Search for supersymmetry in pp collisions at sqrt(s) = 13 TeV in the single-lepton final state using the sum of masses of large-radius jets

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Search for Supersymmetry in pp Collisions at $\sqrt{s} = 13$ TeV in the Single-Lepton Final State Using the Sum of Masses of Large-Radius Jets

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Results are reported from a search for supersymmetric particles in proton-proton collisions in the final state with a single lepton, multiple jets, including at least one b-tagged jet, and large missing transverse momentum. The search uses a sample of proton-proton collision data at $\sqrt{s} = 13$ TeV recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}. The observed event yields in the signal regions are consistent with those expected from standard model backgrounds. The results are interpreted in the context of simplified models of supersymmetry involving gluino pair production, with gluino decay into either on- or off-mass-shell top squarks. Assuming that the top squarks decay into a top quark plus a stable, weakly interacting neutralino, scenarios with gluino masses up to about 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV.

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A central goal of the physics program of the CMS experiment at the CERN LHC [1] is the search for new particles and phenomena beyond the standard model (SM), in particular, for supersymmetry (SUSY) [2–9]. During 2016, CMS recorded a data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}, significantly extending the sensitivity to the production of new heavy particles. The search described here focuses on a generically important experimental signature that is also strongly motivated by SUSY phenomenology. This signature includes a single lepton (an electron or a muon), several jets, arising from the hadronization of energetic quarks and gluons, at least one b-tagged jet, indicative of processes involving third generation quarks, and, finally, $\vec{p}_T^{\,\text{miss}}$, the missing momentum in the direction transverse to the beam. A large value of $p_T^{\text{miss}} \equiv |\vec{p}_T^{\,\text{miss}}|$ can arise from the production of high momentum, weakly interacting particles that escape detection. Searches for SUSY in the single-lepton final state have been performed by both ATLAS and CMS at $\sqrt{s} = 7$ and 8 TeV [10–13] and at $\sqrt{s} = 13$ TeV [14–17]. The present analysis, which introduces extended binning and other improvements, is based largely on methodologies described in detail in Ref. [16], which include the use of large-radius jets and related kinematic variables.

In models based on SUSY, new particles are introduced such that all fermionic (bosonic) degrees of freedom in the SM are paired with corresponding bosonic (fermionic) degrees of freedom in the extended theory. The discovery of a Higgs boson with low mass [18–23] provides a key motivation for SUSY. Stabilizing the Higgs boson mass at a low value, without invoking extreme fine-tuning of parameters, is a major theoretical challenge, referred to as the gauge hierarchy problem [24–29]. This stabilization can be achieved in so-called natural SUSY models [30–34], in which several of the SUSY partners are constrained to be light [33]: the top squarks $\tilde{t}_L$ and $\tilde{t}_R$, which have the same electroweak couplings as the left- (L-) and right- (R-) handed top quarks, respectively, the bottom squark with L-handed couplings, $\tilde{b}_L$, the gluino $\tilde{g}$; and the Higgsinos $\tilde{H}$. This search targets gluino pair production, which has a relatively large cross section for a given mass, with gluino decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$. This process can arise from $\tilde{g} \to \tilde{t}_1\bar{t}$, where the lighter top squark mass eigenstate $\tilde{t}_1$ is produced either on or off mass shell. The symbol $\tilde{\chi}_1^0$ denotes the lightest neutralino, an electrically neutral mass eigenstate that is in general a mixture of the Higgsinos and electroweak gauginos. In R-parity conserving SUSY models [35,36] in which the $\tilde{\chi}_1^0$ is the lightest supersymmetric particle, the $\tilde{\chi}_1^0$ is stable and can, in principle, account for some or all of the astrophysical dark matter [37–39]. The scenario with off-mass-shell top squarks is denoted as T1tttt [40] in simplified model scenarios [41–43]. In natural SUSY models, the top squark is typically lighter than the gluino, so we also search for scenarios with on-shell top squarks, denoted as T5tttt.

Simulated event samples for SM background processes are used to determine correction factors, typically near unity, that are used in conjunction with observed event yields in control regions to determine the SM background contribution in the signal regions. The production of $t\bar{t}$ + jets, W + jets, Z + jets, and QCD multijet events is simulated with the MC generator MadGraph5_amc@nlo@nlo 2.2.2

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[44], with parton distribution functions taken from NNPDF 3.0 [45]. Details on the simulated SM background samples, including other processes with smaller contributions (single top quark, $t\bar{t}+$ bosons, diboson, and $t\bar{t}t\bar{t}$ production) are given in Ref. [16]. The detector simulation is performed with GEANT4 [46]. Simulated event samples for SUSY signal models, used to determine the selection efficiency for signal events, are generated with MADGRAPH5_AMC@NLO@NLO 2.2.2 with up to two additional partons at leading order accuracy and are normalized to cross sections based on Ref. [47]. Because of the large number of mass hypotheses examined in this analysis, the detector simulation in this case is performed with the CMS fast simulation package [48].

Two T1tttt benchmark models are used to illustrate typical signal behavior. The T1tttt(1800,100) model, which we refer to as a noncompressed-spectrum model (NC), has $m(\tilde{g}) = 1800$ GeV, $m(\tilde{\chi}_1^0) = 100$ GeV, and a cross section of 2.8 fb, and corresponds to a scenario with a large gluino-neutralino mass splitting. The T1tttt(1400,1000) model, with $m(\tilde{g}) = 1400$ GeV, $m(\tilde{\chi}_1^0) = 1000$ GeV, and a cross section of 25 fb, corresponds to a scenario with a small gluino-neutralino mass splitting and is referred to as a compressed-spectrum model (C).

The data were recorded with the CMS detector [49], which is constructed around a superconducting solenoid of 6 m diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are the charged particle tracking systems, composed of silicon-pixel and silicon-strip detectors, and the calorimeter systems, consisting of a lead tungstate crystal electromagnetic calorimeter and a brass and scintillator hadron calorimeter. Muons are identified and measured by gas-ionization detectors embedded in the magnetic flux-return yoke outside the solenoid. Events were selected using several triggers [50] that require either large p_T^{miss} or a single lepton (an electron or a muon), with and without significant hadronic activity. The trigger efficiency is measured in data for our analysis requirements to be nearly 100%.

Event reconstruction proceeds from particles identified by the particle-flow (PF) algorithm [51], which uses information from the tracker, calorimeters, and muon systems to identify PF candidates as electrons, muons, charged or neutral hadrons, or photons. Electrons are reconstructed by associating a charged-particle track with electromagnetic calorimeter superclusters [52]. The resulting candidate electrons are required to have transverse momentum $p_T > 20$ GeV and pseudorapidity $|\eta| < 2.5$, and to satisfy identification criteria designed to reject light-parton jets and photon conversions. Muons are reconstructed by associating tracks in the muon system with those found in the silicon tracker [53]. Muon candidates are required to satisfy $p_T > 20$ GeV and $|\eta| < 2.4$. To select leptons from W boson decays, leptons are required to be isolated from other PF candidates. Isolation is quantified using an optimized version [16] of the mini-isolation variable originally suggested in Ref. [54], in which the transverse energy of the particles within a cone around the lepton momentum vector is computed using a cone size that decreases as $1/p_T{}^{\ell}$, where $p_T{}^{\ell}$ is the transverse momentum of the lepton.

To suppress dilepton backgrounds, we veto events that contain a broader category of candidates for the second lepton, referred to as veto tracks. These include two categories of charged-particle tracks: isolated leptons satisfying looser identification criteria than lepton candidates, including a relaxed momentum requirement, $p_T > 10$ GeV, and isolated charged-hadron PF candidates, which must satisfy $p_T > 15$ GeV and $|\eta| < 2.5$. In either case, the charge of the veto track must be opposite to that of the lepton candidate in the event. To maintain a high selection efficiency for signal events, lepton veto tracks must satisfy a requirement on the quantity [55,56] $M_{T2}(\vec{p}^{\ell}, \vec{p}_T^{v}, \vec{p}_T^{\text{miss}}) < 80$ GeV and hadronic veto tracks must satisfy $M_{T2}(\vec{p}^{\ell}, \vec{p}_T^{v}, \vec{p}_T^{\text{miss}}) < 60$ GeV, where v refers to the veto track.

Charged and neutral PF candidates are clustered into jets using the anti-k_T algorithm [57] with radius parameter $R = 0.4$, as implemented in the FASTJET package [58]. Jets are required to satisfy $p_T > 30$ GeV and $|\eta| \leq 2.4$. Additional details and references are given in Ref. [16] on the p_T- and η-dependent jet energy calibration [59], the jet identification requirements, and the subtraction of the energy contribution to the jet p_t from multiple proton-proton interactions from the same or neighboring beam crossings (pileup) [60]. A subset of the jets are tagged as originating from b quarks using the combined secondary vertex algorithm [61,62].

We further cluster the jets with $R = 0.4$ (small-R jets), including those associated with isolated leptons, into $R = 1.4$ (large-R) jets using the anti-k_T algorithm. The masses $m(J_i)$ of the large-R jets reflect the p_T spectrum and multiplicity of the clustered objects, as well as their angular spread. The variable M_J is defined as the sum of all large-R jet masses: $M_J = \sum_{J_i=\text{large}-R\text{jets}} m(J_i)$. For $t\bar{t}$ events with a small contribution from initial-state radiation (ISR), the M_J distribution has an approximate cutoff at $2m_t$. In contrast, the M_J distribution for signal events extends to larger values because of the presence of multiple top quarks in the decay chain. The presence of a significant amount of ISR generates a high-M_J tail in the $t\bar{t}$ background, producing the main source of background in the analysis.

The missing transverse momentum $\vec{p}_T^{\text{miss}}$ is defined as the negative vector sum of the transverse momenta of all PF candidates. To separate backgrounds characterized by the presence of a single W boson decaying leptonically, but without any other source of p_T^{miss}, we use the transverse mass $m_T = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} [1 - \cos(\Delta\phi_{\ell,\vec{p}_T^{\text{miss}}})]}$, where $\Delta\phi_{\ell,\vec{p}_T^{\text{miss}}}$ is the difference between the azimuthal angles of p_T^{ℓ} and $\vec{p}_T^{\text{miss}}$. The quantity H_T is defined as the scalar sum of the transverse momenta of all the small-R jets passing the selection, while $S_T = H_T + p_T^{\ell}$.

We select events with exactly one isolated charged lepton (an electron or a muon), no veto tracks, $S_T > 500$ GeV, $p_T^{\mathrm{miss}} > 200$ GeV, and at least six small-R jets, at least one of which is b tagged. After this set of requirements, referred to as the baseline selection, about 80% of the SM background arises from $t\bar{t}$ production. The contributions from events with a single top quark or a W boson in association with jets are each about 6%–8%; much of the remainder arises from events with a $t\bar{t}$ pair produced in association with a vector boson. After applying the baseline selection, the background from QCD multijet events is negligible.

The analysis is performed using four regions in the M_J-m_T plane: three control regions (CR) and one signal region:

(i) $R1$ (CR): $m_T \leq 140$ GeV, $250 \leq M_J \leq 400$ GeV.

(ii) $R2$ (CR): $m_T \leq 140$ GeV, $M_J > 400$ GeV.

(iii) $R3$ (CR): $m_T > 140$ GeV, $250 \leq M_J \leq 400$ GeV.

(iv) $R4$ (signal region): $m_T > 140$ GeV, $M_J > 400$ GeV.

All four regions are divided in bins of p_T^{miss}, forming three largely independent M_J-m_T planes:

(i) Three p_T^{miss} bins: $200 < p_T^{\mathrm{miss}} \leq 350$ GeV, $350 < p_T^{\mathrm{miss}} \leq 500$ GeV, $p_T^{\mathrm{miss}} > 500$ GeV.

Regions $R2$ and $R4$, which have high M_J, are further divided into bins according to the number of small-R jets (N_{jets}) and the number of b-tagged jets (N_b) as follows:

(ii) Two N_{jets} bins: $6 \leq N_{\mathrm{jets}} \leq 8$, $N_{\mathrm{jets}} \geq 9$.

(iii) Three N_b bins: $N_b = 1$, $N_b = 2$, $N_b \geq 3$, giving a total of 18 bins each. Backgrounds with a single W boson decaying leptonically are strongly suppressed by the requirement $m_T > 140$ GeV, so the background in $R3$ and $R4$ is dominated by dilepton $t\bar{t}$ events. Approximately half of the dilepton background events in $R4$ contain a missed electron or muon, and the other half contain a hadronically decaying τ lepton. Given that the main background processes have two or fewer b quarks, the total SM contribution to the $N_b \geq 3$ bins is very small and is driven by the b tag misidentification rate. Signal events in the T1tttt and T5tttt models populate primarily the bins with $N_b \geq 2$.

The method for predicting the background yields takes advantage of the near absence of correlation between the M_J and m_T variables in $R1$–$R4$, which is a consequence of the high jet multiplicity, p_T^{miss}, and S_T requirements applied in the baseline selection [16]. To satisfy these requirements, background events must typically contain additional jets from ISR. Even though the background at low m_T arises largely from single-lepton $t\bar{t}$ events, while the background at high m_T is dominated by dilepton $t\bar{t}$ events, the shapes of the M_J distributions at low and high m_T become very similar in the presence of multiple ISR jets. We therefore measure this shape at low m_T ($R1$, $R2$) and extrapolate it to high m_T to obtain the background prediction in $R4$. The fitted mean background yields in $R1$–$R4$ are thus related by the constraint $\mu_{R4}^{\mathrm{bkg}} = \kappa \mu_{R3}^{\mathrm{bkg}} \mu_{R2}^{\mathrm{bkg}} / \mu_{R1}^{\mathrm{bkg}}$. Here, κ is a near-unity correction factor obtained from MC simulation of the total background that accounts for a residual m_T-M_J correlation:

$$\kappa = \frac{\mu_{R4}^{\mathrm{MC\,bkg}} / \mu_{R2}^{\mathrm{MC\,bkg}}}{\mu_{R3}^{\mathrm{MC\,bkg}} / \mu_{R1}^{\mathrm{MC\,bkg}}}. \tag{1}$$

This constraint is imposed by relating the expected yields in $R1$–$R4$ to three parameters: an overall background normalization λ and two ratios $R(m_T)$ and $R(M_J)$, where the expected background yields are given by $\mu_{R1}^{\mathrm{bkg}} = \lambda$, $\mu_{R2}^{\mathrm{bkg}} = \lambda R(M_J)$, $\mu_{R3}^{\mathrm{bkg}} = \lambda R(m_T)$, and $\mu_{R4}^{\mathrm{bkg}} = \kappa \lambda R(M_J) R(m_T)$. These quantities are defined such that there is one value of $R(M_J)$ and κ for each bin of p_T^{miss}, N_{jets}, and N_b. Because regions $R1$ and $R3$ are integrated in N_{jets} and N_b, the fit parameters λ and $R(m_T)$ are defined such that there is only one value of these quantities for each bin in p_T^{miss}.

We perform two types of maximum likelihood fits, which are described in detail in Ref. [16]. The predictive fit uses the observed yields in $R1$–$R3$, assuming no signal contribution, to propagate the uncertainties to λ, $R(M_J)$, and $R(m_T)$. The global fit uses the observed yields in all four regions $R1$–$R4$ and allows a signal contribution with a single normalization parameter. The global fit accounts for signal contamination in $R1$–$R3$, which is typically less than 10%, and is used to compute signal limits and significances. The results from the predictive fit simplify theoretical reinterpretation in terms of other models by only requiring comparison of observed and predicted yields in $R4$ rather than all four regions. In both cases, the likelihood function is written as a product of Poisson distributions for the relevant contributions in bins of p_T^{miss}, N_{jets}, and N_b within $R2$ and $R4$, taking into account the correlated yields between the unbinned regions $R1$ and $R3$.

Systematic uncertainties in the background prediction are incorporated in the uncertainty in the double ratio correction factor κ. Discrepancies between the value of κ predicted by simulation and the true value of κ in the data can in principle arise from mismodeling of the background composition or its properties, including detector effects.

To assess the potential impact of such effects on κ, two control samples in data are used: a five-jet control sample and a dilepton control sample. The five-jet control sample is completely dominated by background processes and has a SM composition very similar to that of the analysis regions. In particular, this sample probes the rate at which p_T^{miss} is mismeasured in single-lepton events, which could increase the tail of the m_T distribution. Such events account for about 7% of the background in the signal region at high p_T^{miss}. This small event category can have a κ value that departs significantly from unity, and it is important to validate the modeling of such effects. Using the analogous $R1$–$R4$ regions in the $N_{\mathrm{jets}} = 5$ control sample, κ values are measured in data and are found to be consistent with those obtained from simulation. Because of this consistency, the statistical uncertainty obtained from the comparison in the $N_{\rm jets} = 5$ control sample is assigned as an uncertainty in κ for each $p_T^{\rm miss}$ bin. These uncertainties are taken to be fully correlated over the $N_{\rm jets}$ and N_b bins.

The dilepton control sample is used to test the degree of similarity between the M_J shapes of single-lepton and dilepton $t\bar{t}$ events in the presence of ISR. This sample includes not only events with two identified isolated leptons, but also events with one lepton and an oppositely charged veto track. The usual $R3$ and $R4$ regions are replaced by dilepton events, and the quantity κ is measured in bins of $N_{\rm jets}$. As in the five-jet control sample, the values of κ measured in data are found to be consistent with those observed in simulation, and uncertainties are assigned in a similar way. The uncertainties are treated as independent across $N_{\rm jets}$ bins but fully correlated across N_b and $p_T^{\rm miss}$ bins. The uncertainties from the dilepton and five-jet control samples are treated as uncorrelated. Studies of a broad range of potential mismodeling effects in simulation show that all such effects would be evident in these control samples.

Systematic uncertainties in the expected signal yields account for uncertainties in the trigger, lepton identification, jet identification, and b tagging efficiencies in simulated data, uncertainties in the distributions of $p_T^{\rm miss}$, the number of pileup vertices, and ISR jet multiplicity, and uncertainties in the jet energy corrections, QCD scales, and integrated luminosity [63]. The combined effect of all signal-related uncertainties is typically about 25%.

Table I lists the observed event yields in region $R4$ in data, together with the mean background yields from the predictive fit and the expected signal yields from two benchmark model points. The uncertainties in the predicted background yields include the statistical uncertainties on the event yields in $R1$–$R4$ in data, the statistical uncertainties in the κ values arising from the finite size of simulated event samples, and the systematic uncertainties in κ as assessed from the data control samples. The observed yields are consistent with the background predictions in all of the 18 signal bins within 2 standard deviations, with most of the 18 bins consistent within 1 s.d. The $R4$ bins with $p_T^{\rm miss} > 500$ GeV show an underprediction of the background with respect to the observed yields. However, accounting for the correlations arising from the use of a single, integrated yield in $R3$ across bins in $N_{\rm jets}$ and N_b, the significance of the discrepancy in these six bins in $R4$ is only 1.9 s.d., mostly due to the bins with $N_b = 1$.

To simplify the reinterpretation of the results in terms of other theoretical models, we provide predicted mean background yields for four aggregated search bins, shown in Table II. The aggregate bins are defined such that at least one bin will provide sensitivity to most of the models for which the finely binned analysis has sensitivity. Since the aggregate bins overlap, they are intended to be used one at a time, unlike the 18 nonoverlapping signal bins, which are considered simultaneously in the fit. Each prediction includes all sources of uncertainty. The choice of the best aggregate bin will depend on the model under study. For the T1tttt benchmark models considered in this Letter, using the aggregate bins results in expected upper limits on the

TABLE I. Observed event yields and mean background yields from the predictive fit in the 18 bins of the signal region $R4$. Each bin is specified by the values of $p_T^{\rm miss}$, $N_{\rm jets}$, and N_b. The uncertainties in κ include both a statistical component from the size of the MC samples and a systematic component assessed from the data control samples. The uncertainty in the predicted event yield includes both of these and the statistical uncertainties associated with the data control regions. Yields for the two T1tttt benchmark models NC and C are also given.

$N_{\rm jets}$	N_b	NC	C	κ	Predicted	Observed
$200 < p_T^{\rm miss} \leq 350$ GeV						
6–8	1	0.4	1.9	1.2 ± 0.2	85 ± 14	106
6–8	2	0.6	3.0	1.2 ± 0.2	55.1 ± 9.3	75
6–8	≥3	0.6	2.2	1.5 ± 0.2	16.4 ± 3.0	16
≥9	1	0.2	1.6	1.0 ± 0.2	6.5 ± 1.5	11
≥9	2	0.3	2.1	1.2 ± 0.3	7.6 ± 1.9	11
≥9	≥3	0.4	3.1	1.4 ± 0.3	2.3 ± 0.7	2
$350 < p_T^{\rm miss} \leq 500$ GeV						
6–8	1	0.7	1.1	1.0 ± 0.3	17.4 ± 6.6	25
6–8	2	0.9	1.3	1.1 ± 0.4	13.7 ± 5.3	10
6–8	≥3	0.8	0.9	1.3 ± 0.4	3.8 ± 1.6	1
≥9	1	0.3	1.0	1.1 ± 0.4	1.3 ± 0.6	2
≥9	2	0.5	1.1	0.8 ± 0.3	1.6 ± 0.8	2
≥9	≥3	0.7	2.1	1.2 ± 0.5	0.6 ± 0.4	0
$p_T^{\rm miss} > 500$ GeV						
6–8	1	2.5	0.6	1.0 ± 0.3	1.9 ± 1.5	8
6–8	2	3.6	1.0	1.0 ± 0.4	0.9 ± 0.7	4
6–8	≥3	3.2	0.4	1.5 ± 0.6	0.4 ± 0.4	1
≥9	1	1.0	0.7	1.0 ± 0.4	0.2 ± 0.2	2
≥9	2	1.8	1.2	1.0 ± 0.4	0.1 ± 0.1	0
≥9	≥3	2.3	1.7	3.1 ± 1.5	0.1 ± 0.1	0

TABLE II. Observed event yields and mean background yields from the predictive fit in four aggregate search bins. In all four cases, the predicted yields refer to the signal region $R4$ with the standard m_T>140 GeV and M_J>400 GeV requirements applied in addition to the baseline selection. Unlike the finely binned approach, where all 18 background predictions are computed simultaneously, the four aggregate bin predictions are computed separately. The aggregate bins overlap, causing their background predictions to be highly correlated. Yields for the two T1tttt benchmark models NC and C are also given.

$p_T^{\rm miss}$ [GeV]	$N_{\rm jets}$	N_b	NC	C	κ	Predicted	Observed
>200	≥9	≥3	3.4	6.9	1.4 ± 0.3	3.1 ± 0.8	2
>350	≥9	≥2	5.3	6.2	1.0 ± 0.4	2.7 ± 1.2	2
>500	≥6	≥3	5.4	2.1	1.7 ± 0.6	0.5 ± 0.4	1
>500	≥9	≥1	5.1	3.6	1.2 ± 0.4	0.4 ± 0.4	2

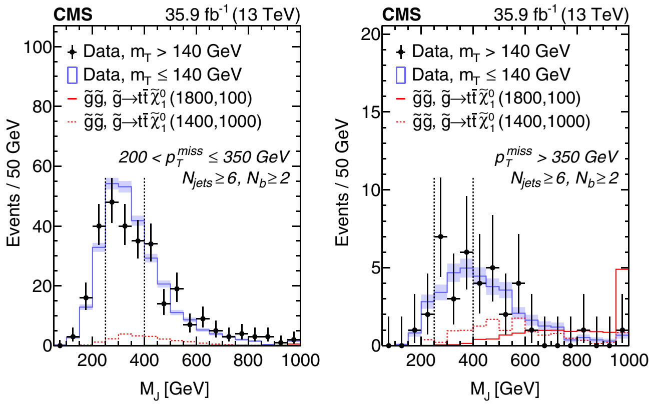

FIG. 1. Distributions of M_J observed in data for $200 < p_T^{\mathrm{miss}} \leq 350$ GeV (left) and $p_T^{\mathrm{miss}} > 350$ GeV (right) with the baseline selection and either $m_T \leq 140$ GeV or $m_T > 140$ GeV. In each plot, the data at low m_T have been normalized to the yield observed at high m_T. The vertical dashed lines at $M_J = 250$ and 400 GeV show the boundaries separating the control and signal regions. The data are integrated over $N_{\mathrm{jets}} \geq 6$ and $N_b \geq 2$. Two SUSY benchmark models, whose contributions are small in the lower p_T^{miss} region, are shown in the solid and dashed red histograms. Overflow events are included in the uppermost bins.

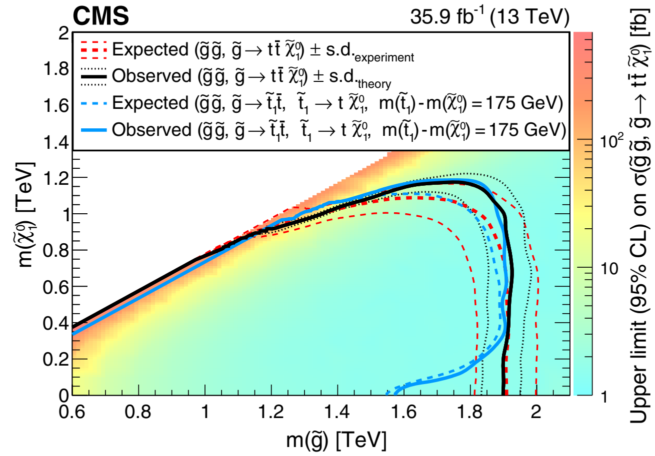

FIG. 2. Observed and expected excluded gluino and neutralino masses at 95% C.L. for the T1tttt and T5tttt models. The black (red) lines show the observed (expected) exclusion and the range associated with the theoretical (experimental) uncertainties for the T1tttt model. The solid (dashed) blue line shows the observed (expected) exclusion for the T5tttt model. The uncertainties for the T5tttt exclusion limits are not shown and are similar to those for the T1tttt model. The color map shows the observed cross section upper limits for the T1tttt model.

cross sections that are 20%–50% higher than those resulting from the full analysis.

Figure 1 compares the shapes of the M_J distributions observed in data in the single-lepton sample for $m_T \leq 140$ GeV and $m_T > 140$ GeV in two regions of p_T^{miss}. The shapes of the two M_J distributions for each p_T^{miss} region are very similar, as expected in the absence of signal. A further correction is applied via the κ factors listed in Table I in M_J ranges larger than the binning shown in the figure. The lower-p_T^{miss} region shows the background behavior with higher statistics, while the higher-p_T^{miss} region has higher sensitivity to the signal.

Figure 2 shows an interpretation of the results as exclusion limits at 95% C.L. for T1tttt and T5tttt. The limits are obtained using the $\mathrm{CL_s}$ method with a profile-likelihood ratio as the test statistic, using asymptotic approximations for the distribution of the test statistic [64–66]. The color map shows the cross section upper limits as a function of $m(\tilde{g})$ and $m(\tilde{\chi}_1^0)$ for T1tttt, assuming a 100% branching fraction for the decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$. The T1tttt model points below the dark solid curve, which extend up to gluino masses of about 1.9 TeV for neutralino masses up to 1 TeV, have a theoretical cross section above the observed cross section upper limit and are thus excluded by this analysis. The dotted black lines around the observed mass limits show the impact of the theoretical uncertainties in the overall signal cross sections arising from uncertainties in the parton distribution functions and the renormalization and factorization scales.

Model points below the light solid curve are excluded at 95% C.L. for the T5tttt model, where it is assumed that the top squark mass is 175 GeV above the neutralino mass, a limiting case in terms of sensitivity to the decay kinematics. The T5tttt simulation does not explicitly include direct top squark pair production. Studies presented in Ref. [16] demonstrate that the effect of this contribution is very small for most of the space of T5tttt model points considered here. For most of the excluded region, the boundaries for T1tttt and T5tttt are very similar, indicating only a weak overall sensitivity to the value of the top squark mass. At low values of $m(\tilde{\chi}_1^0)$ in T5tttt, the sensitivity is reduced because the neutralino carries very little momentum; however, some sensitivity is still provided by dilepton events that escape the lepton veto [16]. For both the T1tttt and T5tttt models, expected limits are computed using the background-only hypothesis, with nuisance parameters assuming their best fit values from the observed data. All limits are computed using results from the global fit.

In summary, we have performed a search for an excess event yield above that expected for SM processes using a data sample of proton-proton collision events with an integrated luminosity of 35.9 fb^{-1} at $\sqrt{s} = 13$ TeV. The signature is characterized by large missing transverse momentum, a single isolated lepton, multiple jets, and at least one b-tagged jet. No significant excesses above the SM backgrounds are observed. The results are interpreted in the framework of simplified models that describe natural SUSY scenarios. For gluino pair production followed by the three-body decay $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ (T1tttt model), gluinos with masses below 1.9 TeV are excluded at 95% confidence level for neutralino masses up to about 1 TeV. For the two-body gluino decay $\tilde{g} \to \tilde{t}_1 \bar{t}$ with $\tilde{t}_1 \to t\tilde{\chi}_1^0$ (T5tttt model), the results are generally similar, except at low neutralino masses, where the excluded gluino mass is somewhat lower. These results extend previous gluino mass limits by about 300 GeV and are among the most stringent constraints on these simplified models of SUSY to date.

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