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SUSY searches with the CMS detector

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Summary. — This paper outlines the most recent SUSY searches performed in 13 TeV proton-proton collisions with the CMS detector. Most of the results presented here are using the data sample collected in the first part of 2016, corresponding to an integrated luminosity of 12.9/ fb.

1. – Introduction

The standard model (SM) of particle physics successfully describes a wide range of phenomena. However, in the SM, the Higgs boson mass is unstable to higher-order corrections, suggesting that the SM is incomplete. Many extensions to the SM have been proposed to provide a more fundamental theory. Supersymmetry (SUSY) [1-8], one such extension, postulates that each SM particle is paired with a SUSY partner from which it differs in spin by one-half unit. Such SUSY particles could possibly be produced in proton-proton collisions at the CERN LHC.

In these proceedings, the most recent SUSY searches performed with the Compact Muon Solenoid (CMS) experiment are presented. The CMS detector is built around a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). The ECAL and HCAL, each composed of a barrel and two endcap sections, extend over a pseudorapidity range $|\eta| < 3.0$. Forward calorimeters on each side of the interaction point encompass $3.0 < |\eta| < 5.0$. The tracking detectors cover $|\eta| < 2.5$. Muons are measured within $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and relevant kinematic variables, is given in ref. [9].

Most of the results presented here are using the data sample collected in the proton-proton collisions at $\sqrt{s} = 13$ TeV taken during the first part of 2016, corresponding to an integrated luminosity of 12.9/ fb.

The searches for supersymmetry with the CMS detector can be divided in four categories: inclusive searches, third generation searches, electroweak searches and specialized searches.

2. – Inclusive searches

The inclusive searches are analyses not dedicated to a specific model, but trying to cover as many topologies as possible.

Hadronic final states are investigated by a jets + missing transverse energy analysis [10]. This search is looking for an anomalously high rate of events with three or more jets, no identified isolated electron, muon, or charged track, large scalar sum of jet transverse momenta (HT), and large missing transverse momentum, estimated with the MHT variable, which is the magnitude of the vector p_T sum of the jets. The principal standard model backgrounds, from events with top quarks, W bosons and jets, Z bosons and jets, and QCD multijet production, are evaluated using control samples in the data. The study is performed in the framework of a global likelihood fit in which the observed numbers of events in 160 exclusive bins in a four-dimensional array of jet multiplicity, tagged bottom quark jet multiplicity, missing transverse momentum in the form of MHT, and HT, are compared to the standard model predictions. The standard model background estimates are found to agree with the observed numbers of events within the uncertainties.

In CMS, three complementary analyses are also performed to investigate hadronic final states in detail, using dedicated kinematical variables to increase the sensitivity. One of these analyses is the MT2 analysis [11], which requires a stransverse mass (MT2) [12] of at least 200 GeV in events with at least two jets. This kinematic mass variable, which can be considered as a generalization of the transverse mass variable MT, was introduced as a means to measure the mass of pair-produced particles in situations where both decay to a final state containing the same type of undetected particle. Another analysis is the α_T analysis [13]. The strategy is built around the use of the kinematic variable α_T [14,15], which provides powerful discrimination against multijet production. Finally,
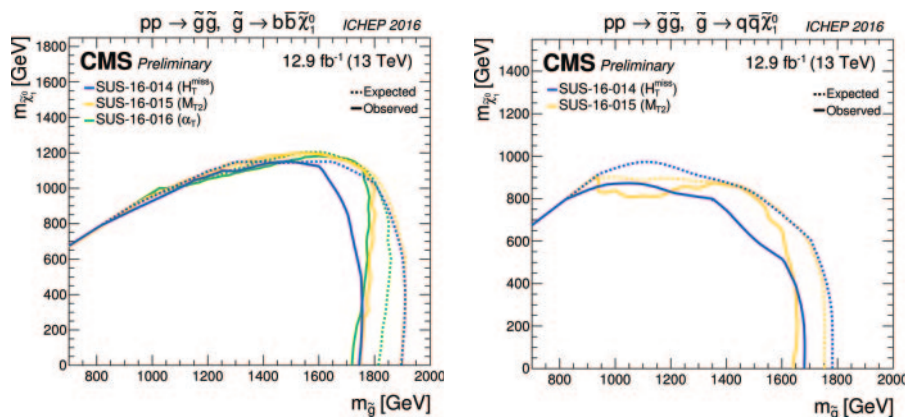

Fig. 1. – Limits on gluino pairs decaying to final states with 4 bottom quarks (left) or light quarks (right), as a function of the lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) and the gluino mass ($m_{\tilde{g}}$), obtained from the CMS inclusive analyses [10, 11, 13].

the razor analysis [16] performed in 2015 is based on the razor kinematic variables MR and R2 [17, 18], which are used as search variables and are generically sensitive to pair production of massive particles with subsequent direct or cascading decays to weakly interacting stable particles.

The results of all these analyses are interpreted in the context of simplified models [19-22]. Because no significant excess is observed, limits are determined as a function of the lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) and the gluino mass ($m_{\tilde{g}}$) for the models of gluino pair production (fig. 1) and as a function of $m_{\tilde{\chi}_1^0}$ and the squark mass ($m_{\tilde{q}}$) for the models of squark-antisquark production (fig. 2).

Leptonic final states are investigated by lepton multiplicities. The one lepton inclusive search [23] is using the azimuthal angle $\Delta\Phi$ (in the plane perpendicular to the beam) between the momentum vectors of the W boson candidate and the lepton to separate the signal from standard model backgrounds. To be sensitive to a large variety of signal topologies, several exclusive search regions are defined, based on the number of jets and b-tagged jets, HT, and the scalar sum of the missing transverse momentum and the transverse momentum of the lepton.

The 2-lepton analysis [24] is asking for two tightly identified same sign leptons and is using three exclusive event selections based on the lepton momenta:

- high-high (HH) selection: two leptons with $p_T > 25\,\mathrm{GeV}$;

- high-low (HL) selection: one lepton with $p_T > 25\,\mathrm{GeV}$ and one lepton with $10 < p_T < 25\,\mathrm{GeV}$; and

- low-low (LL) selection: two leptons with $10 < p_T < 25\,\mathrm{GeV}$.

These selections allow to target signals producing high-p_T leptons in the HH selection, and compressed-spectrum models inducing soft leptons from off-shell W boson decays in the HL and LL signal regions. The background composition also differs among the selections, with mostly irreducible SM backgrounds populating the HH region, and leptons
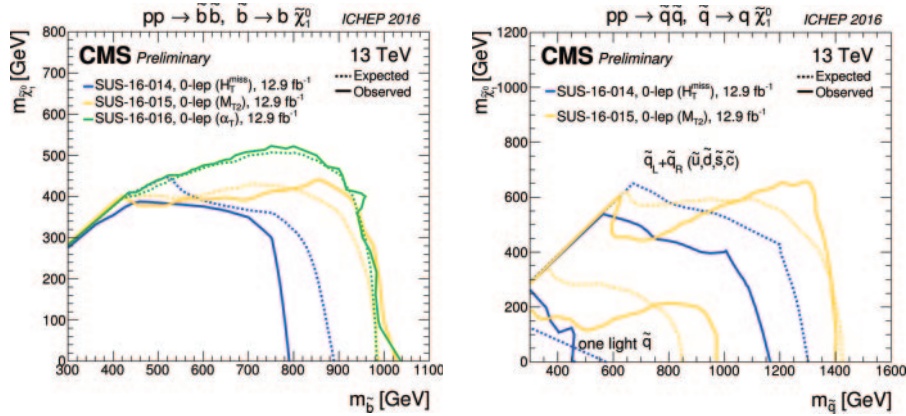

Fig. 2. – Limits on sbottom pairs decaying to final states with two bottom quarks (left) and limits on squark pairs decaying to final states with two quarks (right), as a function of the lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) and the squark mass ($m_{\tilde{q}}$), obtained from the CMS inclusive analyses [10, 11, 13].

not originating from W or Z boson decays in the HL region. The LL region is characterized by very small background, since all processes with at least one lepton originating from an on-shell vector boson are suppressed by the low-p_T requirement.

The multilepton analysis [25] is looking to events with at least three electrons or muons. Search regions are defined by the number of b-tagged jets, missing transverse momentum, hadronic transverse energy, and the invariant mass of opposite-sign, same-flavor dilepton pairs in the events. No significant excess above the standard model background expectation is observed.

3. – Third generation searches

To solve the hierarchy problem in a "natural" way, refs. [26-31] suggest models in which the higgsino mass parameter is of the order of 100 GeV and the masses of the top squark, the bottom squark, and the gluino are near the TeV scale, while the masses of the other sparticles can be beyond the reach of the LHC. To target this scenario, the CMS Collaboration has performed several dedicated third generation searches.

Hadronic final states are investigated by a 0-lepton top tagger analysis [32] and by a dedicated 0-lepton top squark search [33]. The first search relies on the use of a highly efficient algorithm to tag objects consistent with top quark decay and uses their kinematic properties as input to the computation of the stransverse mass (MT2) variable. Exclusive search regions are constructed using the number of identified b jets and top-like objects, and different thresholds on the missing transverse momentum and MT2. The second search is performing two analyses, a "low Δm" analysis that targets scenarios with a very small difference in mass between the top squark and the neutralino, and a "high Δm" analysis that targets topologies typical for larger mass splittings. The "low Δm" analysis is optimized for signal scenarios in which the mass difference between the top squark and neutralino is less than the W boson mass. The signature of such models is experimentally challenging since the visible decay products are typically very soft, often escaping detection. However, such compressed scenarios are particularly interesting since their predicted dark matter relic density is consistent with cosmological observations [34]. A dedicated search targeting this topology has therefore been developed, exploiting the characteristics of such signals to attain improved sensitivity towards such scenarios compared to traditional SUSY searches.

Leptonic final states are investigated with a dedicated 1-lepton top squark search [35]. In this analysis, the events are categorized based on the value of the M_{T2}^W variable [36]. The M_{T2}^W variable attempts to reconstruct the events under the assumption that it has originated in a $t\bar{t} \to ll$ process with one undetected lepton and helps to discriminate signal from the dominant dilepton $t\bar{t}$ background. To increase the sensitivity of this analysis to a mixed decay scenario, when the chargino and neutralino are nearly degenerate, search regions with exactly two jets are used. In these events with low jet multiplicity, the modified topness variable [37] is used to provide improved dilepton $t\bar{t}$ rejection.

Figure 3 summarizes the expected and observed limits obtained with the inclusive and third generation analyses for simplified models with top squarks produced through decays of gluino pairs and for direct top squark production with decay $\tilde{t}_1 \to t\tilde{\chi}_1^0$.

Another dedicated top squark search performed in CMS is the opposite-sign dilepton top squark search [38]. The search focuses on an efficient background reduction strategy using transverse mass variables that suppress the large background of SM $t\bar{t}$ events by several orders of magnitude.
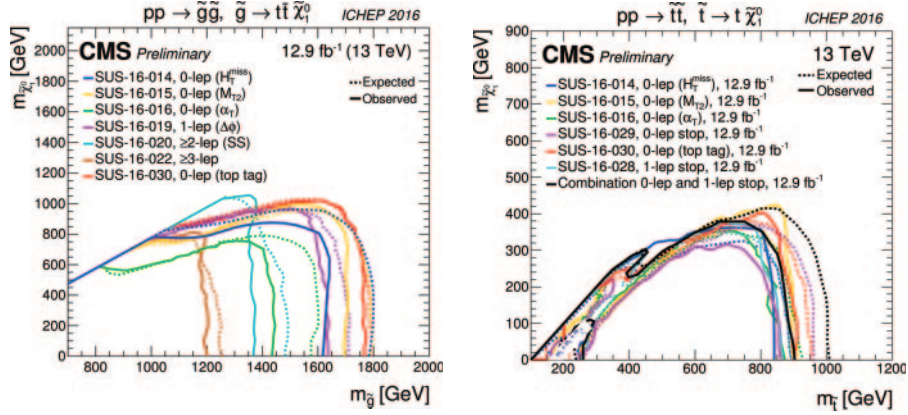
Fig. 3. – Limits on gluino pairs decaying to final states with 4 tops (left) and limits on top squark pairs decaying to final states with two tops (right), as a function of the lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) and the gluino mass ($m_{\tilde{g}}$) or the top squark mass ($m_{\tilde{t}}$), obtained from the CMS inclusiveand third generation analyses [10, 11, 13, 23-25, 32].

The third generation program also includes a search for direct production of bottom and light top squark pairs [39]. This search is performed in a final state of two or three jets accompanied by large missing transverse momentum, as well as large missing transverse mass and contransverse mass calculated from the jets originating from bottom quarks and missing transverse momentum. To be sensitive to the compressed region, the analysis relies on a hard initial-state-radiation jet (ISR) to provide enough boost to bottom and top squark products to be fully or partially visible in the detector.

Finally, a search for supersymmetry with a compressed mass spectrum using events with a high-momentum jet from initial state radiation, high missing momentum, and a low-momentum lepton (as low as 5 GeV) has been performed [40]. In particular, a scenario of top squark pair production is investigated, where the mass difference to the lightest supersymmetric particle (LSP) is smaller than the mass of the W boson. In this case the top squarks could undergo four-body decays to $bff + LSP$. The observed number of events are consistent with the expectation from standard model processes.

4. – Electroweak searches

The absence of an observed signal in the inclusive and third generation searches suggests that strongly produced SUSY particles may be too massive to be probed with the current datasets. In contrast, neutralinos and charginos, mixtures of the superpartners of the SM electroweak gauge bosons and the Higgs boson, can be within the accessible mass range, but due to the absence of color charge, may have eluded detection. This provides strong motivation for dedicated searches for electroweak SUSY particle production. In CMS, four analyses are exploring electroweak SUSY particle production: electroweak SUSY with photons, 1-lepton, 2-lepton and a multilepton search.

The final state considered in the first analysis [41] is characterized by photons and missing transverse momentum. This final state is motivated by the fact that in gauge-mediated supersymmetry breaking (GMSB) models [42-48] the gauginos can decay to photons, or other standard model bosons, and gravitinos. Since in electroweak production scenarios the expected hadronic activity is low compared to strong production, no jet

requirements are used. Additionally, gluino pair production models are considered, where the analysis does not lose sensitivity in scenarios with compressed mass spectra. The observed data are in agreement with the standard model prediction and limits are set on different models of GMSB.

The second analysis [49] is a search for beyond the standard model physics in events with a leptonically-decaying W boson, a Higgs boson decaying to a pair of b-quarks, and missing transverse momentum. This signature is predicted to occur, for example, in supersymmetric models from electroweak production of gauginos. One of the main variable used in this analysis to suppress both semi-leptonic and dileptonic $t\bar{t}$ background is the contransverse mass variable, M_{CT} [50, 51].

The third analysis [52] is a search for new physics in events with two low-momentum opposite-sign leptons and missing transverse momentum. This analysis investigates the production of supersymmetric particles in a scenario in which the mass splitting between the next-to-lightest SUSY particle (NLSP) and the LSP is small. In this case, the events would escape classical search strategies because of the low transverse momenta of the decay products of the NLSP. Signal events can still be distinguished from SM processes if a high-p_T jet from initial-state radiation leads to a boost of the sparticle pair system and enhances the amount of missing transverse momentum, while the other decay products typically remain soft. In the signal scenarios studied in this search, SUSY particles can decay leptonically, and the presence of low-p_T leptons is used to discriminate further against otherwise dominant SM backgrounds, such as multijet production and Z + jets events with invisible Z boson decays.

Finally, the last analysis [53] is a search for the direct electroweak production of charginos and neutralinos, in signatures with two light leptons of the same charge and with three or more leptons including up to two hadronically decaying taus.

For all these electroweak searches, the observed event rates are in agreement with expectations from the standard model. Figure 4 shows some of the limits obtained on charginos and neutralinos masses.
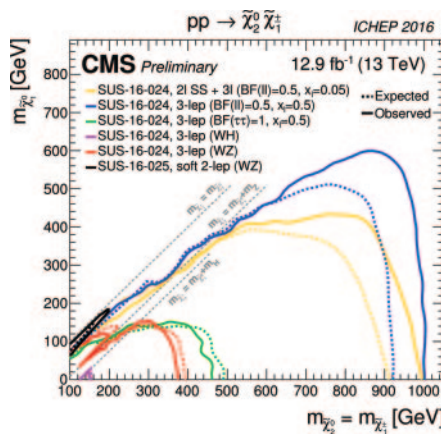

Fig. 4. – Some of the limits obtained from electroweak searches. The corresponding simplified models and assumptions used are described in ref. [52] and ref. [53].

5. – Specialized searches

In addition to all the searches previously presented, some other specific searches are performed in CMS.

One of these searches is a search [54] for physics beyond the standard model in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum. The analysis uses the invariant mass of the lepton pair, searching for a kinematic edge or a resonant-like excess compatible with the Z boson mass. The search for a kinematic edge targets strong production while the resonance search targets both strongly and electroweakly produced new physics. Both search modes use several event categories in order to increase the sensitivity to new physics. These categories are based on several observables related to the lepton pair and the hadronic system in order to optimize signal efficiency and background rejection. A fit is employed to search for a possible kinematic edge position in the strong, non-resonant search. In addition, signal regions are included for which excesses were reported by the ATLAS and CMS Collaborations using $\sqrt{s} = 8\,\text{TeV}$ and $\sqrt{s} = 13\,\text{TeV}$ data. The observations in all signal regions are consistent with the expectations from the standard model.

Another search [55] is the analysis of events selected by requiring one Higgs boson candidate decaying into two photons in association with at least one jet. Events are categorized according to the properties of the Higgs boson candidate(s) and the razor variables (MR and R2) are used to improve discrimination between SUSY signals and the standard model backgrounds. The search is carried out by fitting the diphoton invariant mass distribution in each search region. The result of the search is interpreted in the context of a simplified model of bottom squark production and upper limits on the corresponding production cross section are derived.

Finally, an analysis [56] is focusing on the signature of large multiplicity of jets and b-tagged jets, in a final state with zero or one reconstructed lepton. The results are interpreted in terms of limits on the parameter space for the R-parity-violating supersymmetric extension of the standard model in a benchmark model of gluino pair production where each gluino decays via $g \rightarrow tbs$. Assuming the gluino decays solely to tbs, gluino masses smaller than $1360\,\text{GeV}$ are excluded at a 95% confidence level.

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