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Measurement of the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ in pp collisions at $\sqrt{s} = 8$ TeV

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ABSTRACT

The first measurement of the cross section ratio $\sigma_{t\bar{t}b\bar{b}}/\sigma_{t\bar{t}jj}$ is presented using a data sample corresponding to an integrated luminosity of 19.6 fb^{-1} collected in pp collisions at $\sqrt{s} = 8$ TeV with the CMS detector at the LHC. Events with two leptons (e or μ) and four reconstructed jets, including two identified as b quark jets, in the final state are selected. The ratio is determined for a minimum jet transverse momentum p_T of both 20 and 40 GeV/c. The measured ratio is $0.022 \pm 0.003\,(\text{stat}) \pm 0.005\,(\text{syst})$ for $p_T > 20$ GeV/c. The absolute cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ are also measured. The measured ratio for $p_T > 40$ GeV/c is compatible with a theoretical quantum chromodynamics calculation at next-to-leading order.

1. Introduction

With the observation of a new boson at a mass around 125 GeV/c^2 [1–3] whose properties are consistent with those of the standard model (SM) Higgs boson H [4–9], the SM appears to be complete. One of the most sensitive channels in the discovery of the Higgs boson, $H \to \gamma\gamma$, is expected to have top quark loops both in the production and decay of the Higgs boson in the SM. Hence, it is important to determine the couplings of the new boson to fermions, especially to the top quark. In the SM, one of the most promising channels for a direct measurement of the top quark Yukawa coupling 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.

The expected quantum chromodynamics (QCD) cross section for $t\bar{t}H$ production in pp collisions at $\sqrt{s} = 8$ TeV, calculated to next-to-leading order (NLO), is $0.128^{+0.005}_{-0.012}\,(\text{scale}) \pm 0.010\text{ pb}\,(\text{PDF} + \alpha_S)$ [10], where the uncertainty labelled "scale" refers to the uncertainty from the factorization and renormalization scales (μ_F and μ_R), and the uncertainty labelled "PDF + α_S" comes from the uncertainties in the parton distribution functions (PDFs) and the strong coupling constant α_S. This final state, which has not yet been observed, has an irreducible nonresonant background from the production of a top quark pair in association with a b quark pair. Calculations of the inclusive production cross section for $t\bar{t}$ events with additional jets have been performed to NLO precision [11–16]. For a proton–proton centre-of-mass energy of 8 TeV, the predictions for the production of a top quark pair with two additional jets $t\bar{t}jj$ and with two additional b quark jets $t\bar{t}b\bar{b}$ are $\sigma_{t\bar{t}jj} = 21.0 \pm 2.9\,(\text{scale})$ pb and $\sigma_{t\bar{t}b\bar{b}} = 0.23 \pm 0.05\,(\text{scale})$ pb, respectively [16]. In this calculation, the additional jets are required to have transverse momenta $p_T > 40$ GeV/c and absolute pseudorapidity $|\eta| < 2.5$, while for the $t\bar{t}H$ production value quoted above, no such requirements are applied to the decay products of the Higgs boson. The dominant uncertainties in these calculations are from the factorization and renormalization scales [17,18] caused by the presence of two very different scales in this process, the top quark mass and the jet p_T. Therefore, experimental measurements of $\sigma_{t\bar{t}jj}$ and $\sigma_{t\bar{t}b\bar{b}}$ production can provide a good test of NLO QCD theory and important input about the main background in the search for the $t\bar{t}H$ process.

In this Letter, the first measurements of the cross sections $\sigma_{t\bar{t}b\bar{b}}$ and $\sigma_{t\bar{t}jj}$ and their ratio are presented. The analyzed data sample of pp collisions at a centre-of-mass energy of 8 TeV was collected with the CMS experiment at the CERN LHC and corresponds to an integrated luminosity of 19.6 ± 0.5 fb^{-1} [19]. The primary motivation for measuring the cross section ratio is that many kinematic distributions are expected to be similar for $t\bar{t}b\bar{b}$ and $t\bar{t}jj$, leading to reduced systematic uncertainties in the ratio.

2. CMS detector and event reconstruction

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 superconducting solenoid volume are a sili-

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con 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. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

The particle-flow event algorithm reconstructs and identifies each single particle with an optimized combination of all subdetector information [20,21]. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. 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. The energy of charged hadrons is determined from a combination of their momentum 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.

Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole p_{T} spectrum and detector acceptance. An offset correction is applied to take into account the extra energy clustered in jets due to additional proton–proton interactions within the same bunch crossing (pileup). Jet energy corrections are derived from simulation, and are confirmed with in situ measurements with the energy balance of dijet and photon+jet events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions.

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. [22].

3. Simulation and definition of signal events

Monte Carlo (MC) simulated data samples for the $\mathrm{t\bar{t}}$ signal are generated by the MadGraph (v. 5.1.3.30) event generator [23] with matrix elements (ME) at leading order, allowing up to three additional partons including b quarks. The generated events are interfaced with pythia (v. 6.426) [24] to provide the showering of the partons, and to perform the matching of the soft radiation with the contributions from the ME. The τ lepton decays are handled with tauola (v. 2.75) [25]. The powheg (v. 1.0) generator [26–28] at NLO, interfaced with pythia, is used for cross-checks and systematic studies. A Z/γ^*+jets background sample is simulated in MadGraph. The $\mathrm{t\bar{t}H}$ process is modelled using pythia. The electroweak production of single top quarks ($\mathrm{pp \rightarrow tW}$ and $\mathrm{pp \rightarrow \bar{t}W}$) is simulated in powheg with an approximate next-to-next-to-leading-order (NNLO) cross section calculation [29]. The CTEQ6L1 [30] set of PDFs is used for the MadGraph and pythia samples, while the CTEQ6M [31] set is used for the powheg samples. The CMS detector response is simulated using Geant4 (v. 9.4) [32]. The pileup distribution used in the simulation is weighted to match the one observed in data.

Measurements are reported for two different regions of the phase space: a visible phase space and the full phase space. In the visible phase space, all $\mathrm{t\bar{t}b\bar{b}}$ final state particles ($\mathrm{t\bar{t}b\bar{b} \rightarrow bW^+\bar{b}W^-b\bar{b} \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu}b\bar{b}}$) 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 same experimentally accessible kinematic region. Simulated $\mathrm{t\bar{t}b\bar{b}}$ events are defined to be in the visible phase space and are categorized as coming from the $\mathrm{t\bar{t}jj}$ process if they contain, at the generator level, at least four particle-level jets, including at least two jets originating from b quarks, and two leptons ($\mathrm{t\bar{t}jj \rightarrow bW^+\bar{b}W^-jj \rightarrow b\ell^+\nu\bar{b}\ell^-\bar{\nu}jj}$). Each lepton must have $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$, $|\eta| < 2.4$, and come from the decay of a W boson from one of the top quarks. Electrons or muons originating from the leptonic decays of τ leptons produced in $\mathrm{W} \rightarrow \tau\nu$ decays are included. Jets which are within $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.5$ 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 jets and the lepton. 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 0.5 and are required to satisfy $|\eta| < 2.5$ and $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$, which is lower than the reconstructed minimum jet p_{T}, as described below. The b and c quark jets ("c jets") are identified by the presence of corresponding hadrons containing a b or c quark among the ancestors of the jet constituents. In the case where two jets contain the decay products of the same b hadron, the jet with the higher p_{T} is selected as the b jet. When a b hadron is successfully matched, the c quarks are not considered.

The $\mathrm{t\bar{t}jj}$ sample is composed of four components, distinguished by the flavour of the two jets in addition to the two b jets required from the top quark decays. The four components are the $\mathrm{t\bar{t}b\bar{b}}$ final state with two b jets, the $\mathrm{t\bar{t}bj}$ final state with one b jet and one lighter-flavour jet, the $\mathrm{t\bar{t}c\bar{c}}$ final state with two c jets, and the $\mathrm{t\bar{t}LF}$ 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 $\mathrm{t\bar{t}bj}$ final state is mainly from the merging of two b jets or the loss of one of the b jets caused by the acceptance requirements. Efficiency corrections to the measurement for the visible phase space are mainly from detector effects. The results for the visible phase space are compared with those from MC simulations.

The goal of the full phase space result is to provide a comparison to theoretical calculations, which are generally performed at the parton level. To obtain a full phase space MC sample, the jet reconstruction is performed on the partons (gluons, as well as quarks lighter than top) before hadronization, as well as τ leptons that decay hadronically. As the full hadronization and decay chain is known, only τ leptons that decay hadronically and partons that lead to hadrons are included. The jet reconstruction algorithm is the same as for the visible phase space. Following the jet reconstruction, b jets are identified with a $\Delta R < 0.5$ requirement between the b quarks and parton-level jets, where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle and pseudorapidity differences, respectively, between the directions of the b quark and the parton-level jet. For comparison with theoretical predictions [16], results are quoted for two different jet p_{T} thresholds of $p_{\mathrm{T}} > 20$ and $> 40\ \mathrm{GeV}/c$ on the jets not arising from top quark decays. To clarify the phase space definition, the objects on which the selections are applied are listed in Table 1.

4. Event selection and background estimation

The events are recorded using dilepton triggers with asymmetric thresholds of 8 and 17 GeV/c on the transverse momentum of the leptons. Jets are reconstructed using the same algorithm as in the simulations. 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 $\sum p_{\mathrm{T}}^2$ of its associated tracks. Muon candidates are reconstructed by combining information from the silicon tracker and the muon system [34]. Muon candidates are further required to have a minimum number of hits

Table 1
The objects used to define the visible and full phase space are listed. Details of the parton- and particle-level definitions are described in the text. The symbol t denotes a top quark.

Phase Space (PS)	Parton level	Particle level
Visible PS	–	4 (b) jets and 2 leptons (e, μ)
Full PS	t, t̄ and 2 (b) jets (not from t or t̄)	–

in the silicon tracker and to have a high-quality global fit including a minimum number of hits in the muon detector. Electron candidates are reconstructed by combining a track with energy deposits in the ECAL, taking into account bremsstrahlung photons. Requirements on electron identification variables based on shower shape and track-cluster matching are applied to the reconstructed candidates [35,36]. Muons and electrons must have $p_{\mathrm{T}} > 20$ GeV/c 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 sum of the transverse momenta of all objects in a cone of $\Delta R < 0.3$ around the lepton p_{T} direction to the lepton p_{T}. The objects considered are the charged hadrons associated with the primary vertex as well as the neutral hadrons and photons, whose energies are corrected for the energy from pileup. Thus,

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

Leptons are required to have $I_{\mathrm{rel}} < 0.15$. The efficiencies for the above lepton identification requirements are measured using Z boson candidates in data and are found to be consistent with the values from the simulation. The residual differences are applied as a correction to the simulation.

The event selection requires the presence of two isolated opposite-sign leptons of invariant mass $M_{\ell\ell} > 12$ GeV/c^2. Lepton pairs of the same flavour ($\mathrm{e}^+\mathrm{e}^-$, $\mu^+\mu^-$) are rejected if their invariant mass is within 15 GeV/c^2 of the Z boson mass. The missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the magnitude of the vectorial sum of the transverse momenta of all reconstructed particles in the event [37]. In the same-flavour channels, remaining backgrounds from $Z/\gamma^* +$jets processes are suppressed by demanding $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV. For the $\mathrm{e}^\pm\mu^\mp$ channel, no $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement is applied.

Four or more reconstructed jets are required with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 30$ GeV/c, of which at least two jets must be identified as b jets, using a combined secondary vertex (CSV) algorithm, which combines secondary vertex information with lifetime information of single tracks to produce a b-tagging discriminator [38]. A tight b-tagging requirement on this discriminator is applied, which has an efficiency of about 45% for b jets and a misidentification probability of 0.1% for light-flavour jets.

Differences in the b-tagging efficiencies between data and simulation [38] are accounted for by reweighting the shape of the CSV b-tagging discriminator distribution in the simulation to match that in the data. Data/MC scale factors for this p_{T}- and η-dependent correction are derived separately for light- and heavy-flavour jets. The scale factor for c jets is not measured, owing to the limited amount of data, and is set to unity. Light-flavour scale factors are determined from a control sample enriched in events with a Z boson and exactly two jets. Heavy-flavour scale factors are derived from a tt̄ enriched sample with exactly two jets, excluding $\mathrm{Z} \to \ell\ell$ events.

The background contributions arising from $\mathrm{Z}/\gamma^* +$jets events is estimated in data using the number of events having a dilepton invariant mass of $76 < M_{\ell\ell} < 106$ GeV/c^2, scaled by the ratio of events that fail and pass this selection in the Drell–Yan simulation [39,40]. The multijet and diboson background contributions are negligible after the full event selection.

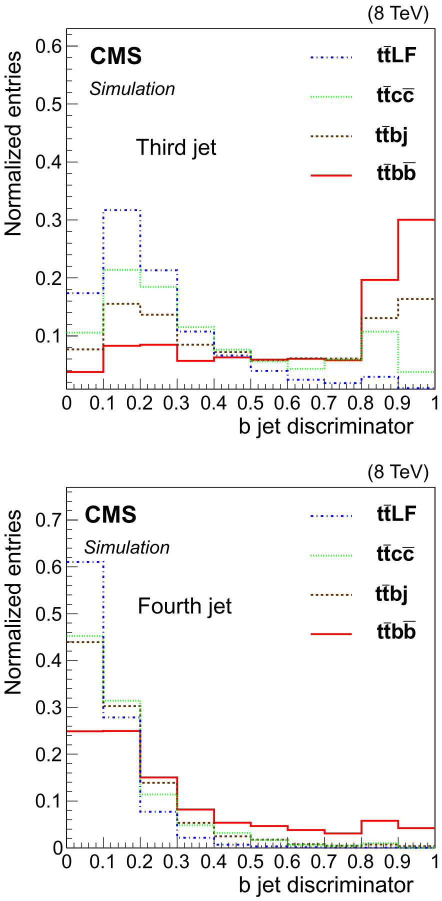

Fig. 1. Normalized distributions of the b jet discriminator for the third (top) and fourth (bottom) jets in an event, sorted in decreasing order of b-tagging discriminator value, after the full event selection. The histograms are obtained from MC simulation and are separated according to jet flavour.

5. Measurement

After the full event selection, the three dilepton categories ee, $\mu\mu$, and eμ are combined, and the ratio of the number of tt̄bb̄ events to tt̄jj events is obtained from the data by fitting the CSV b-tagging discriminator distributions. The distributions of the discriminator from simulation for the third and fourth jets in decreasing order of the b-tagging discriminator, i.e. for the two additional jets not identified as coming from the top quark decays, are shown in Fig. 1. The third and fourth jets from tt̄jj events tend to be light-flavour jets, while these are heavy-flavour jets for tt̄bb̄ events. These two distributions are used to separate tt̄bb̄ from other processes.

Fig. 2 shows the b-tagging discriminator distributions of the third and fourth jets in the events from data and simulation, where the simulation histograms have been scaled to the fit result. The

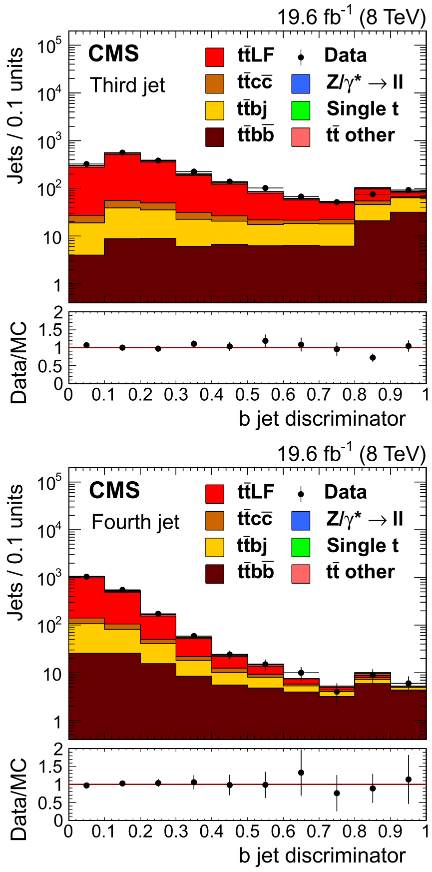

Fig. 2. Distributions of b jet discriminator for the third (top) and fourth (bottom) jets in events in decreasing order of b-tagging discriminator value, after the full event selection. Points are from data and stacked histograms from MC simulation using results from the fit to data. The ratio of the number of data events to the total number of MC events after the fit is shown in the lower panels.

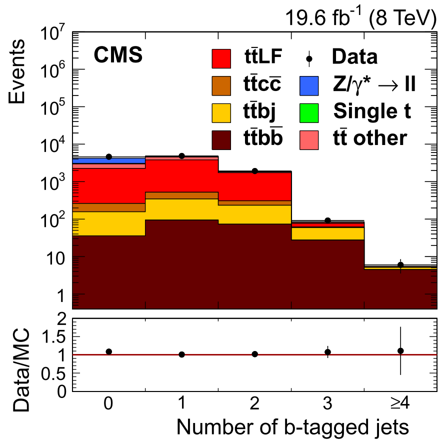

Fig. 3. Distribution of b jet multiplicity after the four-jet requirement but without the b-tagging requirement. Points are from data and stacked histograms from MC simulation using results from the fit to data. The ratio of the number of data events to the total number of MC events after the fit is shown in the lower panel.

Table 2
The number of events for each physics process and for each dilepton category after fitting to the data, their total, and the observed total number of events. The results are after the final event selection. The $Z/\gamma^* \to \ell\ell$ uncertainty is from data, while all other uncertainties include only the statistical uncertainties in the MC samples.

Final state	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$	All
$t\bar{t}b\bar{b}$	18	26	61	105 ± 2
$t\bar{t}$bj	35	48	109	191 ± 3
$t\bar{t}c\bar{c}$	13	19	45	78 ± 2
$t\bar{t}$LF	249	347	840	1438 ± 9
$t\bar{t}$ others	21	25	64	109 ± 3
Single top	7.4	11	24	43 ± 5
$Z/\gamma* \to \ell\ell$	5.7	5.4	3.1	14 ± 7
Total	350	483	1149	1983 ± 13
Data	367	506	1145	2018

fit is performed on both distributions simultaneously, and contains two free parameters, an overall normalization and the ratio of the number of $t\bar{t}b\bar{b}$ events to $t\bar{t}$jj events. The $t\bar{t}c\bar{c}$ and $t\bar{t}$LF contributions are combined, and the ratio of the $t\bar{t}b\bar{b}$ to $t\bar{t}$bj contributions is constrained using the predictions from the MC simulation. Additionally, the background contributions from single top production and from $t\bar{t}$ events that fail the visible phase space requirements (labelled "tt other") are scaled by the normalization parameter. The contribution from $Z/\gamma^* +$jets is fixed from data, as described above. Nuisance parameters are used to account for the uncertainties in the background contributions.

The b-tagged jet multiplicity distribution in Fig. 3 shows the comparison between data and the MC simulation, scaled by the fit results to the data. The results, which include the requirement of four jets but not the b-tagging requirement, indicate that the fit is a good match to the data, as made clear in the lower panel showing the data/MC ratio.

Table 2 gives the predicted number of events for each physics process and for each dilepton category after fitting to the data, as well as a comparison of the total number of events expected from the simulation and observed in data. Since the full event selection requires at least two b-tagged jets, which is usually satisfied by $t\bar{t}$ events, only 3% of the events are from non-$t\bar{t}$ processes. The expected contribution from the $t\bar{t}$H process is 12 events. This contribution is not subtracted from the data.

The ratio of the number of $t\bar{t}b\bar{b}$ to $t\bar{t}$jj events at the reconstruction level obtained from the fit is corrected for the ratio of efficiencies. The event selection efficiencies, defined as the number of $t\bar{t}b\bar{b}$ and $t\bar{t}$jj events after the full event selection divided by the number of events in the corresponding visible phase space are 18.7% and 7.2%, respectively. The $t\bar{t}b\bar{b}$ and $t\bar{t}$jj cross sections in the visible phase space are measured using $\sigma_{\text{visible}} = N/(\epsilon\mathcal{L})$, where $\mathcal{L}$ is the integrated luminosity, N is the number of observed events, and ϵ is the efficiency for each process. However, the NLO theoretical calculation is based on parton-level jets being clustered with partons before hadronization in the full phase space. For the purpose of comparing with the theoretical prediction, the cross sections in the full phase space are extrapolated from the cross sections in the visible phase space using $\sigma_{\text{full}} = \sigma_{\text{visible}}/\mathcal{A}$, where $\mathcal{A}$ is the acceptance. The acceptances for extending $t\bar{t}b\bar{b}$ and $t\bar{t}$jj to the full phase space based on the MadGraph simulation are 2.6% and 2.4%, respectively, including the $t\bar{t}$ to dilepton branching fraction, calculated using the leptonic branching fraction of the W boson [41]. The acceptance is defined as the number of events in the corresponding visible phase space divided by the number of events in the full phase space.

6. Estimation of systematic uncertainties

The systematic uncertainties are determined separately for the $t\bar{t}b\bar{b}$ and $t\bar{t}$jj cross sections and their ratio. In the ratio, many systematic effects cancel, specifically normalization uncertainties such as the ones related to the measurement of the integrated luminosity and the lepton identification including trigger efficiencies, since they are common to both processes. The various systematic uncertainties in the measured values are shown in Table 3 for the visible

Table 3

Summary of the systematic uncertainties from various sources contributing to $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$, $\sigma_{\mathrm{t\bar{t}jj}}$, and the ratio $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ for a jet p_{T} threshold of $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$ in the visible phase space.

Source	$\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ (%)	$\sigma_{\mathrm{t\bar{t}jj}}$ (%)	$\frac{\sigma_{\mathrm{t\bar{t}b\bar{b}}}}{\sigma_{\mathrm{t\bar{t}jj}}}$ (%)
Pileup	1.0	1.0	1.0
JES & JER	11	8.0	5.0
b tag (b quark flavour)	15	< 0.1	15
b tag (c quark flavour)	4.0	< 0.1	4.0
b tag (light flavour)	7.0	< 0.1	7.0
Ratio of $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}bj}$	9.0	< 0.1	9.0
Bkgnd modelling	1.0	1.0	1.0
$\mathrm{t\bar{t}c\bar{c}}$ fraction in the fit	4.2	0.2	4.0
Lepton identification	4.0	4.0	–
MC generator	3.0	3.0	3.0
Scale (μ_F and μ_R)	8.0	3.0	6.0
PS matching	12	5.0	3.0
PDF	4.0	4.0	< 0.1
Eff. ($\mathrm{t\bar{t}c\bar{c}}$ fraction)	–	1.6	1.6
Luminosity	2.6	2.6	–
Total uncertainty	28	12	22

phase space and a jet p_{T} threshold of 20 GeV/c, including the luminosity uncertainty [19] and lepton identification [42], which only affect the absolute cross section measurements. The systematic uncertainty in the lepton identification is assessed using the scale factor obtained from Z boson candidates and also taking into account the different phase space between Z boson and $\mathrm{t\bar{t}}$ events.

The systematic uncertainties associated with the b-tagging discriminator scale factors for b jets and light-flavour jets are studied separately, varying their values within their uncertainties. The b-flavour scale factors are obtained using $\mathrm{t\bar{t}}$ enriched events, and their dominant uncertainty comes from the contamination when one of the b jets is not reconstructed [43] (indicated as "b quark flavour" in Table 3). The c jet scale factor is assumed to be unity with an uncertainty twice as large as the b-tagging scale factor [38] (indicated as "c quark flavour" in Table 3). The light-flavour jet scale factors are determined from Z boson enriched events. Their uncertainty arises because the contribution from the $\mathrm{Z} + \mathrm{b\bar{b}}$ process in this control sample is not well modelled (indicated as "light flavour" in Table 3). The b-tagging discriminator can be affected by the jet energy scale (JES) variations. The systematic uncertainty in the jet energy scale [44] is obtained by varying the jet energy scale factor by one standard deviation for each quark flavour. The uncertainty in the jet energy resolution (JER) is assessed by smearing the simulated jet energy resolution by 10% on average, taking into account the η dependence [44].

The uncertainty arising from constraining the ratio of the $\mathrm{t\bar{t}bj}$ to $\mathrm{t\bar{t}b\bar{b}}$ contributions in the fit to match the MC prediction is evaluated by comparing the result with and without the constraint. The number of pileup interactions in data is estimated from the measured bunch-to-bunch instantaneous luminosity and the total inelastic cross section. The systematic uncertainty in the number of pileup events is estimated by conservatively varying this cross section by 5% to cover all the uncertainties in the modelling of the pileup physics. The contributions from Drell–Yan and single top quark processes are small, and the shapes of the distributions from these backgrounds are similar to those of the $\mathrm{t\bar{t}LF}$ component. Therefore, these backgrounds do not affect the measurement significantly. For the efficiency of $\mathrm{t\bar{t}jj}$ events, the uncertainty owing to the heavy-flavour fraction is estimated by varying the contribution by 50%. An uncertainty to account for the variation of the $\mathrm{t\bar{t}c\bar{c}}$ fraction in the fit is also assigned by varying the contribution by 50%. This variation is chosen because the theoretical uncertainty in the $\mathrm{t\bar{t}jj}$ cross section is less than 50%, and the fitted $\mathrm{t\bar{t}c\bar{c}}$ fraction remains within 50% of the input value when fitting with the $\mathrm{t\bar{t}c\bar{c}}$ contribution as a free parameter.

The dependence of the correction factor for the particle level on the assumptions made in the MC simulation is another source of systematic uncertainty: the generators MadGraph and powheg are compared and the difference in the efficiency ratio is taken as the systematic uncertainty. The uncertainties from the factorization/renormalization scales and the matching scale that separates jets from ME and from parton showers in MadGraph are estimated by varying the scales a factor of two up and down with respect to their reference values. The uncertainties in the PDFs are accounted for by following the PDF4LHC prescription [45].

The total systematic uncertainty in the cross section ratio is 22%, with the dominant contributions from the b-tagging efficiency and the misidentification of light-flavoured partons, followed by the renormalization/factorization and matching scale systematic uncertainties.

The uncertainty in $\sigma_{\mathrm{t\bar{t}jj}}$ is significantly smaller than that in $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ since the measurement of the latter requires the identification of multiple b jets. The uncertainty in $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ is larger than that for the cross section ratio since uncertainties that are common between $\mathrm{t\bar{t}b\bar{b}}$ and $\mathrm{t\bar{t}jj}$, such as the jet energy scale uncertainty, partially or completely cancel in the ratio.

The systematic uncertainties in the measurements with a p_{T} threshold of 40 GeV/c are found to be very similar to those with a 20 GeV/c threshold. The uncertainty from the factorization and renormalization scales for the higher-p_{T} threshold of 40 GeV/c cannot be accurately determined owing to the statistical uncertainties in the MC sample. Thus, the $p_{\mathrm{T}} > 40\ \mathrm{GeV}/c$ threshold measurements use the same scale (μ_F and μ_R) systematic uncertainties as those found for the $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$ threshold results.

In extrapolating the measurements from the visible phase space to the full phase space, the systematic uncertainty in the acceptance is included. The effect of the MC modelling of the acceptance is estimated by comparing the results between MadGraph and powheg. This uncertainty equals 5% for each of the cross section measurements and 2% for the cross section ratio.

7. Results

After correcting for the efficiency ratio and taking into account the systematic uncertainties, the cross section ratio $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ is measured in the visible phase space from a fit to the measured CSV b-tagging discriminator distributions shown in Fig. 2. The measured cross section ratio in the visible phase space for events with particle-level jets and a minimum jet p_{T} of 20 GeV/c is

$$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}} = 0.022 \pm 0.003\,(\mathrm{stat}) \pm 0.005\,(\mathrm{syst}). \tag{2}$$

This result is for the visible phase space, defined as events having two leptons with $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$ and $|\eta| < 2.4$, plus four jets, including two b jets with $p_{\mathrm{T}} > 20\ \mathrm{GeV}/c$ and $|\eta| < 2.5$. The predicted value from both MadGraph and powheg is found to be 0.016 ± 0.002, where the MC uncertainty is the sum in quadrature of the statistical uncertainty and the systematic uncertainties from the factorization/renormalization and the matching scales. The measured cross sections are presented in Table 4. When the $\mathrm{t\bar{t}H}$ contribution is subtracted from the data, the ratio is reduced by only 4%, much less than the overall uncertainty. Therefore, compared to the uncertainties, the contribution from $\mathrm{t\bar{t}H}$ can be considered negligible. The measured full phase space ratio with a minimum p_{T} of 20 GeV/c for parton-level jets is consistent within the uncertainties with the result in the visible phase space.

A NLO theoretical QCD calculation is available for parton-level jets with a $p_{\mathrm{T}} > 40\ \mathrm{GeV}/c$ threshold [16]. The NLO cross section

Table 4
The measured cross sections $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ and $\sigma_{\mathrm{t\bar{t}jj}}$ and their ratio are given for the visible phase space (PS) defined as two leptons with $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.4$ plus four jets, including two b jets with $p_{\mathrm{T}} > 20$ GeV/c and $|\eta| < 2.5$, and the full phase space, corrected for acceptance and branching fractions. The full phase space results are given for jet thresholds of $p_{\mathrm{T}} > 20$ and 40 GeV/c. The uncertainties shown are statistical and systematic, respectively. The predictions of a NLO theoretical calculation for the full phase space and $p_{\mathrm{T}} > 40$ GeV/c are also given [16].

Phase Space (PS)	$\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ [pb]	$\sigma_{\mathrm{t\bar{t}jj}}$ [pb]	$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$
Visible PS (particle)			
Jet $p_{\mathrm{T}} > 20$ GeV/c	$0.029 \pm 0.003 \pm 0.008$	$1.28 \pm 0.03 \pm 0.15$	$0.022 \pm 0.003 \pm 0.005$
Full PS (parton)			
Jet $p_{\mathrm{T}} > 20$ GeV/c	$1.11 \pm 0.11 \pm 0.31$	$52.1 \pm 1.0 \pm 6.8$	$0.021 \pm 0.003 \pm 0.005$
Jet $p_{\mathrm{T}} > 40$ GeV/c	$0.36 \pm 0.08 \pm 0.10$	$16.1 \pm 0.7 \pm 2.1$	$0.022 \pm 0.004 \pm 0.005$
NLO calculation			
Jet $p_{\mathrm{T}} > 40$ GeV/c	0.23 ± 0.05	21.0 ± 2.9	0.011 ± 0.003

values for $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$, $\sigma_{\mathrm{t\bar{t}jj}}$, and the ratio $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ are given in Table 4. To compare with this theoretical prediction, the analysis is repeated for a jet threshold of $p_{\mathrm{T}} > 40$ GeV/c. Correspondingly with a higher jet p_{T} threshold in the event selection, 24 $\mathrm{t\bar{t}b\bar{b}}$ events and 478 $\mathrm{t\bar{t}jj}$ events remain after the full event selection, with the acceptance (including the event selection efficiency) of 0.34% and 0.15%, respectively. The measured cross section ratio in the full phase space with the $p_{\mathrm{T}} > 40$ GeV/c threshold is

$$\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}} = 0.022 \pm 0.004\,(\mathrm{stat}) \pm 0.005\,(\mathrm{syst}). \tag{3}$$

The cross sections in the full phase space for this p_{T} threshold are summarized in Table 4. The measured cross section ratio is higher, but compatible within 1.6 standard deviations with the prediction from the NLO calculation of 0.011 ± 0.003.

8. Summary

A measurement of the cross section ratio $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}}$ has been presented by the CMS experiment, using a data sample of pp collisions at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.6 fb^{-1}. The individual cross sections $\sigma_{\mathrm{t\bar{t}jj}}$ and $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ have also been determined. The cross section ratio was measured in a visible phase space region using the dilepton decay mode of $\mathrm{t\bar{t}}$ events and corrected to the particle level, corresponding to the detector acceptance. The measured cross section ratio in the visible phase space is $\sigma_{\mathrm{t\bar{t}b\bar{b}}}/\sigma_{\mathrm{t\bar{t}jj}} = 0.022 \pm 0.003\,(\mathrm{stat}) \pm 0.005\,(\mathrm{syst})$ with a minimum p_{T} for the particle-level jets of 20 GeV/c. The cross section ratio has also been measured in the full phase space with minimum parton-jet p_{T} thresholds of $p_{\mathrm{T}} > 20$ and > 40 GeV/c in order to compare with a NLO QCD calculation of the cross section ratio. The measurement is compatible within 1.6 standard deviations with the theoretical prediction. These are the first measurements of the cross sections $\sigma_{\mathrm{t\bar{t}b\bar{b}}}$ and $\sigma_{\mathrm{t\bar{t}jj}}$, and their ratio. The result will provide important information about the main background in the search for $\mathrm{t\bar{t}H}$ and as a figure of merit for testing the validity of NLO QCD calculations.

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