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Letter

Measurement of top-quark pair production in association with charm quarks in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

Inclusive cross-sections for top-quark pair production in association with charm quarks are measured with proton–proton collision data at a center-of-mass energy of 13 TeV corresponding to an integrated luminosity of 140 fb^{-1}, collected with the ATLAS experiment at the LHC between 2015 and 2018. The measurements are performed by requiring one or two charged leptons (electrons and muons), two b-tagged jets, and at least one additional jet in the final state. A custom flavor-tagging algorithm is employed for the simultaneous identification of b-jets and c-jets. In a fiducial phase space that replicates the acceptance of the ATLAS detector, the cross-sections for $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ production are measured to be $1.28^{+0.27}_{-0.24}$ pb and $6.4^{+1.0}_{-0.9}$ pb, respectively. The measurements are primarily limited by uncertainties in the modeling of inclusive $t\bar{t}$ and $t\bar{t} + b\bar{b}$ production, in the calibration of the flavor-tagging algorithm, and by data statistics. Cross-section predictions from various $t\bar{t}$ simulations are largely consistent with the measured cross-section values, though all underpredict the observed values by 0.5 to 2.0 standard deviations. In a phase-space volume without requirements on the $t\bar{t}$ decay products and the jet multiplicity, the cross-section ratios of $t\bar{t} + \geq 2c$ and $t\bar{t} + 1c$ to total $t\bar{t}$ + jets production are determined to be $(1.23 \pm 0.25)\%$ and $(8.8 \pm 1.3)\%$.

1. Introduction

Due to its pivotal role in the Standard Model (SM) of particle physics and its potential interactions with new physics in various beyond-SM frameworks, the study of the top quark (t) remains a cornerstone of contemporary particle physics research. In particular, the ATLAS [1] and CMS [2] experiments at the Large Hadron Collider (LHC) have directed their attention towards exploring rare final states involving top-quark pairs ($t\bar{t}$), such as associated production of $t\bar{t}$ with Higgs bosons ($t\bar{t}H$) or gauge bosons ($t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$), and four-top-quark production ($t\bar{t}t\bar{t}$). Measurements of $t\bar{t}H$ with $H \to b\bar{b}$ decay and $t\bar{t}t\bar{t}$ topologies with single-lepton or dilepton final states [3–7] encounter significant challenges due to substantial, irreducible background contributions stemming from $t\bar{t}$ production in association with heavy-flavor quarks, namely bottom (b) and charm (c) quarks. These heavy-flavor quarks can be produced via radiation of a gluon which then splits into a $b\bar{b}$ or $c\bar{c}$ pair. Depending on the kinematics, the $b\bar{b}$ or $c\bar{c}$ pair can form a jet each ($t\bar{t} + b\bar{b}/c\bar{c}$) or merge into a single jet ($t\bar{t} + 1B/1C$). Single b-quark or c-quark production ($t\bar{t} + 1b/c$) can also occur via a b-quark or c-quark originating from the initial state. Illustrative Feynman diagrams for these three production modes are shown in Fig. 1.

Measurements of $t\bar{t} + b\bar{b}$ and $t\bar{t} + c\bar{c}$ production have been limited by the challenging modeling of these processes. While computations of the $t\bar{t} + b\bar{b}$ production cross-section are available at next-to-leading order (NLO) in quantum chromodynamics (QCD) [8–13], the uncertainties in the choice of the renormalization and factorization scales, denoted by μ_R and μ_F, remain sizable, primarily due to the distinct energy scales associated with the $t\bar{t}$ pair and the $b\bar{b}$ pair. Experimental measurements of $t\bar{t} + b\bar{b}$ production were conducted in proton–proton (pp) collision data at the LHC by the ATLAS and CMS experiments at a center-of-mass energy of $\sqrt{s} = 13$ TeV [14–17]. These measurements, along with those of $t\bar{t}H$ ($H \to b\bar{b}$) and $t\bar{t}t\bar{t}$ production, frequently involve determining the $t\bar{t} + \geq 1c$ normalization *in situ* through a free parameter in the fit, compensating for the limited knowledge of this process. Recent ATLAS measurements of $t\bar{t} + b\bar{b}$ and $t\bar{t}H$ ($H \to b\bar{b}$) [5,17] reported the $t\bar{t} + \geq 1c$ normalization factor to be larger than the value predicted by Monte Carlo (MC) simulations. CMS performed a dedicated $t\bar{t} + c\bar{c}$ measurement in $t\bar{t}$ final states with two charged leptons based on Run 2 data corresponding to 41.5 fb^{-1} [18], but did not explicitly measure the $t\bar{t} + 1c/C$ cross-section. The rates of $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$, and $t\bar{t}$ + light jets were found to agree with predictions from MC simulations performed at NLO in the matrix element interfaced with a parton shower (PS) algorithm (NLO+PS) within one to two standard deviations of measurement uncertainties.

Using the complete LHC Run 2 data sample of pp collisions corresponding to an integrated luminosity of 140 fb^{-1}, this Letter presents

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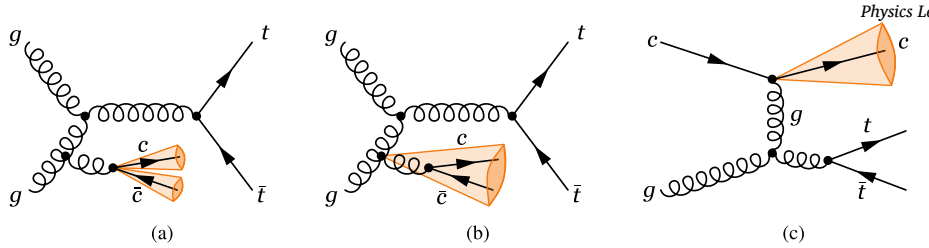

Fig. 1. Illustrative Feynman diagrams for $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ production: (a) $t\bar{t}+c\bar{c}$ production via initial-state gluon radiation where both c-quarks form a jet each, (b) $t\bar{t}+c\bar{c}$ production via initial-state gluon radiation where the two c-quarks are in the same jet, (c) $t\bar{t}+1c$ production where the c-quark originates from the initial state.

the first ATLAS measurement of $t\bar{t}+\geq 1c$ production. The production rates of $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ are determined separately to facilitate more detailed comparisons with theoretical predictions, as these processes are expected to be sensitive to different production mechanisms (cf. Fig. 1). The first comprises all final states with two or more c-jets, e.g., $t\bar{t}+c\bar{c}$ production where both c-quarks form separate jets, while the second includes both $t\bar{t}+1c$ production via a c-quark from the initial state and $t\bar{t}+1C$ production. Events with one or two charged leptons in the final state are considered, targeting $t\bar{t}$ topologies where one or both W bosons from the top quarks decay leptonically. While topologies with one charged lepton (single-lepton) offer larger statistics, they introduce additional complexity due to the potential production of extra c-quarks from the hadronically decaying W boson. Conversely, final states with two charged leptons (dilepton) are rarer but expect less background contamination.

The probabilities for $t\bar{t}$ pairs with additional jets initiated by b-quarks, c-quarks, light quarks, and gluons to enter each analysis region are estimated through NLO+PS simulations of inclusive $t\bar{t}$ and of $t\bar{t}+b\bar{b}$ production. This measurement uses a custom flavor tagging algorithm, termed the b/c-tagger, tailored to simultaneous c-jet and b-jet identification, to define analysis regions sensitive to $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ production. The rates of these processes are then measured in a fiducial phase space designed to replicate the acceptance of the ATLAS detector and in a more inclusive volume. Furthermore, the ratios of $t\bar{t}+\geq 2c$, $t\bar{t}+1c$, and $t\bar{t}+\geq 1b$ to overall $t\bar{t}+$ jets production are extracted and compared with NLO+PS simulations.

2. ATLAS detector

The ATLAS experiment [1] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The ID covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [19] detector which is located close to the beampipe. A two-level trigger system is used to select events [20]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [21] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Simulation of signal and background processes

Samples of simulated events are used to model $t\bar{t}$ + jets production and most background processes. These MC simulated samples were generated employing either the full ATLAS detector simulation [22] based on GEANT4 [23], or a faster simulation where the GEANT4 simulation of the calorimeter response is replaced by a detailed parameterization of the shower shapes [22]. Both simulation methods were found to provide similar modeling for the observables used in this Letter. To account for the effects of multiple interactions in the same and neighboring bunch crossings (pileup), additional interactions were simulated using PYTHIA 8.186 [24] with a set of tuned parameters (*tune*) referred to as A3 [25] and superimposed onto the simulated hard-scatter event. Subsequently, simulated events were reweighted to replicate the pileup conditions observed in the full Run 2 data sample, with a mean number of pp interactions per bunch crossing of 34. All simulated events were processed through the same reconstruction algorithms and analysis chain as the data.

Unless specified otherwise, PYTHIA8 [26] was employed to simulate PS, hadronization, and multi-parton interactions (MPIs). For all samples using PYTHIA8 or HERWIG7 [27–29] for the simulation of the PS, hadronization and MPIs, the decays of b- and c-hadrons were simulated using the EVTGEN program [30]. PYTHIA8 setups use the A14 tune [31] and the NNPDF2.3LO parton distribution function (PDF) set [32]; HERWIG7 setups use the H7UE tune [28] or the default HERWIG tune alongside the MMHT2014LO PDF set [33]. The top-quark mass was set to $m_t = 172.5$ GeV and, unless stated otherwise, the five-flavor scheme (5FS) with massless b-quarks in the matrix element was used for all simulation setups and the corresponding PDF sets.

Inclusive $t\bar{t}$ events were generated with the POWHEG BOX2 [34–37] generator at NLO in QCD employing the NNPDF3.0NLO PDF set [38]. The h_{damp} parameter, which regulates the transverse momentum (p_{T}) of the first additional emission beyond the Born configuration, was set to $1.5\,m_t$ [39]. The hardness scale parameter, which determines the region of phase space vetoed during showering when matched to a PS, was fixed at $p_{\text{T}}^{\text{hard}} = 0$ [40,41]. The scales μ_{R} and μ_{F} were set to the transverse mass of the top quark, $m_{\text{T}}(t) = \sqrt{m_t^2 + p_{\text{T},t}^2}$. In the following, this sample is referred to as $t\bar{t}$ POWHEG+PYTHIA8. To assess uncertainties in the modeling, alternative sets of $t\bar{t}$ events were generated with different configurations: with $p_{\text{T}}^{\text{hard}} = 1$; with $h_{\text{damp}} = 3\,m_t$; and with POWHEG

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upwards. Polar coordinates (r,ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

Box interfaced to Herwig7 instead of Pythia8. To compare the result with another prediction, an additional set was generated with the MadGraph5_aMC@NLO 2.6.0 generator [42] at NLO in QCD, which uses the NNPDF3.0nlo PDF set, MadSpin [43,44] to simulate top-quark decays, and Herwig7 for PS and hadronization [45]. All generated sets of events were reweighted to the predicted cross-section of $\sigma(t\bar{t}) = 832 \pm 51$ pb, as calculated with the Top++2.0 program to next-to-next-to-leading order (NNLO) in QCD, including soft-gluon resummation to next-to-next-to-leading-log order (see Ref. [46] and references therein). The uncertainties include independent variations of μ_{R} and μ_{F}, and variations in the PDF and α_S, following the PDF4LHC prescription with the MSTW2008 68% CL NNLO, CT10 NNLO and NNPDF2.3 5FS PDF sets (see Ref. [47] and references therein, and Refs. [32,48,49]).

The Powheg Box Res [11] generator and OpenLoops [50–52] were used to generate $t\bar{t} + b\bar{b}$ events in the four-flavor scheme (4FS) with massive b-quarks, where the generation of the additional $b\bar{b}$ pair is included in the matrix element, employing the NNPDF3.0nlo 4FS PDF set [38]. The μ_{R} scale was set to $\frac{1}{2}\sqrt[4]{\prod_{i=t,\bar{t},b,\bar{b}} m_{\mathrm{T},i}}$ where $m_{\mathrm{T},i}$ denotes the transverse mass for each parton i. The μ_{F} scale and the h_{damp} parameter were set to $0.5 \times \sum_i m_{\mathrm{T},i}$ with $i \in \{t, \bar{t}, b, \bar{b}, j\}$ and $i \in \{t, \bar{t}, b, \bar{b}\}$, respectively, where j denotes extra partons. The $p_{\mathrm{T}}^{\mathrm{hard}}$ parameter was fixed to 0, and the Born-zero-damp parameter (h_{bzd}), regulating the division between the finite and singular part of the real emission in the NLO calculation, was set to 5. In the following, this sample is referred to as $t\bar{t} + b\bar{b}$ Powheg+Pythia8. To assess uncertainties in the modeling, alternative sets of $t\bar{t} + b\bar{b}$ events were generated with different configurations: with $p_{\mathrm{T}}^{\mathrm{hard}} = 1$; using the dipole recoil scheme instead of the nominal global recoil scheme [11,53]; and interfacing Powheg Box Res with Herwig7 instead of Pythia8. To compare the result with another prediction, alternative sets of $t\bar{t} + b\bar{b}$ events were generated with $h_{\mathrm{bzd}} = 2$. An additional alternative set of events was generated with the Sherpa 2.2.10 generator [54] in the 4FS, for which the virtual corrections for matrix elements at NLO accuracy were provided by Comix [55] and OpenLoops. The Sherpa events were matched with the Sherpa PS algorithm [56] based on Catani–Seymour dipole factorization using the MEPS@NLO prescription [57–60] and a set of tuned parameters developed by the Sherpa authors. All generated sets of events were reweighted to the same prediction cross-section value as computed in Powheg Box Res at NLO in QCD.

A dedicated simulation of $t\bar{t} + c\bar{c}$ production in the three-flavor scheme (3FS) is not available. Hence, $t\bar{t} + c\bar{c}$ contributions are estimated solely using $t\bar{t}$ 5FS simulation, where only the gluon radiation process is simulated in the NLO matrix element, but its splitting into a $c\bar{c}$ pair is done in the PS.

Simulated $t\bar{t}$ and $t\bar{t} + b\bar{b}$ events are sorted into four $t\bar{t}$ + jets categories using particle-level information: $t\bar{t} + \geq 2c$, $t\bar{t} + 1c$, $t\bar{t} + \geq 1b$, and $t\bar{t}$ + light. For the categorization, jets are reconstructed from stable particles[2] following PS and hadronization, using the anti-k_t algorithm [61,62] with a radius parameter $R = 0.4$. They are required to have $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$. The flavor of a particle-level jet is determined by counting b- and c-hadrons with $p_{\mathrm{T}} > 5$ GeV that are *ghost-associated* [63,64] with the jet. Jets with one or more associated b-hadrons are designated as b-jets, while those with one or more associated c-hadrons but no b-hadron are labeled as c-jets. Events are categorized based on the presence of additional particle-level b-jets and c-jets, excluding jets originating from decays of top quarks and W bosons.[3] Events with one or more b-jets are classified as $t\bar{t} + \geq 1b$, those with two or more c-jets but no b-jet are categorized as $t\bar{t} + \geq 2c$, and events with one c-jet but no b-jet are labeled as $t\bar{t} + 1c$. Any remaining events enter the $t\bar{t}$ + light category.

[2] Particle-level objects are considered stable if $\tau > 3 \times 10^{-11}$ s.

[3] The procedure to exclude these jets is as follows: b-quarks and c-quarks originating directly from the decays of top quarks and W bosons are identified in the MC generator record. Then, the b- and c-hadrons closest in ΔR are flagged. Any jet *ghost-associated* with these hadrons is removed from the categorization.

The $t\bar{t}$ + jets categorization at particle level is used to remove the overlap between the inclusive $t\bar{t}$ 5FS simulation and the $t\bar{t} + b\bar{b}$ 4FS simulation. The latter is expected to provide the more accurate modeling of $t\bar{t} + b\bar{b}$ production and is the preferable setup to simulate $t\bar{t} + \geq 1b$ contributions in this analysis. Thus, events are removed from any of the $t\bar{t}$ 5FS setups if they fall into the $t\bar{t} + \geq 1b$ category at particle level. All other events are retained to estimate contributions in the $t\bar{t} + \geq 2c$, $t\bar{t} + 1c$, and $t\bar{t}$ + light categories. Likewise, events from the $t\bar{t} + b\bar{b}$ 4FS simulation are removed if they fall into the $t\bar{t} + \geq 2c$, $t\bar{t} + 1c$, or $t\bar{t}$ + light categories at particle level. The individual cross-sections assigned to the $t\bar{t}$ and $t\bar{t} + b\bar{b}$ samples are retained, and no rescaling is performed after removing the overlapping events.

Various other processes involving top quarks can mimic $t\bar{t}$ + jets topologies. Single-top-quark t-channel, s-channel, and tW production were simulated using Powheg Box2 at NLO in QCD. For t-channel production, events were generated in the 4FS with the NNPDF3.0nlo 4FS PDF set. For s-channel and tW production, events were generated in the 5FS using the NNPDF3.0nlo 5FS PDF set. The tW simulation employed the diagram-removal scheme [65] to treat interference with $t\bar{t}$ production [39]. Additional sets of tW events were generated in different setups: using the diagram-subtraction scheme [39,65]; using Powheg Box2 interfaced with Herwig 7.04; and using MadGraph5_aMC@NLO 2.6.2 interfaced with Pythia8. Powheg Box2+Herwig7 setups were also generated for t-channel and s-channel production. $t\bar{t}H$ production was simulated with Powheg Box2 at NLO in QCD in the 5FS, using the NNPDF3.0nlo PDF set. Additionally, $t\bar{t}W$, $t\bar{t}Z$, tZq, and tWZ events were generated using the MadGraph5_aMC@NLO 2.3.3 generator at NLO in QCD with the NNPDF3.0nlo PDF set. Secondary sets of $t\bar{t}W$ and $t\bar{t}Z$ events were simulated with Sherpa 2.2.0 at leading order (LO) in QCD. In the following, these processes are collectively referred to as *Other Top*.

W + jets and Z + jets events were simulated using the Sherpa 2.2.1 generator employing NLO matrix elements for up to two partons and LO matrix elements for up to four partons, calculated with the Comix and OpenLoops libraries. Diboson events with semileptonic and fully leptonic decays were simulated using Sherpa 2.2.1 and Sherpa 2.2.2, employing NLO matrix elements for up to one additional parton and LO matrix elements for up to three additional partons. W + jets, Z + jets and diboson events were matched with the Sherpa PS algorithm based on Catani–Seymour dipole factorization using the MEPS@NLO prescription and a set of tuned parameters developed by the Sherpa authors. The NNPDF3.0nnlo PDF set [38] was used, and the cross-sections of the samples were reweighted to NNLO predictions [66]. In the following, W + jets, Z + jets and diboson processes are collectively referred to as *Non-Top*.

The cross-section measurements are conducted within a fiducial volume at particle level, closely resembling the detector-level acceptance, ensuring robustness against variations in acceptance predictions from MC simulations. Events in the single-lepton (dilepton) channel must exhibit five (three) or more jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, out of which at least two must be ghost-associated with b-hadrons. No specific requirements are imposed regarding the presence of additional b- or c-jets in the fiducial phase space, but the $t\bar{t}$ + jets categorization is performed as described above. In the single-lepton channel, events must feature exactly one charged lepton ($\ell = e, \mu$), while in the dilepton channel, events must contain exactly two oppositely charged leptons. One lepton must have $p_{\mathrm{T}} > 27$ GeV, any additional lepton must carry $p_{\mathrm{T}} > 10$ GeV, and all are required to be within $|\eta| < 2.5$. Any event featuring a same-flavor lepton pair with an invariant mass below 15 GeV or within the range 83 to 99 GeV is rejected. Leptons are removed if their distance to a jet satisfies $\Delta R < 0.4$. The fiducial phase space accepts approximately 17% of the total number of simulated $t\bar{t} + \geq 1c$ events. The measurements are also performed in a more inclusive phase-space volume without requirements on the $t\bar{t}$ decay products and the jet multiplicity.

4. Event reconstruction and selection

Events are required to have at least one primary vertex with two or more tracks with $p_{\mathrm{T}} > 0.5$ GeV. For events with more than one primary vertex, the hard-scattering primary vertex is selected as the one with the highest sum of squared track p_{T} [67]. A suite of single-electron and single-muon triggers is used to select events with at least one charged lepton [68,69].

Jets are reconstructed using the anti-k_t clustering algorithm with a radius parameter of $R = 0.4$ using particle flow jet constituents that combine measurements from both the ID and the calorimeter [70]. Jet candidates undergo calibration using simulations, with corrections derived from in situ techniques applied to data [71]. They are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, with jets within $|\eta| < 2.4$ and $p_{\mathrm{T}} < 60$ GeV further required to pass the tight working point of the jet vertex tagger [72] to reduce contribution from pileup jets.

Electron candidates are reconstructed from clusters of energy in the EM calorimeter associated with reconstructed tracks from the ID. Their reconstruction, identification, and calibration are detailed in Refs. [73,74]. They must satisfy a set of likelihood-based identification criteria with $p_{\mathrm{T}} > 10$ GeV and $|\eta_{\mathrm{cluster}}| < 2.47$. Electrons in the transition region between the end-caps and barrel region ($1.37 < |\eta_{\mathrm{cluster}}| < 1.52$) are vetoed. Tracks matched to electrons are required to be associated with the primary vertex and satisfy $|z_0 \sin\theta| < 0.5$ mm and $|d_0|/\sigma(d_0) < 5$, where z_0 and d_0 are the longitudinal and transverse impact parameters of the electron track, respectively. For the analysis regions, the identification criteria are tightened, and electrons are required to satisfy a set of variable-radius isolation criteria to reduce contributions from misidentified jets, considering energy depositions in the calorimeter and tracks in the ID [73].

Muons are reconstructed by combining a track from the muon spectrometer with an ID track. Details regarding the reconstruction, identification and calibration of muons are summarized in Refs. [75,76]. The ID tracks must be associated with the primary vertex by passing $|z_0 \sin\theta| < 0.5$ mm and $|d_0|/\sigma(d_0) < 3$. They must fulfill $p_{\mathrm{T}} > 10$ GeV, $|\eta| < 2.5$, and satisfy a set of muon quality criteria. For the analysis regions, the quality criteria are tightened, and muons are required to pass a track-based isolation criterion to reduce contributions from misidentified jets [75].

An overlap removal procedure prevents double counting of energy deposits and improves object resolution and identification efficiencies. Electron candidates sharing tracks with a muon candidate are removed. The nearest jet within $\Delta R < 0.2$ of an electron candidate is removed in favor of the electron. Electrons within $\Delta R < 0.4$ of any jets after this selection are removed in favor of the jet. Muons are removed if they are within $\Delta R < 0.4$ of a jet to reduce contributions from heavy-flavor decays. However, if the jet has fewer than three associated tracks, the muon is kept in favor of the jet.

Jets containing b-hadrons are identified as b-tagged jets using the DL1r algorithm [77], which leverages distinctive b-hadron features like track impact parameters and the presence of displaced vertices in the ID. The algorithm also includes discriminating variables from a recurrent neural network that exploit spatial and kinematic correlations between tracks from the same b-hadron. The DL1r algorithm provides three output scores, p_b, p_c, and p_{light}, and in the standard DL1r calibration, jets are tagged as b-jets using a discriminant $\mathcal{D}_b$ that is built using the Neyman–Pearson lemma [78]:

$$\mathcal{D}_b = \log \frac{p_b}{f_c p_c + (1 - f_c) p_{\mathrm{light}}}.$$

The parameter f_c controls which background contributes more to the decision. To improve the efficiency of selecting jets originating from c-quarks without compromising the b-jet identification performance, the DL1r algorithm was reoptimized as a 2D binned discriminant, the b/c-tagger. This reoptimization was necessary because standard DL1r configurations do not provide calibrated c-tagging working points, requiring a tailored approach to achieve the desired balance between b-jet and c-jet identification. The axes of the discriminant, $\mathcal{D}_c$ and $\mathcal{D}_b$, are calculated from the p_b, p_c, and p_{light} scores following the above formula, with all b- and c-subscripts interchanged for the $\mathcal{D}_c$ discriminant. It was found that $f_b = 0.4$ provides good performance for the b/c-tagger as it leads to a balanced contamination of b-jets and light-flavor jets in the analysis regions; the value of $f_c = 0.018$ was chosen to align the admixture with the standard DL1r calibration.

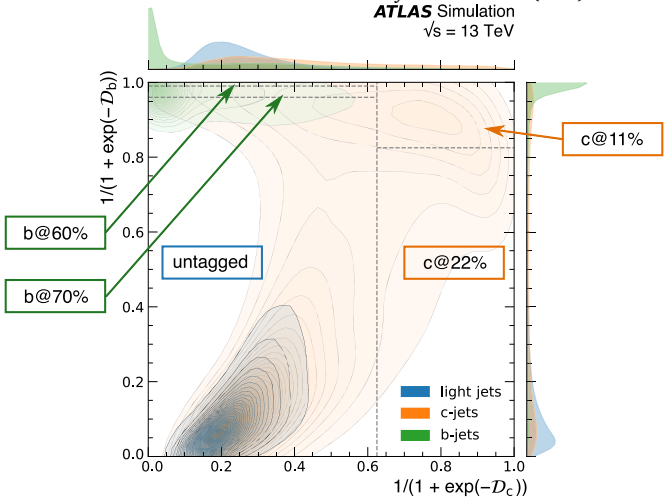

Fig. 2. Distribution of light, c-, and b-jets for the 2D b/c-tagger in simulated $t\bar{t}$ events. Dashed lines correspond to the edges of the working points. For visualization purposes a standard logistic function is applied to both axes of the discriminant. The contours for each jet type are smoothed with a kernel density method to improve readability, with contours corresponding to lines of constant density. The two b-tagging bins comprise the top left corner of the discriminant, with the c-tagging bins to the right of the vertical dashed line. Untagged jets are located in the bottom left corner.

The binning in $\mathcal{D}_c$ and $\mathcal{D}_b$ includes five working points (WPs), two of which are optimized for c-jet identification and two for b-jet identification. The WPs are designed to achieve an approximately constant efficiency for b-jet and c-jet identification across the jet p_{T} and $|\eta|$ range, with $p_{\mathrm{T}} > 20$ GeV. The c-tagging WPs are separated from the others by $\mathcal{D}'_c \geq 0.625$, where the prime indicates that a standard logistic function is applied to the discriminant: $\mathcal{D}'_c = 1/(1 + \exp(-\mathcal{D}_c))$. The tight c-tagging WP includes a tighter cut on $\mathcal{D}'_b$ to increase the light-flavor rejection rate and is designed to achieve an exclusive efficiency of 11% (denoted c@11%).[4] The loose c-tagging WP, which includes c@11%, achieves an inclusive efficiency of 22% (c@22%). The c@11% and c@22% WPs yield b-jet rejection rates of 28.7 and 18.9 and light-flavor rejection rates of 1051 and 104 in simulated $t\bar{t}$ events, respectively. The b-tagging WPs, defined for $\mathcal{D}'_c < 0.625$, use the same $\mathcal{D}'_b$ cuts as the two tightest b-tagging WPs in the standard DL1r calibration. The tighter b-tagging WP is designed to achieve an exclusive efficiency of 60% (b@60%), the looser, which includes b@60%, to achieve an inclusive b-tagging efficiency of 70% (b@70%), with c-jet rejection rates of 37.1 and 12.2 and light-flavor rejection rates of 2320 and 573, respectively. Jets not entering any of the four WP bins are classified as untagged. Consequently, the b/c-tagger comprises a total of five orthogonal bins, with the distribution of light, c- and b-jets illustrated in Fig. 2.

The calibration of the five b/c-tagger WPs follows standard procedures applied to the DL1r algorithm [79–81]. Jets originating from b- and c-quarks are calibrated in data using $t\bar{t}$ events, both selections being orthogonal to the events analyzed in this study by limiting the number

[4] Tightening the cut on $\mathcal{D}'_c$ instead of $\mathcal{D}'_b$ would lead to a more balanced increase in the b-jet and light-flavor rejection rate, but it was found that a focus on higher light-flavor rejection rates yields better $t\bar{t} + \geq 1c$ signal sensitivity.

Table 1
Jet multiplicity and tagging criteria for the signal regions (SRs) and control regions (CRs) in the single-lepton and dilepton channels. All single-lepton regions are defined in the 5-jet-exclusive and 6-jet-inclusive jet selections, all dilepton regions in the 3-jet-exclusive and 4-jet-inclusive jet selections. By construction, $SR^{2\ell}_{tight}$ only exists for the 4-jet-inclusive selection. Identical requirements on inclusive and exclusive working points, e.g., one c@22% and one c@11% in the $CR^{1\ell}_{1}$, indicate a veto of additional tags at the inclusive working point.

	$CR^{1\ell}_{1}$	$CR^{1\ell}_{2}$	$CR^{1\ell}_{3}$	$SR^{1\ell}_{loose}$	$SR^{1\ell}_{tight}$	$CR^{2\ell}_{1}$	$CR^{2\ell}_{2}$	$CR^{2\ell}_{3}$	$SR^{2\ell}_{loose}$	$SR^{2\ell}_{tight}$
N_{jets}	$= 5$ or ≥ 6					$= 3$ or ≥ 4				≥ 4
b@70%	2	–	–	2	2	2	–	≥ 3	2	2
b@60%	–	≥ 3	3	–	–	–	≥ 3	≤ 2	–	–
c@22%	1	0	1	≥ 2	–	0	–	–	1	≥ 2
c@11%	1	–	1	1	≥ 2	–	–	–	–	–

of jets to four (two) in single-lepton (dilepton) final states. All b-tagging calibration scale factors (SFs) are close to unity, with statistical uncertainties dominating the high p_T regime. The c-tagging calibration yields more variation in the SF values. For the b@70% WP, the SFs average around 0.9 and some bins in jet p_T are incompatible with unity within their uncertainties. Light-flavor jet calibration employs the *negative-tag* method [82,83] in conjunction with a *flip-tagger* approach following Ref. [81], and all SFs are compatible with unity within uncertainties. For the b@60% working point, the light-flavor SFs cannot be determined due to the large b-jet contamination and so, following the procedure in Ref. [81], are set to unity with additional uncertainties. The c@11% WP also has large uncertainties due to high contamination of heavy-flavor jets and low statistics. Simulation-to-simulation SFs are derived in bins of jet p_T and $|\eta|$ to account for differences between tagging efficiencies for different PS and hadronization algorithms [84].

A preselection is applied and requires at least one electron or muon with $p_T > 27$ GeV that is matched to the trigger object. The single-lepton channel selects events with exactly one lepton, while the dilepton channel selects those with exactly two oppositely charged leptons. Events must have at least five (three) jets in the single-lepton (dilepton) channel, with at least three (two) b-tagged or c-tagged jets using the b@70% or c@22% working points. For dilepton final states with identical lepton flavors, the same invariant-mass criteria as those applied in the fiducial selection at particle level are imposed. In the single-lepton channel, events are split into those with exactly five jets (5-jet-exclusive) and those with six or more jets (6-jet-inclusive). Similarly, in the dilepton channel, events are categorized as either 3-jet-exclusive or 4-jet-inclusive. Based on the number of identified b- and c-tagged jets, events are further classified into signal regions (SRs) enriched in $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ events, and control regions (CRs), which determine the normalization of the $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light background. An overview of the seven SRs and 12 CRs is shown in Table 1. Approximately 5.3% of the simulated $t\bar{t}+\geq 1c$ events passing the fiducial selection criteria are reconstructed in the analysis regions.

There are four SRs in the single-lepton channel and three SRs in the dilepton channel with different degrees of purity in $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ events. The $SR^{1\ell}_{tight}$ and $SR^{2\ell}_{tight}$ regions target $t\bar{t}+\geq 2c$ events, while $SR^{1\ell}_{loose}$ and $SR^{2\ell}_{loose}$ are dominated by $t\bar{t}+1c$. All seven regions require exactly two b-tagged jets at b@70%. In the single-lepton channel, events featuring at least two c-tagged jets at c@22% with exactly one satisfying the c@11% working point enter the $SR^{1\ell}_{loose}$ regions. Events with two or more c-tagged jets at c@11% are classified into $SR^{1\ell}_{tight}$. The expected purity in $t\bar{t}+\geq 2c$ events in the single-lepton SRs ranges between 10% and 28%, while the predicted $t\bar{t}+1c$ contributions are between 29% and 38%. In the dilepton channel, events with exactly one c-tagged jet at c@22% are sorted into $SR^{2\ell}_{loose}$, while events with at least two enter $SR^{2\ell}_{tight}$, which is only defined in the 4-jet-inclusive selection. In the dilepton regions, the expected purity in $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ events is between 4% and 46%, and between 16% and 38%, respectively.

In the single-lepton channel, three CRs with varying compositions in $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light are defined for each of the two jet multiplicity selections. The $CR^{1\ell}_{1}$ regions select exactly two b-tagged jets at b@70% and exactly one c-tagged jet passing c@22% and c@11%. They are dominated by $t\bar{t}+$ light events. The $CR^{1\ell}_{2}$ regions are characterized by events with three or more b-tagged jets at b@60%, with a veto on c-tagged jets, leading to a mix of $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light. The $CR^{1\ell}_{3}$ regions are pure in $t\bar{t}+\geq 1b$ and select events with exactly three b-tagged jets at b@60% and exactly one c-tagged jet satisfying c@22% and c@11%.

Similarly, the dilepton channel features three CRs for each of the two jet multiplicity selections. The $CR^{2\ell}_{1}$ regions require exactly two b-tagged jets at b@70% and veto c-tagged jets. They are dominated by $t\bar{t}+$ light events. The $CR^{2\ell}_{2}$ regions are pure in $t\bar{t}+\geq 1b$ and select events with three or more b-tagged jets at b@60%. The $CR^{2\ell}_{3}$ regions show a mix of $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light by requiring at least three b-tagged jets at b@70%, with no more than two satisfying the b@60% criteria.

Contributions from processes with non-prompt or misidentified leptons to the single-lepton selection, in the following termed *fake leptons*, were estimated by using the data-driven *matrix method* [85] in dedicated CRs. Prompt-lepton efficiencies were derived in data using a tag-and-probe method in Z-boson decays. Fake-lepton efficiencies were estimated in data in bins of lepton p_T and $|\eta|$ using events with at least three jets, at least two b-tagged jets at the 70% working point of the DL1r tagger, and one lepton fulfilling the looser identification and quality criteria. The isolation requirements were completely dropped. To enrich the selection in fake leptons, only events where the scalar sum of the magnitude of the missing-transverse-momentum vector and the leptonically decaying W-boson mass is no larger than 60 GeV were considered.[5] The fake-lepton contributions to the analysis were then estimated by inverting the efficiency matrix and applying it to the observed event yields in the analysis regions using the looser and the nominal lepton identification and isolation criteria. Fake-lepton contributions to the dilepton selection mainly arise from W + jets and single-lepton $t\bar{t}$ + jets events and were estimated from MC simulation.

5. Systematic uncertainties

The extraction of the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections is subject to various sources of uncertainties, impacting either the overall event yields in a region, the shape of observable distributions considered in the fit, or both.

Experimental sources of uncertainties include uncertainties in the value of the integrated luminosity of the Run 2 data, the simulation

[5] The magnitude of the missing-transverse-momentum vector, denoted E_T^{miss}, is defined as the negative sum of the transverse momenta of the reconstructed and calibrated physical objects, plus a *soft term* built from all other tracks associated with the primary vertex [86] and not matched to a reconstructed object. The mass of the leptonically decaying W boson is calculated from the kinematics of the lepton and the missing transverse momentum.

of pileup events, and effects related to the reconstruction and identification of physics objects used in the analysis. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [87], obtained using the LUCID-2 detector [19] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters. Uncertainties in the modeling of pileup are evaluated by varying the pileup reweighting in MC simulations within its associated uncertainties. Furthermore, lepton identification and isolation efficiencies, momentum scale and resolution, and lepton trigger efficiencies are varied within their uncertainties to evaluate their impact on the measurement [73–76]. The uncertainty in the jet energy scale (JES) is derived from a combination of simulations, test-beam data, and in situ measurements [71]. This uncertainty incorporates contributions from various sources such as jet-flavor composition, η-intercalibration, punch-through, single-particle response, calorimeter response to different jet flavors, and pileup. It comprises 30 uncorrelated JES uncertainty subcomponents. Additionally, the jet energy resolution in simulation is varied by its corresponding uncertainty, which is divided into thirteen uncorrelated sources. The uncertainty associated with the jet vertex tagger is determined by varying its efficiency correction factors [72]. Moreover, uncertainties in the calibration of the b/c-tagger are separately determined for b-jets, c-jets, and light-flavor jets, following the procedures detailed in Refs. [79–81]. They are derived as a function of jet p_{T} and separately for each WP, yielding a total of 45 components for b-jets and 20 each for c-jets and light-flavor jets. For jets with p_{T} values above the range covered by the calibration, extrapolation uncertainties derived from MC simulation are applied.

Uncertainties in the modeling of $t\bar{t}+\geq 2c$, $t\bar{t}+1c$, and $t\bar{t}+$light are considered through several alternative inclusive $t\bar{t}$ simulation setups. The alternative set of events with $p_{\mathrm{T}}^{\mathrm{hard}}=1$ is used to assess the uncertainty in the NLO matching between the matrix elements and the PS. The $h_{\mathrm{damp}}=3\,m_t$ sample assesses the uncertainty in the choice of that parameter. The POWHEG+HERWIG7 setup evaluates the uncertainty in the choice of the PS and hadronization algorithm. Additionally, the nominal set of events is reweighted to scenarios where μ_{R} and μ_{F} in the matrix element are halved and doubled independently to assess the uncertainty in the choice of these parameters. To estimate uncertainties in the modeling of initial-state radiation (ISR) and final-state radiation (FSR), the factorized parameter α_S^{ISR} is varied using the *var3c* variation of the A14 tune, and the renormalization scale associated with α_S^{FSR} is varied to 0.625 and 2 relative to its nominal setting. The uncertainty in the PDF set is estimated by using 30 PDF variations of the PDF4LHC prescription.

Uncertainties in the modeling of the $t\bar{t}+\geq 1b$ contributions are considered through a similar suite of alternative $t\bar{t}+b\bar{b}$ simulation setups. The alternative set of events with $p_{\mathrm{T}}^{\mathrm{hard}}=1$ is used to assess the uncertainty in the NLO matching between the matrix elements and the PS. The uncertainty in the choice of the recoil scheme is evaluated with the set of events generated with the alternative dipole recoil scheme. The POWHEG+HERWIG7 setup is used to evaluate the uncertainty in the selection of the PS and hadronization algorithm. Event weight variations identical to those applied in $t\bar{t}$ simulations, including μ_{R}, μ_{F}, ISR, FSR, and the PDF set, are considered for $t\bar{t}+b\bar{b}$.

All uncertainties considered in the modeling of $t\bar{t}$ + jets production are treated as uncorrelated between the $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 1c$, and $t\bar{t}+$light processes. Moreover, the NLO matching and PS uncertainties for $t\bar{t}+\geq 1c$ ($t\bar{t}+\geq 1b$) are parameterized independently for the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ ($t\bar{t}+\geq 2b$ and $t\bar{t}+1b$) components as the components are sensitive to different effects. Additionally, the $t\bar{t}+$light PS uncertainty is parameterized separately for the 3-jet-exclusive, 4-jet-inclusive, 5-jet-exclusive, and 6-jet-inclusive regions to avoid strong constraints arising from region-to-region migration effects.

For t-channel, s-channel, and tW single-top-quark production, the POWHEG+HERWIG7 setups are used to assess the uncertainty in the choice of the PS and hadronization algorithm. For tW production, the set of events with the diagram-subtraction scheme is used to gauge the uncertainty in the treatment of the interference with $t\bar{t}$, and the NLO matching uncertainty is evaluated using events generated with MADGRAPH5_AMC@NLO+PYTHIA8. An additional 5% normalization uncertainty is assigned to accommodate the uncertainty in the cross-section value [88]. For the t-channel and s-channel predictions, normalization uncertainties of 50% are assigned to cover NLO matching and cross-section uncertainties. The difference between the sets of $t\bar{t}W$ and $t\bar{t}Z$ events generated with MADGRAPH5_AMC@NLO+PYTHIA8 and SHERPA is used as an uncertainty in the prediction for these processes. Additionally, uncertainties of approximately 13% and 11% are assigned to $t\bar{t}W$ and $t\bar{t}Z$, respectively, to accommodate uncertainties in the assigned cross-section values [89]. Conservative normalization uncertainties of 50% are assigned to each of the remaining top-quark processes considered ($t\bar{t}H$, tWZ, tZq) to cover potential mismodeling of the rates of these processes in the probed fiducial phase space. For the W + jets, Z + jets and diboson background, the assigned uncertainties follow those used in previous ATLAS measurements [90]. Normalization uncertainties of 40% and 35% are considered for W + jets and Z + jets processes, based on variations of the μ_{R} and μ_{F} scales and of the matching parameters in the SHERPA generator. Additional 40% uncertainties are assigned to W + jets events with exactly two heavy-flavor jets and at least three heavy-flavor jets based on the same variations. A 50% uncertainty is assigned to the diboson background, which includes uncertainties in the inclusive cross-section and additional jet production [91–93]. None of the modeling uncertainties of the *Other Top* and *Non-Top* categories have any significant impact on the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-section measurements.

The fake-lepton estimate in the single-lepton channel is derived from a data sample with finite statistics, leading to bin-by-bin statistical uncertainties for the fake-electron and fake-muon contributions. In addition, conservative 50% normalization uncertainties are assigned to the data-driven single-lepton and MC-based dilepton estimates.

6. Results

The data from all 19 analysis regions are simultaneously fit using a binned profile likelihood approach using the HistFactory [94] and RooFit [95] toolkits. Systematic uncertainties are incorporated as nuisance parameters in the fit and are constrained by a Gaussian penalty term present in the likelihood function. The statistical uncertainty arising from the limited number of simulated events is included in the likelihood in the form of additional nuisance parameters with Poisson constraint terms. To determine the production cross-sections of the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ processes, and to control the $t\bar{t}+\geq 1b$ and $t\bar{t}+$light background processes, normalization factors are defined for all four $t\bar{t}$ + jets categories. These factors, μ_i, serve as unconstrained normalization factors in the profile likelihood fit, and they are applied to both fiducial and non-fiducial $t\bar{t}$ + jets events. The inclusive $t\bar{t}$ + jets normalization factor is computed following

$$\mu(t\bar{t}+\text{jets})=\sum_i \mu_i R_i^{\mathrm{MC}} \quad \text{for } i\in\{t\bar{t}+\geq 1b, t\bar{t}+\geq 2c, t\bar{t}+1c, t\bar{t}+\text{light}\}, \tag{1}$$

where R_i^{MC} is the predicted cross-section ratio of process i to overall $t\bar{t}$ + jets production in MC simulation.

Each of the 12 CRs is represented as a single bin in the fit. $\mathrm{SR}_{\mathrm{loose}}^{1\ell 5\mathrm{j}}$ and $\mathrm{SR}_{\mathrm{tight}}^{1\ell 5\mathrm{j}}$ use the invariant mass between the two geometrically closest c-tagged jets to increase sensitivity to differences between the $t\bar{t}+\geq 2c$, $t\bar{t}+1c$, and $t\bar{t}+$light contributions (only considering c-tagged jets passing $c@11\%$ in $\mathrm{SR}_{\mathrm{tight}}^{1\ell 5\mathrm{j}}$). Due to c-jets originating from the decay of the W boson, the contribution from $t\bar{t}+$light is enhanced around the W-boson mass. $\mathrm{SR}_{\mathrm{loose}}^{2\ell 3\mathrm{j}}$ uses the invariant mass between the c-tagged jet and the geometrically closest b-tagged jet. All three regions use four bins with varying width to maximize sensitivity to the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ contributions. In the 4-jet-inclusive and 6-jet-inclusive SRs, the jet multiplicity is used to enhance the separation between $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 2c$,

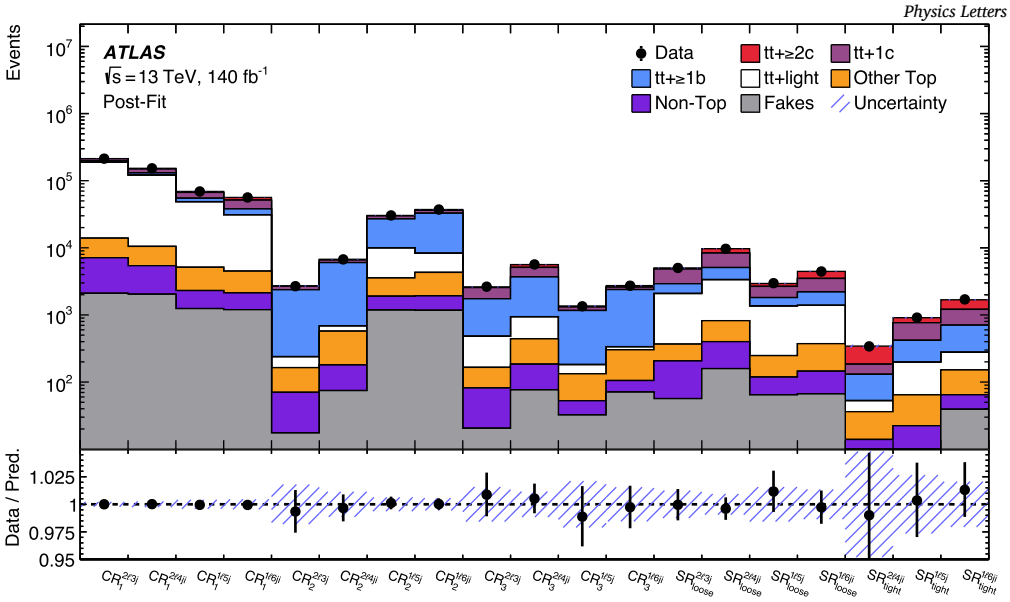

Fig. 3. Post-fit agreement between data and MC simulation in the 12 control regions (CRs) and seven signal regions (SRs). The error bars indicate data statistical uncertainties. The hatched uncertainty bands include all uncertainties and their correlations. *Other Top* includes single-top-quark production and associated production of $t\bar{t}$ and single top quarks with bosons. *Non-Top* includes W + jets, Z + jets, and diboson processes.

$t\bar{t}+1c$, and $t\bar{t}+$ light processes, fitting $6 \leq N_{\text{jets}} \leq 9$ and $4 \leq N_{\text{jets}} \leq 7$ in the single-lepton and dilepton channels, respectively. Overflow events are included in the last bin of each distribution.

Post-fit comparisons between data and simulation for all regions are depicted in Fig. 3. The fitted observable distributions of the SRs are shown in Figs. 4 and 5. Good agreement between data and simulation is observed in all regions and observables with varying relative contributions of the $t\bar{t}$ + jets categories. The goodness of fit was evaluated using a *saturated model* [96] and the compatibility with data was found to be 98%.

The $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ normalization factors obtained from this fit are used to extract the observed fiducial cross-sections by scaling them with the predicted cross-sections for the fiducial phase space introduced in Section 3. Theoretical uncertainties in the predicted cross-sections owing to the μ_{R} and μ_{F} scale choice and the used PDF set are not propagated to the extracted fiducial cross-section values. The fiducial cross-sections for $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ processes are determined to be

$$\sigma^{\text{fid}}(t\bar{t}+\geq 2c) = 1.28\,^{+0.16}_{-0.10}\,(\text{stat})\,^{+0.21}_{-0.22}\,(\text{syst})\ \text{pb} = 1.28\,^{+0.27}_{-0.24}\ \text{pb}, \tag{2}$$

$$\sigma^{\text{fid}}(t\bar{t}+1c) = 6.4\,^{+0.5}_{-0.4}\,(\text{stat}) \pm 0.8\,(\text{syst})\ \text{pb} = 6.4\,^{+1.0}_{-0.9}\ \text{pb}. \tag{3}$$

The breakdown into statistical and systematic uncertainties is estimated from the covariance matrix of the profile likelihood fit, following Ref. [97]. The precision of the measured $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections is limited by uncertainties in the modeling of $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$, and $t\bar{t}+$ light, in particular in the NLO matching and the PS, by uncertainties in the b/c-tagger calibration, as well as by data statistics. Table 2 provides a detailed breakdown of the uncertainties that affect the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections in the fiducial phase space. The uncertainty in the $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light normalization factors on the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections is included in the data statistics entry. The fit constrains several nuisance parameters that strongly impact the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections, with none falling below 50% of their prior values. Noteworthy constraints are placed on the $t\bar{t}+\geq 1c$ FSR and $t\bar{t}+1c$ PS nuisance parameters, which arise primarily from discrepancies between the predicted rates of $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ events in the signal regions. No significant pulls of the nuisance parameters are observed in the fit. The measured $t\bar{t}+\geq 1b$ normalization factor is compatible with those obtained in a dedicated ATLAS $t\bar{t}+b\bar{b}$ measurement performed in a fiducial phase space targeting $e+\mu$ final states [17], reaching a similar level of relative precision.

Table 2
Breakdown of the fiducial $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-section uncertainties. Systematic uncertainties are grouped into signal and background modeling, instrumental, and MC statistics categories. The table lists the fractional uncertainty in the measured cross-sections in percent and is estimated from the covariance matrix of the profile likelihood fit, following Ref. [97]. Individual groups of uncertainties can be added in quadrature to obtain the total uncertainty. JES and JER denote the jet energy scale and resolution uncertainties, respectively. The fractional uncertainties in the fitted $t\bar{t}+\geq 1b$ and $t\bar{t}+$ light normalization factors are included in the data statistics category. For presentation purposes, all uncertainties are symmetrized.

Uncertainty group	Fractional uncertainty [%] on	
	$\sigma^{\text{fid}}(t\bar{t}+\geq 2c)$	$\sigma^{\text{fid}}(t\bar{t}+1c)$
$t\bar{t}+\geq 1c$ modeling	9	8
Background modeling:		
$t\bar{t}+\geq 1b$	4	4
$t\bar{t}+$ light	6	4
Others	2.5	1.7
Instrumental:		
b-tagging	2.2	1.8
c-tagging	9	4
light mis-tagging	2.2	3.4
JES/JER	6	3.5
Others	1.3	0.9
MC statistics	3.1	2.5
Total systematic uncertainty	17	12
Data statistical uncertainty	11	7
Total	20	14

The measured values for the four processes and the overall $t\bar{t}$ + jets production are depicted in Fig. 6 and listed in Table 3, along with several NLO+PS predictions from different MC simulations. The predictions for $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ are largely consistent with the measurements, but underpredict the observed cross-sections by 0.5 to 2.0 standard deviations. Considering variations of the μ_{R} and μ_{F} scales and uncertainties in the PDF choice of the predictions, the POWHEG+PYTHIA8 setups agree with the measured $t\bar{t}+\geq 2c$ ($t\bar{t}+1c$) values within 0.5 to 0.8 (0.9 to 1.1) standard deviations of measurement and prediction uncertainties. In contrast, POWHEG+HERWIG7 and MADGRAPH5_AMC@NLO+HERWIG7

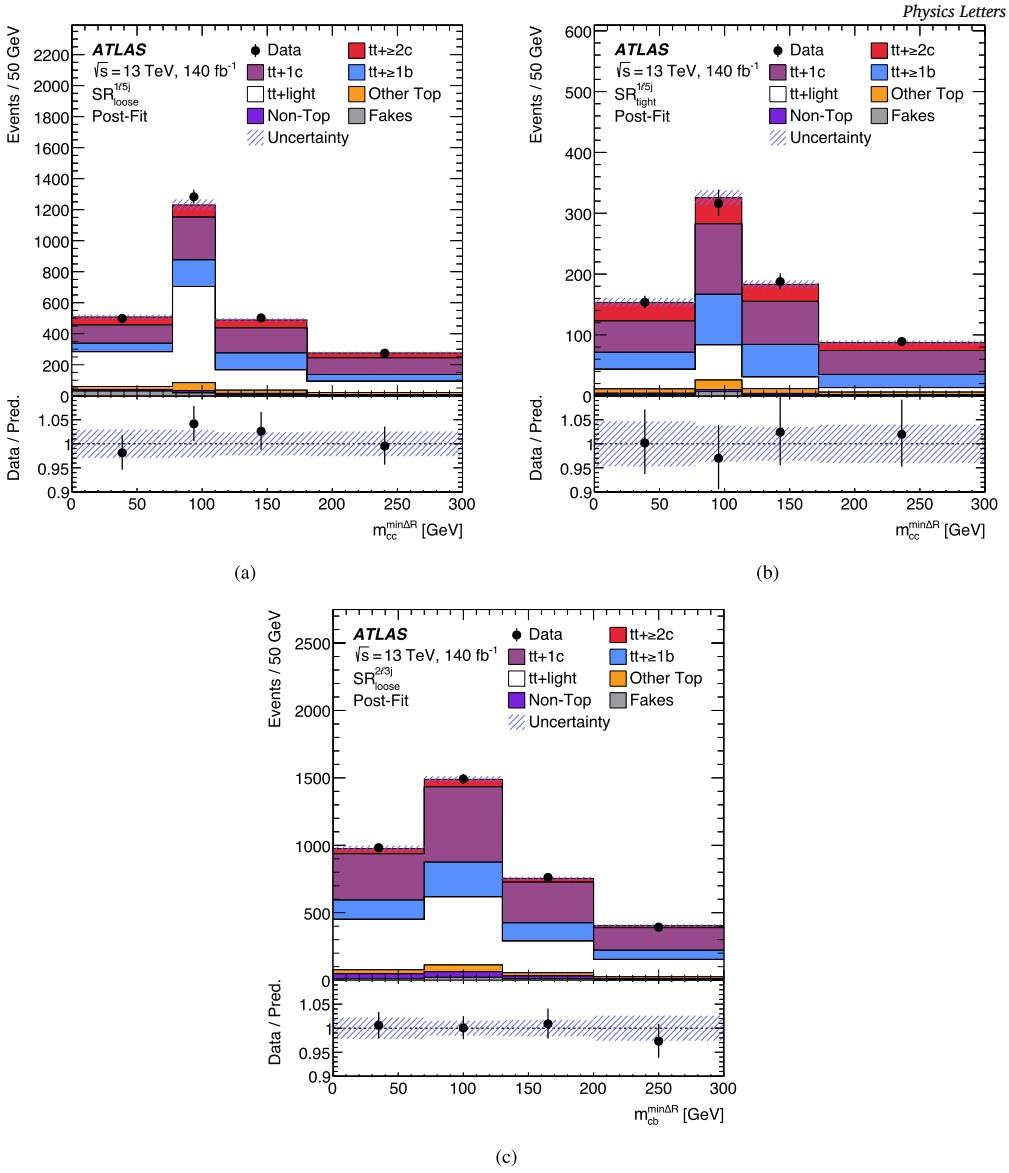

Fig. 4. Post-fit agreement between data and MC prediction for the observables used in the 5-jet-exclusive and 3-jet-exclusive signal regions (SRs): (a) $\mathrm{SR}^{1\ell 5\mathrm{j}}_{\mathrm{loose}}$ and (b) $\mathrm{SR}^{1\ell 5\mathrm{j}}_{\mathrm{tight}}$, both using the invariant mass of the two geometrically closest c-tagged jets, $m_{cc}^{\mathrm{min}\Delta R}$, for the latter only considering c-tagged jets passing $c@11\%$; (c) $\mathrm{SR}^{2\ell 3\mathrm{j}}_{\mathrm{loose}}$ using the invariant mass of the selected c-tagged jet and the geometrically closest b-tagged jet, $m_{cb}^{\mathrm{min}\Delta R}$. The hatched uncertainty bands include all uncertainties and their correlations. The last bins contain overflow events. *Other Top* includes single-top-quark production and associated production of $t\bar{t}$ and single top quarks with bosons. *Non-Top* includes W + jets, Z + jets, and diboson processes.

fall short by 25% to 40%, aligning with the measured values at 1.2 to 2.0 standard deviations. For $t\bar{t}+\geq 1b$, $t\bar{t}+$light, and $t\bar{t}$ + jets, most NLO+PS predictions agree with the measured cross-sections within measurement uncertainties.

To test the compatibility of the two channels, an additional fit was performed where the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ normalization factors were parameterized independently in the single-lepton and dilepton regions. The single-lepton channel measures $\sigma^{\mathrm{fid}}(t\bar{t}+\geq 2c) = (1.5 \pm 0.4)$ pb and $\sigma^{\mathrm{fid}}(t\bar{t}+1c) = (6.4 \pm 1.1)$ pb, and the dilepton channel $\sigma^{\mathrm{fid}}(t\bar{t}+\geq 2c) = (1.18 \pm 0.25)$ pb and $\sigma^{\mathrm{fid}}(t\bar{t}+1c) = (6.4 \pm 1.0)$ pb. The results in both channels are consistent with the nominal results within their uncertainties. The compatibility of this fit with the nominal setup was evaluated by performing a χ^2 test on the log-likelihood difference, yielding a compatibility of 58%. In a second test, the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ normalization factors were parameterized through one joint parameter of interest, and the NLO matching and PS uncertainties of the two processes were treated as correlated. The resulting cross-section of $\sigma^{\mathrm{fid}}(t\bar{t}+\geq 1c) = (8.2 \pm 0.9)$ pb is consistent with the sum of the $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ cross-sections in the nominal setup within uncertainties, but shows increased relative precision.

A measurement of the cross-sections in the more inclusive phase space yields $\sigma^{\mathrm{inc}}(t\bar{t}+\geq 2c) = (5.4 \pm 1.1)$ pb and $\sigma^{\mathrm{inc}}(t\bar{t}+1c) = (38 \pm 6)$ pb, showing moderately increased relative uncertainties compared with the fiducial cross-sections.

The normalization factors $\mu(t\bar{t}+\geq 1b)$, $\mu(t\bar{t}+\geq 2c)$, $\mu(t\bar{t}+1c)$, and $\mu(t\bar{t}+\text{light})$ are used to determine the cross-section ratios of these processes to total $t\bar{t}$ + jets production. These measurements benefit from the cancelation of several systematic uncertainties related to detector instrumentation and calibrations, potentially reducing the overall systematic uncertainties. In the more inclusive phase space, the measurement yields ratios of $R^{\mathrm{inc}}_{t\bar{t}+\geq 2c} = (1.23 \pm 0.25)\%$ and $R^{\mathrm{inc}}_{t\bar{t}+1c} = (8.8 \pm 1.3)\%$. In the fiducial phase space, these ratios increase to $R^{\mathrm{fid}}_{t\bar{t}+\geq 2c} = (2.7 \pm 0.5)\%$ and $R^{\mathrm{fid}}_{t\bar{t}+1c} = (13.7 \pm 1.8)\%$. In both phase spaces, the POWHEG+PYTHIA8 simulations underpredict the ratios, but agree with the measured $R^{\mathrm{inc}}_{t\bar{t}+\geq 2c}$ and $R^{\mathrm{inc}}_{t\bar{t}+1c}$ values within 0.9 and 1.1 standard deviations, and in the fidu-

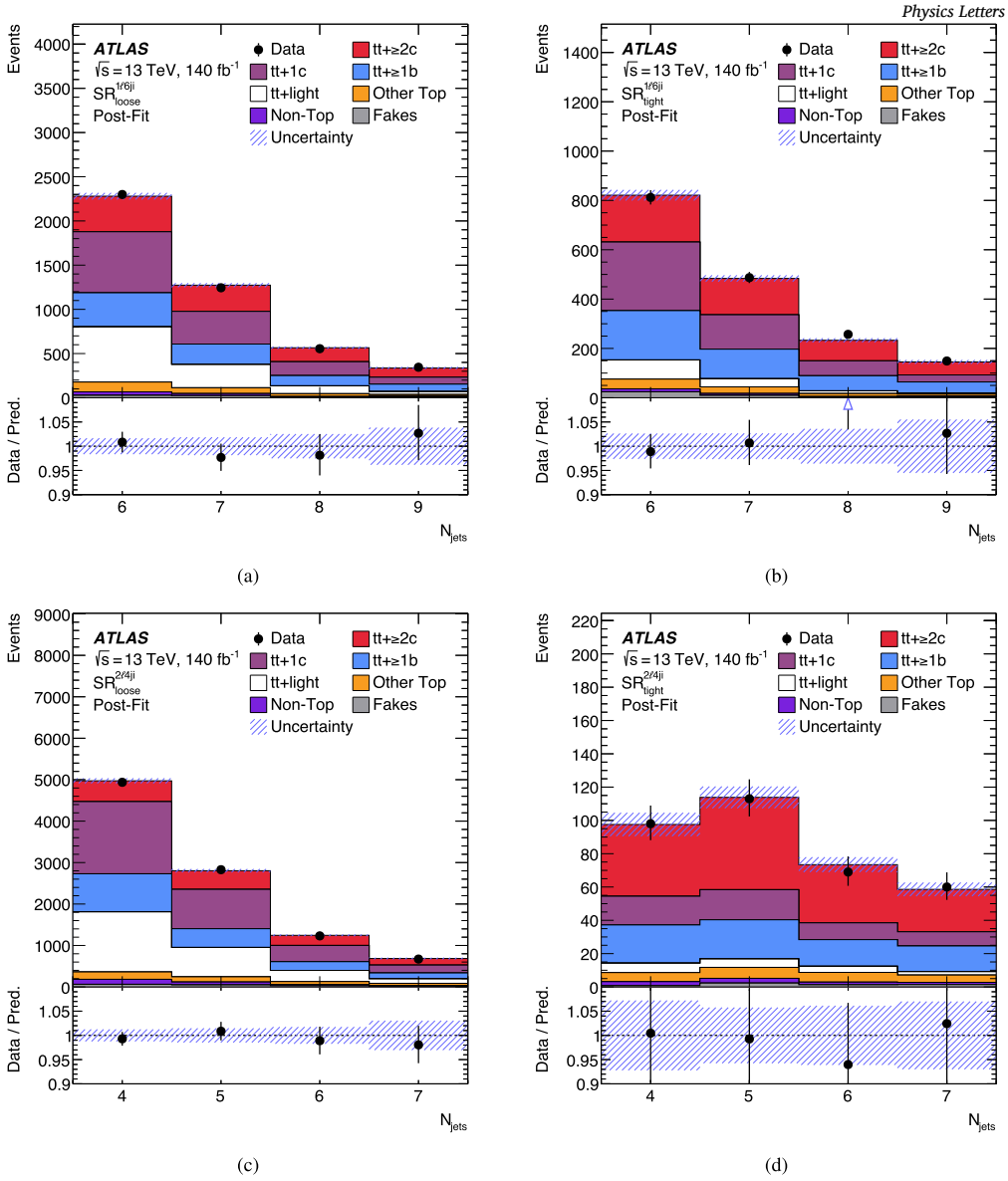

Fig. 5. Post-fit agreement between data and MC prediction for the observables used in the (a) loose 6-jet-inclusive, (b) tight 6-jet-inclusive, (c) loose 4-jet-inclusive, and (d) tight 4-jet-inclusive signal regions (SRs). All regions use the jet multiplicity, N_{jets}, as a fit observable. The hatched uncertainty bands include all uncertainties and their correlations. The last bins contain overflow events. *Other Top* includes single-top-quark production and associated production of $t\bar{t}$ and single top quarks with bosons. *Non-Top* includes W + jets, Z + jets, and diboson processes.

Table 3
Measured fiducial cross-section values in comparison with various NLO+PS predictions. The uncertainties in the predictions include independent and simultaneous variations of the μ_{R} and μ_{F} scales and uncertainties in the choice of the PDF set, but no uncertainties in the parton shower or hadronization. The uncertainties in the measured values include all statistical and systematic uncertainties. For presentation purposes, the quoted measurement and prediction uncertainties are symmetrized.

	$t\bar{t}+\geq 2c$ [pb]	$t\bar{t}+1c$ [pb]	$t\bar{t}+\geq 1b$ [pb]	$t\bar{t}+$ light [pb]	$t\bar{t}+$ jets [pb]
$t\bar{t}$ POWHEG+PYTHIA 8	1.04 ± 0.18	5.1 ± 0.8	3.2 ± 0.5	40 ± 6	50 ± 7
$t\bar{t}$ POWHEG+PYTHIA 8, $h_{\text{damp}} = 3\,m_t$	1.12 ± 0.16	5.4 ± 0.7	3.3 ± 0.5	41 ± 5	51 ± 7
$t\bar{t}$ POWHEG+PYTHIA 8, $p_{\text{T}}^{\text{hard}} = 1$	1.05 ± 0.18	5.2 ± 0.8	3.1 ± 0.5	40 ± 6	50 ± 7
$t\bar{t}$ POWHEG+HERWIG 7	0.94 ± 0.16	4.2 ± 0.7	3.3 ± 0.5	43 ± 6	52 ± 8
$t\bar{t}$ MADGRAPH5_AMC@NLO+HERWIG 7	0.74 ± 0.19	4.0 ± 0.8	2.7 ± 0.6	46 ± 8	53 ± 10
$t\bar{t}+b\bar{b}$ POWHEG+PYTHIA 8	—	—	3.2 ± 1.6	—	—
$t\bar{t}+b\bar{b}$ POWHEG+PYTHIA 8, $p_{\text{T}}^{\text{hard}} = 1$	—	—	2.8 ± 1.3	—	—
$t\bar{t}+b\bar{b}$ POWHEG+PYTHIA 8, $h_{\text{bzd}} = 2$	—	—	3.1 ± 1.5	—	—
$t\bar{t}+b\bar{b}$ POWHEG+PYTHIA 8, dipole recoil	—	—	3.0 ± 1.4	—	—
$t\bar{t}+b\bar{b}$ POWHEG+HERWIG 7	—	—	3.1 ± 1.6	—	—
$t\bar{t}+b\bar{b}$ SHERPA 2.2.10	—	—	3.5 ± 1.0	—	—
Data	1.28 ± 0.25	6.4 ± 0.9	3.46 ± 0.24	36.0 ± 1.8	47.1 ± 2.3

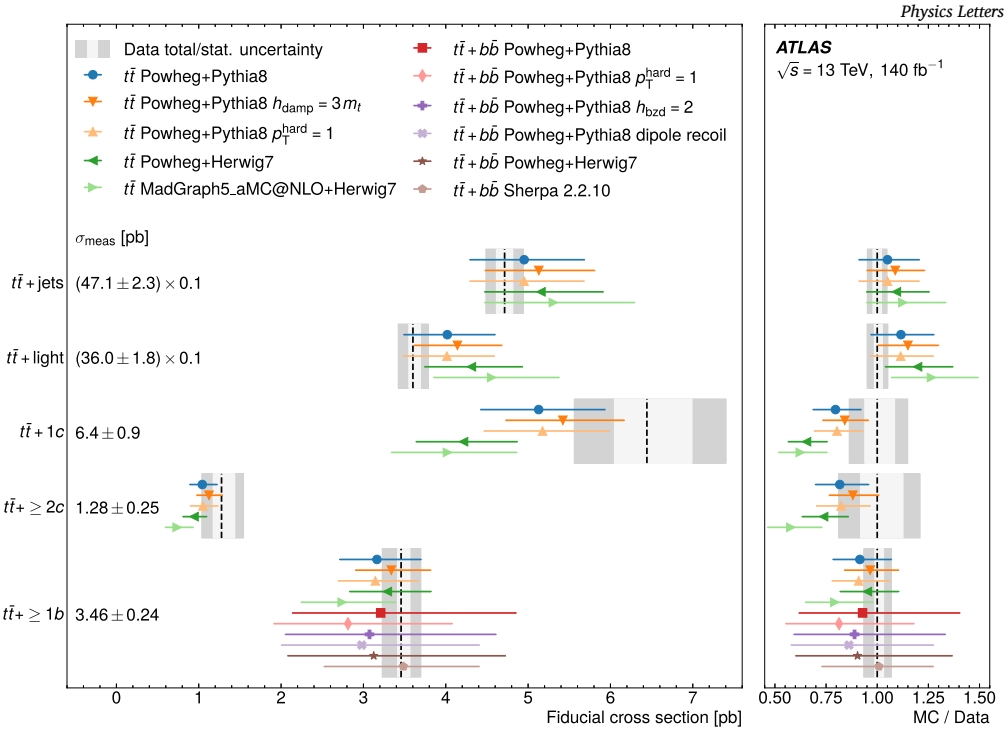

Fig. 6. Measured fiducial cross-section values in comparison with various NLO+PS predictions from inclusive $t\bar{t}$ and $t\bar{t}+b\bar{b}$ simulations. The boxes in the background represent the statistical and total uncertainties of the values extracted from data. The uncertainty bars of the predictions include independent and simultaneous variations of the μ_R and μ_F scales and uncertainties in the choice of the PDF set, but no uncertainties in the parton shower or hadronization. The measured and computed values for $t\bar{t}$ + jets and $t\bar{t}$ + light are scaled by a factor of 0.1 to facilitate visualization. For presentation purposes, the quoted measurement uncertainties are symmetrized.

Table 4
Measured and predicted values for the $t\bar{t}+\geq 1b$, $t\bar{t}+\geq 2c$, and $t\bar{t}+1c$ cross-sections and for the cross-section ratios of these processes to total $t\bar{t}$ + jets production. The quoted uncertainties in the measurements include statistical and systematic uncertainties. The predictions are taken from the nominal setup using inclusive $t\bar{t}$ POWHEG+PYTHIA8 predictions for the $t\bar{t}+\geq 2c$, $t\bar{t}+1c$, and $t\bar{t}$ + light processes, and $t\bar{t}+b\bar{b}$ POWHEG+PYTHIA8 predictions for the $t\bar{t}+\geq 1b$ process. The first use the five-flavor scheme (5FS), the latter the four-flavor scheme (4FS), where the b-quarks are treated as massive particles and are included in the matrix element calculation. The uncertainties in the predictions include independent and simultaneous variations of the μ_R and μ_F scales and uncertainties in the choice of the PDF set.

	Measured	$t\bar{t}$ or $t\bar{t}+b\bar{b}$ POWHEG+PYTHIA8
$\sigma^{fid}(t\bar{t}+\geq 1b)$ [pb]	3.46 ± 0.24	3.2 ± 1.6
$\sigma^{fid}(t\bar{t}+\geq 2c)$ [pb]	1.28 ± 0.25	1.04 ± 0.18
$\sigma^{fid}(t\bar{t}+1c)$ [pb]	6.4 ± 0.9	5.1 ± 0.8
$\sigma^{inc}(t\bar{t}+\geq 1b)$ [pb]	13.0 ± 0.9	12 ± 4
$\sigma^{inc}(t\bar{t}+\geq 2c)$ [pb]	5.4 ± 1.1	4.4 ± 0.7
$\sigma^{inc}(t\bar{t}+1c)$ [pb]	38 ± 6	31 ± 4
$R^{fid}_{t\bar{t}+\geq 1b}$ [%]	7.2 ± 0.4	6.5 ± 3.3
$R^{fid}_{t\bar{t}+\geq 2c}$ [%]	2.7 ± 0.5	2.1 ± 0.4
$R^{fid}_{t\bar{t}+1c}$ [%]	13.7 ± 1.8	10.3 ± 1.6
$R^{inc}_{t\bar{t}+\geq 1b}$ [%]	3.14 ± 0.23	2.6 ± 0.8
$R^{inc}_{t\bar{t}+\geq 2c}$ [%]	1.23 ± 0.25	0.97 ± 0.16
$R^{inc}_{t\bar{t}+1c}$ [%]	8.8 ± 1.3	6.9 ± 1.0

cial phase space within 1.0 and 1.4 standard deviations, respectively. A summary of all results is given in Table 4.

7. Conclusion

The production of $t\bar{t}$ pairs in association with heavy-flavor jets, $t\bar{t}+b\bar{b}$ and $t\bar{t}+c\bar{c}$, is a background in many measurements of rare SM processes and searches for new physics, yet a challenging process to model precisely. This Letter presents a measurement of the production of $t\bar{t}$ with additional jets initiated by charm quarks with the ATLAS experiment at the LHC. The analysis exploits the full ATLAS Run 2 pp collision data sample at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 140 fb^{-1}, and considers events with one or two charged leptons in the final state. A custom flavor tagging algorithm, termed the b/c-tagger, tailored to simultaneously tag c-jets and b-jets, is employed to define analysis regions sensitive to both $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ production which are determined separately for the first time. Using a profile likelihood fit approach, the cross-sections for $t\bar{t}$ production with two or more additional c-jets and one additional c-jet are found to be $\sigma^{fid}(t\bar{t}+\geq 2c) = 1.28^{+0.27}_{-0.24}$ pb and $\sigma^{fid}(t\bar{t}+1c) = 6.4^{+1.0}_{-0.9}$ pb in a fiducial volume that mimics the acceptance of the ATLAS detector. NLO+PS predictions for $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ are largely consistent with the measurements, though all underpredict the observed values. POWHEG+PYTHIA8 setups agree with the measured values within 0.5 to 1.1 standard deviations, while POWHEG+HERWIG7 and MADGRAPH5_AMC@NLO+HERWIG7 predict cross-sections up to 40% lower than the measurements, with agreement observed at the level of up to 2.0 standard deviations. The precision of the measured cross-sections is limited by uncertainties in the modeling of $t\bar{t}+\geq 1c$, $t\bar{t}+\geq 1b$, and $t\bar{t}$ + light, and in the b/c-tagger calibration, as well as by data statistics. The cross-section ratios of $t\bar{t}+\geq 2c$ and $t\bar{t}+1c$ to total $t\bar{t}$ + jets production are found to be $R^{inc}_{t\bar{t}+\geq 2c} = (1.23 \pm 0.25)\%$ and $R^{inc}_{t\bar{t}+1c} = (8.8 \pm 1.3)\%$ in a phase-space volume without requirements on the $t\bar{t}$ decay products and the jet multiplicity. These results provide crucial inputs for improving the modeling of $t\bar{t}$ production with additional c-jets, which would benefit from 3FS $t\bar{t}+c\bar{c}$ simulations that incorporate the gluon splitting to a $c\bar{c}$ pair into the matrix element calculation. Understanding $t\bar{t}+\geq 1c$ production is essential for precision measurements of even rarer SM processes and for searches for physics beyond the SM, where $t\bar{t}+\geq 1c$ is an important background.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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