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Measurements of $t\bar{t}$ cross sections in association with b jets and inclusive jets and their ratio using dilepton final states in pp collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

The cross sections for the production of $t\bar{t}b\bar{b}$ and $t\bar{t}jj$ events and their ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ are measured using data corresponding to an integrated luminosity of 2.3 fb^{-1}collected in pp collisions at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC. Events with two leptons (e or μ) and at least four reconstructed jets, including at least two identified as b quark jets, in the final state are selected. In the full phase space, the measured ratio is $0.022 \pm 0.003\,(\text{stat}) \pm 0.006\,(\text{syst})$, the cross section $\sigma_{t\bar{t}b\bar{b}}$ is $4.0 \pm 0.6\,(\text{stat}) \pm 1.3\,(\text{syst})$ pb and $\sigma_{t\bar{t}jj}$ is $184 \pm 6\,(\text{stat}) \pm 33\,(\text{syst})$ pb. The measurements are compared with the standard model expectations obtained from a POWHEG simulation at next-to-leading-order interfaced with PYTHIA.

1. Introduction

Since the discovery of the Higgs boson [1–3], its properties have been measured and compared to the standard model (SM) prediction [4–9]. However, the coupling of the top quark to the Higgs boson remains to be determined. Although it appears indirectly through loops in the gluon–gluon fusion production process and in the $H \to \gamma\gamma$ decay channel, a direct measurement has yet to be completed. One of the most promising channels for a direct measurement of the top quark Yukawa coupling in the SM is the production of the Higgs boson in association with a $t\bar{t}$ pair ($t\bar{t}H$), where the Higgs boson decays to $b\bar{b}$, thus leading to a $t\bar{t}b\bar{b}$ final state. This final state, which has not been observed yet [10], has an irreducible nonresonant background from the production of a top quark pair in association with a b quark pair produced via gluon splitting ($g \to b\bar{b}$).

Calculations of the inclusive production cross section for $t\bar{t}$ events with additional jets have been performed to next-to-leading-order (NLO) precision for proton–proton centre-of-mass energies of 7, 8, and 13 TeV [11]. The dominant uncertainties in these calculations are from the choice of the factorization (μ_F) and renormalization (μ_R) scales [12,13], and are complicated by the presence of two very different scales in this process: the top quark mass and the jet transverse momentum (p_T). Therefore, experimental measurements of production cross sections $pp \to t\bar{t}jj$ ($\sigma_{t\bar{t}jj}$) and $pp \to t\bar{t}b\bar{b}$ ($\sigma_{t\bar{t}b\bar{b}}$) can provide an important test of NLO quantum chromodynamics (QCD) theory calculations and important input for describing the main background in the search for the $t\bar{t}H$ process. Previous cross section and ratio measurements at $\sqrt{s} = 7$ and 8 TeV have been reported by the CMS [14,15] and ATLAS Collaborations [16].

In this Letter, the measurements of the cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio are presented using a data sample of pp collisions collected at a centre-of-mass energy of 13 TeV at the CERN LHC by the CMS experiment, and corresponding to an integrated luminosity of 2.3 fb^{-1} [17]. Events are selected with the final state consisting of two leptons (e or μ) and at least four reconstructed jets, of which at least two are identified as b quark jets. The cross section ratio is measured with a smaller systematic uncertainty exploiting the partial cancellation of uncertainties.

2. The CMS detector and event simulation

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (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

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endcap detectors. Muons are reconstructed in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [18].

The Monte Carlo (MC) simulated samples for the $t\bar{t}$ signal are generated by the POWHEG (v2) event generator [19–21] at NLO, interfaced with PYTHIA (v8.205) [22,23] using the tune CUETP8M1 [24] to provide the showering of the partons and to match soft radiation with the contributions from the matrix elements (MEs). The NNPDF3.0 [25] set of the parton distribution functions (PDFs) is used. The MADGRAPH (v5.1.5.11) event generator [26] with MEs at leading order (LO), allowing up to three additional partons, including b quarks, and the MADGRAPH5_aMC@NLO (v2.2.2) event generator [27] are both used for cross-checks and studies of systematic uncertainties. The $t\bar{t}$ samples are normalized to the next-to-next-to-leading-order (NNLO) cross section calculation [28]. The W+jets and Z/γ^*+jets processes are simulated in MADGRAPH5_aMC@NLO and are normalized to their NNLO cross sections [29]. The single top quark associated production with a W boson ($pp \to tW$ and $pp \to \bar{t}W$) is simulated in the five-flavour scheme in POWHEG (v1) at NLO and normalized to an approximate NNLO cross section calculation [30], while the t-channel single top quark events are simulated in the four-flavour scheme in MADGRAPH5_aMC@NLO. The multijet production is modelled in PYTHIA with LO MEs. The CMS detector response is simulated using GEANT4 (v9.4) [31]. The events in simulation include the effects of additional interactions in the same or nearby bunch crossings (pileup) and are weighted according to the vertex distribution observed in data. The number of pileup interactions in data is estimated from the measured bunch-to-bunch instantaneous luminosity and the total inelastic cross section [32].

3. Definition of signal events

Measurements are reported for two different regions of the phase space: the visible and the full phase space. The result in the visible phase space is measured at the particle level, using the stable particles after the hadronization, to reduce the possible theoretical and modelling uncertainties, while the purpose of performing the result in the full phase space is to facilitate comparisons to NLO calculations or measurements in other decay modes.

To define the visible phase space, all $t\bar{t}b\bar{b}$ final-state particles except the neutrinos, i.e. the charged leptons and jets originating from the decays of the top quarks, as well as the two additional b quark jets ("b jets"), are required to be within the experimentally accessible kinematic region. The leptons must have $p_T > 20$ GeV, and $|\eta| < 2.4$. Electrons or muons originating from the leptonic decays of τ leptons produced in $W \to \tau\nu$ decays are included. The particle-level jets are obtained by combining all final-state particles, excluding neutrinos, at the generator level with an anti-k_T clustering algorithm [33] with a distance parameter of 0.4 and are required to satisfy $|\eta| < 2.5$ and $p_T > 20$ GeV, which is lower than the reconstructed minimum jet p_T due to jet resolution – to have all events that pass the reconstructed jet p_T in the visible phase space. Jets that are within $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.5$ units of an identified electron or muon are removed, where $\Delta\phi$ and $\Delta\eta$ are the differences in azimuthal angle and pseudorapidity between the directions of the jet and the lepton. To identify the b and c quark jets ("c jets") unambiguously, the b and c hadron momenta are scaled down to a negligible value and included in the jet clustering (so called "ghost matching") [34]. The b and c jets are then identified by the presence of the corresponding "ghost" hadrons among the jet constituents.

Simulated events are categorized as coming from the $t\bar{t}jj$ process if they contain at least four particle-level jets, including at least two jets originating from b quarks, and two leptons ($t\bar{t}jj \to bW^+\bar{b}W^-jj \to b\ell^+\nu\bar{b}\ell^-\bar{\nu}jj$). The $t\bar{t}jj$ sample contains four components according to the number of b and c jets in addition to the two b jets required from the top quark decays. The four components are the $t\bar{t}b\bar{b}$ final state with two b jets, the $t\bar{t}bj$ final state with one b jet and one lighter-flavour jet, the $t\bar{t}c\bar{c}$ final state with two c jets, and the $t\bar{t}$LF final state with two light-flavour jets (from a gluon or u, d, or s quark) or one light-flavour jet and one c jet. The $t\bar{t}bj$ final state mainly originates from the merging of two b jets or the loss of one of the b jets caused by the acceptance requirements.

4. Event selection

The events are recorded at $\sqrt{s} = 13$ TeV using a dilepton trigger [35] that requires the presence of two isolated leptons (e or μ) both with p_T larger than 17 GeV.

The particle-flow (PF) event algorithm [36,37] reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex 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 reconstructed by combining information from the silicon tracker and the muon system [38]. The energy of charged hadrons is determined from a combination of their momenta measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

The leptons and all charged hadrons that are associated with jets are required to originate from the primary vertex, defined as the vertex with the highest $\sum p_T^2$ of its associated tracks. Muon candidates are further required to have a high-quality fit including a minimum number of hits in both systems. Requirements on electron identification variables based on shower shape and track-cluster matching are further applied to the reconstructed electron candidates [39–41]. Muons and electrons must have $p_T > 20$ GeV and $|\eta| < 2.4$.

To reduce the background contributions of muons or electrons from semileptonic heavy-flavour decays, relative isolation criteria are applied. The relative isolation parameter, I_{rel}, is defined as the ratio of the summed p_T of all objects in a cone of $\Delta R = 0.3$ ($\Delta R = 0.4$) units around the electron (muon) direction to the lepton p_T. Different cone sizes for electron and muon are used to maximize the sensitivity. The objects considered are the charged hadrons associated with the primary vertex as well as the neutral hadrons and photons, whose energies are corrected to take into account pileup effects. Thus,

$$I_{rel} = \frac{\sum p_T^{\text{charged hadron}} + \sum p_T^{\text{neutral hadron}} + \sum p_T^{\text{photon}}}{p_T^{\text{lepton}}}. \qquad (1)$$

The muon candidates are required to have $I_{rel} < 0.15$. For the electron candidates, different I_{rel} thresholds (0.077 or 0.068) are applied depending on the pseudorapidity of the candidate ($|\eta| < 1.48$ or $1.48 \le |\eta| < 2.40$). These thresholds are obtained from a multivariate analysis technique and result from the considerable

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