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Measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV with lepton + jets final states

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A B S T R A C T

A measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV is presented. The results are based on data corresponding to an integrated luminosity of 2.3 fb^{-1} collected by the CMS detector at the LHC. Selected events are required to have one isolated, high transverse momentum electron or muon, large missing transverse energy, and hadronic jets, at least one of which must be consistent with having originated from a b quark. The measured cross section is $158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})$ pb, in agreement with standard model predictions.

1. Introduction

Since the discovery of the top quark at the Fermilab Tevatron collider [1,2], considerable advances have been made in understanding its production rates and decay properties in $p\bar{p}$ collisions. The advent of pp collisions at the Large Hadron Collider (LHC) [3] has started a new phase of top quark physics, and the first measurement at the higher center-of-mass energy of 7 TeV was the top quark pair production cross section [4–7]. A precise measurement of the $t\bar{t}$ cross section provides constraints for QCD calculations presently available up to approximate next-to-next-to-leading order (NNLO) [8–11]. It is also important for probing new physics processes that can manifest themselves as an enhancement of the $t\bar{t}$ production rate.

In this Letter, we present a precise measurement of the $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 7$ TeV utilizing a data set corresponding to an integrated luminosity of 2.3 fb^{-1} recorded by the Compact Muon Solenoid (CMS) experiment at the LHC.

In the standard model (SM), top quarks are produced in pp collisions predominantly via the strong interaction as $t\bar{t}$ pairs, with each top quark decaying almost exclusively into a W boson and a bottom quark. In the analysis presented here, $t\bar{t}$ events are identified in final states in which one of the W bosons decays into a quark pair and the other into a charged lepton (electron or muon) and a neutrino, resulting in events that contain an electron or a muon, a neutrino, and four hadronic jets, two of which result from hadronization of the b and $\bar{b}$ quarks (b-jets). In order to improve the purity of the $t\bar{t}$ candidate event sample, we employ b-tagging algorithms, which are optimized for identification of b-jets. Decays of W bosons into τ leptons are not specifically selected in this analysis, albeit some events enter the event sample due to leptonic decays of the τ.

The technique for measuring the $t\bar{t}$ cross section from the candidate event sample consists of a simultaneous profile likelihood fit to the distribution of invariant masses of particles belonging to identified displaced vertices. These fits are performed as a function of the jet and b-tag multiplicities in the event. The method is similar to the one that was used in a previous CMS measurement [4], though a larger data sample is now studied. Several alternative methods have been employed. In one of these, we perform an inclusive measurement of $t\bar{t}$ production cross section without b-jet identification requirement, while others incorporate different b-tagging algorithms.

2. The CMS detector

The characteristic feature of the CMS detector is a superconducting solenoid of 6 m in diameter, providing an axial magnetic

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field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip subdetectors, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\ln[\tan\theta/2]$, with θ being the polar angle of the trajectory of the particle with respect to the counterclockwise-beam direction. Within the field volume, the silicon detectors are surrounded by a crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter that provide high resolution energy measurement of photons, electrons and hadronic jets. Muon detection systems are located outside of the solenoid and embedded in the steel return yoke. They provide muon detection in the range $|\eta| < 2.4$. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A detailed description of the CMS detector can be found in Ref. [12].

3. Event selection

The sample of candidate $t\bar{t}$ events is collected using dedicated triggers, which require either a muon with transverse momentum (p_T) larger than 30 GeV or a high-p_T electron. The criteria for the electron trigger evolved during the course of data-taking in order to maintain a reasonable trigger rate as the instantaneous luminosity of the LHC increased. For the initial data set, corresponding to an integrated luminosity 0.9 fb^{-1}, the threshold on the p_T of electron candidates varied between 27 and 32 GeV. For the second part of the data set (1.4 fb^{-1}) the trigger required the presence of an electron with $p_T > 25$ GeV and at least three hadronic jets with $p_T > 30$ GeV.

The recorded events are reconstructed using the CMS particle-flow algorithm [13], which categorizes observable particles into muons, electrons, photons, charged and neutral hadrons. Energy calibration is performed separately for each particle type. In the offline selection, muons are required to have a good-quality track with $p_T > 35$ GeV and $|\eta| < 2.1$, and the reconstructed tracks in the silicon tracker are consistent with the track information from the muon systems [14]. Electrons are identified using a combination of the shower shape information in electromagnetic calorimeter and track-cluster matching [15], and are required to have $p_T > 35$ GeV and $|\eta| < 2.5$. Electron candidates in the transition region between the barrel and forward electromagnetic calorimeters, $1.44 < |\eta| < 1.57$, are not used for the measurement. We also reject electrons coming from photon conversions [15].

Since the lepton from a W decay is expected to be isolated from other activity in the event, we apply isolation requirements. The relative isolation is defined as $I_{\text{rel}} = (\sum E_T^{\text{charged}} + \sum E_T^{\text{photon}} + \sum E_T^{\text{neutral}})/p_T$, where p_T is the lepton transverse momentum, and E_T^{charged}, E_T^{photon}, and E_T^{neutral} are transverse energies of the charged particles, the reconstructed photons, and the neutral particles not identified as photons. The sum of the transverse energies is computed in a cone of size $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the lepton direction, excluding the lepton candidate itself. We require I_{rel} to be less than 0.125 for muons and 0.10 for electrons.

The signal events are required to have only one electron or muon whose origin is consistent with the reconstructed primary pp interaction vertex [16], defined as the vertex with the largest value for the scalar sum of the p_T of the associated tracks. Events with an additional electron or muon candidate that satisfies less strict lepton identification requirements are vetoed.

Jets are reconstructed using the particle-flow algorithm and are clustered using the anti-k_T jet technique [17] with a distance parameter of 0.5, as implemented in FastJet v2.4.2 [18,19]. In order to account for extra activity within a jet cone from multiple pp interactions per beam crossing, referred to as a pileup, jet energies are corrected for charged hadrons that originate from a vertex other than the primary one, and for the amount of pileup expected in the jet area from neutral jet constituents. Jet energies are also corrected for non-linearities due to different responses in the endcap and barrel calorimeters, and differences between true and simulated calorimeter responses [20]. Each jet is required to have a transverse momentum $p_T > 35$ GeV and $|\eta| < 2.4$. We select events with at least one jet, or at least three jets for events collected with the electron + jets trigger. To reduce background processes, we require at least one of the jets to be identified as a b-jet by a displaced secondary vertex algorithm known as *Simple Secondary Vertex High Efficiency* [21] with a medium working point. The algorithm has a b-tag efficiency of 55% and a light parton (u, d, s, g) mistag rate of 1.5%.

In addition, events are required to have a significant amount of missing transverse energy ($\not\!\!E_T$) as evidence of a neutrino from the W boson decay. This is defined as the magnitude of the negative vector sum of the transverse momenta of all of the objects found by the particle-flow algorithm. We require $\not\!\!E_T > 20$ GeV for both the electron + jets and muon + jets channels.

4. Signal and background modeling

Pair production of top quarks is modeled using the MadGraph v5.1.1 [22] Monte Carlo (MC) event generator, assuming the mass of the top quark $m_t = 172.5$ GeV. The top quark pairs are generated with up to three additional hard jets using pythia v6.424 with tune Z2 [23] to model parton-showering (PS), and the shower matching is performed using the k_T-MLM prescription [22]. The generated events are further passed through the full CMS detector simulation based on Geant4 [24]. The presence of pileup is incorporated by simulating additional interactions with a multiplicity matching that observed in data.

Leptonically decaying W + jets events constitute by far the largest background. These together with Z + jets events are also generated using MadGraph with up to four jets subject to the matrix-element (ME) description. The W + jets events are generated inclusively with respect to jet flavor. Reconstructed jets are further matched to partons in the simulation, and the W + bottom quark and W + charm quark components are separated from the W + light-flavor (u, d, s, and gluon) component based on the parton flavor.

Other backgrounds include single-top-quark production, simulated with powheg v1.0 [25–27], QCD multijet simulated with pythia, and photon + jet events, which constitute a background for the electron + jets channel, generated by MadGraph. The set of parton distribution functions used by MadGraph is CTEQ6L1 [28], while powheg and pythia use CTEQ6M [28].

The W and Drell–Yan production processes are normalized based on NNLO cross sections, determined using fewz [29]. They correspond to $\sigma_{W\to\ell\nu} = 31.3 \pm 1.6$ nb and $\sigma_{Z/\gamma^*\to\ell\ell} = 3048 \pm 132$ pb, where for the Drell–Yan production the invariant mass of two leptons ($\ell = e$ or μ) is greater than 50 GeV. The single-top-quark t-channel production is normalized to the recent CMS measurement of $\sigma_t = 67.2 \pm 6.1$ pb [30]. The single-top-quark associated production (tW) is normalized to the approximate NNLO cross section $\sigma_{tW} = 15.7 \pm 1.2$ pb [31], and the s-channel is normalized to the next-to-next-to-leading-logarithm prediction of $\sigma_t = 4.6 \pm 0.2$ pb [32].

The QCD multijet normalization is obtained by fitting SM contributions to the full $\not\!\!E_T$ distribution in data, though only the yield of QCD multijet events with $\not\!\!E_T > 20$ GeV enters the normalization. For the electron + jets channel, the QCD multijet background distributions are obtained from MC, and for the muon + jets channel, they are obtained from a background-enriched data sample defined as $I_{\text{rel}} > 0.125$ and $\not\!\!E_T < 20$ GeV.

5. Cross section measurement

The $t\bar{t}$ cross section measurement is performed using a maximum profile likelihood fit to the number of reconstructed jets ($N_{\rm jet}$), the number of b-tagged jets ($N_{\rm tag}$), and the secondary vertex mass (SVM) distribution in the data. We consider ten event sub-samples with $N_{\rm jet}$ values of 1–4 and $\geqslant 5$, and $N_{\rm tag}$ values of 1 and $\geqslant 2$. The SVM is defined as the mass of the sum of four-vectors of the tracks associated to the secondary vertex with an assumption that all particles have the pion mass. For events with two b-tagged jets, SVM corresponds to the highest-$p_{\rm T}$ b-tagged jet. The SVM distribution yields a good discrimination between the contributions from light- and heavy-flavor quark production [4]. The results are obtained by maximizing a binned Poisson likelihood that incorporates contributions from $t\bar{t}$, W + jets, Z + jets, single-top-quark, and QCD multijet production processes. Performing a simultaneous fit across different jet and b-tag multiplicity bins, including regions dominated by background events, constrains the background contributions, resulting in a more precise measurement of the $t\bar{t}$ production cross section.

The W + jets, Z + jets, and single-top-quark background processes are initially normalized to the expected event yields according to their theoretical cross sections. The QCD and photon + jets normalizations are evaluated as described above individually in each $N_{\rm jet}$ and $N_{\rm tag}$ sub-sample, for both channels. These background normalizations are the initial values that enter the profile likelihood fit. The cross section measurement is performed by fitting to the data to obtain corrections to these initial values. The W + jets backgrounds are split into W + b jets, W + c jets, and W + light-flavor (LF) sub-samples, with all three components free in the fit. During the likelihood maximization, the normalizations of each of these components are extracted. The normalizations of the $t\bar{t}$ and W+jets contributions are allowed to float freely. The contributions from small backgrounds, QCD multijet and Z+jets, are conservatively constrained with Gaussian uncertainties of 100% and 30% of their expected event yields, respectively. The single-top-quark contribution is constrained with an uncertainty of 10% [30].

The expected event yield for each background component, per $N_{\rm jet}$ and $N_{\rm tag}$, is also a function of other parameters, such as the jet energy scale (JES), the b-tagging efficiency and the mistag rate. In addition, the $N_{\rm jet}$ spectrum is affected by the choice of the renormalization and factorization (Q^2) scales. For the W + jets simulation we use a dynamical mass scale of $(m_{\rm W})^2 + (\sum p_{\rm T}^{\rm jet})^2$, where $m_{\rm W}$ is the mass of the W and $\sum p_{\rm T}^{\rm jet}$ is the sum of the transverse momenta from the jets in the event. The magnitude of the scale is allowed to vary in the fit by incorporating an effective parameter c_{Q^2} into the likelihood with initial value 1.0, and which is allowed to vary between 0.5 and 2.0. The profile likelihood maximization provides simultaneous measurements of each of these parameters, background contributions and the $t\bar{t}$ cross section.

There are alternative control samples to estimate the JES, the b-tagging efficiency and the mistag rate. The JES uncertainty is measured in control samples to be approximately 3% [20], and this determines a Gaussian constraint on this parameter in the likelihood. To account for differences between simulation and data in the b-tagging efficiencies and the mistag rates, we weight the tagged jets in the simulation up or down by a data-to-simulation scale factor. The b-tagging efficiency and the mistag rate scale factors are constrained to be 1.0 ± 0.1 in the fit, where 10% is the uncertainty in the b-tagging efficiency and the mistag rate [21].

The systematic uncertainties related to JES, Q^2 scale, b-tagging and mistag scale factors are included as nuisance parameters in the profile likelihood fit. Other systematic uncertainties are not directly included in the profile likelihood and taken as additional systematic uncertainties outside of the fit result and are described below.

The efficiencies for triggering, reconstructing, and identifying isolated leptons are determined using $Z \to ee$ and $Z \to \mu\mu$ samples of events, and found to be very similar in the data and simulation. We correct for small differences observed, and account for an additional systematic uncertainty of 3% on these values. The unclustered energy in the detector results in an additional resolution uncertainty of less than 1% on the $\not\!\!E_{\rm T}$ scale. The difference in jet energy resolution determined in simulation and data results in an uncertainty of less than 1%.

The theoretical uncertainties in modeling of $t\bar{t}$ production are evaluated from dedicated simulated event samples by varying the theoretical parameters of interest around their nominal values. Such variations are used to construct alternative distributions, from which simulated events can be generated. For each variation, 4000 pseudo-experiments are generated and fitted with the standard configuration. The mean bias of the fitted $t\bar{t}$ cross section is taken as the size of the systematic uncertainty due to the source under study. These include differences in the $t\bar{t}$ signal due to renormalization and factorization scales (4%), the scale for the ME partons to PS matching scheme (2%), pileup modeling in simulation (less than 1%), and the parton distribution function model (less than 1%). The total uncertainty for the $t\bar{t}$ modeling, when adding the above uncertainties in quadrature, is 5.0%.

The systematic uncertainty on the SVM shape is also considered. We have studied several effects, which include pixel resolution and jet-track-association modeling, as well as pileup dependence. These have a negligible effect on the SVM shapes of $t\bar{t}$, single-top-quark, W and Z + jets events. The uncertainty on the SVM shape from QCD multijet background is obtained as follows. For the electron + jets channel we generate pseudo-experiments based on the default and alternative QCD shapes obtained from simulation. To increase the statistical accuracy of the QCD multijet background, the default shape employed in the fit is taken from events with relaxed requirements on the electron isolation and identification, and no $\not\!\!E_{\rm T}$ requirement imposed. The alternative shape is obtained from the region corresponding to the event selection used in the $t\bar{t}$ cross section measurement. For the muon + jets channel, the statistical fluctuations in the normalization for the $\not\!\!E_{\rm T}$ distributions obtained from muon non-isolated ($I_{\rm rel} > 0.125$) and isolated ($I_{\rm rel} < 0.125$) regions are taken as the systematic uncertainty. The integrated luminosity of the event sample is determined with an uncertainty of 2.2% [33].

The list of systematic uncertainties is summarized in Table 1. These include both the uncertainties related to the nuisance parameters in the likelihood fit and the additional uncertainties evaluated from alternative distributions as described above. The individual systematic uncertainties related to the nuisance parameters in the fit are shown for illustrative purposes only. These are obtained as follows. First, the total fit uncertainty is evaluated when the parameter of interest is fixed in the fit. Then this uncertainty is subtracted in quadrature from the total fit uncertainty when all parameters are varied in the fit. Since the treatment of the Q^2 uncertainty in the likelihood fit is dependent on parametrization, we also performed the cross-check with the Q^2 uncertainty treated outside of the fit, and obtained consistent results. The combined systematic uncertainty of the measurement is 6.5%, taking into account the correlations between the nuisance parameters.

The measurement is performed separately for the electron + jets and muon + jets channels, as well as simultaneously for both channels, yielding

Electron + jets

$$\sigma_{t\bar{t}} = 160.6 \pm 3.2\,(\text{stat.}) \pm 11.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \tag{1}$$

Table 1
List of systematic uncertainties for the electron + jets, muon + jets, and the combined analysis. Due to the correlation between the fit parameters, the combined number is not the root of the quadratic sum of the contributions.

Source	Electron channel	Muon channel	Combined analysis
Quantity	Uncertainty (%)		
Lepton ID/reconstruction/trigger efficiency	3.0	2.0	3.0
$\not\!\!E_{\mathrm{T}}$ resolution due to unclustered energy	0.9	0.3	0.8
Jet energy resolution	0.5	0.5	0.6
$\mathrm{t\bar{t}}$ + jets renorm./fact. scales	3.5	4.3	4.3
$\mathrm{t\bar{t}}$ + jets ME to PS matching	2.2	1.8	2.2
Pileup	0.5	0.2	0.6
Parton distribution function choice	0.3	0.3	0.3
QCD multijet SVM distribution	1.4	0.4	0.6
Subtotal	5.5	5.1	5.9
Nuisance parameter	Uncertainty (%)		
Jet energy scale	3.9	3.0	2.4
b-tagging efficiency and mistag rate	3.5	2.8	2.1
W + jets renorm./fact. scale	1.6	1.5	1.6
Total systematic uncertainty	7.0	6.2	6.5

Muon + jets

$$\sigma_{\mathrm{t\bar{t}}} = 164.2 \pm 2.8\,(\text{stat.}) \pm 10.1\,(\text{syst.}) \pm 3.6\,(\text{lum.})\ \text{pb}, \qquad (2)$$

and

Combined

$$\sigma_{\mathrm{t\bar{t}}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}. \qquad (3)$$

The comparison of the corresponding observed and fitted SVM distributions is shown in Figs. 1 and 2. As a by-product, the fit provides the size of contributions from the SM processes that are backgrounds to $\mathrm{t\bar{t}}$ production, as well as in-situ evaluations of other parameters varied in the profile likelihood fit, such as the b-tagging efficiency and the JES correction factor (on top of the standard jet corrections). The results of the combined fit, as well as the results of the fits performed in the electron + jets and muon + jets samples separately, are listed in Table 2, with correlations among parameters shown in Table 3. The $\mathrm{t\bar{t}}$ cross section is given in pb, while the contributions from other standard model processes are quoted as scale factors with respect to their theoretical predictions described above. These measured scale factors do not account for a full treatment of the systematic uncertainties and hence are strictly valid only in the context of the fit presented in this Letter. The b-tagging scale factor defined as the ratio of the b-tagging efficiencies in data and simulation is determined to be 96 ± 1%, consistent between the electron + jets and muon + jets channels. The JES correction factor is found to be 100.4 ± 1.6% and 98.1 ± 1.2% in the electron + jets and muon + jets channels, respectively, yielding 100.2 ± 1.0% in the combined fit.

The W + c jets contribution in the data is found to be larger than SM predictions, both in the electron + jets and muon + jets channels. This contribution includes single charm and double charm production, which are both present in the selected events. The W + b jets contribution in the data is also found to be slightly higher than in the simulation. The W + LF jets scale factor in the electron channel is significantly lower than in the muon case. This is because of the presence of a much larger QCD multijet contribution in the electron sample, and its large correlation with the W + LF jets component. The combined W + LF jets/QCD multijet scale factors for muons and electrons are in agreement, being 0.84 ± 0.09% and 0.71 ± 0.07%, respectively.

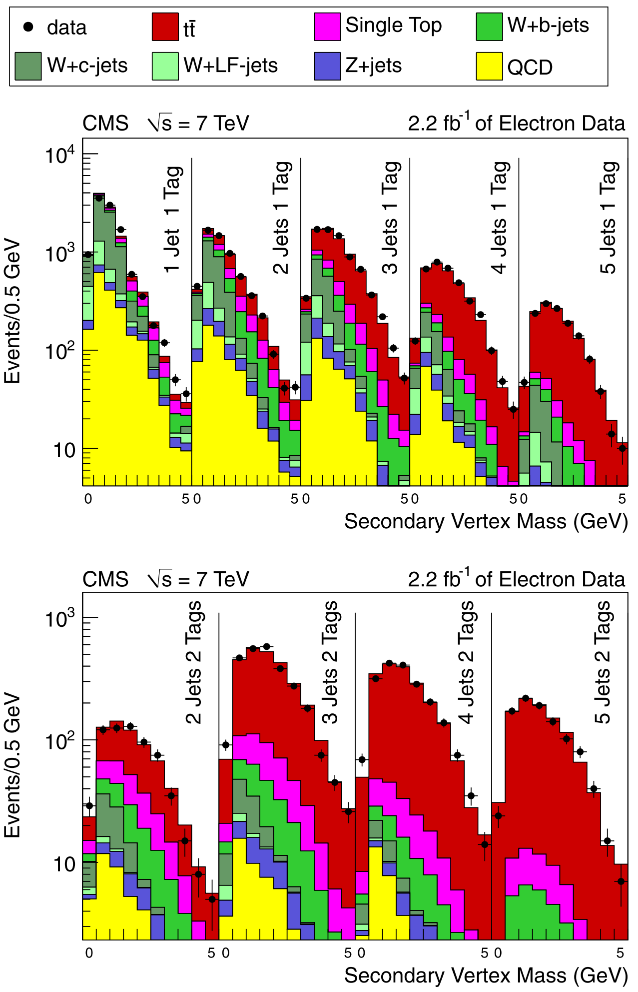

Fig. 1. Results of the combined fit for the electron + jets channel, for single b-tag events (top panel), and for ⩾2b-tag events (bottom panel). The distributions within each panel correspond to events with 1-, 2-, 3-, 4-, and ⩾5-jets, respectively. The error bars indicate statistical uncertainties only.

Table 2
Results of the fit to the combined electron + jets and muon + jets sample, and each channel individually. The contributions from the background processes are quoted as scale factors with respect to their theoretical predictions. The scale factors do not account for a full treatment of the systematic uncertainties and are strictly valid only in the context of the fit. For brevity, the QCD parameters are not shown.

Fit parameters	Electron + jets	Muon + jets	Combined
$\sigma_{t\bar{t}}$ (pb)	160.6 ± 6.6	164.2 ± 5.5	158.1 ± 4.1
Single top	1.05 ± 0.10	1.08 ± 0.10	1.17 ± 0.10
W + b jets	1.19 ± 0.35	0.95 ± 0.18	1.28 ± 0.16
W + c jets	1.54 ± 0.15	1.48 ± 0.05	1.55 ± 0.04
W + LF jets	0.20 ± 0.08	0.57 ± 0.07	0.52 ± 0.06
Z + jets	1.13 ± 0.29	1.08 ± 0.29	1.43 ± 0.29
c_{Q^2}	1.02 ± 0.16	0.94 ± 0.06	1.05 ± 0.05
b-tag	0.95 ± 0.01	0.97 ± 0.01	0.96 ± 0.01
JES	1.00 ± 0.02	0.98 ± 0.01	1.00 ± 0.01
Mistag	1.00 ± 0.10	1.00 ± 0.10	1.00 ± 0.10

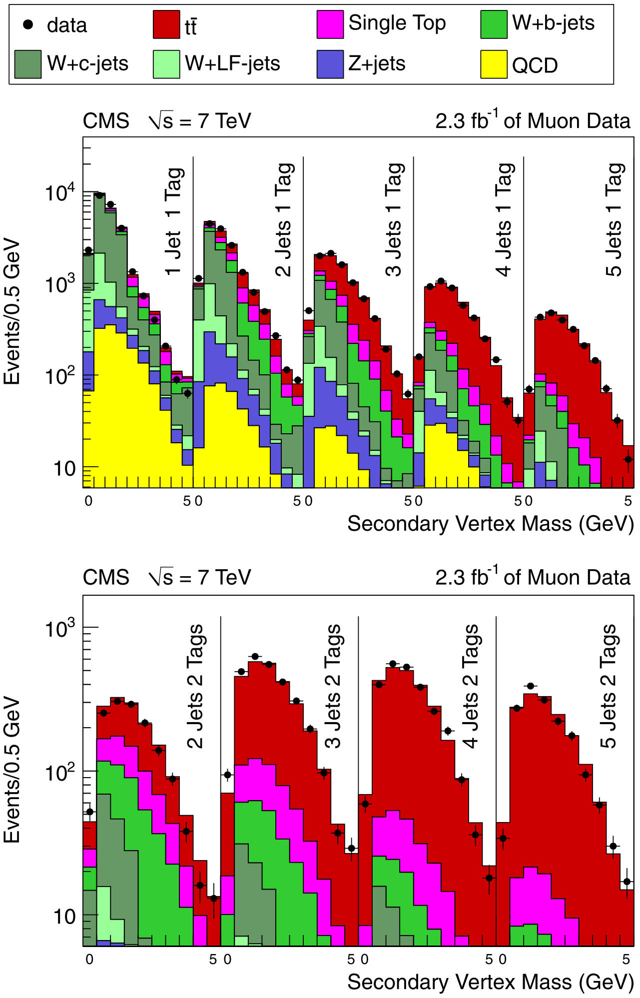

Fig. 2. Results of the combined fit for the muon + jets channel, for single b-tag events (top panel), and for ⩾2b-tag events (bottom panel). The distributions within each panel correspond to events with 1-, 2-, 3-, 4-, and ⩾5-jets, respectively. The error bars indicate statistical uncertainties only.

Because of large correlated uncertainties and due to differences in the correlation matrix for the electron + jets and muon + jets channels, which result from different QCD multi jet contributions in the two channels, the result of the combined fit resides outside of the individual electron + jets and muon + jets measurements. The correlation matrix for the combined fit is given in Table 3. Using 4000 alternative data sets constructed from the simulated events we determine that the combined cross section lies between the individual channel results only in 60% of the cases. For the combined fit we have seven out of ten parameters that are common to both channels, residing outside of the $\pm 1\sigma$ interval between individual electron + jets and muon + jets measurements. Using simulated events we determine this to occur in 10% of the cases.

The $t\bar{t}$ cross section is measured assuming a value of the top quark mass $m_t = 172.5$ GeV. The measured cross section of $t\bar{t}$ production has a dependence on m_t, which is evaluated using dedicated MC samples and can be parameterized in the range of 160–185 GeV as

$$\sigma_{t\bar{t}} = 158.1\ \text{pb} - (m_t - 172.5\ \text{GeV}) \times (1.14 \pm 0.18\ \text{pb/GeV}). \quad (4)$$

6. Alternative analyses

In addition to the main result, we have performed several alternative analyses in the electron + jets and the muon + jets channels using different event selections and different methods to suppress background contributions and measure the $t\bar{t}$ cross section. One analysis does not rely on b-tagging, a second one makes use of the kinematical information from the top quark decays, and a third one relies on a data-based estimate of the dominant background.

The analysis without relying on use of the b-tagging algorithms considers the data set corresponding to 4.6 fb^{-1} (4.9 fb^{-1}) in the electron (muon) + jets channel. The selected events are required to have an electron with $p_T > 35$ GeV or a muon with $p_T > 26$ GeV, and at least 4 jets with $p_T > 30$ GeV. No missing transverse energy requirement is imposed.

The cross section is measured using a binned log-likelihood fit to the mass of the three-jet combination with the highest p_T in the event (M_3). The $t\bar{t}$, W/Z + jets, and QCD multijet components are unconstrained during the fit, with the QCD multijet contributions in the electron + jets and muon + jets channels treated independently. The single-top-quark normalization is constrained to within 30% of its theoretical value.

The $t\bar{t}$, single-top-quark, and W/Z + jets processes are modeled using the simulation, while the QCD multijet contribution is estimated from data using a side-band region with the relative isolation of the lepton greater than 0.25. Signal events, as well as W + jets events, are heavily suppressed by this selection, and subtracted based on simulation. The shape of the subtracted QCD multijet contribution is used for the fit in the signal region, since the M_3 distribution of QCD events does not depend on the relative isolation of the lepton in the event.

Table 3
Correlation matrix of the combined fit to the electron + jets plus muon + jets samples. Only non-QCD parameters are shown.

	$t\bar{t}$	Single t	W + b	W + c	W + LF	Z + jets	c_{Q^2}	b-tag	JES	Mistag
$t\bar{t}$	1.00	−0.13	−0.48	0.33	0.03	0.07	−0.07	−0.70	−0.81	0.00
Single t	−0.13	1.00	−0.52	0.04	0.03	−0.03	0.06	−0.08	0.09	−0.00
W + b	−0.48	−0.52	1.00	0.05	0.13	−0.16	0.27	0.26	0.42	−0.02
W + c	0.33	0.04	0.05	1.00	0.01	0.15	0.71	−0.38	−0.26	−0.02
W + LF	0.03	0.03	0.13	0.01	1.00	−0.19	0.21	−0.03	−0.05	−0.83
Z + jets	0.07	−0.03	−0.16	0.15	−0.19	1.00	0.23	−0.01	−0.10	0.01
c_{Q^2}	−0.07	0.06	0.27	0.71	0.21	0.23	1.00	−0.02	0.15	−0.02
b-tag	−0.70	−0.08	0.26	−0.38	−0.03	−0.01	−0.02	1.00	0.43	−0.02
JES	−0.81	0.09	0.42	−0.26	−0.05	−0.10	0.15	0.43	1.00	0.01
Mistag	0.00	−0.00	−0.02	−0.02	−0.83	0.01	−0.02	−0.02	0.01	1.00

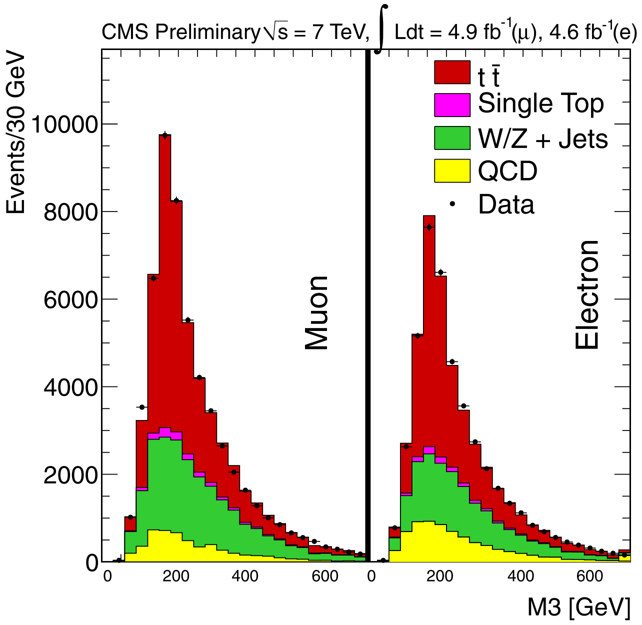

Fig. 3. The mass of the three-jet combination with the highest transverse momenta.

The observed and the fitted M_3 distributions are shown in Fig. 3. The dominant sources of systematic uncertainty are JES, ME to PS matching, and the Q^2 scale uncertainties. In the electron + jets channel the cross section measurement yields

$$\sigma_{t\bar{t}} = 157.1 \pm 3.7\,(\text{stat.})^{+17.2}_{-11.4}\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \tag{5}$$

in the muon + jets channel the cross section is measured as

$$\sigma_{t\bar{t}} = 161.6 \pm 3.5\,(\text{stat.})^{+14.8}_{-22.1}\,(\text{syst.}) \pm 3.6\,(\text{lum.})\ \text{pb}. \tag{6}$$

The combined measurement in the electron + jets and muon + jets channels yields a cross section of

$$\sigma_{t\bar{t}} = 159.7 \pm 2.6\,(\text{stat.})^{+13.1}_{-14.7}\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}. \tag{7}$$

Another measurement uses kinematic information from the leptonic top quark decay $t \to bW \to b\ell\nu_\ell$, namely the mass of the two-particle system consisting of a lepton and a jet associated with a b quark. The jet-to-parton assignment among the four leading jets is performed minimizing a least-squares residual based on the masses of the reconstructed W boson and hadronically decaying top quark in $t \to bW \to bq\bar{q}'$. The baseline event selection is similar to the reference analysis, complemented with the requirement that the jet assigned to the leptonic top quark decay is b-tagged using an algorithm based on measuring the significance of a track impact parameter [21]. The technique is applied to the muon + jets data sample, corresponding to an integrated luminosity 4.9 fb^{-1}. The result of this measurement is $\sigma_{t\bar{t}} = 162.4 \pm 5.4\,(\text{stat.})^{+7.5}_{-11.0}\,(\text{syst.}) \pm 3.6\,(\text{lum.})$ pb, where the dominant systematic uncertainty is due to the JES.

Finally, the third method does not rely on MC simulation for the W + jets background, but exploits the W charge asymmetry [34] in W + jets production at the LHC. The shape of the lepton pseudorapidity distribution for the W + jets component is obtained from the data by subtracting the observed distribution for ℓ^- from the one corresponding to ℓ^+. The $t\bar{t}$ cross section is measured by fitting a combination of signal and background components to the observed lepton $|\eta|$ spectrum using a data sample corresponding to an integrated luminosity of 0.9 (1.0) fb^{-1} for electron (muon) + jets. The $t\bar{t}$ cross section is measured with a large expected uncertainty of 42% (23%) in the electron (muon)+jets channel, and agrees with the results of the other analyses.

7. Summary

The $t\bar{t}$ production cross section measurement has been performed at $\sqrt{s} = 7$ TeV using the data collected with the CMS detector and corresponding to an integrated luminosity of 2.3 fb^{-1}.

The $t\bar{t}$ cross section is measured using a profile likelihood fit to the number of reconstructed jets, the number of b-tagged jets, and the secondary vertex mass distribution. The measured cross section for an assumed top quark mass of 172.5 GeV is

$$\sigma_{t\bar{t}} = 158.1 \pm 2.1\,(\text{stat.}) \pm 10.2\,(\text{syst.}) \pm 3.5\,(\text{lum.})\ \text{pb}, \tag{8}$$

which is in agreement with the QCD predictions of 164^{+10}_{-13} pb [8,9], 163^{+11}_{-10} pb [10] and 149 ± 11 pb [11] that are based on the full next-to-leading-order (NLO) matrix elements and the resummation of the leading and NLO soft logarithms.

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