Abstract

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Supersymmetry searches at CMS

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Abstract

The CMS experiment at the LHC has published results derived from a dataset of an integrated luminosity $L = 35.9 \text{ fb}^{-1}$ recorded with proton-proton collisions at centre-of-mass energy $\sqrt{s} = 13 \text{ TeV}$ in 2016. In this overview, selected CMS results of searches for supersymmetry will be presented as available in the summer of 2018.

Keywords: CMS experiment, supersymmetry, long-lived particles

1. Supersymmetry

The high expectations for a new supersymmetric particle discovery were not confirmed experimentally so far. However, the supersymmetry (SUSY) [1] remains an attractive theory allowing to explain known limitations [2] of the Standard Model. The supersymmetry is in agreement with a mass of the discovered Higgs boson [3] and by foreseeing a stable lightest supersymmetric particle (LSP) in the R-parity [1] conserving (RPC) SUSY models can provide a dark matter candidate [4]. The phenomenology of supersymmetric theories is widely diverse, therefore the search strategy for SUSY adopted by the CMS experiment [5] includes a broad range of searches in all all dominant production modes, redundant analyses sensitive to the same signatures and complementary inclusive and dedicated searches for "natural" (RPC) [6] and "less-natural" but also well motivated SUSY models. These models include a concept of R-parity violating (RPV) [7], different phenomenological models with gauge-mediated supersymmetry breaking (GMSB) [8] or Split SUSY [9]. It give rise to unusual signatures of long-lived particles (LLP) [10]. In general, the CMS searches are performed in a model independent way and the results are interpreted in the context of the Simplified Model Spectra [14] with a short decay chain. Experimental limits are shown for new particle masses and cross-sections on their production. In 2018, the CMS experiment published many results obtained with a dataset of proton-proton (pp) collisions at 13 TeV of an integrated luminosity of $L = 35.9 \text{ fb}^{-1}$. In this publication, the selected CMS results of searches for supersymmetry will be presented to provide a status of experimental reach for supersymmetric particles.

2. Strong supersymmetry

In the hadron collider the production of strongly interaction supersymmetric particles, pairs of gluinos or squarks ($\tilde{g} \tilde{g}$, $\tilde{g} \tilde{q}$, $\tilde{q} \tilde{q}$) is favoured. The main signature of the strongly-coupled SUSY is an event reached in jets from the hadronic decay of gluino or squarks and a genuine missing transverse energy (MET) from neutralino ($\tilde{\chi}_1^0$), which is assumed to be the LSP. In the decay chain of massive supersymmetric particle may also be produced $b$-quarks or leptons ($\ell = \mu$ or $e$). The CMS is searching for theses particles using as a main discriminant not only MET, but other kinematic variables. These searches are performed in bins of number of jets and number of $b$-tagged jets for fully-hadronic, and single- and di-lepton final states. Such an approach

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allows to increase sensitivity of searches and perform complementary analyses. The results of analyses are interpreted in terms of mass limits on supersymmetric particles, since no signal from SUSY has been detected.

The summary of the Run 2 CMS searches with pp data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of $L = 35.9 \, \text{fb}^{-1}$ is given in Fig. 1. For several analyses, the observed limit contours are weaker than the expected ones due to not significant excesses in data. The overall mass exclusion limit on gluino mass is slightly greater than 2.0 TeV.

2.1. Search for supersymmetry with the $\alpha_T$ variable

The CMS experiment performed a search for supersymmetry in final states with jets and missing transverse energy using a kinematical variable $\alpha_T$ [12], which is a powerful discriminator between events with misreconstructed and genuine MET. The variable is sensitive to the topology of di-jet event. In case of more jets of events, an event is transformed into two mega-jets, since $\alpha_T$ can be calculated for the di-jet event: $\alpha_T = E_T^\text{jett} / M_T$, is defined as a ratio of an energy of less energetic jet, $E_T^\text{jett}$, and transverse mass of di-jet system, $M_T = \sqrt{(H_T^\text{jett})^2 - (H_T^\text{miss})^2}$, where $H_T = \sum p_T^\text{jet}$. In case of the QCD background, jets are back-to-back in the $\phi$ plane and $\alpha_T$ is equal 0.5 for a perfectly measured di-jet event with $E_T^\text{jett} = E_T^{\text{jet}}$ in the limit of large jet momenta compared to jet masses. $\alpha_T$ is smaller than 0.5 in the case of an imbalance in the measured energies of back-to-back jets. When the two jets are not back-to-back and balancing genuine MET, which is the case of the signal (SUSY) topology, $\alpha_T$ is greater than 0.5. The discriminant power of $\alpha_T$ is presented in Fig. 2. With the cut on $\alpha_T$, the QCD background is significantly suppressed. Further variables are also employed to discriminate against multijet production and suppress this background process to a negligible level. The remaining background consists mainly from: $t\bar{t}$ + jets, $W$ + jets, $Z \rightarrow \nu\nu$ and is predicted in the signal region from observed counts in control regions.

The $\alpha_T$ gives sensitivity to wide variety of the signal topologies, including monojet-like events. The event categorization is defined by numbers of jets, $b$-tagged jets and bins of $H_T$. Around 200 bins, where the search is performed, are considered in the analysis. In all categories, no significant tension is observed between the predictions and data in the signal region. Therefore, the mass limits are determined in the parameter spaces of simplified models that assume the production and prompt decay of gluino or squark pairs.

The strongest exclusion bounds for squark masses are 1050, 1000, and 1325 GeV for bottom, top, and mass degenerate light-flavour squarks, respectively. The corresponding mass bounds on the neutralino $\tilde{\chi}_0^1$ from squark decays are 500, 400, and 575 GeV. These results are shown in Fig. 3. The gluino mass is probed up to 1900 GeV. The strongest mass bound on the $\tilde{\chi}_0^1$ from the gluino decay is 1150 GeV.

![Figure 1: The observed (solid) and expected (dashed) 95% CL mass limits for simplified models of strong gluino pair production obtained by complementary searches in the CMS experiment with $L = 35.9 \, \text{fb}^{-1}$ [11].](image1.png)

![Figure 2: CMS $\alpha_T$ search [13]: The main kinematical discriminant distribution in data and simulation for events satisfying the baseline selection criteria plus the additional requirements $n_{\text{jet}} \geq 2$, $p_T^{\text{jet}} > 100 \, \text{GeV}$, and $H_T > 900 \, \text{GeV}$.](image2.png)
The search has demonstrated its sensitivity in searching for long-lived gluino pairs that decay to final states containing displaced jets and MET the undetected \( \bar{\chi}^0_1 \) particles. The long-lived gluino, with an assumed proper decay length \( c\tau_0 \), is expected to hadronize with SM particles and form a bound state known as an R-hadron [9]. (A dedicated search for R-hadron is described in Sec. 6.) The model-dependent matter interactions of R-hadrons are not considered by default. The sensitivity of this search is only moderately dependent on the matter interactions for models with \( c\tau_0 \leq 1 \text{ m} \), while no dependence is found for models with \( c\tau_0 \) below 1 m. Models that assume a \( \bar{\chi}^0_1 \) mass of 100 GeV and gluino masses up to 1600 GeV are excluded for a proper decay length \( c\tau_0 \) below 0.1 mm. The bound on the gluino mass strengthens to 1750 GeV at \( c\tau_0 = 1 \text{ mm} \), before weakening to 900–1000 GeV for models with \( c\tau_0 > 10 \text{ m} \). For all values of \( c\tau_0 \) considered, the exclusion bounds on the gluino mass weaken to about 1 TeV when the difference between the \( \tilde{g} \) and \( \bar{\chi}^0_1 \) mass is small. The search provides coverage of the \( c\tau_0 \) parameter space for models involving long-lived gluinos, such as the region \( c\tau_0 < 1 \text{ mm} \), that is complementary to the coverage provided by dedicated techniques at the CMS (Sec. 6).

2.2. Compressed spectra

The searches for SUSY with compressed spectra get the motivation from the cosmological observations [16] pointing out that the lightest top squark can be almost degenerate with the LSP. Due to the small mass difference between \( \tilde{t}_1 \) and the \( \chi^0_1 \) LSP, two-body (\( \tilde{t}_1 \to t \chi^0_1 \), \( \tilde{t}_1 \to b \chi^0_1 \)) and three-body (\( \tilde{t}_1 \to bW^+\chi^0_1 \)) decays of the lightest top squark are kinematically forbidden, and the two-body (\( \tilde{t}_1 \to c\chi^0_1 \)) decay can be also suppressed depending on the details of the model. The open decays which remain are four-body decays: \( \tilde{t}_1 \to b f \bar{f}' \chi^0_1 \) and \( \tilde{t}_1 \to b \chi^0_1 \to b f \bar{f}' \chi^0_1 \), which is possible if the mass of the lightest chargino is lower than the top squark mass. The fermions \( f \) and \( f' \), which can be either quarks or leptons, are expected to be soft, namely to have a low transverse momentum.

The CMS has performed a search [17] with final states considered contain jets, MET, and exactly one lepton, which can be either an electron or a muon, originating from the decay of the top squark or the chargino. The preselection is sensitive to events where the presence of a jet from initial-state radiation leads to a boost of the top squark pair and sizable MET. The lepton can be efficiently reconstructed and identified with \( p_T \) as low as 5.0 and 3.5 GeV for electrons and muons, re-
Two analysis techniques are used, targeting different decay modes of the $\tilde{t}_1$: a sequential selection (CC) and a multivariate technique (MVA). MVA optimizes the search across the $(m(\tilde{t}_1), m(\tilde{\chi}^0_1))$ space and improves upon the sensitivity of the CC approach for this scenario. No evidence for the production of top squarks is found, and mass limits at 95% CL are set. The results for the MVA search are shown in Fig. 5. This excludes top squark masses up to 420 and 560 GeV at $\Delta m = 10$ and 80 GeV, respectively. The CC approach covers the chargino-mediated decays, where the chargino mass is taken as the average of the top squark and the neutralino masses, probing $t_1$ masses up to 540 GeV for $\Delta m = 40$ GeV. These results represent the most stringent limits to date on the top squark pair production cross section for mass differences between the top squark and the lightest neutralino below the W boson mass, and for decays proceeding through the four-body or the chargino-mediated modes.

3. Electroweak supersymmetry

If masses of squarks and gluinos are too massive to be produced at LHC, then the electroweak production of charginos ($\tilde{\chi}^\pm_1$) and neutralinos ($\tilde{\chi}^0_2$) can probe the existence of supersymmetry. Many electroweak SUSY topologies are considered to search for at CMS. They are focused on chargino-neutralino ($\tilde{\chi}^\pm_1\tilde{\chi}^0_2$) production, which decay to LSP and one of SM bosons: W, Z, or H in a following way: $\tilde{\chi}^\pm_1 \rightarrow W L \tilde{\chi}^0_1$ or $\tilde{\chi}^0_2 \rightarrow Z \tilde{\chi}^0_1$, or $\tilde{\chi}^0_2 \rightarrow H \tilde{\chi}^0_1$, where $\tilde{\chi}^0_1$ is the LSP. The semi-final state consists of two bosons WZ or WH, and produce a multi-lepton final state, including soft leptons or di-photons. In all these searches no significant deviations from the SM expectations have been observed. The summary plot of the electroweakly-coupled SUSY is shown in Fig. 6. For a massless LSP $\tilde{\chi}^0_1$ in the chargino-neutralino model, the combined result gives an upper observed (expected) limit in the $\tilde{\chi}^0_1$ mass of about 610 (500) GeV for the WZ topology and 480 (460) GeV for the WH topology. In a model of neutralino-neutralino production decay to ZZ and LSPs (gravitino $\tilde{G}$), CMS probes [15] neutralino masses up to around 650 GeV. Assuming GMSB production where the neutralino has a branching fraction of 50% to the Z boson and 50% to the Higgs boson, neutralino masses up to around 500 GeV are excluded.

The mass degenerate spectra between LSP and the next-to-the-lightest (NLSP) chargino or neutralino is experimentally challenging. Instead of energetic leptons as soft a few GeV muons and electrons are required to be reconstructed. The CMS has achieved sensitivity to the mass difference $\Delta m (\tilde{\chi}^0_2, \tilde{\chi}^0_1)$ in a range between

![Figure 5: CMS SUSY with compressed spectra search [17]:
The exclusion limit at 95% CL for the four-body decay of the top squark as a function of $t_1$ mass and $\Delta m$ for the MVA approach. The colour shading corresponds to the observed limit on the cross section. Solid black (dashed red) lines represent the observed (expected) limits, derived using the expected $t_1$ pair production cross section. Thick lines represent the central values and the thin lines the variations due to the theoretical or experimental uncertainties.](image)

![Figure 6: The observed (solid) and expected (dashed) 95% CL mass limits for simplified models of electroweak chargino-neutralino production obtained by complementary searches in the CMS experiment with $\mathcal{L} = 35.9$ fb$^{-1}$ [11].](image)
5 GeV and 35 GeV and has excluded masses of $\tilde{\chi}^0_2$ up to 230 GeV for $\Delta m (\tilde{\chi}^0_2, \tilde{\chi}^0_1)$ of 20 GeV as shown by a black curve in Fig. 6. The results represent the most stringent constraints to date for all scenarios considered.

4. R-parity violating supersymmetry

There is no fundamental reason for R-parity conservation, therefore models with R-parity violation are considered to complete the coverage of SUSY parameter space. The minimal flavor violating (MVF) arise from the SM Yukawa couplings and is consistent with the strong experimental constraints on baryon and lepton number violation involving the lightest two generations. Therefore a small MFV can be considered with $\lambda_{tbs}$ from gluino pair prompt decaying to SM quarks, $\tilde{g} \rightarrow t \bar{t} \rightarrow tbs$.

The 13 TeV CMS analysis [18] searches in a single-lepton ($e$ or $\mu$) final state for an excess of events with a large number of identified $b$-quark jets in regions determined as a function of the jet multiplicity and the sum of masses of large-radius jets, $M_J$ without a MET requirement. An example distribution with results for a bin with large expected signal contribution for $N_{lep} = 1$, $M_J > 1000$ GeV, $N_{jet} \geq 8$ is shown in Fig. 7 (top). The $N_b$ distributions in data are well described by the fit and the observed data are consistent with the background-only hypothesis for all search bins. An upper limit of approximately 10 fb is determined for the gluino-gluino production cross section using a benchmark RPV model of gluino pair production with a prompt three-body decay to $tbs$ quarks, $\tilde{g} \rightarrow t\bar{t} \rightarrow tbs$.

The supersymmetric models with RPV allow for different production mechanisms, such as the resonant production of sleptons from quarks, which are recently investigated in the CMS detector. CMS has targeted resonant slepton ($\tilde{\mu}, \tilde{\nu}_\mu$) production via the RPV coupling $\lambda'_{211}$ in final states with two same-sign muons and at least two jets in the final state [19]. Same-sign dilepton production is rare in the SM and is therefore well suited as a signature for new physics searches. The sources of the SM background are divided into processes with two prompt muons and processes with at least one non-prompt muon, and they are estimated from data.

No significant excess over the background expectation is observed. Upper cross section limits are set in the context of two simplified models covering the dominant production mechanisms in a modified constrained minimal supersymmetric model (cMSSM) [20] with $\lambda'_{211}$ as additional coupling. These exclusion limits are translated into $\lambda'_{211}$ coupling limits and presented in Fig. 8. The results represent the first at LHC and the most stringent limits on this particular model of RPV SUSY.

5. GMSB

Gauge-mediated SUSY breaking models [8] allow for a natural suppression of flavour violations in the SUSY sector and can give rise to final states with photons and jets. In GMSB models, pair-produced gluinos or squarks decay to photons and gravitinos ($\tilde{G}$) via short-lived next-to-the-lightest (NSLP) neutralinos. In the final state at least one photon, large transverse momentum imbalance ($p_T^{miss}$), and large total transverse
Figure 8: CMS RPV search [19]: Upper coupling limits as a function of \( m_0 \) and \( m_{1/2} \) for a modified cmSSM with \( \lambda'_{211} \) as additional RPV coupling. The color scale at the right side of the figure indicates the coupling limit value for specific parameter combinations. These limits are derived from the upper cross section limits of simplified model shown below. For four \( \lambda'_{211} \) values (0.004, 0.01, 0.02, 0.03), the coupling limits are shown as black contour line.

Figure 9: CMS GMSB search [21]: (top) Observed data compared to the background prediction for high \( H_T \). The expectation for two GMSB models are shown in coloured lines. (bottom) Exclusion limits at 95% CL for one of GMSB models. The solid black curve represents the observed exclusion contour and the uncertainty due to the signal cross section.

The data are interpreted in simplified models of gluino and squark pair production, in which gluinos or squarks decay via neutralinos to photons. Fig. 9(bottom) shows exclusion mass limits for one of the GMSB models. Due to observation of local excesses the observed limits are weaker then expected ones. Gluino masses of up to 1.50 – 2.00 TeV and squark masses up to 1.30 – 1.65 TeV are excluded at 95% CL, depending on the neutralino mass and branching fraction.
6. Long-lived particles

Massive, long-lived particles (LLPs) do not exist in the SM. Therefore, any sign of them would be an indication of new physics. There are many extensions of the SM that predict LLPs. Also cosmology provide hints that exotic charged and not-stable particles could exist. The CMS experiment searches [22] for the stopped LLPs that decay out of time with respect to the presence of proton bunches in the detector.

The LLPs will stop inside the detector material if they lose all of their kinetic energy while traversing the detector. This energy loss can occur via nuclear interactions if LLPs are strongly interacting (in Split SUSY [9] for gluinos and top squarks which hadronize into R-hadrons and decay to the LSP neutralino $\tilde{\chi}_1^0$) and/or through ionization if they are charged (for exotic particles called MCHAMPs with multiples of the elementary charge $|Q| = 2e$ and decay to two same-sign muons, MCHAMP $\rightarrow \mu^+ \mu^-$). If these stopped LLPs have lifetimes longer than tens of nanoseconds, most of their decays would be reconstructed as separate events unrelated to their production. Owing to the difficulty of differentiating between the LLP decay products and SM particles from LHC pp collisions, these subsequent decays are most easily identified when there are no proton bunches in the detector with a custom triggers. The detector is quiet during these out-of-collision time periods with the exception of rare non-collision backgrounds, such as cosmic rays, beam halo particles, and detector noise. This background is modeled with data, and estimated by extrapolating distribution from a background-dominated region to the signal region.

One search targets hadronic decays detected in the calorimeters, and the other looks for decays to muon pairs in the muon system. These two search channels are analyzed independently using data collected by the CMS experiment in 2015 and 2016 with separate dedicated triggers. The calorimeter (muon) search uses $\sqrt{s} = 13$ TeV data corresponding to an integrated luminosity of 38.6 (39.0) fb$^{-1}$ collected with LHC pp collisions separated by 25 ns during a search interval totaling 721 (744) hours.

The data show no excess over background. The results are interpreted in several scenarios that predict LLPs. Production cross section limits are set as a function of the mean proper lifetime and the mass of the LLPs, for lifetimes between 100 ns and 10 days. Results for the muon search are shown in Fig. 10. For lifetimes between 10 $\mu$s and 1000 s, gluinos with masses between 400 and 980 GeV (as illustrated in Fig. 10 (top)) are excluded. For the same lifetimes range, MCHAMPs with masses between 100 and 440 GeV and $|Q| = 2e$ are also excluded. The detection sensitivity and the cross section limit (Fig. 10 (bottom)) are degraded for very small lifetimes, since any particle detected within two bunch crossings (25 ns) are vetoed. The limit curve is then flat for lifetimes greater than one orbit ($\sim 10^{-4}$ s), since the numbers of observed and background events are constant. Finally, the sensitivity and effective luminosity are degraded for lifetimes larger than an LHC fill (few hours).

In the calorimeter search, combining the results from the 2015 and 2016 analyses and assuming BR of 100% for $g \rightarrow g \tilde{\chi}_1^0$ ($g \rightarrow q\bar{q} \tilde{\chi}_1^0$), gluinos with lifetimes from...
10 μs and 1000 s, $m_{\tilde{g}} < 1385$ (1393) GeV are excluded. These are the most stringent limits to date on the mass of hadronically decaying stopped LLPs, and this is the first search at the LHC for stopped LLPs that decay to muons.

### 7. Summary and prospects

The LHC Run 2 data from 2016 corresponding to $\mathcal{L} = 35.9$ fb$^{-1}$ of an integrated luminosity from the energy in pp collisions at LHC at a centre-of-mass energy 13 TeV allowed for numerous searches for new physics. The CMS experiment search for supersymmetry in a model independent way by looking signatures of hypothetical signal. These signatures include unusual and experimentally challenging signals from long-lived particles. Although a huge effort, no signal of new physics has been found so far in the data collected by the CMS detector. Therefore, the mass and cross section limits on many di-plex or compressed spectra. CMS is working on developments to improve the discriminating power of the analyses. Finally, by the end of 2018, around of 150 fb$^{-1}$ of 13 TeV data is expected, which may reveal the new physics if it exists.

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### References


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