

Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

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Search for Supersymmetry at the LHC in Events with Jets and Missing Transverse Energy

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A search for events with jets and missing transverse energy is performed in a data sample of pp collisions collected at $\sqrt{s} = 7$ TeV by the CMS experiment at the LHC. The analyzed data sample corresponds to an integrated luminosity of 1.14 fb^{-1} . In this search, a kinematic variable α_T is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. No excess of events over the standard model expectation is found. Exclusion limits in the parameter space of the constrained minimal supersymmetric extension of the standard model are set. In this model, squark masses below 1.1 TeV are excluded at 95% C.L. Gluino masses below 1.1 TeV are also ruled out at 95% C.L. for values of the universal scalar mass parameter below 500 GeV.

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The standard model (SM) of particle physics is generally considered to be valid only at low energy scales and is expected to be superseded by a more complete theory at higher scales. Supersymmetric (SUSY) extensions to the SM [1–8] introduce a large number of new particles with the same quantum numbers as their SM partners, but differing by half a unit of spin. If R -parity conservation [9] is assumed, supersymmetric particles, such as squarks and gluinos, are produced in pairs and decay to the lightest, stable supersymmetric particle (LSP). If the LSP is neutral and weakly interacting, a typical signature is a final state of multijets accompanied by significant missing transverse energy, \cancel{E}_T . Experiments at the Tevatron [10–13], $S\bar{p}\bar{p}S$ [14,15], HERA [16,17], and LEP [18] colliders have performed extensive searches for signs of SUSY. In 2010, the Large Hadron Collider (LHC) at CERN delivered an integrated luminosity of almost 50 pb^{-1} at a center-of-mass energy $\sqrt{s} = 7$ TeV, leading to several new searches from both the ATLAS Collaboration [19–22] and CMS Collaboration [23–27].

This Letter presents a search for SUSY based on a data sample corresponding to an integrated luminosity of $1.14 \pm 0.05 \text{ fb}^{-1}$. The search strategy follows Ref. [23] and is designed to be sensitive to \cancel{E}_T signatures in events with two or more energetic jets. The search is not optimized for any particular model of SUSY and is applicable to other new physics scenarios with a \cancel{E}_T signature. In this Letter, nevertheless, the results are interpreted in the constrained minimal supersymmetric extension of the standard model (CMSSM) [28–30]. The CMSSM is described by the following five parameters: the universal scalar and

gaugino mass parameters, m_0 and $m_{1/2}$; the universal trilinear soft SUSY-breaking parameter, A_0 ; the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$; and the sign of the Higgs mixing parameter, μ . We consider only parameter sets for which the LSP is the lightest neutralino. The following example parameter set, referred to as LM6, is used to illustrate possible CMSSM yields: $m_0 = 85 \text{ GeV}$, $m_{1/2} = 400 \text{ GeV}$, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$.

A detailed description of the CMS apparatus can be found in Ref. [31]. Its central feature is a superconducting solenoid providing an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with several particle detection systems. Charged particle trajectories are measured by a silicon pixel and strip tracker system, with full azimuth (ϕ) coverage and a pseudorapidity (η) acceptance from -2.5 to $+2.5$. Here, $\eta \equiv -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise beam direction. A lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass or scintillator hadron calorimeter surround the tracking volume and provide coverage in η from -3 to $+3$. The forward hadron calorimeter extends symmetrically the coverage by a further two units in η . Muons are identified in gas ionization detectors embedded in the steel return yoke of the magnet. The CMS detector is nearly hermetic, which allows for momentum-balance measurements in the plane transverse to the beam axis.

The offline event reconstruction and selection criteria described below are explained in more detail in Ref. [23]. Jets are reconstructed from the energy deposits in the calorimeter towers, clustered by the anti- k_T algorithm [32] with a size parameter of 0.5. The raw jet energies measured by the calorimeter systems are corrected to establish a uniform relative response in η and a calibrated absolute response in transverse momentum p_T with an associated uncertainty between 2% and 4%, depending on the jet η and p_T [33]. Jets considered in the analysis

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are required to have transverse energy $E_T > 50$ GeV. Events are vetoed if any additional jet satisfies $E_T > 50$ GeV and $|\eta| > 3$, or rare, spurious signals are identified in the calorimeters [34,35]. The highest- E_T jet is required to be within the central tracker acceptance and the two highest- E_T jets must each have $E_T > 100$ GeV. To suppress SM processes with genuine \cancel{E}_T from neutrinos, events containing an isolated electron [36] or muon [37] with $p_T > 10$ GeV are vetoed. To select a pure multijet topology, events are vetoed in which an isolated photon [38] with $p_T > 25$ GeV is found.

The following two variables characterize the visible energy and missing momentum in the transverse plane: the scalar sum of the transverse energy E_T of jets, defined as $H_T = \sum_{i=1}^{N_{\text{jet}}} E_{T,i}$, and the magnitude of the vector sum of the transverse momenta \vec{p}_T of jets, defined as $H_T = |\sum_{i=1}^{N_{\text{jet}}} \vec{p}_{T,i}|$, where N_{jet} is the number of jets with $E_T > 50$ GeV. Significant hadronic activity in the event is ensured by requiring $H_T > 275$ GeV. Following these selections, the background from multijet production, a manifestation of quantum chromodynamics (QCD), is still several orders of magnitude larger than the typical signal expected from SUSY. While the bulk of these multijet events do not exhibit significant \cancel{E}_T , large values can be observed due to stochastic fluctuations in the measurement of jet energies or mismeasurements caused by nonuniformities in the calibration of the calorimeters or detector inefficiencies.

The α_T kinematic variable, first introduced in Refs. [39–41], is used in the selection to efficiently reject events either without significant \cancel{E}_T or with transverse energy mismeasurements, while retaining a large sensitivity to new physics with genuine \cancel{E}_T signatures. For events with two jets, the variable is defined as $\alpha_T = E_T^{j_2} / M_T = E_T^{j_2} / \sqrt{H_T^2 - H_T^{j_1^2}}$, where $E_T^{j_2}$ is the transverse energy of the less-energetic jet, and M_T is the transverse mass of the dijet system. For a perfectly measured dijet event with $E_T^{j_1} = E_T^{j_2}$ and jets back to back in ϕ , and in the limit of large jet momenta compared to their masses, the value of α_T is 0.5. In the case of an imbalance in the measured transverse energies of back-to-back jets, α_T is smaller than 0.5. Values significantly greater than 0.5 are observed when the two jets are not back to back and balancing genuine \cancel{E}_T . For events with three or more jets, a dijet system is formed by combining the jets in the event into two *pseudojets*. The total E_T of each of the two pseudojets is calculated as the scalar sum of the measured E_T of contributing jets. The combination chosen is the one that minimizes the E_T difference between the two pseudojets. This simple clustering criterion provides the best separation between QCD multijet events and events with genuine \cancel{E}_T . Events with multiple jets with $E_T < 50$ GeV or with severe jet energy undermeasurements due to detector inefficiencies can lead to values of α_T slightly above 0.5. Such events are

effectively rejected by requiring $\alpha_T > 0.55$ and by applying dedicated vetoes, described further in Ref. [23]. These final selections complete the definition of the hadronic signal sample. A disjoint hadronic control sample consisting predominantly of QCD multijet events is defined by requiring $\alpha_T < 0.55$.

As can be seen in Fig. 1, the only expected remaining backgrounds with $\alpha_T > 0.55$ stem from SM processes with genuine \cancel{E}_T in the final state. In the dijet case, the largest backgrounds with genuine \cancel{E}_T are the associated production of W or Z bosons with jets, followed by either the weak decays $Z \rightarrow \nu\bar{\nu}$ or $W \rightarrow \tau\nu$, where the τ decays hadronically and is identified as a jet, or by leptonic decays that are not rejected by the dedicated electron or muon vetoes. At higher jet multiplicities, top quark production, followed by semileptonic weak top quark decay, becomes important.

Events in the hadronic signal sample are recorded with a trigger condition that identifies candidate events with energetic jets and significant \cancel{E}_T . Events are selected if they have $H_T > 250$ GeV and \cancel{E}_T above a threshold that evolves with instantaneous luminosity, from 60 to 90 GeV. In the region $275 < H_T < 325$ GeV, the efficiency with which events satisfying the full reconstruction and selection criteria are triggered is $0.99^{+0.01}_{-0.02}$. For events with $H_T > 325$ GeV, the efficiency is $1.00^{+0.00}_{-0.03}$. A set of pre-scaled H_T trigger conditions are used to record events for the hadronic control sample.

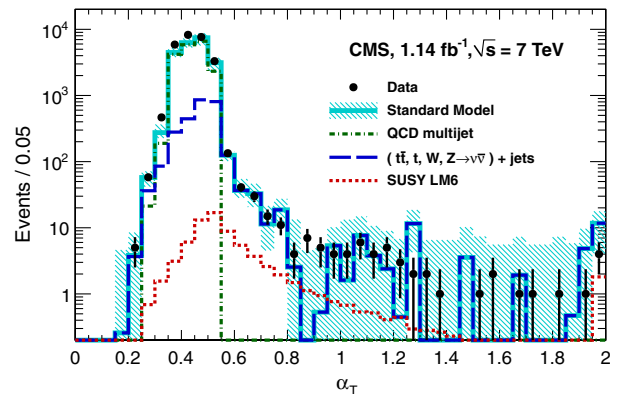


FIG. 1 (color online). The distribution of α_T , described in the text, for events in data with two or more jets (black dots with error bars representing the statistical uncertainties), after all event selection criteria except α_T are applied and $H_T > 375$ GeV. For illustrative purposes only, expected yields from simulation are also shown for QCD multijet events (dot-dashed line), associated production of top quarks, W , or Z with jets (long-dashed line), the sum of all aforementioned SM processes (solid line) and the SUSY LM6 model (dotted line). The uncertainties for the SM expectation, due to the limited accuracy of the available simulation data sets and jet energy calibrations, are represented by the hatched area. The highest bin contains the overflows.

The analysis makes use of two additional data samples to estimate the backgrounds with genuine \cancel{E}_T . First, a $\mu + \text{jets}$ sample is recorded with the hadronic trigger condition described above. The event selection, following closely the prescription described in Ref. [42], requires a single, isolated muon with $p_T > 10$ GeV in the final state and the transverse mass of the muon and H_T system to be larger than 30 GeV to ensure a sample rich in W bosons. The muon is required to be separated from the closest jet in the event by $\Delta\eta$ and $\Delta\phi$ such that the distance $\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5$. Second, a $\gamma + \text{jets}$ sample is selected using a dedicated photon trigger condition requiring a localized, large energy deposit in the ECAL with $p_T > 90$ GeV and that satisfies loose photon identification and isolation criteria [38]. The offline selection requires a single photon to be reconstructed with $p_T > 100$ GeV, $|\eta| < 1.45$, satisfying tight isolation criteria, and with a minimum distance to any jet of $\Delta R > 1.0$. For these selection criteria, the photon trigger condition is found to be fully efficient.

The hadronic signal region is divided into eight bins of H_T : two bins of width 50 GeV in the range $275 < H_T < 375$ GeV, five bins of width 100 GeV in the range $375 < H_T < 875$ GeV, and a final open bin, $H_T > 875$ GeV. As in Ref. [23], jet E_T thresholds are scaled down from their nominal values in the lowest two H_T bins to maintain jet multiplicities and thus comparable event kinematics, topologies, and background composition throughout the entire H_T range. The background estimation methods described below are combined in the statistical interpretation of the observed data yields to provide a single prediction of the SM background in each H_T bin of the hadronic signal region. With respect to Ref. [23], these refinements provide greater sensitivity across a broader SUSY parameter space and, in the context of CMSSM, up to higher-mass states.

The $\mu + \text{jets}$ data sample provides an estimate of the contributions from top quark and W production (leading to $W + \text{jets}$ final states) still remaining in each H_T bin of the hadronic signal region after all selection criteria are applied. Factors obtained from simulation [23] are then used to translate the yields in the $\mu + \text{jets}$ sample to estimates in each H_T bin of the hadronic signal region. These factors are found to be only weakly dependent on H_T , ranging from 1.14 at low H_T to 0.90 at high H_T . Conservative uncertainties on all the parameters entering these translation factors are assigned. The total systematic uncertainty is estimated to be 30%, dominated by the uncertainty on the efficiency for vetoing leptons. The remaining irreducible background of $Z \rightarrow \nu\bar{\nu} + \text{jets}$ events in the hadronic signal sample is estimated from $\gamma + \text{jets}$ events. These two processes have similar kinematic properties when the photon is ignored [43,44], while the latter has a larger production cross section. Translation factors that account for the ratio of cross sections for $\gamma + \text{jets}$ and $Z \rightarrow \nu\bar{\nu} + \text{jets}$, and their relative acceptances, are obtained from simulation [23] and

are used to estimate the number of $Z \rightarrow \nu\bar{\nu} + \text{jets}$ events in each H_T bin of the hadronic signal region. As is the case of the $\mu + \text{jets}$ sample, these translation factors are only weakly dependent on H_T , ranging from 0.35 at low H_T to 0.45 at high H_T . The main systematic uncertainties on these factors are associated with the ratio of cross sections between $\gamma + \text{jets}$ and $Z \rightarrow \nu\bar{\nu} + \text{jets}$ in the simulation (30%), the efficiency for photon identification (20%), and the purity of the photon selection (20%), which add up in quadrature to 40%. These uncertainty estimates are verified by predicting the number of $\mu + \text{two-jet}$ events in each H_T bin using the $\gamma + \text{two-jet}$ sample. The requirement of exactly two jets suppresses the top quark contribution in the muon sample, thus leaving a relatively pure $W + \text{jets}$ sample that is kinematically similar to the $Z \rightarrow \nu\bar{\nu} + \text{jets}$ sample. The predicted and observed event yields are consistent within the assigned systematic uncertainties.

Furthermore, the H_T dependence of the ratio R_{α_T} is exploited to constrain the SM background estimate for each H_T bin. This ratio is defined as the number of events with α_T above and below a threshold value of 0.55 for a given bin in H_T . The denominator of the ratio is always dominated by events from QCD multijet production and is measured in data with samples selected by the set of prescaled H_T trigger conditions. The chosen α_T threshold ensures that, for a given bin in H_T , the numerator of the ratio is dominated by events from SM processes with genuine \cancel{E}_T from neutrinos, with no significant contribution from QCD multijet production. As observed in Ref. [23], this property leads to R_{α_T} being independent of H_T . The remaining backgrounds are those with genuine \cancel{E}_T from associated production of top quarks, W , or Z with jets. By relaxing the α_T threshold to values lower than 0.55, the numerator is instead dominated by mismeasured QCD multijet events, and an exponential dependence of R_{α_T} on H_T is observed [23]. The behaviors of α_T and $R_{\alpha_T}(H_T)$ are observed in data and simulation to be robust against the effects of multiple pp collisions per beam crossing (pileup). In the statistical interpretation of the analysis, $R_{\alpha_T}(H_T)$ is modeled as a superposition of a H_T -independent contribution from SM processes with genuine \cancel{E}_T , and an exponentially falling contribution to accommodate any potential QCD contamination. The latter is considered even though no evidence of a significant QCD contamination is found in the hadronic signal region.

To obtain an accurate and consistent prediction of the SM background, a simultaneous binned likelihood fit using information from all three data samples is performed. The fit maximizes the likelihood $L_{\text{total}} = L_{\text{hadronic}} \times L_{\mu+\text{jets}} \times L_{\gamma+\text{jets}}$, where L_{hadronic} characterizes $R_{\alpha_T}(H_T)$ in the hadronic sample with a single exponential function, Ae^{-kH_T} , to accommodate any QCD contamination and a constant, H_T -independent contribution, B , to describe SM processes with genuine \cancel{E}_T . The likelihoods $L_{\mu+\text{jets}}$ and $L_{\gamma+\text{jets}}$ describe the H_T -dependent yields in the $\mu + \text{jets}$ and

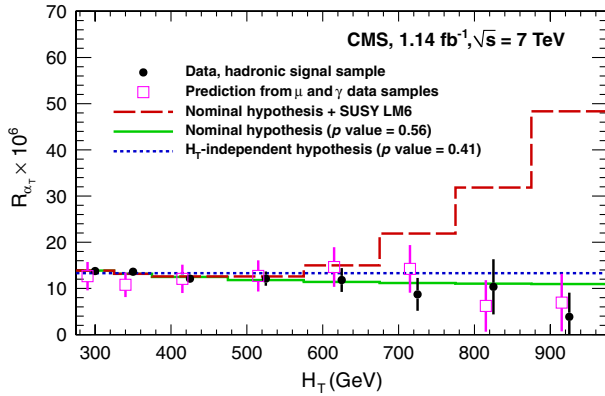


FIG. 2 (color online). The ratio R_{α_T} as a function of H_T , as measured in the hadronic data samples (black dots with error bars representing the statistical uncertainties). The ratios using the direct predictions from the μ + jets and γ + jets samples are shown as open squares (offset for clarity, with error bars representing the statistical and systematic uncertainties). Also shown is the result of the simultaneous fit to the three data samples (solid line); the analogous result when assuming a H_T -independent hypothesis (dotted line); and, for illustrative purposes only, the expectation from the SUSY LM6 model when superimposed on the nominal fit result (long-dashed line).

γ + jets samples. For each H_T bin, these yields are related to the numerator of $R_{\alpha_T}(H_T)$, measured in the hadronic signal sample, via the translation factors from the simulation.

With a fit probability (p value) of 0.56, the hypothesis for the R_{α_T} dependence on H_T reproduces the data well, as shown in Fig. 2. The only parameter with a significant nonzero value as determined by the fit is the constant term $B = (1.1 \pm 0.2) \times 10^{-5}$. The other two fit parameters, $A = (1.4 \pm 1.9) \times 10^{-5}$ and $k = (5.2 \pm 5.6) \times 10^{-3} \text{ GeV}^{-1}$, are compatible with zero, indicating that no significant QCD contamination has been observed in the signal region. Furthermore, as a cross check, the fit is repeated with the assumption that R_{α_T} is independent of H_T , which in turn implies that the numerator of the ratio is fully dominated by SM backgrounds with genuine \cancel{E}_T . The result of this fit, shown in Fig. 2, has a p value of 0.41 and is in good agreement with the nominal fit.

To validate the background estimation of the simultaneous fit, the μ + jets and γ + jets samples are used to

predict directly the SM backgrounds with genuine \cancel{E}_T in the different H_T bins, independently of the fit. The prediction for each H_T bin is taken as the numerator of the ratio R_{α_T} , and the observed behavior in H_T is shown in Fig. 2. This cross-check confirms, within the statistical and systematic uncertainties, the H_T independence of R_{α_T} when the numerator is dominated by SM events with genuine \cancel{E}_T .

The fit results for all three data samples are listed in Table I, along with the observed yields in the data. Good agreement between the measured H_T distribution and the fit is observed for all three data samples, indicating that the observed yields are compatible with the SM background expectation provided by the fit. The uncertainties listed with the SM predictions are obtained from an ensemble of pseudoexperiments. Figure 3 compares the result of the simultaneous fit to the observed yields in the hadronic signal sample.

Given the lack of an excess of events above the expected SM backgrounds, limits are set in the parameter space of the CMSSM. At each point of the parameter space, the SUSY particle spectrum is calculated with SOFTSUSY [45], and the signal events are generated at leading order with PYTHIA 6.4 [46]. Inclusive, process-dependent, next-to-leading-order (NLO) cross sections, obtained with the program PROSPINO [47], are used to calculate the observed and expected exclusion contours. The simulated signal events are reweighted so that the distribution of number of pileup events per beam crossing from the simulation matches that observed in data. Uncertainties on the SM background prediction, the luminosity measurement (4.5%) [48], the total acceptance times efficiency of the selection for the considered signal model (4.5%) [23,49], and NLO cross section and parton distribution functions (10%) are included in the limit. Although signal contributions to the total yield in each of the three considered data samples are allowed, the only relevant signal contribution originates from the hadronic data sample in the case of the CMSSM.

Figure 4 shows the observed and expected exclusion limits at 95% confidence level (C.L.) in the $(m_0, m_{1/2})$ plane for $\tan\beta = 10$ and $A_0 = 0 \text{ GeV}$, calculated with the CL_s method [50]. For this choice of parameters in the CMSSM, squark masses below 1.1 TeV are excluded and gluino masses below the same value are ruled out for

TABLE I. Comparison of the measured yields in the different H_T bins for the hadronic, μ + jets and γ + jets samples with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

H_T bin (GeV)	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
SM hadronic	787^{+32}_{-22}	310^{+8}_{-12}	202^{+9}_{-9}	$60.4^{+4.2}_{-3.0}$	$20.3^{+1.8}_{-1.1}$	$7.7^{+0.8}_{-0.5}$	$3.2^{+0.4}_{-0.2}$	$2.8^{+0.4}_{-0.2}$
Data hadronic	782	321	196	62	21	6	3	1
SM μ + jets	367^{+15}_{-15}	182^{+8}_{-9}	113^{+8}_{-7}	$36.5^{+3.8}_{-3.3}$	$13.4^{+2.2}_{-1.8}$	$4.0^{+1.4}_{-1.2}$	$0.8^{+0.9}_{-0.1}$	$0.7^{+0.9}_{-0.1}$
Data μ + jets	389	156	113	39	17	5	0	0
SM γ + jets	834^{+28}_{-30}	325^{+17}_{-17}	210^{+12}_{-12}	$64.7^{+6.9}_{-7.0}$	$21.1^{+3.9}_{-4.3}$	$10.5^{+2.5}_{-2.6}$	$6.1^{+0.9}_{-1.7}$	$5.5^{+0.9}_{-1.6}$
Data γ + jets	849	307	210	67	24	12	4	4

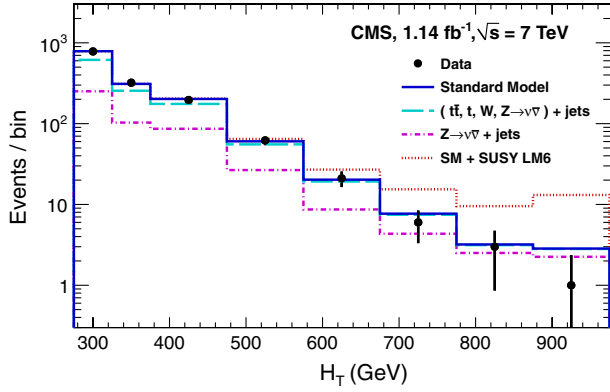


FIG. 3 (color online). The observed event yields versus H_T in the hadronic signal sample (black dots with error bars representing the statistical uncertainties). Also shown are the expectations given by the simultaneous fit for the $Z \rightarrow \nu\bar{\nu} + \text{jets}$ process (dot-dashed line); the associated production of top, W , or Z with jets (long-dashed line); the sum of QCD and all aforementioned processes (solid line); and, for illustrative purposes only, the SUSY LM6 model superimposed on the SM expectation (dotted line).

$m_0 < 500$ GeV. The exclusion limit changes at most by 20 GeV in the $(m_0, m_{1/2})$ plane for different parameter values (e.g., $\tan\beta = 40$ and $A_0 = -500$ GeV), indicating that the limit is only weakly dependent on these parameters.

In summary, the first search for supersymmetry from CMS based on an integrated luminosity in excess of 1 fb^{-1} has been reported. Final states with two or more jets and significant \cancel{E}_T , as expected from high-mass squark and gluino production and decays, have been analyzed. The search has been performed in eight bins of the scalar sum of the transverse energy of jets, H_T , considering events with H_T in excess of 275 GeV. The sum of standard model backgrounds per H_T bin has been estimated from

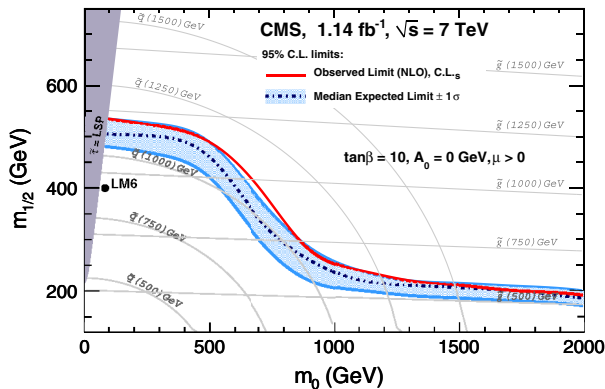


FIG. 4 (color online). Observed and expected 95% C.L. exclusion contours in the CMSSM $(m_0, m_{1/2})$ plane ($\tan\beta = 10$, $A_0 = 0$, $\mu > 0$) using NLO signal cross sections with the $C.L._s$ method. The expected limit is shown with its 68% C.L. range. The SUSY benchmark model LM6 is also shown.

a simultaneous binned likelihood fit to hadronic, $\mu + \text{jets}$, and $\gamma + \text{jets}$ samples. The observed yields in the eight H_T bins have been found to be in agreement with the expected contributions from standard model processes. Limits on the CMSSM parameters have been derived and squark masses below 1.1 TeV are excluded at 95% C.L. in this model. Gluino masses in the same range are ruled out at 95% C.L. for $m_0 < 500$ GeV. This limit represents a tight constraint on the parameter space of SUSY models like the CMSSM.

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