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Search for New Physics in the Multijet and Missing Transverse Momentum Final State in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV

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A search for physics beyond the standard model is performed in events with at least three jets and large missing transverse momentum produced in proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV. No significant excess of events above the expected backgrounds is observed in 4.98 fb^{-1} of data collected with the CMS detector at the Large Hadron Collider. The results are presented in the context of the constrained minimal supersymmetric extension of the standard model and more generically for simplified models. For the simplified models of gluino-gluino and squark-squark production, gluino masses below 1.0 TeV and squark masses below 0.76 TeV are excluded in case the lightest supersymmetric particle mass is below 200 GeV. These results significantly extend previous searches.

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Many extensions of the standard model (SM) of particle physics have been proposed to address the shortcomings of the SM, e.g., problems concerning the gauge hierarchy and identity of dark matter [1–3]. Supersymmetry (SUSY) is one such new physics model, which postulates a new symmetry that relates fermionic and bosonic degrees of freedom and introduces a superpartner for each SM particle. In R-parity conserving models [4], SUSY particles are produced in pairs, and the lightest SUSY particle (LSP) is stable. If the LSP is weakly interacting and neutral, it serves as a candidate for dark matter. At the Large Hadron Collider (LHC), squarks ($\tilde{q}$) and gluinos ($\tilde{g}$), the superpartners of the quarks and gluons, would be produced via the strong interaction and decay to SM particles and two LSPs. A typical signature is the all-hadronic final state, characterized by multiple jets arising from quarks and gluons, and large missing transverse momentum due to the unobserved LSPs.

Searches in this final state have been performed by experiments at the Fermilab Tevatron [5,6] and at the LHC [7–15]. This Letter presents a search in events with multiple jets and large missing transverse momentum produced in 7 TeV pp collisions using a data sample corresponding to an integrated luminosity of $4.98 \pm 0.11\ \text{fb}^{-1}$ [16] collected with the Compact Muon Solenoid (CMS) detector. The search strategy follows Ref. [7] but uses more than 100 times the amount of data. This search is not specifically optimized for a particular SUSY model but is sensitive to a variety of new physics models that lead to the multijet final state with large missing transverse momentum. The results of this search are interpreted in the context of the constrained minimal supersymmetric extension of the SM (CMSSM) [17–19] and in a more general context for simplified models [20,21] of new particles decaying to one or two jets and a stable weakly interacting particle.

The central feature of the CMS detector [22] is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter, and the brass and scintillator hadron calorimeter. Charged particles are measured by the silicon tracker, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$ [23]. The calorimeters surrounding the tracking volume cover $|\eta| < 3$. Outside the field, the quartz and steel forward hadron calorimeters extend the coverage to $|\eta| < 5$. Muons are identified in gas ionization detectors, covering $|\eta| < 2.4$, embedded in the steel return yoke of the magnet. A two-tier trigger system selects the pp collision events for use in this search.

The recorded events are reconstructed using the particle-flow algorithm [24], which reconstructs particles, namely, charged hadrons, photons, neutral hadrons, muons, and electrons, using the information from all subdetectors. These particles are then clustered into jets using the anti-k_T clustering algorithm with distance parameter 0.5 [25]. Corrections are applied to account for the dependence of the jet response on transverse momentum p_T and η [26] and for the effects of additional (pileup) pp collisions overlapping with the collision of interest [27,28].

The event sample for the search is selected by requiring at least three jets with $p_T > 50$ and $|\eta| < 2.5$. The further selection is based on two variables: H_T, defined as $H_T = \sum p_T$ where the sum is carried out over jets with $p_T > 50$ GeV and $|\eta| < 2.5$, and $\vec{\not{H}}_T$, defined as $\vec{\not{H}}_T = -\sum \vec{p}_T$

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where the sum is over jets with $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 5$. Events are required to have $H_{\mathrm{T}} > 500$ GeV and $\not\!\!H_{\mathrm{T}} > 200$ GeV, where $\not\!\!H_{\mathrm{T}}$ is the magnitude of the $\vec{\not\!\!H}_{\mathrm{T}}$. The $\not\!\!H_{\mathrm{T}}$ requirement rejects most of the QCD multijet background. Events with $\vec{\not\!\!H}_{\mathrm{T}}$ aligned in azimuth with one of the two leading jets with $\Delta\phi < 0.5$ rad or along the third jet with $\Delta\phi < 0.3$ rad are removed to further reduce the QCD multijet background. Events containing isolated muons or electrons with $p_{\mathrm{T}} > 10$ GeV are also vetoed in order to reject $t\bar{t}$ and W/Z + jets backgrounds with leptons in the final state [7,29,30]. Events are also rejected if a jet with $p_{\mathrm{T}} > 30$ GeV has an electromagnetic p_{T} fraction larger than 0.95 or a neutral hadron p_{T} fraction larger than 0.90. In addition, events affected by instrumental effects, particles from noncollision sources, and poor reconstruction quality are rejected (event cleaning) [7,31]. All these requirements constitute the baseline selection [32]. The event sample used in this search is collected by triggering on both H_{T} and $\not\!\!H_{\mathrm{T}}$ or only on H_{T}. The H_{T} threshold ranges from 160 to 350 GeV, and the $\not\!\!H_{\mathrm{T}}$ threshold ranges from 60 to 110 GeV. The trigger efficiency is measured to be consistent with 100% for the baseline event selection.

To increase the sensitivity of the search to the different kinematic regions of signal events, the sample of 1885 events passing the baseline selection is divided into 14 subsamples defined in terms of the H_{T} and $\not\!\!H_{\mathrm{T}}$ values (search selections), as listed in the first column of Table I.

The SM backgrounds mainly consist of $Z(\nu\bar{\nu})$ + jets events and $W(\ell\nu)$ + jets events from W or $t\bar{t}$ production ($\ell = e$, μ, or τ). The $W(\ell\nu)$ + jets events pass the search selection when the e/μ escapes detection or a τ decays hadronically. The QCD multijet events also contribute to the background when leptonic decays of heavy-flavor hadrons inside jets or jet energy mismeasurements lead to a large $\not\!\!H_{\mathrm{T}}$. The contributions from other SM processes are found to be negligible. In this search, all of the backgrounds are estimated from data [7].

Several Monte Carlo (MC) samples are used to model the signal as well as to develop and validate the background prediction methods. The $t\bar{t}$, W/Z + jets, and γ + jets samples are produced using the MADGRAPH5 [33] generator, interfaced with the PYTHIA 6.4.24 [34] parton-shower model. The $t\bar{t}$ and W/Z + jets samples are scaled up to the next-to-leading-order (NLO) or next-to-next-to-leading-order cross section predictions [35,36]. The QCD multijet and SUSY signal production is simulated with PYTHIA 6.4.24, the CTEQ6L [37] parton distribution functions (PDFs), and a CMS custom underlying event tuning [38]. The generated events are passed through a GEANT4-based [39] detector simulation and have the same distribution of pileup pp interactions as observed in the data.

The $Z(\nu\bar{\nu})$ + jets background contribution is estimated using γ + jets events by treating photons as $Z \rightarrow \nu\bar{\nu}$ decays. The Z boson and photon exhibit similar kinematic properties at high p_{T}, and the hadronic component of events is similar in the two cases [40–43]. A γ + jets sample is collected by triggering on a γ candidate with or without an additional requirement on H_{T}, depending on the data-taking period. The photon candidates [44] are required to be isolated from other particles in the tracker and calorimeters and to have the shower shape consistent with that for a prompt photon. In order to predict the $Z(\nu\bar{\nu})$ + jets background, the γ + jets sample is corrected for the γ reconstruction efficiency and purity, both measured from data [7], and the $Z(\nu\bar{\nu})$ + jets/γ + jets production ratio, obtained from the MADGRAPH simulation samples, which also takes into account the detector acceptance for photons. The total multiplicative correction factor to obtain the $Z(\nu\bar{\nu})$ + jets

TABLE I. Event yields for different backgrounds for the 14 search selections together with the total backgrounds, as determined from the collision data, and number of events observed in data. The quoted uncertainties are the combinations of the statistical and systematic uncertainties.

Selection H_{T} (GeV)	$\not\!\!H_{\mathrm{T}}$ (GeV)	$Z \rightarrow \nu\bar{\nu}$	$t\bar{t}/W \rightarrow e, \mu + X$	$t\bar{t}/W \rightarrow \tau_{\mathrm{h}} + X$	QCD multijet	Total background	Data
500–800	200–350	359 ± 81	327 ± 47	349 ± 40	119 ± 77	1154 ± 128	1269
500–800	350–500	112 ± 26	48 ± 9	62.5 ± 8.7	2.2 ± 2.2	225 ± 29	236
500–800	500–600	17.6 ± 4.9	5.0 ± 2.2	8.7 ± 2.5	0.0 ± 0.1	31.3 ± 5.9	22
500–800	>600	5.5 ± 2.6	0.8 ± 0.8	2.0 ± 1.8	0.0 ± 0.0	8.3 ± 3.2	6
800–1000	200–350	48 ± 19	58 ± 15	56.3 ± 8.3	35 ± 24	197 ± 35	177
800–1000	350–500	16.0 ± 6.7	5.4 ± 2.3	7.2 ± 2.0	$1.2^{+1.3}_{-1.2}$	29.8 ± 7.5	24
800–1000	500–600	7.1 ± 3.7	2.4 ± 1.5	1.3 ± 0.6	$0.0^{+0.2}_{0.0}$	10.8 ± 4.0	6
800–1000	>600	3.3 ± 1.7	0.7 ± 0.7	1.0 ± 0.3	$0.0^{+0.1}_{0.0}$	5.0 ± 1.9	5
1000–1200	200–350	10.9 ± 5.1	13.7 ± 3.8	21.9 ± 4.6	19.7 ± 13.3	66 ± 15	71
1000–1200	350–500	5.5 ± 3.0	5.0 ± 4.4	2.9 ± 1.3	$0.4^{+0.7}_{-0.4}$	13.8 ± 5.5	12
1000–1200	>500	2.2 ± 1.7	1.6 ± 1.2	2.3 ± 1.0	$0.0^{+0.2}_{0.0}$	6.1 ± 2.3	4
1200–1400	200–350	3.1 ± 1.8	4.2 ± 2.1	6.2 ± 1.8	11.7 ± 8.3	25.2 ± 8.9	29
1200–1400	>350	2.3 ± 1.5	2.3 ± 1.4	$0.6^{+0.8}_{-0.6}$	$0.2^{+0.6}_{-0.2}$	5.4 ± 2.3	8
>1400	>200	3.2 ± 1.8	2.7 ± 1.6	1.1 ± 0.5	12.0 ± 9.1	19.0 ± 9.4	16

background prediction from the γ + jets event yield is 0.28 ± 0.06 for the baseline selection. The dominant systematic uncertainties on this background estimation originate from the theoretical uncertainty on the γ/Z cross section ratio (20–40%) [40,43], the detector acceptance (5–7%), and the γ reconstruction and isolation efficiency (1–10%), depending on the search regions.

As a cross check, the $Z(\nu\bar{\nu})$ + jets background is also estimated using $Z(\mu^+\mu^-)$ + jets events by treating muons as neutrinos and correcting for the acceptance and efficiencies of the $Z(\mu^+\mu^-)$ + jets event selection and the ratio of branching fractions $\mathcal{B}(\rightarrow \nu\bar{\nu})/\mathcal{B}(\rightarrow \mu^+\mu^-) = 5.95 \pm 0.02$ [45]. The $Z(\nu\bar{\nu})$ + jets background estimated with this method is found to be consistent with the one from the γ + jets events.

The $W(\ell\nu)$ + jets events ($\ell = e$ or μ) from W or top quark production constitute a background when an electron or muon is not identified or is nonisolated and therefore passes the lepton veto. This background is estimated from a μ + jets control sample, selected with the same criteria as those used for the search, except that we require exactly one rather than zero isolated μ. The transverse mass $m_T = \sqrt{2p_T^\mu \not\!\!E_T[1 - \cos(\Delta\phi)]}$ is required to be less than 100 GeV in order to select events containing a $W \rightarrow \mu\nu$ decay and to suppress possible new physics signal contamination, i.e., the signal events resulting in the μ + jets sample used for the background estimation. Here, $\not\!\!E_T$ is the missing transverse energy [31], and $\Delta\phi$ is the azimuthal angle between the μ and the $\not\!\!E_T$. Events are weighted according to $(1/\epsilon_{\text{iso}}^{\mu})[(1-\epsilon_{\text{reco}}^{e,\mu})/\epsilon_{\text{reco}}^{\mu}]$ and $(\epsilon_{\text{reco}}^{e,\mu}/\epsilon_{\text{reco}}^{\mu})[(1-\epsilon_{\text{iso}}^{e,\mu})/\epsilon_{\text{iso}}^{\mu}]$ in order to predict events with unidentified leptons and nonisolated leptons, where $\epsilon_{\text{reco}}^{e,\mu}$ and $\epsilon_{\text{iso}}^{e,\mu}$ are the reconstruction and isolation efficiencies of the electrons and muons. The lepton reconstruction efficiencies are obtained from MC simulation, while the isolation efficiencies are extracted by applying a "tag-and-probe" method [46] on the $Z(\ell^+\ell^-)$ + jets events in data. The lepton reconstruction and identification efficiencies are parametrized in lepton p_T and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ relative to the closest jet, in order to account for the kinematic differences between $Z(\ell^+\ell^-)$ + jets events and the $t\bar{t}$ and W + jets events. Leptons that are out of acceptance and events lost due to the m_T requirement are accounted for using factors determined from simulation. This background estimation method based on the collision data is validated by applying it to a MC sample and comparing the predicted and the true detector-level background distributions.

The predicted background for each search region is listed in Table I. On this background estimation, low statistics in the μ + jets control sample are the dominant source of uncertainty in most of the search regions. The modeling of the lepton reconstruction and isolation efficiencies yields a 10% uncertainty. An additional uncertainty of 4–20% varying for different search regions is assigned based on the statistical power of the validation of this background estimation method. A 3% uncertainty accounts for the effect of the presence of QCD, Z, or diboson events in the μ + jets sample, which are modeled by MC simulation.

The background from the hadronic decay of τ leptons (τ_h) is estimated from a sample of μ + jets events, selected from inclusive μ or $\mu+ \geq 2$-jet triggers by requiring exactly one μ with $p_T > 20$ GeV and $|\eta| < 2.1$. In this sample, the muon p_T is replaced with a jet p_T taken randomly from a simulated response function for a hadronically decaying τ lepton. The H_T and $\not\!\!H_T$ of the event are recalculated including this τ jet, and the search selections are applied to predict the τ_h background. The τ-jet response function for $p_T^{\text{jet}}/p_T^{\tau}$ is obtained from simulated $t\bar{t}$ and $W(\tau\nu)$ + jets events by matching the reconstructed τ jet with the generated τ. Corrections are applied to account for the trigger efficiency, acceptance, and efficiency of the μ selection, and the ratio of branching fractions $\mathcal{B}(W \rightarrow \tau_h\nu)/\mathcal{B}(W \rightarrow \mu\nu) = 0.69 \pm 0.05$ [45]. This τ_h background estimation method is validated by applying it to the W and $t\bar{t}$ MC samples, and 6–13% uncertainties are assigned mainly to reflect the statistical power of this validation. The other main systematic uncertainties arise from the μ acceptance ($\leq 13\%$); the τ-jet response function ($\leq 20\%$); and the subtraction of residual QCD multijet, $Z(\mu^+\mu^-)$ + jets, and $(t\bar{t}/W) \rightarrow \tau\nu + X \rightarrow \mu\nu + X$ backgrounds ($\leq 2\%$), where the quoted uncertainties apply to all search regions.

The QCD background is estimated from collision data [7] recorded with a set of triggers having an H_T threshold ranging from 150 to 700 GeV. The data samples used include the electroweak contributions not removed by the lepton veto and any potential new physics events; however, their cross section is negligible compared to the QCD multijet cross section. First, the p_T values of the jets with $p_T > 15$ GeV in these events are adjusted within the jet p_T resolution, using a kinematic fit such that the events are balanced in the transverse plane. The jet p_T values in the rebalanced events are then smeared with the measured jet resolutions to predict the QCD multijet background. The jet p_T response functions are determined as a function of p_T and η using a QCD multijet MC sample that includes heavy-flavor quarks. The width and tail of the p_T response functions are subsequently adjusted to account for the differences in the resolutions measured in simulation and in data [26]. The width (σ) of the Gaussian part of the simulated response is 5 (30)% narrower than what is observed in the data for $|\eta| < 0.5$ $(2.3 < |\eta| < 5.0)$. After correcting for this difference, the fraction of jets with response more than 2.5σ away from the mean value is consistent with that in the data within uncertainties. The main uncertainties in this QCD estimation method arise from the shape of the jet response functions, including the Gaussian width, the tails, the heavy-flavor contribution, and the effect of pileup on jets in an event. The method has been validated in simulated QCD multijet events within the statistical uncertainties (30–50%), which are assigned as an additional uncertainty. The total uncertainty adds up to 60–70%.

The predicted yields of the SM background and the number of events observed in data are summarized in Table I for the 14 search regions. Figure 1 shows the H_T and $\not{H}_\mathrm{T}$ distributions predicted for the SM background, together with those observed in data. The data are consistent with the SM background estimates.

The 95% confidence level (C.L.) upper limits on the CMSSM signal cross section are set using a modified frequentist CL_s method, taking the profile likelihood as a test statistic [47–49]. The results from 14 exclusive search regions are combined into one test statistic considering the bin-to-bin correlations of the systematic uncertainties. The CMSSM model has five independent parameters: the universal scalar and gaugino masses at the grand unification scale, m_0 and $m_{1/2}$; the trilinear coupling, A_0; the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$; and the sign of the Higgsino mixing parameter, μ. The signal cross section is calculated at NLO and next-to-leading-log (NLL) accuracy [50–52]. The H_T and $\not{H}_\mathrm{T}$ distributions predicted for a low-mass CMSSM benchmark parameter set LM5, $m_0 = 230$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$, are shown in Fig. 1.

The acceptance times efficiency of the event selection for signal events is evaluated using the simulated CMSSM samples. The uncertainties on the background predictions, the luminosity determination (2.2%) [16], the signal acceptance and efficiency arising from the jet energy correction (8%), the jet energy resolution (2%), the PDF (6%), the trigger inefficiency (2%), and the event cleaning [31] (3%) are taken into account by the limit-setting procedure. The possible overprediction of the backgrounds due to the presence of the signal in the data samples used for the background prediction is estimated to be about 3–20%, depending on $(m_0, m_{1/2})$ values, and subtracted when testing for the signal + background hypothesis in the CL_s method.

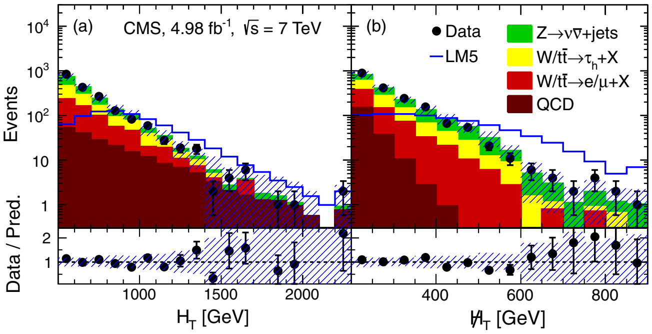

FIG. 1 (color online). The (a) H_T and (b) $\not{H}_\mathrm{T}$ distributions in the search data samples (circles) compared with histograms showing predictions of the SM background and SUSY signal (LM5, see the text) for events passing the baseline selection. The hatched region indicates the uncertainties on the background predictions. The last bin contains all events above the maximum values of H_T and $\not{H}_\mathrm{T}$ in the figures. The ratio of the observed data to the background predictions is also shown.

The upper limits on the CMSSM signal cross section are mapped into lower limits in the $(m_0, m_{1/2})$ plane (exclusion contour), as shown in Fig. 2 [32,53]. The exclusion contours are also shown for the cases in which the signal cross section is varied by changing the renormalization and factorization scales by a factor of 2 and using the PDF4LHC recommendation [54] for the PDF uncertainty to illustrate the sensitivity of the exclusion to the signal cross section uncertainty. Conservatively, using the -1σ theory uncertainty values on the observed limit, squark masses below 1.2 TeV and gluino masses below 0.72 TeV are excluded for the chosen CMSSM parameter set.

The search results are also presented in a more general context of simplified models [20,21] of new particles ($\tilde{q}$ or $\tilde{g}$) decaying to one or two jets and an undetectable weakly interacting particle ($\tilde{\chi}^0$). The model used here includes the production of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ pairs and their decays for a wide range of $(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ values, and other SUSY particles are decoupled by being given masses beyond the reach of the LHC. The signal acceptance times efficiency [32] and its uncertainty are evaluated in the same way as used for the CMSSM but using the simulated simplified model signal samples. The observed and expected 95% C.L. upper limits on the signal cross section of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production are shown in Fig. 3 in the

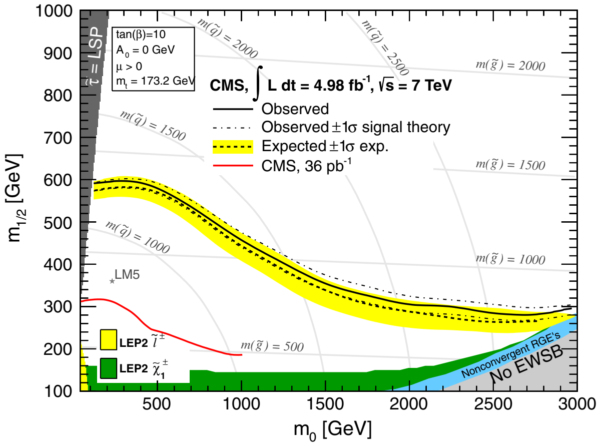

FIG. 2 (color online). The observed and expected 95% C.L. limits in the CMSSM $(m_0, m_{1/2})$ plane. The shaded region around the expected limit shows the $\pm 1\sigma$ variation in the expected limit, while the dot-dashed curves show the variation in the observed limit when the signal cross section is varied by its theoretical uncertainties. The remaining CMSSM parameters are $\tan\beta = 10$, $\mu > 0$, and $A_0 = 0$. The limits from an earlier CMS search [7] and from other experiments [55] are also shown. The limits from Ref. [7] are shown only up to 1000 GeV in m_0, as done in [7]. The regions where the superpartner of the τ lepton ($\tilde{\tau}$) is the LSP, the renormalization group equations (RGEs) do not converge, or there is no electroweak symmetry breaking (EWSB) [53], are also indicated.

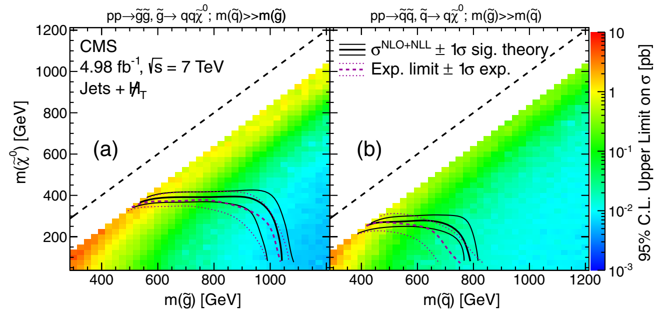

FIG. 3 (color online). The observed and expected 95% C.L. upper limits on the (a) $\tilde{g}\tilde{g}$ and (b) $\tilde{q}\tilde{q}$ cross sections in the $(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ planes obtained with the simplified model. Also shown are the $\pm 1\sigma$ variation in the expected limit and the variation in the observed limit when the signal cross section is varied by its theoretical uncertainties.

$(m(\tilde{g}), m(\tilde{\chi}^0))$ and $(m(\tilde{q}), m(\tilde{\chi}^0))$ planes, together with contours where the signal cross sections from the NLO + NLL calculations [50–52] are excluded. The results are presented only in the region of $m(\tilde{g}, \tilde{q}) - m(\tilde{\chi}^0) > 150$ GeV, since the estimation of signal acceptance times efficiency becomes unreliable due to its strong dependence on the modeling of QCD radiation when the mass difference $m(\tilde{g}, \tilde{q}) - m(\tilde{\chi}^0)$ is smaller. In this model, the $m(\tilde{g})$ values below 1.0 TeV and $m(\tilde{q})$ values below 0.76 TeV are excluded for $m(\tilde{\chi}^0) < 200$ GeV.

In summary, a search for new physics has been performed in the final state with at least three jets and large $H\!\!\!/_T$ using a data sample corresponding to an integrated luminosity of 4.98 fb^{-1} collected in 7 TeV pp collisions with the CMS detector at the LHC. The observed numbers of events are consistent with the estimated SM background contributions, and 95% C.L. exclusion limits are set in the CMSSM parameter space which significantly extend the previous results. For the simplified models of $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production, the $m(\tilde{g})$ values below 1.0 TeV and $m(\tilde{q})$ values below 0.76 TeV are excluded for $m(\tilde{\chi}^0) < 200$ GeV.

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