

Searches for supersymmetry with the CMS detector at the LHC

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Abstract. We present the results of searches for supersymmetry performed using the datasets collected in 2011-2012 by the CMS experiment at the LHC in pp-collisions at center-of-mass energy of 7 and 8 TeV. The results are interpreted in the light of simplified models.

1. Introduction

The standard model (SM) of particle physics is a very successful theory which has been confirmed by an enormous amount of experimental data. However, the consensus view is that this model is incomplete. As yet, there is no candidate particle for dark matter, and the loop corrections to the mass of the Higgs boson require many orders of magnitude of tuning to stabilize. Supersymmetry (SUSY) is an attractive alternative which would augment the SM, providing new particles which would stabilize the Higgs mass, provide for gauge coupling unification, and provide a dark matter candidate. SUSY is not simply a single theory with a single phenomenology, it is an entire family of theories each with their own free parameters and unique phenomenologies.

Many of the first analyses performed using LHC data were constructed within the confines of particular models of SUSY, such as the minimal supersymmetric standard model. As yet, no excesses characteristic of these models have been observed. This has largely prompted a new strategy in which simplified models which broadly encompass large portions of SUSY phenomenology are used to characterize the observations made in the signature based searches that are performed.

The analyses discussed here are based on the 7 TeV and 8 TeV datasets, and utilize between 5 and 11.7 fb^{-1} of integrated luminosity using the CMS detector. The CMS experiment is described in detail elsewhere [1], but provides for precise reconstruction and identification of electrons, photons and muons. Taus, and hadronic jets, and missing transverse energy are identified using particle flow techniques which allow for better efficiency and precision for these objects [2].

2. Gluino production

2.1. All hadronic search using α_T

Searches in all hadronic final states are sensitive to a wide variety of SUSY processes, and also tend to have the largest cross sections. These searches also have enormous backgrounds due to inclusive QCD jet production, which requires both a precise measurement of the missing transverse energy and all other event information that can discriminate between jet production and the production of SUSY particles.



The variable α_T is created in order to separate QCD events from events with true missing transverse energy from the escape of the lightest SUSY particle (LSP). In the simplest case of a QCD dijet event, α_T reduces to Equation 1, where

$$\alpha_T = \sqrt{\frac{\frac{p_{T,j2}}{p_{T,j1}}}{2(1 - \cos \Delta\phi)}} \quad (1)$$

$p_{T,j1}$ is the leading jet transverse momentum (p_T), $p_{T,j2}$ is the trailing jet p_T , and $\Delta\phi$ is the difference in azimuthal angle between the jets. If one assumes that these two jets have exactly the same measured transverse momentum, and are exactly back to back, one would calculate 0.5 for α_T . For any imbalance between the jets, this value would have to be smaller (assuming the jets are still back to back, the ratio between the trailing jet and the leading jet would be less than one). Only in the case where the angular difference indicates that the jets are not back to back, and the transverse momenta are almost equal, this value is larger than 0.5 which indicates that this is a topology more likely to originate from an event with true missing transverse energy, and not simply the result of a mismeasurement. The generalized form of this equation (for any number of jets) localizes most backgrounds with no true missing transverse energy at low values of α_T . The remaining electroweak backgrounds, those with neutrinos and true missing transverse energy are estimated from a combination of data control samples and Monte Carlo translation factors.

No significant excess is observed, and limits on the cross section as a function of the gluino mass and the mass of the LSP are set in a number of different simplified scenarios [3]. Cross section limits are set by performing a maximum likelihood fit across all bins of the sum of hadronic transverse energy (H_T), the number of jets, and number of jets tagged as being associated with the decay of a b-quark (or b-jets), to maximize sensitivity to those models with many jets and associated heavy flavor production. Cross section limits on one particular model, in which gluinos are pair produced, are shown in Figure 1. This analysis makes use of 11.7 fb^{-1} of 8 TeV data.

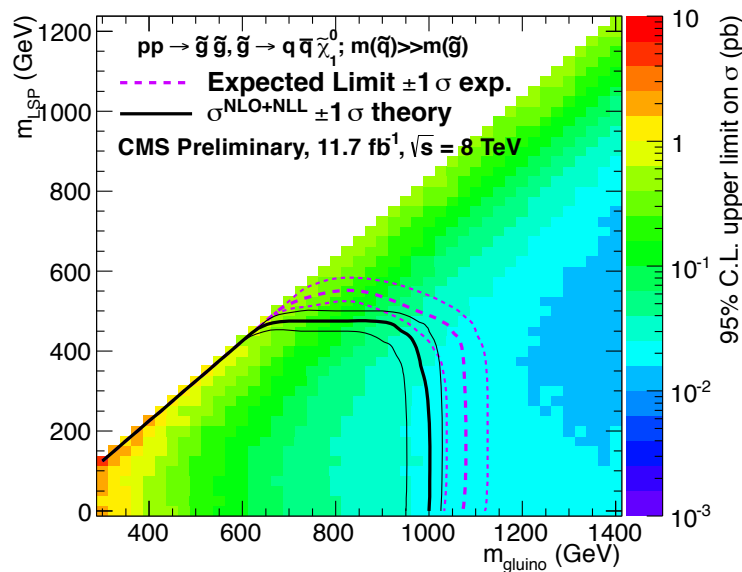


Figure 1. Cross section limits in one particular simplified model using the α_T variable as a function of gluino mass and the LSP mass.

2.2. Searches with leptons and hadronic jets

As an alternative to searching inclusively only requiring large amounts of hadronic energy, searches with multiple leptons have far smaller cross sections for SUSY production, but also smaller backgrounds from SM processes. One particular simplified model gives a large number of potential leptons in the final state: gluinos are pair produced, and then each gluino decays into a pair of top-quarks and the LSP. Two particular searches are highlighted here, one in which two same sign leptons are required with hadronic jets, and one in which at least three leptons are required along with additional hadronic activity.

The dilepton search required at least two leptons (e or μ) p_T greater than 20 GeV, which also have the same charge, and two hadronic jets with $p_T > 40$ GeV. The significant backgrounds to this final state originate from fake leptons (which have random charges), real leptons in which the charge is mismeasured (a more significant problem for e than for μ), and rare SM processes such as $t\bar{t}W$ and $t\bar{t}Z$. Events are separated into bins of jet multiplicity and how many jets had associated heavy flavor tags. The expected number of background events model the observed number of candidate events well, bin by bin, and cross section limits are again obtained, see Figure 2 as a representative example [4]. This analysis makes use of 10.5 fb^{-1} of 8 TeV data.

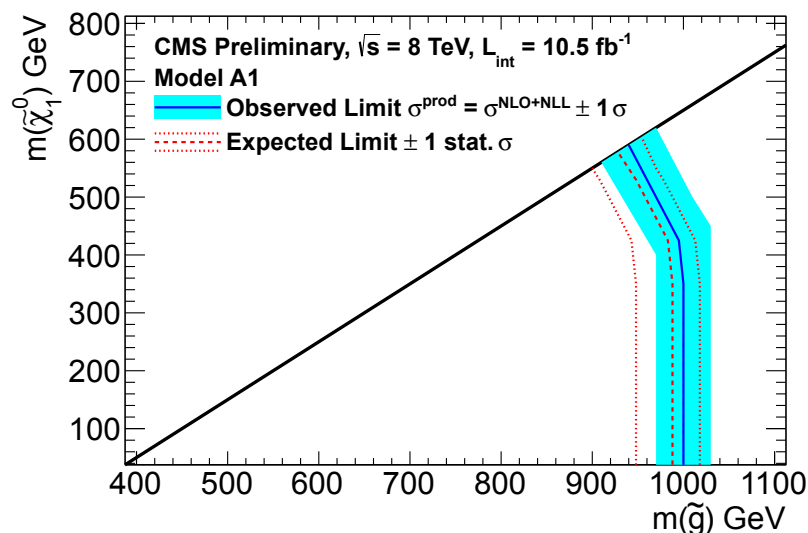


Figure 2. Cross section limit in simplified model where same sign leptons and jets are required.

Requiring at least three leptons in the final state substantially further reduces backgrounds from SM sources. In this case, three leptons are required, where these leptons can be e , μ , or hadronically decaying τ . Topologies are then split into categories by flavor, presence of a τ , missing transverse energy, additional leptons, hadronic activity, and heavy flavor jets. Over all of these categories, there are no significant excesses observed, and limits are set on the cross section in simplified models, an example of which is shown in Figure 3 [5]. This analysis makes use of 9.2 fb^{-1} of 8 TeV data.

3. Stop production

Given the large Yukawa coupling of the top-quark to the Higgs boson, the stop (supersymmetric partner to the top) is expected to play a significant role in naturalizing the Higgs mass (providing corrections that reduce the amount of tuning required in the model). In two simplified scenarios considered here, the pair produced stop decays either to the top quark and the LSP,

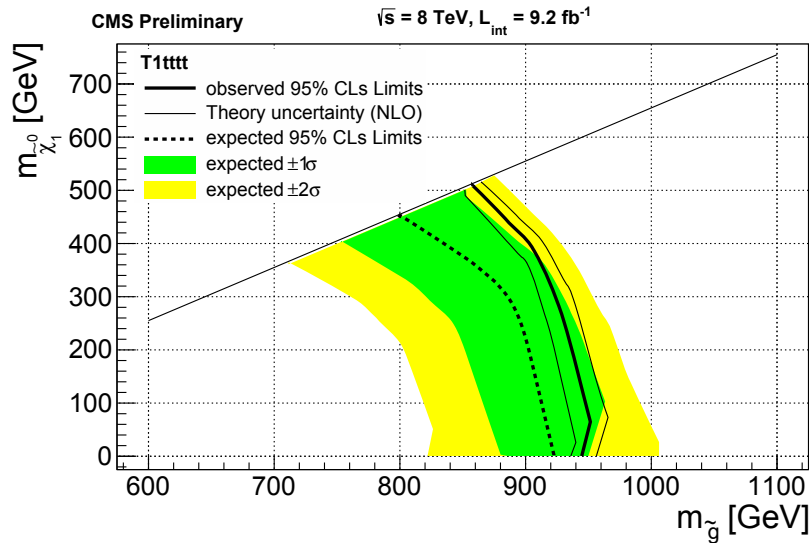


Figure 3. Cross section limits in simplified model using multilepton final states.

or decays to a b-quark and a chargino, which subsequently decays to a W boson and the LSP. Two separate analyses (disjoint at the selection level) are shown here, one in which the decay products are all hadronic (no leptons allowed), and a second in which at least one lepton is required and the transverse mass of the lepton and missing transverse energy is used to search for the presence of the stop.

The stop search in the all hadronic mode attempts to maintain sensitivity to both of the previously described stop decay scenarios. At least five hadronic jets are required (with at least one b-tagged), and isolated leptons are vetoed. The jets are required to be separated from the missing transverse energy. Three separate selections are examined beyond the baseline requirements, with tighter cuts on the missing transverse energy, the number of jets and the separation between the b-tagged jet and the missing transverse energy. In all three cases the number of observed events is consistent with the background expectations, but the uncertainties on the backgrounds in the end gave the best expected limits with the simpler baseline selection, and thus these selection requirements are chosen for the result. One cross section limit is shown in Figure 4, and the applicable simplified model limits may be found in [6]. This analysis makes use of 4.96 fb^{-1} of 7 TeV data.

In the second stop search analysis at least one lepton is explicitly required. The transverse mass (M_T) of the lepton and missing transverse energy is then formed. The transverse mass in this case can be larger than that of the W-mass, which minimizes backgrounds from inclusive top production. The candidate sample is then split into control regions by number of leptons and number of b-tagged jets to validate the Monte Carlo description of the backgrounds, where the signal region is with one and only one lepton and at least one b-tagged jet. A number of different minimum missing transverse energy (from 100-400 GeV) and transverse mass selections (from 120 to 150 GeV) were used to optimize the expected limit in multiple simplified model scenarios. No excess above the expected number of events is observed and the limits from one of the simplified models are shown in Figure 5 [7]. This analysis uses 9.7 fb^{-1} of 8 TeV data.

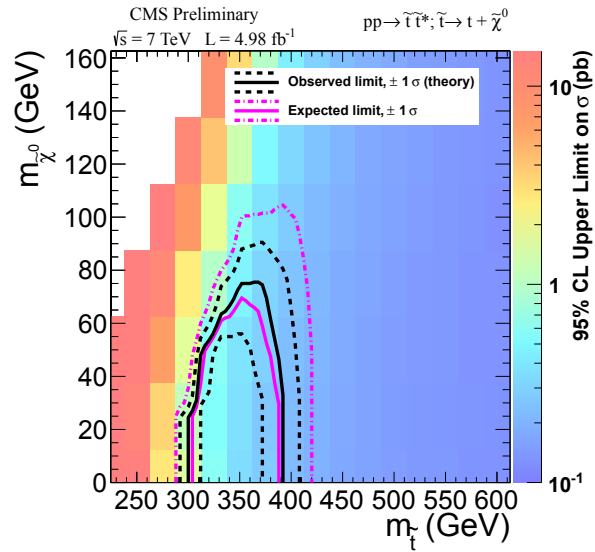


Figure 4. Cross section limits from all hadronic stop search as a function of stop mass and LSP mass, in the scenario where the stop decays to the top quark and LSP.

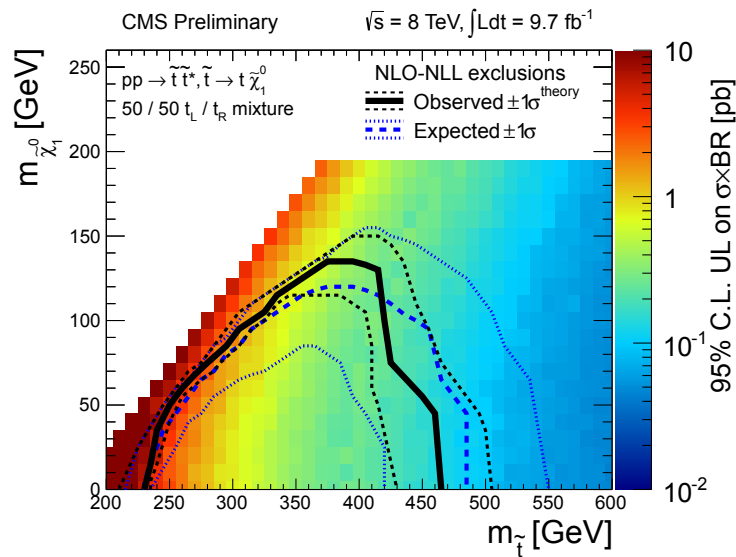


Figure 5. Limits on stop mass and LSP mass from M_T based stop search.

4. Electroweak production

All of the previously discussed analyses made use of lepton multiplicity, hadronic energy and missing transverse energy in searching for gluino and stop production. If instead we search for production of charginos and neutralinos, the presence of additional hadronic activity is no longer assured (except for the cases where that hadronic activity originates from the decay of an electroweak boson). The results of searches mentioned here span multiple final states, with three isolated leptons, two same sign leptons, four isolated leptons, two isolated leptons and two jets, and two non-resonant leptons. In each of these cases heavy flavor jets are explicitly vetoed.

These analyses are all performed on 9.2 fb^{-1} of 8 TeV data.

In the trilepton search, events which have at least three leptons (e , μ or τ) are selected, where at least two of the leptons must be electrons or muons, and the lead electron or muon must have a $p_T > 20 \text{ GeV}$. All other leptons are required to have $p_T > 10 \text{ GeV}$, except for taus which must also be $p_T > 20$. Missing transverse energy is required to be greater than 50 GeV. The major SM backgrounds to this final state are inclusive WZ production and $t\bar{t}$.

As a complement to the trilepton final states, two same sign leptons can be required to regain some of the acceptance that is lost from having required three well reconstructed leptons, though the p_T requirements and isolation are tightened in order to reduce hadronic backgrounds.

Since in both channels the observed number of events are consistent with the expectation, cross section limits are set on chargino and neutralino production in simplified models. The observed three-lepton and same-sign lepton limits for a particular choice of simplified model are shown in Figure 6 [8].

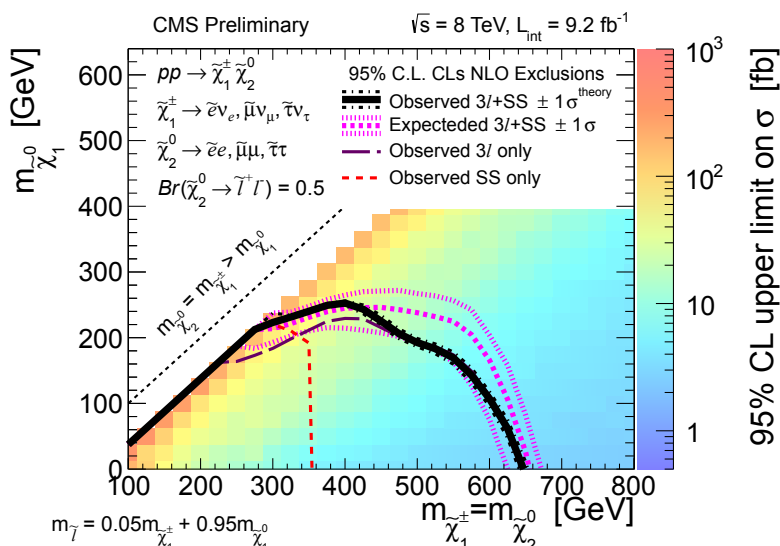


Figure 6. Chargino and neutralino cross section limits from the three-lepton and same-sign lepton analyses, along with the combined limits.

In a similar attempt to mitigate the acceptance cost of requiring an three leptons, an analysis in which two (and only two) leptons and at least two jets are required. The missing transverse energy is then used to search for an excess above the SM WZ/ZZ processes. No excess is observed, and the cross section limits, along with the three-lepton search cross section limits are shown in Figure 7. In an additional dilepton search, events in which the dilepton invariant mass was inconsistent with that of the Z boson, and at least 60 GeV of missing transverse energy are used along with a topological variable (the transverse contranverse mass defined in [9]). Production of charginos would lead to a sensitive to mass endpoint in the distribution at the mass of the chargino. Template shapes in this variable are defined and then normalized to the region of the topological variable where the background dominates. No excess in the expected signal region was observed, and cross section limits on direct chargino pair production were obtained, see Figure 8.

Four lepton events are used to search for pair-produced neutralinos in which each neutralino

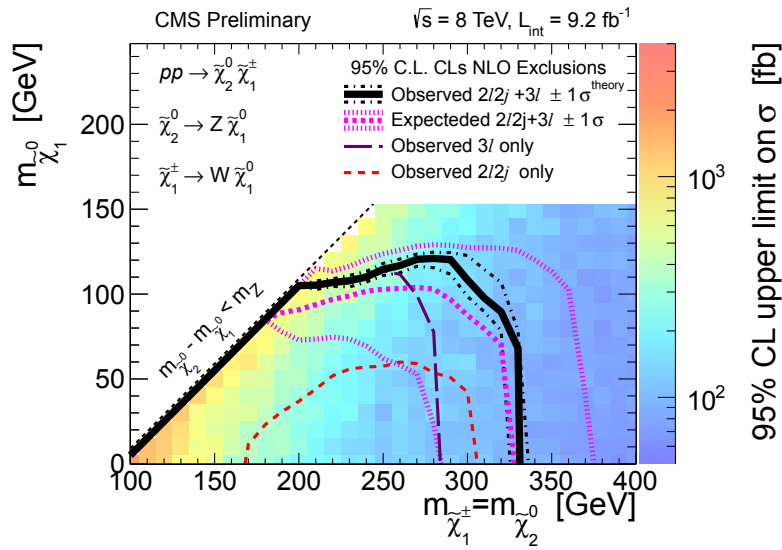


Figure 7. Chargino and neutralino cross section limits from the three-lepton and two-lepton plus two jets search, along with the combined limits.

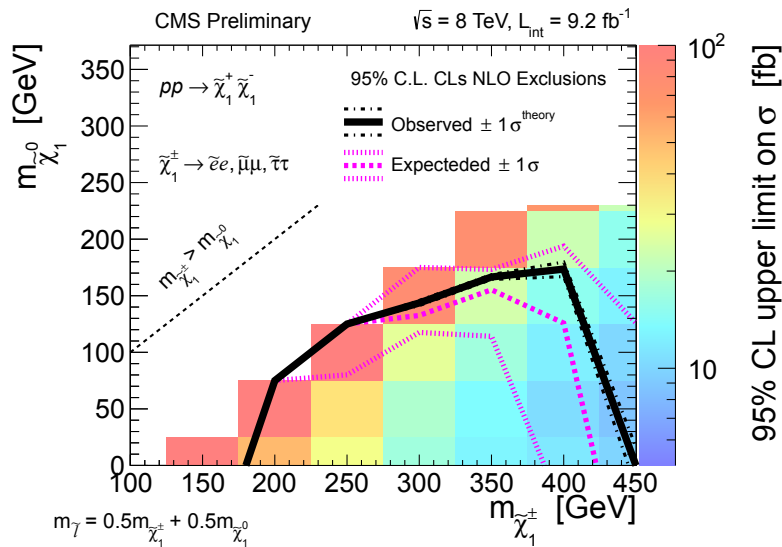


Figure 8. Chargino cross section limits using non-resonant dilepton events and topological variable.

decays to an LSP and a Z-boson which subsequently decays to four leptons, of which at most one can be a hadronic tau. Each event must have exactly four leptons, and then candidate events are binned in missing transverse energy. The major SM background process is continuum ZZ production. No excess is observed and limits are set both in the simplified model scenarios and in a higgsino enhanced gauge mediated supersymmetry breaking model (GMSB). The cross section limits for this GMSB scenario are shown in Figure 9.

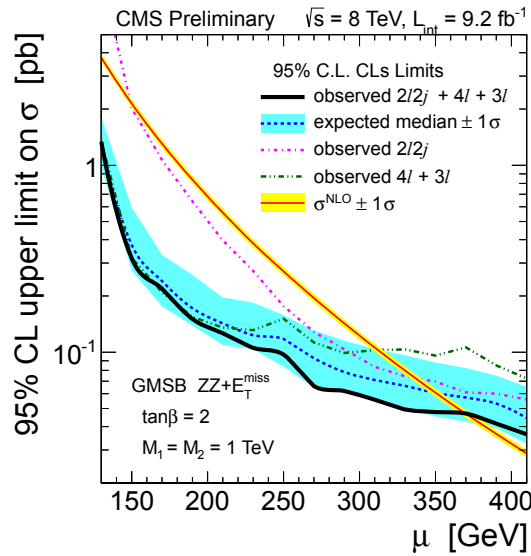


Figure 9. Four lepton cross section limit in the higgsino enhanced GMSB model.

5. Stealth SUSY

In a final search topology, we consider the case where there is neither an abundance of leptons, nor is there significant missing transverse energy. Such models arise when SUSY is augmented with a hidden sector wherein there is a singlet state which is almost mass degenerate with its SM counterpart. One can therefore have pair produced squarks which then decay to a neutralino via the emission of a quark. In a GMSB like scenario, the neutralino then decays to the singlino via the emission of a photon, and then the singlino state can decay to the SM singlet state via the emission of a gravitino (the LSP), which carries away very little energy due to the small mass difference, leading to a final state with very little missing transverse energy (see Figure 10). The end result is an event with two photons (given the decay of both the squarks), many jets and low missing transverse energy. This kind of final state would evade most constraints from the previously shown analyses, and calls for a different strategy to maintain sensitivity.

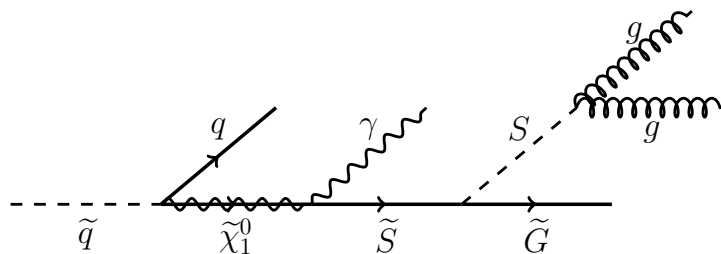


Figure 10. An example Stealth SUSY decay chain.

To search for these final states, the following assumptions are made: that the SUSY events will populate a region of high total energy (due to the high mass of the squarks) and high object multiplicity, and also that the total scalar sum of the object transverse energy (S_T) from the QCD background will be the same regardless of the object multiplicity (this is verified in both

data and Monte Carlo). The shape of the S_T distribution can therefore be taken from the low object multiplicity sideband, and then normalized to the low S_T region of the high multiplicity signal region (allowing extrapolation to where the SUSY signal should live). This is performed both in the 4 and 5 (or more) bins of jet multiplicity, in order to optimize sensitivity. No excess is observed in the data, and limits are placed both on the Stealth SUSY model, but also as a function of the the S_T variable itself (generalizing to any new physics that would manifest itself in high energy and object multiplicity)[10], see Figure 11. This analysis utilizes 4.96 fb^{-1} of 7 TeV data.

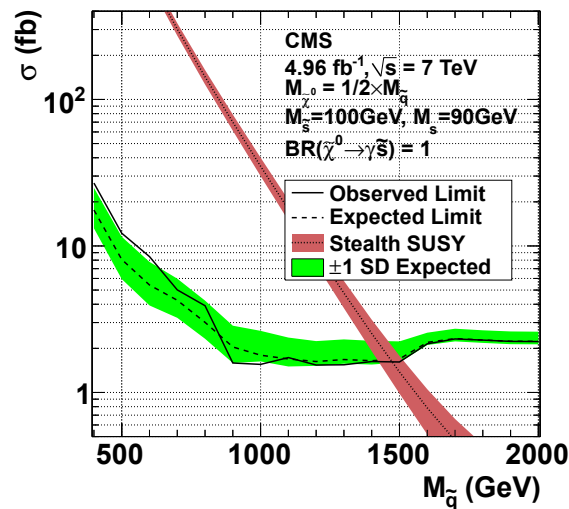


Figure 11. Limit on the squark mass in the Stealth SUSY model.

6. Conclusions

We have presented an array of searches for supersymmetry at the LHC, presented in a more generalized formalism of simplified models. No excesses are observed. These models provide a more useful set of constraints across a variety of SUSY models than previous more constrained analyses.

References

- [1] Chatrchyan S et al. [CMS Collaboration], *Journ. of Instrumentation* **3** S08004, 2008.
- [2] Chatrchyan S et al. [CMS Collaboration], “Commissioning of the Particle-Flow Reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV”, CMS Physics Analysis Summary CMS-PAS-PFT-10-002, (2010).
- [3] Chatrchyan S et al. [CMS Collaboration], “Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, 3, or at least 4 b -quark jets in 8 TeV pp collisions using the variable $\text{Alpha}T$ ”, CMS Physics Analysis Summary CMS-PAS-SUS-12-028, (2012).
- [4] Chatrchyan S et al. [CMS Collaboration], “Search for new physics in events with same-sign dileptons and b jets in pp collisions at $\sqrt{s} = 8 \text{ TeV}$ ”, Preprint hep-ex/1212.6194.
- [5] Chatrchyan S et al. [CMS Collaboration], “A Search for Anomalous Production of Events with three or more leptons using 9.2 fb^{-1} ”, CMS Physics Analysis Summary CMS-PAS-SUS-12-026, (2012).
- [6] Chatrchyan S et al. [CMS Collaboration], “Scalar Top Quark Search with Jets and Missing Momentum in pp Collisions at $\sqrt{s} = 7 \text{ TeV}$ ”, CMS Physics Analysis Summary CMS-PAS-SUS-11-030, (2012).

- [7] Chatrchyan S et al. [CMS Collaboration], "*Search for direct top squark pair production in events with a single isolated lepton, jets and missing transverse energy at $\sqrt{s} = 8$ TeV*", CMS Physics Analysis Summary CMS-PAS-SUS-12-023, (2012).
- [8] Chatrchyan S et al. [CMS Collaboration], "*Search for direct EWK production of SUSY particles in multilepton modes with 8 TeV data*", CMS Physics Analysis Summary CMS-PAS-SUS-12-022 (2012).
- [9] Matchev K and Park M. "*A general method for determining the masses of semi-invisibly decaying particles at hadron colliders*", Preprint hep-ex/0910.1584.
- [10] Chatrchyan S et al. [CMS Collaboration], "*Search for supersymmetry in events with photons and low missing transverse energy in pp collisions at 7 TeV*", *Phys. Lett. B* **719** 42, (2013).