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CMS Physics Analysis Summary

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Search for supersymmetry in events with photons and low missing transverse energy

The CMS Collaboration

Abstract

Many supersymmetric and exotic models of new physics predict production of events with low missing transverse energy and many energetic final-state objects, including electroweak gauge bosons. The *Stealth Supersymmetry* model yields this signature while conserving R-parity by means of a new hidden sector in which supersymmetry is approximately conserved. We present results of a general search for new physics in events with two photons and four or more hadronic jets produced in proton-proton collisions at $\sqrt{s} = 7$ TeV with no requirement on missing transverse energy. The study is based on a data sample corresponding to 4.98 fb^{-1} of integrated luminosity collected with the CMS detector in 2011. We observe no excess over the standard model expectation, and interpret this observation as a lower limit on the squark mass in the framework of Stealth Supersymmetry. We exclude squark masses less than 1430 GeV at the 95% confidence level. This is the first study of its kind.

1 Introduction

Many searches for supersymmetry (SUSY) reduce standard model (SM) backgrounds by requiring the presence of large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) carried away by the lightest superpartner (LSP). It has been pointed out that this approach neglects well motivated SUSY models that predict low $E_{\mathrm{T}}^{\mathrm{miss}}$ – models characterized by R-parity [1] violation, gauge mediated SUSY breaking [2], and light hidden sectors [3–6]. As the parameter space available for high-$E_{\mathrm{T}}^{\mathrm{miss}}$ SUSY has been reduced by recent LHC results, interest in low-$E_{\mathrm{T}}^{\mathrm{miss}}$ alternatives has increased.

New analysis techniques are required to reduce the SM background without the discriminating power of large $E_{\mathrm{T}}^{\mathrm{miss}}$. Searches based on signatures with high multiplicity of final-state objects, large scalar sum of the transverse momenta p_T of final-state objects, and a requirement of photons or leptons in the final state provide sensitivity to production of events with vector bosons and many jets, which arise naturally in SUSY [4]. Such searches are sensitive to a wide range of models because of their generality. Including a requirement of photons (or leptons) provides sensitivity to models of extra dimensions, heavy-flavor compositeness, and Little Higgs [7–9] in addition to SUSY models.

In this paper we describe a search for new physics in events with two photons and four or more hadronic jets with no requirement on $E_{\mathrm{T}}^{\mathrm{miss}}$ and a quantitative interpretation of the search results in the framework of the Stealth SUSY model [5, 10]. This is the first search of this kind. The analysis is based on a data sample corresponding to $4.98 \pm 0.11\ \mathrm{fb}^{-1}$ of integrated luminosity collected with the Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider.

A detailed description of the CMS detector can be found elsewhere [11]. The CMS coordinate system is right-handed with the origin at the center of the detector, the x-axis directed toward the center of the LHC ring, and the y-axis directed upward; ϕ is the azimuthal angle, θ the polar angle, and the pseudorapidity $\eta = -\ln(\tan[\theta/2])$. The central feature of the CMS apparatus is a superconducting solenoid that surrounds the silicon pixel and strip tracker as well as the barrel and endcap calorimeters (covering the region $|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadronic calorimeter (HCAL). For the barrel calorimeters ($|\eta| < 1.479$), the modules are arranged in projective towers. The ECAL possesses an η-ϕ segmentation of 0.019×0.019, and an energy resolution of $2.8\%/\sqrt{E} \oplus 12\%/E \oplus 0.3\%$ (E in GeV); the HCAL has 0.087×0.087 segmentation and a resolution of approximately $100\%/\sqrt{E}$ (E in GeV).

2 Stealth Supersymmetry

Because there exist no SUSY particles with masses identical to their SM partners, supersymmetry must necessarily be a spontaneously broken symmetry. The scale at which this breaking occurs depends largely on the choice of breaking mechanism, with many models, such as gauge-mediated SUSY [2], predicting breaking at relatively low scales.

The simplest Stealth SUSY models assume low scale SUSY breaking and introduce an additional hidden sector of particles at the weak scale in which only a small amount of SUSY breaking occurs through interactions with SM fields, such that the hidden spectrum is approximately supersymmetric and hidden sector superpartners are nearly mass degenerate. The lightest superpartner in the visible sector (LVSP) can decay without violating R-parity as long as there exists a lighter hidden sector SUSY particle (LHSP). In the subsequent decay of the LHSP to its SM partner and the LSP, the near mass generacy leaves little phase space for the LSP to carry momentum. In this way, Stealth SUSY models naturally produce signatures of low $E_{\mathrm{T}}^{\mathrm{miss}}$ without any special tuning of masses.

In this paper we consider a simplified model that includes degenerate squarks, a "bino-like" LVSP $\widetilde{\chi}_1^0$, and a hidden sector containing a new singlet state S and its fermionic "singlino" superpartner $\widetilde{\mathrm{S}}$. The model is similar to the T2 model described in Ref. [12] with two differences: the addition of the hidden sector and the participation of a gluino with mass of 1500 GeV in the production mechanism. After production of two squarks, each squark decays to a quark and $\widetilde{\chi}_1^0$; each $\widetilde{\chi}_1^0$ decays to $\widetilde{\mathrm{S}}$, which subsequently decays to S and a gravitino, $\widetilde{\mathrm{S}} \to \widetilde{\mathrm{G}}\mathrm{S}$. The singlet state is even under R-parity and can decay back to SM jets via S$\to$gg. The resulting gravitino is soft, since the hidden sector partners are nearly mass degenerate, $m_{\widetilde{\mathrm{S}}} - m_{\mathrm{S}} \ll m_{\widetilde{\mathrm{S}}}$, and so the final state tends to include a small amount of $E_{\mathrm{T}}^{\mathrm{miss}}$. The resulting decay chain,

$$\widetilde{\mathrm{q}} \to \mathrm{q}(\widetilde{\chi}_1^0 \to \gamma(\widetilde{\mathrm{S}} \to \widetilde{\mathrm{G}}(\mathrm{S} \to \mathrm{gg}))), \qquad (1)$$

is shown in Fig. 1.

The model can be characterized by the masses of the squark, $\widetilde{\chi}_1^0$, singlino, and singlet. In the present study, we consider a range of squark masses from 400 to 2000 GeV, while assuming singlino and singlet masses of 100 GeV and 90 GeV, respectively, and a $\widetilde{\chi}_1^0$ mass of half the squark mass. We also assume that the $\widetilde{\chi}_1^0$ decay produces a photon and a singlino 100% of the time; however, in the limit where the $\widetilde{\chi}_1^0$-singlino mass difference is much larger than the mass of the Z, the branching ratio for $\widetilde{\chi}_1^0 \to \mathrm{Z} + \widetilde{\mathrm{S}}$ is $\sin^2\theta_W \simeq 0.23$.

We calculate the production cross section as a function of squark mass at next-to-leading order (NLO) accuracy including the resummation of soft gluon emission at next-to-leading logarithmic accuracy (NLL) as described in Ref. [13]. For each squark mass point, we determine signal acceptances and leading order plus leading logarithm (LO) cross sections using the PYTHIA 6.424-cms event generator [14] with the D6T parameter set [15] and the CTEQ6L1 [16] parton distribution functions (PDFs) followed by a full simulation [17] of the CMS detector. The acceptance for each of the dominant subprocesses (proton-proton $\to$ squark-squark, squark-antisquark, squark-gluino, and gluino-gluino) is weighted with the appropriate NLO/LO K-factor to account for NLO-LO differences in subprocess contribution to the total cross section; we find that the total corrected acceptance is within 5% of the PYTHIA acceptance at all squark masses.

For events with five or more jets, the signal acceptance rises monotonically from 17% to 35% for squark masses of 400 to 1100 GeV and falls monotonically from 35% to 25% for squark masses of 1100 to 2000 GeV. For events with four jets, the acceptance is 12-13% of the acceptance for five or more jets for squark masses less than 1500 GeV and negligible for squark mass greater than or equal to 1500 GeV.

3 Analysis Overview

We define the primary discriminating observable S_T as the scalar sum of the p_T of all jets and photons and $E_{\mathrm{T}}^{\mathrm{miss}}$ (for $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV) in an event:

$$S_T = \not{E}_T + \sum_{\gamma} E_T + \sum_{\text{jets}} p_T \qquad (2)$$

The Stealth SUSY model described above produces events with two high p_T photons, six jets, and S_T of approximately twice the squark mass. We define the search region as events with two

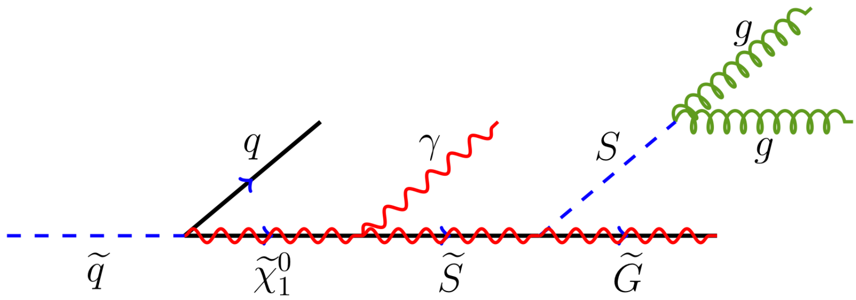

Figure 1: Feynman diagram for the Stealth SUSY decay of a squark ($\widetilde{\mathrm{q}}$) into a quark (q) and bino-like neutralino ($\widetilde{\chi}_1^0$), subsequent decay of $\widetilde{\chi}_1^0$ into a photon (γ) and singlino ($\widetilde{\mathrm{S}}$), and subsequent decay of the singlino into a singlet (S) and gravitino ($\widetilde{\mathrm{G}}$); the singlet decays into two gluons (g).

isolated photons, four or more jets, and S_T greater than an optimized threshold that depends on squark mass.

To understand if the observed S_T spectrum is consistent with the expectation for SM processes, we derive a background estimate as a function of S_T from the data using a signal-depleted jet-multiplicity control sample composed of events passing selection with two or three jets and a signal-depleted S_T sideband composed of events passing the selection with $600 < S_T < 700$ GeV. We take the shape of the S_T spectrum from the jet-multiplicity control sample and the normalization from the S_T sideband. The assumption that the S_T shape is independent of final-state object multiplicity is known as "S_T scaling." This method of background estimation, which was first used in the 2010 CMS search for black holes [18] (most recently updated in Ref. [19]), is described below.

Having determined the expected signal and background rates as functions of S_T and jet multiplicity, we compare the observed numbers of events to the signal and background expectations for each squark mass. We use these event counts to quantitatively test for the presence of signal with modified frequentist CL_S method [20, 21]. The 4-jet rate for signal is large enough to preclude use of the 4-jet bin as a sideband because of potential signal contamination, but small enough to result in reduced sensitivity to Stealth SUSY in this jet multiplicity bin (relative to the ≥5-jet bin). To avoid the 4-jet bin diluting the sensitivity of the ≥5-jet bin, we perform the final counting experiment in two bins of jet multiplicity: 4-jets and ≥5-jets.

Because the observed events conform to a falling spectrum and the signal events are broadly peaked at S_T of approximately twice the squark mass, we perform each counting experiment in the region above an S_T threshold optimized for the hypothesis being tested. We observe no excess and use the data to determine the cross-section limit as a function of squark mass. By comparing this limit to the predicted cross section, we determine the lower limit on the squark mass in the framework of Stealth SUSY.

4 Data and Selection

The event selection criteria of the present analysis are identical to those used in the CMS search for supersymmetry in events with photons, jets, and missing energy [22]. Events are recorded with the CMS two-level trigger system requiring the presence of one photon with transverse energy (E_T) greater than 36 GeV and a second with E_T greater than 22 GeV. To suppress hadronic jets giving rise to photon candidates, these triggers require the latter to be isolated from other activity in the tracker, ECAL, and HCAL. As instantaneous luminosity increased throughout 2011, isolation requirements were gradually changed to keep the trigger rate approximately constant; the isolation in the trigger is always less restrictive than offline requirements described below.

Photon candidates are reconstructed from clusters of energy in the ECAL barrel with $|\eta| < 1.44$. Candidate events are required to have a leading photon with $E_T > 40$ GeV and an additional photon with $E_T > 25$ GeV; at these thresholds the triggers are more than 99% efficient. We require the ECAL cluster shape to be consistent with that expected for a photon, and the energy detected in HCAL behind the photon shower not to exceed 5% of the ECAL energy. We ensure isolation from other activity in the event by requiring that the scalar E_T sum of tracks and calorimeter deposits within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ of the photon candidate's direction be less than 6 GeV after correcting for contributions from the products of secondary collisions in the event (pile-up) and the candidate itself. These criteria efficiently select both photons and electrons; we consider as photons those candidates that cannot be matched to hit patterns in the pixel detector.

Jets are reconstructed with the particle-flow algorithm [23], which simultaneously reconstructs all particles produced in a collision based on information from all detector sub-systems and identifies each as a charged or neutral hadron, photon, muon, or electron. All these particles are clustered into jets with the anti-k_T clustering algorithm with distance parameter of 0.5. To remove jets arising from potential instrumental and non-collision backgrounds, we require the fraction of jet energy coming from charged and neutral electromagnetic deposits to be less than 0.99, the neutral hadron fraction to be less than 0.99, and the charged hadron fraction to be greater than zero. The jet energy and momentum are corrected for the nonlinear response of the calorimeter and the effects of pile-up. Jets are required to be isolated from photon candidates by $\Delta R < 0.5$ and to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$.

For background studies, we select a control sample from the data composed of events with one photon and two or more jets (photon+jets) using the criteria described in Ref. [22]. All criteria are the same as those for the primary data sample with two photons and jets (diphoton+jets), except where changes are necessary because of differences in the trigger: we require that events include a single photon with $E_T > 80$ GeV and $H_T > 450$ GeV, where H_T is defined as the scalar sum of the p_T of jets with $p_T > 40$ GeV and $|\eta| < 3.0$. We also perform background studies with a diphoton plus zero to four jets sample generated with MADGRAPH5 [24] followed by PYTHIA for hadronization, the parametrized simulation of the CMS detector known as "Fastsim" [25], and the same selection as the primary diphoton+jets data sample.

5 Background Estimate

The backgrounds to this search come mainly from SM production of photon+jets and diphoton+jets events. We estimate the contribution of these backgrounds to the search region with a data-driven method based on the observation of S_T scaling. In Ref. [18], it was observed that the shape of the S_T distribution in jet-dominated events is independent of the number of final-state objects in the event, which allows the shape of the S_T distribution in events with low jet multiplicity to be used as the expected shape for events with high jet multiplicity.

We explore whether the observation of S_T scaling holds for events with photons in addition to jets using the simulated diphoton+jets sample and the large photon+jets data control sample described above. In Figure 2, we compare the S_T spectra for subsamples of the photon+jets sample characterized by jet multiplicity of two, three, four, or five or more jets. We show the spectra (area-normalized for $S_T > 800$ GeV) along with the n-jet/2-jet ratio where n = 3, 4, $\geq$5, and $\geq$3. The shape of each ratio is consistent with a flat line within the statistical uncertainty. For instance, we fit the $\geq$3-jet/2-jet ratio in the right panel of Fig. 2 with the function $a + bx$ where $x \equiv S_T/\sqrt{s}$ and find $a = 1.0 \pm 0.2$ and $b = -0.3 \pm 1.1$. Allowing for this slope in the background prediction would decrease the expected background rate at S_T of 1500 GeV by (6 ± 22)%; the total systematic uncertainty on the background rate at high S_T (described below) is 110%. In the diphoton+jets sample simulated with MADGRAPH, each of the n-jet/2-jet ratios are also consistent with a flat shape, but with larger statistical uncertainty. We conclude that the S_T shape is independent of jet multiplicity for events containing photons and jets, as is observed for hadronic events in Refs. [18, 19]. We proceed to determine the background shape using the primary diphoton+jets data sample as described below.

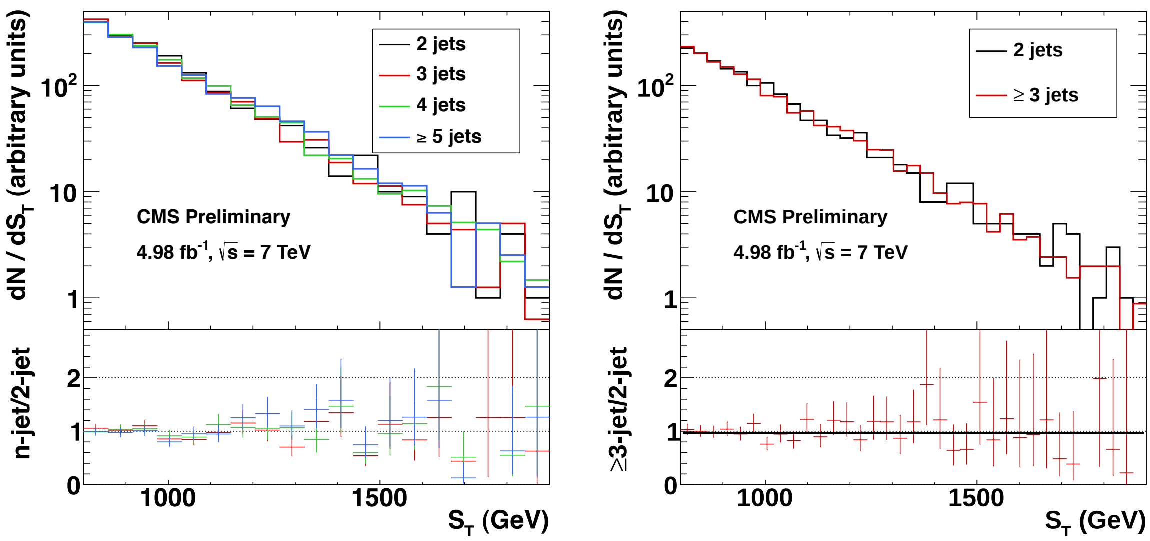

Figure 2: We show S_T spectra from the photon+jets data control sample, area-normalized for $S_T > 800$ GeV. On the left are the spectra for events with two, three, four, and five or more jets along with the n-jet/2-jet ratio where n = 3, 4, or $\geq$5. On the right we show spectra for events with two and three or more jets along with the $\geq$3-jet/2-jet ratio.

We determine the shape of the S_T distribution for the background with a fit to the signal-depleted data sample composed of events with two or three jets, in the process verifying that the shapes from exclusive 2-jet and 3-jet samples agree. The nominal functional form of the shape is $1/(x)^p$; two additional functions ($e^{p_0 x}$, $1/x^{p_1 + p_2 \log(x)}$) are used to estimate the systematic uncertainty related to choice of function. In the 2-jet (3-jet) data we find a best fit value of $p = 5.00 \pm 0.45$ (5.03 ± 0.45) for the nominal function. For the statistical analysis, we use the value $p = 5.02 \pm 0.32$ from the simultaneous fit of both jet multiplicity bins.

We normalize this background shape using $\geq$4-jet data in a low-S_T sideband with $600 < S_T < 700$ GeV. We take the overall normalization from all events in this sideband, and we take the 4-jet fraction of the overall normalization from the diphoton+jets MADGRAPH sample because we find that the simulation reproduces well the fractions observed in data, but with smaller uncertainty. The 4-jet fraction from simulation is (56.4 ± 4.1)%, and the fraction from data is (59.7 ± 5.8)%.

6 Systematic Uncertainty

At each squark mass point, we estimate that the following experimental sources of uncertainty affect our knowledge of the expected numbers of signal events at the stated level: jet energy scale (3%), statistical uncertainty on signal acceptance from finite simulated samples (1-2%), and the measurement of integrated luminosity (2.2%). We find that variations in pile-up and PDFs have negligible effect on the signal acceptance.

We estimate that the following sources of uncertainty affect our knowledge of the expected background at the stated level depending on squark mass: statistical uncertainty from the background normalization method (15%), statistical uncertainty on the background shape (10-55%), and the choice of background function (5-100%). We take the change in background expectation obtained by varying the shape parameter by ±1 standard deviation as the statistical uncertainty on the background shape. We take the largest change in background expectation obtained when using the alternate fit functions instead of the nominal function as the uncertainty related to choice of background function. The relative effect of these background uncertainties is large at high S_T where very few background events are expected.

The theoretical uncertainty on the predicted cross section related to PDFs, renormalization and factorization scales, and α_S variations is estimated to be 9-57% for squark masses from 400 to 2000 GeV; the dominant source is the PDF uncertainty.

7 Results

The observed S_T spectra in events with four jets and five or more jets are shown in Fig. 3 along with the background expectation and its uncertainty. We also report the observed and expected counts in Table 1. The data are in good agreement with the background expectation. The local p-value for the most significant excess with respect to the background expectation in the 4-jet ($\geq$5-jet) bin is 0.11 (0.04) for $1200 < S_T < 1250$ GeV ($850 < S_T < 900$ GeV). We use the data to determine upper limits on the Stealth SUSY cross section under the assumptions stated in Sec. 2.

For squark masses from 400 to 2000 GeV (in 100 GeV steps), we count the numbers of events with S_T greater than a threshold that depends on squark mass. The threshold at each mass point is chosen to maximize Z_{Bi} [26] computed in the $\geq$5-jet bin; the optimal thresholds range from 800 to 2400 GeV for squark masses of 400 to 2000 GeV.

We determine upper limits on the Stealth SUSY cross section using the modified frequentist $\mathrm{CL_s}$ method [20, 21] with a profile likelihood test statistic constructed from the Poisson probabilities of the observed numbers of events given the background expectation, the predicted signal cross section and acceptance, and the integrated luminosity.

Systematic uncertainties on the expected numbers of background events, the signal acceptance, and the integrated luminosity are treated as nuisance parameters with log normal prior distributions for multiplicative uncertainties and a Gamma function prior distribution for the uncertainty related to the sideband normalization. The theoretical uncertainty on the predicted cross section does not enter the cross-section limit, but is used in determining the limit on squark mass.

In Fig. 4 we show the observed and median expected cross-section limit as functions of squark mass along with the contours corresponding to ±1 standard deviation about the median expected limit. We also show the predicted NLO+NLL cross section as a band with ±1 standard

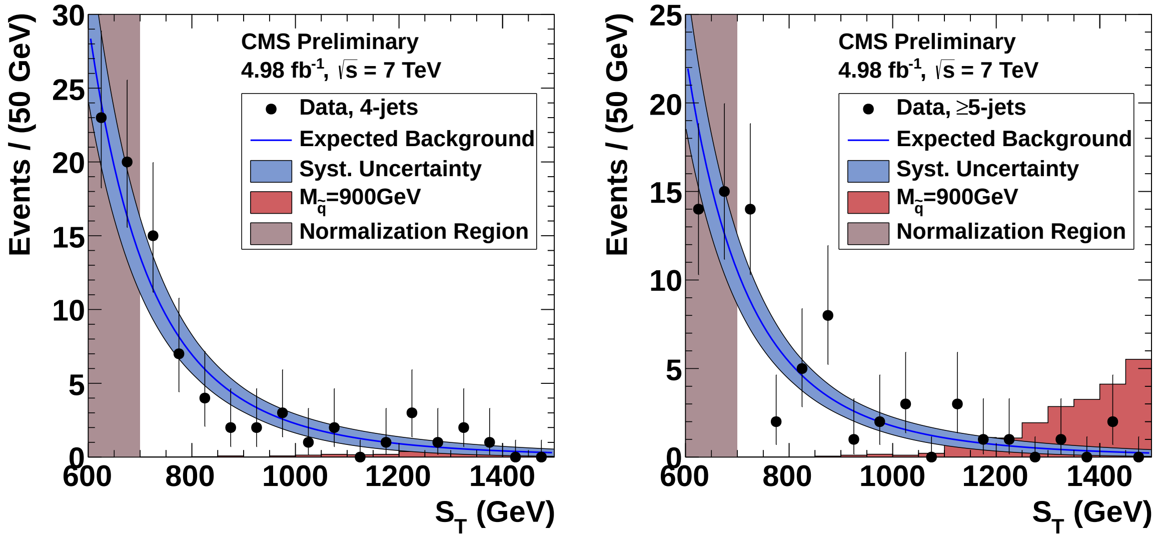

Figure 3: Observed S_T spectra, data-driven background expectation with systematic uncertainty, and predicted signal for a squark mass of 900 GeV in events with four jets (left) and five or more jets (right).

Table 1: Numbers of expected background events and observed events versus S_T for events with four jets and five or more jets.

S_T Range (GeV)	4-jet Data		≥5-jet Data	
	Expected Background	Observed	Expected Background	Observed
600-650	24.2 ± 4.5	23	18.7 ± 3.5	14
650-700	16.4 ± 3.1	20	12.7 ± 2.4	15
700-750	11.5 ± 2.1	15	8.9 ± 1.7	14
750-800	8.2 ± 1.5	7	6.3 ± 1.2	2
800-850	6.0 ± 1.1	4	4.6 ± 0.9	5
850-900	4.4 ± 0.9	2	3.4 ± 0.7	8
900-950	3.4 ± 0.7	2	2.6 ± 0.6	1
950-1000	2.6 ± 0.7	3	2.0 ± 0.5	2
1000-1050	2.0 ± 0.6	1	1.6 ± 0.5	3
1050-1100	1.6 ± 0.6	2	1.2 ± 0.4	0
1100-1150	1.3 ± 0.5	0	1.0 ± 0.4	3
1150-1200	1.0 ± 0.5	1	0.8 ± 0.4	1
1200-1250	0.8 ± 0.4	3	0.6 ± 0.3	1
1250-1300	0.7 ± 0.4	1	0.5 ± 0.3	0
1300-1350	0.6 ± 0.4	2	0.4 ± 0.3	1
1350-1400	0.5 ± 0.3	1	0.4 ± 0.3	0
1400-1450	0.4 ± 0.3	0	0.3 ± 0.2	2
1450-1500	0.3 ± 0.3	0	0.2 ± 0.2	0
≥1500	2.2 ± 1.8	0	1.7 ± 1.4	0

deviation theoretical uncertainty. Based on the intersection of the cross-section limit and the conservative edge of the predicted cross-section band, we exclude squarks with mass less than 1430 GeV at the 95% CL for the Stealth SUSY model described in Sec. 2. This is the first limit on Stealth SUSY production.

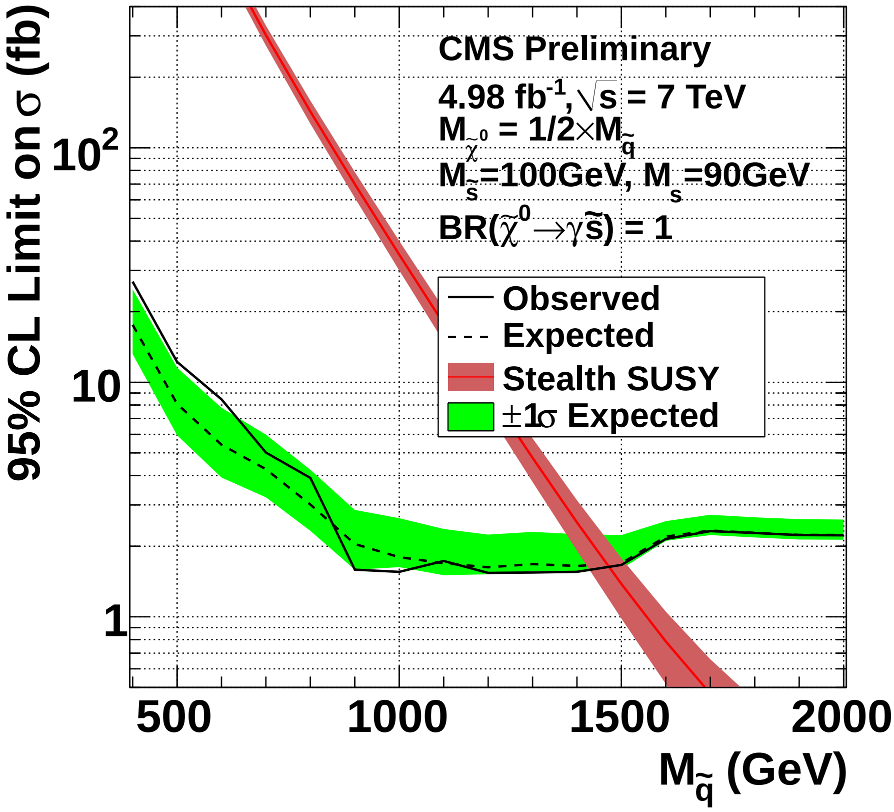

Figure 4: Cross-section limit as a function of squark mass. We show the observed limit, median expected limit, and median expected limit ±1 standard deviation obtained with the CL_S method. We also show the predicted NLO+NLL cross section from Stealth SUSY with a band denoting one standard deviation of theoretical uncertainty.

8 Summary

We perform a search for new physics in events with two photons and four or more hadronic jets. The selection requirements are general and provide sensitivity to a broad range of new physics. We observe no excess over the SM expectation in a data sample corresponding to 4.98 fb^{-1} of integrated luminosity collected in 2011. We use the data to compute a lower limit on the squark mass of 1430 GeV at the 95% confidence level in the framework of Stealth SUSY. The excluded Stealth SUSY points have soft $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra predicting 1.5 ± 0.1 (21.3 ± 1.6) events with $E_{\mathrm{T}}^{\mathrm{miss}} > 100$ GeV for squark mass of 1400 (800) GeV. This is the first limit on the parameters of the Stealth SUSY model.

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