Search for Supersymmetry at CMS

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Search for Supersymmetry at CMS

Christian Autermann
RWTH Aachen University, I. Physikalisches Institut B, 52056 Aachen, Germany
E-mail: christian.autermann@cern.ch

Abstract. CMS has searched for supersymmetry using the full dataset recorded until the end of 2012, at a center-of-mass energy of 8 TeV corresponding to an integrated luminosity of 20 fb\(^{-1}\). The observations are consistent with the expectations from the standard model. CMS maintains a broad spectrum of search strategies that target a wide range of supersymmetric scenarios. A selection of results from very inclusive and almost model-independent searches to very specific and specialized analyses will be discussed in this article.

1. Introduction

Supersymmetry extends the standard model by adding a new SUSY-particle for each standard model particle. The superpartners differ in spin by \(\frac{1}{2}\) and in mass, because the supersymmetry is broken. All other properties of the superpartners, such as charges and couplings, are identical, so that the corrections to the Higgs mass-squared parameter cancel at first order. The remaining correction terms depend on the superpartner masses but only logarithmically on the energy scale. As long as the superpartner mass-differences, in particular the 3\(^{rd}\) generation squark masses, are not too large, no unnatural amount of fine-tuning is necessary. Supersymmetry provides a dark matter candidate particle, if the \(R\)-parity and thus the lepton- and baryon-number violating couplings are sufficiently small. The lightest stable supersymmetric particle (LSP) is typically the neutralino.

No direct evidence for supersymmetry has been observed at the CMS experiment [1] yet. Electroweak precision measurements of standard model parameters, like the \(B_s \rightarrow \mu^+\mu^-\) branching fraction [2] or the Higgs mass measurements [3] constrain the supersymmetry parameter space. In combination with direct searches, models like the constrained minimal supersymmetric standard model (cMSSM) can be tested [4]. The Fittino cMSSM-fit shows that parameter points in best agreement with all constraints have particles masses of typically more than 1 TeV and p-values of less than 2.5\%. With this justification the simplest cMSSM can therefore be assumed to be excluded at more than 95% confidence-level (CL).

As the details of the supersymmetry breaking mechanism are unknown and simplest models like the cMSSM have become uninteresting, search analyses are organized, optimized, and interpreted using simplified model spectra (SMS). The SMS model typical production processes of supersymmetric particles and their decays, where the involved sparticles masses are the only free parameters. The resulting cross section limits are typically presented in these mass planes. In the following, the various searches for supersymmetry are discussed in the order of specialization: First, inclusive analyses with very few model assumptions and therefore typically good sensitivity over wide parameter regions are presented, followed by increasingly specialized searches.
2. Inclusive searches

Inclusive searches for supersymmetry obtain generally good sensitivity over wide regions of the accessible SUSY phase-space, also because only a small amount of model dependent optimization of the analyses is necessary. Searches in the fully hadronic final state require the selected events only to have large missing transverse energy \( E_T^{\text{miss}} \) caused by the two LSPs. Alternatively, analyses attempt to identify the two cascade decay-chains through hemisphere algorithms, exploiting the mass hierarchy of the SUSY particles. Two exemplary analyses approaches are discussed in this section.

In the \( E_T^{\text{miss}} + \text{jets} \) search [5] the data sample is divided into 36 statistically independent signal search regions that are combined into one likelihood-ratio test-statistic, rather than optimizing the selection for particular signal scenarios. The signal regions are defined with respect to three jet multiplicity categories (3 – 5, 6 – 7, and 8 or more jets), the scalar sum of jet transverse momenta \( H_T \) and the missing transverse jet-momentum \( H_T^{\text{miss}} \). \( H_T^{\text{miss}} \) and \( E_T^{\text{miss}} \) are similar, except that the \( H_T^{\text{miss}} \) is calculated only from jets, while the \( E_T^{\text{miss}} \) uses all calorimeter energy depositions, thus reducing the influence of noise and multiple simultaneous interactions.

An alternative approach [6] is based on the \( M_{T2} \) variable, which is a measure of the transverse momentum imbalance in an event and replaces the \( E_T^{\text{miss}} \)-like variables. Similarly as before, multiple statistically independent search regions are defined with respect to the value of the \( M_{T2} \) variable, the hadronic energy in the event \( H_T \), the jet multiplicity, and the number of jets identified as originating from bottom quarks.

The precise estimation of the standard model backgrounds is the key to all search analyses and especially challenging in the fully hadronic final state, which therefore serves well as an example to discuss the different data-driven background estimation strategies. Typically the individual background sources are estimate from, and validated in, data control regions. The QCD-multijet background source is difficult to simulate with Monte Carlo (MC) generators, because of the large QCD cross-section and the rare probability for effects that lead to \( E_T^{\text{miss}} \).

![Figure 1. Summary of the observed number of events in each of the 36 search regions in comparison to the corresponding background prediction for the \( H_T^{\text{miss}} + \text{jets} \) analysis [5]. The hatched region shows the total uncertainty of the background prediction. Good agreement, and therefore no sign for new physics, is observed. The different statistically independent bins are combined into one single likelihood-ratio test-statistic, maximizing the analysis sensitivity to the signal over a wide range of the examined phase-space.](image-url)
in the final state. This background can be modeled by data events, where the jet momenta are adjusted in a first step, such that the $E_T^{\text{miss}}$ vanishes. At this stage, the sample of these events are comparable to generator level QCD-multijet simulation. In a second step, the jet momenta are smeared according to jet energy resolution templates, that also can be determined on data events and where especially non-Gaussian tails are of crucial importance. The resulting data-driven QCD-multijet estimation models the expected background with an uncertainty of typically better than 50%, depending on the signal region. Backgrounds with genuine $E_T^{\text{miss}}$ like $W \rightarrow \nu \tau_{\text{had}}$ can be modeled using a muon data-sample, where the muon per event is replaced with a jet and the $E_T^{\text{miss}}$ is recalculated according to a tau-energy response template, that models the hadronic decay of tau leptons. The same data control sample can be used to describe the $t\bar{t} \rightarrow q\bar{q}b\bar{b}l\nu$ and $W \rightarrow l\nu$ backgrounds, where the lepton fails the acceptance or identification criteria. Finally, the $Z \rightarrow \mu^+\mu^-$ background is of relevance and can be modeled through $Z \rightarrow \tau^+\tau^-$, $W \rightarrow \mu\nu$, or $\gamma$+jets events. The relative importance of all four standard model backgrounds depends on the signal phase-space region under study.

The observed numbers of events are found to be consistent with the expected standard model background evaluated from the data, as shown in Figure 1 for the $H_T^{\text{miss}}$+jets analysis. The results are presented in the context of simplified models (Fig. 2, left) for the $H_T^{\text{miss}}$+jets analysis and (Fig. 2, right) for the $M_{T2}$ analysis, where final states are described by the pair production of new particles decaying to one, two, or more jets and a weakly interacting stable neutral particle, e.g. the lightest supersymmetric particle (LSP). Squark masses below 780 GeV and gluino masses of up to $1.1-1.3$ TeV are excluded at 95% CL within the studied models depending on the neutralino masses and on the squark flavour.

![Figure 2](image_url)

Figure 2. The observed 95% CL upper cross section limits together with the observed and expected exclusion contours on (left) the squark-squark production in the $m(\text{squark})$-$m(\text{LSP})$ mass plane and (right) for gluino pair production, with $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ in the $m(\text{gluino})$-$m(\text{LSP})$ simplified model plane. The upper set of curves for the limits on squark pair-production corresponds to the scenario where the first two generations of squarks are degenerate and light, while the lower set corresponds to only one light accessible squark.

3. Searches for 3rd generation squarks

Searches for direct production of 3rd generation squarks are of particular interest because the naturalness arguments require sbottom and stop squarks to be light, approximately below one
TeV. Therefore, the cross section for a direct production of stop and sbottom squarks, as shown in Figures 3, 4 can be sufficiently large. Two exemplary searches for 3rd generation squarks pair production are discussed in the following.

The search [7] for pairs of top squarks decaying to a top quark and a stable, weakly interacting, massive particle selects events containing multiple jets, with at least one identified as originating from a b-quark, and large missing transverse momentum. The search also employs a novel top quark tagging algorithm for identifying a top quark candidate decaying hadronically. The observed event yields are consistent with the SM expectations. Assuming both top squarks decay always into a top quark and a weakly interacting, neutral particle $\tilde{\chi}_1^0$, the production of top squarks with mass less than 535 GeV is excluded at 95% CL for $\tilde{\chi}_1^0$ masses less than 10 GeV.

The search [8] for direct production of bottom squark pairs is performed in a final state of two jets, where at least one is tagged as originating from a b-quark, accompanied by large missing transverse momentum, as well as large transverse mass and contransverse mass $M_{CT}$ calculated from the jets and missing transverse momentum [9]. The signal region is defined by exclusive bins with respect to the b-tagged jet multiplicity and $M_{CT}$. The standard model backgrounds are modeled using $\mu$ + jets data samples, with and without a b-tag. The estimated standard model background is found to be in good agreement with the observed data. The results are interpreted in terms of a simplified model production of a pair of bottom squarks with each bottom squark decaying to a bottom quark and a weakly interacting stable neutral particle. The production of bottom squarks with mass up to 700 GeV is excluded at 95% CL for neutralino masses less than 50 GeV.

Figure 5 shows a summary of the CMS direct stop search results in the stop mass – neutralino mass plane. The exclusion contours reach up to stop masses of 750 GeV and neutralino masses of up to 250 GeV, covering a significant amount of the interesting phase-space. Nevertheless, white regions on the map, where a perfectly natural SUSY scenarios could hide at relative low masses, are observable. Here, future specialized analyses, as well as improved standard model $tt$ and $WW$ theory predictions that allow better distinction between signal and background, will be crucial to examine this interesting region further.

4. Searches for gauge mediated supersymmetry breaking scenarios
A different flavour of supersymmetry are models with gauge mediated supersymmetry breaking (GMSB), where the Gravitino $\tilde{G}$ with negligible mass $\lesssim 1$ GeV is the LSP and the next-to-lightest supersymmetric particles (NLSP) determines the final state. In the following the NLSP is assumed to be the neutralino $\tilde{\chi}_1^0$.

Two searches for gauge mediated supersymmetry breaking scenarios are presented that are sensitive to a bino- or wino-like neutralino mixing. Here, decays like $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$ and $\tilde{\chi}_1^0 \rightarrow \tilde{G}Z$
are possible, leading to final states with \( E_T^{\text{miss}} \), jets, and possibly photons. The analyses pursue different inclusive search strategies. One analysis [10] requires at least one photon and a large amount of missing transverse energy, while the other analysis [11] selects events with at least two photons and uses hemisphere algorithms to calculate kinematical "razor" variables \( M_R \) and \( R^2 \) to search for the signal. The standard model background expectation is dominated by QCD-multijet and direct photon+jet production, as well as processes with initial state photon radiation. The background is mainly evaluated directly from the data.

While the above discussed searches assume strong production of squarks and gluinos in the context of a GMSB scenario with bino- and wino-like neutralino mixings, also more specialized searches were developed. The stop-higgsino search [12] assumes that only the supersymmetric partners of the top-quark and the Higgs boson (higgsino-like neutralino) are accessible, leading to direct stop pair production. In the stop decays standard model b-quarks and Higgs bosons \( h \) are created. Events with two photons forming a Higgs boson candidate and at least two b-quark jets are selected by the analysis.

The results are interpreted in the context of General Gauge Mediated (GGM) [13] supersymmetry and within simplified model scenarios. No evidence for SUSY production is found, and 95% CL upper limits are set on the production cross section. Lower limits from the single-photon analysis for wino-like neutralino mixings range beyond 0.8 TeV in gluino mass and 1 TeV in squark mass in the studied GGM phase space, as shown in Fig. 7, extending previous limits by up to 300 GeV and 500 GeV, respectively. In the case of higgsino-like neutralino mixing stop mass below 360 GeV to 410 GeV can be excluded, depending on the higgsino mass.

**Figure 5.** Summary of limits for direct stop searches in the stop mass – neutralino mass plane. The present searches are insensitive in regions where the mass difference between the stop and the neutralino is similar to the standard model top or the W-boson mass. In these cases the analyses cannot distinguish the two stop decays from standard model \( t\bar{t} \) or \( WW \) production. Similarly, near the diagonal where the stop and neutralino are nearly mass-degenerate the final state consists only of \( E_T^{\text{miss}} \) and only very soft decay products. Specialized analyses can gain sensitivity in these regions.
Figure 6. Observed $E_T^{miss}$ distribution of the single-photon analysis [10] compared to the standard model background estimated from data control regions (left). The $E_T^{miss} > 100$ GeV bins are combined, and interpreted in the GGM m(squark) - m(gluino) mass plane for wino-like neutralino mixing (right).

Figure 7. Observed distribution of the “razor” variable $M_R$ [11] compared to the standard model background estimation from a data sideband region (left). Cross section limits and exclusion contours for a $g\tilde{g} \to q\bar{q}q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$ simplified model are shown in the m(gluino) - m($\tilde{\chi}_1^0$) mass plane (right).

5. Searches for electroweak production of supersymmetry
Electroweak production of supersymmetry has significantly lower cross section compared to strong production. In addition, the particles in the final state have less energy compared to events of strong production, which makes a discovery of new physics in these channels extremely challenging. On the other hand, gaugino masses might be rather light in contrast to squark
and gluinos. Here, a search [14] for electroweak pair production of neutralinos and charginos, leading
to decay channels with Higgs, Z, and W bosons and undetected lightest SUSY particles (gravitinos \( \tilde{G} \) in the GMSB framework or neutralinos \( \tilde{\chi}^0_1 \)) is discussed. The produced neutralinos may decay either to a Higgs boson (h) and an LSP, or to a Z boson and an LSP, leading to \( hh \), \( hZ \), and \( ZZ \) states with missing transverse energy \( E_T^{miss} \). Charginos may directly decay to W bosons and an LSP, leading to \( hW \) states with \( E_T^{miss} \). The decays of a Higgs boson to a bottom-quark pair, to a photon pair, and to final states with leptons are considered in conjunction with hadronic and leptonic decay modes of the Z and W bosons.

The signal sensitive variables utilized to discriminate signal against the standard model background
depend on the analysis channel and include large values of either missing transverse energy \( E_T^{miss} \), transverse mass \( M_T \), or the scalar sum \( S_T \) of the two boson transverse momenta. In Fig. 8 the sensitivity of the individual analysis channels is shown in the plane of the higgsino-like neutralino mass versus the branching fraction of the neutralino decay into a standard model Higgs boson and the gravitino LSP.

No evidence is found for supersymmetric particles, and 95% CL upper limits are evaluated for the respective pair production cross sections and for neutralino and chargino mass values. Higgsinos with a mass value below 380 GeV are excluded. For small values of the LSP mass, chargino mass values up to 210 GeV can be excluded, where the \( \tilde{\chi}^0_1 \) and \( \tilde{\chi}^\pm_1 \) masses are taken to be equal. Figure 8 shows the obtained exclusion contours in the plane of the higgsino-like neutralino mass versus the branching fraction of the neutralino decay into a standard model Higgs boson and the gravitino LSP.

![Figure 8](image-url)

**Figure 8.** Sensitivity (left) of the individual analysis channels and (right) obtained exclusion contours of the search for electroweak pair production of gauginos [14] shown in the plane of the higgsino-like neutralino mass versus the branching fraction of the neutralino decay into a standard model Higgs boson and the gravitino LSP.

6. ** Searches for stealth supersymmetry**

The previously discussed searches for supersymmetry assume \( R \)-parity conservation and are therefore characterized by large missing transverse momentum due to the undetectable LSPs. This, however, is not a necessary property of supersymmetry. The LSP might be charged and thus detectable, or it can be unstable if the \( R \)-parity is violated. As a benchmark scenario for supersymmetry with only little or no \( E_T^{miss} \) a search [15] for stealth supersymmetry [16] is discussed. Stealth SUSY models naturally produce low-\( E_T^{miss} \) signatures without violating \( R \)-parity. Low-scale SUSY breaking is assumed and a new hidden sector of particles at the weak scale is introduced, analogous to the SUSY-breaking sector, through which the typical non-stealth LSP, the neutralino \( \tilde{\chi}_1^0 \), can decay into a lighter hidden-sector SUSY particle \( \tilde{S} \). The
gaugino becomes the lightest visible sector SUSY particle (LVSP), the LSP $\tilde{G}$ in the stealth-model is produced from the decay of the hidden-sector SUSY particle to its standard model partner $S$. Since the superpartners are nearly mass degenerate, the produced LSP gains only little momentum, so that only little $E_T^{miss}$ is observable in the detector.

The analysis is performed in a final state with two photons, sensitive to $\chi^0_1 \to S \gamma$ decays or an oppositely charged electron and muon, sensitive to e.g. $\chi^+_1 \to SW$ decays. The background is estimated from data side-band regions and found to be consistent with the observed data. The derived limits constrain the masses of squarks and neutralinos in the framework of stealth SUSY. In the photon-analysis 95% CL lower limits on squark masses between 700 GeV and 1650 GeV are derived, depending on the neutralino mass. In the lepton analysis squark masses below 550 GeV at the 95% CL can be excluded.

7. Searches for supersymmetry with a dilepton invariant mass edge

An example for a highly specialized supersymmetry analysis carried out at CMS is the search [17] for a kinematical edge in the invariant mass spectrum of two leptons of same flavor and opposite charge ($e^+e^-$ or $\mu^+\mu^-$). The signal has a characteristic triangular shape, if the two leptons are created in a three body decay of a gaugino, e.g. in a supersymmetric cascade decay. In particular, a heavy neutralino can decay via a slepton into a lighter neutralino and two leptons, e.g. $\tilde{\chi}^0_2 \to l^+l^- \to \tilde{\chi}^0_1 l^+l^-$. The intermediate slepton can be on- or off-shell, which slightly influences the shape of the triangular invariant dilepton mass distribution. The upper edge is determined by the mass difference of the two involved neutralinos. A decay via an on-shell $Z$-boson is also possible $\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 Z \to \tilde{\chi}^0_1 l^+l^-$. The analysis is not particular sensitive to the details of the production process and requires jets and missing transverse momentum in addition to two opposite-sign same-flavor leptons. A feature of the analysis is, that the signal region is dominated ($\sim 99\%$) by $t\bar{t}$ background, which is flavor symmetric with respect to the two leptons, i.e. has as many $e^+e^- + \mu^+\mu^-$ events as it has $\mu^+e^- + \mu^-e^+$ events. Therefore, a data control-region with two opposite-charge but also opposite flavor leptons can be used to model the flavor-symmetric background with good precision. Systematic uncertainties arise only from differences in the lepton trigger, reconstruction, and isolation efficiencies and are of the same order as the statistical uncertainties of the data signal- or control-samples corresponding to 4%, if both leptons are reconstructed in the central detector.

Two analysis strategies are pursued: Counting experiments in three invariant dilepton mass $m_{ll}$ regions below the $Z$-resonance, on-$Z$, and above the $Z$-resonance are performed, where the standard model background is estimated as explained above. The observed results are presented in Table 1. Remarkably, an excess of $2.6\sigma$ is observed in the central low-$m_{ll}$ region. A second analysis approach is to perform an unbinned maximum likelihood fit simultaneously to all events in the dilepton same-flavor signal region and the opposite-flavor background control region. The fit determines the free parameters of the signal shape parametrization as shown in Figure 9; an edge position at $m_{ll} = 78.7 \pm 1.4$ GeV is found with a signal strength of $126 \pm 41$ events in the central detector region corresponding to a local significance of $2.4\sigma$ consistent with the result of the counting experiment.

The result has led to the publication of various interpretations, for example [18, 19]. Meanwhile, the ATLAS collaboration has performed a corresponding analysis [20] with slightly different selection criteria. Here, the observed data is well consistent with the standard model background expectations in the low-$m_{ll}$ region beneath the $Z$-resonance. However, the same ATLAS analysis observes an excess of $3\sigma$ on the $Z$-resonance, where the CMS analysis observes good agreement, however in this case the CMS selection is significantly looser than the ATLAS selection with respect to $E_T^{miss}$ and the jet energy requirements. In summary, the best explanation for the observed excesses is at this point statistical fluctuations.
Figure 9. Result of the unbinned maximum-likelihood fit shown in the central dilepton same-flavor signal region of the edge analysis [17]. The fit was performed simultaneously to all events in the signal and in the opposite-flavor background control region. The background and signal shapes were parametrized and the free parameters were determined by the maximum-likelihood of the unbinned fit. The best fit finds a signal of $126 \pm 41$ events with an upper edge position of $m_{\ell\ell} = 78.7 \pm 1.4$ GeV. This corresponds to a local significance of $2.4\sigma$, consistent with the counting experiment.

Table 1. Results of the edge-search [17] counting experiment for event yields in the signal regions. Low-mass refers to $20 < m_{\ell\ell} < 70$ GeV, on-Z to $81 < m_{\ell\ell} < 101$ GeV, and high-mass to $m_{\ell\ell} > 120$ GeV.

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<th>Low-mass</th>
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<td>471 $\pm$ 32</td>
<td>173 $\pm$ 17</td>
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<td>$5^{+20}_{-20}$</td>
<td>$16^{+37}_{-38}$</td>
<td>$-3^{+20}_{-21}$</td>
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<tr>
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<td>$0.4 \sigma$</td>
<td>&lt;0.1 $\sigma$</td>
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8. Conclusion
CMS has searched for supersymmetry using the full dataset recorded until 2012 corresponding to about $20 \text{ fb}^{-1}$ at a center-of-mass energy of 8 TeV. The observed data is in agreement with the expectations from the standard model, as demonstrated in Fig. 10. Exclusion limits for squark and gluino masses reach up to and beyond 1 TeV. Limits on 3rd generation squark masses reach between 500 GeV and 800 GeV. The limits on electroweak gauginos and sleptons range typically between 200 GeV and 500 GeV. The reach with respect to all sparticle masses will be extended by at least a factor of two with the total expected data of the high luminosity LHC run. If the naturalness argument is a good guiding principle, than a discovery of supersymmetry might be just around the corner.

References
[2] V. Khachatryan et al. [CMS and LHCb Collaborations], “Observation of the rare $B^0_s \to \mu^+\mu^-$ decay from the combined analysis of CMS and LHCb data”, arXiv:1411.4413 [hep-ex].
Figure 10. CMS supersymmetry search results per search channel. The distribution is a symmetric Gaussian with a mean at zero, indicating an overall good agreement with the standard model expectations. The peak at small values is caused by channels where only a small amount of background is expected and zero events are observed. The largest excess is from the dilepton analysis, discussed above. Correlation of channels are ignored and upward and downward systematic uncertainty fluctuations were symmetrized for this plot. The plot was prepared with the help of J. Lange.


