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Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, or ≥ 3 b-quark jets in 7 TeV pp collisions using the variable α_T

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Abstract: A search for supersymmetry in final states with jets and missing transverse energy is performed in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$. The data sample corresponds to an integrated luminosity of $4.98\,\mathrm{fb}^{-1}$ collected by the CMS experiment at the LHC. In this search, a dimensionless kinematic variable, α_T, is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. The search is performed in a signal region that is binned in the scalar sum of the transverse energy of jets and the number of jets identified as originating from a bottom quark. No excess of events over the standard model expectation is found. Exclusion limits are set in the parameter space of the constrained minimal supersymmetric extension of the standard model, and also in simplified models, with a special emphasis on compressed spectra and third-generation scenarios.

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Contents

1 Introduction

Supersymmetry (SUSY) is generally regarded as one of the likely extensions to the standard model (SM) of particle physics [1–8]. It is based on the unique extension of the space-time symmetry group underpinning the SM, introducing a relationship between fermions and bosons. A low-energy realisation of SUSY, e.g. at the TeV scale, is motivated by the cancellation of the quadratically divergent loop corrections to the Higgs boson mass in the SM [7, 8]. These corrections are proportional to the masses of the particles that couple to the Higgs boson. The most relevant terms come from the interplay between the masses of the third generation (top and bottom) squarks, and the largest Yukawa coupling (of the top quark).

In order to avoid large cancellations in these loop corrections, the difference in masses between the top quark and the third generation squarks must not be too large [9]. While the majority of SUSY particles might not be accessible at the present energy and luminosity delivered by the Large Hadron Collider (LHC), the recent discovery of a low-mass Higgs boson candidate [10, 11] motivates models in which top and bottom squarks appear at the TeV scale. Furthermore, if the multiplicative quantum number R-parity [12] is conserved, SUSY particles will be produced in pairs and decay to SM particles and the lightest SUSY particle (LSP), which is generally assumed to be weakly interacting and massive. This would result in a final state that is rich in jets, especially those originating from bottom quarks, and contains a significant amount of missing transverse energy, $\not{E}_{\mathrm{T}}$.

This paper summarises a search that is designed to be sensitive to missing transverse energy signatures in events with two or more energetic jets that are categorised according to the number of reconstructed jets originating from bottom quarks (b-quark jets) per event. With respect to previous searches [13, 14], this refinement provides improved sensitivity to third generation squark signatures. However, the same inclusive search strategy is deployed, thus maintaining the ability to identify a wide variety of SUSY event topologies arising from the pair production and decay of massive coloured sparticles.

The ATLAS and Compact Muon Solenoid (CMS) experiments have performed various searches [13–21] for the production of massive coloured sparticles and their subsequent decay to a final state of jets and missing transverse energy. These searches were performed with a dataset of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$, and no significant deviations from SM expectations were observed. The majority of these searches have been interpreted in the context of a specific model of SUSY breaking, the constrained minimal supersymmetric extension of the standard model (CMSSM) [22–24]. The simplifying assumption of this model is universality at an energy scale of $\mathcal{O}(10^{16})$ GeV which makes the CMSSM a useful framework to study SUSY phenomenology at colliders, and to serve as a benchmark for the performance of experimental searches.

However, the universality conditions of the CMSSM result in significant restrictions on the possible SUSY particle mass spectra and thus kinematic signatures. This limits the interpretation of the results in scenarios such as the direct production of third-generation squarks and compressed spectra, where the mass difference between the primary produced sparticle (e.g., a squark or a gluino) and the LSP is small. Therefore, in order to complement the interpretation within the CMSSM, simplified models [25–27] are also used to interpret the search results. These models are characterised using a limited set of SUSY particles (production and decay) and enable comprehensive studies of individual SUSY event topologies. The simplified model studies can be performed without limitations on fundamental properties such as decay modes, production cross sections, and sparticle masses. A special emphasis is placed on interpretation within models involving compressed spectra or third generation squarks.

2 The CMS apparatus

The central feature of the CMS detector is a superconducting solenoid, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with several particle detection systems. Silicon pixel and strip tracking systems measure charged particle trajectories with full azimuthal (ϕ) coverage and a pseudorapidity acceptance of $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise beam direction. The resolutions on the transverse momentum (p_{T}) and impact parameter of a charged particle with $p_{\mathrm{T}} < 40\,\mathrm{GeV}$ are typically 1% and 15 μm, respectively. A lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron calorimeter surround the tracking volume. The region outside the solenoid is covered by an iron/quartz-fiber hadron calorimeter. The ECAL covers $|\eta| < 3.0$ and provides an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The hadron calorimeters cover $|\eta| < 5.0$ with a resolution in jet energy, E (GeV), of about $100\%/\sqrt{\mathrm{E}}$ for the region $|\eta| < 3.0$. Muons are identified in gas-ionization detectors, covering $|\eta| < 2.4$, embedded in the steel return yoke. The CMS detector is nearly hermetic, which allows momentum-balance measurements in the plane transverse to the beam axis. A two-tier trigger system is designed to select the most interesting pp collision events for use in physics analysis. A detailed description of the CMS detector can be found elsewhere [28].

3 Object definitions and event reconstruction

The event reconstruction and selection criteria follow the procedure described in refs. [13, 14]. Jets are reconstructed from energy deposits in the calorimeters, clustered by the anti-k_{T} algorithm [29] with a distance 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 with an associated uncertainty between 2% and 4%, depending on the jet η and p_{T} [30]. Jets considered in the analysis are required to have transverse energy $E_{\mathrm{T}} > 50\,\mathrm{GeV}$ and the two highest-E_{T} jets must each satisfy $E_{\mathrm{T}} > 100\,\mathrm{GeV}$. These two E_{T} requirements change under special circumstances described in section 4. The highest-E_{T} jet is additionally required to be within the central tracker acceptance ($|\eta| < 2.5$). Events are vetoed if any additional jet satisfies both $E_{\mathrm{T}} > 50\,\mathrm{GeV}$ and $|\eta| > 3$, or rare, spurious signals are identified in the calorimeters [31]. To suppress SM processes with genuine $\not\!\!E_{\mathrm{T}}$ from neutrinos in the final state, an event is vetoed if it contains an isolated electron [32] or muon [33] with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. Further, events with an isolated photon [34] with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ are also vetoed.

The presence of a b-quark jet is identified through a vertex that is displaced with respect to the primary interaction, using an algorithm that attempts to reconstruct a secondary vertex using tracks from charged particles associated to each jet. Using a likelihood ratio technique, the combined secondary vertex algorithm [35] incorporates several variables related to the vertex, such as decay length significance, mass, and track multiplicity, to build a discriminator that distinguishes between jets originating from bottom quarks and those from other sources. These include jets from charm quarks (c-quark jets) and light-flavour quarks. The algorithm also provides a value for this discriminator based on single-track properties, when no secondary vertices have been reconstructed. Discriminator values above a certain threshold are used to tag jets as originating from b quarks. This threshold is chosen such that the mistagging rate, the probability to tag a jet originating from a light-flavour quark, is approximately 1% for jets with transverse momenta of 80 GeV [35, 36]. The same threshold results in a b-tagging efficiency, the probability to correctly tag a jet as originating from a bottom quark, in the range 60–70% [35, 36].

The following two variables characterise the visible energy and missing momentum in the transverse plane: the scalar sum of the transverse energy E_{T} of jets, defined as $H_{\mathrm{T}} = \sum_{i=1}^{N_{\mathrm{jet}}} E_{\mathrm{T}}^{\mathrm{j}_i}$, and the magnitude of the vector sum of the transverse momenta $\vec{p_{\mathrm{T}}}$ of jets, defined as $\not\!\!H_{\mathrm{T}} = |\sum_{i=1}^{N_{\mathrm{jet}}} \vec{p_{\mathrm{T}}}^{\mathrm{j}_i}|$, where N_{jet} is the number of jets above the E_{T} threshold. Significant hadronic activity in the event is ensured by requiring $H_{\mathrm{T}} > 275\,\mathrm{GeV}$. Following these selections, the background from multijet production, a manifestation of quantum chromodynamics (QCD), is still several orders of magnitude larger than the typical yields expected from a SUSY signal.

4 Selecting events with missing transverse energy

The α_{T} kinematic variable [13, 37] is used to efficiently reject multijet events without significant $\not\!\!E_{\mathrm{T}}$, including those with transverse energy mismeasurements, while retaining a large sensitivity to new physics with genuine $\not\!\!E_{\mathrm{T}}$ signatures. For dijet events, the α_{T} variable is defined as:

$$\alpha_{\mathrm{T}} = \frac{{E_{\mathrm{T}}}^{\mathrm{j}_2}}{M_{\mathrm{T}}}, \qquad M_{\mathrm{T}} = \sqrt{\left(\sum_{i=1}^{2} {E_{\mathrm{T}}}^{\mathrm{j}_i}\right)^2 - \left(\sum_{i=1}^{2} p_x^{\mathrm{j}_i}\right)^2 - \left(\sum_{i=1}^{2} p_y^{\mathrm{j}_i}\right)^2}. \tag{4.1}$$

where ${E_{\mathrm{T}}}^{\mathrm{j}_2}$ 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 ${E_{\mathrm{T}}}^{\mathrm{j}_1} = {E_{\mathrm{T}}}^{\mathrm{j}_2}$ and jets back-to-back in ϕ, and in the limit in which each jet's momentum is large compared with its mass, 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, recoiling against genuine $\not\!\!E_{\mathrm{T}}$.

For events with three or more jets, an equivalent dijet system is formed by combining the jets in the event into two pseudo-jets. The E_{T} of each of the two pseudo-jets is calculated as the scalar sum of the measured E_{T} of the contributing jets. The combination chosen is the one that minimises the E_{T} difference (ΔH_{T}) between the two pseudo-jets. This simple clustering criterion provides the best separation between multijet events and events with genuine $\not\!\!E_{\mathrm{T}}$. Thus, in the case of events with at least three jets, the α_{T} variable can be defined as:

$$\alpha_{\mathrm{T}} = \frac{1}{2} \cdot \frac{H_{\mathrm{T}} - \Delta H_{\mathrm{T}}}{\sqrt{{H_{\mathrm{T}}}^2 - {\not\!\!H_{\mathrm{T}}}^2}} = \frac{1}{2} \cdot \frac{1 - (\Delta H_{\mathrm{T}}/H_{\mathrm{T}})}{\sqrt{1 - (\not\!\!H_{\mathrm{T}}/H_{\mathrm{T}})^2}} \tag{4.2}$$

Events with extremely rare but large stochastic fluctuations in the calorimetric measurements of jet energies can lead to values of α_{T} slightly above 0.5. Such events are rejected by requiring $\alpha_{\mathrm{T}} > 0.55$. A similar behaviour is observed in events with reconstruction failures, severe energy losses due to detector inefficiencies, or jets below the E_{T} threshold that result in significant $\not\!\!H_{\mathrm{T}}$ relative to the value of $\not\!\!E_{\mathrm{T}}$ (as measured by the calorimeter systems, which is not affected by jet E_{T} thresholds). These classes of events are rejected by applying dedicated vetoes, described further in ref. [14]. The leakage above 0.5 becomes smaller with increasing H_{T} due to the increase in average jet energy and thus an improvement in jet energy resolution. Further, the relative impact of jets falling below the E_{T} threshold is reduced as the energy scale of the event (i.e. H_{T}) increases.

The signal region is defined by $H_\mathrm{T} > 275\,\mathrm{GeV}$ and $\alpha_\mathrm{T} > 0.55$, which is divided into eight bins in H_T: two bins of width 50 GeV in the range $275 < H_\mathrm{T} < 375\,\mathrm{GeV}$, five bins of width 100 GeV in the range $375 < H_\mathrm{T} < 875\,\mathrm{GeV}$, and a final open bin, $H_\mathrm{T} > 875\,\mathrm{GeV}$. As in ref. [14], the jet E_T threshold is scaled for the two lowest H_T bins leading to thresholds of 37 GeV and 43 GeV. The two highest-E_T jet thresholds are scaled to 73 GeV and 87 GeV. This approach maintains SM background admixtures and event kinematics similar to those observed for the higher H_T bins. Events are further categorised according to whether they contain exactly zero, one, two, or at least three reconstructed b-quark jets.

Events in the signal region are recorded with a dedicated trigger condition that must satisfy simultaneously the requirements $H_\mathrm{T} > 250\,\mathrm{GeV}$ and $\alpha_\mathrm{T} > 0.53$, with the latter threshold increasing to 0.60 towards the end of 2011 due to higher instantaneous luminosities. The efficiency with which events that would satisfy the signal region selection criteria also satisfy the trigger conditions is measured in data to be $(82.8 \pm 1.1)\%$, $(95.9 \pm 0.9)\%$, and $(> 98.5 \pm 0.9)\%$ for the regions $275 < H_\mathrm{T} < 325\,\mathrm{GeV}$, $325 < H_\mathrm{T} < 375\,\mathrm{GeV}$, and $H_\mathrm{T} > 375\,\mathrm{GeV}$, respectively.

A disjoint hadronic control sample consisting predominantly of multijet events is defined by inverting the α_T requirement for a given H_T region, which is used primarily in the estimation of any residual background from multijet events. These events are recorded by a set of triggers with thresholds only in H_T.

5 Background estimation from data

Once all the signal region selection requirements have been imposed, the contribution from multijet events is expected to be negligible. The remaining significant backgrounds in the signal region stem from SM processes with genuine $\not\!\!E_\mathrm{T}$ in the final state. In the case of events where no b-quark jets are identified, the largest backgrounds with genuine $\not\!\!E_\mathrm{T}$ arise from the production of W and Z bosons in association with jets. The weak decay $\mathrm{Z} \to \nu\bar{\nu}$ is the only significant contribution from Z + jets events. For W + jets events, the two dominant sources are leptonic W decays in which the lepton is not reconstructed or fails the isolation or acceptance requirements, and the weak decay $\mathrm{W} \to \tau\nu$ where the τ decays hadronically and is identified as a jet. Contributions from SM processes such as single-top, Drell-Yan, and diboson production are also expected. For events with one or more reconstructed b-quark jets, $\mathrm{t\bar{t}}$ production followed by semi-leptonic weak decays becomes the most important single background source. For events with only one reconstructed b-quark jet, the contribution of both W + jets and Z + jets backgrounds are of a similar size to the $\mathrm{t\bar{t}}$ background. For events with two reconstructed b-quark jets, $\mathrm{t\bar{t}}$ production dominates, while events with three or more reconstructed b-quark jets originate almost exclusively from $\mathrm{t\bar{t}}$ events, in which at least one jet is misidentified as originating from a bottom quark.

In order to estimate the contributions from each of these backgrounds, three data control samples are used, which are binned in the same way as the signal region. The irreducible background of $\mathrm{Z} \to \nu\bar{\nu}$ + jets events in the signal region is estimated from two independent data samples of $\mathrm{Z} \to \mu\mu$ + jets and γ + jets events, both of which share the kinematic properties of $\mathrm{Z} \to \nu\bar{\nu}$ + jets but have different acceptances. The $\mathrm{Z} \to \mu\mu$ +

jets events have identical kinematic properties to the $Z \to \nu\overline{\nu}$ + jets background when the two muons are ignored, but a smaller branching fraction, while the γ + jets events have similar kinematic properties when the photon is ignored [13, 38], but a larger production cross section. A μ + jets data sample provides an estimate for all other SM backgrounds, which is dominated by $t\bar{t}$ and W production leading to W + jets final states.

The event selection criteria for the control samples are defined to ensure that any potential contamination from multijet events is negligible. Further, the same selection criteria also strongly suppress contributions from a wide variety of SUSY models, including those considered in this analysis. Any potential signal contamination in the data control samples is accounted for in the fitting procedure described in section 6.

5.1 Definition of data control samples

The μ + jets sample is recorded using two different trigger strategies, to account for evolving trigger conditions during the 2011 run. The hadronic trigger condition, combining H_T and α_T, is used for the region $275 < H_T < 375$ GeV. Here, the event selection, following closely the prescription described in ref. [39], requires exactly one isolated muon that satisfies stringent quality criteria, with $p_T > 10$ GeV and $|\eta| < 2.1$. In order for the trigger to be maximally efficient, the requirement $\alpha_T > 0.55$ is also imposed. For the region $H_T > 375$ GeV, the trigger condition requires both a muon above a p_T threshold as high as 40 GeV and $H_T > 300$ GeV. The muon must satisfy $p_T > 45$ GeV in order for the trigger to be maximally efficient, at (91.3 ± 0.1)%. The requirement $\alpha_T > 0.55$ is again imposed when zero b-quark jets are reconstructed per event. For events in which at least one b-quark jet is reconstructed, no α_T requirement is used. This approach increases the statistical precision of predictions derived from event samples containing b-quark jets, while the impact of relaxing the α_T requirement is tested with a dedicated set of closure tests described in section 5.2.

In addition to the requirements described above, further selection criteria are applied. The transverse mass of the muon and $\not\!\!E_T$ system must 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.5$. To ensure that this sample is disjoint from the $\mu\mu$ + jets sample, the event is rejected if a second muon candidate is identified that does not satisfy all quality criteria or is non-isolated or is outside the acceptance, and the two muon candidates have an invariant mass that is within a window of ± 25 GeV around the mass of the Z boson.

The $\mu\mu$ + jets sample follows the same trigger strategy and muon identification criteria as the μ + jets sample. The event selection requires exactly two oppositely charged, isolated muons satisfying stringent quality criteria, and an invariant mass within a window of ± 25 GeV around the mass of the Z boson. Each muon is required to be separated from the nearest jet in the event by the distance $\Delta R > 0.5$. The same α_T requirements are used as for the μ + jets sample.

The γ + jets sample is selected using a dedicated photon trigger condition requiring a localised energy deposit in the ECAL with $E_T > 135$ GeV that satisfies loose photon identification and isolation criteria [34]. The event selection requires $H_T > 375$ GeV, $\alpha_T > 0.55$, and a single photon to be reconstructed with $E_T > 150$ 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.

5.2 Method and systematic studies

The method used to estimate the SM background contributions in the signal region relies on the use of transfer factors, which are functions of H_T and the number of b-quark jets per event, n_b, and are computed separately for each data control sample. These transfer factors are determined from simulation samples generated with MadGraph v4.22 [40] interfaced to pythia 6.4 tune Z2 [41], and the geant 4-based [42] CMS detector simulation. Each factor is defined as the ratio of yields from simulation in a given bin of the signal region, $N_\mathrm{MC}^\mathrm{signal}(H_\mathrm{T}, n_\mathrm{b})$ and the corresponding bin of one control sample, $N_\mathrm{MC}^\mathrm{control}(H_\mathrm{T}, n_\mathrm{b})$. The factors are used to translate the observed yield measured in a control sample bin, $N_\mathrm{obs}^\mathrm{control}(H_\mathrm{T}, n_\mathrm{b})$ into an expectation for one or more SM background processes in the corresponding bin of the signal region, $N_\mathrm{pred}^\mathrm{signal}(H_\mathrm{T}, n_\mathrm{b})$:

$$N_\mathrm{pred}^\mathrm{signal}(H_\mathrm{T}, n_\mathrm{b}) = N_\mathrm{obs}^\mathrm{control}(H_\mathrm{T}, n_\mathrm{b}) \times \frac{N_\mathrm{MC}^\mathrm{signal}(H_\mathrm{T}, n_\mathrm{b})}{N_\mathrm{MC}^\mathrm{control}(H_\mathrm{T}, n_\mathrm{b})} \,. \tag{5.1}$$

In order to maximise sensitivity to potential new physics signatures in final states with multiple b-quark jets, a method that improves the statistical power of the predictions from simulation, particularly for $n_\mathrm{b} \geq 2$, is employed. The distribution of n_b is estimated from generator-level information contained in the simulation, namely the number of reconstruction-level jets matched to underlying b quarks, $n_\mathrm{b}^\mathrm{gen}$, and light quarks, $n_\mathrm{q}^\mathrm{gen}$, per event. All relevant combinations of $n_\mathrm{b}^\mathrm{gen}$ and $n_\mathrm{q}^\mathrm{gen}$ are considered, and event counts are recorded in bins of H_T for each combination $N(n_\mathrm{b}^\mathrm{gen}, n_\mathrm{q}^\mathrm{gen}, H_\mathrm{T})$. The b-tagging efficiency, ϵ, and a flavour-averaged mistagging rate, m, are also determined from simulation for each H_T bin, with both quantities averaged over jet p_T and η. Corrections are applied on a jet-by-jet basis to both ϵ and m in order to match the corresponding measurements with data [35, 36]. This information is sufficient to predict n_b and thus also determine the yield from simulation for a given bin, $N(H_\mathrm{T}, n_\mathrm{b})$:

$$N(H_\mathrm{T}, n_\mathrm{b}) = \sum_{n_\mathrm{b}^\mathrm{gen}+n_\mathrm{q}^\mathrm{gen}=N_\mathrm{jet}} \; \sum_{n_\mathrm{b}^\mathrm{tag}+n_\mathrm{q}^\mathrm{tag}=n_\mathrm{b}} N(n_\mathrm{b}^\mathrm{gen}, n_\mathrm{q}^\mathrm{gen}, H_\mathrm{T}) \times P(n_\mathrm{b}^\mathrm{tag}; n_\mathrm{b}^\mathrm{gen}, \epsilon) \times P(n_\mathrm{q}^\mathrm{tag}; n_\mathrm{q}^\mathrm{gen}, m) \tag{5.2}$$

where $n_\mathrm{b}^\mathrm{tag}$ and $n_\mathrm{q}^\mathrm{tag}$ are the number of times a reconstruction-level b-quark jet originates from an underlying b-quark and light-quark respectively, and $P(n_\mathrm{b}^\mathrm{tag}; n_\mathrm{b}^\mathrm{gen}, \epsilon)$ and $P(n_\mathrm{q}^\mathrm{tag}; n_\mathrm{q}^\mathrm{gen}, m)$ are the binomial probabilities for this to happen. The predicted yields are found to be in good agreement with the yields obtained directly from the simulation in those bins with significant population.

The method exploits the ability to determine precisely $N(n_\mathrm{b}^\mathrm{gen}, n_\mathrm{q}^\mathrm{gen}, H_\mathrm{T})$, ϵ, and m independently of n_b, which means that event yields for a given b-quark jet multiplicity can be predicted with a higher statistical precision than obtained directly from simulation. A precise determination of m is particularly important for events with $n_\mathrm{b} \geq 3$, which occurs

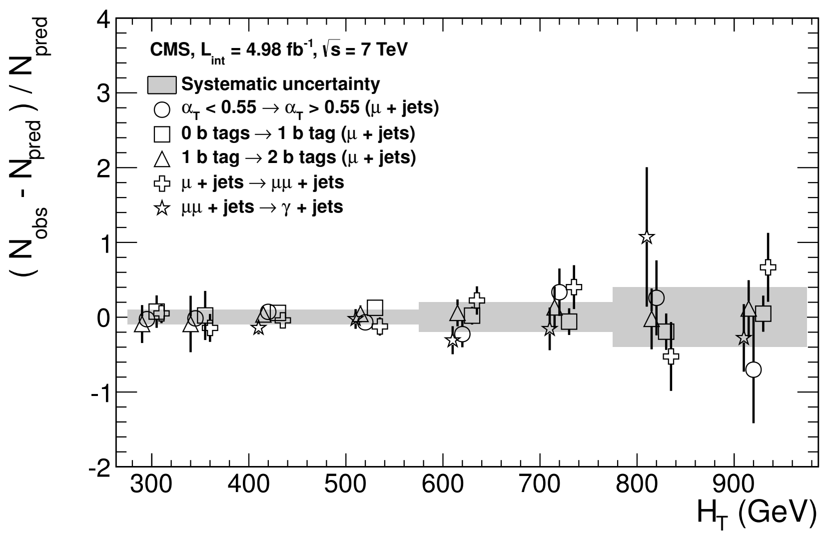

Figure 1. A set of five closure tests, described in the text, that use the three data control samples to probe key ingredients of the simulation modelling of the SM backgrounds, as a function of H_T. Error bars represent statistical uncertainties only. The shaded bands represent the H_T-dependent systematic uncertainties assigned to the transfer factors.

in the SM because of the presence of mistagged jets in the event. In this case, the largest background is $t\bar{t}$, with two correctly tagged b-quark jets and an additional mistagged jet.

The magnitudes of the transfer factors are dependent on the control sample and independent of the b-quark jet multiplicity, within statistical uncertainties. For the γ + jets sample, the factors are also independent of H_T with values of approximately 0.4. For the μ + jets and $\mu\mu$ + jets control samples, for which the α_T requirement is dropped from the selection criteria in the region $H_T > 375\,\text{GeV}$, the factors decrease smoothly with increasing HT and are in the ranges 0.2 to 0.05 and 2 to 0.33, respectively. This variation arises from W + jets and Z + jets events in the signal region, for which the efficiency of the $\alpha_T > 0.55$ requirement is dependent on H_T.

A systematic uncertainty is assigned to each transfer factor to account for theoretical uncertainties [38] and also for limitations in the simulation modelling of event kinematics [13]. The magnitudes of the uncertainties are determined from a representative set of closure tests in data, in which yields from one of the three independent control samples, along with the corresponding transfer factors obtained from simulation, are used to predict the yields in another control sample, following the same prescription defined in eq. (5.1). Hence, the closure tests provide a consistency check between the predicted and observed yields in the data control samples, from which the validity of the method and the transfer factors can be established.

A set of five closure tests use the three data control samples to probe key ingredients of the simulation modelling of the SM backgrounds with genuine $\not\!\!E_T$ as a function of H_T, as shown in figure 1. The first three closure tests are carried out within the μ + jets sample, and probe the modelling of the α_{T} distribution in genuine $\not{E}_{\mathrm{T}}$ events (circles), the relative contributions of W + jets and $\mathrm{t\bar{t}}$ events (squares), and the modelling of the reconstruction of b-quark jets (triangles), respectively. The fourth test (crosses), connecting the μ + jets and $\mu\mu$ + jets control samples, addresses the modelling of the relative contributions of Z + jets to the sum of both W + jets and $\mathrm{t\bar{t}}$ events, while the fifth test (stars) deals with the consistency between the Z→ $\mu\mu$ + jets and γ + jets samples. All individual closure tests demonstrate, within the statistical precision of each test, that there are no significant biases inherent in the transfer factors obtained from simulation. The level of closure achieved in these tests is used to estimate the systematic uncertainties that are assigned to the transfer factors, which are determined for three regions $275 < H_{\mathrm{T}} < 575\,\mathrm{GeV}$, $575 < H_{\mathrm{T}} < 775\,\mathrm{GeV}$, and $H_{\mathrm{T}} > 775\,\mathrm{GeV}$ to be 10%, 20%, and 40%, respectively.

A further dedicated study to account for potential systematic effects arising from the modelling of the reconstruction of b-quark jets in the simulation has been performed. After correcting the efficiency and mistagging rates of b-quark jets in simulation for residual differences as measured in data, the corresponding uncertainties on these corrections are propagated to the transfer factors and found to be at the sub-percent level. In addition, several robustness tests are performed, including treating c-quark jets as b-quark jets in the yield estimates throughout, as well as ignoring the contribution from hadronic τ-lepton decays. These tests also demonstrate sub-percent effects on the transfer factors, highlighting the insensitivity to potential mismodelling in simulation. Hence, the H_{T}-dependent systematic uncertainties of 10%, 20%, and 40% are used for all b-quark jet multiplicities.

6 Results

A likelihood model of the observations in all four data samples is used to obtain a consistent prediction of the SM background, and to test for the presence of a variety of signal models. It is written as

$$L_{\mathrm{total}} = \prod_{n_{\mathrm{b}}=0}^{2} \left(L^{n_{\mathrm{b}}}_{\mathrm{hadronic}} \times L^{n_{\mathrm{b}}}_{\mu+\mathrm{jets}} \times L^{n_{\mathrm{b}}}_{\mu\mu+\mathrm{jets}} \times L^{n_{\mathrm{b}}}_{\gamma+\mathrm{jets}} \right) \times L^{\geq 3}_{\mathrm{hadronic}} \times L^{\geq 3}_{\mu+\mathrm{jets}}\,, \tag{6.1}$$

where $L^{n_{\mathrm{b}}}_{\mathrm{hadronic}}$ describes the yields in the eight H_{T} bins of the signal region when exactly n_{b} reconstructed b-quark jets are required. In each bin of H_{T}, the observation is modelled as Poisson-distributed about the sum of a SM expectation and a potential signal contribution. The components of this SM expectation are related to the expected yields in the control samples via transfer factors derived from simulation, as described in section 5.2. Signal contributions in each of the four data samples are considered, though the only significant contribution occurs in the signal region and not the control samples. The systematic uncertainties associated with the transfer factors are accounted for with nuisance parameters, the measurements of which are treated as normally-distributed. Since for $n_{\mathrm{b}} \geq 3$ the dominant SM background arises from top events, only the μ + jets control sample is used in the likelihood to determine the total contribution from all (non-multijet) SM backgrounds in the signal region.

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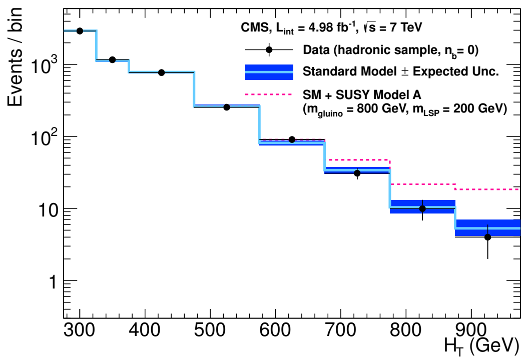
$\backslash H_T$ [GeV] # b-quark jets$\backslash$	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
0 (SM)	2933^{+56}_{-52}	1139^{+17}_{-40}	783^{+17}_{-27}	261^{+14}_{-8}	$81.5^{+6.5}_{-6.5}$	$34.2^{+4.0}_{-3.8}$	$10.4^{+2.8}_{-1.8}$	$5.3^{+1.7}_{-1.1}$
0 (Data)	2919	1166	769	255	91	31	10	4
1 (SM)	630^{+26}_{-25}	271^{+10}_{-16}	202^{+10}_{-6}	$78.0^{+6.9}_{-1.9}$	$24.2^{+2.9}_{-2.0}$	$10.6^{+1.7}_{-1.3}$	$2.9^{+0.9}_{-0.5}$	$2.2^{+0.7}_{-0.4}$
1 (Data)	614	294	214	71	20	6	4	0
2 (SM)	162^{+13}_{-12}	$61.8^{+4.8}_{-6.3}$	$58.8^{+4.8}_{-2.6}$	$28.0^{+3.5}_{-1.1}$	$9.0^{+1.4}_{-1.0}$	$7.1^{+1.4}_{-1.0}$	$0.6^{+0.3}_{-0.2}$	$0.9^{+0.4}_{-0.2}$
2 (Data)	160	68	52	19	11	7	0	2
≥3 (SM)	$10.5^{+3.5}_{-2.2}$	$7.1^{+2.2}_{-1.8}$	$5.8^{+1.4}_{-0.9}$	$3.1^{+1.0}_{-0.7}$	$1.7^{+0.5}_{-0.4}$	$0.7^{+0.5}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.1}_{-0.1}$
≥3 (Data)	10	8	8	1	0	0	0	0

Table 1. Comparison of the observed yields in the different H_T and b-quark jet multiplicity bins for the signal region with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

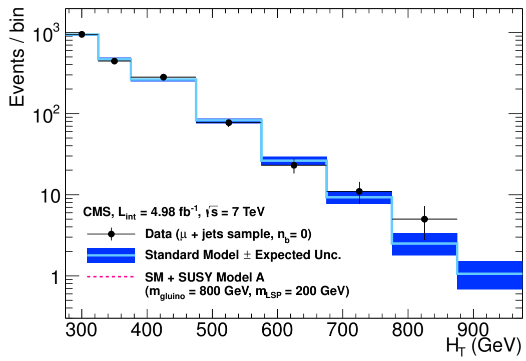
In addition, any potential contribution from multijet background in the signal region is accounted for by using the ratio of events which result in a value of α_T above and below some threshold value for a given H_T bin. The dependence of this ratio, R_{α_T}, on H_T is modelled as a falling exponential function: $A_{n_b} e^{-k H_T}$ [14]. A common parameter k is used for all four categories of b-quark jet multiplicity, and is constrained via measurements in a multijet-enriched data side-band satisfying the criteria $H_T < 575$ GeV and $0.52 < \alpha_T < 0.55$. A further side-band, defined by inverting the $\not{H}_T/\not{E}_T$ requirement of ref. [14], is used to confirm that this method provides an unbiased estimate of k and to determine a systematic uncertainty.

In order to test the compatibility of the observed yields with the expectations from SM processes only, signal contributions are fixed to zero and the likelihood function is maximised over all parameters. The maximum likelihood values of the multijet normalisation parameters A_{n_b} are found to be compatible with zero, within uncertainties, confirming the hypothesis that the multijet background is negligible after the final selection. Further, the SM expected yields obtained from an alternate fit, in which these normalisation parameters are fixed to zero, agree well with those obtained from the nominal fit.

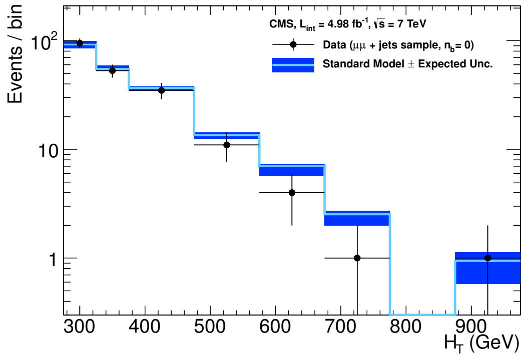
The signal region data yields, as well as the SM expectations obtained from the simultaneous fit across all samples, are shown in table 1. A comparison of the observed yields and the SM expectations in bins of H_T for events with exactly zero, one, two, and at least three reconstructed b-quark jets are shown in figures 2, 3, 4, and 5, respectively, for the signal region and the three control samples. In all four categories of b-quark jet multiplicity, the samples are well described by the SM hypothesis. In particular, no significant excess above the SM expectation is observed in the signal region.



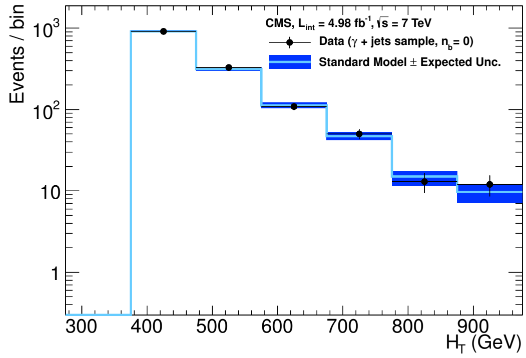
(a) Signal region



(b) μ + jets sample



(c) $\mu\mu$ + jets sample



(d) γ + jets sample

Figure 2. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region, (b) μ + jets, (c) $\mu\mu$ + jets, and (d) γ + jets samples when requiring exactly zero reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta dashed line) in the signal region for the simplified model A (defined in section 7.2) with $m_{\tilde{g}} = 800\,\mathrm{GeV}$ and $m_\mathrm{LSP} = 200\,\mathrm{GeV}$ is superimposed on the SM background expectation.

7 Interpretation of the results

Limits are set in the parameter space of the CMSSM and in a set of simplified models that characterise both third-generation squark production and compressed SUSY spectra scenarios. The CL$_s$ method [43, 44] is used to compute the limits, with the one-sided profile likelihood ratio as the test statistic [45]. The sampling distributions for the test statistic are built by generating pseudo-data from the likelihood function, using the respective maximum-likelihood values of the nuisance parameters under the background-only and signal-plus-background hypotheses.

Events samples for the CMSSM and simplified models are generated at leading order with PYTHIA 6.4 [41]. Inclusive, process-dependent, next-to-leading order calculations with next-to-leading logarithmic corrections [46–50] (NLO+NLL) of SUSY production cross

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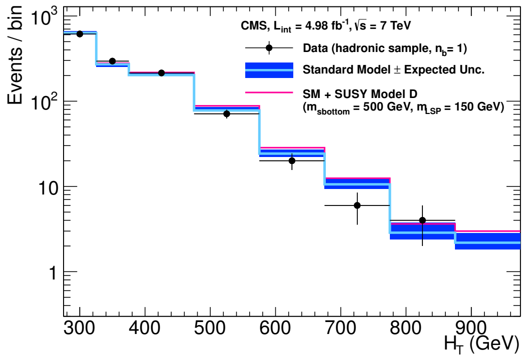
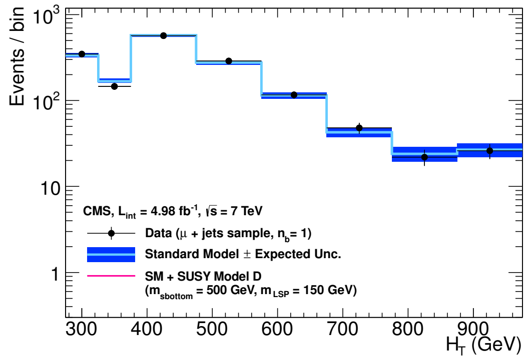
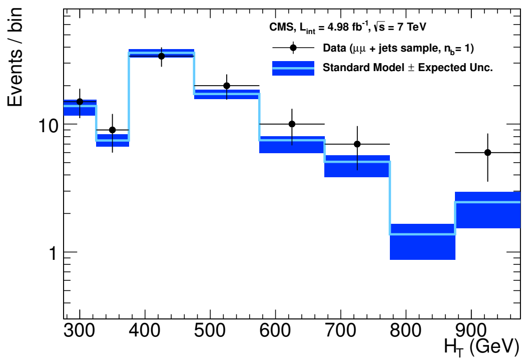


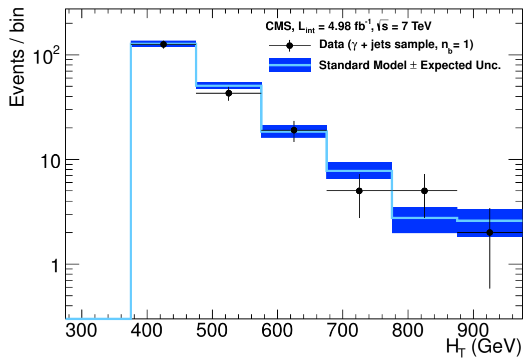
(a) Signal region



(b) μ + jets sample



(c) $\mu\mu$ + jets sample



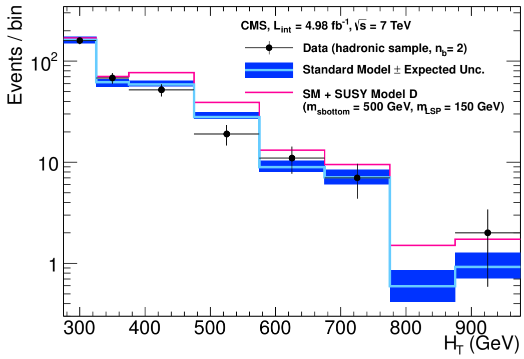
(d) γ + jets sample

Figure 3. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) signal region, (b) μ + jets, (c) $\mu\mu$ + jets, and (d) γ + jets samples. Same as figure 2, except requiring exactly one reconstructed b-quark jet. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500\,\mathrm{GeV}$ and $m_{\mathrm{LSP}} = 150\,\mathrm{GeV}$ is superimposed on the SM background expectation.

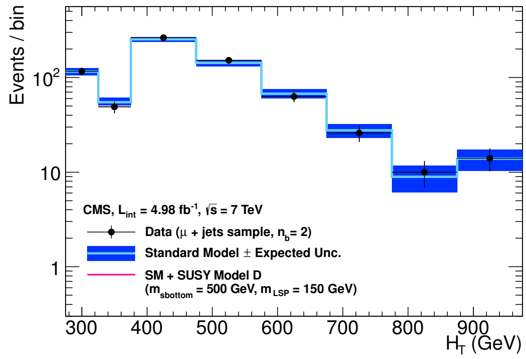
sections are obtained with the program PROSPINO [51] and CTEQ6M [52] parton distribution functions. The simulated signal events include multiple interactions per LHC bunch crossing (pileup) with the distribution of reconstructed vertices that match the one observed in data.

7.1 Interpretation in the CMSSM

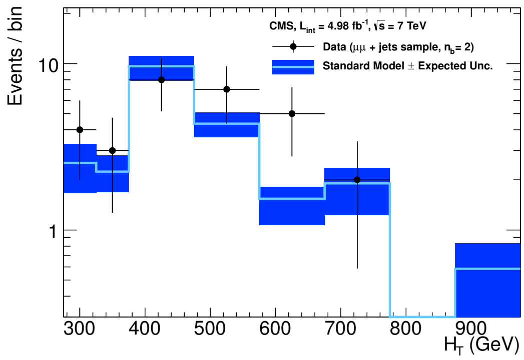
The CMSSM is described by the following five parameters: the universal scalar and gaugino mass parameters, m_0 and $m_{1/2}$; the universal trilinear soft SUSY-breaking parameter, A_0; the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$; and the sign of the Higgs mixing parameter, μ. At each point in the parameter space of the CMSSM, the SUSY particle spectrum is calculated with SoftSUSY [53]. Experimental uncertainties on the SM background prediction (10–40%), the luminosity measurement (2.2%) [54], and



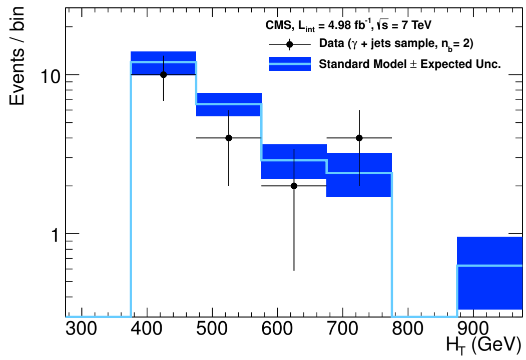
(a) Signal region



(b) μ + jets sample



(c) $\mu\mu$ + jets sample

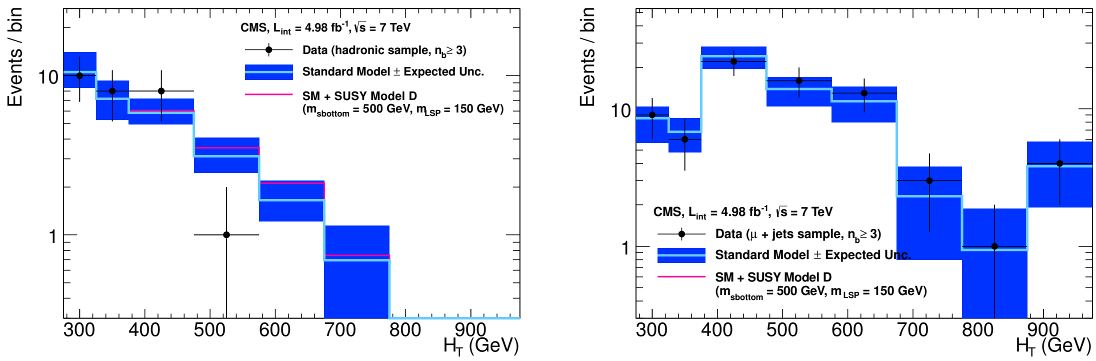


(d) γ + jets sample

Figure 4. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_{T} for the (a) signal region, (b) μ + jets, (c) $\mu\mu$ + jets, and (d) γ + jets samples. Same as figure 2, except requiring exactly two reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500\,\mathrm{GeV}$ and $m_{\mathrm{LSP}} = 150\,\mathrm{GeV}$ is superimposed on the SM background expectation.

the total selection efficiency times acceptance for the considered signal model (16%) are included in the calculation of the limit. The dominant sources of uncertainty on the signal efficiency times acceptance are derived from systematic variations of parton distribution functions, and corrections applied to jet energies and b-tagging efficiency and mistag rates.

Figure 6 shows the observed and expected exclusion limits at 95% confidence level (CL) in the $(m_0, m_{1/2})$ plane for $\tan\beta = 10$ and $A_0 = 0\,\mathrm{GeV}$, calculated with the NLO+NLL SUSY production cross section. For this choice of parameter values, squark masses below 1250 GeV are excluded at 95% CL, as are gluino masses below the same value for the region $m_0 < 600\,\mathrm{GeV}$. In the region $600 < m_0 < 3000\,\mathrm{GeV}$, gluino masses below 700 GeV are excluded, while the squark mass in the excluded models varies in the range 1250–2500 GeV, depending on the value of m_0. The mass limits are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty [55].



(a) Signal region **(b)** μ + jets sample

Figure 5. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region and (b) μ + jets samples. Same as figure 2, except requiring at least three reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500\,\text{GeV}$ and $m_{\text{LSP}} = 150\,\text{GeV}$ is superimposed on the SM background expectation.

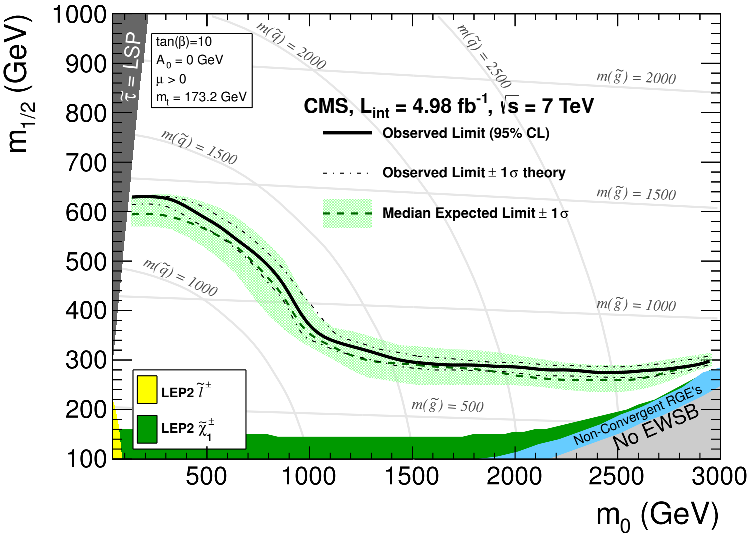


Figure 6. Exclusion contours at 95% CL in the CMSSM $(m_0, m_{1/2})$ plane ($\tan\beta = 10, A_0 = 0, \mu > 0$) calculated with NLO+NLL SUSY production cross sections and the CL$_s$ method. The solid black line indicates the observed exclusion region. The dotted-dashed black lines represent the observed excluded region when varying the production cross section by its theoretical uncertainty. The expected median exclusion region (green dashed line) $\pm 1\sigma$ (green band) are also shown. The CMSSM template is taken from ref. [56].

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Model	Production and decay modes	Figure	$m^{\text{best}}_{\tilde{q}(\tilde{g})}$ (GeV)	$m^{\text{best}}_{\text{LSP}}$ (GeV)
A	$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$	7a	≈950	≈400
B	$pp \to \tilde{q}\tilde{q} \to q\tilde{\chi}^0\bar{q}\tilde{\chi}^0$	7b	≈750	≈275
C	$pp \to \tilde{t}\tilde{t} \to t\tilde{\chi}^0\bar{t}\tilde{\chi}^0$	7c	–	–
D	$pp \to \tilde{b}\tilde{b} \to b\tilde{\chi}^0\bar{b}\tilde{\chi}^0$	7d	≈500	≈175
E	$pp \to \tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}^0 t\bar{t}\tilde{\chi}^0$	7e	≈850	≈250
F	$pp \to \tilde{g}\tilde{g} \to b\bar{b}\tilde{\chi}^0 b\bar{b}\tilde{\chi}^0$	7f	≈1025	≈550

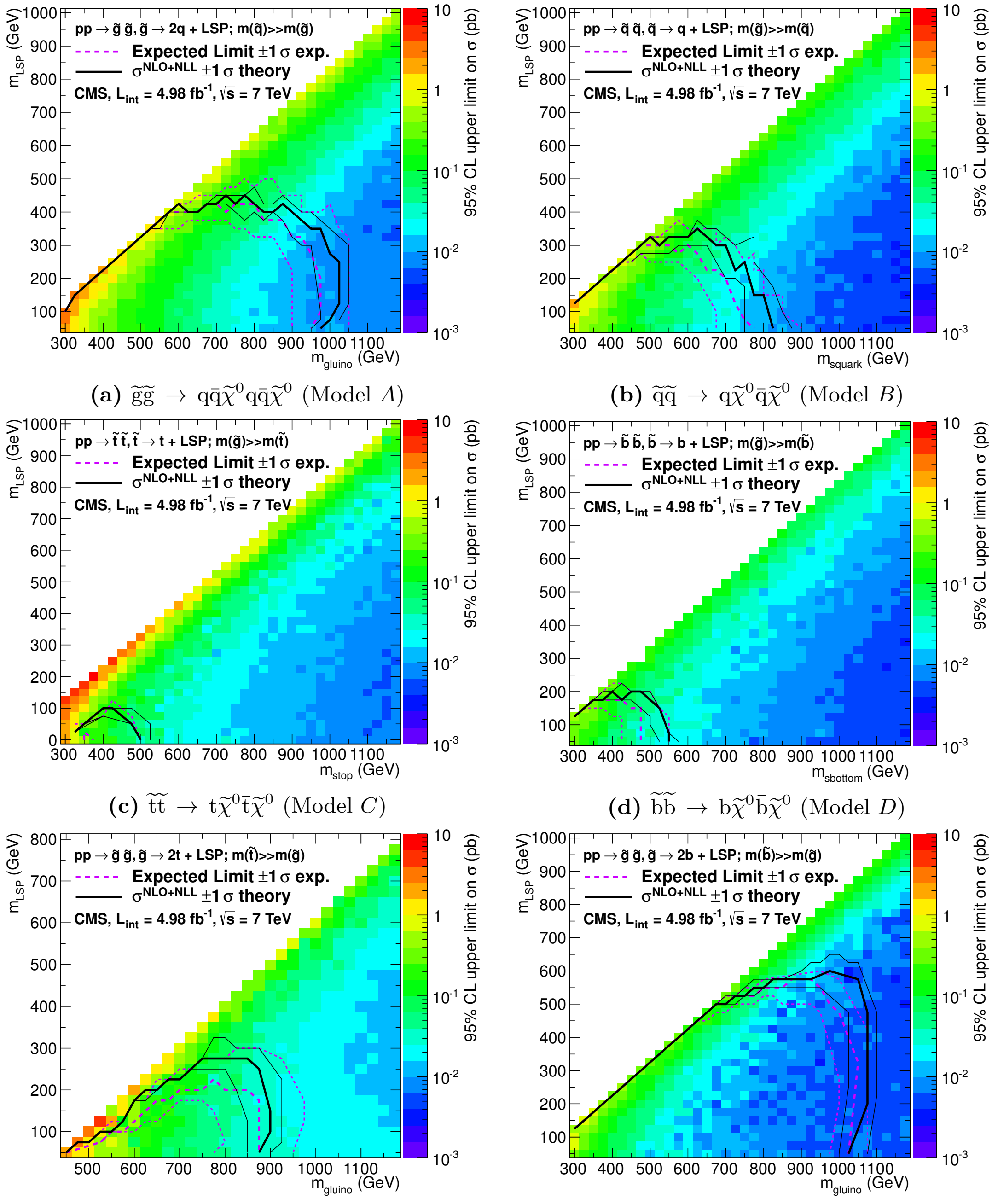
Table 2. The first three columns define the production and decay modes for various simplified models. The last two columns indicate the search sensitivity for these models, where $m^{\text{best}}_{\tilde{q}(\tilde{g})}$ and $m^{\text{best}}_{\text{LSP}}$ represent the largest mass beyond which no limit can be set for squarks/gluinos and the LSP, respectively. The exclusion range for $m_{\tilde{q}(\tilde{g})}$ is bounded from below by the kinematic region considered for each simplified model, as defined in the text. The quoted estimates are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty. For model C, the search is at the threshold of sensitivity for the considered $(m_{\tilde{q}}, m_{\text{LSP}})$ parameter space, as discussed in the text.

7.2 Interpretation with simplified models

The data observations are also interpreted using simplified models that characterise third-generation squark production and compressed spectra scenarios, where the mass difference between the primary produced sparticle (e.g. a squark or a gluino) and the LSP is rather small. The production and decay modes of the models under consideration are summarised in table 2. The simplified models A and B are used to characterise the pair production of gluinos and first- or second-generation squarks, respectively, depending on their mass as well as on the LSP mass. Simplified models C to F describe various production and decay mechanisms in the context of third-generation squarks.

Experimental uncertainties on the SM background predictions (10–40)%, the luminosity measurement (2.2%), and the total acceptance times efficiency of the selection for the considered signal model (12%−18%) are included in the calculation of the limit. Signal efficiency in the kinematic region defined by $0 < m_{\tilde{g}(\tilde{q})} - m_{\text{LSP}} < 175\,\text{GeV}$ or $m_{\tilde{g}(\tilde{q})} < 300\,\text{GeV}$ is due in part to the presence of initial-state radiation. Given the large associated uncertainties, no interpretation is provided for this kinematic region. In the case of model E, for which pair-produced gluinos decay to $t\bar{t}$ pairs and the LSP, the region $0 < m_{\tilde{g}} - m_{\text{LSP}} < 400\,\text{GeV}$ is not considered.

Figure 7 shows the upper limit on the cross section at 95% CL as a function of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ and m_{LSP} for various simplified models. The point-to-point fluctuations are due to the finite number of pseudo-experiments used to determine the observed upper limit. The solid thick black line indicates the observed exclusion region assuming NLO+NLL SUSY cross section for squark pair production in the limit of very massive gluinos (or vice versa). The thin black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The dashed purple lines indicate the median (thick line) $\pm 1\,\sigma$ (thin lines) expected exclusion regions.



(a) $\widetilde{g}\widetilde{g} \rightarrow q\bar{q}\widetilde{\chi}^0 q\bar{q}\widetilde{\chi}^0$ (Model *A*)
(b) $\widetilde{q}\widetilde{q} \rightarrow q\widetilde{\chi}^0\bar{q}\widetilde{\chi}^0$ (Model *B*)
(c) $\widetilde{t}\widetilde{t} \rightarrow t\widetilde{\chi}^0\bar{t}\widetilde{\chi}^0$ (Model *C*)
(d) $\widetilde{b}\widetilde{b} \rightarrow b\widetilde{\chi}^0\bar{b}\widetilde{\chi}^0$ (Model *D*)
(e) $\widetilde{g}\widetilde{g} \rightarrow t\bar{t}\widetilde{\chi}^0 t\bar{t}\widetilde{\chi}^0$ (Model *E*)
(f) $\widetilde{g}\widetilde{g} \rightarrow b\bar{b}\widetilde{\chi}^0 b\bar{b}\widetilde{\chi}^0$ (Model *F*)

Figure 7. Upper limit on cross section at 95% CL as a function of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ and m_{LSP} for various simplified models. The solid thick black line indicates the observed exclusion region assuming NLO+NLL SUSY production cross section. The thin black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The dashed purple lines indicate the median (thick line) $\pm 1\sigma$ (thin lines) expected exclusion regions. The mass ranges considered for models *C* and *E* differ from the other models.

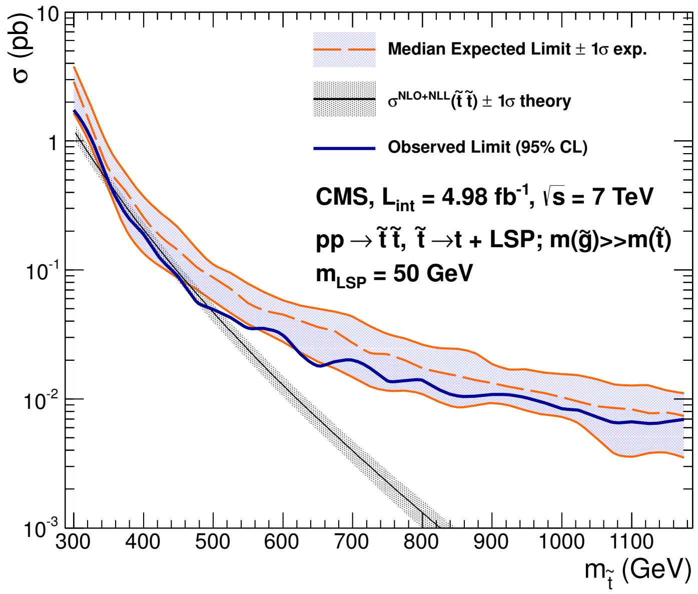


Figure 8. Excluded cross section versus top squark mass for a model in which pair-produced top squarks decay to two top quarks and two neutralinos of mass $m_{\rm LSP} = 50\,\text{GeV}$. The solid blue line indicates the observed cross section upper limit (95% CL) as a function of the top squark mass, $m_{\tilde{t}}$. The dashed orange line and blue band indicate the median expected excluded cross section with experimental uncertainties. The solid black line and grey band indicate the NLO+NLL SUSY top squark pair-production cross section and theoretical uncertainties.

The most stringent mass limits on the pair-produced sparticles are obtained at low LSP masses, while the limits typically weaken for compressed spectra, i.e., points close to the diagonal. In particular, for all of the considered simplified models, there is an LSP mass beyond which no limit can be set. This is illustrated in figure 7a, where the most stringent limit on the gluino mass is obtained at around 950 GeV for low LSP masses, while this limit weakens to below 900 GeV when the LSP mass reaches 350 GeV. For LSP masses above 400 GeV, no gluino masses can be excluded. Table 2 summarises these two extreme cases for models A to F. The estimates on the mass limits are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty.

No exclusion of direct top squark pair production (model C) assuming the NLO+NLL production cross section is expected with the analysed dataset and for LSP masses greater than 50 GeV. Figure 8 shows the observed upper limit at 95% CL on the cross section as a function of the top squark mass ($m_{\tilde{t}}$) only, for a fixed LSP mass of $m_{\rm LSP} = 50\,\text{GeV}$. Within the mass range $350 < m_{\tilde{t}} < 475\,\text{GeV}$, the observed upper limit fluctuates about the theoretical production cross section minus 1σ uncertainty. This mass range is fully excluded when considering the nominal production cross section.

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8 Summary

A search for supersymmetry using the CMS detector is reported, based on a data sample of pp collisions collected at $\sqrt{s} = 7\,\mathrm{TeV}$, corresponding to an integrated luminosity of $4.98 \pm 0.11\,\mathrm{fb}^{-1}$. Final states with two or more jets and significant $\not\!\!E_{\mathrm{T}}$, as expected from high-mass squark and gluino production and decays, have been analysed. An exclusive search has been performed in a binned signal region defined by the scalar sum of the transverse energy of jets, H_{T}, and the number of jets identified to originate from a bottom quark. The sum of standard model backgrounds per bin has been estimated from a simultaneous binned likelihood fit to hadronic, μ + jets, $\mu\mu$ + jets, and γ + jets samples. The observed yields are found to be in agreement with the expected contributions from standard model processes. Limits in the CMSSM $(m_0, m_{1/2})$ plane for $\tan\beta = 10$, $A_0 = 0\,\mathrm{GeV}$, and $\mu > 0$ have been derived. For this choice of parameter values, gluino masses below 700 GeV are excluded at 95% CL. The exclusion increases to 1250 GeV for squarks and gluinos of comparable mass. Furthermore, exclusion limits are also set in simplified models, with a special emphasis on third generation squarks and compressed spectra scenarios. In the considered models with gluino pair production and for small LSP masses, typical exclusion limits of the gluino mass are around 1 TeV. For simplified models with squark pair production, first or second generation squarks are excluded up to around 750 GeV and bottom squarks are excluded up to around 500 GeV, again for small LSP masses. No exclusion is expected for direct pair production of top squarks that each decay to a top quark and a neutralino of mass $m_{\mathrm{LSP}} > 50\,\mathrm{GeV}$. However, within the mass range $350 < m_{\tilde{\mathrm{t}}} < 475\,\mathrm{GeV}$ and for $m_{\mathrm{LSP}} = 50\,\mathrm{GeV}$, the observed upper limit fluctuates about the theoretical production cross section minus $1\,\sigma$ uncertainty. Thus, for the simplified models under consideration, the most constraining limits on the LSP and third-generation squark masses indicate that a large range of SUSY parameter space is yet to be probed by the LHC.

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Acknowledgments

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