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Search for supersymmetry in events with one lepton and multiple jets exploiting the angular correlation between the lepton and the missing transverse momentum in proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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ABSTRACT

Results are presented from a search for supersymmetry in events with a single electron or muon and hadronic jets. The data correspond to a sample of proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$ with an integrated luminosity of $35.9\,\text{fb}^{-1}$, recorded in 2016 by the CMS experiment. A number of exclusive search regions are defined according to the number of jets, the number of b-tagged jets, the scalar sum of the transverse momenta of the jets, and the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. Standard model background events are reduced significantly by requiring a large azimuthal angle between the direction of the lepton and of the reconstructed W boson, computed under the hypothesis that all of the missing transverse momentum in the event arises from a neutrino produced in the leptonic decay of the W boson. The numbers of observed events are consistent with the expectations from standard model processes, and the results are used to set lower limits on supersymmetric particle masses in the context of two simplified models of gluino pair production. In the first model, where each gluino decays to a top quark–antiquark pair and a neutralino, gluino masses up to 1.8 TeV are excluded at the 95% CL. The second model considers a three-body decay to a light quark–antiquark pair and a chargino, which subsequently decays to a W boson and a neutralino. In this model, gluinos are excluded up to 1.9 TeV.

1. Introduction

Supersymmetry (SUSY) [1–8] is a promising extension of the standard model (SM) of particle physics. The addition of supersymmetric partners to the SM particles can lead to the suppression of quadratically divergent loop corrections to the mass squared of the Higgs boson [9]. Furthermore, in SUSY models with R-parity conservation [10], the lightest supersymmetric particle (LSP) can provide a dark matter candidate [11,12].

This paper presents a search for SUSY in the single-lepton channel using data recorded in 2016 by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$ of proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$. The analysis is an update of the search in Ref. [13], which was performed using the significantly smaller data sample collected by CMS in 2015. Similar searches were performed by the CMS and ATLAS experiments at $\sqrt{s} = 7\,\text{TeV}$ [14–16], 8 TeV [17–19], and 13 TeV [20–22].

The results are interpreted within the framework of simplified models [23–26] of gluino pair production in which the LSP is the lightest neutralino, $\widetilde{\chi}_1^0$, and the lepton is produced in the decay of a W boson that originates either from top-quark (t) or chargino ($\widetilde{\chi}_1^{\pm}$) decay. In the T1tttt model shown in Fig. 1 (upper), gluinos ($\widetilde{\text{g}}$) undergo three-body decays to $\text{t}\bar{\text{t}} + \widetilde{\chi}_1^0$. In the T5qqqqWW model shown in Fig. 1 (lower), the gluinos undergo three-body decays to a first- or second-generation quark–antiquark pair ($\text{q}\bar{\text{q}}'$) and a $\widetilde{\chi}_1^{\pm}$. The chargino is assumed to have mass $m_{\widetilde{\chi}_1^{\pm}} = 0.5(m_{\widetilde{\text{g}}} + m_{\widetilde{\chi}_1^0})$ and to decay to a $\widetilde{\chi}_1^0$ and a W boson.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel

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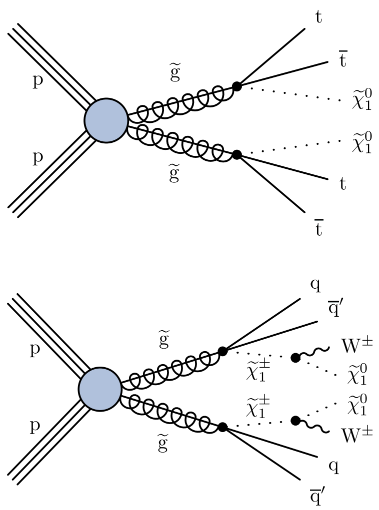

Fig. 1. Diagrams showing the simplified models (upper) T1tttt and (lower) T5qqqqWW.

and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [27]. In what follows, the azimuthal angle around the counterclockwise beam axis is denoted by ϕ.

3. Event reconstruction and simulation

The analysis makes use of the particle-flow event algorithm [28], which reconstructs and identifies each individual particle with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy.

The degree of isolation of a lepton from other particles provides a strong indication of whether it was produced within a jet, as would be expected from the fragmentation of a b quark, or in the leptonic decay of a W boson, which can be produced either directly or in decays of heavy particles such as the top quark. The isolation is characterized by the scalar sum of the transverse momenta (p_T) of all particles within a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton momentum vector, excluding the contribution of the lepton and the contribution of charged particles not associated with the primary interaction vertex. In the calculation of the isolation variable, an area-based correction is employed to remove the contribution of particles from "pileup" [29], i.e. additional proton–proton collisions within the same or neighboring bunch crossings. The isolation variable I_{rel} is defined as the ratio of the scalar sum of the p_T in the cone to the transverse momentum of the lepton, p_T^ℓ. To maintain high efficiency for signal events, which can contain a large number of jets from the SUSY decay chains, a cone radius that depends on p_T^ℓ, is used: $R = 0.2$ for $p_T^\ell < 50\,\text{GeV}$, $10/p_T^\ell\,[\text{GeV}]$ for $50 < p_T^\ell < 200\,\text{GeV}$, and 0.05 for $p_T^\ell > 200\,\text{GeV}$. This p_T dependent isolation definition additionally reduces the accidental overlap between jets and the lepton in regions where the SUSY decay products are boosted. Accepted muons and electrons are required to satisfy $I_{rel} < 0.2$ and $I_{rel} < 0.1$, respectively.

Jets are clustered using the anti-k_T algorithm [30] with a distance parameter of 0.4 [31], as implemented in the FastJet package [32]. The momentum of a jet, which is determined as the vectorial sum of all particle momenta in the jet, is found from simulation to be within 5 to 10% of the true momentum over the full p_T spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from pileup [29]. Jet energy corrections are derived from simulation and confirmed with in-situ measurements of the energy balance in dijet, Z+jets, and photon+jet events [33]. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions. They have negligible impact on the efficiency for signal events. Jets originating from b quarks are identified with an inclusive combined secondary vertex tagging algorithm (CSVv2) [34,35] that uses both secondary-vertex and track-based information. The working point is chosen to provide a b tagging efficiency of ≈63%, a c tagging efficiency of ≈12%, and a light-flavor and gluon misidentification rate of ≈0.9% for jets with $p_T > 20\,\text{GeV}$ in simulated $t\bar{t}$ events [35]. Double counting of objects is avoided by not considering jets that lie within a cone of radius 0.4 around a selected lepton. To avoid double counting of objects as both a lepton and a jet, jets that lie within a cone of radius $R = 0.4$ of a lepton are not considered.

The missing transverse momentum vector, $\vec{p}_T^{\,miss}$, is defined as the projection onto the plane perpendicular to the beam axis of the negative vector sum of the momenta of all reconstructed particle-flow objects in an event. Jet energy corrections are propagated to $\vec{p}_T^{\,miss}$. Its magnitude is referred to as p_T^{miss}.

To estimate corrections to transfer factors extracted from data, and to determine certain small backgrounds, Monte Carlo (MC) simulation is used. The leading-order (LO) event generators MadGraph5_amc@nlo v.2.2.2 or v.2.3.3 [36] are used to simulate $t\bar{t}$+jets, W+jets, $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ events, in the following referred to as DY+jets, and multijet events, in the following named QCD events. Events with a single top quark in the final state are generated using the next-to-leading order (NLO) powhegv2.0 and powheg programs [37–41] for the t-channel and tW production, respectively. The s-channel single-top process and the production of both $t\bar{t}W$ and $t\bar{t}Z$, commonly referred to as $t\bar{t}V$, are simulated using the NLO MadGraph5_amc@nlo v.2.2.2 generator [36]. The simulated background samples are normalized using the most accurate cross section calculations available [36,40–50], which generally correspond to NLO or next-to-NLO (NNLO) precision. All signal events are generated with MadGraph5_amc@nlo v.2.2.2, with up to two final-state partons in addition to the gluino pair. MadGraph5_amc@nlo uses the NNPDF3.0LO and the NNPDF3.0NLO PDF [51] for processes with LO or NLO accuracy, respectively. Gluino decays are based on a unit matrix element [52], with signal production cross sections computed at NLO with next-to-leading-logarithm (NLL) accuracy [53–57].

Several benchmarks SUSY models, corresponding to different scenarios for the gluino and neutralino masses, are used to study the kinematic properties of the signal and to illustrate the numbers of events expected from SUSY. The benchmarks are denoted by the model name and the two key parameters, namely $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$. As example, T1tttt(1.4, 1.1) corresponds to the T1tttt model with $m_{\tilde{g}} = 1.4\,\text{TeV}$ and $m_{\tilde{\chi}_1^0} = 1.1\,\text{TeV}$. A second benchmark, T1tttt(1.9, 0.1), is also used in this analysis. Similarly, two benchmark points are used to study the T5qqqqWW model: T5qqqqWW(1.9, 0.1) and T5qqqqWW(1.5, 1.0). For the two T5qqqqWW benchmark models, the mass of the intermediate chargino is taken to be 1.0 TeV and 1.25 TeV, respectively.

The evolution and hadronization of partons is performed using PYTHIA 8.212 [52] with the CUETP8M1 tune [58]. Pileup is generated for a nominal distribution in the number of pp interactions per bunch crossing, which is subsequently reweighted to match the corresponding distribution observed in data. The detector response for all backgrounds is modeled using a detailed simulation based GEANT4 [59], while a fast simulation program [60] is used to reduce computation time for signal events. The fast simulation has been validated against detailed GEANT4-based simulations in reconstructed objects relevant to this search, and corresponding efficiency corrections based on data are applied to simulated background and signal events, respectively.

4. Trigger and event selection

This analysis requires events containing a loosely isolated electron or muon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and a scalar sum of the jet transverse momenta in the event, H_{T}, with values greater than 400 GeV at the trigger level. To maximize the overall efficiency, additional trigger paths were added requiring missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}} > 100$, 110, or 120 GeV), isolated leptons ($p_{\mathrm{T}} > 27\,\mathrm{GeV}$ for electrons and $p_{\mathrm{T}} > 24\,\mathrm{GeV}$ for muons) or leptons with no isolation requirement but with a higher p_{T} threshold ($p_{\mathrm{T}} > 105\,\mathrm{GeV}$ or $p_{\mathrm{T}} > 115\,\mathrm{GeV}$ for electrons and $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ for muons). The trigger efficiency is measured in control samples recorded either with single-lepton triggers or with triggers with a requirement on H_{T}. After applying the offline event selection requirements, an overall trigger efficiency of $(98 \pm 1)\%$ is observed for the electron channel and negligible inefficiency for the muon channel.

The event selection is similar to that presented in Ref. [13], with improvements as noted to enhance the sensitivity of the analysis. Leptons (electrons or muons) must satisfy $p_{\mathrm{T}} > 25\,\mathrm{GeV}$. Additional leptons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ that satisfy looser selection criteria of $I_{\mathrm{rel}} < 0.4$ are referred to as "veto" leptons. To reduce the contribution from standard model processes that produce higher lepton multiplicities, events with one or more veto leptons are rejected.

Jets are required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$ to be considered for the calculation of higher level quantities such as H_{T}, the number of jets (n_{jet}), and the number of b-tagged jets (n_{b}). A number of exclusive kinematic regions, denoted as "search bins", are defined according to n_{jet}, n_{b}, H_{T}, and the quantity $p_{\mathrm{T}}^{\ell} + p_{\mathrm{T}}^{\mathrm{miss}}$ (L_{T}). All search bins are required to contain at least five jets with the two highest-p_{T} jets satisfying $p_{\mathrm{T}} > 80\,\mathrm{GeV}$. Search bins with zero b-tagged jets, called "0-b", are mainly sensitive to the T5qqqqWW model, while search bins with at least one b-tagged jet, called "multi-b", are mainly sensitive to the T1tttt model. For the latter, the requirement on the number of jets is increased to six, since the presence of four top quarks results in an increased jet multiplicity in signal events.

To ensure that the analysis is sensitive both to signals with high $p_{\mathrm{T}}^{\mathrm{miss}}$ as well as with small $p_{\mathrm{T}}^{\mathrm{miss}}$ but with large lepton p_{T}, no explicit threshold on $p_{\mathrm{T}}^{\mathrm{miss}}$ is imposed. Instead, L_{T} is required to be $>250\,\mathrm{GeV}$. Because of the trigger requirements and the extensive jet activity expected in the chosen SUSY models, H_{T} is required to be $>500\,\mathrm{GeV}$.

An important background arises from $\mathrm{t\bar{t}}$+jets events in which both W bosons decay leptonically and one lepton does not fulfill the selection criteria for veto leptons. In an extension of the previous analysis [13], and to suppress this background, events containing at least one isolated high-p_{T} charged track are rejected in certain cases. The high-p_{T} track can arise from $\tau \to \nu_\tau +$hadron decays or muon or electron tracks of poor quality. The relative isolation of such tracks within a cone of $R = 0.3$ around the track candidate is required to be smaller than 0.1 or 0.2 for hadron or lepton particle-flow candidates, respectively. For events containing such isolated track candidates, the M_{T2} variable [61] is used:

$$M_{\mathrm{T2}}(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,t}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}) = \min_{\vec{p}_{\mathrm{T}}^{\,(1)}+\vec{p}_{\mathrm{T}}^{\,(2)}=\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}} \left\{ \max\left[M_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,(1)}), M_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\,t}, \vec{p}_{\mathrm{T}}^{\,(2)}) \right] \right\},$$

where $\vec{p}_{\mathrm{T}}^{\,t}$ and $\vec{p}_{\mathrm{T}}^{\,\ell}$ are the transverse momenta of the isolated track and the selected lepton respectively, and M_{T} is the transverse mass. The minimization runs over all possible splittings of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ assuming two lost massless particles, as in dileptonic $\mathrm{t\bar{t}}$ decays that contain two neutrinos. The isolated track with highest p_{T} and opposite charge relative to the selected lepton is chosen where $\vec{p}_{\mathrm{T}}^{\,t}$ is required to be $>5\,\mathrm{GeV}$. Events with a hadronic or leptonic isolated track with M_{T2} below 60 or 80 GeV, respectively, are rejected. This requirement removes approximately 40% of dilepton $\mathrm{t\bar{t}}$+jets events, while rejecting only 8–15% of the events in the SUSY benchmark models.

After these selections, the dominant remaining backgrounds are W+jets events in which the W boson decays leptonically, and $\mathrm{t\bar{t}}$+jets events in which one of the W bosons from the top quarks decays leptonically and the other W boson decays hadronically. Both backgrounds are suppressed by requiring a large azimuthal angle $\Delta\phi$ between the lepton and the presumed W boson. The transverse momentum of the leptonically decaying W boson is estimated as the sum of $\vec{p}_{\mathrm{T}}^{\,\ell}$ and $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ vectors. In background events from W+jets and $\mathrm{t\bar{t}}$+jets with a single W-boson's leptonic decay, the $\Delta\phi$ distribution falls sharply and has a maximum value determined by the mass and p_{T} of the W boson. In the SUSY models investigated here, $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ receives a large contribution from the two neutralino LSPs. As a consequence, large values of $\Delta\phi$ are possible and the resulting $\Delta\phi$ distribution in signal events is roughly uniform. The $\Delta\phi$ variable can therefore be used to define the search region (SR) as events with large $\Delta\phi$, while events with small $\Delta\phi$ constitute the control region (CR), which is used to estimate the SM background in the SR. For illustration, Fig. 2 shows the $\Delta\phi$ distributions in two tightened multi-b and 0-b search bins as defined in Table 6. The magnitude of the angle between the W boson and the lepton is inversely proportional to the W boson momentum, which at high p_{T} is approximated by L_{T}. Therefore, the $\Delta\phi$ threshold used in defining the SR varies between 0.5 and 1, depending on L_{T}.

The definitions of the search bins, along with the $\Delta\phi$ values selected for the SRs, are given in Tables 4 and 5 for the multi-b and 0-b analyses, respectively. The name convention assigns a letter to each n_{jet} and n_{b} category and a number from 0 up to 10 for each H_{T} and L_{T} selection. The multi-b and the 0-b analysis employ 39 and 28 search bins, respectively.

5. Background estimation

The method for estimating the background from SM processes is the same as the one presented in Ref. [13]. For completeness, a summary of the procedure is presented below.

The dominant backgrounds in all search bins arise from semi-leptonically decaying $\mathrm{t\bar{t}}$ and leptonic W+jets events. In each search bin, the number of background events in the SR, i.e. the yield of events at high $\Delta\phi$, is determined using the number of events in the CR, i.e. the events at low $\Delta\phi$, along with a transfer factor R_{CS} that relates the events observed in the CR, $N_{\mathrm{data}}(\mathrm{CR})$, to those expected in the SR, $N_{\mathrm{data}}(\mathrm{SR})$, as $R_{\mathrm{CS}} = N_{\mathrm{data}}(\mathrm{SR})/N_{\mathrm{data}}(\mathrm{CR})$.

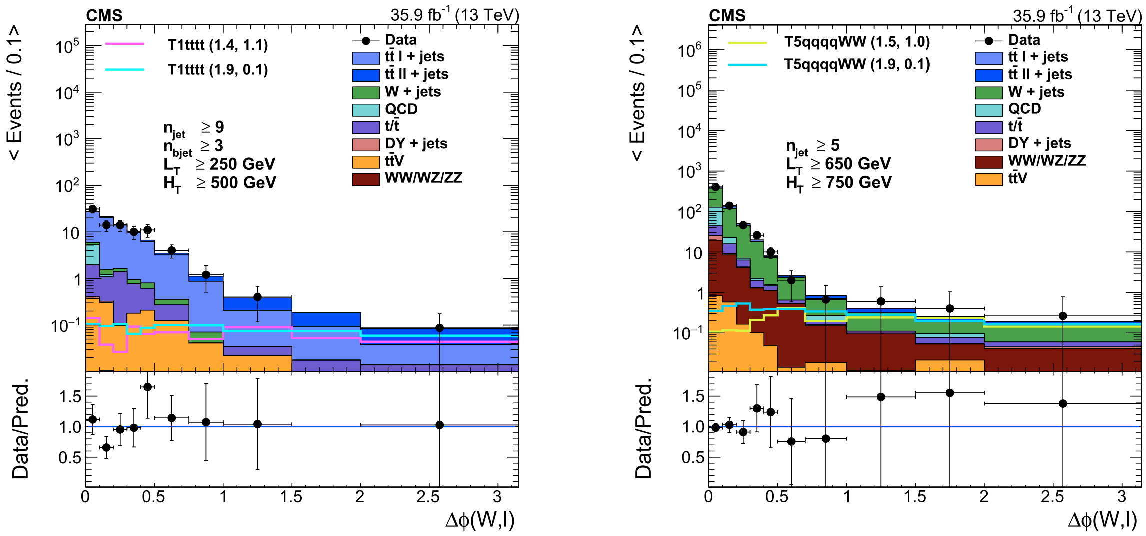

Fig. 2. Comparison of the $\Delta\phi$ distribution for (left) the multi-b and (right) the 0-b analysis for two of the search bins given in Table 6. The simulated background events are stacked on top of each other and several signal points are overlaid for illustration. The wider bins are normalized to a bin width of 0.1. The ratio of data to simulation is given in the lower panels. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

Table 1
Overview of the definitions of the various regions and samples employed in the analysis. For the QCD fit the electron (e) sample is used, while for the determination (det.) of $R_{CS}(W^{\pm})$ the muon (μ) sample is used. Regions corresponding to blank cells are not used in the analysis.

Analysis	Multi-b analysis		0-b analysis	
	$n_b = 0$	$n_b \geq 1$	$n_b = 0$	$n_b \geq 1$
$n_{jet} = 3$	QCD bkg. fit (e sample)		$R_{CS}(W^{\pm})$ det. (μ sample), QCD bkg. fit (e sample)	
$n_{jet} = 4$		R_{CS} det.		$R_{CS}(t\bar{t}$+jets) det.
$n_{jet} = 5$			search bins	
$n_{jet} \geq 6$		search bins		

This transfer factor is measured in kinematic regions in data with a lower number of jets, n_{jet}, where the contribution from the signal is negligible. Potential residual differences in transfer factors in the low- and high-n_{jet} regions are determined through simulation, where a correction factor, denoted by κ, is determined for each search bin as $\kappa = R_{CS}^{MC}(\text{high-}n_{jet})/R_{CS}^{MC}(\text{low-}n_{jet})$.

In the multi-b analysis, the regions with one b tag and four or five jets consist of approximately 80% $t\bar{t}$+jets and 15–20% W+jets and single top quark events. In all other multi-b regions the $t\bar{t}$ background is dominant. For this reason, only one transfer factor is calculated in the CRs with four or five jets to account for all backgrounds except QCD for each L_T, H_T and n_b range. This factor is then used to estimate the background in each SR of the search bins with $n_{jet} \in [6–8]$ or $n_{jet} \geq 9$. A single transfer factor is used for the $n_b \geq 2$ search bins with the same H_T and L_T, since these factors are found to be essentially independent of n_b.

In the 0-b search bins, the contributions from W+jets and $t\bar{t}$+jets are roughly equal, and a transfer factor for each background is determined in each of the search bins in n_{jet}, H_T, and L_T. The transfer factor for $t\bar{t}$+jets events is measured in data using events with $n_{jet} \in [4, 5]$ and $n_b \geq 1$. For W+jets events, the transfer factor is measured also in data in events with $n_{jet} \in [3, 4]$ and $n_b = 0$; the jet multiplicity used for W+jets is lower than in $t\bar{t}$+jets to limit the contamination from $t\bar{t}$+jets events. The relative contribution of the $t\bar{t}$+jets and W+jets components in the CR of each search bin is determined by a fit of the n_b multiplicity distribution in the CR of the high-n_{jet} regions, using templates of the n_b multiplicity distributions for W+jets and $t\bar{t}$+jets that are obtained from simulation. Additional backgrounds, including those from single top quark production, are found to be small and are taken from simulation.

About 10–15% of the SM background events in the electron channel CRs are expected to be QCD, and arise mainly from jets misidentified as electrons or from photon conversions in the tracker. In the SRs, however, the QCD background has been found to be negligible. It is estimated from data, using "antiselected" events in which the electrons fail the criteria for selected electrons but satisfy looser identification and isolation requirements. These events are scaled by the ratio of jets and photons that pass the tight electron-identification requirements to the number of antiselected electron candidates in a QCD-enriched sample that consists of no b-tagged jets and three or four jets. To account for the QCD background in the data, the QCD background is subtracted from the number of events in the CR in the calculation of the transfer factor R_{CS} as well as from the number of events in the CR in each search bin. The prediction of the number of events in the SR of each search bin is then defined as:

$$N_{pred}(SR) = R_{CS}\kappa \left[N_{data}^{high\text{-}n_{jet}}(CR) - N_{QCD\ pred}^{high\text{-}n_{jet}}(CR) \right].$$

The various (n_{jet}, n_b) regions employed in the analysis are described in Table 1.

6. Systematic uncertainties

The systematic uncertainties are divided into two categories: those that affect the estimate of the background from SM processes, and those that affect the expected signal yields.

The main systematic uncertainty on the background estimate arises from the uncertainty on the value of the transfer factor R_{CS}. The latter is measured in low-n_{jet} data but is then applied in the search bins that have higher jet multiplicities. The modeling of jets from initial-state radiation (ISR) is obtained from a data sample populated mainly by dilepton $t\bar{t}$+jets events. This sample is defined by two opposite-sign leptons (electrons or muons), excluding events with same-flavor leptons within a window of ± 10 GeV around the Z-boson mass, and two b-tagged jets, such that any other remaining jets are interpreted as ISR. In simulation, all jets that cannot be matched to daughter particles from the hard interaction are treated as ISR jets. The difference between the number of ISR jets observed and simulated is then used to reweigh simulated $t\bar{t}$+jets events in all analysis selections. The reweighting factors vary between 0.92 and 0.51 for N_J^{ISR} between 1 and 6. We take one half of the deviation from unity as the systematic uncertainty on these reweighting factors.

The presence of two neutrinos in dilepton $t\bar{t}$+jets events tends to produce larger angles between the lepton and the presumed W boson than in single-lepton $t\bar{t}$+jets events. As a result, the fraction of dilepton $t\bar{t}$+jets in which the second lepton does not pass the veto lepton requirements, is larger at high $\Delta\phi$ values, i.e. in the SR, than in the CR. This fraction as a function of n_{jet} must be described well in the simulation, as the differences in the transfer factors between the low-n_{jet} and high-n_{jet} events, i.e. the κ factors, are determined in simulation. This assumption is tested using dilepton events, selected as described in the previous paragraph and split into a 0-b and a multi-b category. To study the behavior of the background from dilepton events that remain in the single-lepton selection because of the loss of one lepton, one of the two leptons is removed from the event. Since in this type of background, the lost leptons arise principally from $\tau \to$ hadrons $+ \nu$ decays, and to account for the p_T^{miss} due to the neutrino from the τ decay, the lepton removed is replaced by a jet with 2/3 of the p_T of the original lepton and the L_T, $\Delta\phi$, and H_T values are recalculated for the resulting "single-lepton" event. To maximize the number of events in the dilepton $t\bar{t}$+jets control sample, no $\Delta\phi$ requirement is applied, and all events are used twice, with each reconstructed lepton considered as the lost lepton. The jet multiplicity in the single-lepton baseline selection (excluding the SR) is compared with that in the corresponding simulated event sample. In addition, the jet multiplicity in the dilepton $t\bar{t}$+jets control sample in data is compared with the corresponding simulated event sample. From these two comparisons a double-ratio is formed. The remaining differences in the double-ratio, which are of the order of 3–6% per n_{jet} bin, are corrected through the calculated κ factors, and propagated as a systematic uncertainty.

Uncertainties in the background estimate that also affect the signal arise from uncertainties in the jet energy scale (JES) [31], from uncertainties in the scale factors correcting the efficiencies and misidentification rate for b tagging [35], and from uncertainties in the reconstruction and identification efficiencies of leptons [62,63].

In each case, the systematic uncertainty in the background is estimated by changing the corresponding correction factors within their uncertainties. After each such change in the JES, the H_T and p_T^{miss} in each event are recalculated. Similarly, the uncertainty arising from pileup is estimated by varying the inelastic cross section by its 5% uncertainty [64].

The W+jets and $t\bar{t}$+jets cross sections are varied independently by 30% [65] to account for possible biases in the estimation of the background composition in terms of W+jets *vs.* $t\bar{t}$+jets events, which changes slightly the value of κ. These changes have only a small impact on the 0-b analysis, where the relative fraction of the two processes is determined from a fit. In the multi-b analysis, the differences in the κ values of less than 3% are propagated to the background estimates. The $t\bar{t}V$ cross section is varied by 100%. The systematic uncertainty in the QCD background depends on n_{jet} and n_b, and ranges from 25% up to 100% for the highest n_b region.

Table 2
Summary of systematic uncertainties in the total background estimates for the multi-b and for the 0-b analyses.

Source	Uncertainty for multi-b [%]	Uncertainty for 0-b [%]
Dilepton control sample	0.9–7.0	0.3–18
JES	0.3–18	0.7–26
Tagging of b jets	0.1–0.9	0.1–2.5
Mistagging of light flavor jets	0.1–2.2	0.3–0.8
σ(W+jets)	0.3–9.3	0.3–10
$\sigma(t\bar{t})$	0.1–7.5	0.7–13
$\sigma(t\bar{t}V)$	0.2–20	0.1–3.8
W polarization	0.1–3.3	0.7–14
ISR reweighting ($t\bar{t}$)	0.5–7.0	0.2–11
Pileup	0.4–7.1	0.1–20
Statistical uncertainty in MC events	5–30	5–36

Table 3
Summary of the systematic uncertainties and their average effect on the yields for the benchmark points defined in the text. The values, which are quite similar for the multi-b and the 0-b analyses, are usually larger for compressed scenarios, where the mass difference between the gluino and the lightest neutralino is small.

Source	Uncertainty [%]
Trigger	2
Pileup	10
Lepton efficiency	2
Isolated track veto	4
Luminosity	2.5
ISR	2–25
Tagging of b jets	1–6
Mistagging of light flavor jets	1–4
JES	3–40
Factorization/renormalization scale	1–3
p_T^{miss}	2–20

The polarization of W bosons is changed by reweighting events by the factor $w(\cos\theta^*) = 1 + \alpha(1 - \cos\theta^*)^2$, where θ^* is the angle between the charged lepton and W boson in the W boson rest frame. For W+jets events, we use $\alpha = 0.1$, guided by the measurements and theoretical uncertainties [66–69]. For $t\bar{t}$+jets events, we use $\alpha = 0.05$ [70–73]. For W+jets events, where the initial state can have different polarizations for W^+ and W^- bosons, the uncertainty is determined by the larger change in κ resulting from reweighting only the W^+ bosons in the sample, and from reweighting all W bosons.

For the 0-b analysis, an additional systematic uncertainty is based on linear fits of R_{CS} as a function of n_{jet} that are found to describe the dependence within statistical uncertainties. A 50% cross section uncertainty is used for all backgrounds other than W+jets, $t\bar{t}$+jets, $t\bar{t}V$, and QCD.

For the signal, an uncertainty in ISR is applied using the approach described previously for the reweighting of the distribution of ISR jets in $t\bar{t}$+jets as both, signal and $t\bar{t}$+jets, rely on MadGraph5_amc@nlo for event generation. Half of the correction is used as an estimate of the uncertainty as is propagated to the signal acceptance. To gauge their impact, the factorization and renormalization scales are changed up and down by a factor of 2.

Finally, the luminosity is measured using the pixel cluster counting method [74], with the absolute luminosity obtained using Van der Meer scans. The resulting uncertainty is estimated to be 2.5% [75].

The impact of the systematic uncertainties on the estimate of the total background in the multi-b and 0-b analyses is summarized in Table 2. While systematic uncertainties are determined for each signal point, typical values for most signals are summarized for illustration in Table 3.

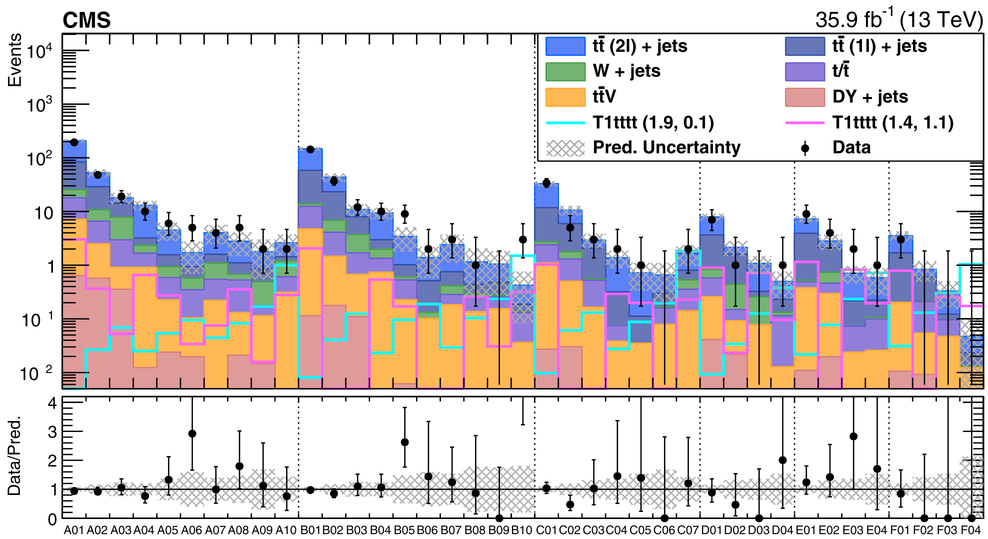

Fig. 3. Multi-b search: comparison of the numbers of events observed in the data and the numbers expected from the estimated SM backgrounds in the 39 search bins defined in the text, with details given in Table 4. Upper panel: the data are represented by black points with error bars, while the total SM background expected is shown as a hatched region that represents the uncertainty. For illustration, the relative fraction of the different SM background contributions determined in simulation is shown by the stacked, colored histograms, normalized so that their sum is equal to the background estimated using data control regions, as described in the text. The expected event yields for two T1tttt SUSY benchmark models are represented by the open histograms. Lower panel: the ratio of the number of events observed in data to the number of events expected from the SM background in each search bin. The error bars on the data points indicate the statistical uncertainty in the ratio, while the gray hatched region indicates the uncertainty on this ratio from the uncertainty in the background estimate.

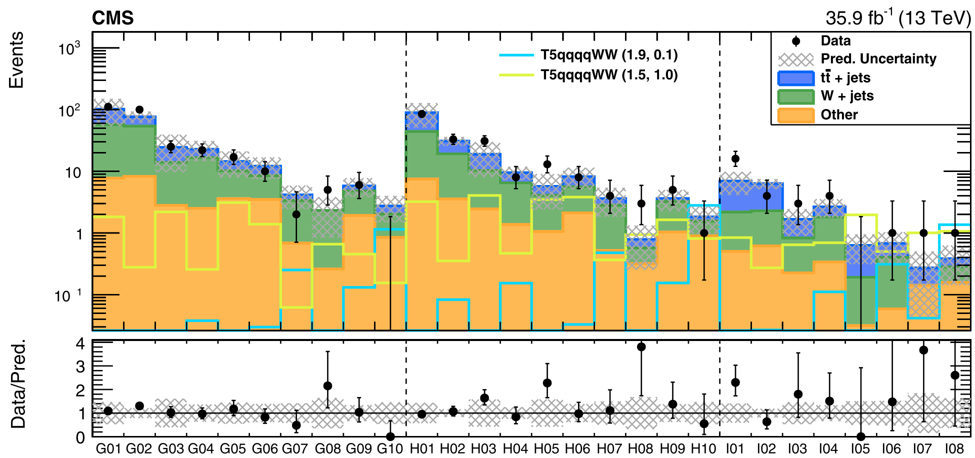

Fig. 4. 0-b search: comparison of the numbers of events observed in the data and the numbers expected from the estimated SM backgrounds in the 28 search bins defined in the text, with details given in Table 5. Upper panel: the data are represented by black points with error bars, while the total SM background expected is shown as a hatched region that represents the uncertainty. The filled, stacked histograms represent the predictions for $t\bar{t}$+jets, W+jets events, and the remaining backgrounds. The expected yields from two T5qqqqWW SUSY benchmark models are represented as solid lines. Lower panel: the ratio of the number of events observed in data to the number of events expected from the SM background in each search bin. The error bars on the data points indicate the statistical uncertainty in the ratio, while the gray hatched region indicates the uncertainty on this ratio from the uncertainty in the background estimate.

7. Results and interpretation

The data in the search regions are compared to the background estimates in Fig. 3 for the multi-b events, where the outline of the filled histogram represents the total estimated number of background events. For illustration, the expected composition of the background is shown, assuming the relative fractions of the different SM processes ($t\bar{t}$+jets, W+jets, and other backgrounds), as determinated from simulation.

Fig. 4 displays the estimates and data observed in the 0-b events. The filled histogram represents the estimates from data for $t\bar{t}$+jets and W+jets events and the remaining backgrounds, which include the QCD estimate determined from data and rare backgrounds determined from simulation.

To facilitate the reinterpretation of the results in terms of models not considered here, a comparison of the background estimates and the observed number of events in the SR of a few aggregated search bins is presented in Table 6. The results for all bins, compared to two benchmark points, are given in Tables 4 and 5 for the multi-b and 0-b analyses, respectively. The data agree with the expectations from the SM and no significant excess is observed.

The absence of any significant excess consistent with the SUSY signals considered in the analysis is used to set limits in the parameter space of the gluino and lightest neutralino masses. Separate likelihood functions, one for the multi-b analysis and one for the 0-b analysis, are constructed from the Poisson probability functions for the CR and SR at both high and low jet multiplicities. This includes the κ values that correct any residual differences in

Table 4
Definition of search bins and naming convention in the multi-b search. Also given are the $\Delta\phi$ values that are used to define the CRs and the SRs, the numbers of expected background events with combined statistical and systematic uncertainties, the observed numbers of events, and the expected numbers of signal events in the multi-b search bins.

n_{jet}	n_b	L_T [GeV]	$\Delta\phi$ [rad]	H_T [GeV]	Bin name	Signal T1tttt ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$) [TeV] (1.9, 0.1)	Signal T1tttt ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$) [TeV] (1.4, 1.1)	Predicted background	Observed data
[6, 8]	=1	[250, 450]	1.0	[500, 1000]	A01	<0.01	3.02 ± 0.24	206 ± 15	194
				[1000, 1500]	A02	0.03 ± 0.01	0.37 ± 0.08	52.5 ± 8.2	48
				≥1500	A03	0.07 ± 0.01	0.05 ± 0.03	18.0 ± 4.2	19
		[450, 600]	0.75	[500, 1000]	A04	0.03 ± 0.01	0.66 ± 0.11	13.1 ± 2.7	10
				[1000, 1500]	A05	0.05 ± 0.01	0.27 ± 0.07	4.5 ± 1.7	6
				≥1500	A06	0.09 ± 0.01	0.03 ± 0.02	1.7 ± 1.0	5
		[600, 750]	0.5	[500, 1000]	A07	0.04 ± 0.01	0.08 ± 0.04	4.0 ± 1.6	4
				[1000, 1500]	A08	0.08 ± 0.01	0.35 ± 0.08	2.8 ± 1.3	5
				≥1500	A09	0.17 ± 0.02	0.02 ± 0.02	1.8 ± 1.2	2
		≥750	0.5	≥500	A10	1.01 ± 0.04	0.28 ± 0.07	2.6 ± 1.1	2
	=2	[250, 450]	1.0	[500, 1000]	B01	0.01 ± 0.01	2.06 ± 0.20	147 ± 11	143
				[1000, 1500]	B02	0.04 ± 0.01	<0.01	43.5 ± 7.5	37
				≥1500	B03	0.13 ± 0.01	<0.01	10.9 ± 2.8	12
		[450, 600]	0.75	[500, 1000]	B04	0.02 ± 0.01	0.54 ± 0.10	9.4 ± 2.2	10
				[1000, 1500]	B05	0.10 ± 0.01	0.17 ± 0.06	3.4 ± 1.7	9
				≥1500	B06	0.19 ± 0.02	<0.01	1.39 ± 0.82	2
		[600, 750]	0.5	[500, 1000]	B07	0.03 ± 0.01	<0.01	2.4 ± 1.3	3
				[1000, 1500]	B08	0.10 ± 0.01	0.26 ± 0.07	1.16 ± 0.90	1
				≥1500	B09	0.24 ± 0.02	0.03 ± 0.02	1.05 ± 0.78	0
		≥750	0.5	≥500	B10	1.50 ± 0.05	0.32 ± 0.08	0.42 ± 0.34	3
	≥3	[250, 450]	1.0	[500, 1000]	C01	0.01 ± 0.01	1.03 ± 0.14	32.9 ± 3.3	34
				[1000, 1500]	C02	0.06 ± 0.01	<0.01	10.6 ± 2.1	5
				≥1500	C03	0.13 ± 0.01	<0.01	2.93 ± 0.91	3
		[450, 600]	0.75	[500, 1000]	C04	0.03 ± 0.01	0.29 ± 0.07	1.38 ± 0.50	2
				[1000, 1500]	C05	0.09 ± 0.01	0.20 ± 0.06	0.72 ± 0.39	1
				≥1500	C06	0.20 ± 0.02	<0.01	0.66 ± 0.45	0
		≥600	0.5	≥500	C07	1.85 ± 0.05	0.23 ± 0.06	1.66 ± 0.69	2
≥9	=1	[250, 450]	1.0	[500, 1500]	D01	0.01 ± 0.01	0.90 ± 0.12	7.9 ± 1.1	7
				≥1500	D02	0.03 ± 0.01	0.02 ± 0.02	2.15 ± 0.67	1
		≥450	0.75	[500, 1500]	D03	0.13 ± 0.01	0.72 ± 0.11	1.08 ± 0.39	0
				≥1500	D04	0.38 ± 0.02	0.10 ± 0.04	0.50 ± 0.27	1
	=2	[250, 450]	1.0	[500, 1500]	E01	0.02 ± 0.01	1.15 ± 0.14	7.26 ± 0.97	9
				≥1500	E02	0.08 ± 0.01	<0.01	2.81 ± 0.89	4
		≥450	0.75	[500, 1500]	E03	0.23 ± 0.02	0.83 ± 0.12	0.71 ± 0.26	2
				≥1500	E04	0.72 ± 0.03	0.20 ± 0.05	0.59 ± 0.31	1
	≥3	[250, 450]	1.0	[500, 1500]	F01	0.03 ± 0.01	0.79 ± 0.11	3.55 ± 0.72	3
				≥1500	F02	0.13 ± 0.01	<0.01	0.83 ± 0.35	0
		≥450	0.75	[500, 1500]	F03	0.31 ± 0.02	0.26 ± 0.06	0.33 ± 0.17	0
				≥1500	F04	1.04 ± 0.04	0.17 ± 0.05	0.05 ± 0.05	0

the R_{CS} transfer factors for regions with different jet multiplicities. As discussed previously, the values of κ are obtained from simulation, and their uncertainties are incorporated in the likelihood through log-normal constraints. The estimated contribution from QCD events in the CR is also included. A possible signal contamination, which can be up to 10% for the shown benchmark points, is taken into account by including signal terms in the likelihood for both the low-n_{jet} regions as well as for the low-$\Delta\phi$ CR of the search bins. For the 0-b analysis, the relative contributions from W+jets and $t\bar{t}$+jets events determined in the fits to the n_b distribution in the CR are treated as external measurements. The correlation between the W+jets and $t\bar{t}$+jets production that is introduced by such fits is also taken into account. A "profile" likelihood ratio is used as test statistic. The limits at the 95% confidence level (CL) are calculated using the asymptotic formulae [76] of the CL_s criterion [77,78].

The 95% CL upper limits on the cross sections, set in the T1tttt model using the multi-b analysis, and in the T5qqqqWW model using the 0-b analysis, are shown in Fig. 5. Using the $\tilde{g}\tilde{g}$ pair production cross section calculated at NLO within NLL accuracy, exclusion limits are provided as a function of the $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0})$ mass hypothesis for the data and for the simulation. For neutralino masses below 800 GeV, gluino masses up to 1.8 TeV are excluded at the 95% CL in the T1tttt model. Neutralinos are excluded up to 1.1 TeV for gluino masses below 1.7 TeV. In the T5qqqqWW model, gluino masses up to 1.9 TeV are excluded at the 95% CL for neutralino masses below 300 GeV. Neutralinos are excluded up to 950 GeV for gluino masses below 1.2 TeV.

8. Summary

A search for supersymmetry has been performed using a 35.9 fb^{-1} sample of proton–proton collisions at $\sqrt{s} = 13$ TeV, recorded by the CMS experiment in 2016. Several exclusive search bins are defined that differ in the number of jets, the number of b-tagged jets, the scalar sum of all jet transverse momenta as well as the scalar sum of the missing transverse momentum and the transverse momentum of the lepton. The main background processes, which arise from W+jets and $t\bar{t}$+jets in a final state with exactly one lepton and multiple jets, is reduced significantly by requiring a large azimuthal angle between the direction of the lepton and of the reconstructed W boson, computed under the hypothesis

Table 5
Definition of search bins and naming convention in the 0-b search. Also given are the $\Delta\phi$ values that are used to define the CRs and the SRs, the numbers of expected background events with combined statistical and systematic uncertainties, the observed numbers of events, and the expected numbers of signal events in the 0-b search bins.

n_{jet}	L_T [GeV]	$\Delta\phi$ [rad]	H_T [GeV]	Bin name	Signal T5qqqqWW ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$) [TeV] (1.5, 1.0)	(1.9, 0.1)	Predicted background	Observed data
5	[250, 350]	1.0	[500, 750]	G01	1.82 ± 0.29	<0.01	102 ± 48	111
			≥750	G02	0.21 ± 0.09	0.01 ± 0.01	77 ± 16	100
	[350, 450]	1.0	[500, 750]	G03	2.25 ± 0.32	<0.01	24 ± 15	25
			≥750	G04	0.29 ± 0.11	0.04 ± 0.01	22.8 ± 8.3	22
	[450, 650]	0.75	[500, 750]	G05	3.02 ± 0.37	<0.01	14.5 ± 6.5	17
			[750, 1250]	G06	1.40 ± 0.25	0.04 ± 0.02	12.1 ± 4.7	10
			≥1250	G07	0.08 ± 0.06	0.25 ± 0.04	4.2 ± 1.7	2
	≥650	0.5	[500, 750]	G08	0.74 ± 0.18	0.01 ± 0.01	2.3 ± 1.5	5
			[750, 1250]	G09	0.49 ± 0.15	0.12 ± 0.03	5.8 ± 2.0	6
			≥1250	G10	0.14 ± 0.07	1.15 ± 0.08	2.7 ± 1.3	0
[6, 7]	[250, 350]	1.0	[500, 1000]	H01	3.02 ± 0.36	<0.01	89 ± 38	85
			≥1000	H02	0.31 ± 0.10	0.09 ± 0.02	30.9 ± 5.1	33
	[350, 450]	1.0	[500, 1000]	H03	4.13 ± 0.41	0.01 ± 0.01	19 ± 11	31
			≥1000	H04	0.52 ± 0.14	0.14 ± 0.03	9.5 ± 2.3	8
	[450, 650]	0.75	[500, 750]	H05	3.63 ± 0.39	<0.01	5.7 ± 3.3	13
			[750, 1250]	H06	3.79 ± 0.39	0.03 ± 0.01	8.2 ± 3.2	8
			≥1250	H07	0.36 ± 0.12	0.47 ± 0.05	3.6 ± 1.8	4
	≥650	0.5	[500, 750]	H08	0.89 ± 0.19	<0.01	0.79 ± 0.53	3
			[750, 1250]	H09	1.77 ± 0.26	0.15 ± 0.03	3.6 ± 1.4	5
			≥1250	H10	0.83 ± 0.18	2.83 ± 0.12	1.83 ± 0.86	1
≥8	[250, 350]	1.0	[500, 1000]	I01	0.88 ± 0.18	<0.01	7.0 ± 2.8	16
			≥1000	I02	0.26 ± 0.09	0.03 ± 0.01	6.3 ± 1.2	4
	[350, 450]	1.0	[500, 1000]	I03	0.55 ± 0.14	<0.01	1.67 ± 0.77	3
			≥1000	I04	0.72 ± 0.15	0.11 ± 0.02	2.65 ± 0.89	4
	[450, 650]	0.75	[500, 1250]	I05	2.07 ± 0.26	0.01 ± 0.01	0.63 ± 0.32	0
			≥1250	I06	0.45 ± 0.12	0.3 ± 0.04	0.68 ± 0.35	1
	≥650	0.5	[500, 1250]	I07	0.97 ± 0.18	0.04 ± 0.01	0.27 ± 0.23	1
			≥1250	I08	1.12 ± 0.18	1.37 ± 0.08	0.38 ± 0.24	1

Table 6
Numbers of expected background events with combined statistical and systematic uncertainty and the observed numbers of events in aggregated search bins. The expected number of signal events for the two corresponding benchmark signals for the multi-b and 0-b analyses, respectively, are given as well.

n_b	n_{jet}	L_T [GeV]	$\Delta\phi$ [rad]	H_T [GeV]	Signal T1tttt ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$) [TeV] (1.4, 1.1)	(1.9, 0.1)	Predicted background	Observed data
≥1	≥6	≥600	0.5	≥1000	2.66 ± 0.30	7.39 ± 0.14	11.2 ± 3.6	13
≥3	≥6	≥600	0.5	≥1000	0.48 ± 0.12	3.07 ± 0.09	0.84 ± 0.48	1
≥2	≥9	≥450	0.75	≥500	1.35 ± 0.20	2.34 ± 0.08	1.61 ± 0.43	3
≥2	≥9	≥450	0.75	≥1500	0.37 ± 0.10	1.79 ± 0.07	0.64 ± 0.33	1
≥3	≥9	≥250	1.0	≥500	1.12 ± 0.19	1.33 ± 0.06	4.58 ± 0.83	3
≥3	≥9	≥250	1.0	≥1500	0.12 ± 0.05	1.02 ± 0.05	0.81 ± 0.33	0
≥3	≥9	≥450	0.75	≥500	0.41 ± 0.11	1.37 ± 0.06	0.37 ± 0.17	0
≥3	≥9	≥450	0.75	≥1500	0.17 ± 0.07	1.06 ± 0.05	0.05 ± 0.05	0
					Signal T5qqqqWW ($m_{\tilde{g}}$, $m_{\tilde{\chi}^0}$) [TeV] (1.5, 1.0)	(1.9, 0.1)		
0	≥5	≥650	0.5	≥750	6.15 ± 0.57	6.29 ± 0.20	18.4 ± 5.1	14
0	≥6	≥450	0.75	≥500	16.59 ± 0.94	5.28 ± 0.19	28.8 ± 6.8	37
0	≥6	≥650	0.5	≥1000	4.01 ± 0.46	4.98 ± 0.18	5.1 ± 1.8	4
0	≥7	≥450	0.75	≥500	9.47 ± 0.71	3.54 ± 0.15	9.7 ± 2.5	11
0	≥7	≥650	0.5	≥500	4.28 ± 0.48	3.30 ± 0.15	3.8 ± 1.2	4
0	≥8	≥250	1.0	≥1250	1.82 ± 0.31	1.71 ± 0.11	7.2 ± 1.9	8

that all of the missing transverse momentum in the event arises from a neutrino produced in the leptonic decay of the W boson. The event yields observed in data are in agreement with the standard model background, which is estimated using control regions in data and corrections based on simulation. The lack of any significant excess of events is interpreted in terms of limits on the parameters of two simplified models that describe gluino pair production.

For the T1tttt simplified model, in which each gluino decays to a $t\bar{t}$ pair and the lightest neutralino, gluino masses up to 1.8 TeV are excluded for neutralino masses below 800 GeV. Neutralino masses below 1.1 TeV are excluded for a gluino mass up to 1.7 TeV. This result extends the exclusion limit from the previous analysis [13] on gluino masses by about 250 GeV. The second simplified model, T5qqqqWW, also describes gluino pair production, but with decays to first- or second-generation quarks and

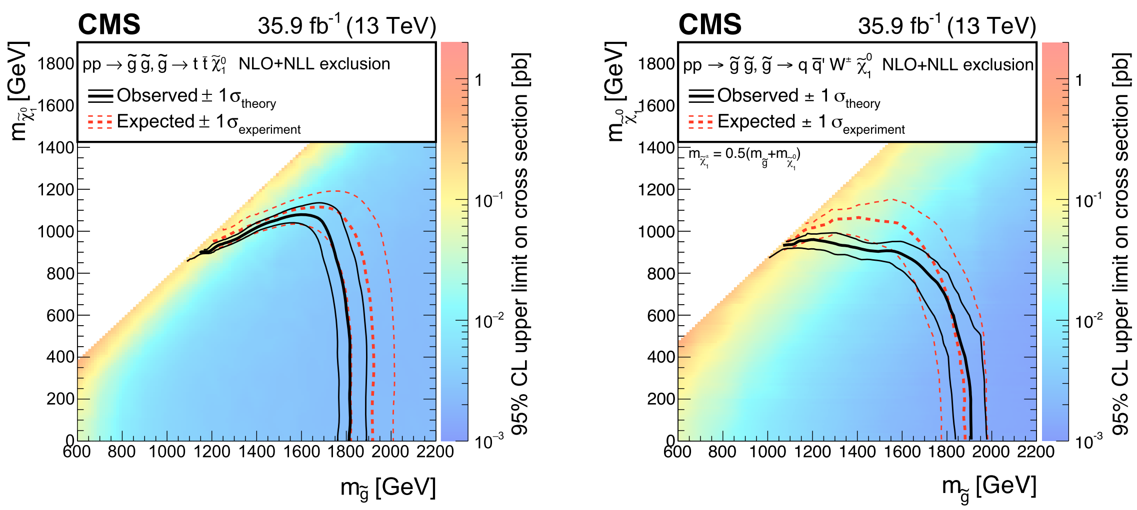

Fig. 5. Cross section limits at a 95% CL for the (left) T1tttt and (right) T5qqqqWW models, as a function of the gluino and LSP masses. In T5qqqqWW, the pair-produced gluinos decay to first- or second-generation quark–antiquark pairs ($q\bar{q}$) and a chargino ($\tilde{\chi}_1^{\pm}$) with its mass taken to be $m_{\tilde{\chi}_1^{\pm}} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. The solid black (dashed red) lines correspond to the observed (expected) mass limits, with the thicker lines representing the central values and the thinner lines representing the limits of 68% uncertainty bands related to the theoretical (experimental) uncertainties.

a chargino, which decays to a W boson and the lightest neutralino. The chargino mass in this decay channel is assumed to be $m_{\tilde{\chi}_1^{\pm}} = 0.5(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$. Gluino masses below 1.9 TeV are excluded for neutralino masses below 300 GeV. This corresponds to an improvement of about 500 GeV over the previous result [13]. For a gluino mass of 1.2 TeV, neutralinos with masses up to 950 GeV are excluded.

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