PROCEEDINGS OF SCIENCE

Supersymmetry searches with heavy object tagging and tau leptons in CMS

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There has been significant progress in the recent past on the usage of sophisticated machine learning techniques for the tagging of hadronically decaying heavy objects with large-radius jets, and the identification of tau leptons decaying to hadrons. These techniques have revolutionized searches for Supersymmetry at the LHC. This report summarizes the recent searches for Supersymmetry in CMS, using heavy object tagging and tau lepton identification. These results have been obtained using the full LHC Run-2 proton-proton collision data set collected at a center of mass energy of 13 TeV.

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1. Introduction

The standard model (SM) is the most successful theory of elementary particle physics to date. However, it is an incomplete theory as it is unable to provide satisfactory answers to various fundamental problems like the existence of dark matter/energy, origin of gravitational interaction, stability of the Higgs boson mass, etc. In order to address these shortcomings, several extensions to the SM have been proposed, of which Supersymmetry (SUSY) is one of the most extensively studied. SUSY postulates that for every boson there exists a fermionic superpartner and vice versa. Some of the typical benchmark scenarios exploring different regions of the SUSY parameter space are presented in Fig. 1 (left panel). Depending on the mass hierarchy and the composition (bino, wino, or higgsino-like) of the charginos and neutralinos, each of these scenarios will have different final state particles and kinematic properties, thereby requiring a dedicated search that is optimized for that particular event topology. For instance, if the mass difference between supersymmetric particles (sparticles) is large enough, the massive sparticle can decay to heavy SM particles like the top quark or $W/Z/H$ bosons. Examples of the allowed decay modes of the top squark $\tilde{t}_1$ for different mass differences with respect to the lightest neutralino $\tilde{\chi}^0_1$, are illustrated in Fig. 1 (right panel). If the mass gap is even larger, these SM objects can be highly energetic (boosted) and decay hadronically to produce a collimated beam particles (jets) in a cone. The radius R of the cone can be approximated as $R = 2M/p_T$, where M and p_T are the mass and transverse momentum of the heavy SM particle, respectively. Hence the cone radius of such jets will typically be larger compared to jets from the direct production of light quarks and gluons. Tagging such large radius jets requires sophisticated techniques. Another scenario discussed here arises when sparticle decay modes to third generation leptons are enhanced, thereby producing tau leptons (τ) in the final state. Such final states have a large background contribution from quark and gluon jets misidentified as hadronically decaying tau leptons (τ_h), thereby necessitating the use of specialized algorithms for identifying genuine τ_h candidates. The results summarized in this report have been obtained using the full LHC Run-2 proton-proton collision data set recorded by CMS [1].

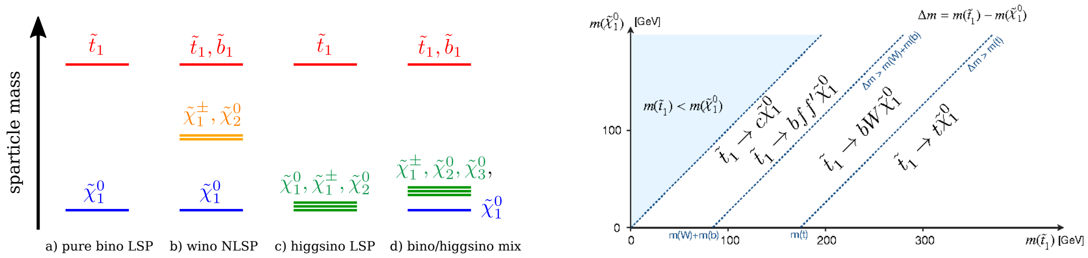

Figure 1: Left: sketch of a few typical SUSY benchmark scenarios. Right: sketch [2] of the allowed decay modes of $\tilde{t}_1$ for different mass gaps $\Delta m(\tilde{t}_1, \tilde{\chi}^0_1)$, assuming other sparticles are decoupled.

2. Searches with tau leptons

2.1 Tau slepton production

This analysis [3] searches for the pair production of tau sleptons ($\tilde{\tau}$), which is motivated by early universe $\tilde{\tau}$–$\tilde{\chi}^0_1$ coannihilation scenarios where the $\tilde{\tau}$ is the next-to-lightest sparticle. The $\tilde{\tau}$

promptly decays to a τ and a $\tilde{\chi}_1^0$ in this model. A gauge mediated SUSY breaking scenario is also considered, where the $\tilde{\tau}$ has a macroscopic proper lifetime and decays to a τ and a nearly massless gravitino ($\tilde{G}$). The long-lived $\tilde{\tau}$ decays within a few centimeters of the primary interaction vertex (PV). This produces τ_h candidates that are displaced from the PV. The diagram of the process is shown in Fig. 2 (left panel). Events in the search region (SR) are required to have exactly two oppositely charged τ_h candidates, which are identified using the deep neural network (DNN) based DeepTau algorithm [4]. The SR is binned in terms of the "stransverse mass" m_{T2} [5, 6] of the two τ_h candidates, and the sum of their transverse masses. The stransverse mass is a generalization of transverse mass for events where the missing momentum arises from two or more invisible particles. An orthogonal SR targeting the long-lived scenario is defined using displaced τ_h candidates, which are required to have a 3-dimensional impact parameter greater than 100 μm with respect to the PV. No significant differences are observed between the observed data and predicted background. Figure 2 (central panel) shows the upper limit at 95% confidence level (CL) on the prompt $\tilde{\tau}$ pair production cross-section (σ). The upper limit on the long-lived $\tilde{\tau}$ pair production cross-section is presented in Fig. 2 (right panel).

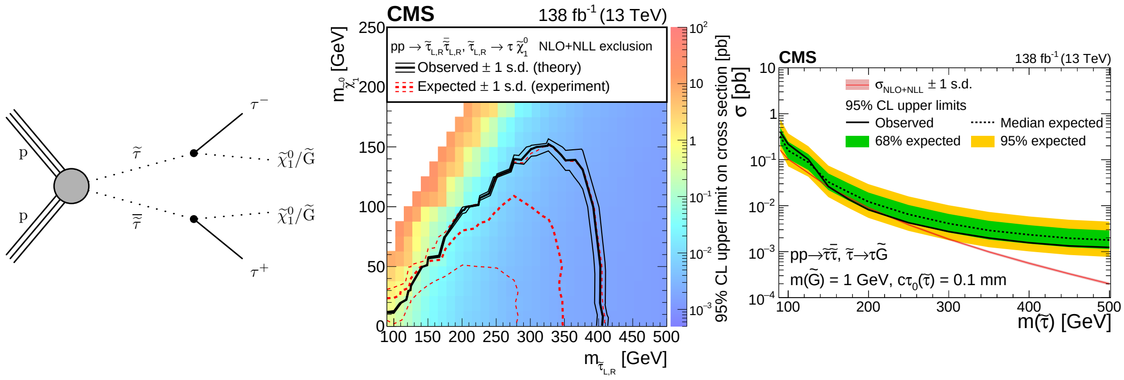

Figure 2: Left: diagram of $\tilde{\tau}$ pair production and decay. Center: upper limit on $\sigma(\tilde{\tau}\tilde{\tau})$ at 95% CL for the prompt scenario, in the plane of $m_{\tilde{\tau}}$ and $m_{\tilde{\chi}_1^0}$, considering the left and right handed components of the $\tilde{\tau}$ to be mass degenerate. Right: upper limit on $\sigma(\tilde{\tau}\tilde{\tau})$ at 95% CL as a function of $m_{\tilde{\tau}}$, for a proper $\tilde{\tau}$ lifetime (decay length) of 0.1 mm, considering a maximal mixing between the left and right handed components of the $\tilde{\tau}$.

2.2 Chargino and neutralino production

This search [7] explores the pair production of mass degenerate charginos ($\tilde{\chi}_1^\pm$) and heavy neutralinos ($\tilde{\chi}_2^0$) which then decay to leptons, neutrinos, and $\tilde{\chi}_1^0$ via sleptons ($\tilde{\ell}$) and sneutrinos ($\tilde{\nu}$). Figure 3 shows the diagrams of these processes. Three different cases are considered: (i) a flavor democratic scenario, where the sleptons are left handed and decays to all lepton flavors have equal probabilities, (ii) a τ-enriched scenario, where the chargino preferably decays (couples) to τ sleptons/leptons but the neutralino decay is flavor democratic, and (iii) a τ-dominated scenario, where both the chargino and neutralino decay (couple) exclusively to τ sleptons/leptons. The SR is binned in terms of the missing transverse momentum p_T^{miss}, the stransverse and invariant masses of the e, μ and τ_h candidate pairs. The τ_h candidates are identified with the aforementioned DeepTau algorithm. The predicted background is found to be consistent with the observed data. Upper limits on the cross sections of the considered processes are presented in Fig. 4 for the three aforementioned scenarios.

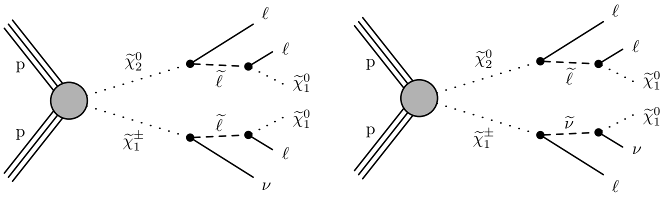

Figure 3: Diagrams of $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production and decay.

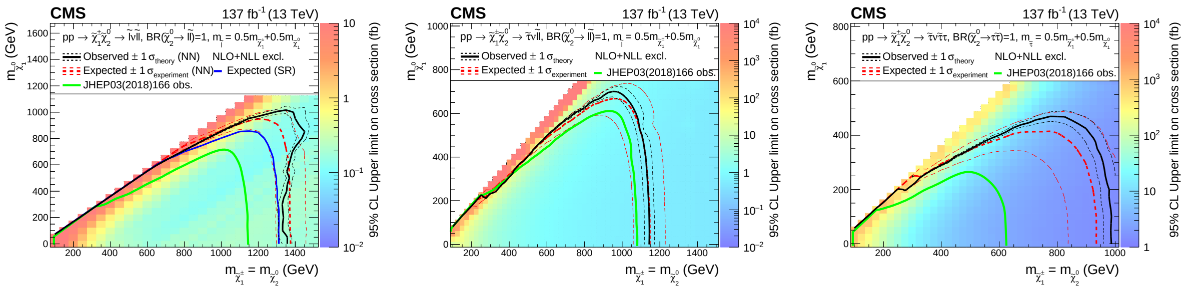

Figure 4: Upper limits on $\sigma(\tilde{\chi}_1^{\pm}\ \tilde{\chi}_2^0\ )$ at 95% CL, for the flavor democratic (left panel), τ-enriched (central panel), and τ-dominated (right panel) scenarios, in the plane of $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$.

2.3 Top squark production

The model studied in this search [8] explores $\tilde{t}_1$ pair production in scenarios where the chargino has a dominant higgsino component and $\tan\beta$ is large, thereby favoring decays to τ leptons. The diagrams of the considered processes are presented in Fig. 5 (left and central panels). Both fully hadronic (both τ decay to hadrons) and semileptonic (one τ decays to hadrons and the other to an electron e or a muon μ) decays are included in the search. Events in the SR are required to have an oppositely charged $e\tau_{\mathrm{h}}$, $\mu\tau_{\mathrm{h}}$ or $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ pair. The τ_{h} candidates are identified with the aforementioned DeepTau algorithm, and the SR is binned in terms of p_T^{miss}, m_{T2} of the previously stated pair, and the scalar sum of the transverse momenta of the lepton, τ_{h} candidates, and jets in the event. No significant differences are observed between the observed data and predicted background. The upper limit on the production cross-section of this process is presented in Fig. 5 (right panel).

3. Electroweak SUSY searches with heavy objects

This search [9] probes chargino and neutralino production in three different scenarios: (i) mass degenerate $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ or $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pair, (ii) mass degenerate wino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ and $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ pairs, with a light bino-like $\tilde{\chi}_1^0$, and (iii) mass degenerate higgsino-like $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_3^0$ and $\tilde{\chi}_2^0\tilde{\chi}_3^0$ pairs, with a light bino-like $\tilde{\chi}_1^0$. The diagrams of these processes are presented in Fig. 6. The heavy charginos and neutralinos decay to boosted W, Z, and H bosons, which are reconstructed with anti-k_T jets of radius 0.8 (AK8 jets), and tagged using the DNN based DeepAK8 [10] tagger. The number AK8

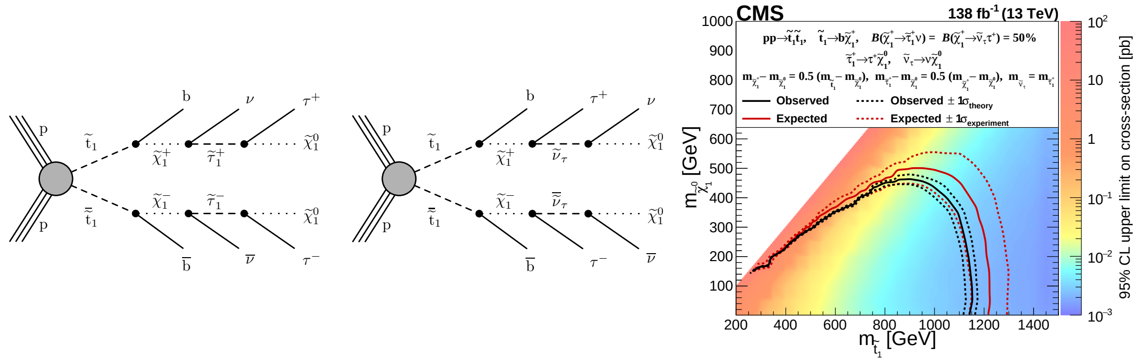

Figure 5: Left and center: diagrams of $\tilde{t}_1$ pair production and decay with τ leptons in the final state. Right: upper limit on $\sigma(\tilde{t}_1\tilde{t}_1)$ at 95% CL in the plane of $m_{\tilde{t}_1}$ and $m_{\tilde{\chi}^0_1}$.

jets tagged as a W, Z, or H candidate, is used to define the SR. The predicted background is found to be consistent with the observed data. Upper limits on the production cross-sections of the different processes are presented in Fig. 7. Note that neutralino pair production with a decay to two Higgs bosons ($\tilde{\chi}^0_1\tilde{\chi}^0_1 \to HH\tilde{G}\tilde{G}$ and $\tilde{\chi}^0_2\tilde{\chi}^0_3 \to HH\tilde{\chi}^0_1\tilde{\chi}^0_1$) has been performed in Ref. [11].

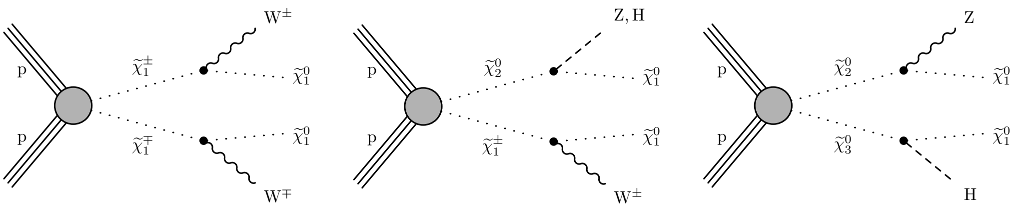

Figure 6: Diagrams of the chargino and neutralino pair production and decay into W, Z, and H bosons.

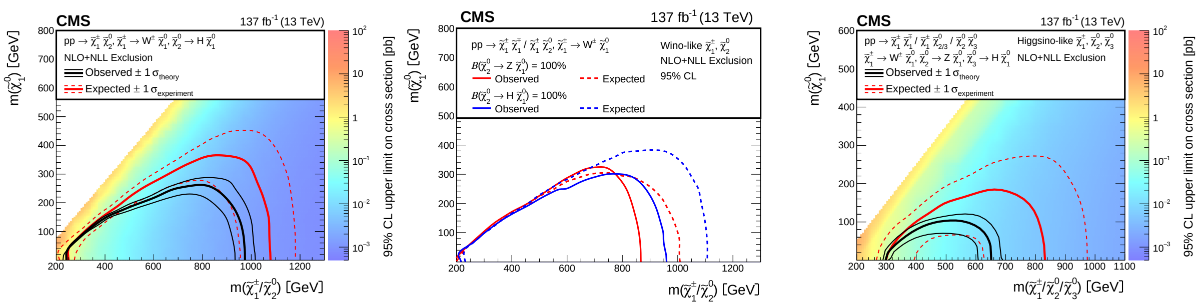

Figure 7: Left: upper limit on $\sigma(\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ at 95% CL in the plane of $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2}$ and $m_{\tilde{\chi}^0_1}$, for the decay mode $\tilde{\chi}^0_2 \to H\tilde{\chi}^0_1$. Center: the exclusion region at 95% CL in the the plane of $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2}$ and $m_{\tilde{\chi}^0_1}$, for a wino-like $\tilde{\chi}^\pm_1\tilde{\chi}^0_2$ production. Right: upper limit on $\sigma(\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1/\tilde{\chi}^\pm_1\tilde{\chi}^0_2/\tilde{\chi}^\pm_1\tilde{\chi}^0_3/\tilde{\chi}^0_2\tilde{\chi}^0_3)$ for the higgsino-like scenario at 95% CL, in the plane of $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2/\tilde{\chi}^0_2}$ and $m_{\tilde{\chi}^0_1}$.

4. Strong SUSY searches with heavy objects

4.1 Search with boosted Z bosons

The gluino ($\tilde{g}$) pair production process explored in this paper [12] is shown in Fig. 8 (left panel). If the mass of the $\tilde{\chi}_2^0$ is close to that of the heavy gluino, the Z bosons will be highly boosted, and the $\tilde{\chi}_1^0$ will produce a large p_T^{miss} . Hadronically decaying boosted Z bosons are reconstructed with AK8 jets and tagged using the soft-drop declustering algorithm [13]. Events in the SR are required to have two AK8 jets tagged as Z candidates and a high value of p_T^{miss}. No significant differences are observed between the p_T^{miss} spectra in the observed data and predicted background. The upper limit on the cross section of the process are presented in Fig. 8 (right panel).

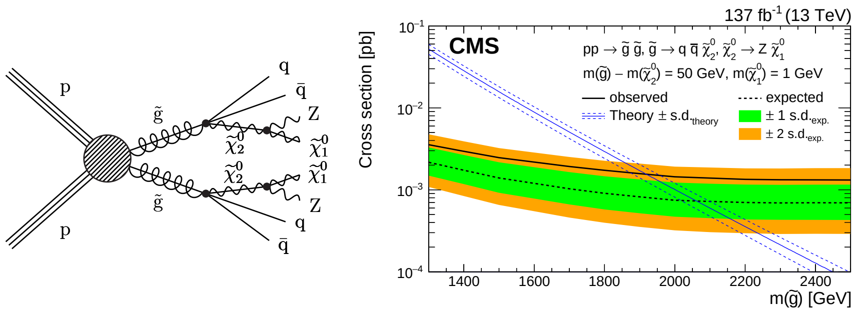

Figure 8: Left: diagram of gluino pair production decaying to Z bosons via heavy neutralinos. Right: upper limit on $\sigma(\tilde{g}\tilde{g})$ at 95% CL as a function of $m_{\tilde{g}}$.

4.2 Search with boosted Higgs bosons

This search [14] considers a similar process as that described in Sec. 4.1, except that the heavy $\tilde{\chi}_2^0$ decays to a H boson instead of a Z boson. The diagram of this process is shown in Fig. 9. Such decays are preferred when the higgsino component of the $\tilde{\chi}_2^0$ is dominant. The boosted H decays are reconstructed with AK8 jets and tagged using the DNN based DeepDoubleBvL algorithm [15]. In addition to the boosted scenario, this study also considers the resolved situation where the H boson is not boosted, and thus decays into two well separated bottom quarks that are reconstructed as anti-k_T jets of radius 0.4 (AK4 jets) and tagged as b-jets using the DNN based DeepCSV [16] algorithm. The SR bins are defined in terms of p_T^{miss}, the number of b-jets, and the number of H candidates in the event. The predicted background is found to be consistent with the observed data. The upper limit on the cross section of the process are presented in Fig. 9 (right panel).

4.3 Search with boosted top quarks and W bosons

The gluino pair production processes explored in this search [11] are presented in Fig. 10. Two different gluino decay modes are considered: (i) the gluino decays directly to top quarks, and (ii) the gluino decays to a W boson via a chargino. They are referred to as the “multi-b" (because the top quarks decay to produce multiple bottom quarks in the final state), and “zero-b" models, respectively. Boosted hadronically decaying top quarks and W bosons are reconstructed using AK8 jets and tagged with the DeepAK8 algorithm. In addition, resolved top quark decays are also considered, which are identified using a boosted decision tree. Events in the SR are required to

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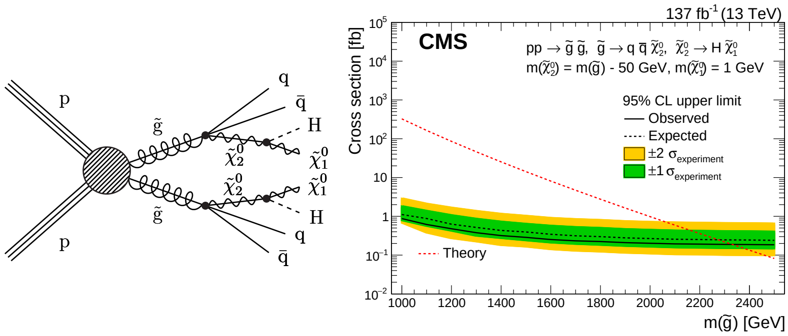

Figure 9: Left: diagram of gluino pair production decaying to H bosons via heavy neutralinos. Right: upper limit on $\sigma(\tilde{g}\tilde{g})$ at 95% CL as a function of $m_{\tilde{g}}$.

have exactly one well identified electron or muon, and the SR is binned in terms of the number of AK4 jets, b-jets, top quark and W boson candidates, the scalar sum of the lepton p_T and p_T^{miss} , and the scalar sum of all hadronic jets. The predicted background yields in all the SR bins are found to be consistent with the observed data. Figure 11 shows the upper limits on the cross sections of the two models.

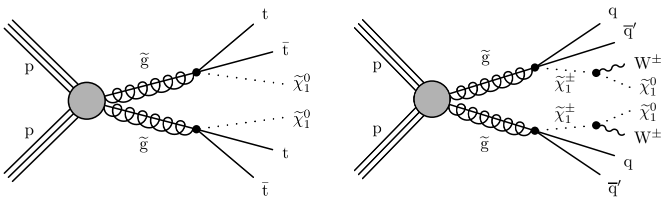

Figure 10: Left (right): diagram of gluino pair production and decay for the multi-b (zero-b) models.

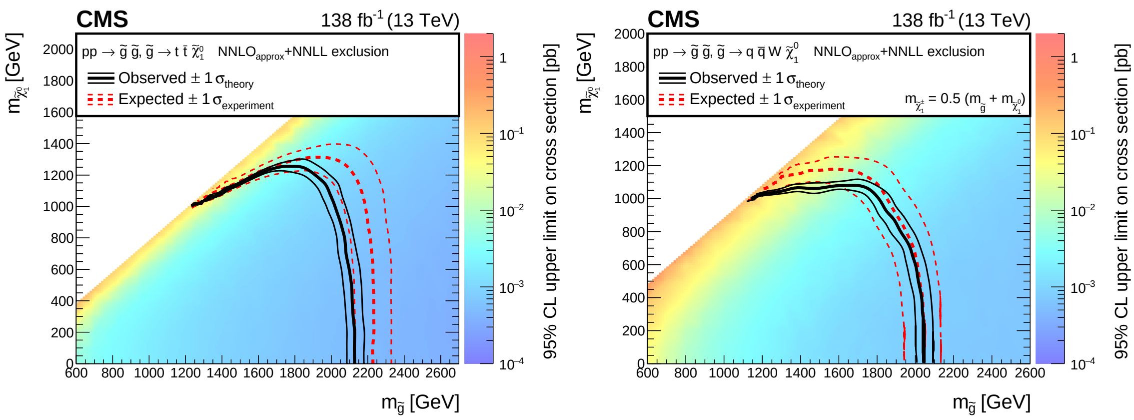

Figure 11: Left (right): upper limit on $\sigma(\tilde{g}\tilde{g})$ at 95% CL in the plane of $m_{\tilde{g}}$ and $m_{\tilde{\chi}^0_1}$, for the multi-b (zero-b) model.

5. Summary

Several searches with tau leptons and boosted heavy objects in the final state have been performed by the CMS Collaboration, exploring a wide variety of SUSY models. Some of the recent results with the full Run-2 data set have been summarized in this report. These studies typically involve the usage of specialized algorithms to identify hadronic decays of tau leptons and boosted heavy SM particles. The reaches of the search program with tau leptons and heavy object tagging can potentially be further expanded in Run-3, with the application of new state-of-the-art machine learning techniques.

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