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Searches for strong production of supersymmetry at CMS

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Results of searches for the production of supersymmetric partners of gluons and quarks are presented. They are based on pp collisions recorded by the CMS experiment at $\sqrt{s} = 13\,\text{TeV}$. The searches are performed in final states with 0, 1, or more leptons and are either generic, or specifically designed for the production of third-generation squarks. In the most favorable scenarios, mass limits reach up to 2 TeV.

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1. Introduction

Supersymmetry (SUSY) is one of the promising candidates for extending the standard model (SM) and can offer solutions to multiple shortcomings of the SM. In this document three searches [1–3] for strongly produced SUSY particles in R-partiy conserving models are briefly described. The analyses described here are performed in various final states and kinematic regions and are based on the 2016 pp collision data collected at the CMS detector [4] corresponding to an integrated luminosity of 36 fb^{-1}. The searches take advantage of simplified model spectra (SMS) which have the benefit of reducing the model dependence of the analyses. In simplified models, the squarks and gluinos have the largest production cross sections which further motivates searches for the strong production of SUSY.

2. Search for natural and split SUSY in all jet final states

This analysis [1] is an inclusive search for SUSY in final states with jets and missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$). In addition to targeting the production of squarks and gluinos, this search is also sensitive to simplified models inspired by split SUSY scenarios. Similar to natural SUSY models, split SUSY scenarios allow for the unification of gauge couplings and also offer a suitable dark matter candidate as the lightest supersymmetric particle (LSP). Split SUSY, however does not offer a solution to the hierarchy problem as it requires the bosonic SUSY particles to be much heavier than the electroweak scale. In split SUSY models with R-parity conservation the gluinos can obtain relatively long lifetimes due to the highly virtual squark states. The gluinos with lifetimes larger than a picosecond can form color singlet states (R-hadrons) with gluons and quarks until decaying into a quark-antiquark pair and a neutralino.

Events with jets and $p_{\mathrm{T}}^{\mathrm{miss}}$ are dominated by multijet QCD events in which mismeasurements of jet energies can lead to relatively large values of $p_{\mathrm{T}}^{\mathrm{miss}}$. Dedicated kinematical variables, α_{T} and $\Delta\phi^*_{min}$ are used to reduce this background to subpercent level with respect to the electroweak backgrounds while maintaining high acceptance for events with genuine $p_{\mathrm{T}}^{\mathrm{miss}}$. The α_{T} variable in a dijet system is defined as the ratio of the energy of the subleading jet to the transverse mass (M_{T}) of the dijet system and has a value of 0.5 in a well measured back-to-back dijet event. For multijet events a generalized version of the variable is used instead. The $\Delta\phi^*_{min}$ variable in the event is defined as the minimum azimuthal angle between a jet and the vectorial sum of the transverse momenta of all other jets. Events with $\Delta\phi^*_{min} > 0.5$ and $\alpha_{\mathrm{T}} \gtrsim 0.5$ are then selected in order to select events with a genuine $p_{\mathrm{T}}^{\mathrm{miss}}$ and to suppress the QCD background.

Sensitivity to the signals of interest are obtained by an extensive categorization of the events based on variables such as, number of jets (N_j), number of jets tagged as having originated from a bottom quark (N_b), the scalar (H_{T}) and vectorial ($H_{\mathrm{T}}^{\mathrm{miss}}$) sum of the jet transverse momenta. In events with low N_j and N_b the dominant irreducible background process is the associated production of jets with Z bosons decaying to two neutrinos ($Z \to \nu\nu$+jets). Moreover, events with the associated production of jets with leptonically decaying W bosons (W+jets) can also have significant contributions in these regions. These events, referred to as the "lost lepton" background, can escape the lepton veto and enter the signal region if the lepton is not reconstructed due to lack of isolation or geometrical acceptance. For categories including larger N_j and N_b values, the domi-

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nant background is the semileptonic decay of pair produced top quarks ($t\bar{t}$). Other processes such as single production of top quarks, diboson production and production of $t\bar{t}$ in association with a boson ($t\bar{t}X$) have residual contributions to the signal regions (SRs).

The contributions of the multijet backgrounds in each set of N_j and H_T categories are estimated from three separate control regions (CRs) defined in terms of $\Delta\phi^*_{min}$ and the ratio of $p_\mathrm{T}^\mathrm{miss}$, $H_\mathrm{T}^\mathrm{miss}$. Simulated samples are used for extrapolating the data-based estimates to the signal regions. The lost lepton and the $Z \to \nu\nu$+jets backgrounds are estimated from data control regions enriched in μ+jets and $\mu\mu$+jets events respectively. Simulated samples are used to obtain transfer factors in bins of N_j, N_b, and H_T. Simulation-based templates of $H_\mathrm{T}^\mathrm{miss}$ are then used to obtain the final background estimation in the SRs.

Finally, the SM predictions in the SRs and CRs are obtained by performing a binned likelihood fit. The observed number of events in the SRs are found to be compatible with the predicted SM contributions. The results are then interpreted in various SMS scenarios including production of squarks and gluinos in natural SUSY models as shown in Fig. 1 (top). Although not specifically designed for long-lived gluinos, this search still shows sensitivity for production of gluinos with proper decay lengths ranging between 10^{-3}-10^{5}mm as seen in Fig. 1 (bottom).

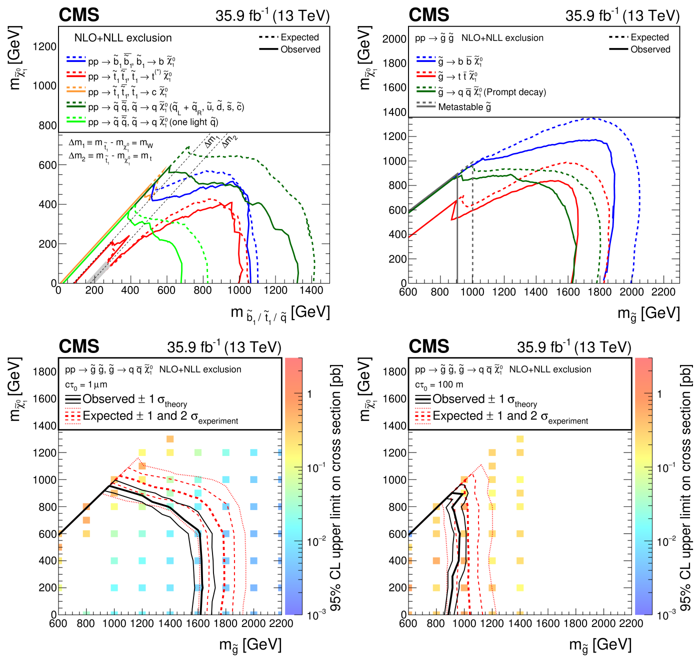

Figure 1: Exclusion contours for the production of squarks (top left) gluinos (top right) and split SUSY gluinos with $c\tau_0 = 1\mu$m (bottom left) and $c\tau_0 = 100$m (bottom right) [1].

3. Search for compressed SUSY in single lepton channel

This search [2] focuses on the pair production of top squarks in simplified models with a nearly degenerate neutralino as the LSP. In particular compressed scenarios in which the mass difference (Δm) between the top squark and the LSP is between 10-80 GeV are considered. SUSY models

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with a compressed mass spectrum are motivated by cosmological observations as the coannihilation between the top squarks and the LSPs can help obtain the observed dark matter relic densities. In these scenarios the direct four-body (or chargino-mediated) decay of the top squark into a b quark, a fermion pair and the LSP can result in final states with soft leptons, soft b-jets and moderate $p_{\mathrm{T}}^{\mathrm{miss}}$. In addition to a sequential selection approach (CC) sensitive to both scenarios, this search also includes a multivariate analysis (MVA) approach which targets only the four-body scenario. Both approaches select events with an energetic jet attributed to an initial state radiation (ISR), require at least one muon (electron) with $p_{\mathrm{T}} > 3.5(5)\,\mathrm{GeV}$ and share similar requirements of H_{T}, $p_{\mathrm{T}}^{\mathrm{miss}}$ in order to reduce the contribution of the main backgrounds (W+jets and $\mathrm{t\bar{t}}$).

The general strategy of the CC search is to exploit the soft leptons of the signal and define the signal regions by $p_{\mathrm{T}}(\ell) < 30\,\mathrm{GeV}$. The normalization of the main backgrounds in each signal region is then obtained from a corresponding control region by reversing the $p_{\mathrm{T}}(\ell)$ requirement of the SR to $p_{\mathrm{T}}(\ell) > 30\,\mathrm{GeV}$. In order to maintain sensitivity to a wide range of signal kinematics in the CC search, two sets of signal regions are devised. The first set of signal regions targets smaller values of Δm, where the b-jets would likely be too soft to be reconstructed. Therefore in this region events with a b-jet are vetoed. The second set of signal regions is targeted towards signals with larger Δm. Events in these regions are then required to have a soft b-jet with a $p_{\mathrm{T}} < 60\,\mathrm{GeV}$ but events with more energetic b-jets are vetoed in order to keep the $\mathrm{t\bar{t}}$ background under control. The signal regions are then categorized according to M_{T}, $p_{\mathrm{T}}(\ell)$, and further selections on combinations of $p_{\mathrm{T}}^{\mathrm{miss}}$ with H_{T} or p_{T} of the ISR jet candidate.

For the MVA analysis a boosted decision tree (BDT) is trained on the four-body signal against the dominant backgrounds. A separate BDT training is performed for each set of Δm by combining signals samples with the same Δm and different top squark masses. In addition to the variables used in defining the CC SRs, the input variables of the MVA also include variables such as angular separation between the lepton and b-jet, the p_{T} of the b-jet and the number of jets in the event. The output of the BDT in data has been shown to be in good agreement with that of the MC in various validation regions. For each Δm, the SR (CR) is defined as the region where the BDT output is larger (smaller) than a threshold BDT value. The normalization of the prompt backgrounds in the BDT SR is obtained in the corresponding BDT CR. The contribution due to nonprompt sources of leptons in both CC and MVA approaches is estimated from data in side-band regions with non-isolated leptons and by measuring the probability of a non-isolated lepton to be selected as a lepton in the analysis.

The observed number of events in the CC and MVA SRs shows no significant deviation from the SM predictions. The MVA (CC) results are used to set limits on the four-body (and chargino-mediated) simplified models assuming a prompt decay of the top squark and a 100% branching ratio for each model. The MVA and CC limits for the four-body scenario are compatible for Δm <30, while for larger Δm the MVA performs significantly better and can exclude top squark masses of up to $560\,\mathrm{GeV}$ for $\Delta m = 80\,\mathrm{GeV}$ (Fig. 2 left). The CC results are combined with the previously published results in the hadronic channel of both scenarios [5]. The combined results for the chargino-mediated scenario are shown in Fig. 2 (right). The mass of the chargino is assumed to be equal to the average of the top squark and LSP masses.

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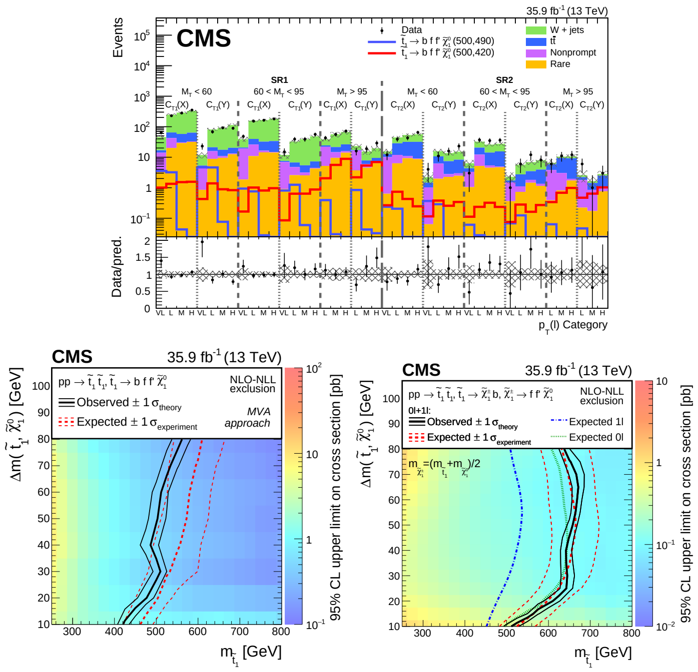

Figure 2: The expected SM contribution and the observed data in the CC signal regions (top). Exclusion contours for the four-body scenario (bottom-left) using the MVA approach. The combined CC and hadronic exclusion contours for the chargino-mediated scenario (bottom-right) [2].

4. Search for top squark pair production in the two lepton channel

This analysis [3] is a search for the pair production of top squarks in events with two oppositely charged (OC) leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$. The analysis is also sensitive to models of direct chargino production which are not discussed in this document. The search is optimized for mass scenarios with $m_W < \Delta m < m_t$, but larger mass gaps are also considered for completeness. In this mass region, the top squark would go through a three-body decay to a W boson, a b-quark and an LSP. In addition, a model with chargino-mediated decays analogous to the one described in the previous section is considered.

The baseline selection is defined based on the characteristics of signals and includes events with $p_{\mathrm{T}}^{\mathrm{miss}} > 140\,\mathrm{GeV}$, and a transverse momentum $p_{\mathrm{T}} > 25(20)\,\mathrm{GeV}$ for the leading (subleading) lepton. Both same flavor (SF) and different flavor (DF) lepton pairs are considered. The dilepton invariant mass is required to be greater than 20 GeV for SF and DF and to be more than 15 GeV away from the mass of the Z boson in the case of SF leptons. For further suppression of these backgrounds the $M_{\mathrm{T2}}(\ell\ell)$ variable, a generalization of the transverse mass, is used. The $M_{\mathrm{T2}}(\ell\ell)$ distributions of dominant backgrounds ($\mathrm{t\bar{t}}$, $\mathrm{t}W$ and WW events) have a kinematic endpoint at m_W, while for the signal, the $p_{\mathrm{T}}^{\mathrm{miss}}$ contribution of the neutralinos results in a more uniform $M_{\mathrm{T2}}(\ell\ell)$ distribution. Signal regions are defined for SF and DF leptons in bins of $p_{\mathrm{T}}^{\mathrm{miss}}$, N_b, N_j and N_{ISR}. In order to take advantage of the shape differences between the $M_{\mathrm{T2}}(\ell\ell)$ distributions in signal and backgrounds, each signal region is further divided into $M_{\mathrm{T2}}(\ell\ell)$ bins with boundaries ranging from 20-120 GeV.

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The $M_{T2}(\ell\ell)$ distributions of the main backgrounds are verified in a p_T^{miss} sideband ($100 < p_T^{miss} < 160$ GeV) and also for $p_T^{miss} > 140$ GeV where events $WZ \to 3\ell\nu$ are used to emulate the $M_{T2}(\ell\ell)$ shape of the main backgrounds. The observed $M_{T2}(\ell\ell)$ shapes in both CRs is found to be described well by the simulation. The normalization for the main backgrounds is extracted by a maximum-likelihood fit from the low $M_{T2}(\ell\ell)$ region which is dominated by these backgrounds. The normalization of the subleading backgrounds ($t\bar{t}Z$, WZ, ZZ and Drell-Yan events) is estimated from data in dedicated control regions enriched by each process with their data/simulation correction factors ranging from 0.97-1.44. The observed values in the SR show no significant deviation from the SM predictions. The results are then used to set limits on the pair production of top squarks assuming 100% branching fractions for each of the models. For the three-body scenario ($m_W < \Delta m < m_t$) top squark masses of up 420 GeV for $\Delta m = 80$ GeV are excluded while for the chargino mediated scenario top squark masses in the range 225-325 GeV are excluded for $\Delta m \approx 2\,m_W$.

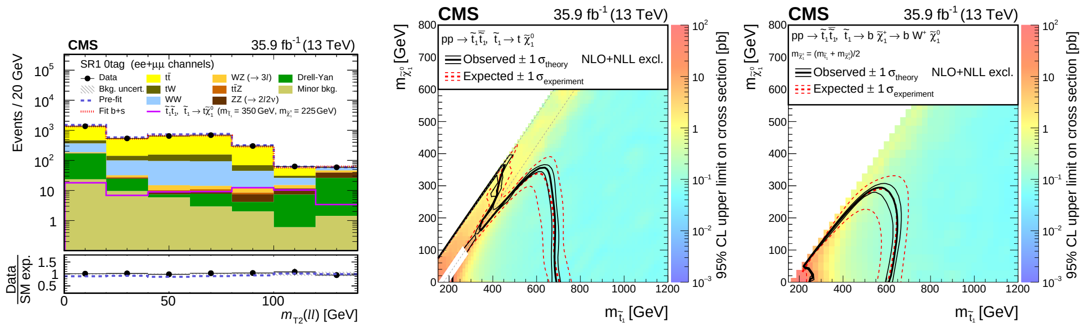

Figure 3: An $M_{T2}(\ell\ell)$ distribution including data, SM backgrounds and a signal example (left). Exclusion contours for the top squark production with a decay via top quark (middle) and the chargino-mediated scenario (right) [3].

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