PROCEEDINGS OF SCIENCE

Searches for compressed supersymmetry scenarios with the CMS experiment

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Results from the CMS experiment are presented on searches for supersymmetric particles targeting models with compressed spectra with small mass splitting between the accessible supersymmetric partners of Standard Model particles. Such a spectrum presents unique experimental challenges, thus new techniques are utilized to address these difficult scenarios. The searches use proton-proton collision data at the center of mass energy of 13 TeV collected during the LHC Run 2.

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[*] Speaker

1. Introduction

Strong constraints exist on the Minimal Supersymmetric Standard Model (MSSM) as a result of a comprehensive research program at the LHC and previous accelerator experiments. There are, however, still uncovered areas of the MSSM phase space where experimental sensitivity is lower and thus where supersymmetry (SUSY) might yet be found. This conference report summarizes recent results [3–5] on compressed supersymmetry searches, whereby previous exclusion limits could be improved.

The top quark is the heaviest fermion in the Standard Model, therefore the lighter of its supersymmetric partners ($\tilde{t}_1$), referred to as the scalar top quark or stop, could be the lightest scalar quark due to significant left-right mixing [6]. Cosmological observations [7] imply, that if SUSY is indeed realized in nature, then for many models the lightest stop quark would be nearly mass degenerate with the lightest supersymmetric particle (LSP). When the mass splitting (Δm) between $\tilde{t}_1$ and the neutralino LSP is taken to be smaller than the mass of the W boson, the two- and three-body decays of the stop are kinematically forbidden ($t\tilde{\chi}^0_1$, $bW\tilde{\chi}^0_1$), and the flavour-changing two-body decay to $c\tilde{\chi}^0_1$ can be suppressed depending on model parameters. This motivates the search for its four-body decay to $bf\bar{f}'\tilde{\chi}^0_1$ in a simplified model, where the f and $\bar{f}'$ fermions may be either quarks or leptons.

A detailed description of the CMS detector can be found in Refs. [1, 2].

2. Search for final states with two or three soft leptons

The first result [3] covers searches for supersymmetry in final states with two (2ℓ) or three (3ℓ) soft leptons and missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$). The considered processes involve the associated production of the lightest supersymmetric particle (LSP) which is the lightest neutralino ($\tilde{\chi}^0_1$), and the lightest chargino ($\tilde{\chi}^\pm_1$) that has nearly degenerate mass with the LSP. The search covers three electroweakino signal models, that were covered by the presentation on electroweak SUSY [12], and two simplified models of scalar top quark production assuming that SUSY particles other than the ones appearing in the final state are too massive to affect observable quantities. The first model assumes that the stop is the next-to lightest supersymmetric particle (NLSP) that decays via a four-body process into $\tilde{t} \rightarrow bf\bar{f}'\tilde{\chi}^0_1$. In the second model, each stop decays to a b quark and a chargino, and then the chargino is taken to decay to the LSP and a fermion pair $f\bar{f}'$ with 100% branching ratio, leading to a similar final state. For each scenario, the mass difference (Δm) between the stop and the LSP is taken to be between $10 - 80$ GeV.

The analysis requires events with a distinct signature consisting of two soft leptons that form an opposite charged pair, and large missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) enhanced by a jet required from initial state radiation (ISR). The search region (SR) of the analysis is binned primarily in the amount of $p_{\mathrm{T}}^{\mathrm{miss}}$. For the stop search with 2 leptons, four bins are defined: (125, 200], (200, 290], (290, 340], (340, ∞) in GeV. Further categorization variables are introduced: the p_{T} of the leading lepton, and the dilepton invariant mass to define control regions (CR) to model the background.

The event selection criteria applied in all SR groups are based on lepton quantities, hadronic activity, hard b-jet veto, and further cuts on the event topology that are detailed in Ref. [3]. Expected and observed exclusion limits are shown in figure 1 for both stop signal models. A clear drop in the exclusion is evident around $\Delta m = 20$ GeV, which is caused by the smaller acceptance in this region due to the minimum lepton p_{T} requirement of 5 GeV for electrons and 3.5 GeV for muons in the SR. At $\Delta m = 20$ GeV mass splitting, the scalar top quark is excluded up to 480 GeV in the direct four-body decay scenario, and up to 540 GeV when the decay goes through a light chargino.

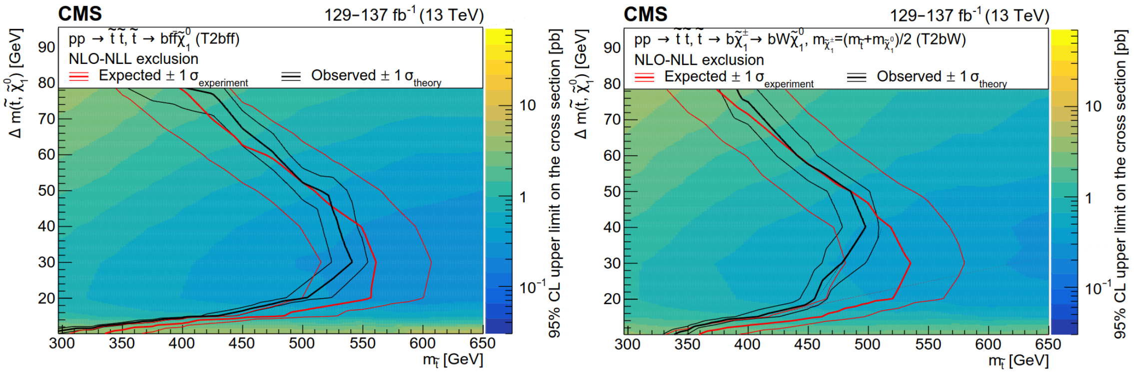

Figure 1: The observed (black) and expected (red) 95% CL exclusion curves for the stop pair search with two opposite-charge soft leptons assuming direct four-body (left) and chargino-mediated (right) decays. [3]

3. Search for stop quarks in final states with a soft lepton

Searches for the stop quark were performed in Ref. [4], assuming 100% branching fraction to the 4-body decay $b f \bar{f}' \tilde{\chi}_1^0$ in a simplified model, where the f and $\bar{f}'$ fermions may be either quarks or leptons, and the mass splitting between the lighter stop and the LSP is taken to be smaller than m_W.

The event selection of the analysis is optimized using the machine learning method of boosted decision trees [8] (BDTs). BDTs can effectively take advantage of the correlations between discriminating variables of signal and background processes, and yield a single discriminator value as output. If the event passes the determined threshold, it passes selection. Eight BDTs are fitted between $\Delta m = 10, 20 \ldots 80$ GeV. The five most relevant input variables to the BDTs in order of discriminating power are: p_{T} of the lepton, $p_{\mathrm{T}}^{\mathrm{miss}}$, p_{T} of the ISR jet, H_{T} and m_{T}.

The expected and observed exclusion limits are shown in figure 2. Maximum sensitivity is reached at $\Delta m \approx m_{\mathrm{W}}$, where the stop mass is excluded up to 700 GeV. The lowest sensitivity is in the $\Delta m = 10$ GeV region due to the lower acceptance caused by the lower p_{T} spectrum of the decay products, and the exclusion of the stop mass only goes up to 480 GeV. The limits of the previous analysis [9] are improved by 60 GeV at low Δm, and by 140 GeV at high Δm. At intermediate and high Δm, the exclusion is comparable to the results of a similar ATLAS search [10], but at low Δm the excluded stop mass is 120 GeV higher, attributed to the more inclusive preselection criteria and multivariate tools.

4. Search for disappearing tracks

The latest results [5] dive into the world of ultra-compressed SUSY. A pure wino or higgsino LSP is assumed, and its co-annihilation partner is taken to be the lightest chargino ($\tilde{\chi}_1^{\pm}$), having only

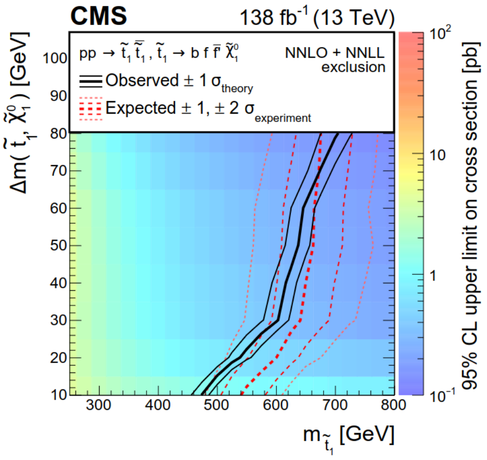

Figure 2: The 95% CL upper limits on the cross section for stop production and the 4-body decay in the plane of the mass of the stop and its mass splitting with the LSP, using the combined 2016, 2017 and 2018 data. [4]

a few hundred MeV larger mass. The chargino may have a long lifetime decaying via $\tilde{\chi}^{\pm}_1 \to \tilde{\chi}^0_1\pi^{\pm}$ process due to the restricted kinematic phase space in such a compressed scenario. The chargino decay length can thus reach the order of 10 – 100 centimeters. In the final state, the pion has extremely low momentum of only a few hundred MeV, which is too low to be reconstructed, and the neutralino escapes the detector as missing transverse energy. This is a prime example of the distinct experimental phenomena known as a disappearing track (DTk), therefore the signature in the detector is a chargino track that ends abruptly with no further hits beyond. These disappearing tracks are classified as long or short in the study, the former having no hits in the outer two layers of the tracker strips, and the latter having no hits at all in the tracker strips. This analysis was performed for a benchmark model with a $c\tau = 10$ cm characteristic decay length of the chargino, and also for a model with $c\tau = 200$ cm.

A number of simplified models are considered for chargino production, such as top squark-associated $\tilde{\chi}^{\pm}_1$ production ($\tilde{t} \to t\tilde{\chi}^0_1, \tilde{t} \to b\tilde{\chi}^{\pm}_1$), bottom squark-associated $\tilde{\chi}^{\pm}_1$ production ($\tilde{b} \to b\tilde{\chi}^0_1$, $\tilde{b} \to t\tilde{\chi}^{\pm}_1$) and gluino-associated $\tilde{\chi}^{\pm}_1$ production ($\tilde{g} \to b\bar{b}\tilde{\chi}^0_1$, $\tilde{g} \to t\bar{t}\tilde{\chi}^0_1$, $\tilde{g} \to t\bar{b}\tilde{\chi}^-_1$, $\tilde{g} \to b\bar{t}\tilde{\chi}^+_1$). These and other models are detailed in Ref. [5]. The selection of disappearing tracks is done by a machine learning based disappearing chargino tagger in addition to criteria on number of hits, isolation, impact parameter, and measures of the track-fit quality. Separate BDTs are trained for the long and short tracks. The search regions are defined based on the classifier output. Further classification of the tracks is possible based on the lost energy in the pixel detector ($\frac{dE}{dx}$).

Signal event selection requires the presence of at least one disappearing track candidate, at least one jet, $p_{\mathrm{T}}^{\mathrm{miss}}$ higher than 30 GeV, and the transverse mass calculated from the DTk and $p_{\mathrm{T}}^{\mathrm{miss}}$ to be higher than 20 GeV. The search is conducted in four channels: the hadronic DTk channel with no leptons, the electron+DTk channel with at least one electron, and the muon+DTk channel with at least one muon. An $N_{\mathrm{DTk}} \geq 2$ channel is also defined for events with two or more disappearing track candidates.

The signal region is binned per each channel in the range of hard $p_{\mathrm{T}}^{\mathrm{miss}}$, number of jets and b-jets, number of long or short disappearing tracks and $\frac{dE}{dx}$. The full binning table and the associated bin numbers are found in Ref. [5].

The observed exclusion limits on the cross section for top squark-associated $\tilde{\chi}_1^{\pm}$ production assuming $c\tau = 10$ cm characteristic decay length and the observed and expected lower limit contours are shown on the right side of figure 3. On the left, the corresponding exclusion figure is shown for the previous study[11] for the combined stop result. When comparing the results, a significant increase in exclusion by up to hundreds of GeV is observed with the disappearing track analysis. Scalar top quarks are excluded up to 1600 GeV and the neutralino LSP is excluded up to 850 GeV for top squark-associated $\tilde{\chi}_1^{\pm}$ production.

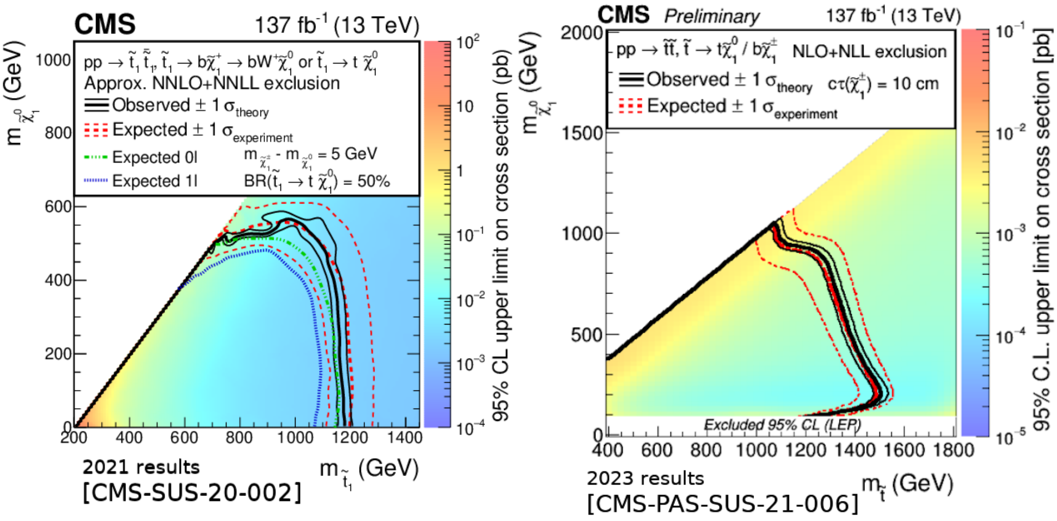

Figure 3: The 95% CL upper limits on the cross section and the expected and observed exclusion contours for the combined stop result from Ref. [11] (left) and for the top squark-associated $\tilde{\chi}_1^{\pm}$ production from the disappearing track analysis[5] (right). The exclusion sensitivity has increased by several hundreds of GeV with the new 2023 analysis.

5. Summary

In the Run 2 data CMS was used to probe the SUSY parameter space, including the compressed region. No sign of new physics has been observed despite the increase in sensitivity, nonetheless the parameter space has been further constrained. The new results for disappearing track search significantly improve the previously established exclusion region. More refined experimental developments in machine learning and new reconstruction techniques are expected to give further results in the upcoming analyses. Compressed searches will largely benefit from Run 3 and 4 data due to the higher luminosity and detector improvements, which gives reasons for excitement.

6. Acknowledgements

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