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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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ABSTRACT

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.