Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A measurement of the production cross section of top quark pairs in association with two $b$ jets ($t\bar{t}b\bar{b}$) is presented, using data collected in pp collisions at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The cross section is measured in the all-jet decay channel of the top quark pairs by selecting events containing at least eight jets, of which two are identified as originating from the hadronisation of $b$ quarks. A combination of multivariate analysis techniques is used to reduce the large background consisting uniquely of jets produced through the strong interaction, and to discriminate the jets originating from the top quark decays and additional jets. The cross section is measured for the visible $t\bar{t}b\bar{b}$ phase space, as well as for the full phase space, for which it is determined to be $5.5 \pm 0.3$ (stat) $^{+1.6}_{-1.3}$ (syst) pb. The measured cross sections are compared with predictions of several event generators and are found to be generally higher than the theoretical predictions.
1 Introduction

At the CERN LHC, top quark pairs are produced with copious amounts of extra jets, including jets resulting from the hadronisation of b quarks (b jets). Top quark pair production in association with a pair of b jets, \( t\bar{b}b\), is challenging to model because of the presence of very different scales in the process and because of the nonzero mass of b quarks. Improving the accuracy of perturbative quantum chromodynamics (QCD) predictions for this process is crucial, since it represents an important background for numerous searches or measurements at the LHC. In particular, \( t\bar{t} \) production in association with a Higgs boson (\( t\bar{t}H \)), where the Higgs boson decays to \( b\bar{b} \), suffers from an irreducible \( t\bar{b}b\) background [1–6]. Searches for four top quark production (\( t\bar{t}t\bar{t} \)) are also affected by this background [7–9]. Both of these processes are important to study since they allow direct access to the top quark Yukawa coupling, a crucial parameter of the standard model. An improved understanding of the \( t\bar{b}b\) process would help reduce the uncertainty in their measurements.

Theoretical predictions for the production cross section of \( t\bar{t} \) in association with jets have been performed at next-to-leading order (NLO) in QCD matched with the parton shower (PS), with up to two additional massless partons in the matrix element [10–17]. Calculations of the \( t\bar{b}b\) cross section at NLO in QCD with massive b quarks, matched with the PS, have recently become available [18–20]. Measurements of the \( t\bar{b}b\) process represent stringent tests of perturbative QCD calculations, and can thus provide valuable guidance for improving the various frameworks used for these calculations. The \( t\bar{b}b\) production cross section has previously been measured at \( \sqrt{s} = 8 \) and 13 TeV by the ATLAS and CMS Collaborations, in events with one or two charged leptons [21–25].

This note focuses on the fully-hadronic final state of \( t\bar{t} \) production, where both top quarks decay into three jets, leading to a signature of four b jets and four light jets for the \( t\bar{b}b\) process. This all-jet final state is favoured by a large branching ratio and allows a complete reconstruction of the top quarks, but suffers from a large background from QCD multijet production, as well as from the difficulty to identify which jets originate from decaying top quarks. Multivariate analysis techniques are developed and implemented to mitigate these problems. The \( t\bar{b}b\) cross section is measured using a sample of pp collisions delivered at a centre-of-mass energy of 13 TeV by the LHC and collected by the CMS experiment corresponding to an integrated luminosity of 35.9 fb\(^{-1}\) [26].

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 (\( \eta \)) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers 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. [27].

Samples of \( t\bar{t} \) events are simulated at NLO in QCD using \textsc{powheg v2} [28–31]. Single top quark production in the \( t \) channel or in association with a W boson, and \( t\bar{t}H \) production are simulated at NLO with \textsc{powheg} [32–34]. Production of W or Z bosons in association with jets (V+jets), as well as QCD multijet events, are simulated at leading order (LO) with \textsc{mad-}
The 

\texttt{MADGRAPH5_aMC@NLO} \cite{35} and the MLM merging scheme \cite{36}. The \texttt{MADGRAPH5_aMC@NLO} generator is used at NLO for simulating associated production of top quark pairs with W or Z bosons (ttV). Diboson processes (WW, WZ and ZZ) are simulated at LO using \texttt{PYTHIA 8.212} \cite{37}.

All simulated processes are processed with \texttt{PYTHIA} for modelling of the parton showering, hadronisation, and underlying event (UE). The NNPDF 3.0 \cite{38} parton distribution functions (PDFs) are used throughout, and the CUETP8M1 underlying event tune \cite{39} is used for all processes except for the tt, ttH and single top quark processes, for which the tune CUETP8M2T4 is used, which was customised by CMS with an updated strong coupling for initial-state radiation \cite{40}. Simulation of the CMS detector response is based on \texttt{GEANT4} \cite{41}. Additional pp interactions in the same or neighbouring bunch crossings (pileup) are simulated with \texttt{PYTHIA} and overlaid with generated events according to the pileup distribution measured in data.

The various simulated processes are normalised to state-of-the-art predictions for the production cross sections. The tt, V+jets, single top quark and W+W− samples are normalised to next-to-NLO (NNLO) precision in QCD \cite{42–45}, while remaining processes such as ttV, ttH and diboson production are normalised to NLO in QCD \cite{35, 46}.

\section*{3 Signal phase space definitions}

The ttbB production cross section is measured for three different definitions of the phase space. Two definitions for ttbB events in the visible phase space (VPS) are considered: one that is based exclusively on stable generated particles after hadronisation (parton-agnostic, PA), and one that also uses parton-level information after radiation emission (parton-based, PB). The former facilitates comparisons with predictions from event generators, while the latter is closer to the approach taken by searches for ttH production to define the contribution due to the ttbB process. The cross section is reported for the full phase space (FPS) by correcting the cross section in the VPS by the experimental acceptance.

Particle-level jets are defined by clustering stable generated final-state particles, excluding neutrinos, using the anti-\texttt{kT} algorithm \cite{47, 48} with a distance parameter of 0.4. These jets are identified unambiguously as b or c jets by rescaling the momenta of generated b and c hadrons to a negligible value and including them in the clustering procedure. A jet is considered as b jet if it is matched to a least one b hadron, and as c jet if matched with at least one c hadron and no b hadron.

Events in the generated tt sample are divided into exclusive categories according to the flavour of the jets that do not originate from the decay of top quarks, called “additional” jets. The b or c jets are considered to originate from a top quark if one of the clustered b or c hadrons features a top quark in its simulation history. Additional jets are required to have a transverse momentum \( p_T \) above 20 GeV, and absolute pseudorapidity \( |\eta| < 2.4 \). Events are categorised as ttbB if they contain at least two additional b jets, which defines the full phase space for which the ttbB cross section is measured. Events with a single additional b jet are categorised as ttb (tt2b) if that b jet is matched with exactly one (at least two) b hadron(s). If at least one additional c jet is present the event is called tftc; all remaining events are called ttjj.

For the PB definition of the ttbB VPS, at least eight jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.4 \) should be present, of which at least six have \( p_T > 30 \text{ GeV} \). At least four of these jets should be b jets, and at least two of those should not originate from top quarks. That last requirement is relaxed for the PA VPS definition, in order to be independent of the origin of the b jets, and thus of the simulated parton content. Some ttbB events in the FPS failing the VPS requirements may
still be reconstructed and selected because of resolution effects, and are referred to as out of acceptance (OOA).

4 Event reconstruction and selection

The particle-flow algorithm [49] aims to reconstruct and identify each individual particle in an event, with an optimised combination of information from the various elements of the CMS detector. The reconstructed vertex with the largest value of summed object $p_T^2$ is taken to be the primary $pp$ interaction vertex, where the considered objects are those returned by a jet clustering algorithm applied to the tracks assigned to the vertex, and the associated missing transverse momentum, taken as the negative vector sum of those objects’ transverse momenta. The energy of photons is obtained from the ECAL measurement. The energy of electrons 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. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are clustered from the reconstructed particles using the anti-$k_T$ algorithm with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5 to 10% of the true momentum over the whole transverse momentum spectrum and detector acceptance. Pileup interactions can contribute additional tracks and calorimetric energy depositions to the jet momentum. To mitigate this effect, tracks identified to be originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation to bring the average measured response of a jet to that of a particle-level jet. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to account for any residual differences in jet energy scale in data and simulation [50]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures.

A combined secondary vertex b tagging algorithm (CSVv2) is used to identify jets originating from the hadronisation of b quarks [51], with an efficiency for identifying b jets in simulated $tt$ events of about 65%. Referring to light-flavour jets as jets originating from the hadronisation of u, d, s quarks or gluons, the b tagging algorithm’s misidentification probability for c and light-flavour jets is about 10% and 1%, respectively. The distribution of the discriminator score for b and light-flavour jets in the simulation is calibrated to match the distribution measured in control samples of $tt$ events with exactly two leptons (electrons or muons) and two jets, and Z bosons produced in association with jets where the Z bosons decay to pairs of electrons or muons. The calibration is achieved by reweighting events using scale factors that are parameterised by the jet flavour, $p_T$, $|\eta|$, and b tagging discriminator score [51].

Data are collected using two dedicated triggers, both requiring at least six jets with $|\eta| < 2.4$. The first (second) trigger considers jets with $p_T > 40\text{ GeV}$ ($30\text{ GeV}$), and requires that the jet scalar $p_T$ sum $H_T$ exceeds 450 GeV ($400\text{ GeV}$) and that at least one (two) of the jets is b tagged. The efficiency of these triggers is measured in the simulation, as well as in a data control sample collected using independent single-muon triggers. The trigger efficiency in the simulation is
corrected to match the efficiency observed in the data by reweighting events using scale factors defined as the ratio between the efficiencies in the data and in the simulation.

An offline preselection is applied to recorded and simulated events, by requiring the presence of at least six jets with $p_T > 40$ GeV and $|\eta| < 2.4$, of which at least two are $b$ tagged, and $H_T > 500$ GeV. Additional jets in the events are considered if they satisfy $p_T > 30$ GeV and $|\eta| < 2.4$. Events are vetoed if they contain electrons or muons with $p_T > 15$ GeV and $|\eta| < 2.4$, that satisfy loose identification criteria and are isolated from hadronic activity [52, 53].

5 Multivariate analysis

The final state considered in this analysis is plagued by a large background from QCD multijet production, as well as by the difficulty to identify the jets not stemming from top quark decays. To address these challenges and improve the sensitivity to the $tt\bar{b}b$ signal, several multivariate analysis tools have been employed.

The QCD multijet background can be discriminated from $tt\bar{b}b$ production by observing that the latter is expected to contain four light-quark jets from $W$ boson decays per event, whereas the former is enriched in gluon jets. Gluon and quark jets are separated using a quark-gluon likelihood (QGL) variable, based on jet substructure observables [54, 55]. Using the individual jet QGL values, the likelihood of an event to contain $N_q$ quark jets and $N_g$ gluon jets is defined as:

$$L(N_q, N_g) = \sum_{\text{perm}} \left( \prod_{i=N_q+1}^{N_q+N_g} f_q(\zeta_i) f_g(\zeta_i) \right)$$

where the sums run over all possible assignments of $N_q$ jets to quarks and $N_g$ jets to gluons, $\zeta_i$ is the QGL discriminator of the $i$th jet, and $f_q$ and $f_g$ are the probability densities for $\zeta_i$ under the hypothesis of (u, d, s or c) quark or gluon origin, respectively. When computing $L(N_q, N_g)$, $b$-tagged jets are not considered. Based on the event likelihoods with $N_q = 4$ and $N_g = 0$, as well as $N_q = 0$ and $N_g = 4$, the QGL ratio (QGLR) is defined as $QGLR = L(4, 0) / (L(4, 0) + L(0, 4))$. Other values for $N_q$ and $N_g$ have been tried but led to reduced discrimination between multijet and $tt\bar{b}b$ production. We correct the modelling of the QGL in the simulation by reweighting each event based on the origin (quark/gluon) and the QGL value of all jets in the event, where the weights are measured using data samples enriched in $Z$+jets and dijet events [55]. After applying this correction, a good agreement is found between data and simulation.

In order to address the large combinatorial ambiguity in identifying the additional jets in the events, we have trained a boosted decision tree (BDT) using the TMVA package [56], henceforth referred to as “permutation BDT”. In events with eight reconstructed jets, there are 28 ways to select six of those as originating from the fully-hadronic decay of a top quark pair, and there are 90 ways to match those six jets to the six partons from the top quark decay chains. Some permutations are indistinguishable and are not considered, i.e. the permutation of two jets assigned to a $W$ boson decay is not considered, and neither is the permutation of three jets assigned to a $t$ or $\bar{t}$ decay. To reduce the large number of permutations, the least favoured ones are rejected using the following quantity:

$$\chi^2 = (M(j_1, j_3, j_4) - m_t)^2/\sigma_t^2 + (M(j_3, j_4) - m_W)^2/\sigma_W^2 + (M(j_2, j_5, j_6) - m_t)^2/\sigma_t^2 + (M(j_5, j_6) - m_W)^2/\sigma_W^2.$$  (2)
where \( M(\ldots) \) denotes the invariant mass of the given jets, and \( \sigma_W = 10.9 \text{ GeV} \) and \( \sigma_t = 17.8 \text{ GeV} \) are the experimental resolutions on the two- and three-jet invariant masses as determined from the simulation. The BDT is trained using simulated \( \bar{t}t \) events after applying the above preselection criteria, requiring the presence of at least seven jets, and reducing the number of permutations by requiring that \( \chi^2 < 33.38 \). The correct jet-parton assignment is considered as a signal in the training, while all other distinguishable combinations are treated as background. Input variables used for the BDT include jet b tagging discriminator scores and kinematic quantities such as invariant masses of pairs and triplets of jets, angular openings between jets, and the \( p_T \) of jets. For each permutation, only quantities pertaining to the six jets assumed to originate from the top quarks are used in the training. For \( \bar{t}t \) events with eight jets where all six jets from the top quark decays have been selected, the permutation BDT identifies the correct permutation with about 60% efficiency.

As a further handle to reduce the QCD multijet background, we have trained a second BDT to discriminate this background from inclusive \( \bar{t}t+jets \) production. However, while supervised training of multivariate classifiers relies on samples of simulated events, the poor modelling of multijet production and the insufficient size of the available simulated samples limit the achievable discrimination power. A proposed method to alleviate these shortcomings is classification without labels (CWoLa). In this weakly supervised approach, the classifier is trained using data, whereby one region in the data is treated as background and another, orthogonal region is treated as signal. The resulting classifier converges to the optimal classifier to distinguish between the signal and the background, provided that the relative rates of the actual signal and background processes are different in the two regions, but that for both the signal and background processes, the distributions of the variables entering the CWoLa classifier are independent of the quantity used to define the two regions [57]. The CWoLa BDT is trained using a sample of data with exactly seven jets, where two orthogonal regions are defined by requiring that the QGLR is below or above 0.95. The first and second regions are expected to contain about 10% and 20% of \( \bar{t}t \) events, respectively. Variables used for constructing the CWoLa BDT are kinematic quantities similar to those used in the permutation BDT, the output value of the permutation BDT, and the b tagging discriminator scores of the two jets identified by the permutation BDT as stemming from top quark decays. Only the six jets identified by the permutation BDT as coming from the top quark decays are used to define the CWoLa BDT input variables. The performance of the resulting classifier, measured in the region with at least eight jets, is found to be comparable to that of a supervised classifier trained using simulated samples.

### 6 Cross section measurements

To measure the \( \bar{t}t\bar{b}\bar{b} \) cross section, we require in addition to the preselection criteria the presence of at least eight jets, and \( \chi^2 < 33.38 \). The distributions of the QGLR and of the CWoLa BDT for selected events are shown in Fig. 1. The cross section is extracted from a binned maximum-likelihood fit to a two-dimensional distribution (referred to as 2DCSV) built using the largest and second-largest b tagging discriminator scores among the jets determined to be additional jets by the permutation BDT. In order to increase the signal purity and the precision in the measurement, we define a signal region (SR) by requiring that the CWoLa BDT score be above 0.5, and the QGLR be above 0.8. These thresholds are optimised to obtain the best expected precision in the cross section.

The QCD multijet background is estimated from the data. Three control regions (CRs) orthogonal to the SR have been defined by inverting the requirements on the CWoLa BDT and the
Figure 1: Left: distribution of the QGLR. Right: distribution of the CWoLa BDT. Both distributions are shown after preselection, requiring $\chi^2 < 33.38$, and at least eight selected jets. All processes are taken from the simulation. The multijet contribution is scaled to match the total yields in data, after the other processes including the $t\bar{t}b\bar{b}$ signal have been normalised to their corresponding theoretical cross sections. The small backgrounds include $t\bar{t}V$, $t\bar{t}H$, single top quark, $V$-jets and diboson production. The lower panels show the ratio between the observed data and the predictions. Hatched bands in the upper and grey bands in the lower panel indicate the statistical uncertainty in the predictions, dominated by the uncertainties in the simulated multijet background.
7. Systematic uncertainties

QGLR: the CR1 (BDT < 0.5, QGLR > 0.8), the CR2 (BDT < 0.5, QGLR < 0.8), and the CR3 (BDT > 0.5, QGLR < 0.8). For multijet production, the CWoLa BDT score and the QGLR are nearly independent, so that in each bin $i$ of the 2DCSV distribution the number of multijet events in the SR, $N_{i}^{SR}$, can be estimated from the number of multijet events in the CRs as:

$$\frac{N_{i}^{SR}}{N_{i}^{CR3}} = \frac{N_{i}^{CR1}}{N_{i}^{CR2}}.$$  \hspace{1cm} (3)

In order to properly take into account the small but non-negligible signal contribution in the CRs, a combined fit of the four regions is performed, where the multijet rates $N_{i}^{CR3}$, $N_{i}^{CR1}$ and $N_{i}^{CR2}$ are free to vary in the fit. The assumption of Eq. (3) on which this estimation relies is confirmed using the simulation, and we check that it is also satisfied in the data for distributions such as the invariant mass of the reconstructed W bosons and top quarks. In addition, we validate it by performing goodness-of-fit tests using alternative definitions of the four regions in the plane formed by the QGLR and the CWoLa BDT, excluding the SR as defined above.

The likelihood is a product of independent Poisson likelihoods, defined for each bin $i$ of the 2DCSV distributions in the four event regions using the following expression for the number of events in bin $i$:

$$N_{i} = \mu T_{i}^{sig.}(\theta) + \sum_{k \in \text{sim. bkg}} T_{i}^{k}(\theta) + N_{i},$$  \hspace{1cm} (4)

where $\mu$ is a signal strength parameter, $T_{i}^{k}$ is the expected yield for process $k$ in bin $i$, “sig.” includes the contributions from $t\bar{t}b\bar{b}$, $t\bar{t}2b$ and $t\bar{t}b$, and $\theta$ are nuisance parameters affecting the predicted yields of the various processes. The parameters $N_{i}$ are used to estimate the multijet background from the combined fit of the four regions: they are free parameters in the CRs and are given by Eq. (3) in the SR. The likelihood also features constraint terms for each of the nuisance parameters considered in the fit. Different templates are built from $t\bar{t}b\bar{b}$ events matching the VPS requirements, denoted $t\bar{t}b\bar{b}$ (VPS), and from events failing these requirements, denoted $t\bar{t}b\bar{b}$ (OOA). For the $t\bar{t}b\bar{b}$ (VPS) templates, the effect of nuisance parameters corresponding to theoretical uncertainties is such that the $t\bar{t}b\bar{b}$ cross section in the VPS is preserved, while no such requirement is made for the other templates. The uncertainty in the measured cross section is obtained by profiling the nuisance parameters. As described in the next section, some uncertainties are not profiled and are added in quadrature with the uncertainty obtained from the fit. The fit is repeated for each of the two definitions for $t\bar{t}b\bar{b}$ events in the VPS described in Section 3, leading to different $t\bar{t}b\bar{b}$ and $t\bar{t}b\bar{b}$ (OOA) templates. The total $t\bar{t}b\bar{b}$ cross section is obtained by dividing the cross section for the PB VPS by the acceptance, estimated to be $(29.4 \pm 1.8)\%$.

7 Systematic uncertainties

Several sources of systematic uncertainties affecting the predictions for the signal and background processes entering the analysis are considered. These uncertainties may affect the normalisation of the templates entering the fit, or may alter both their shape and their normalisation. The migration of events between the four regions is taken into account when relevant. Experimental sources of uncertainties are taken to be 100% correlated for all signal and background distributions estimated using the simulation, while only a subset of theoretical uncertainties are correlated among the $t\bar{t}+jets$ components.

The modelling of the shape of the b tagging discriminator in the simulation represents a leading source of systematic uncertainty. Several uncertainties in the calibration of the b tagging
discriminator distribution are propagated independently to the shape and normalisation of the 2DCSV templates. These are related to the uncertainty in the amount of contamination by light-(heavy-) flavour jets in the control samples used for the measurement of heavy (light) jet correction factors, as well as to the statistical uncertainty in these measurements [51]. Since no dedicated measurement is performed for c jets, the uncertainty in the shape of the b tagging discriminator distribution for c jets is conservatively taken to be twice the relative uncertainty considered for b jets. In total, six different nuisance parameters are introduced to estimate the uncertainty due to b tagging.

We evaluate the effect due to the uncertainty in the jet energy scale (JES) and resolution (JER) by shifting the jet four-momenta using correction factors that depend on jet $p_T$ and $|\eta|$ for the JES and jet $|\eta|$ for the JER [50]. Several sources of uncertainty affect the measurement of the JES, and their impact on the measurement is evaluated independently. The uncertainty in the JES is also propagated to the b tagging calibration, and the resulting effect on the distribution of the b tagging discriminators is taken to be correlated with the effect on the jet momenta.

Uncertainties pertaining to the QGL are estimated conservatively by removing or doubling the scale factors applied to correct the distribution of the QGL in the simulation [55]. The uncertainty in the integrated luminosity is evaluated to be 2.5% [26]. Uncertainties in the trigger efficiency are estimated by varying the trigger scale factors by their uncertainty determined from the efficiency measurements in data and simulation. The total inelastic pp cross section is varied by 4.6% [58] to produce different distributions of the expected number of pileup interactions, which are used to reweight simulated events. We take into account the limited size of the simulated samples by varying independently the predicted yields in every bin by their statistical uncertainties.

Theoretical uncertainties in the modelling of the $t\bar{t}$+jets process enter this analysis both through the efficiency to reconstruct and select $t\bar{t}b\bar{b}$ events, and through the contamination from $t\bar{t}c\bar{c}$ and $t\bar{t}jj$ backgrounds. The uncertainties in the renormalisation and factorisation scales ($\mu_R$ and $\mu_F$) are estimated by varying both scales independently by a factor of two up or down in the event generation, omitting the two cases where the scales are varied in opposite directions, and taking the envelope of the six resulting variations. Likewise, the uncertainties related to the choice of the scale in the PS is evaluated by varying the scale in the initial-state shower by factors of $2^{\pm1}$, and the scale in the final-state shower by factors of $2^{\pm0.5}$. Propagation of the uncertainties associated with the PDFs, as well as with the value of the strong coupling in the PDFs, has been achieved by reweighting generated events using variations of the NNPDF 3.0 set [38]. The impact of the choice of the matching scale $h_{\text{damp}} = 1.58m_t$ between the matrix element generator and the PS in POWHEG is evaluated using simulated samples generated with different choices of $h_{\text{damp}} = m_t$ and $h_{\text{damp}} = 2.24m_t$. We evaluate the uncertainty related to the UE tune by varying the tune parameters according to their uncertainties. The uncertainty from the modelling of colour reconnection (CR) in the final state is evaluated by considering four alternatives to the PYTHIA default, which is based on multiple-particle interactions (MPI) with early resonance decays (ERD) switched off. These alternatives are an MPI-based scheme with ERD switched on, a QCD-inspired scheme [59], and a gluon-move scheme with ERD either off or on [60]. Since the spectrum of the top quark $p_T$ is known to be softer in the data than in the simulation [61–68], we evaluate the effect of this mismodelling by reweighting the generated events to match the top quark $p_T$ distribution measured in data. The latter two uncertainties are not evaluated using profiled nuisance parameters, but by repeating the measurement using varied signal and background predictions. The differences in the measured cross sections are taken as the corresponding uncertainties and are added in quadrature with the uncertainty obtained from the profile likelihood. Uncertainties related to the $\mu_R$ and $\mu_F$ scales, the PS scale,
and the $h_{\text{damp}}$ choice are taken to be uncorrelated for the $t\bar{t}b\bar{b}$ (VPS), $t\bar{t}b\bar{b}$ (OOA), $t\bar{t}b$, $t\bar{t}2b$, $t\bar{t}c\bar{c}$ and $t\bar{t}jj$ templates, while the other modelling uncertainties are taken to be correlated for all $t\bar{t}$ events. In addition to the aforementioned modelling uncertainties, we assign an uncertainty of 50% to the normalisation of $t\bar{t}c\bar{c}$ to cover the lack of precise measurements of this process. The results are stable when doubling that uncertainty.

Compared to $t\bar{t}$+jets and multijet production, the contribution of other background processes such as $t\bar{t}V$, $t\bar{t}H$, V+jets, diboson and single top quark production is small. We assign uncertainties to their predicted rates based on the PDF and $\mu_R/\mu_F$ scale uncertainties in their theoretical cross sections.

Table 1 summarises the contributions of the various sources of systematic uncertainties to the total uncertainty in the cross sections measured in the VPS. The theoretical uncertainty in the acceptance due to the various sources listed above is estimated to be 6% and is added in quadrature with the uncertainty in the VPS (PB) cross section to yield the systematic uncertainty in the total $t\bar{t}b\bar{b}$ cross section.

Table 1: The various sources of systematic uncertainties and their respective contribution, quoted as a percentage of the measured cross section, to the total systematic uncertainty in the measured $t\bar{t}b\bar{b}$ cross section in the VPS for the two $t\bar{t}b\bar{b}$ definitions.

<table>
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<th>Source</th>
<th>VPS (PA)</th>
<th>VPS (PB)</th>
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<td>Quark-gluon likelihood</td>
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<td>$b$ tagging</td>
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<td>$+5.0/−5.4$</td>
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<td>$+2.5/−2.2$</td>
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<tr>
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<td>UE tune</td>
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<td>$+9.0/−5.2$</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>$±7.2$</td>
<td>$±7.1$</td>
</tr>
<tr>
<td>Shower matching ($h_{\text{damp}}$)</td>
<td>$+4.3/−2.8$</td>
<td>$+3.8/−2.7$</td>
</tr>
<tr>
<td>$t\bar{t}c\bar{c}$ normalisation</td>
<td>$+3.2/−4.4$</td>
<td>$+2.9/−4.5$</td>
</tr>
<tr>
<td>Top quark $p_T$ modelling</td>
<td>$±2.5$</td>
<td>$±2.4$</td>
</tr>
<tr>
<td>PDFs</td>
<td>$+2.2/−2.0$</td>
<td>$+2.2/−2.0$</td>
</tr>
</tbody>
</table>

8 Results

The result of the maximum-likelihood fit described in Section 6 is shown in Fig. 2 for the 2DCSV distributions in the four event regions. The measured cross section for the two $t\bar{t}b\bar{b}$ definitions in the VPS, as well as for the FPS introduced in Section 3, are given in Table 2. Due to the large overlap between the two definitions of the $t\bar{t}b\bar{b}$ VPS, the measured cross sections are numerically equal. The measurements are compared with NLO predictions from POWHEG for inclusive $t\bar{t}$ production interfaced with either PYTHIA or HERWIG++ [69], using the EE5C UE tune [70] for the latter, and MADGRAPH5_amc@NLO interfaced with PYTHIA for $t\bar{t}$ production with up to three extra massless partons (five-flavour scheme, 5FS) merged using the FxFx scheme [71], and for $t\bar{t}b\bar{b}$ production with massive $b$ quarks (four-flavour scheme, 4FS). The predicted cross sections are not rescaled by any NLO to NNLO K-factor, which for inclusive $t\bar{t}$ production amounts to 1.1–1.15 [42]. Measured and predicted cross sections are shown in
Figure 2: Distribution of the 2DCSV in the CR1 (upper left), SR (upper right), CR2 (lower left) and CR3 (lower right) regions. For visualisation purposes, the two-dimensional distribution of the largest and second-largest b tagging discriminator scores of the additional jets has been unrolled to one dimension, and the resulting bins have been ordered to increasing values of the ratio between expected signal and background yields in each bin in the SR. The contribution due to QCD multijet production is estimated from the data in the four regions according to the method described in Section 6. As a result, the multijet contributions in the CR1, CR2 and CR3 match the differences between the yields in data and from the other processes. The small backgrounds include t\(tV\), t\(tH\), single top quark, V+jets and diboson production. Hatched and grey bands correspond to post fit uncertainties, and bottom panels show the ratio between data and post fit predictions.
Fig. 3. The predictions underestimate the measured cross section by a factor of 1.5–2.4, which is consistent with the results from Refs. [21–25]. Calculations from POWHEG+PYTHIA are compatible with the measured values, within uncertainties.

Table 2: Measured and predicted cross sections (in pb) for the different definitions of the t\(\bar{b}\)\(\bar{b}\) phase space considered in this analysis. For the measurements, the first uncertainty is statistical, while the second is the systematic uncertainty. The uncertainties in the predicted cross sections include the statistical uncertainty, the PDF uncertainties, and the \(\mu_R\) and \(\mu_F\) scale variations. Parton shower scale uncertainties are not included, and amount to about 15% for POWHEG+PYTHIA. Unless specified otherwise, PYTHIA is used for the modelling of the parton shower, hadronisation and underlying event.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>VPS (PA)</th>
<th>VPS (PB)</th>
<th>FPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>POWHEG (t(\bar{t}))</td>
<td>1.6 ± 0.1(^{+0.5}_{-0.4})</td>
<td>1.6 ± 0.1(^{+0.5}_{-0.4})</td>
<td>5.5 ± 0.3(^{+1.6}_{-1.3})</td>
</tr>
<tr>
<td>POWHEG (t(\bar{t})) + HERWIG++</td>
<td>1.1 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>3.5 ± 0.6</td>
</tr>
<tr>
<td>MG5_AMC@NLO (4FS t(\bar{t})b(\bar{b}))</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>3.0 ± 0.5</td>
</tr>
<tr>
<td>MG5_AMC@NLO (5FS t(\bar{t})+jets FxFx)</td>
<td>0.8 ± 0.2</td>
<td>0.8 ± 0.2</td>
<td>2.3 ± 0.7</td>
</tr>
</tbody>
</table>

9 Summary

The first measurement of the t\(\bar{t}\)b\(\bar{b}\) cross section \(\sigma_{t\bar{t}b\bar{b}}\) in the all-jets final state, using 35.9 fb\(^{-1}\) of data collected in pp collisions at \(\sqrt{s} = 13\) TeV, has been presented. The cross section is measured in the visible particle-level phase space using two definitions of t\(\bar{t}\)b\(\bar{b}\) events, as well as in the full phase space. One definition in the visible phase space does not rely on parton-level information, while the other uses parton-level information to identify the particle-level jets that do not originate from the decay of the top quarks. For both definitions, the cross section is measured to be \(\sigma_{t\bar{t}b\bar{b}} = 1.6 ± 0.1\) (stat)\(^{+0.5}_{-0.4}\) (syst) pb. The cross section in the full phase space is obtained by correcting this latter measurement for the experimental acceptance on the jets stemming from the top quarks, yielding 5.5 ± 0.3 (stat)\(^{+1.6}_{-1.3}\) (syst) pb. This measurement provides valuable input to studies of the t\(\bar{t}\)H process, where the Higgs boson decays into a pair of b quarks, and for which the normalisation and modelling of the t\(\bar{t}\)b\(\bar{b}\) process represent a leading source of systematic uncertainty. Furthermore, these results represent a stringent test for perturbative QCD predictions at the LHC. The tensions between measurements and theoretical predictions call for new developments in the modelling of the associated production of top quark pairs and b jets.

References


[3] ATLAS Collaboration, “Search for the standard model Higgs boson produced in association with top quarks and decaying into a b\(\bar{b}\) pair in pp collisions at \(\sqrt{s} = 13\) TeV
Figure 3: Comparison of the measured $t\bar{t}b\bar{b}$ production cross sections with predictions from several Monte Carlo generators, for the three definitions of the $t\bar{t}b\bar{b}$ phase space. Uncertainty bands in the theoretical cross sections include the statistical uncertainty as well as the uncertainties due to the PDFs and to the $\mu_R$ and $\mu_F$ scale variations.


[23] CMS Collaboration, “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”, Phys. Lett. B 746 (2015) 132, doi:10.1016/j.physletb.2015.04.060, arXiv:1411.5621.


