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Search for supersymmetry with a compressed mass spectrum in events with a soft τ lepton, a highly energetic jet, and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

The first search for supersymmetry in events with an experimental signature of one soft, hadronically decaying τ lepton, one energetic jet from initial-state radiation, and large transverse momentum imbalance is presented. These event signatures are consistent with direct or indirect production of scalar τ leptons ($\widetilde{\tau}$) in supersymmetric models that exhibit coannihilation between the $\widetilde{\tau}$ and the lightest neutralino ($\widetilde{\chi}^0_1$), and that could generate the observed relic density of dark matter. The data correspond to an integrated luminosity of $77.2\,\text{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ collected with the CMS detector at the LHC in 2016 and 2017. The results are interpreted in a supersymmetric scenario with a small mass difference (Δm) between the chargino ($\widetilde{\chi}^{\pm}_1$) or next-to-lightest neutralino ($\widetilde{\chi}^0_2$), and the $\widetilde{\chi}^0_1$. The mass of the $\widetilde{\tau}$ is assumed to be the average of the $\widetilde{\chi}^{\pm}_1$ and $\widetilde{\chi}^0_1$ masses. The data are consistent with standard model background predictions. Upper limits at 95% confidence level are set on the sum of the $\widetilde{\chi}^{\pm}_1$, $\widetilde{\chi}^0_2$, and $\widetilde{\tau}$ production cross sections for $\Delta m(\widetilde{\chi}^{\pm}_1, \widetilde{\chi}^0_1) = 50\,\text{GeV}$, resulting in a lower limit of $290\,\text{GeV}$ on the mass of the $\widetilde{\chi}^{\pm}_1$, which is the most stringent to date and surpasses the bounds from the LEP experiments.

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Supersymmetry (SUSY) [1–7] is a theoretical extension of the standard model (SM) that could describe the particle nature of dark matter (DM) and solve the gauge hierarchy problem. In SUSY models assuming $\mathcal{R}$ parity [8] conservation, if the lightest neutralino ($\widetilde{\chi}^0_1$) is the lightest SUSY particle, it is neutral, stable, and could have undergone annihilation-production interactions with SM particles in the early universe to give the DM relic density observed today [9, 10]. In models with a bino (Z-like) $\widetilde{\chi}^0_1$, these interactions alone are insufficient to produce the correct DM relic abundance. As such, a model of coannihilation (CA) can be introduced, where CA refers to the interaction of $\widetilde{\chi}^0_1$ with another SUSY particle resulting in the production of SM particles [11].

This Letter describes a search for the production of stau particles ($\widetilde{\tau}$), SUSY partners of the τ lepton, considering a mass difference (Δm) between the $\widetilde{\chi}^0_1$ and $\widetilde{\tau}$ of $\leq 50\,\text{GeV}$. These scenarios are motivated by models including $\widetilde{\tau}$-$\widetilde{\chi}^0_1$ CA [12–19], where the calculated relic DM density is consistent with that measured by the WMAP and Planck Collaborations [9, 10]. The CA cross section is exponentially enhanced by small $\Delta m(\widetilde{\tau}, \widetilde{\chi}^0_1)$.

In proton-proton (pp) collisions at the LHC, $\widetilde{\tau}$ particles can be produced directly in pairs or in decays of heavier SUSY particles. The $\widetilde{\tau}$ can decay to a τ lepton and $\widetilde{\chi}^0_1$. The analysis described in this Letter requires an extra jet (j) from initial-state radiation (ISR). The recoil effect from the ISR jet facilitates the detection of momentum imbalance and identification of the low-energy (soft) τ lepton decay products [18–26]. Thus, this analysis focuses on $\text{pp} \to \widetilde{\tau}\widetilde{\tau}\text{j}$ production and indirect $\widetilde{\tau}$ production via decays of the lightest chargino ($\widetilde{\chi}^{\pm}_1$) or the next-to-lightest neutralino ($\widetilde{\chi}^0_2$) in processes like $\text{pp} \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^{\mp}_1\text{j} \to \widetilde{\tau}\widetilde{\tau}\nu_\tau\nu_\tau\text{j} \to \tau\widetilde{\chi}^0_1\tau\widetilde{\chi}^0_1\nu_\tau\nu_\tau\text{j}$ and $\text{pp} \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^0_2\text{j} \to \widetilde{\tau}\nu_\tau\widetilde{\tau}\tau\text{j} \to \tau\widetilde{\chi}^0_1\nu_\tau\tau\widetilde{\chi}^0_1\tau\text{j}$, which can be the dominant production mechanisms for $\widetilde{\tau}$ via decays of heavier SUSY particles. While these processes yield final states with multiple τ leptons, the average transverse momentum (p_T) of the τ leptons is $\Delta m/2$ and below the reconstruction threshold in the $\Delta m(\widetilde{\tau}, \widetilde{\chi}^0_1) \leq 50\,\text{GeV}$ scenarios. The visible decay products of the τ leptons have lower p_T than the decaying particles, so it is difficult to identify more than one τ lepton in a signal event. Furthermore, leptonic decays of τ leptons have a smaller branching fraction ($\mathcal{B}$) than hadronic decays (τ_h), and, on average, smaller visible p_T. Electrons and muons from such decays are also indistinguishable from prompt production of electrons and muons. Hence, we search for events with exactly one soft τ_h candidate and missing transverse momentum recoiling against a high-p_T ISR jet.

The strategy above allows this analysis to probe the $\widetilde{\tau}$-$\widetilde{\chi}^0_1$ CA region with $\Delta m(\widetilde{\tau}, \widetilde{\chi}^0_1) \leq 50\,\text{GeV}$. This is the first collider search for compressed SUSY spectra using this strategy. Earlier searches from the CMS and ATLAS Collaborations [27–33] that relate to the scenarios in this Letter produced weaker results than those from the LEP experiments [34–37]. Data collected in 2016 and 2017 with the CMS experiment [38] in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ is used. The data sample corresponds to an integrated luminosity of $77.2\,\text{fb}^{-1}$.

The central feature of the CMS apparatus [38] is 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, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage of the barrel and endcap detectors up to $|\eta| < 5.2$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector can be found in Ref. [38].

Events are reconstructed from particle candidates (electrons, muons, photons, and hadrons) identified using the particle-flow (PF) algorithm [39]. The algorithm combines information from all detectors to classify final-state particles produced in the collision. Jets are clustered using the anti-k_{T} clustering algorithm [40, 41] with a distance parameter of 0.4. Identification criteria are applied to jet candidates to remove anomalous effects from the calorimeters [42]. For jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.4$, the identification efficiency is >99% [43].

The jet energy scale and resolution are corrected depending on the p_{T} and η of the jet [44]. Jets originating from the hadronization of b quarks are identified using the combined secondary vertex algorithm [45]. This analysis uses the loose working point of the algorithm, which has an identification efficiency of 80% for b jets and a light-flavor quark or gluon misidentification rate of 10%.

Electrons and muons are used in control samples and as vetoes in the signal sample selection. Electrons are reconstructed and identified combining information from the ECAL and the tracking system [46]. Muons are reconstructed using the tracker and muon chambers, and requiring consistency with low-energy measurements in the calorimeters [47]. For this analysis, the electron (muon) identification efficiency is 85 (96)%, for leptons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.1$.

Hadronic decays of τ leptons are reconstructed and identified using the hadrons-plus-strips algorithm [48], designed to optimize τ_{h} reconstruction by considering specific τ_{h} decay modes. To suppress backgrounds from light-flavor quark or gluon jets, τ_{h} candidates are required to pass a threshold value of a multivariate discriminator that takes variables related to isolation and τ lepton lifetime as input. The tight isolation working point is used, which results in a τ_{h} identification efficiency of 55% for this analysis, and a 0.2–5% probability for a jet to be misidentified as a τ_{h}, depending on the p_{T} and η values of the τ_{h} candidate [48]. The τ_{h} candidates are subject to additional requirements, based on consistency among measurements in the tracker, calorimeters, and muon detectors, to distinguish them from electrons and muons.

The missing transverse momentum $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is the negative vector p_{T} sum of all PF candidates. Its magnitude is $p_{\mathrm{T}}^{\text{miss}}$. Production of undetected particles such as SM neutrinos and the $\tilde{\chi}_1^0$ is inferred from the measured $p_{\mathrm{T}}^{\text{miss}}$ [49, 50]. The jet corrections described are propagated as corrections to $p_{\mathrm{T}}^{\text{miss}}$, which improves agreement in $p_{\mathrm{T}}^{\text{miss}}$ between simulation and data.

The dominant SM background processes contributing to the search are W/Z boson production in association with jets (W+jets and Z+jets), top quark pairs ($\mathrm{t\bar{t}}$), and quantum chromodynamics (QCD) multijet processes. The contributions of W+jets and Z+jets events contain genuine τ_{h} candidates, energetic jets, and $p_{\mathrm{T}}^{\text{miss}}$ from neutrinos. Background from $\mathrm{t\bar{t}}$ events is characterized by two b quark jets in addition to a genuine τ_{h}. QCD multijet events are characterized by jets misidentified as τ_{h}, and the estimated yield of this background is derived from data.

Simulated samples for Z+jets, W+jets, $\mathrm{t\bar{t}}$+jets, and single top quark events are produced with the MADGRAPH5_aMC@NLO 2.6.0 program [51] at leading order (LO) precision. The LO PYTHIA generator is used to model diboson (VV) processes. Two sets of signal event samples are generated using MADGRAPH5_aMC@NLO 2.3.3 at LO precision. The first set considers the sum of $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{0}$, and $\tilde{\tau}\tilde{\tau}$ production with up to two jets. The $\tilde{\tau}\tilde{\tau}$ process represents <2% of the total cross section. Models with a bino $\tilde{\chi}_1^0$ and wino (W-like) $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ are considered. We assume a simplified model scenario [52] with a left-handed $\tilde{\tau}$, $\mathcal{B}(\tilde{\chi}_2^0 \to \tau\tilde{\tau} \to \tau\tau\tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_1^{\pm} \to \nu_\tau\tilde{\tau} \to \nu_\tau\tau\tilde{\chi}_1^0) = 100\%$, and $m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$. This set of samples is motivated by the importance of the chargino-neutralino sector in connecting SUSY models and DM. We refer to this model as SUSY signal model 1 (SSM1). The second set considers direct production of left-handed $\tilde{\tau}$ pairs with up to two jets. Although the search for direct $\tilde{\tau}$ production with $\Delta m(\tilde{\tau},\tilde{\chi}_1^0) \leq 50\,\mathrm{GeV}$ is challenging because of the small production cross section and low signal acceptance, this set of samples is included to highlight the improved sensitivity in this analysis, compared to previous non-ISR searches [31, 34–37, 53–57]. This second set of samples allows for reinterpretation in other scenarios with $\widetilde{\tau}$-like particles. We refer to this model as SUSY signal model 2 (SSM2). It is noted that the masses of $\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0$ are sufficiently large (10 TeV) to be considered decoupled in SSM2. The MADGRAPH5_aMC@NLO generator is interfaced with PYTHIA 8.212 [58] using the CUETP8M1 and CP5 tunes [59, 60] for parton shower and fragmentation in the 2016 and 2017 simulated samples, respectively. The NNPDF3.0 LO and NLO [61] parton distribution functions (PDFs) are used in the event generation. The CMS detector response is simulated using the GEANT4 [62] package for background samples, and the CMS fast simulation package [63] for signal samples. To model the effect of additional pp interactions within the same bunch crossing or nearby bunch crossings, minimum bias events generated with PYTHIA are added to the simulated samples with a frequency distribution per bunch crossing weighted to match that observed in data. MC background yields are normalized to the integrated luminosity using next-to-next-to-leading order (NNLO) or next-to-leading order (NLO) cross sections, while signal production cross sections are calculated at NLO with next-to-leading logarithmic (NLL) soft-gluon resummation calculations [64–67].

Events are recorded using a $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger [68]. The trigger efficiency is measured using data events with one muon, resulting in a sample enriched in W+jets events (95% purity in simulation). Selected events are required to have $p_{\mathrm{T}}^{\mathrm{miss}} > 230\,\mathrm{GeV}$, where the trigger is fully efficient, and exactly one identified τ_{h} candidate with $|\eta| < 2.1$ and $20 < p_{\mathrm{T}}(\tau_{\mathrm{h}}) < 40\,\mathrm{GeV}$. The requirement of exactly one τ_{h} candidate and the upper limit on p_{T} reduce the W+jets, Z+jets, and $\mathrm{t\bar{t}}$+jets backgrounds. The highest-p_{T} jet is referred to as the ISR jet ($\mathrm{j_{ISR}}$) and is required to satisfy $p_{\mathrm{T}} > 100\,\mathrm{GeV}$ and $|\eta| < 2.4$. The absolute difference in the azimuthal angle (ϕ) between the ISR jet and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is required to be greater than 0.7 radians ($|\Delta\phi(\mathrm{j_{ISR}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})| > 0.7$ radians) to reduce QCD multijet events containing large $p_{\mathrm{T}}^{\mathrm{miss}}$ from jet mismeasurements. To reduce background processes with top quarks, events with b-tagged jets are rejected. Events with well-identified and isolated electrons or muons with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.1$ are rejected.

The transverse mass of the selected τ_{h} candidate and the $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, defined as

$$m_{\mathrm{T}}(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \tau_{\mathrm{h}}) = \sqrt{2 p_{\mathrm{T}}^{\mathrm{miss}} p_{\mathrm{T}}(\tau_{\mathrm{h}})(1 - \cos\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \tau_{\mathrm{h}}))},$$

is the main observable to search for the presence of signal events. The m_{T} in signal events probes the SUSY mass scale, and is expected to be larger on average than for the backgrounds. The strategy is to search for a broad enhancement in the high-m_{T} part of the spectrum.

The yield and m_{T} shape of the QCD multijet background are estimated from data using control regions (CRs) enriched in QCD multijet events and with negligible signal contamination. MC simulations are used to extrapolate the W/Z+jets and $\mathrm{t\bar{t}}$+jets background yields from a CR to the signal region (SR) and to model m_{T} shapes. The agreement between data and simulation in these CRs is used to validate the modeling of the τ_{h} selections and to measure data-to-simulation scale factors to correct the modeling of the ISR jet and the $p_{\mathrm{T}}^{\mathrm{miss}}$. To calculate the correction factor, contributions from nontargeted backgrounds are subtracted from data. The uncertainty in these background processes is propagated to the final systematic uncertainty in the background predictions. Small contributions from single top quark and diboson production are estimated using simulation.

The correct modeling in the simulation of background events, in particular the W/Z+jets processes, can be affected by requiring an ISR jet. This modeling is studied using a $\mathrm{Z}(\rightarrow \mu\mu)$+jets CR in data. This CR provides a measurement of the p_{T} spectrum resulting from a high-p_{T} ISR jet, decoupling the effects of ISR modeling from the measurement of $p_{\mathrm{T}}^{\mathrm{miss}}$. The p_{T} of the Z boson is measured by vectorially summing the transverse momenta of the two muons from the

Z decay. The ratio between data and simulation in the $p_{\mathrm{T}}(\mu\mu)$ distribution is used to obtain p_{T}-dependent correction factors, ranging from 0.79 to 1.12. The factors are validated using a $\mathrm{W}(\rightarrow \mu\nu_{\mu})$+jets enriched sample. After applying these correction factors, we find agreement between the observed and predicted yields and shapes of distributions. These ISR correction factors are applied to all Drell–Yan processes, including the W/Z+jets backgrounds and signal processes.

A $\mathrm{Z}(\rightarrow \tau_{\mathrm{h}}\tau_{\mathrm{h}})$+jets CR is defined to study the modeling of τ_{h} reconstruction and identification. The CR is obtained by requiring two τ_{h} candidates with $p_{\mathrm{T}} > 60\,\mathrm{GeV}$ and $|\eta| < 2.1$, selected by a dedicated $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ trigger [31, 69–71]. The two τ_{h} candidates of a pair must have opposite electric charge and a reconstructed mass between 50 and 100 GeV, and all other requirements are the same as for SR events. The contribution of QCD multijet events in the $\mathrm{Z}(\rightarrow \tau_{\mathrm{h}}\tau_{\mathrm{h}})$+jets CR is estimated from data using CRs obtained with τ_{h} pairs with the same electric charge. The transfer factor between same- and opposite-sign events is calculated using events with loosened τ_{h} isolation requirements and $m(\tau_{\mathrm{h}}\tau_{\mathrm{h}}) > 100\,\mathrm{GeV}$. Correction factors of 0.92 ± 0.05 and 0.95 ± 0.04 for $\mathrm{Z}(\rightarrow \tau_{\mathrm{h}}\tau_{\mathrm{h}})$+jets are measured in this CR for the 2016 and 2017 data sets, respectively. The uncertainties are purely statistical. These correction factors are used to scale the $\mathrm{Z}(\rightarrow \tau\tau)$+jets prediction in the SR.

The contribution from $\mathrm{t\bar{t}}$ events in the SR is less than 15% of the total expected background. Correction factors of 0.94 ± 0.05 and 0.95 ± 0.04 are measured for the 2016 and 2017 data sets, respectively, in a CR obtained by selecting events with two b-tagged jets and one τ_{h} candidate with tighter isolation requirements with respect to the SR. These requirements allow for a $\mathrm{t\bar{t}}$ CR sample with high purity. The correction factor is applied to scale the prediction of $\mathrm{t\bar{t}}$ events in the SR.

A CR enriched with QCD multijet events ($\mathrm{CR}_{\mathrm{QCD}}$) is obtained by requiring the same criteria for the SR but selecting τ_{h} candidates that fail the tight and pass the loose τ_{h} isolation. The contribution from nonmultijet events is subtracted using simulation, adjusted for the scale factors discussed above. The shape and normalization of the multijet background in the SR are predicted by multiplying the data yields in $\mathrm{CR}_{\mathrm{QCD}}$ with transfer factors ("tight-to-loose" ratios) to account for the isolation efficiency. The $p_{\mathrm{T}}(\tau_{\mathrm{h}})$-dependent transfer factors are derived in a $\mathrm{W}(\rightarrow \mu\nu_{\mu})+\tau_{\mathrm{h}}$ CR, where the τ_{h} is a misidentified jet. These transfer factors, which range from 0.2 to 0.4, are validated in a region enriched in QCD multijet events by inverting the $\Delta\phi(\mathrm{j}_{\mathrm{ISR}}, \vec{p}_{\mathrm{T}}^{\text{miss}})$ requirement.

A major source of systematic uncertainty is the closure of the background estimation methods, where closure refers to tests (on data and simulation) which demonstrate that the background determination techniques reproduce the expected background distributions in both rate and shape within the statistical uncertainties. The background estimation uncertainty from the closure tests is 2–6% for nonmultijet backgrounds. For the QCD multijet background, this uncertainty is determined by the deviation of the tight-to-loose ratios obtained in a $\mathrm{Z}(\rightarrow \mu\mu)+\tau_{\mathrm{h}}$ CR, where the τ_{h} is a misidentified jet, from those in the $\mathrm{W}(\rightarrow \mu\nu_{\mu})+\tau_{\mathrm{h}}$ region. This uncertainty depends on $p_{\mathrm{T}}\,(\tau_{\mathrm{h}})$ and varies from 4 to 29%. Shape-based systematic uncertainties from the use of ISR correction factors are determined by varying these factors by ±1 standard deviation of their uncertainty and examining effects on the m_{T} distribution. This uncertainty is a few percent at low m_{T} and 15% at high m_{T}. Although the corrected background m_{T} shapes are consistent with the data distributions within statistical uncertainties, data-to-simulation ratios of the m_{T} distributions are fit with a first-order polynomial, and the deviation of the fit from unity, as a function of m_{T}, is taken as an uncertainty in the shape. This results in up to 20% uncertainty in a given m_{T} bin.

The signal and background yields estimated from simulation are affected by similar sources of systematic uncertainty, with small differences between the 2016 and 2017 data sets. The uncertainty from the τ_h identification and isolation requirements ranges between 6 and 9%, depending on the year and process [48]. Efficiencies for the electron and muon reconstruction, identification, and isolation requirements are considered because of the extra lepton vetoes in the SR and their use in the CRs [46, 47, 72], with an uncertainty of $\leq$1%. The $p_\mathrm{T}^\mathrm{miss}$ scale uncertainties due to the jet energy scale (2–5% depending on η and p_T) result in an uncertainty of 1–3% depending on m_T. The event acceptance for the ISR selection depends on the reconstruction and identification efficiencies and the energy scale of jets. A $p_\mathrm{T}^\mathrm{miss}$-dependent uncertainty in the measured trigger efficiency results in a 3% uncertainty. The uncertainty in event acceptance from the PDF set used in simulation is evaluated in accordance with the PDF4LHC recommendations [73] by comparing results using the CTEQ6.6L, MSTW08, and NNPDF10 PDF sets [74–76] with those from the default PDF set. A systematic uncertainty in the signal accounts for differences between the fast and GEANT4 simulations, which depends on m_T and varies from 3 to 11%. The uncertainty in the integrated luminosity corresponds to 2.5 [77] and 2.3% [78] for the 2016 and 2017 data, respectively.

Figure 1 shows the $m_\mathrm{T}(p_\mathrm{T}^\mathrm{miss}, \tau_\mathrm{h})$ distribution for events in the SR. The binning used in Fig. 1 is optimized to achieve the best discovery potential for the SSM1 scenarios, resulting in bins of 10 GeV width between m_T of 0 and 120 GeV, bins of 20 GeV width between m_T of 120 and 200 GeV, and one bin of 300 GeV width for $m_\mathrm{T} > 200$ GeV. For a SSM1 benchmark sample with $m(\widetilde{\chi}_1^\pm) = 200$ GeV, $m(\widetilde{\tau}) = 175$ GeV, and $m(\widetilde{\chi}_1^0) = 150$ GeV, the signal-to-background ratio ranges from $\approx$1/25 at low m_T to $\approx$1/3 at high m_T.

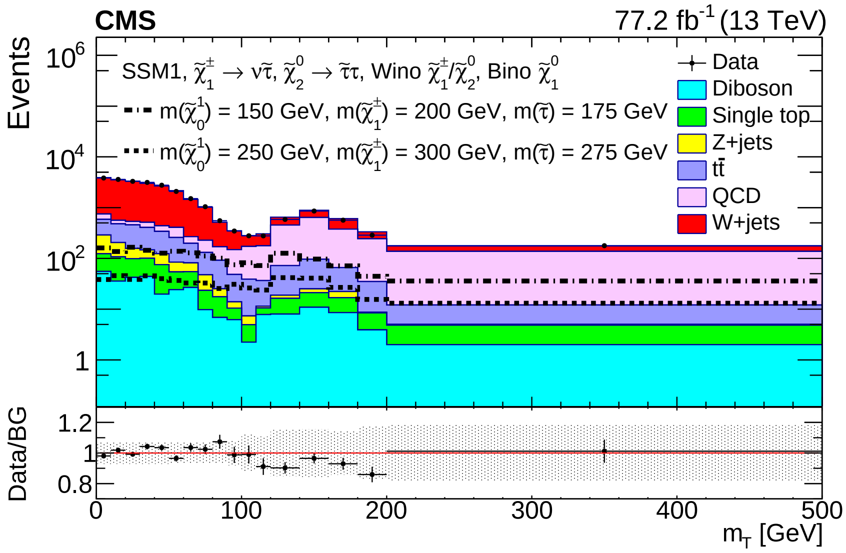

Figure 1: The m_T distribution for SR events with 2016 plus 2017 data. In the upper panel, the solid colors correspond to the expected background processes, the black dots to the observed data, and the dashed lines to the expected signal from simulation. The lower panel shows the ratio between the observed data and the total expected pre-fit background (BG). The shaded band corresponds to the total pre-fit uncertainty on the BG prediction, while the error bars on the black dots represent the statistical uncertainties on the data yields.

No significant excess above the background prediction is observed. The 95% confidence level (CL) upper limits are set on the SSM1 signal production cross sections as a function of $m(\widetilde{\chi}_1^\pm)$ for fixed $\Delta m(\widetilde{\chi}_1^\pm, \widetilde{\chi}_1^0) = 50$ GeV and $m(\widetilde{\tau}) = 0.5m(\widetilde{\chi}_1^\pm) + 0.5m(\widetilde{\chi}_1^0)$ (Fig. 2 left). This benchmark is motivated by: (*i*) LHC searches to date have no sensitivity in these SSM1 compressed spec-

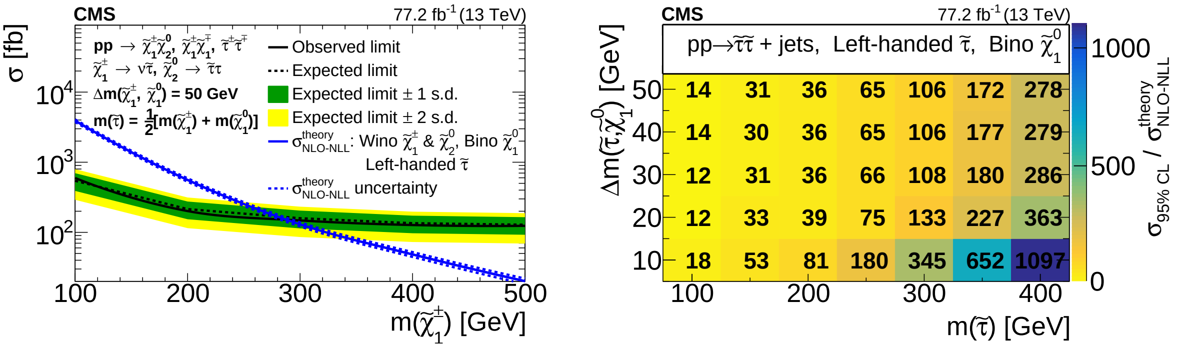

Figure 2: (left) The 95% confidence level (CL) upper limits on the SSM1 production cross sections ($\sigma_{95\%\,\text{CL}}$) as a function of $m(\tilde{\chi}_1^{\pm})$. The solid blue line shows the theoretical cross section, and the dashed blue line its uncertainty. The observed limit is shown with the solid black line, while the expected limit is shown with the dashed black line. The green (yellow) band corresponds to the one (two) standard deviation range about the central value of the expected limit. (right) The ratio of the 95% CL upper limit on the direct $\tilde{\tau}$ pair production signal cross section in SSM2 to the theoretical cross section, as a function of $m(\tilde{\tau})$ and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$.

trum scenarios; and (*ii*) SSM1 scenarios with $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 25\,\text{GeV}$ provide the right CA cross section to give a DM relic density consistent with experiment [12–19]. Figure 2 right shows the observed 95% CL upper limits on the SSM2 signal production cross sections as a function of $m(\tilde{\tau})$ and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$. The limits are estimated following the modified frequentist construction CL_s method [79–81]. Maximum likelihood fits are performed using the final m_T distributions for 2016 and 2017 data to construct a combined profile likelihood ratio test statistic [79] in bins of m_T. Systematic uncertainties are represented by nuisance parameters, assuming log-normal priors for normalization parameters, and Gaussian priors for shape uncertainties. Statistical uncertainties in the shape templates are accounted for by the technique described in Ref. [82]. Correlations among the signal and backgrounds have been considered. For example, the uncertainty in the integrated luminosity is treated as fully correlated across signal and backgrounds, while uncertainties from event acceptance variation with different sets of PDFs or variations in the ISR correction factors, in a given m_T bin, are treated as uncorrelated. Uncertainties from the closure tests are treated as uncorrelated. We note that the statistical uncertainty dominates the sensitivity.

For SSM1, we exclude $\tilde{\chi}_2^0/\tilde{\chi}_1^{\pm}$ with masses below 290 GeV for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) = 50\,\text{GeV}$ and $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\tau}) = 25\,\text{GeV}$. Prior experimental constraints on the SUSY parameters with these $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ and $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\tau})$ values using non-ISR searches [27–32] have not exceeded those of the LEP experiments for indirect $\tilde{\tau}$ production [34–37]. Thus the search presented in this Letter provides the first results from the LHC to surpass the LEP bound of 103.5 GeV for $m(\tilde{\chi}_1^{\pm})$ for such compressed scenarios. For SSM2, small $\tilde{\tau}\tilde{\tau}$ production cross sections and low signal acceptances make these scenarios challenging, especially when $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) \leq 50\,\text{GeV}$. For a $\tilde{\tau}$ mass of 100 GeV and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 30\,\text{GeV}$, for example, the observed limit is 12 times the theoretical cross section. It is again noted that the SSM2 results are included in this Letter to highlight the improved sensitivity in this analysis compared to previous non-ISR searches. A direct comparison with the most sensitive non-ISR search, Ref. [57], shows $\approx \times 4$ improvement in the cross section upper limit for the SSM2 scenario with $m(\tilde{\tau}) = 150\,\text{GeV}$ and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 50\,\text{GeV}$.

In summary, we have presented a search for compressed supersymmetry. It is the first collider search with exactly one soft, hadronically-decaying tau lepton and missing transverse momentum recoiling against an initial-state radiation jet with high transverse momentum. The search utilizes data corresponding to an integrated luminosity of $77.2\,\text{fb}^{-1}$ collected with the CMS detector in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$. This search targets scenarios where the mass difference (Δm) between the stau ($\widetilde{\tau}$) particle and the lightest neutralino ($\widetilde{\chi}_1^0$) is $\leq$50 GeV. This is motivated by models considering $\widetilde{\tau}$-$\widetilde{\chi}_1^0$ CA to maintain consistency in the relic DM density between particle physics and cosmology. In the context of the minimal supersymmetric standard model, the search considers electroweak production of $\widetilde{\tau}$ via decays of the lightest chargino ($\widetilde{\chi}_1^\pm$) and the next-to-lightest neutralino ($\widetilde{\chi}_2^0$), and direct production of $\widetilde{\tau}$. The data do not reveal evidence for new physics. For a mass splitting $\Delta m(\widetilde{\chi}_1^\pm, \widetilde{\chi}_1^0) = 50\,\text{GeV}$ and a branching fraction of 100% for $\widetilde{\chi}_1^\pm \to \widetilde{\tau}\nu_\tau \to \tau\widetilde{\chi}_1^0\nu_\tau$, $\widetilde{\chi}_1^\pm$ masses up to 290 GeV are excluded at 95% confidence level. This sensitivity exceeds that of all other $\widetilde{\tau}$ searches to date in these scenarios. The search presented in this Letter provides the first results from the LHC to surpass the LEP bounds.

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