μ_{R} and μ_{F} scales, PS scale, ME and PS matching, PDFs, and underlying event tune. Furthermore, a normalization uncertainty is considered for each background process. The total uncertainty is calculated by combining the effects of all the individual systematic components, assuming they are independent. The sources of systematic uncertainties and the methods for their estimation are outlined below.

Lepton-related uncertainties: Lepton reconstruction and identification efficiencies are mea-

sured using DY events in simulation and low-pileup pp collision data at 5.02 TeV, similarly to what is described in Refs. [24]. Corrections are derived using the “tag-and-probe” method [57] as functions of the lepton p_T and η , and are applied to the simulation to match the efficiencies in data. The uncertainty in these corrections is estimated through the variation of different parameters in the fitting templates of the method, as well as in the tag selection criteria, and is propagated to the measurements as one single source per lepton flavour, including the statistical and systematic uncertainties. It is around 0.5% for both lepton flavours.

The HLT trigger efficiency is estimated using a cross-trigger technique. This consists in measuring it in data using the muon trigger as reference for the electron trigger efficiency and vice-versa in the case of muons. The related uncertainty is estimated by combining a statistical contribution, evaluated with the Clopper–Pearson method [58] and a systematic contribution, from simulation to data efficiency ratios in several lepton p_T and $|\eta|$ bins. It is found to be around 1–3% for electrons and 0.8–1.6% for muons.

Jet-related uncertainties: The contribution of the uncertainty in the JES is parametrized as a function of jet p_T and η , usually resulting in variations of no more than a few percent as described in Ref. [31]. Fourteen different sources of uncertainties are considered, and treated as independent nuisance parameters. The uncertainty due to the accuracy of the jet energy resolution (JER) is determined by changing the JER correction scale factor from its nominal value by ± 1 standard deviation (s.d.), depending also on the p_T and η of the jet.

p_T^{miss} -related uncertainty: The uncertainty in p_T^{miss} from the contribution of unclustered energy (energy which is not aggregated into a specific cluster in the calorimeters) is evaluated based on the momentum resolution of the different PF candidates. In addition, JER, JES, and lepton energy scale effects are propagated to p_T^{miss} .

b tagging uncertainties: In order to match the efficiency of the b tagging algorithm evaluated on simulated samples to that observed in data, appropriate scale factors must be applied as a function of p_T and $|\eta|$ of the jets. These scale factors are derived with an associated uncertainty, coming from different sources such as JES and JER. Their effect in the analysis is estimated by varying the scale factors by their uncertainties, and propagating the effect to all the categories in the analysis. Tagging and mistagging are taken as two independent sources of uncertainty.

L1 trigger efficiency: During the data taking, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the region $|\eta| > 2$ caused a trigger inefficiency [21]. Simulations are corrected to mimic this behaviour observed in data. This correction has an inherent uncertainty associated to the method used to calculate it, which is propagated to the measurements by varying the correction by its associated uncertainty.

Scale choice: The uncertainty related to the missing higher-order diagrams in POWHEG is estimated by independently varying each of the μ_F and μ_R choices a factor 2 or 1/2, excluding combinations with variations in opposite directions.

PS scale: The effect of the choice of PS scale is studied by changing separately the scale used for the initial- and final-state radiation by a factor 2 and 1/2 with respect to its nominal value.

ME and PS matching: The effect of the ME and PS matching is taken into account using the h_{damp} parameter of the POWHEG generator, with a nominal value of $(1.4^{+0.9}_{-0.5}) m_{\text{top}}$ [47].

The uncertainty is estimated by varying this parameter, using dedicated signal samples. The variation with respect to the central value of the signal acceptance is taken as the uncertainty. Due to the limited size of the dedicated simulated samples, a smoothing method following the lowess technique is applied [59].

Parton distribution functions: The uncertainty arising from the choice of the proton PDFs is determined by reweighing the sample of simulated signal events according to 100 replicas from the NNPDF3.1 NNLO PDF set [60]. An extra contribution from the variation of $\alpha_S(m_Z)$ corresponding to its uncertainty is considered.

Underlying event tune: The parameters of PYTHIA related to the underlying event tune [47] are adjusted to match observations in data. We consider changes in these parameters as sources of uncertainties and we use dedicated signal samples accounting for these changes. The variation with respect to the central value of the signal acceptance is taken as the uncertainty. Due to the limited size of the dedicated samples, a smoothing method following the lowess technique is applied [59].

Background normalization: The uncertainty in the $t\bar{W}$ production cross section is taken to be 5.6%, and 5.0% is used both for the $t\bar{t}$ production, and the single top quark production in the s channel, based on the theoretical uncertainties [51, 52, 54]. A normalization uncertainty of 40 (30)% is applied to the QCD background in the e +jets (μ +jets) categories and decorrelated per lepton flavour, and jet and b -tagged jet multiplicity bin. Normalization uncertainties of 20% are assigned in the W +jets background estimates (for the three W +light, W + c , and W + b contributions). A 30% normalization uncertainty is assigned to the DY +jets background estimate. These uncertainties are designated following the prescription of other analyses using the same data set, since the detector conditions and analysis strategy are very similar to the ones presented in this work [61, 62].

Pileup and integrated luminosity: Uncertainties related to pileup are not considered since the number of pileup events is small. The uncertainty in the measurement of the integrated luminosity is estimated to be 1.9% [63, 64].

QCD background estimation method: A systematic contribution is considered to account for uncertainties in the shape estimation of the distributions for the QCD multijet background, as discussed in Section 5. The uncertainty is decorrelated per lepton flavour, and jet and b -tagged jet multiplicity bin.

Most of these uncertainties, especially those coming from experimental effects, affect both the shape of the distributions used in the fit and their normalization through acceptance. Modelling uncertainties that are calculated with several weights, such as PDF and scale uncertainties, are estimated for each region of the analysis and applied as normalization uncertainties in each of the regions. Uncertainties of the background normalization and of the integrated luminosity uncertainty are treated as global normalization uncertainties.

7 Signal extraction and results

The cross sections are obtained by performing two independent profile ML fits in the twelve analysis categories, using the CMS COMBINE tool [65]. The fits are performed on the distributions of the MVA score for the 2j1b categories and of $|\eta_{u_0}|$ for the others. The selection of $|\eta_{u_0}|$ is motivated by the distinctive feature of the signal process, where the recoiling light quark tends to be produced in the forward region of the detector. Using the MVA score distribution instead

of $|\eta_{u_0}|$ for the 2j1b categories results in an absolute reduction of 8% in the final uncertainty of the result. The inclusive cross section $\sigma(tq+\bar{t}q)$ is obtained by fitting a common signal strength modifier (r), representing the ratio of the observed signal to the theoretical prediction, to both the tq and $\bar{t}q$ processes. In the case of the individual top quark and antiquark cross sections, $\sigma(tq)$ and $\sigma(\bar{t}q)$, two independent modifiers are fit. Signal strength modifiers are fitted simultaneously with nuisance parameters related to the systematic uncertainties. In the fits, eight bins are used for the MVA score and seven for the leading untagged jet $|\eta|$ distributions, resulting in 88 bins. The MVA score and $|\eta_{u_0}|$ distributions for all the categories after the fit are shown in Fig. 6.

A cross section of $\sigma(tq+\bar{t}q) = 25.5^{+5.6}_{-5.3}$ pb is measured, corresponding to a relative uncertainty of around $\pm 21\%$, with a systematic uncertainty of around $\pm 16\%$, an integrated luminosity uncertainty of $\pm 1.9\%$, and a statistical uncertainty of $\pm 14\%$. The dominant sources of uncertainty are those associated with the b tagging scale factors and the $W+c$ jets normalization. Figure 7 shows the impact of the different systematic uncertainties on the signal strength and the constraints on the nuisance parameters. The impact is defined as the shift $\Delta\hat{r}$ induced in r when the nuisance parameter θ is varied by ± 1 s.d. around the value obtained after the fit. The figure also shows the ratios $(\hat{\theta} - \theta_0)/\Delta\theta$, where $\hat{\theta}$ and θ_0 are the values of a given nuisance parameter after and before the fit, and $\Delta\theta$ is the corresponding uncertainty before the fit. In the case of $W+c$ jets normalization, the ratio is displaced from zero because of the tension between data and prediction in the first two bins in some of the MVA score distributions, related to the difficult modelling of the W +jets background.

Using a similar approach, likelihood scans are performed for the top quark and antiquark cross sections separately. In this case, the likelihood is minimized leaving both the signal strength for the top quark and for the top antiquark cross section unconstrained. The top quark cross section is measured to be $\sigma(tq) = 17.7^{+3.9}_{-3.7}$ pb, corresponding to a relative uncertainty of around $\pm 21\%$, with a systematic uncertainty of $\pm 14\%$, a luminosity uncertainty of $\pm 1.9\%$, and a statistical uncertainty of $\pm 16\%$. The top antiquark cross section is measured to be $\sigma(\bar{t}q) = 6.7^{+3.2}_{-3.0}$ pb, corresponding to a relative uncertainty of around $\pm 46\%$, with a systematic uncertainty of around $\pm 34\%$, a luminosity uncertainty of $\pm 1.9\%$, and a statistical uncertainty of around $\pm 30\%$. The correlation coefficient between the two signal strengths is 0.36 and the two-dimensional confidence region for both parameters is shown in Fig. 8, in which a good agreement with the SM predictions is seen.

Finally, the ratio of the top quark and antiquark cross sections is also extracted by performing a third ML fit to the same distributions, where the cross section ratio and the inclusive cross section are treated as unconstrained parameters. This procedure permits to handle correlated uncertainties correctly, which is not achieved by taking the arithmetic ratio of the previously reported individual cross sections. With this approach, the ratio is found to be $\mathcal{R}_{t-\text{ch}} = 2.7^{+1.5}_{-0.8} (\text{stat})^{+1.2}_{-0.3} (\text{syst}) = 2.7^{+1.9}_{-0.8}$.

In addition to these measurements, the t -channel total cross section can be used to calculate the absolute value of the Cabibbo–Kobayashi–Maskawa ME, $|V_{tb}|$, since it has a dependence on $f_{LV}^2|V_{tb}|^2$. In this context, f_{LV} is an anomalous form factor which is unity under the SM, or $f_{LV} \neq 1$ for physics beyond the SM. Under the assumption that the other MEs, $|V_{td}|$ and $|V_{ts}|$, are significantly smaller than $|V_{tb}|$, and that the top quark decays only to a b quark and a W boson, $|f_{LV}V_{tb}| = 0.92 \pm 0.09 (\text{exp}) \pm 0.01 (\text{theo})$ is measured. The first uncertainty accounts for all the uncertainties in the measurement whereas the second one considers the uncertainties of the theoretical prediction.

Figure 9 presents a summary of t -channel single top quark cross section measurements by

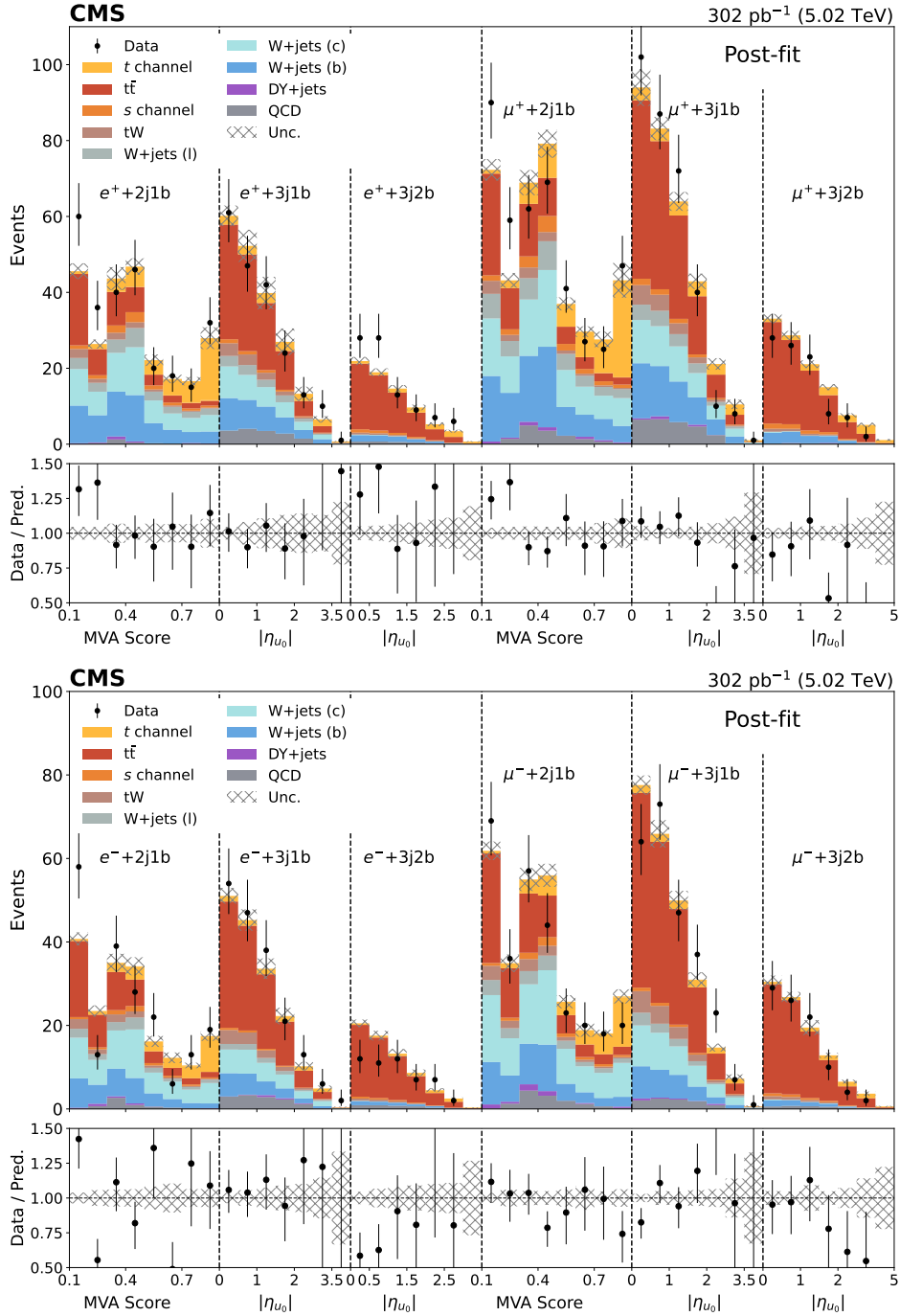


Figure 6: Distributions for the ℓ^+ +jets (upper) and ℓ^- +jets (lower) categories where the prediction parameters are set to the values obtained in the fit. They show the MVA score and $|\eta_{u_0}|$ distributions, which are the fitted variables in the ML fit in the 2j1b category and the categories with three jets, respectively. The vertical error bars represent the statistical uncertainty associated to the data, and the hatched band the uncertainty of the prediction, after the fit. All uncertainties considered in the analysis are included in the uncertainty band. The lower panels show the ratio of data to prediction. The first and last bins in the MVA output distributions include underflow and overflow events, respectively.

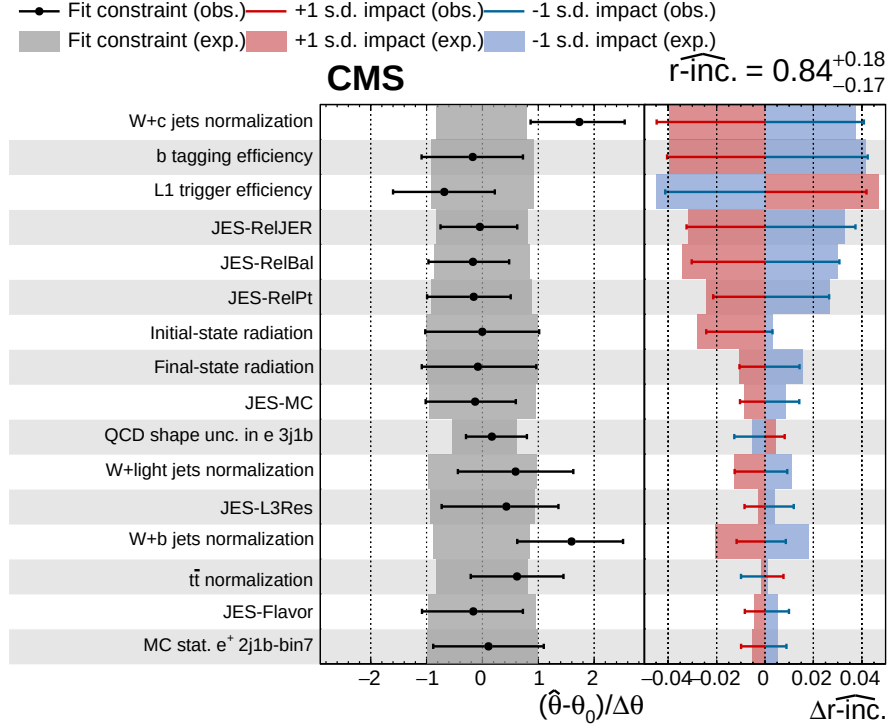


Figure 7: The largest impacts of nuisance parameters on the signal strength, $\Delta r\text{-inc.}$ (right column) and ratios $(\hat{\theta} - \theta_0)/\Delta\theta$ (middle column) for the nuisance parameters listed in the left column from the ML fit used to determine the measured $tq + \bar{t}q$ cross section. The horizontal bars in the middle column show the ratio of the uncertainties of the fit result to the pre-fit ones, indicating the constraint on the nuisance parameter. The JES uncertainties are divided into several sources related to the various methods used to extract the uncertainties as described in Ref. [31].

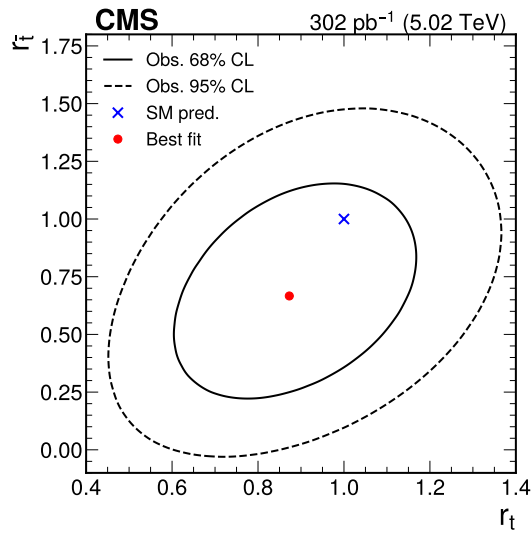


Figure 8: Two-dimensional 68 and 95% confidence level regions for the signal strengths modifying the top quark (r_t) and antiquark ($r_{\bar{t}}$) cross sections individually, represented by the solid and dashed lines respectively. The blue cross indicates the SM prediction and the red dot the best fit for both signal strengths.

the CMS Collaboration at different $\sqrt{s}$, including the measurement described in this paper. All of them show a good agreement with SM predictions. Also, results presented here are consistent with those obtained by the ATLAS experiment at the same energy [14]. In addition, a comparison between the NNLO prediction from the MCFM MC generator with different PDF sets [54] for both the measured cross section and the ratio of individual cross sections is shown in Fig. 10, where the expected results using different PDF sets are all seen to agree well with the measured values.

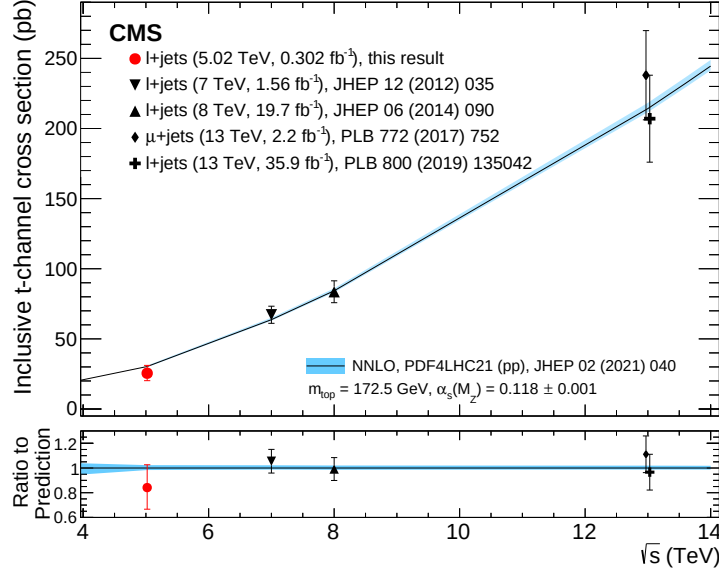


Figure 9: Summary of the CMS measurements of the t -channel single top quark production cross section as a function of $\sqrt{s}$.

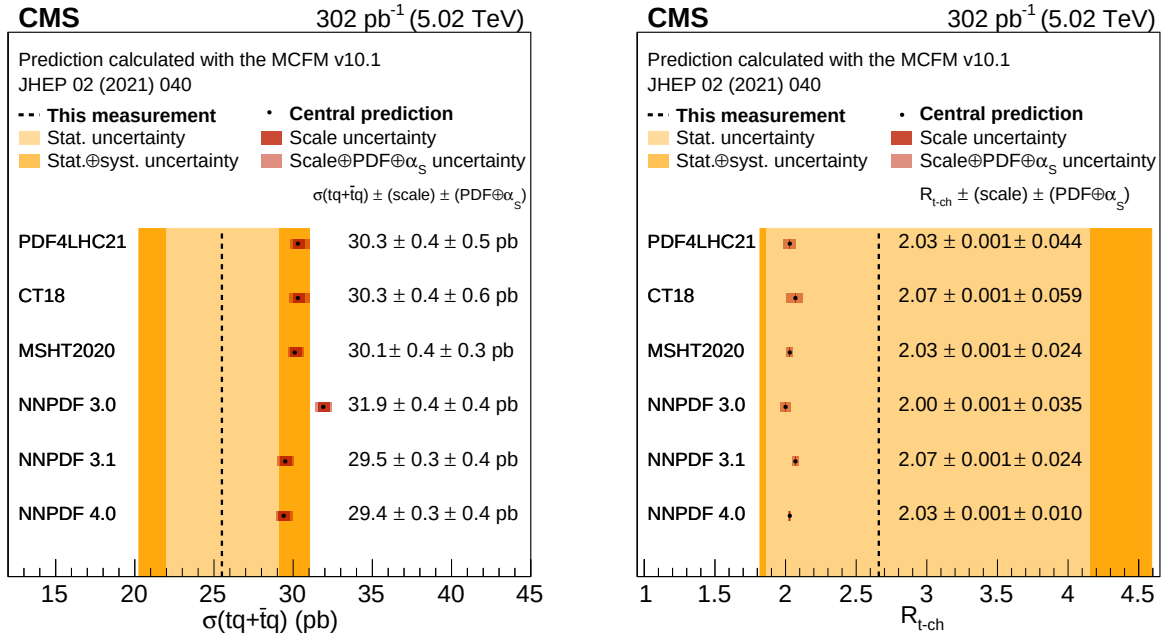


Figure 10: Comparison of the measured values at $\sqrt{s} = 5.02 \text{ TeV}$ with predictions using different PDF sets, calculated with the MCFM program [54] for $\sigma(tq+\bar{t}q)$ (left) and $R_{t\text{-ch}}$ (right).

8 Summary

A measurement of the single top quark t -channel production cross section in proton-proton collisions at a centre-of-mass energy of 5.02 TeV is performed for events with one electron or one muon and multiple jets using data collected by the CMS experiment in 2017 in conditions of low number of additional interactions per bunch crossing, corresponding to an integrated luminosity of 302 pb^{-1} . This represents the first CMS measurement of the process at that energy. The main background in the analysis originates from W +jets and top quark pair production, both estimated using simulation. Smaller contributions from quantum chromodynamics multijet events are derived from data. The cross section is measured through a maximum likelihood fit to the observed event yields in twelve categories defined in terms of the number of jets and b -tagged jets, the lepton flavour and electric charge. The cross sections are found to be $\sigma(tq+\bar{t}q) = 25.5^{+3.6}_{-3.5}(\text{stat})^{+4.2}_{-3.9}(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb}$, $\sigma(tq) = 17.7^{+2.9}_{-2.7}(\text{stat})^{+2.6}_{-2.4}(\text{syst}) \pm 0.3(\text{lumi}) \text{ pb}$, and $\sigma(\bar{t}q) = 6.7^{+2.4}_{-1.6}(\text{stat})^{+2.1}_{-2.5}(\text{syst}) \pm 0.1(\text{lumi}) \text{ pb}$. The ratio between the individual cross sections is found to be $\mathcal{R}_{t\text{-ch}} = 2.7^{+1.5}_{-0.8}(\text{stat})^{+1.2}_{-0.3}(\text{syst})$. These results are used to calculate the absolute value of the Cabibbo–Kobayashi–Maskawa matrix element, which is found to be $|f_{tV}V_{tb}| = 0.92 \pm 0.09(\text{exp}) \pm 0.01(\text{theo})$. All the results are in good agreement with the standard model predictions.

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- ⁶⁹Also at Milli Savunma University, Istanbul, Turkey
- ⁷⁰Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey
- ⁷¹Also at Kafkas University, Kars, Turkey
- ⁷²Now at Istanbul Okan University, Istanbul, Turkey
- ⁷³Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
- ⁷⁴Also at Istinye University, Istanbul, Turkey
- ⁷⁵Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- ⁷⁶Also at Monash University, Faculty of Science, Clayton, Australia
- ⁷⁷Also at Università di Torino, Torino, Italy
- ⁷⁸Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- ⁷⁹Also at California Lutheran University, Thousand Oaks, California, USA
- ⁸⁰Also at California Institute of Technology, Pasadena, California, USA
- ⁸¹Also at United States Naval Academy, Annapolis, Maryland, USA
- ⁸²Also at Bingol University, Bingol, Turkey
- ⁸³Also at Georgian Technical University, Tbilisi, Georgia
- ⁸⁴Also at Sinop University, Sinop, Turkey
- ⁸⁵Also at Erciyes University, Kayseri, Turkey
- ⁸⁶Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
- ⁸⁷Now at another institute formerly covered by a cooperation agreement with CERN
- ⁸⁸Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar
- ⁸⁹Also at Yerevan Physics Institute, Yerevan, Armenia
- ⁹⁰Also at Imperial College, London, United Kingdom