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A search for new phenomena in final states with one or more jets and missing transverse momentum with the α_T variable at 13 TeV

The CMS Collaboration

Abstract

A search for new-physics phenomena is performed in final states containing one or more jets and an imbalance in transverse momentum in pp collisions at a centre-of-mass energy of 13 TeV. The analysed data sample, recorded with the CMS detector at the CERN LHC, corresponds to an integrated luminosity of $2.3\,\text{fb}^{-1}$. Several kinematic variables are employed to suppress the dominant background, multi-jet production, as well as to discriminate effectively between other standard model and new-physics processes. The search provides sensitivity to a broad range of new-physics models that yield a stable weakly interacting massive particle. The number of observed candidate events is found to agree with the expected contributions from standard model processes, and the result is interpreted in the mass parameter space of fourteen simplified supersymmetric models that assume the pair production of gluinos or squarks and a range of decay modes. For models that assume gluino pair production, masses up to 1575 GeV and 975 GeV are excluded for gluinos and neutralinos, respectively. For models involving the pair production of top squarks and compressed mass spectra, top squark masses up to 400 GeV are excluded.

1 Introduction

The standard model (SM) of particle physics is successful in describing a wide range of phenomena and the model is currently being extensively tested at high energies with collider-based experiments. To date, with the exception of massive neutrinos [1–3], no further contrary evidence has yet been established. The SM is widely believed to be only an effective approximation of a more complete theory that supersedes it at a higher energy scale. Supersymmetry (SUSY) [4–7] is a modification to the SM that extends its underlying space-time symmetry group. For each boson (fermion) in the SM, a fermionic (bosonic) superpartner, which differs in spin by one-half unit, is introduced.

The proposed supersymmetric extension of the SM is compelling from a theoretical perspective, as the addition of superpartners to SM particles can modify the running of the gauge coupling constants such that their unification can be achieved at a high scale [8–10]. A more topical perspective, given the recently discovered Higgs boson [11–13], is the assumption that the superpartners can alleviate the gauge hierarchy problem of the SM by compensating for radiative corrections to the Higgs mass from loop processes involving SM particles [14, 15]. These corrections have a power-law dependence on scale, which can only be accommodated in the SM through an extreme level of fine tuning of the bare Higgs mass. A "natural" solution from SUSY, with minimal fine-tuning, requires the $\widetilde{\chi}_1^0$, $\widetilde{t}_L$, $\widetilde{t}_R$, $\widetilde{b}_L$, and $\widetilde{g}$ to have masses at or near the electroweak scale [16]. These natural constraints, which can be relaxed at the expense of some level of fine tuning, imply the presence of states that may be produced by the CERN LHC.

Experimentally, SUSY is testable through the prediction of an extensive array of new observable states (of unknown masses) [17, 18]. The gluinos $\widetilde{g}$, light- and heavy-flavour squarks $\widetilde{q}, \widetilde{b}, \widetilde{t}$, and sleptons $\widetilde{\ell}$ are, respectively, the superpartners to gluons, quarks, and leptons. An extended Higgs sector is also predicted, as well as four neutralino $\widetilde{\chi}_{1,2,3,4}^0$ and two chargino $\widetilde{\chi}_{1,2}^\pm$ states that arise from mixing between the higgsino and gaugino states, which are the superpartners of the Higgs and electroweak gauge bosons. The assumption of R-parity conservation [19] has important consequences for cosmology and collider phenomenology. Supersymmetric particles are expected to be produced in pairs at the LHC, with heavy states decaying eventually to the lightest stable SUSY particle (LSP). The LSP is generally assumed to be the $\widetilde{\chi}_1^0$, which is weakly interacting and massive. This SUSY particle is considered to be a candidate for dark matter (DM) [20], the existence of which is supported by astrophysical data [21]. Hence, the characteristic signature of natural SUSY production at the LHC is a final state containing an abundance of jets, possibly originating from top or bottom quarks, accompanied by a significant transverse momentum imbalance, $\vec{p}_T^{\text{miss}}$.

The lack of evidence to date for SUSY has also focused attention on regions of the parameter space with weak coverage, which includes natural models [22–26]. For example, models in which both the $\widetilde{t}$ and the $\widetilde{\chi}_1^0$ are light and nearly degenerate in mass are phenomenologically well motivated [27–30]. This class of models, with "compressed" mass spectra, typically yield SM particles with low transverse momenta from the decays of SUSY particles. Hence, searches rely on the associated production of jets, often resulting from initial-state radiation (ISR), to achieve experimental acceptance.

This paper presents an inclusive search for new-physics phenomena in hadronic final states with one or more energetic jets and an imbalance in $\vec{p}_T^{\text{miss}}$, performed in proton-proton (pp) collisions at a centre-of-mass energy $\sqrt{s} = 13\,\text{TeV}$. The analysed data sample corresponds to an integrated luminosity of $2.3 \pm 0.1\,\text{fb}^{-1}$ collected by the CMS experiment. Earlier searches

using the same technique have been performed in pp collisions at both $\sqrt{s} = 7$ [31–33] and 8 TeV [34, 35] by the CMS Collaboration. The increase in the centre-of-mass energy of the LHC, from $\sqrt{s} = 8$ to 13 TeV, provides a unique opportunity to search for the characteristic signatures of new physics at the TeV scale. For example, the increase in $\sqrt{s}$ leads to a factor $\gtrsim 45$ increase in the parton luminosity [36] for the pair production of coloured SUSY particles, each of mass 1.5 TeV, which were beyond the reach of searches performed at $\sqrt{s} = 8$ TeV by the ATLAS [37, 38] (and references therein) and CMS [39–46] Collaborations. Several searches in this final state have already provided results with the first data, interpreted within the context of SUSY, at this new energy frontier [47–53].

To ensure sensitivity to the broadest possible region of the SUSY parameter space, an inclusive strategy is adopted. The strategy focuses on maintaining high acceptance through the application of selection criteria with the lowest possible thresholds, and the categorisation of candidate signal events according to multiple discriminating variables. The search is sufficiently generic and inclusive to provide sensitivity to a wide range of non-SUSY models that postulate the existence of a stable, weakly interacting, massive particle, assumed to be consistent with the nature of DM. In addition to the jets $+ \vec{p}_T^{\mathrm{miss}}$ topology, the search considers final states containing a "monojet" topology, which is expected to improve the sensitivity to DM particle production in pp collisions [54, 55].

This search is based on an examination of the number of reconstructed jets per event, the number of these jets identified as originating from bottom quarks, and the scalar and vector sums of transverse momenta of these jets. These variables provide sensitivity to the different production mechanisms of massive coloured SUSY particles at hadron colliders (i.e. squark-squark, squark-gluino, and gluino-gluino), third-generation squark signatures, and both large and small mass splittings between the parent SUSY particle and the LSP.

The dominant background process for a search in all-jet final states is multijet production, a manifestation of quantum chromodynamics (QCD). An accurate estimate of this background is difficult to achieve, given the lack of precise theoretical predictions for the multijet production cross section and kinematic properties. Hence, this search adopts a strategy that employs several variables to reduce the multijet contribution to a low level with respect to other SM backgrounds, rather than estimate a significant contribution with high precision.

The search is built around two variables, defined in Section 5.3, that are designed to provide robust discrimination against multijet events at the energy and luminosity frontier. A dimensionless kinematic variable α_T [31, 56] provides powerful discrimination against multijet production. The α_T variable is constructed from jet-based quantities and provides discrimination between genuine sources of $\vec{p}_T^{\mathrm{miss}}$ from stable, weakly interacting particles such as neutrinos or neutralinos that escape the detector, and instrumental sources such as the mismeasurements of jet energies. The $\Delta\phi_{\mathrm{min}}^*$ [31] variable exploits azimuthal angular information and also provides strong rejection power against multijet events, including rare energetic events in which neutrinos carry a significant fraction of the energy of a jet due to semileptonic decays of heavy-flavour mesons. Very restrictive requirements on the α_T and $\Delta\phi_{\mathrm{min}}^*$ variables are employed in this search to ensure a low level of contamination from the multijet background.

The organisation of this paper is as follows. Sections 2 and 3 describe, respectively, the CMS apparatus and the simulated event samples. Sections 4 and 5 describe the event reconstruction and selection criteria used to identify candidate signal events and control region samples. Section 6 provides details on the estimation of the multijet and all other SM backgrounds. Finally, the search results and interpretations, in terms of simplified SUSY models, are described in Sections 7 and 8, and summarised in Section 9.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with several particle detection systems. A silicon pixel and strip tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. A lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections, extend over a range $|\eta| < 3.0$. Outside the bore of the solenoid, forward calorimeters extend the coverage to $|\eta| < 5.0$, and muons are measured within $|\eta| < 2.4$ by gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. A two-tier trigger system selects pp collision events of interest. The first level of the trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage. The CMS detector is nearly hermetic, which allows for momentum balance measurements in the plane transverse to the beam axis. 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. [57].

3 Simulated event samples

The search relies on multiple event samples, in data or generated from Monte Carlo (MC) simulations, to estimate the contributions from SM backgrounds, as described in Section 5. The SM backgrounds for the search are QCD multijet production and the associated production of jets and top quark-antiquark ($t\bar{t}$), single top, and vector boson (W, $Z \to \nu\bar{\nu}$). Residual contributions from other processes, such as WW, WZ, ZZ (diboson) production and the associated production of $t\bar{t}$ and a W or Z boson, are also considered. Other processes, such as Drell–Yan ($q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$) and γ+jets production, are also relevant for some control regions, defined in Section 5.5.

The MADGRAPH5_AMC@NLO 2.2.2 [58] event generator code is used at leading-order (LO) accuracy to produce samples of W+jets, Z+jets, γ+jets, $t\bar{t}$, and multijet events. The same code is used at next-to-leading-order (NLO) accuracy to generate samples of single top quarks (both s- and t-channel production), WZ, ZZ, $t\bar{t}$W, and $t\bar{t}$Z events. The NLO POWHEG v2 [59, 60] generator is used to describe WW events and the Wt-channel production of single top quark events. The simulated samples are normalised according to production cross sections that are calculated with NLO and next-to-NLO precision [58, 60–65], or with LO precision in the case of multijet and γ+jets production. The GEANT4 [66] package is used to simulate the detector response.

Event samples for signal models involving gluino or squark pair production, in association with up to two additional partons, are generated at LO with MADGRAPH5_AMC@NLO, and the decay of the SUSY particles is performed with PYTHIA 8.205 [67]. Inclusive, process-dependent, signal production cross sections are calculated with NLO plus next-to-leading-logarithmic (NLL) accuracy [68–73]. The theoretical systematic uncertainties are typically dominated by the parton density function (PDF) uncertainties, evaluated using the CTEQ6.6 [74] and MSTW2008 [36] PDFs. The detector response for signal models is provided by the CMS fast simulation package [75].

The NNPDF3.0 LO and NLO [76] parton distribution functions (PDFs) are used, respectively, with the LO and NLO generators described above. The LO PYTHIA program with the CUETP8M1

underlying event tune [77] is used to describe parton showering and hadronisation for all sim-
ulated samples. To model the effects of multiple pp collisions within the same or neighbouring
bunch crossings (pileup), all simulated events are generated with a nominal distribution of pp
interactions per bunch crossing and then reweighted to match the pileup distribution as mea-
sured in data. On average, approximately fifteen different pp collisions, identifiable via their
primary interaction vertex, are reconstructed per event. Finally, (near-unity) corrections to the
normalisation of the simulated samples for the γ+jets, $W(\to \mu\nu)$+jets, $t\bar{t}$, and $Z(\to \mu\mu)$+jets,
and, equivalently, $Z(\to \nu\bar{\nu})$+jets processes are derived using data sidebands to the control re-
gions.

4   Event reconstruction

Global event reconstruction is provided by the particle flow (PF) algorithm [78, 79], designed
to identify each particle using an optimised combination of information from all detector sys-
tems. In this process, the identification of the particle type (photon, electron, muon, charged
hadron, neutral hadron) plays an important role in the determination of the particle direction
and energy.

The primary vertex (PV) for each recorded event is assumed to be the reconstructed vertex with
the largest sum of charged-particle track p_{T}^2 values that is found within 24 cm and 2 cm of the
centre of the detector in the directions along and perpendicular to the beam axis, respectively.
Charged-particle tracks associated with reconstructed vertices from pileup are not considered
by the PF algorithm as part of the global event reconstruction.

Photons [80] are identified as ECAL energy clusters not linked to the extrapolation of any
charged-particle track to the ECAL. The energy of photons is directly obtained from the ECAL
measurement, corrected for the effects of pileup. Various quality-related criteria must be sat-
isfied in order to identify photons with high efficiency while minimising the misidentification
of electrons and associated bremsstrahlung, jets, or ECAL noise as photons. The criteria include
the following: the shower shape of the energy deposition in the ECAL must be consistent with
that expected from a photon, the energy detected in the HCAL behind the photon shower must
not exceed 5% of the photon energy, and no matched hits in the pixel tracker must be found.

Electrons [81] are identified as a charged-particle track associated with an ECAL cluster com-
patible with the track trajectory, as well as additional ECAL energy clusters from potential
bremsstrahlung photons emitted as the electron traverses material of the silicon tracker. The en-
ergy of electrons is determined from a combination of the track momentum at the main interac-
tion vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung
photons associated with the track. The quality criteria required for electrons are similar to those
for photons, with regards to the ECAL shower shape and the relative contributions to the total
energy deposited in the ECAL and HCAL. Additional requirements are also made on the asso-
ciated track, which consider the track quality, energy-momentum matching, and compatibility
with the PV in terms of the transverse and longitudinal impact parameters.

Muons [82] are identified as a track in the silicon tracker consistent with either a track or several
hits in the muon system. The track and hit parameters must satisfy various quality-related
criteria, described in Ref. [82]. The energy of muons is obtained from the corresponding track
momentum.

Charged hadrons are identified as charged-particle tracks not classified as either electrons or
muons. The energy of charged hadrons is determined from a combination of the track momen-

183 tum and the corresponding ECAL and HCAL energies, corrected for the effects of pileup and
184 the response function of the calorimeters to hadronic showers. Neutral hadrons are identified
185 as HCAL energy clusters not linked to any charged-hadron trajectory, or as ECAL and HCAL
186 energy excesses with respect to the expected charged-hadron energy deposit. The energy of
187 neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

188 Photons are required to be isolated from other activity in the event, such as charged and neu-
189 tral hadrons, within a cone $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the photon trajectory, cor-
190 rected for pileup effects and for contributions from the photon itself. Electrons and muons
191 are also required to be isolated from other activity in the event, primarily to suppress back-
192 ground contributions from semileptonic heavy-flavour decays in multijet events. The isolation
193 $I_{\text{rel}}^{\text{mini}}$ is defined as the scalar p_{T} sum of all charged and neutral hadrons, and photons, within
194 a cone around the lepton direction, divided by the lepton p_{T}. The ("mini") cone radius is de-
195 pendent on the lepton p_{T}, primarily to identify with high efficiency the collimated daughter
196 particles of semileptonically decaying Lorentz-boosted top quarks, according to the following:
197 $R = 0.2$ and 0.05 for, respectively, $p_{\text{T}} < 50\,\text{GeV}$ and $p_{\text{T}} > 200\,\text{GeV}$, and $R = 10\,\text{GeV}/p_{\text{T}}$ for
198 $50 < p_{\text{T}} < 200\,\text{GeV}$. The variable $I_{\text{rel}}^{\text{mini}}$ excludes contributions from the lepton itself and is
199 corrected for the effects of pileup. The isolation for electrons and muons is required to satisfy,
200 respectively, $I_{\text{rel}}^{\text{mini}} < 0.1$ and 0.2 for the signal region and nonleptonic control sample selection
201 criteria. A tighter definition of muon isolation I_{rel}^{μ} is used for the definition of control regions
202 that are required to contain at least one muon. The variable I_{rel}^{μ} is determined identically to
203 $I_{\text{rel}}^{\text{mini}}$ except that a cone of fixed radius $R = 0.4$ is assumed.

204 Electron and muon candidates identified by the PF algorithm that do not satisfy the quality
205 criteria or the $I_{\text{rel}}^{\text{mini}}$ isolation requirements described above, as well as charged hadrons, are
206 collectively labelled as "single isolated tracks" if they are isolated from neighbouring charged-
207 particle tracks associated to the PV. The isolation $I_{\text{rel}}^{\text{track}}$ is defined as the scalar p_{T} sum of
208 charged-particle tracks (excluding the track under consideration) within a cone $\Delta R < 0.3$
209 around the track direction, divided by the track p_{T}. The requirement $I_{\text{rel}}^{\text{track}} < 0.1$ is imposed.

210 Jets are clustered from the PF candidate particles with the infrared- and collinear-safe anti-k_t
211 algorithm [83], operated with a distance parameter of 0.4. The jet momentum is determined as
212 the vectorial sum of all particle momenta in the jet, and is found in the simulation to be within
213 5 to 10% of its true momentum over the whole p_{T} spectrum and detector acceptance. Jet energy
214 corrections, to account for pileup [84] and to establish a uniform relative response in η and a
215 calibrated absolute response in p_{T}, are derived from the simulation, and are confirmed with
216 in situ measurements using the energy balance in dijet and photon+jet events [85]. The jet en-
217 ergy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, compared
218 to about 40%, 12%, and 5% obtained when the calorimeters alone are used for jet clustering.
219 All jets are required to satisfy loose requirements on the relative composition of their particle
220 constituents to reject noise in the calorimeter systems or failures in event reconstruction.

221 Jets are identified as originating from b quarks using the combined secondary vertex algo-
222 rithm [86]. Control regions in data [87] are used to measure the probability of correctly identi-
223 fying jets as originating from b quarks (b tagging efficiency), and the probability of misidenti-
224 fying jets originating from light-flavour partons (u, d, s quarks or gluons) or a charm quark as
225 a b-tagged jet (the light-flavour and charm mistag probabilities). A working point is employed
226 that yields a b tagging efficiency of 65%, and charm and light-flavour mistag probabilities of
227 approximately 12 and 1%, respectively, for jets with p_{T} that is typical of $t\bar{t}$ events.

228 An estimator of $\vec{p}_{\text{T}}^{\text{miss}}$ is given by the projection on the plane perpendicular to the beams of the
229 negative vector sum of the momenta of all candidate particles in an event [88], as determined

by the PF algorithm. Its magnitude is referred to as E_T^{miss}.

5 Event selection

The kinematic selection criteria used to define the signal region, containing a sample of candidate signal events, as well as a number of control regions in data, are described below. The criteria are based on the physics objects defined by the event reconstruction algorithms described in Section 4.

5.1 Common preselection criteria

A number of beam- and detector-related effects, such as beam halo, reconstruction failures, spurious detector noise, or event misreconstruction due to detector inefficiencies, can lead to events with anomalous levels of activity. These events, which can exhibit large, nonphysical values of E_T^{miss}, are rejected with high efficiency by applying a range of dedicated vetoes [88, 89].

In order to suppress SM processes with genuine $\vec{p}_T^{miss}$ from neutrinos, events containing an isolated electron or muon that satisfy $p_T > 10\,\text{GeV}$ and $|\eta| < 2.5$ are vetoed. Events containing an isolated photon with $p_T > 25\,\text{GeV}$ and $|\eta| < 2.5$ are also vetoed, in order to select only multijet final states. Furthermore, events containing a single isolated track satisfying $p_T > 10\,\text{GeV}$ and $|\eta| < 2.5$ are vetoed in order to reduce the background contribution from final states containing hadronically decaying tau leptons.

Each jet j_i considered by this search is required to satisfy $p_T^{j_i} > 40\,\text{GeV}$ and $|\eta^{j_i}| < 3$. The number of jets within this experimental acceptance is labelled henceforth as n_{jet}. The highest p_T jet in the event is required to have $p_T^{j_1} > 100\,\text{GeV}$ and $|\eta^{j_1}| < 2.5$. The second-highest p_T jet in the event is used to categorise events, as described in Section 5.2. If the jet satisfies $p_T^{j_2} > 100\,\text{GeV}$, then this category of events is labelled "symmetric" and targets primarily topologies resulting from pair-produced SUSY particles. If the jet satisfies $40 < p_T^{j_2} < 100\,\text{GeV}$ then the event is labelled as "asymmetric", and if there exists no second jet with $p_T^{j_2} > 40\,\text{GeV}$, the event is labelled "monojet". The asymmetric and monojet topologies target models involving the direct production of stable, weakly interacting, massive particles. The mass scale of the physics processes being probed is characterised by the scalar p_T sum of the jets, defined as $H_T = \sum_{i=1}^{n_{jet}} p_T^{j_i}$. The magnitude of the vector $\vec{p}_T$ sum of these jets, defined by $H_T^{miss} = |\sum_{i=1}^{n_{jet}} \vec{p}_T^{j_i}|$, is used to identify events with significant imbalance in transverse momentum. Events are vetoed if any jet satisfies $p_T > 40\,\text{GeV}$ and $|\eta| > 3$ to ensure that jets reconstructed in the forward regions of the detector do not contribute significantly to H_T^{miss}.

The dimensionless variable H_T^{miss}/E_T^{miss} is used to remove events that contain several jets with transverse momenta below the jet p_T thresholds but an appreciable vector p_T sum so as to contribute significantly to H_T^{miss} relative to E_T^{miss}. This background is typical of multijet events, which is suppressed by requiring $H_T^{miss}/E_T^{miss} < 1.25$. The requirement is imposed as part of the common preselection criteria used to define all control samples to minimise potential systematic biases associated with the simulation modelling for this variable. A high efficiency is maintained for SM or new-physics processes that produce unobserved particles, which are characterised by large values of $\vec{p}_T^{miss}$ and values of H_T^{miss}/E_T^{miss} close to unity.

Significant jet activity and missing transverse momentum in the event is ensured by requiring $H_T > 200\,\text{GeV}$ and $H_T^{miss} > 130\,\text{GeV}$, respectively. These requirements complete the common preselection criteria, summarised in Table 1, used to define a sample of all-jet events characterised by high jet activity and appreciable $\vec{p}_T^{miss}$.

Table 1: Summary of the event selection criteria and categorisation used to define the signal and control regions.

Common preselection	
E_T^{miss} quality	Filters related to beam and instrumental effects, and reconstruction failures
Lepton/photon vetoes	$p_T > 10, 10, 25\,\text{GeV}$ for isolated tracks, leptons, photons (respectively) and $|\eta| < 2.5$
Jet j_i acceptance	Consider each jet j_i that satisfies $p_T^{j_i} > 40\,\text{GeV}$ and $|\eta^{j_i}| < 3$
Jet j_1 acceptance	$p_T^{j_1} > 100\,\text{GeV}$ and $|\eta^{j_1}| < 2.5$
Jet j_2 acceptance	$p_T^{j_2} < 40\,\text{GeV}$ (monojet), $40 < p_T^{j_2} < 100\,\text{GeV}$ (asymmetric), $p_T^{j_2} > 100\,\text{GeV}$ (symmetric)
Forward jet veto	Veto events containing jet satisfying $p_T > 40\,\text{GeV}$ and $|\eta| > 3$
Jets below threshold	$H_T^{miss}/E_T^{miss} < 1.25$
Energy sums	$H_T > 200\,\text{GeV}$ and $H_T^{miss} > 130\,\text{GeV}$
Event categorisation	
n_{jet}	1 (monojet), 2, 3, 4, ≥ 5 (asymmetric), 2, 3, 4, ≥ 5 (symmetric)
n_b	0, 1, 2, ≥ 3 ($n_b \leq n_{jet}$)
H_T (GeV)	200, 250, 300, 350, 400, 500, 600, $> 800\,\text{GeV}$ (bins can be dropped/merged $vs.$ n_{jet}, Table 2)
Signal region (SR)	Preselection +
QCD multijet rejection	$\alpha_T > 0.65, 0.60, 0.55, 0.53, 0.52, 0.52, 0.52$ (mapped to H_T bins in range $200 < H_T < 800\,\text{GeV}$)
QCD multijet rejection	$\Delta\phi_{min}^* > 0.5$ ($n_{jet} \geq 2$) or $\Delta\phi_{min}^{*25} > 0.5$ ($n_{jet} = 1$)
Control regions (CR)	Preselection +
Multijet-enriched	SR + $H_T^{miss}/E_T^{miss} > 1.25$ (inverted)
γ+jets	1γ with $p_T > 200\,\text{GeV}$, $|\eta| < 1.45$, $\Delta R(\gamma, j_i) > 1.0$, $H_T > 400\,\text{GeV}$, same α_T req. as SR
μ+jets	1μ with $p_T > 30\,\text{GeV}$, $|\eta| < 2.1$, $I_{rel}^\mu < 0.1$, $\Delta R(\mu, j_i) > 0.5$, $30 < m_T(\vec{p}_T^\mu, \vec{p}_T^{miss}) < 125\,\text{GeV}$
$\mu^\pm\mu^\mp$+jets	2μ with $p_T > 30\,\text{GeV}$, $|\eta| < 2.1$, $I_{rel}^\mu < 0.1$, $\Delta R(\mu_{1,2}, j_i) > 0.5$, $|m_{\mu\mu} - m_Z| < 25\,\text{GeV}$

5.2 Event categorisation

Events selected by the common preselection criteria are categorised according to n_{jet}, the number of b-tagged jets n_b, and H_T. Nine categories in n_{jet} are employed: the monojet topology ($n_{jet} = 1$) and four n_{jet} bins (2, 3, 4, ≥ 5) for each of the asymmetric and symmetric topologies. Events are also categorised by n_b (0, 1, 2, ≥ 3), where n_b is bounded from above by n_{jet}, resulting in 32 categories in terms of both n_{jet} and n_b. For each (n_{jet}, n_b) category, events are binned according to H_T: four $50\,\text{GeV}$ bins at low jet activity in the range $200 < H_T < 400\,\text{GeV}$, two $100\,\text{GeV}$ bins in the range $400 < H_T < 600\,\text{GeV}$, one bin covering the region $600 < H_T < 800\,\text{GeV}$, and a final open bin for $H_T > 800\,\text{GeV}$. These categorisations are summarised in Table 1. The H_T binning scheme is adapted independently per (n_{jet}, n_b) category by removing or merging bins to satisfy a threshold on the minimum number of data events in the control regions, which are used to estimate SM backgrounds, provide checks, and validate assumptions within the methods. The lower bounds of the first and final (open) bins in H_T are summarised in Table 2. In summary, the search employs a categorisation scheme for events that results in 191 bins, defined in terms of n_{jet}, n_b, and H_T.

5.3 Signal region

For events satisfying the common preselection criteria described above, the multijet background dominates over all other SM backgrounds. Several variables are employed to reduce the multijet contribution to a negligible level with respect to other SM backgrounds.

The dimensionless kinematic variable α_T [31, 56], defined in Eq. (2) below, is used to provide discrimination against multijet events that do not contain significant $\vec{p}_T^{miss}$ or that contain large $\vec{p}_T^{miss}$ only because of p_T mismeasurements, while retaining sensitivity to new-physics events with significant $\vec{p}_T^{miss}$. The α_T variable depends solely on the transverse component of jet four-

Table 2: Summary of the lower bounds of the first and final bins in H_T (the latter in parentheses) as a function of n_{jet} and n_b.

$n_{jet} \backslash n_b$	0	1	2	≥ 3
Monojet				
1	200 (600)	200 (500)	-	-
Asymmetric				
2	200 (600)	200 (500)	200 (400)	-
3	200 (600)	200 (600)	200 (500)	200 (300)
4	200 (600)	200 (600)	200 (600)	250 (400)
≥ 5	250 (600)	250 (600)	250 (600)	300 (500)
Symmetric				
2	200 (800)	200 (800)	200 (600)	-
3	200 (800)	250 (800)	250 (800)	- (250)
4	300 (800)	300 (800)	300 (800)	300 (800)
≥ 5	350 (800)	350 (800)	350 (800)	350 (800)

momenta and is intrinsically robust against the presence of jet energy mismeasurements in multijet systems. For events containing only two jets, α_T is defined as $\alpha_T = E_T^{j_2} / M_T$, where $E_T = E \sin\theta$, where E is the energy of the jet and θ is its polar angle with respect to the beam axis, $E_T^{j_2}$ is the transverse energy of the jet with smaller E_T, and M_T is the transverse mass of the dijet system, defined as:

$$M_T = \sqrt{ \left(\sum_{i=1}^{2} E_T^{j_i} \right)^2 - \left(\sum_{i=1}^{2} p_x^{j_i} \right)^2 - \left(\sum_{i=1}^{2} p_y^{j_i} \right)^2 }, \tag{1}$$

where $E_T^{j_i}$, $p_x^{j_i}$, and $p_y^{j_i}$ are, respectively, the transverse energy, and the x and y components of the transverse momentum of jet j_i. For a perfectly measured dijet event with $E_T^{j_1} = E_T^{j_2}$ and back-to-back jets ($\Delta\phi = \pi$), and in the limit in which the momentum of each jet is large compared with its mass, the value of α_T is 0.5. For an imbalance in the E_T of back-to-back jets, α_T is reduced to a value < 0.5, which gives the variable its intrinsic robustness. Values significantly greater than 0.5 are observed when the two jets are not back-to-back and recoil against $\vec{p}_T^{\,miss}$ from weakly interacting particles that escape the detector.

The definition of the α_T variable can be generalised for events with more than two jets [31]. The mass scale for any process is characterised through the scalar sum of the jet transverse energies, defined as $\mathcal{E}_T = \sum_{i=1}^{N_{jet}} E_T^{j_i}$, where N_{jet} is the number of jets with E_T above a predefined threshold. (The definition of $\mathcal{E}_T$ should be contrasted with that of H_T, the scalar sum of the jet transverse momenta.) For events with three or more jets, a pseudo-dijet system is formed by combining the jets in the event into two pseudo-jets. The $\mathcal{E}_T$ for each of the two pseudo-jets is given by the scalar E_T sum of its contributing jets. The combination chosen is the one that minimises $\Delta\mathcal{E}_T$, defined as the difference between these sums for the two pseudo-jets. This clustering criterion assumes a balanced-event hypothesis, which provides strong separation between SM multijet events and events with genuine $\vec{p}_T^{\,miss}$. The α_T definition can be generalised to:

$$\alpha_T = \frac{1}{2} \frac{\mathcal{E}_T - \Delta\mathcal{E}_T}{\sqrt{(\mathcal{E}_T)^2 - (H_T^{miss})^2}}. \tag{2}$$

When jet energies are mismeasured, or there are neutrinos from heavy-flavour quark decays,

the magnitudes of H_T^{miss} and $\Delta\mathcal{E}_T$ are highly correlated. This correlation is much weaker for R-parity-conserving SUSY events, where each of the two decay chains produces an undetected LSP.

Multijet events populate the region $\alpha_T < 0.5$ and the α_T distribution is characterised by a sharp edge at 0.5, beyond which the multijet event yield falls by several orders of magnitude. Multijet events with extremely rare but large stochastic fluctuations in the calorimetric measurements of jet energies can lead to values of α_T slightly above 0.5. The edge at 0.5 sharpens with increasing H_T for multijet events, primarily due to a corresponding increase in the average jet energy and consequently a (relative) improvement in the jet energy resolution.

For events containing at least two jets, thresholds on the minimum allowed α_T values are applied independent of n_{jet} and n_b but dependent on H_T, for events that satisfy $200 < H_T < 800\,\text{GeV}$. The α_T thresholds vary between 0.65 to 0.52 for, respectively, the regions $200 < H_T < 250\,\text{GeV}$ and $400 < H_T < 800\,\text{GeV}$. No requirement on α_T is made for the region $H_T > 800\,\text{GeV}$. The thresholds employed are summarised in Table 1. The α_T thresholds are motivated both by the trigger conditions used to record the candidate signal events, described below, and by simulation-based studies and estimates of the multijet background derived from data.

An additional variable is based on the minimum azimuthal separation between a jet and the negative vector $\vec{p}_T$ sum derived from all other jets in the event [31],

$$\Delta\phi_{min}^* = \min_{\forall\,j_k\,\in\,[1,n_{jet}]} \Delta\phi(\vec{p}_T^{j_k}, -\sum_{\substack{j_i=1\\j_i\neq j_k}}^{n_{jet}} \vec{p}_T^{j_i}). \tag{3}$$

This variable discriminates between final states with genuine $\vec{p}_T^{miss}$, e.g. from the leptonic decay of the W boson, and energetic multijet events that have significant $\vec{p}_T^{miss}$ through jet energy mismeasurements or through the production of neutrinos, collinear with the axis of a jet, from semileptonic heavy-flavour decays. Multijet events populate the region $\Delta\phi_{min}^* < 0.5$, with the multijet distribution peaking at a value of zero and falling approximately exponentially over five orders of magnitude to a single-event level at a value of $\Delta\phi_{min}^* \approx 0.5$, which is close to the distance parameter value of 0.4 used by the anti-k_t jet clustering algorithm. Events with a genuine source of $\vec{p}_T^{miss}$ exhibit a long tail in $\Delta\phi_{min}^*$ with values as large as π. The $\Delta\phi_{min}^*$ variable provides comparable or improved performance in terms of discrimination according to a simple signal-to-background metric for a wide range of signal models with respect to more widely used variables such as:

$$\Delta\phi_{min} = \min_{\forall\,j_k\,\in\,[1,n_{jet}]} \Delta\phi(\vec{p}_T^{j_k}, -\sum_{j_i=1}^{n_{jet}} \vec{p}_T^{j_i}). \tag{4}$$

A requirement of $\Delta\phi_{min}^* > 0.5$ is sufficient to effectively suppress the multijet background to a negligible level while maintaining high efficiency for new-physics signatures. The combined rejection power of the α_T and $\Delta\phi_{min}^*$ requirements for the region $200 < H_T < 800\,\text{GeV}$ is sufficient to suppress multijet events to the few percent level with respect to all other SM backgrounds in all H_T bins for all event categories of the signal region. For the region $H_T > 800\,\text{GeV}$, a similar control of the multijet background is achieved solely with the $\Delta\phi_{min}^* > 0.5$ requirement.

Figure 1 illustrates the performance of the α_T and $\Delta\phi_{min}^*$ variables by showing their distributions observed in data for events that satisfy $n_{jet} \geq 2$ and all other selection criteria that define
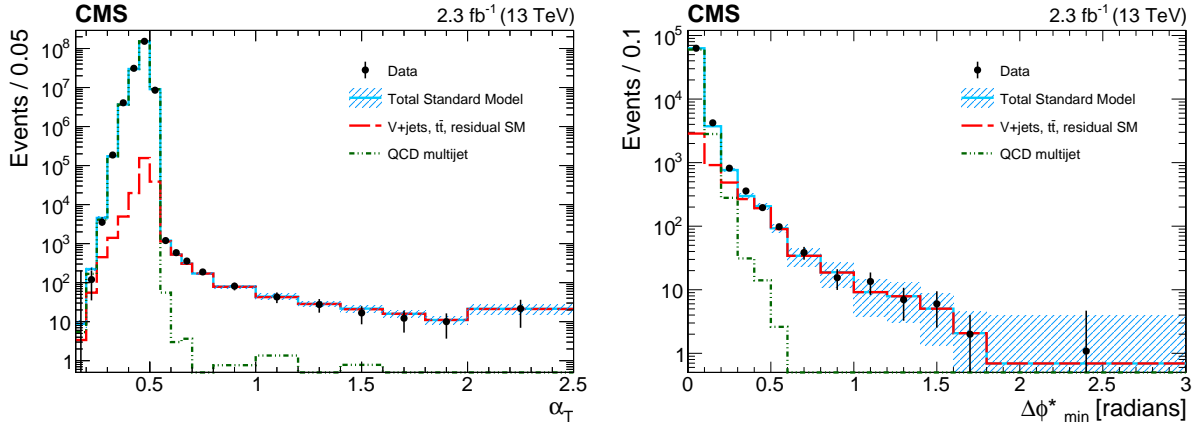
Figure 1: (Left) The α_T distribution observed in data for events that are recorded with an inclusive set of trigger conditions and satisfy either the common preselection criteria and $\alpha_T < 0.55$, or the full signal region selection criteria and $\alpha_T > 0.55$, as well as the additional requirement $H_T > 300\,\text{GeV}$. (Right) The $\Delta\phi^*_{\text{min}}$ distribution observed in data for events that are recorded with an inclusive set of trigger conditions and satisfy the full signal region selection criteria for the region $H_T > 800\,\text{GeV}$. The requirement $n_{\text{jet}} \geq 2$ is imposed for both distributions. The statistical uncertainties for the multijet and SM expectations are represented by the hatched areas (visible only for statistically limited bins). The final bin of each distribution contains the overflow events.

the signal region, summarised in Table 1, as well as the following modifications. In the case of the α_T distribution, the events that satisfy $\alpha_T < 0.55$ must fulfill only the common preselection criteria defined in Table 1, and no H_T^{miss} requirement is made. Further, all events are required to satisfy $H_T > 300\,\text{GeV}$. In the case of the $\Delta\phi^*_{\text{min}}$ distribution, the only additional requirement is $H_T > 800\,\text{GeV}$. For both distributions, the events are recorded with a set of inclusive trigger conditions that are independent of the α_T and $\Delta\phi^*_{\text{min}}$ variables. The distributions for the QCD multijet background are determined from simulation while all other SM backgrounds (vector boson production in association with jets, $t\bar{t}$, and other residual contributions from rare SM processes) are estimated using a μ+jets data control sample, described in Section 6.2. The contribution from multijet events is observed to fall by more than five orders of magnitude for both variables.

The α_T and $\Delta\phi^*_{\text{min}}$ requirements described above, in conjunction with the common preselection requirements $H_T^{\text{miss}} > 130\,\text{GeV}$ and $H_T^{\text{miss}}/E_T^{\text{miss}} < 1.25$, provide strong rejection power against the multijet background for events that satisfy $n_{\text{jet}} \geq 2$. For monojet events, a modification to the $\Delta\phi^*_{\text{min}}$ variable, which considers soft jets with $p_T > 25\,\text{GeV}$ ($\Delta\phi^{*25}_{\text{min}}$), is utilised. No α_T requirement is imposed, and $\Delta\phi^{*25}_{\text{min}} > 0.5$ is sufficient to suppress contributions from multijet events to a negligible level. The aforementioned requirements complete the event selection criteria for the signal region.

Finally, $\Delta\phi^{*25}_{\text{min}}$ is also used as a control variable for events that satisfy $n_{\text{jet}} \geq 2$ to identify multijet contributions arising from instrumental effects, such as inefficient detector elements or detector noise. The axis of any jet that satisfies $\Delta\phi^{*25}_{\text{min}} < 0.5$ is used to identify localised behaviour in the (η, ϕ) plane, which may be indicative of instrumental defects. No significant anomalies are observed in the sample of candidate signal events following the application of the dedicated vetoes described in Section 5.1.

Multiple trigger conditions are employed in combination to record signal candidate events. A

set of trigger conditions utilise calculations of both H_T and α_T to record events with two or more jets. An event is recorded if it satisfies any of the following pairs of (H_T, α_T) thresholds, (200,0.57), (250,0.55), (300,0.53), (350,0.52), or (400,0.51), as well as a requirement on the mean value of the two highest p_T jets, $\langle p_T^{j1} + p_T^{j2} \rangle > 90\,\text{GeV}$. These requirements are collectively labelled as the "H_T–α_T" triggers. In addition, candidate signal events with one or more jets are also recorded if they satisfy the requirements $H_T^{\text{miss}} > 90\,\text{GeV}$ and $E_T^{\text{miss}} > 90\,\text{GeV}$. Finally, for events that satisfy $H_T > 800\,\text{GeV}$, an additional trigger condition, defined by $H_T > 800\,\text{GeV}$, is employed in addition to the H_T–α_T trigger requirements to record events characterised by high activity in the calorimeters with high efficiency. The trigger-level jet energies are corrected to account for energy scale and pileup effects. The aforementioned triggers are employed in combination to provide efficiencies at or near 100% for all bins in the signal region.

5.4 Using H_T^{miss} templates

Following the event selection criteria described above, which provide a sample of signal candidate events with a negligible contribution from multijet events, further discriminating power is required to separate new-physics signatures from the remaining SM backgrounds, which are dominated by the production of $t\bar{t}$ or $W(\to \ell\nu)$+jets and $Z(\to \nu\bar{\nu})$+jets events. Given the characteristic signature of SUSY production at the LHC is a final state of multijets accompanied by large values of $\vec{p}_T^{\text{miss}}$ from the LSPs, the search exploits the use of the H_T^{miss} variable as an additional discriminant between new-physics and SM processes.

The search relies directly on simulation to determine a template for each (n_{jet}, n_b, H_T) bin that describes the expected distribution of events as a function of H_T^{miss}. These templates are used by the likelihood function as a model for the data, details of which can be found in Section 7. The templates are extensively validated against data in multiple control regions, and these studies are used to establish the uncertainty in the simulation modelling of the H_T^{miss} variable. The effects of theoretical and experimental uncertainties on the H_T^{miss} distributions are also studied. Further details can be found in Section 6.2.

5.5 Control regions

Four control regions in data are employed to estimate the background contributions from SM processes, which modify and expand the common preselection criteria described above according to the descriptions found below and summarised in Table 1. The first control region comprises a multijet-enriched sample of events, and is defined by the signal region selection criteria and the inverted requirement $H_T^{\text{miss}}/E_T^{\text{miss}} > 1.25$. The events are recorded with the signal triggers described above, and the sample is used to estimate the multijet background in the signal region. Three additional control regions, defined by inverting one of the photon or lepton vetoes to select samples of γ+jets, μ+jets, or $\mu\mu$+jets events, are used to estimate the background contributions from SM processes with final states containing genuine $\vec{p}_T^{\text{miss}}$, which are primarily $t\bar{t}$, $W(\to \ell\nu)$+jets, and $Z(\to \nu\bar{\nu})$+jets.

Additional kinematic requirements are employed to ensure the control samples are enriched in the same SM processes that contribute to background events in the signal region, and are depleted in contributions from multijet production or a wide variety of SUSY models (i.e. so-called signal contamination). The samples are defined, and their events are identically categorised and binned, such that the kinematic properties of events in the control regions and the signal candidate events resemble as closely as possible one another once the photon, muon, or dimuon system is ignored in the calculation of quantities such as H_T and H_T^{miss}. The selections are summarised in Table 1 and described below.

The γ+jets event sample is defined by the common preselection requirements, but the photon veto is inverted and each event is required to contain a single isolated photon, as defined in Section 4, that satisfies $p_T > 200$ GeV and $|\eta| < 1.45$ and is well separated from each jet j_i in the event according to $\Delta R(\gamma, j_i) > 1.0$. In addition, events must satisfy $H_T > 400$ GeV, as well as the same H_T-dependent α_T requirements used to define the signal region. The events are recorded using a single-photon trigger condition and the selection criteria result in a trigger efficiency of $\gtrsim 99\%$.

The μ+jets event sample is defined by the common preselection requirements, but the muon veto is inverted and each event is required to contain a single isolated muon, as defined in Section 4, that satisfies $p_T > 30$ GeV and $|\eta| < 2.1$ and is well separated from each jet j_i in the event according to $\Delta R(\mu, j_i) > 0.5$. The transverse mass formed by the transverse momenta of the muon and $\vec{p}_T^{\text{miss}}$ system must satisfy $30 < m_T < 125$ GeV to select a sample of events rich in W bosons, produced promptly or from the decay of top quarks. The $\mu\mu$+jets sample uses a similar set of selection criteria as the μ+jets sample, but specifically requires two oppositely charged isolated muons that both satisfy $p_T > 30$ GeV and $|\eta| < 2.1$ and are well separated from the jets in the event ($\Delta R(\mu_{1,2}, j_i) > 0.5$). The muons are also required to have a dilepton invariant mass within a ± 25 GeV window around the nominal mass of the Z boson [21]. For both the muon and dimuon samples, no requirement is made on α_T in order to increase the statistical precision of the predictions from these samples. Both the μ+jets and $\mu\mu$+jets samples are recorded using a trigger that requires an isolated muon. The selection criteria of the μ+jets and $\mu\mu$+jets event samples are chosen so that the trigger is maximally efficient, with values in the region of $\sim 90\%$ and $\sim 99\%$, respectively.

6 Estimation of backgrounds

6.1 Multijet background

The signal region is defined in a manner that suppresses the expected contribution from multijet production to the percent level with respect to the total expected background from other SM processes for all signal region bins. This is achieved primarily through the application of very tight requirements on the variables α_T and $\Delta\phi^*_{\text{min}}$, as described in Section 5.3, as well as the requirement $H_T^{\text{miss}}/E_T^{\text{miss}} < 1.25$. In this section, we discuss these requirements further, and present the estimate of the suppression of the multijet background.

The contamination from multijet events in the signal region is estimated using a multijet-enriched data sideband to the signal region, defined by the (inverted) requirement $H_T^{\text{miss}}/E_T^{\text{miss}} > 1.25$. The observed counts in data, categorised according to n_{jet} and H_T, are corrected to account for contamination from nonmultijet SM processes, and the corrected counts $\mathcal{N}^{\text{data}}(n_{\text{jet}}, H_T)$ are assumed to arise solely from QCD multijet production. The nonmultijet processes, which comprise vector boson and $t\bar{t}$ production and residual contributions from other SM processes, are estimated using the μ+jets control region, as described in Section 6.2.

Independent ratios $\mathcal{R}^{\text{QCD}}(n_{\text{jet}}, H_T)$ of the number of multijet events that satisfy the requirement $H_T^{\text{miss}}/E_T^{\text{miss}} < 1.25$ to the number that fail are determined from simulation for events categorised according to n_{jet} and H_T, and inclusively with respect to n_b and H_T^{miss}. The product of each ratio $\mathcal{R}^{\text{QCD}}(n_{\text{jet}}, H_T)$ and the corresponding corrected data count $\mathcal{N}^{\text{data}}(n_{\text{jet}}, H_T)$ provides the estimate of the multijet background $\mathcal{P}(n_{\text{jet}}, H_T)$. The distributions of the predicted event counts $\mathcal{P}(n_{\text{jet}}, H_T)$ as a function of n_b and H_T^{miss} are implemented with the multiplier terms $\mathcal{K}_{n_{\text{jet}}, H_T}(n_b, H_T^{\text{miss}})$, and are assumed to be identical to the distributions expected for the nonmultijet backgrounds. This final assumption is based on studies in simulation and is a valid
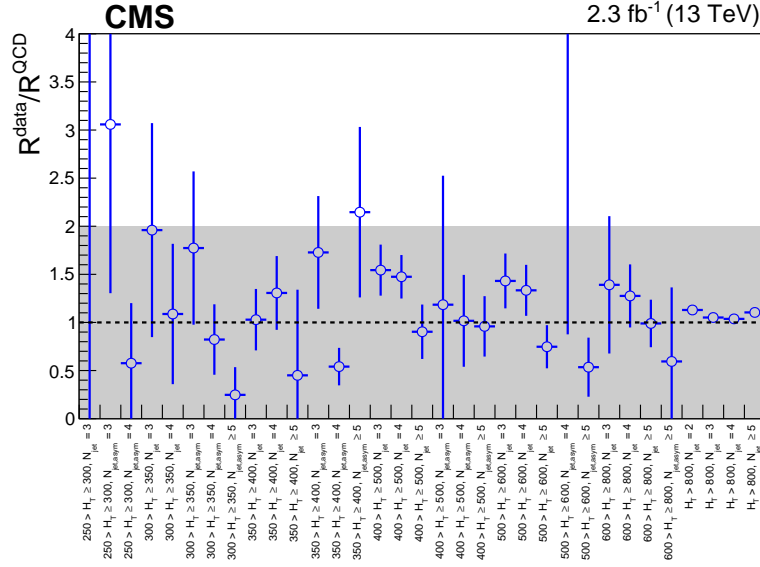
Figure 2: Validation of the ratio $\mathcal{R}^{QCD}$ determined from simulation in bins of n_{jet} and H_T by comparing with an equivalent ratio $\mathcal{R}^{data}$ constructed from data in a multijet-enriched sideband to the signal region. A value of unity is expected for the double ratio $\mathcal{R}^{data}/\mathcal{R}^{QCD}$, and the grey shaded band represents the assumed systematic uncertainty of 100% in $\mathcal{R}^{QCD}$.

approximation given the magnitude of the statistical and systematic uncertainties in the ratios $\mathcal{R}^{QCD}(n_{jet}, H_T)$, as described below. Assuming i, j, k, and l are the bin indices for, respectively, n_{jet}, H_T, n_b, and H_T^{miss}:

$$\mathcal{P}(i,j,k,l) = \mathcal{N}^{data}(i,j) \, \mathcal{R}^{QCD}(i,j) \, \mathcal{K}_{i,j}(k,l). \tag{5}$$

The use of simulation to determine $\mathcal{R}^{QCD}(n_{jet}, H_T)$ is validated using a multijet-enriched data sideband defined by $\Delta\phi_{min}^* < 0.5$. Each ratio $\mathcal{R}^{data}(n_{jet}, H_T)$ is constructed from data counts, corrected to account for contributions from nonmultijet processes, and compared with the corresponding ratio $\mathcal{R}^{QCD}(n_{jet}, H_T)$, determined from simulation, through the double ratio $\mathcal{R}^{data}/\mathcal{R}^{QCD}$, as shown in Fig. 2. The double ratios are observed to be close to, or statistically compatible with, unity across the full phase space of the signal region, including the bins at high H_T, which exhibit the highest statistical precision. In addition to statistical uncertainties as large as $\sim 100\%$, a systematic uncertainty of 100% in $\mathcal{R}^{QCD}$ is assumed to adequately cover the observed level of agreement for the full signal region phase space, as well as any limitations in the assumptions concerning $\mathcal{K}_{n_{jet}, H_T}(n_b, H_T^{miss})$ for all event categories defined in terms of n_{jet} and H_T.

6.2 Backgrounds with genuine E_T^{miss}

Following the suppression of multijet events through the use of the α_T and $\Delta\phi_{min}^*$ variables, the dominant nonmultijet backgrounds involve SM processes that produce high-p_T neutrinos in the final state. In events with few jets or few b quark jets, the associated production of W or Z bosons and jets, with the decays $W^\pm \to \ell\nu$ ($\ell = e, \mu, \tau$) or $Z \to \nu\bar{\nu}$, dominate the background counts. For W boson decays that yield an electron or muon (possibly originating from leptonic τ decays), the background contributions result from events containing an e or μ that are not rejected by the lepton vetoes. The veto of events containing at least one isolated track further

suppresses these backgrounds, including those from single-prong τ-lepton decays. At higher jet or b-quark jet multiplicities, single top quark and $t\bar{t}$ production, followed by semileptonic top quark decay, also become an important source of background.

The method to estimate the nonmultijet backgrounds in the signal region relies on the use of a transfer ($\mathcal{T}$) factor determined from simulation that is constructed per bin (in terms of n_{jet}, n_{b}, and H_{T}) per control region. Each $\mathcal{T}$ factor is defined as the ratio of the expected yields in the same (n_{jet}, n_{b}, H_{T}) bins of the signal region $\mathcal{N}_{\text{MC}}^{\text{SR}}$ and one of the control regions $\mathcal{N}_{\text{MC}}^{\text{CR}}$. The $\mathcal{T}$ factors are used to extrapolate from the event yields observed in each bin of a data control sample $\mathcal{N}_{\text{data}}^{\text{CR}}$ to provide an estimate for the background, integrated over $H_{\text{T}}^{\text{miss}}$, from a particular SM process or processes in the corresponding bin of the signal region $\mathcal{N}_{\text{data}}^{\text{SR}}$. The superscript SR or CR refers to, respectively, the process or processes being estimated and one of the μ+jets, $\mu\mu$+jets, and γ+jets control regions, described in Section 5.5. The subscript refers to whether the counts are obtained from data, simulation ("MC"), or an estimate ("pred").

The method aims to minimise the effects of simulation mismodelling, as many systematic biases in the simulation are expected to largely cancel in the $\mathcal{T}$ factors, given that the events in any given (n_{jet}, n_{b}, H_{T}) bin of the control regions closely mirror those in the corresponding bin in the signal region in terms of the event scale, topology, and kinematics, and the relative background compositions. In short, minimal extrapolations are made. Uncertainties in the $\mathcal{T}$ factors are determined from data, as described below.

Three independent estimates of the irreducible background of $Z \to \nu\bar{\nu}$ + jets events are determined from the γ+jets, $\mu\mu$+jets, and μ+jets data control samples. The γ+jets and $Z \to \mu\mu$ + jets processes have similar kinematic properties when the photon or muons are ignored [90], albeit different acceptances. In addition, the γ+jets process has a larger production cross section than $Z \to \nu\bar{\nu}$ + jets events. The μ+jets data sample is used to provide an estimate for both the $Z \to \nu\bar{\nu}$ + jets background, as well as the other dominant SM processes, $t\bar{t}$ and W boson production (labelled collectively as W/$t\bar{t}$). Residual contributions from all other SM relevant processes, such as single top quark, diboson, and Drell–Yan production, are also included as part of the W/$t\bar{t}$ estimate from the μ+jets sample. The definition of the various $\mathcal{T}$ factors used in the search are given below:

$$\mathcal{N}_{\text{pred}}^{\text{W}/t\bar{t}} = \mathcal{T}_{\mu+\text{jets}}^{\text{W}/t\bar{t}} \, \mathcal{N}_{\text{data}}^{\mu+\text{jets}}, \qquad \mathcal{T}_{\mu+\text{jets}}^{\text{W}/t\bar{t}} = \left(\frac{\mathcal{N}_{\text{MC}}^{\text{W}/t\bar{t}}}{\mathcal{N}_{\text{MC}}^{\mu+\text{jets}}} \right); \qquad (6)$$

$$\mathcal{N}_{\text{pred}}^{Z \to \nu\bar{\nu}} = \mathcal{T}_{\mu+\text{jets}}^{Z \to \nu\bar{\nu}} \, \mathcal{N}_{\text{data}}^{\mu+\text{jets}}, \qquad \mathcal{T}_{\mu+\text{jets}}^{Z \to \nu\bar{\nu}} = \left(\frac{\mathcal{N}_{\text{MC}}^{Z \to \nu\bar{\nu}}}{\mathcal{N}_{\text{MC}}^{\mu+\text{jets}}} \right); \qquad (7)$$

$$\mathcal{N}_{\text{pred}}^{Z \to \nu\bar{\nu}} = \mathcal{T}_{\mu\mu+\text{jets}}^{Z \to \nu\bar{\nu}} \, \mathcal{N}_{\text{data}}^{\mu\mu+\text{jets}}, \qquad \mathcal{T}_{\mu\mu+\text{jets}}^{Z \to \nu\bar{\nu}} = \left(\frac{\mathcal{N}_{\text{MC}}^{Z \to \nu\bar{\nu}}}{\mathcal{N}_{\text{MC}}^{\mu\mu+\text{jets}}} \right); \qquad (8)$$

$$\mathcal{N}_{\text{pred}}^{Z \to \nu\bar{\nu}} = \mathcal{T}_{\gamma+\text{jets}}^{Z \to \nu\bar{\nu}} \, \mathcal{N}_{\text{data}}^{\gamma+\text{jets}}, \qquad \mathcal{T}_{\gamma+\text{jets}}^{Z \to \nu\bar{\nu}} = \left(\frac{\mathcal{N}_{\text{MC}}^{Z \to \nu\bar{\nu}}}{\mathcal{N}_{\text{MC}}^{\gamma+\text{jets}}} \right). \qquad (9)$$

The likelihood function, described in Section 7, encodes the estimate via the $\mathcal{T}$ factors of the W/$t\bar{t}$ background, as well as the three independent estimates of the $Z \to \nu\bar{\nu}$ background, which are considered simultaneously.

Several sources of uncertainty in the $\mathcal{T}$ factors are evaluated. The most relevant effects are discussed below, and generally fall into one of two categories. The first category concerns un-

certainties in the "scale factor" corrections applied to simulation, which are determined using inclusive data samples that are defined by loose selection criteria, to account for the mismodelling of theoretical and experimental parameters. The second category concerns "closure tests" in data that probe various aspects of the accuracy of the simulation to model correctly the $\mathcal{T}$ factors in the phase space of this search.

The uncertainties in the $\mathcal{T}$ factors are studied for variations in scale factors related to the jet energy scale (that result in uncertainties in the $\mathcal{T}$ factors as large as $\sim 15\%$), the efficiency and misidentification probability of b quark jets (up to 5%), and the efficiency to identify well-reconstructed, isolated leptons (up to $\sim 5\%$). A 5% uncertainty in the total inelastic cross section, $\sigma_\mathrm{in} = 69.0 \pm 3.5\,\mathrm{mb}$ [91], is assumed and propagated through to the reweighting procedure to account for differences between the simulated measured pileup, which results in changes of up to $\sim 10\%$. The modelling of the transverse momentum of top quarks (p_T^t) is evaluated by comparing the simulated and measured p_T spectra of reconstructed top objects in $t\bar{t}$ events. Simulated events are reweighted according to scale factors that decrease from a value of ~ 1.2 to ~ 0.7, with uncertainties of ~ 10–20%, within the range $p_\mathrm{T}^\mathrm{t} < 400\,\mathrm{GeV}$. The systematic uncertainties in $\mathcal{T}_{\mu+\mathrm{jets}}^{\mathrm{W}/t\bar{t}}$ arising from variations in the p_T^t scale factors are typically small ($\lesssim 5\%$), due to the comparable phase space probed by the signal and control regions, while larger uncertainties ($\lesssim 20\%$) in $\mathcal{T}_{\mu+\mathrm{jets}}^{\mathrm{Z}\to\nu\bar{\nu}}$ are observed due to the potential for significant contamination from $t\bar{t}$ when using $\mathrm{W}(\to \ell\nu)$+jets to predict $\mathrm{Z}(\to\nu\bar{\nu})$+jets.

Table 3: Systematic uncertainties (in percent) in the transfer ($\mathcal{T}$) factors used in the method to estimate the SM backgrounds with genuine $\vec{p}_\mathrm{T}^\mathrm{miss}$ in the signal region. The quoted ranges provide representative values of the observed variations as a function of n_jet and H_T.

Systematic source	Uncertainty in $\mathcal{T}$ factor [%]			
	$\mathcal{T}_{\mu+\mathrm{jets}}^{\mathrm{W}/t\bar{t}}$	$\mathcal{T}_{\mu+\mathrm{jets}}^{\mathrm{Z}\to\nu\bar{\nu}}$	$\mathcal{T}_{\mu\mu+\mathrm{jets}}^{\mathrm{Z}\to\nu\bar{\nu}}$	$\mathcal{T}_{\gamma+\mathrm{jets}}^{\mathrm{Z}\to\nu\bar{\nu}}$
Scale factors (applied to simulation):				
Jet energy scale	< 15%	< 15%	< 10%	< 15%
b tagging eff & mistag rate	< 5%	< 5%	< 2%	< 2%
Lepton identification	2 − 5%	2 − 5%	2 − 5%	−
Pileup	< 10%	< 6%	< 4%	< 3%
Top quark p_T	< 5%	< 20%	< 4%	−
Closure tests:				
W/Z ratio	−	10 − 30%	−	−
Z/γ ratio	−	−	−	10 − 30%
W/$t\bar{t}$ composition	10 − 100%	−	−	−
W polarisation	5 − 50%	5 − 50%	−	−
α_T / $\Delta\phi_\mathrm{min}^*$	5 − 80%	5 − 80%	50 − 80%	−

The aforementioned systematic uncertainties, resulting from variations in scale factors, are summarised in Table 3, along with representative magnitudes. Each source of uncertainty is assumed to vary with a fully correlated behaviour across the full phase space of the signal and control regions.

The second category of sources of uncertainty are determined from sets of "closure tests" based on data control samples [34]. Each set uses the observed event counts in up to eight bins in H_T for each of the nine n_jet event categories in one of the three independent data control regions. These counts are used with the corresponding $\mathcal{T}$ factors, determined from simulation, to obtain a prediction $\mathcal{N}^\mathrm{pred}(n_\mathrm{jet}, H_\mathrm{T})$ of the observed yields $\mathcal{N}^\mathrm{obs}(n_\mathrm{jet}, H_\mathrm{T})$ in another control sample (or, in one case, n_b event category).

557 Each set of tests targets a specific (potential) source of bias in the simulation modelling that may
558 introduce an n_{jet}- or H_{T}-dependent source of systematic bias in the $\mathcal{T}$ factors [34]. Several sets of
559 tests are performed. The Z/γ ratio determined from simulation is tested against the same ratio
560 measured using $Z(\to \mu\mu)$+jets events and the γ+jets sample. The W/Z ratio is also probed
561 using the μ+jets and $\mu\mu$+jets samples, which directly tests the simulation modelling of vector
562 boson production, as well as the modelling of $t\bar{t}$ contamination in the μ+jets sample. A further
563 set probes the modelling of the relative composition between $W(\to \ell\nu)$+jets and $t\bar{t}$ events using
564 μ+jets events containing exactly zero or one more b-tagged jets, which represents a larger
565 extrapolation in relative composition than used in the search. The effects of W polarisation are
566 probed by using μ+jets events with a positively charged muon to predict those containing a
567 negatively charged muon. Finally, the accuracy of the modelling of the efficiencies of the α_{T}
568 and $\Delta\phi^*_{\text{min}}$ requirements are estimated using the μ+jets sample.

569 For each set of tests, the level of closure, $(\mathcal{N}^{\text{obs}} - \mathcal{N}^{\text{pred}})/\mathcal{N}^{\text{obs}}$, which considers only statistical
570 uncertainties, is inspected to ensure no statistically significant biases are observed as a function
571 of the nine n_{jet} categories or the eight H_{T} bins. In the absence of such a bias, the level of closure
572 is recomputed by integrating over either all monojet and asymmetric n_{jet} categories, or the
573 symmetric n_{jet} categories. The level of closure and its statistical uncertainty are combined in
574 quadrature to determine additional contributions to the uncertainties in the $\mathcal{T}$ factors. These
575 uncertainties are considered to be fully correlated between the monojet and asymmetric n_{jet}
576 categories or the symmetric n_{jet} categories, and fully uncorrelated between these two regions
577 in n_{jet} and H_{T} bins. If the closure tests use the $\mu\mu$+jets sample, the level of closure is determined
578 by additionally integrating over pairs of adjacent H_{T} bins. These uncertainties, derived from
579 the closure tests in data, are summarised in Table 3, along with representative magnitudes.
580 These uncertainties are the dominant contribution to the total uncertainty in the $\mathcal{T}$ factors, due
581 to the limited number of events in the data control regions.

582 As introduced in Section 5.4, templates are derived from simulation to predict the $H_{\text{T}}^{\text{miss}}$ distri-
583 butions of the background. The uncertainties in the $\mathcal{T}$ factors are used to constrain the normal-
584 isation of the $H_{\text{T}}^{\text{miss}}$ templates. The uncertainties in the $H_{\text{T}}^{\text{miss}}$ shape are discussed below.

585 The accuracy to which the simulation describes the $H_{\text{T}}^{\text{miss}}$ distributions is evaluated with re-
586 spect to data in each $(n_{\text{jet}}, n_{\text{b}}, H_{\text{T}})$ bin in each of the μ+jets, $\mu\mu$+jets, and γ+jets data control
587 regions. The level of agreement between data and simulation, defined in terms of the ratio of
588 observed and expected counts (from simulation) as a function of $H_{\text{T}}^{\text{miss}}$, is parameterised using
589 an orthogonal first-order polynomial, $f(x) = p_0 + p_1(\bar{x} - x)$, and described by two uncorre-
590 lated parameters, p_0 and p_1. A binned likelihood fit is performed in each $(n_{\text{jet}}, n_{\text{b}}, H_{\text{T}})$ bin of
591 each control region, and the best fit value p_1 and its uncertainty is used to determine the pres-
592 ence of biases dependent on $H_{\text{T}}^{\text{miss}}$. The pull of p_1 from a value of zero is defined as the best fit
593 value over its standard deviation, considering only statistical uncertainties associated with the
594 finite size of the data and simulated samples.

595 The lower bound of the final (open) bin in $H_{\text{T}}^{\text{miss}}$ is not more than 800 GeV and is bounded from
596 above by the upper bound of the H_{T} bin in question. The lower bound of the final $H_{\text{T}}^{\text{miss}}$ bin is
597 merged with lower bins if fewer than ten events in the data control regions are observed. If a
598 bin in $(n_{\text{jet}}, n_{\text{b}}, H_{\text{T}})$ contains fewer than ten events, the $H_{\text{T}}^{\text{miss}}$ template is not used. The merging
599 of bins is typically only relevant for event categories that satisfy $n_{\text{b}} \geq 2$.

600 The presence of systematic biases is evaluated at a statistical level by considering the distri-
601 bution of pulls obtained from each control region, which are consistent with statistical fluc-
602 tuations, with no indication of trends across the full phase space of each control region. The
603 p-values obtained from the fits are uniformly distributed.

⁶⁰⁴ The uncertainty in the H_T^{miss} modelling is extracted under the hypothesis of no bias. This is
⁶⁰⁵ done using the maximum likelihood (ML) values of the fit parameters to determine the statisti-
⁶⁰⁶ cal precision to which this hypothesis can be confirmed. The quadrature sum of the ML value
⁶⁰⁷ and its uncertainty for p_1 from each fit is used to define alternative templates that represent
⁶⁰⁸ $\pm 1\sigma$ variations to the nominal H_T^{miss} template. These alternative templates are encoded in the
⁶⁰⁹ likelihood function, as described in Section 7. The observed variations are compatible with the
⁶¹⁰ expected values obtained from studies relying only on simulated event samples. The uncer-
⁶¹¹ tainties in the final H_T^{miss} bin of the templates depend on the event category and H_T bin, and
⁶¹² are typically found to be in the range ~ 10–100%.

⁶¹³ The effect on the H_T^{miss} templates is determined under $\pm 1\sigma$ variations in the jet energy scale,
⁶¹⁴ the efficiency and misidentification probability of b quark jets, the efficiency to identify well-
⁶¹⁵ reconstructed, isolated leptons, the pileup reweighting, and the modelling of the top quark p_T.
⁶¹⁶ These effects are easily covered by the uncertainties determined from data, as described above,
⁶¹⁷ across the full phase space of the control regions, which mirror closely that of the signal region.

7 Results

⁶¹⁹ A model of the observations in all data samples, described by a likelihood function, is used to
⁶²⁰ obtain a prediction of the SM backgrounds and to test for the presence of new-physics signals
⁶²¹ if the signal region is included in the ML fit. The observation in each bin defined by the n_{jet}, n_b,
⁶²² H_T, and H_T^{miss} variables is modelled as a Poisson-distributed variable around the SM expecta-
⁶²³ tion and a potential signal contribution (assumed to be zero in the following discussion), where
⁶²⁴ the SM expectation is the sum over the estimated contributions from all background processes
⁶²⁵ according to the methods described in Section 6.

⁶²⁶ The nonmultijet backgrounds are related to the expected yields in the μ+jets, $\mu\mu$+jets, and $\gamma+$
⁶²⁷ jets control samples via the transfer factors derived from simulation, as described in Section 5.5.
⁶²⁸ Estimates of the contribution from multijet events in the signal region are determined according
⁶²⁹ to the method described in Section 6.1, and are included in the likelihood function.

⁶³⁰ The systematic uncertainties summarised in Table 3 are accommodated in the likelihood func-
⁶³¹ tion through the use of nuisance parameters, the measurements of which are assumed to follow
⁶³² a log-normal distribution. Alternative templates are used to describe the uncertainties in the
⁶³³ modelling of the H_T^{miss} variable. A vertical template morphing scheme [92] is used to inter-
⁶³⁴ polate between the nominal and alternative H_T^{miss} templates. A nuisance parameter controls
⁶³⁵ the interpolation, which is Gaussian distributed with a mean of zero and a standard deviation
⁶³⁶ of one, where ± 1 corresponds to the alternative templates for a $\pm 1\sigma$ variation in the uncer-
⁶³⁷ tainty. Each template is interpolated quadratically between $\pm 1\sigma$, and a linear extrapolation is
⁶³⁸ employed beyond these bounds.

⁶³⁹ The "pre-fit" result of this search, which considers the observations in the control regions only,
⁶⁴⁰ is summarised in Figs. 3–5 for, respectively, the monojet, asymmetric, and symmetric topolo-
⁶⁴¹ gies. The figures also show the significance of deviations observed in data with respect to the
⁶⁴² "pre-fit" SM expectations, expressed in terms of the total uncertainty in the SM expectations.
⁶⁴³ Figures 3–5 also summarise the pulls from the "post-fit" result, which is based on a ML fit to
⁶⁴⁴ observations in the signal region as well as the control regions.

⁶⁴⁵ The data are well described by the background-only hypothesis. A goodness-of-fit test, based
⁶⁴⁶ on a log likelihood ratio, is performed to quantify the degree of compatibility between the
⁶⁴⁷ observed yields and the expectations under the background-only hypothesis. The alternative
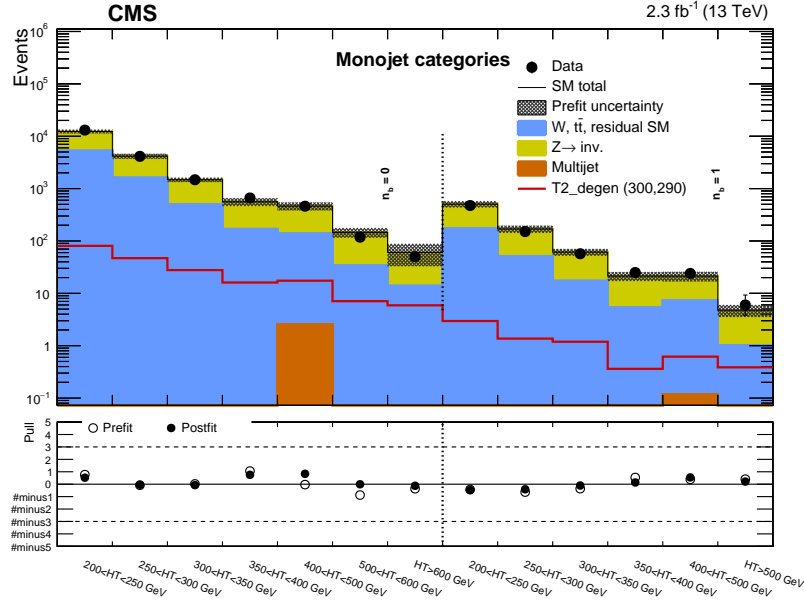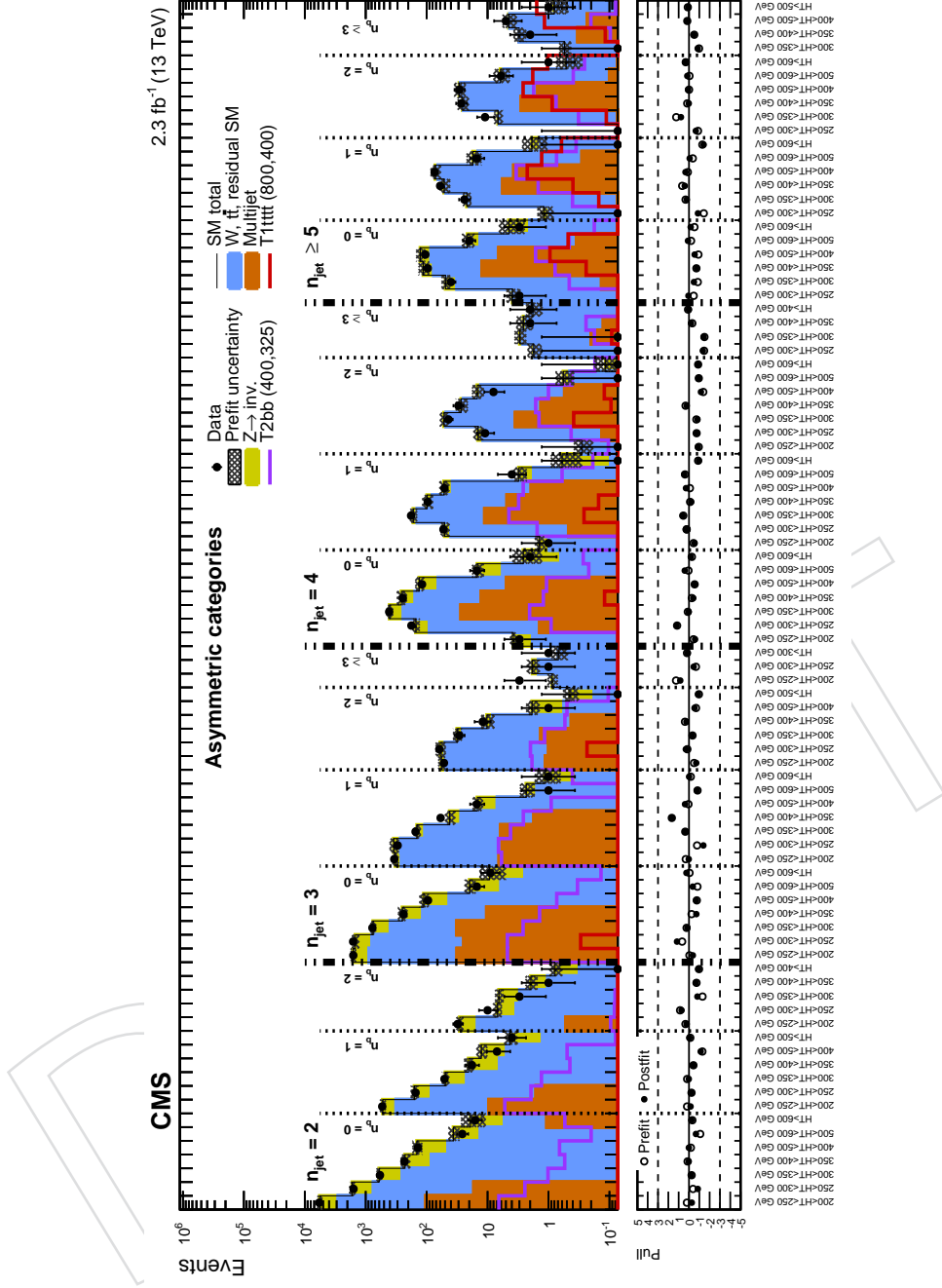
Figure 3: (Upper panel) Event yields observed in data (solid circles) and "pre-fit" SM expectations with their associated uncertainties (black histogram with shaded band), integrated over H_T^{miss}, as a function of n_b and H_T for the monojet category ($n_{jet} = 1$) in the signal region. For illustration only, the expectations for a benchmark model (T2tt_degen with $m_{\tilde{t}} = 300\,\text{GeV}$ and $m_{\tilde{\chi}_1^0} = 290\,\text{GeV}$) are superimposed on the SM-only expectations. (Lower panel) The significance of deviations (pulls) observed in data with respect to the "pre-fit" (open circles) and "post-fit" (closed circles) SM expectations, expressed in terms of the total uncertainty in the SM expectations. The pulls are indicative only and, due to inter-bin correlations, cannot be considered independently.

648 hypothesis is defined by a "saturated" model [93], for which the background expectation is
649 set equal to the observed number of events, and provides a reference for the largest value that
650 the likelihood can take for any model for the given data set. Hence, this reference can be used
651 as a reasonable normalisation for the maximum observed for a more constraining model. A
652 p-value of 0.20 is observed for the fit over the full signal region, and p-values in the range 0.04–
653 1.00, consistent with a uniform distribution, are obtained when considering events categorised
654 according to n_{jet}.

655 The covariance and correlation matrices for the pre-fit SM expectations in all bins of the signal
656 region, defined by n_{jet}, n_b, H_T, and integrated over H_T^{miss}, are determined from 500 pseudo-
657 experiments by sampling the pre-fit nuisance parameters under the background-only hypoth-
658 esis. The SM expectations for different n_{jet} and n_b categories exhibit a nonnegligible level of
659 covariance within the same H_T bin, primarily as a result of the systematic uncertainties eval-
660 uated from closure tests, described in Section 6.2, that integrate yields over n_{jet} and n_b. Bins
661 adjacent and next-to-adjacent in n_{jet} and/or n_b can have correlation coefficients in the range
662 0.2–0.4, and, infrequently, as large as ~ 0.5. Otherwise, the correlation coefficients are < 0.2.
663 Anticorrelation coefficients are typically not larger than ~ 0.2.

664 Figure 6 shows the event yields observed in data and "pre-fit" SM expectations with their
665 associated uncertainties as a function of H_T^{miss} for two categories of signal candidate events,
666 which provide good sensitivity to models with high-mass gluinos. For illustration only, the
667 expected counts from benchmark signal models that described the pair production and decay

Figure 4: (Upper panel) Event yields observed in data (solid circles) and "pre-fit" SM expectations with their associated uncertainties (black histogram with shaded band), integrated over H_T^{miss}, as a function of n_{jet}, n_b, and H_T for the "asymmetric" n_{jet} categories in the signal region. For illustration only, the expectations for two benchmark models (T2bb with $m_{\tilde{b}} = 400\,\text{GeV}$ and $m_{\tilde{\chi}_1^0} = 325\,\text{GeV}$, T1tttt with $m_{\tilde{g}} = 800\,\text{GeV}$ and $m_{\tilde{\chi}_1^0} = 400\,\text{GeV}$) are superimposed on the SM-only expectations. (Lower panel) The significance of deviations (pulls) observed in data with respect to the "pre-fit" (open circles) and "post-fit" (closed circles) SM expectations, expressed in terms of the total uncertainty in the SM expectations. The pulls are indicative only and, due to inter-bin correlations, cannot be considered independently.
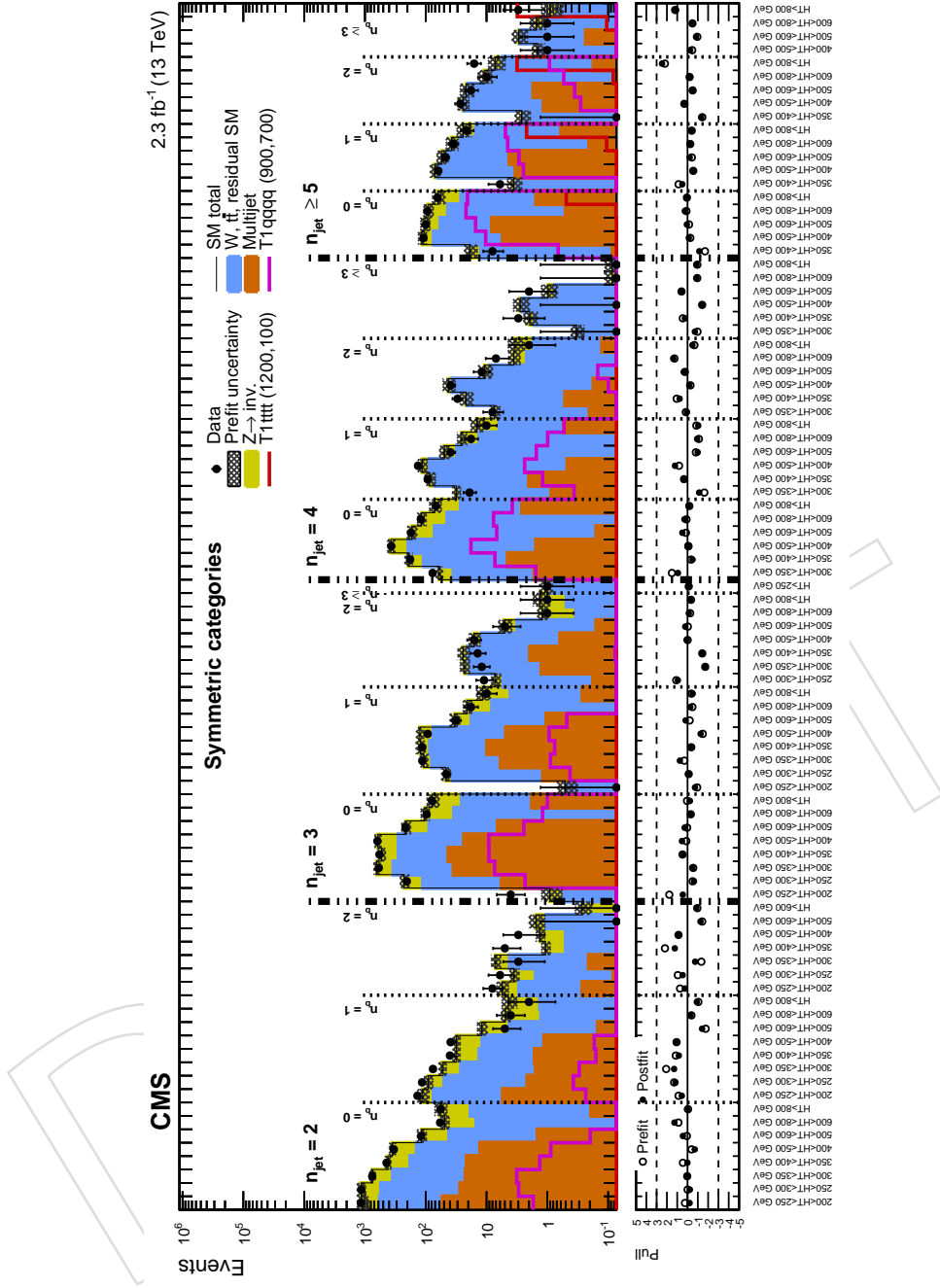
Figure 5: (Upper panel) Event yields observed in data (solid circles) and "pre-fit" SM expectations with their associated uncertainties (black histogram with shaded band), integrated over H_T^{miss}, as a function of n_{jet}, n_b, and H_T for the "symmetric" n_{jet} categories in the signal region. For illustration only, the expectations for two benchmark models (T1tttt with $m_{\tilde{g}} = 1200$ GeV and $m_{\tilde{\chi}_1^0} = 100$ GeV, T1qqqq with $m_{\tilde{g}} = 900$ GeV and $m_{\tilde{\chi}_1^0} = 700$ GeV) are superimposed on the SM-only expectations. (Lower panel) The significance of deviations (pulls) observed in data with respect to the "pre-fit" (open circles) and "post-fit" (closed circles) SM expectations, expressed in terms of the total uncertainty in the SM expectations. The pulls are indicative only and, due to inter-bin correlations, cannot be considered independently.
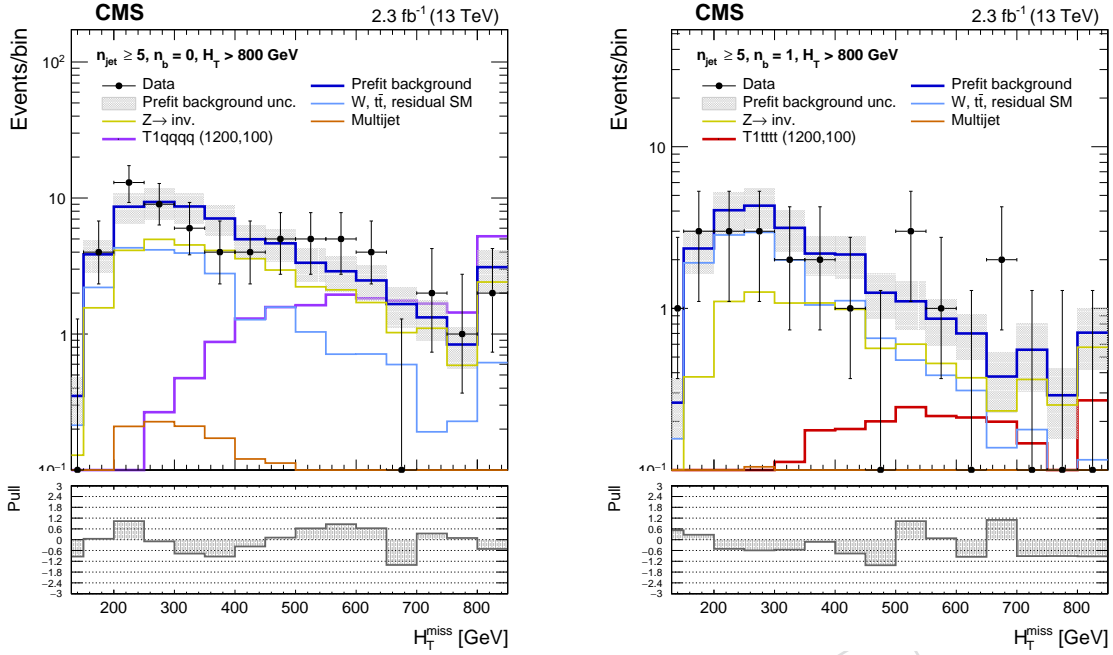
Figure 6: Event yields observed in data (solid circles) and "pre-fit" SM expectations with their associated uncertainties (blue histogram with shaded band) as a function of H_T^{miss} for events in the signal region that satisfy $n_{jet} \geq 5$, $H_T > 800\,\text{GeV}$, and (left) $n_b = 0$ or (right) $n_b = 1$. For illustration only, the expectations for one of two benchmark models (T1qqqq and T1tttt, both with $m_{\widetilde{g}} = 1200\,\text{GeV}$ and $m_{\widetilde{\chi}_1^0} = 100\,\text{GeV}$) are superimposed on the SM-only expectations. The lower panels indicate the significance of deviations (pulls) observed in data with respect to both the "pre-fit" SM expectations, expressed in terms of the total uncertainty in the SM expectations. The pulls are indicative only and, due to inter-bin correlations, cannot be considered independently.

668 of gluinos, described further in Section 8, are also shown.

8 Interpretation

8.1 Specification for simplified models

671 The results of the search are used to constrain simplified SUSY models [94–96]. Each model
672 assumes the pair production of gluinos or squarks and their subsequent prompt decays to SM
673 particles and the LSP ($\widetilde{\chi}_1^0$) with a 100% branching fraction (unless indicated otherwise). The
674 gluino decays contain intermediate on-shell SUSY particle states (such as the top squark, $\widetilde{t}$, or
675 the chargino, $\widetilde{\chi}_1^{\pm}$) for a subset of the models. All other SUSY particles are assumed to be too
676 heavy ($m_{\widetilde{g}}/m_{\widetilde{q}} = 10\,\text{TeV}$) to be produced directly. Three-body decays of gluinos are assumed to
677 occur via off-shell squarks of light or heavy flavour. Off-shell decays are processed by PYTHIA
678 in a single three- or four-body step, without taking into account the width or polarisation of the
679 parent: this is true for the top squark four-body decay ($\widetilde{t} \rightarrow bff'\widetilde{\chi}_1^0$), as well as the three-body
680 decay of the chargino ($\widetilde{\chi}_1^{\pm} \rightarrow ff'\widetilde{\chi}_1^0$), where f and f' are fermions produced in the decay of an
681 intermediate off-shell W boson.

682 Fourteen unique production and decay modes are considered, which yield a range of topolo-
683 gies and final states (with only the all-jet final state considered in this search). Each class of

simplified model is identified by a label that indicates the topology and final state, and scans in the gluino or squark ($m_{\widetilde{g}}/m_{\widetilde{q}}$) and LSP ($m_{\widetilde{\chi}_1^0}$) mass parameter space are performed. Table 4 summarises the production and decay modes, as well as any additional assumptions that define the simplified models. The models can be categorised according to the following descriptions: the gluino-mediated and direct production of light-flavour squarks, the gluino-mediated production of off-shell third-generation squarks, the "natural" gluino-mediated production of on-shell top squarks, and the direct production of on-shell third-generation squarks. In the case of direct pair production of light-flavour squarks, two different assumptions on the theoretical production cross section are made. For the "eightfold" scenario (T2qq_8fold), the scalar partners to left- and right-handed quarks of the u, d, s, and c flavours are assumed to be light and degenerate in mass, with other squark states decoupled to a high mass. For the "onefold" scenario (T2qq_1fold), only a single light squark is assumed to participate in the interaction and all other squarks are decoupled to a high mass.

Under the signal+background hypothesis, and in the presence of a nonzero signal contribution, a modified frequentist approach is used to determine upper limits at the 95% confidence level (CL) on the cross section, σ_{UL} (pb), to produce pairs of SUSY particles as a function of the parent SUSY particle and the LSP masses. The limits can be expressed in terms of the signal strength parameter, μ, which is determined relative to the theoretical cross section that is calculated at NLO+NLL accuracy. An Asimov data set [97] is used to determined the expected upper limit on the allowed cross section for a given model. The potential contributions from a new-physics signal to each of the signal and control regions are considered, even though the only significant contribution occurs in the signal region and not in the control regions (i.e. signal contamination). The approach is based on the one-sided (so called LHC-style) profile likelihood ratio as the test statistic [98] and the CL$_s$ criterion [99, 100]. Asymptotic formulae [97] are

Table 4: A summary of the simplified SUSY models used to interpret the results of this search. All on-shell SUSY particles in the decay are stated.

Model class	Production	Decay	Additional assumptions
Gluino-mediated and direct production of light-flavour squarks			
T1qqqq	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{q}q\widetilde{\chi}_1^0$	–
T2qq_8fold	$pp \to \widetilde{q}\bar{\widetilde{q}}$	$\widetilde{q} \to q\widetilde{\chi}_1^0$	$m_{\widetilde{q}} = m_{\widetilde{q}_L} = m_{\widetilde{q}_R}$, $\widetilde{q} = \{\widetilde{u}, \widetilde{d}, \widetilde{s}, \widetilde{c}\}$
T2qq_1fold	$pp \to \widetilde{q}\bar{\widetilde{q}}$	$\widetilde{q} \to q\widetilde{\chi}_1^0$	$m_{\widetilde{q}(\widetilde{q}\neq\widetilde{u}_L)} \gg m_{\widetilde{u}_L}$
Gluino-mediated production of off-shell third-generation squarks			
T1bbbb	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{b}b\widetilde{\chi}_1^0$	–
T1tttt	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{t}t^* \to \bar{t}t\widetilde{\chi}_1^0$	–
T1ttbb	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{t}b\widetilde{\chi}_1^\pm \to \bar{t}bW^*\widetilde{\chi}_1^0$	$m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} = 5\,\mathrm{GeV}$
Natural gluino-mediated production of on-shell top squarks			
T5tttt_DM175	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{\widetilde{t}}t \to \bar{t}t\widetilde{\chi}_1^0$	$m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = 175\,\mathrm{GeV}$
T5ttcc	$pp \to \widetilde{g}\widetilde{g}$	$\widetilde{g} \to \bar{\widetilde{t}}t \to \bar{t}c\widetilde{\chi}_1^0$	$m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = 20\,\mathrm{GeV}$
Direct production of on-shell third-generation squarks			
T2bb	$pp \to \widetilde{b}\bar{\widetilde{b}}$	$\widetilde{b} \to b\widetilde{\chi}_1^0$	–
T2tb	$pp \to \widetilde{t}\bar{\widetilde{t}}$	$\widetilde{t} \to t\widetilde{\chi}_1^0$ or $b\widetilde{\chi}_1^\pm \to bW^*\widetilde{\chi}_1^0$	50/50%, $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} = 5\,\mathrm{GeV}$
T2tt	$pp \to \widetilde{t}\bar{\widetilde{t}}$	$\widetilde{t} \to t\widetilde{\chi}_1^0$	–
T2cc	$pp \to \widetilde{t}\bar{\widetilde{t}}$	$\widetilde{t} \to c\widetilde{\chi}_1^0$	$10 < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < 80\,\mathrm{GeV}$
T2tt_degen	$pp \to \widetilde{t}\bar{\widetilde{t}}$	$\widetilde{t} \to bW^*\widetilde{\chi}_1^0$	$10 < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < 80\,\mathrm{GeV}$
T2tt_mixed	$pp \to \widetilde{t}\bar{\widetilde{t}}$	$\widetilde{t} \to c\widetilde{\chi}_1^0$ or $bW^*\widetilde{\chi}_1^0$	50/50%, $10 < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < 80\,\mathrm{GeV}$

Table 5: A summary of benchmark simplified models, the most sensitive n_{jet} categories, and representative values for the corresponding experimental acceptance times efficiency ($\mathcal{A} \times \varepsilon$), the dominant systematic uncertainties, the theoretical production cross section (σ_{theory}), and the expected and observed upper limits on the production cross section, expressed in terms of the signal strength parameter (μ).

Benchmark models ($m_{\text{SUSY}}, m_{\text{LSP}}$) [GeV]		Most sensitive n_{jet} categories	$\mathcal{A} \times \varepsilon$ [%]	Systematic uncertainties [%]				σ_{theory} [fb]	μ (95% CL)	
				MC stat.	ISR	JEC	$SF_{\text{b-tag}}$		Exp.	Obs.
T1qqqq	(1300, 100)	≥5, 4, 3, 2	9.4	7-30	~2	4-21	2-14	46.1	0.79	0.76
	(900, 700)	≥5, ≥5a, 4, 4a	5.6	10-33	1-13	1-26	1-10	677	0.58	0.44
T2qq_8fold	(1050, 100)	≥5, 3, 4, 2	17.9	7-33	1-4	3-16	1-11	35.2	0.90	0.63
	(650, 550)	≥5, 4, ≥5a, 4a	2.6	10-28	1-16	2-29	1-6	864	0.93	0.80
T2qq_1fold	(600, 50)	≥5, 3, 2, 4	13.4	5-33	1-5	1-30	1-8	177	0.78	0.84
	(400, 250)	≥5, 4, ≥5a, 3	2.9	8-30	1-8	3-25	1-7	1849	0.73	0.71
T1bbbb	(1500, 100)	≥5, 4, 3, 2	10.1	5-17	1-2	1-12	2-22	14.2	0.81	0.79
	(1000, 800)	≥5, 4, ≥5a, 4a	4.9	8-31	1-17	1-40	1-14	325	0.33	0.32
T1tttt	(1300, 100)	≥5, ≥5a, 4, 3	2.4	7-16	1-2	2-7	2-12	46.1	1.00	1.89
	(800, 400)	≥5, ≥5a, 4, 4a	0.6	7-27	1-2	3-45	1-8	1490	0.56	1.03
T1ttbb	(1300, 100)	≥5, 4, 3, ≥5a	3.8	9-32	1-2	3-16	2-19	46.1	0.60	0.91
	(1000, 700)	≥5, ≥5a, 4, 3	3.4	9-30	1-9	3-65	1-14	325	0.51	0.70
T5tttt_DM175	(800, 100)	≥5, ≥5a, 3, 4	0.2	12-20	2-4	3-5	1-6	1490	0.69	1.19
	(700, 400)	≥5, ≥5a, 4, 4a	0.2	20-29	2-10	8-10	1-2	3530	1.00	1.35
T5ttcc	(1200, 200)	≥5, 4, 3, ≥5a	4.9	6-25	5-25	3-21	1-24	85.6	0.58	0.87
	(750, 600)	≥5, ≥5a, 4, 4a	1.0	9-23	1-4	5-21	1-3	2270	0.89	0.72
T2bb	(800, 50)	2, 3, 4, ≥5	1.5	5-31	2-6	1-21	1-23	28.3	0.96	1.06
	(375, 300)	≥5, 4, 3a, 3	0.1	8-33	1-10	3-25	1-7	2610	0.67	0.87
T2tb	(600, 50)	≥5, 4, 3, 2	6.1	3-28	1-3	1-22	1-17	175	0.70	1.35
	(350, 225)	≥5, 4, 3, 3a	1.0	9-33	1-4	2-41	1-8	3790	0.79	0.88
T2tt	(700, 50)	≥5, 4, 3, ≥5a	8.1	8-33	1-4	2-22	1-21	67.0	0.90	1.19
	(350, 100)	≥5, ≥5a, 4a, 4	1.4	7-31	1-1	1-28	1-7	3790	0.44	0.50
T2cc	(325, 305)	≥5, 4, 3, 2	0.8	3-32	1-27	1-27	1-12	5600	0.92	0.68
T2_degen	(300, 290)	3, 4, ≥5, 2	0.9	2-27	1-27	1-25	1-12	8520	0.56	0.41
T2tt_mixed	(300, 250)	≥5, 4, ≥5a, 4a	0.4	3-33	1-27	1-33	1-13	8520	0.99	0.58

708 utilised to approximate the distributions of the test statistics under the SM background-only
709 and signal+background hypotheses.

710 ## 8.2 Acceptances and uncertainties

711 The experimental acceptance times efficiency ($\mathcal{A} \times \varepsilon$) and its uncertainty are evaluated indepen-
712 dently for each model class as a function of ($m_{\text{SUSY}}, m_{\text{LSP}}$). Table 5 summarises $\mathcal{A} \times \varepsilon$ for a num-
713 ber of benchmark models for which the search yields an expected exclusion ($\mu \lesssim 1$). For each
714 topology, typically two different pairs of parent SUSY particle and LSP masses ($m_{\text{SUSY}}, m_{\text{LSP}}$)
715 are chosen that are characterised by a large and a small (i.e. "compressed") difference in parent
716 SUSY particle and LSP masses. The four most sensitive event categories, defined in terms of
717 n_{jet}, are used to determine σ_{UL}. The categories used per benchmark model are listed in Table 5,
718 along with $\mathcal{A} \times \varepsilon$ determined for these four categories.

719 Contributions from several sources to the uncertainty in $\mathcal{A} \times \varepsilon$ are considered. Each source of
720 uncertainty is included in the likelihood function via alternative shapes to the nominal $H_{\text{T}}^{\text{miss}}$

templates evaluated from simulated signal events categorised according to n_{jet}, n_b, and H_T. Correlations are taken into account where appropriate, including those relevant to signal contamination in the control regions. The morphing scheme that interpolates between the nominal and alternative H_T^{miss} templates, described in Section 7, is also used for the simulated signal samples.

In addition to the uncertainty in the integrated luminosity of 2.7% [101], the following sources of uncertainty are dominant: the statistical uncertainty arising from the finite size of simulated signal samples, the modelling of ISR, the jet energy corrections (JEC) evaluated in simulation, and the modelling of scale factors applied to simulated event samples that correct for differences in the efficiency and misidentification probability of b-quark jets ($SF_{b\text{-}tag}$). The magnitude of each contribution depends on the model and the masses of the parent SUSY particle and LSP.

The $\mathcal{A} \times \varepsilon$ for models with small mass splittings (e.g. $m_{\widetilde{q}} - m_{\widetilde{\chi}_1^0} \lesssim m_t$) is due largely to ISR, the modelling of which is evaluated by comparing the simulated and measured p_T spectra of the system recoiling against the ISR jets in $t\bar{t}$ events, using the technique described in Ref. [102]. The uncertainty can be as large as $\sim$30%, and is the dominant systematic uncertainty for systems with a compressed mass spectrum. Uncertainties in the jet energy scale, as large as $\sim$40%, can also be dominant for models characterised by high jet multiplicities in the final state. The uncertainties in $SF_{b\text{-}tag}$ can be as large as $\sim$25%. Table 5 summarises these dominant contributions to the uncertainty in $\mathcal{A} \times \varepsilon$ for a range of benchmark models. Characteristic values for each model are expressed in terms of a range that is representative of the values across all bins of the signal region. The upper bound for each range may be subject to moderate statistical fluctuations.

Further uncertainties with subdominant contributions are considered on a similar footing. The uncertainties in the efficiency of identifying well-reconstructed, isolated leptons are considered, with a typical magnitude of $\sim$5% and treated as anticorrelated between the signal and control regions. The uncertainty of 5% in σ_{in} is propagated through to the reweighting procedure to account for differences between the simulated and measured pileup. Finally, uncertainties in the simulation modelling of the efficiencies of the trigger strategy employed by the search are typically <10%.

The choice of PDF set, or variations therein, predominantly affects $\mathcal{A} \times \varepsilon$ through changes in the p_T spectrum of the system recoil, which is covered by the ISR uncertainty, hence no additional uncertainty is adopted. Uncertainties in $\mathcal{A} \times \varepsilon$ due to variations in the renormalisation and factorisation scales are determined to be relatively small. In both cases, contributions to the uncertainty in the theoretical production cross section are considered.

8.3 Cross section and mass exclusions

Limits for each of the aforementioned benchmark models are summarised in Table 5, expressed in terms of μ. All benchmark models are expected to be excluded. The observed limits fluctuate around the expected μ values, with some models exhibiting a moderately weaker than expected limit.

Figures 7 and 8 summarise the disfavoured regions of the mass parameter space for the fourteen classes of simplified models. These regions are derived by comparing the upper limits on the measured fiducial cross section, corrected for the experimental $\mathcal{A} \times \varepsilon$, with the theoretical cross sections calculated at NLO+NLL accuracy in α_s [73]. The former cross section value is determined as a function of $m_{\widetilde{g}}$ or $m_{\widetilde{q}}$ and $m_{\widetilde{\chi}_1^0}$, while the latter has a dependence solely on $m_{\widetilde{g}}$ or $m_{\widetilde{q}}$. The exclusion of models is evaluated using observed data counts in the signal region
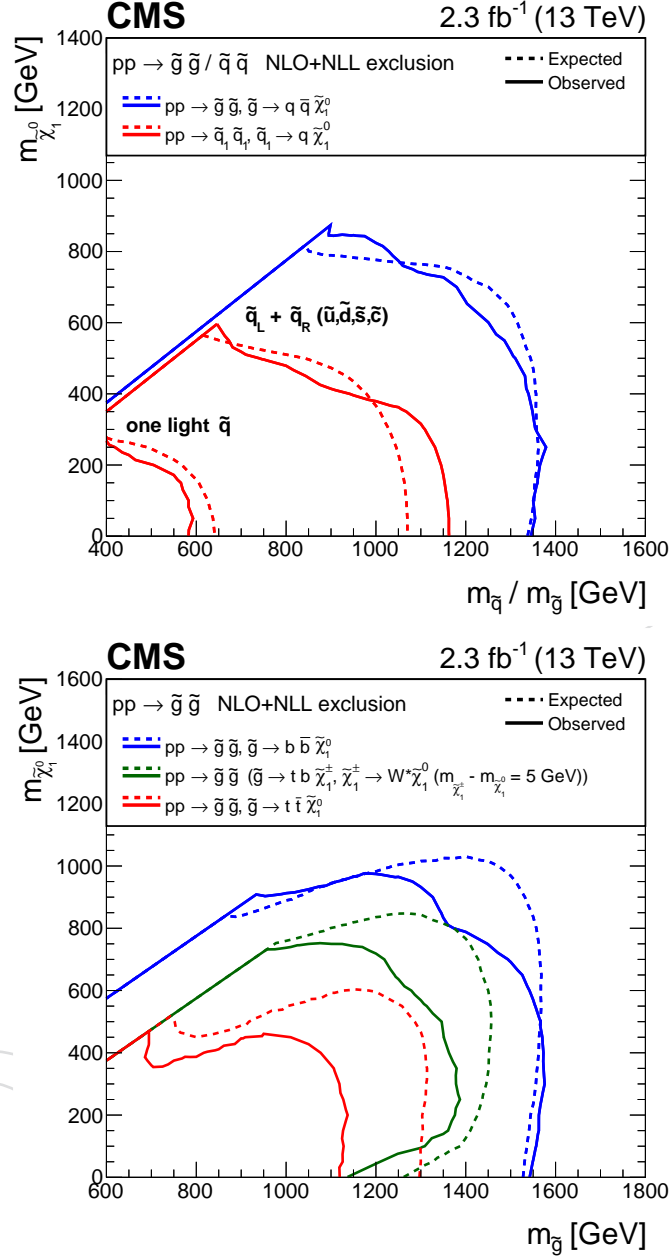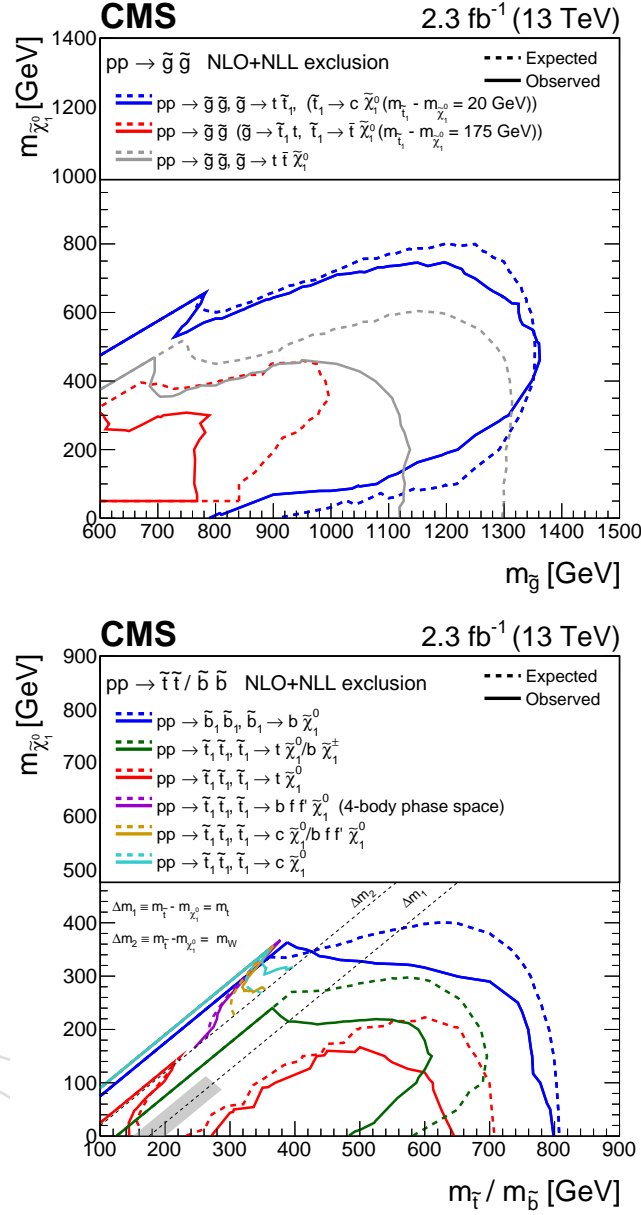
Figure 7: Observed and expected mass exclusions at 95% CL (indicated, respectively, by solid and dashed contours) for various classes of simplified models. (Upper) Gluino-mediated or direct pair production of light-flavour squarks. The two scenarios involve, respectively, the decay $\widetilde{g} \to \overline{q}q\widetilde{\chi}_1^0$ (T1qqqq) and $\widetilde{q} \to q\widetilde{\chi}_1^0$, and the latter involves two assumptions on the mass degeneracy of the squarks (T2qq_8fold and T2qq_1fold). (Lower) Three scenarios involving the gluino-mediated pair production of off-shell third-generation squarks: $\widetilde{g} \to \overline{b}b\widetilde{\chi}_1^0$ (T1bbbb), $\widetilde{g} \to \overline{t}t^* \to \overline{t}t\widetilde{\chi}_1^0$ (T1tttt), and $\widetilde{g} \to \overline{t}b\widetilde{\chi}_1^\pm \to \overline{t}bW^*\widetilde{\chi}_1^0$ (T1ttbb).

Figure 8: Observed and expected mass exclusions at 95% CL (indicated, respectively, by solid and dashed contours) for a number of simplified models. (Upper) Two scenarios involving the gluino-mediated pair production of on-shell top squarks: $\widetilde{g} \to \overline{t}t \to \overline{t}t\widetilde{\chi}_1^0$ with $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = 175\,\text{GeV}$ (T5tttt_DM175) and $\widetilde{g} \to \overline{t}t \to \overline{t}c\widetilde{\chi}_1^0$ with $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = 20\,\text{GeV}$ (T5ttcc). Also shown, for comparison, is T1tttt. (Lower) Six scenarios involving the direct pair production of third-generation squarks. The first scenario involves the pair production of bottom squarks, $\widetilde{b} \to b\widetilde{\chi}_1^0$ (T2bb). Two scenarios involve the decay of top squark pairs as follows: $\widetilde{t} \to t\widetilde{\chi}_1^0$ or $\widetilde{t} \to b\widetilde{\chi}_1^\pm \to bW^*\widetilde{\chi}_1^0$ with $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} = 5\,\text{GeV}$ and branching fractions 50/50% (T2tb), or $\widetilde{t} \to t\widetilde{\chi}_1^0$ (T2tt). The final three scenarios consider top squark decays under the assumption $10 < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < 80\,\text{GeV}$: $\widetilde{t} \to c\widetilde{\chi}_1^0$ (T2cc), $\widetilde{t} \to bW^*\widetilde{\chi}_1^0$ (T2tt_degen), and $\widetilde{t} \to c\widetilde{\chi}_1^0$ or $\widetilde{t} \to bW^*\widetilde{\chi}_1^0$ with branching fractions 50/50% (T2tt_mixed). The grey shaded region denotes T2tt models that are not considered for interpretation.

766 (solid contours) and also expected counts based on an Asimov data set (dashed contours).

767 Figure 7 (upper) shows the excluded mass parameter space for models that assume the gluino-
768 mediated or direct production of light-flavour squarks. The excluded region extends to higher
769 masses for the gluino-mediated production of light-flavour squarks (T1qqqq), with respect to
770 direct pair production when assuming an eightfold degeneracy in mass (T2qq_8fold), due to
771 a combination of a higher gluino pair production cross section and a final state characterised
772 by higher jet multiplicities, which are exploited to provide better signal-to-background sepa-
773 ration. The excluded mass region is significantly reduced when assuming only a single light
774 squark (T2qq_1fold), with limits weakening due to the lower production cross section, com-
775 pounded by the reduced signal-to-background ratios achieved in the core of distributions in
776 the discriminating variables.

777 Figure 7 (lower) shows the exclusion contours for models that assume the gluino-mediated
778 pair production of off-shell third-generation squarks. For the topologies T1tttt and T1bbbb,
779 each gluino is assumed to undergo a three-body decay via, respectively, an off-shell top or
780 bottom squark to a quark-antiquark pair of the same flavour and the $\widetilde{\chi}_1^0$. In the case of T1ttbb,
781 each gluino is assumed to undergo a three-body decay to an on-shell chargino, $\widetilde{\chi}_1^\pm$, a bottom
782 quark, and a top antiquark. The chargino mass is defined relative to the neutralino mass via
783 the expression $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} = 5\,\text{GeV}$. The chargino decays promptly to the $\widetilde{\chi}_1^0$ and an off-shell
784 W boson. The excluded mass regions differ significantly for these topologies, primarily due to
785 the different number of (on-shell) W bosons in their final states, resulting in the highest $\mathcal{A} \times \varepsilon$
786 for T1bbbb and lowest for T1tttt. Further, $\mathcal{A} \times \varepsilon$ has a strong dependence on jet multiplicity,
787 which is highest for T1tttt, due to the $\Delta\phi_{\text{min}}^*$ variable. An additional feature for T1ttbb is
788 the weakening of the mass limit at low values of $m_{\widetilde{\chi}_1^0}$, when $m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_1^0} + 5\,\text{GeV} \lesssim m_\text{t}$. In
789 this scenario, the $\widetilde{\chi}_1^\pm$ (and hence $\widetilde{\chi}_1^0$) is not highly Lorentz boosted relative to the top quark
790 resulting from the three-body decay of the gluino. Hence, two $\widetilde{\chi}_1^0$ SUSY particles do not carry
791 away significant $\vec{p}_\text{T}^{\text{miss}}$, which is instead realised through W boson decays to neutrinos and
792 "lost" leptons or τ leptons that decay to neutrinos and hadrons. The observed mass limits
793 for these topologies are up to $\sim$2 standard deviations weaker than the expected limits. These
794 differences are due to upward fluctuations in data for two contiguous bins that satisfy the
795 requirements $n_\text{jet} \geq 5$, $n_\text{b} \geq 2$, and $H_\text{T} > 800\,\text{GeV}$. This region has the highest sensitivity to
796 models involving gluino production and decays to third-generation quarks (via on- or off-shell
797 squarks). The observed counts are consistent with statistical fluctuations and the events do
798 not exhibit anomalous nonphysical behaviour. The events are distributed in H_T^{miss} consistent
799 with expectation, hence models characterised by high values of H_T^{miss}, such as T1bbbb with
800 $m_{\widetilde{g}} \gg m_{\widetilde{\chi}_1^0}$ or $m_{\widetilde{g}} \approx m_{\widetilde{\chi}_1^0}$, are less compatible with the data counts in this high-n_jet, n_b, and H_T
801 region.

802 Figure 8 (upper) shows exclusion contours for models that assume gluino pair production,
803 with each gluino decaying to a top quark and an on-shell top squark, the latter of which de-
804 cays to SM particles and the LSP, $\widetilde{\chi}_1^0$. As discussed earlier, these models can be considered as
805 representations of a "natural" solution to the little hierarchy problem. Two different scenarios
806 are considered for the decay of the top squarks. The T5tttt_DM175 models assume a two-
807 body decay to a top quark and the $\widetilde{\chi}_1^0$, with the top squark mass defined relative to the $\widetilde{\chi}_1^0$ as
808 $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = m_\text{t}$. Models that satisfy $m_{\widetilde{\chi}_1^0} < 50\,\text{GeV}$ are not considered here, as the $\widetilde{\chi}_0^0$ particles
809 carry very little momentum. The T5ttcc models assume $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} = 20\,\text{GeV}$ and two-body
810 decays to a charm quark and the $\widetilde{\chi}_1^0$.

811 Finally, Fig. 8 (lower) shows exclusion contours for models that assume the direct production
812 of pairs of third-generation squarks. For the T2bb models, bottom squarks are pair produced

and each decays to a bottom quark and the $\widetilde{\chi}_1^0$. The T2tt models assume top squarks are pair produced and each is assumed to undergo a two- or three-body decay to, respectively, a top quark and the $\widetilde{\chi}_1^0$ when $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} > m_t$ is satisfied, or a b quark, an on-shell W boson, and the $\widetilde{\chi}_1^0$ for the condition $m_W < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < m_t$. Models that satisfy $|m_{\widetilde{t}} - m_t - m_{\widetilde{\chi}_1^0}| < 25\,\text{GeV}$ and $m_{\widetilde{t}} + m_{\widetilde{\chi}_1^0} < 375\,\text{GeV}$ are not considered here, as σ_{UL} is a strong function of $m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0}$ in this low-$m_{\widetilde{t}}$ region, due to the high levels of signal contamination found in the μ+jets control region for models that resemble the $t\bar{t}$ background in terms of their topological and kinematic properties. The T2tb models also assume the pair production of top squarks, with each undergoing a two-body decay to either a top quark and the $\widetilde{\chi}_1^0$, or a bottom quark and the $\widetilde{\chi}_1^\pm$, with equal branching fractions of 50%. As for the T1ttbb models, the chargino mass is defined relative to the neutralino mass via the expression $m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0} = 5\,\text{GeV}$, and the chargino decays promptly to the $\widetilde{\chi}_1^0$ and an off-shell W boson. The excluded mass regions differ significantly for the T2bb, T2tb, and T2tt topologies, in an analogous way to the T1bbbb, T1ttbb, and T1tttt models described above. The difference in the mass exclusions is due primarily to the different number of (on-shell) W bosons in the final states, which affects $\mathcal{A} \times \varepsilon$ through the presence of leptons from the decay of the W boson. An additional feature for T2tb is the weakening of the mass limit at low values of $m_{\widetilde{\chi}_1^0}$, when $m_{\widetilde{\chi}_1^\pm} = m_{\widetilde{\chi}_1^0} + 5\,\text{GeV} \lesssim m_t$. Moderately weaker than expected mass limits are observed for all models involving two-body decays, which is traced to mild upward fluctuations in data for events satisfying $n_{\text{jet}} = 2$, $n_b = 2$, and $350 < H_T < 500\,\text{GeV}$.

Figure 8 (lower) also shows exclusion contours for models that assume the pair production of top squarks but a near-mass-degenerate system that satisfies $10\,\text{GeV} < m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0} < m_W$. Two decays of the top squark are considered. The T2cc and T2tt_degen models assume two- and four-body decays of the top squark to, respectively, a charm quark and the $\widetilde{\chi}_1^0$, or to $bf\bar{f}'\widetilde{\chi}_1^0$, where f and $\bar{f}'$ are fermions produced in the decay of an intermediate off-shell W boson. A third class of models, T2tt_mixed, assumes both these decay modes with an equal branching fraction of 50%. For T2cc, the excluded mass region is relatively stable as a function of the mass splitting $\Delta m = m_{\widetilde{t}} - m_{\widetilde{\chi}_1^0}$, with $\widetilde{t}$ masses excluded up to 400 GeV. For T2tt_degen, the excluded mass region is strongly dependent on Δm, weakening considerably for increasing values of Δm due to the increased momentum phase space available to leptons produced in the four-body decay. The T2tt_mixed models exhibit an intermediate behaviour. Mass limits for all three model classes converge for the smallest mass splitting considered, $\Delta m = 10\,\text{GeV}$, when the SM particles from the $\widetilde{t}$ decay are extremely soft and outside the experimental acceptance. An approximately contiguous mass exclusion limit is observed across the transition from the T2tt_degen four-body to the T2tt three-body decay of the $\widetilde{t}$, as the top quark moves on-shell. The excluded mass region weakens further as $\Delta m \to m_t$.

Table 6 summarises the strongest expected and observed excluded $m_{\widetilde{g}}$ or $m_{\widetilde{q}}$ and $m_{\widetilde{\chi}_1^0}$ masses for each class of simplified model.

9 Summary

An inclusive search for new-physics phenomena is reported, based on data from pp collisions at $\sqrt{s} = 13\,\text{TeV}$. The data are recorded with the CMS detector and correspond to an integrated luminosity of $2.3 \pm 0.1\,\text{fb}^{-1}$. The final states analysed contain one or more jets with large transverse momenta and a significant imbalance of transverse momentum, as expected from the production of massive coloured SUSY particles, each decaying to SM particles and the lightest stable, weakly-interacting, SUSY particle.

Table 6: Summary of the mass limits obtained for the fourteen classes of simplified models. The limits indicate the strongest observed and expected (in parentheses) mass exclusions in $\widetilde{g}$, $\widetilde{q}$, $\widetilde{b}$, $\widetilde{t}$, and $\widetilde{\chi}_1^0$. The quoted values have uncertainties of ± 25 and ± 10 GeV for models involving the pair production of, respectively, gluinos and squarks.

Model class	Parent SUSY particle	Best mass limit [GeV]	
		$\widetilde{g}/\widetilde{q}/\widetilde{b}/\widetilde{t}$	$\widetilde{\chi}_1^0$
T1qqqq	$\widetilde{g}$	1375 (1350)	875 (850)
T2qq_8fold	$\widetilde{q}$	1150 (1075)	600 (550)
T2qq_1fold	$\widetilde{q}$	575 (650)	275 (275)
T1bbbb	$\widetilde{g}$	1575 (1575)	975 (1025)
T1tttt	$\widetilde{g}$	1125 (1325)	475 (600)
T1ttbb	$\widetilde{g}$	1375 (1450)	750 (850)
T5tttt_DM175	$\widetilde{g}$	800 (1000)	300 (450)
T5ttcc	$\widetilde{g}$	1350 (1350)	700 (800)
T2bb	$\widetilde{b}$	800 (800)	360 (400)
T2tb	$\widetilde{t}$	610 (690)	240 (300)
T2tt (3-body)	$\widetilde{t}$	670 (720)	210 (240)
T2tt (2-body)	$\widetilde{t}$	280 (280)	200 (200)
T2cc	$\widetilde{t}$	400 (350)	310 (340)
T2tt_degen	$\widetilde{t}$	370 (360)	360 (350)
T2tt_mixed	$\widetilde{t}$	360 (350)	350 (340)

857 The sums of the standard model backgrounds are estimated from a simultaneous binned like-
858 lihood fit to the observed yields for samples of events categorised according to the number of
859 reconstructed jets, the number of jets identified as originating from b quarks, and the scalar
860 and the magnitude of the vector sums of the transverse momenta of jets. In addition to the
861 signal region, μ+jets, $\mu\mu$+jets, and γ+jets control regions are considered in the likelihood fit.
862 The observed yields are found to be in agreement with the expected contributions from stan-
863 dard model processes. The search result is interpreted in the mass parameter space of fourteen
864 simplified SUSY models that assume the pair production of gluinos or squarks and a range
865 of decay modes. The models cover scenarios that involve the gluino-mediated or direct pro-
866 duction or light- or heavy-flavour squarks, spectra with intermediate SUSY particle states and
867 nonunity branching fractions, "natural" spectra with gluinos and on-shell top squarks, and
868 nearly mass-degenerate spectra.

869 The increase in the centre-of-mass energy of the LHC, from 8 to 13 TeV, provides a significant
870 gain in sensitivity to heavy particle states such as gluinos. In the case of pair-produced gluinos,
871 each decaying via an off-shell b squark to the b quark and the LSP, models with masses up to
872 $\sim$1.6 and $\sim$1.0 TeV are excluded for, respectively, the gluino and LSP. These limits improve on
873 those obtained at $\sqrt{s} = 8$ TeV by, respectively, $\sim$250 and $\sim$300 GeV. In the case of direct pair
874 production, models with masses up to $\sim$800 and $\sim$350 GeV are excluded for, respectively, the b
875 squark and LSP. These mass limits are sensitive to the assumptions on the squark flavour and
876 the presence of intermediate states, such as charginos.

877 Finally, a comprehensive study of nearly mass-degenerate models involving top squark pair
878 production is performed. The two decay modes of the top squark are the loop-induced two-
879 body decay to the neutralino and one c quark, and the four-body decay to the neutralino, one
880 b quark, and an off-shell W boson. A third scenario is considered in which the two modes are
881 simultaneously open, each with a branching ratio of 50%. Masses of the top squark and LSP
882 up to, respectively, 400 and 360 GeV are excluded, depending on the decay modes considered.

In summary, the analysis provides sensitivity across a large region of the "natural" SUSY parameter space, as characterised by interpretations with several simplified models. In particular, these studies improve on existing limits for nearly mass-degenerate models involving the production of pairs of top squarks.

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