Search for Supersymmetry with a Compressed Mass Spectrum in Events with a Soft $\tau$ Lepton, a Highly Energetic Jet, and Large Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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The first search for supersymmetry in events with an experimental signature of one soft, hadronically decaying $\tau$ 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 $\tau$ leptons ($\tilde{\tau}$) in supersymmetric models that exhibit coannihilation between the $\tilde{\tau}$ and the lightest neutralino ($\tilde{\chi}^0_1$), and that could generate the observed relic density of dark matter. The data correspond to an integrated luminosity of 77.2 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ 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 ($\Delta m$) between the chargino ($\tilde{\chi}^\pm_1$) or next-to-lightest neutralino ($\tilde{\chi}^0_2$), and the $\tilde{\chi}^0_1$. The mass of the $\tilde{\tau}$ is assumed to be the average of the $\tilde{\chi}^+_1$ and $\tilde{\chi}^0_1$ masses. The data are consistent with standard model background predictions. Upper limits at 95% confidence level are set on the sum of the $\Delta m(\tilde{\chi}^+_1, \tilde{\chi}^0_1) = 50$ GeV, resulting in a lower limit of 290 GeV on the mass of the $\tilde{\chi}^+_1$, 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 $R$ parity [8] conservation, if the lightest neutralino ($\tilde{\chi}^0_1$) 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) $\tilde{\chi}^0_1$, 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 $\tilde{\chi}^0_1$ with another SUSY particle resulting in the production of SM particles [11].

This Letter describes a search for the production of stau particles ($\tilde{\tau}$), SUSY partners of the $\tau$ lepton, considering a mass difference ($\Delta m$) between the $\tilde{\chi}^0_1$ and $\tilde{\tau}$ of $\leq 50$ GeV. These scenarios are motivated by models including $\tilde{\tau}$-$\tilde{\chi}^0_1$ 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 $\Delta m(\tilde{\tau}, \tilde{\chi}^0_1)$.

In proton-proton ($pp$) collisions at the LHC, $\tilde{\tau}$ particles can be produced directly in pairs or in decays of heavier SUSY particles. The $\tilde{\tau}$ can decay to a $\tau$ lepton and $\tilde{\chi}^0_1$. 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) $\tau$ lepton decay products [18–26]. Thus, this analysis focuses on $pp \rightarrow \tilde{\tau}\tilde{\tau}j$ production and indirect $\tilde{\tau}$ production via decays of the lightest chargino ($\tilde{\chi}^\pm_1$) or the next-to-lightest neutralino ($\tilde{\chi}^0_2$) in processes like $pp \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1 \rightarrow \tilde{\tau}\nu\tau\nu\tau$ and $pp \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1 \rightarrow \tilde{\tau}\tau\tilde{\nu}\tilde{\nu} \rightarrow \tilde{\tau}\tilde{\chi}^0_1\nu\tau\tilde{\chi}^0_1\tau$, which can be the dominant production mechanisms for $\tilde{\tau}$ via decays of heavier SUSY particles. While these processes yield final states with multiple $\tau$ leptons, the average transverse momentum ($p_T$) of the $\tau$ leptons is $\Delta m/2$ and below the reconstruction threshold in $\Delta m(\tilde{\tau}, \tilde{\chi}^0_1) \leq 50$ GeV scenarios. The visible decay products of the $\tau$ leptons have lower $p_T$ than the decaying particles, so it is difficult to identify more than one $\tau$ lepton in a signal event. Furthermore, leptonic decays of $\tau$ leptons have a smaller branching fraction ($B$) than hadronic decays ($\tau_h$), 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...
\(\tau_h\) candidate and missing transverse momentum recoiling against a high-\(p_T\) ISR jet.

The strategy above allows this to probe the \(\tilde{\tau}+\chi_1^0\) CA region with \(\Delta m(\tilde{\tau}, \chi_1^0) \leq 50\) 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 \(\sqrt{s} = 13\) TeV is used. The data sample corresponds to an integrated luminosity of 77.2 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 (\(\eta\)) coverage of the barrel and endcap detectors up to \(|\eta| < 5.2\). Muons are measured in gaseionization 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 \(p_T > 30\) GeV and \(|\eta| < 2.4\), the identification efficiency is \(\approx 99\%\) [43].

The jet energy scale and resolution are corrected depending on the \(p_T\) and \(\eta\) 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 \(p_T > 10\) GeV and \(|\eta| < 2.1\).

Hadronic decays of \(\tau\) leptons are reconstructed and identified using the hadrons-plus-strips algorithm [48], designed to optimize \(\tau_h\) reconstruction by considering specific \(\tau_h\) decay modes. To suppress backgrounds from light-flavor quark or gluon jets, \(\tau_h\) candidates are required to pass a threshold value of a multivariate discriminator that takes variables related to isolation and \(\tau\) lepton lifetime as input. The tight isolation working point is used, which results in a \(\tau_h\) identification efficiency of 55\% for this analysis, and a 0.2–5\% probability for a jet to be misidentified as a \(\tau_h\), depending on the \(p_T\) and \(\eta\) values of the \(\tau_h\) candidate [48]. The \(\tau_h\) 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 \(\vec{p}_{T\text{miss}}\) is the negative vector \(p_T\) sum of all PF candidates. Its magnitude is \(p_{T\text{miss}}\). Production of undetected particles such as SM neutrinos and the \(\chi_1^0\) is inferred from the measured \(p_{T\text{miss}}\) [49,50]. The jet corrections described are propagated as corrections to \(p_{T\text{miss}}\), which improves agreement in \(p_{T\text{miss}}\) between simulation and data.

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

Simulated samples for \(Z + \text{jets} \), \(W + \text{jets} \), \(t\bar{t} + \text{jets} \), and single top quark events are produced with the MADGRAPH 5_{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 MADGRAPH 5_{aMC@NLO} 2.3.3 at LO precision. The first set considers the sum of \(\chi_1^0 + \chi_1^0\), \(\chi_2^0 + \chi_2^0\), 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 \(\chi_1^0\) and wino (W-like) \(\chi_2^0\) and \(\chi_3^0\) are considered. We assume a simplified model scenario [52] with a left-handed \(\tilde{\tau}\), \(B(\chi_2^0 \rightarrow \tilde{\tau} + \tau ) = B(\tilde{\chi}_1^0 \rightarrow \nu_{\tilde{\tau}} \rightarrow \nu + \chi_1^0) = 100\%\), and \(m(\chi_1^0) = m(\chi_2^0)\). 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 \(\Delta m(\tilde{\tau}, \chi_1^0) \leq 50\) 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 \(\tilde{\tau}\)-like particles. We refer to this model as SUSY signal model 2 (SSM2).

It is noted that the masses of \(\chi_1^0/\chi_2^0\) are sufficiently large (10 TeV) to be considered decoupled in SSM2.
The MADGRAPH 5_MC@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 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 $p_T^{\text{miss}}$ 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 $p_T^{\text{miss}} > 230$ GeV, where the trigger is fully efficient, and exactly one identified $\tau_h$ candidate with $|\eta| < 2.1$ and $20 < p_T(\tau_h) < 40$ GeV. The requirement of exactly one $\tau_h$ candidate and the upper limit on $p_T$ reduce the $W +$ jets, $Z +$ jets, and $\tau^+\tau^-$ backgrounds. The highest-$p_T$ jet is referred to as the ISR jet ($j_{\text{ISR}}$) and is required to satisfy $p_T > 100$ GeV and $|\eta| < 2.4$. The absolute difference in the azimuthal angle ($\phi$) between the ISR jet and $p_T^{\text{miss}}$ is required to be greater than 0.7 radians ($|\Delta\phi(j_{\text{ISR}}, p_T^{\text{miss}})| > 0.7$ radians) to reduce QCD multijet events containing large $p_T^{\text{miss}}$ from jet mismatches. To reduce QCD multijet processes with top quarks, events with $b$-tagged jets are rejected. Events with well-identified and isolated electrons or muons with $p_T > 10$ GeV and $|\eta| < 2.1$ are rejected.

The transverse mass of the selected $\tau_h$ candidate and the $p_T^{\text{miss}}$, defined as

$$m_T(p_T^{\text{miss}}, \tau_h) = \sqrt{2p_T^{\text{miss}}p_T(\tau_h)[1 - \cos\Delta\phi(p_T^{\text{miss}}, \tau_h)]},$$

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 $\tau^+\tau^-$ backgrounds to 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 $\tau_h$ selections and to measure data-to-simulation scale factors to correct the modeling of the ISR jet and the $p_T^{\text{miss}}$. 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 $Z(\rightarrow\mu\mu) +$ 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 $p_T^{\text{miss}}$. 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 $p_T(\mu\mu)$ distribution is used to obtain $p_T$-dependent correction factors, ranging from 0.79 to 1.12. The factors are validated using a $W(\rightarrow\mu\nu) +$ 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 $Z(\rightarrow\tau_h\tau_h) +$ jets CR is defined to study the modeling of $\tau_h$ reconstruction and identification. The CR is obtained by requiring two $\tau_h$ candidates with $p_T > 60$ GeV and $|\eta| < 2.1$, selected by a dedicated $\tau_h\tau_h$ trigger [31,69–71]. The two $\tau_h$ 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 $Z(\rightarrow\tau_h\tau_h) +$ jets CR is estimated from data using CRs obtained with $\tau_h$ pairs with the same electric charge. The transfer factor between same- and opposite-sign events is calculated using events with loosened $\tau_h$ isolation requirements and $m(\tau_h\tau_h) > 100$ GeV. Correction factors of $0.92 \pm 0.05$ and $0.95 \pm 0.04$ for $Z(\rightarrow\tau_h\tau_h) +$ 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 $Z(\rightarrow\tau\tau) +$ jets prediction in the SR.

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

A CR enriched with QCD multijet events (CR_QCD) is obtained by requiring the same criteria for the SR but
selecting \( \tau_h \) candidates that fail the tight and pass the loose \( \tau_h \) 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 CR\(_{QCD} \) with transfer factors ("tight-to-loose" ratios) to account for the isolation efficiency. The \( p_T(\tau_h) \)-dependent transfer factors are derived in a \( W(\rightarrow \mu \nu) + \tau_h \) CR, where the \( \tau_h \) 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 \( \Delta \phi(J_{ISR}, \vec{p}_T^{miss}) \) 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 \( Z(\rightarrow \mu \nu) + \tau_h \) CR, where the \( \tau_h \) is a misidentified jet, from those in the \( W(\rightarrow \mu \nu) + \tau_h \) region. This uncertainty depends on \( p_T(\tau_h) \) and varies from 4 to 29%. Shape-based systematic uncertainties from the use of ISR correction factors are determined by varying these factors by \( \pm 1 \) 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 \( \tau_h \) 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 \( p_T^{miss} \) scale uncertainties due to the jet energy scale (2–5% depending on \( \eta \) 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 \( p_T^{miss} \)-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 \( m_T(\tau_h, p_T^{miss}) \) 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 \( m_T > 200 \) GeV. For a SSM1 benchmark sample with \( m(\chi_{1}^\pm) = 200 \) GeV, \( m(\tilde{\tau}) = 175 \) GeV, and \( m(\tilde{\chi}_1^0) = 150 \) GeV, the signal-to-background ratio ranges from \( \approx 1/25 \) at low \( m_T \) to \( \approx 1/3 \) at high \( m_T \).

No significant excess above the background prediction is observed. The 95% confidence level (C.L.) upper limits are set on the SSM1 signal production cross sections as a function of \( m(\tilde{\chi}_1^\pm) \) for fixed \( \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 50 \) GeV and \( m(\tilde{\tau}) = 0.5m(\tilde{\chi}_1^\pm) + 0.5m(\tilde{\chi}_1^0) \) (Fig. 2 left). This benchmark is motivated by: (i) LHC searches to date have no sensitivity in these SSM1 compressed spectrum scenarios; and (ii) SSM1 scenarios with \( \Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 25 \) 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% C.L. 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 backgrounds, while uncertainties from event acceptance variation with different sets of PDFs or variations in the ISR backgrounds, while uncertainties from event acceptance variation with different sets of PDFs or variations in the ISR background.

For SSM1, we exclude $\tilde{\chi}_2^0/\tilde{\chi}_1^0$ with masses below 290 GeV for $\Delta m(\tilde{\chi}_1^+; \tilde{\chi}_1^0) = 50$ GeV and $\Delta m(\tilde{\chi}_1^+; \tilde{\chi}_1^0) = 25$ GeV. Prior experimental constraints on the SUSY parameters with these $\Delta m(\tilde{\chi}_1^+; \tilde{\chi}_1^0)$ and $\Delta m(\tilde{\chi}_1^+; \tilde{\chi}_1^0)$ 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 $m(\tilde{\chi}_1^0)$ for such compressed scenarios.

For SSM2, small $\tilde{\tau}\tilde{\tau}$ production cross sections and low signal acceptances make these scenarios challenging, especially when $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) \leq 50$ GeV. For a $\tilde{\tau}$ mass of 100 GeV and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 30$ 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 $\approx 4 \times 4$ improvement in the cross section upper limit for the SSM2 scenario with $m(\tilde{\tau}) = 150$ GeV and $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) = 50$ 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 fb$^{-1}$ collected with the CMS detector in proton-proton collisions at $\sqrt{s} = 13$ TeV. This search targets scenarios where the mass difference ($\Delta m$) between the tau ($\tilde{\tau}$) particle and the lightest neutralino ($\tilde{\chi}_1^0$) is $\leq 50$ GeV. This is motivated by models considering $\tilde{\tau}$-$\tilde{\chi}_1^0$ 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 $\tilde{\tau}$ via decays of the lightest chargino ($\tilde{\chi}_1^\pm$) and the next-to-lightest neutralino ($\tilde{\chi}_2^0$), and direct production of $\tilde{\tau}$. The data do not reveal evidence for new physics. For a mass splitting $\Delta m(\tilde{\chi}_1^0, \tilde{\chi}_1^\pm) = 50$ GeV and a branching fraction of 100% for $\tilde{\tau} \to \ell\nu\tau$, $\tilde{\chi}_1^\pm$ masses up to 290 GeV are excluded at 95% confidence level. This sensitivity exceeds that of all other $\tilde{\tau}$ 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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31 Helsinki Institute of Physics, Helsinki, Finland
32 Lappeenranta University of Technology, Lappeenranta, Finland
33 IRFU, CEA, Universite Paris-Saclay, Gif-sur-Yvette, France
34 Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris
35 Universite de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
36 Centre de Calcul de l’Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France
37 Universite de Lyon, Universite Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nuclaire de Lyon, Villeurbanne, France
38 Georgian Technical University, Tbilisi, Georgia
39 Tbilisi State University, Tbilisi, Georgia
40 RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
41 RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
42 RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
43 Deutsches Elektronen-Synchrotron, Hamburg, Germany
44 University of Hamburg, Hamburg, Germany
45 Karlsruhe Institut fuer Technologie, Karlsruhe, Germany
46 Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
47 National and Kapodistrian University of Athens, Athens, Greece
48 National Technical University of Athens, Athens, Greece
49 University of Ioannina, Ioannina, Greece
50 MTA-ELTE Lendulet CMS Particle and Nuclear Physics Group, Eotvos Lorand University, Budapest, Hungary
51 Wigner Research Centre for Physics, Budapest, Hungary
52 Institute of Nuclear Research ATOMKI, Debrecen, Hungary
53 Institute of Physics, University of Debrecen, Debrecen, Hungary
54 Esterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary
55 Indian Institute of Science (IISc), Bangalore, India
56 National Institute of Science Education and Research, HBNI, Bhubaneswar, India
57 Panjab University, Chandigarh, India
58 University of Delhi, Delhi, India
59 Saha Institute of Nuclear Physics, HBNI, Kolkata, India
60 Indian Institute of Technology Madras, Madras, India
61 Bhabha Atomic Research Centre, Mumbai, India
62 Tata Institute of Fundamental Research-A, Mumbai, India
63 Tata Institute of Fundamental Research-B, Mumbai, India
64 Indian Institute of Science Education and Research (IISER), Pune, India
65 Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
66 University College Dublin, Dublin, Ireland
<table>
<thead>
<tr>
<th>Institution Name</th>
<th>City, Country</th>
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<tr>
<td>Joint Institute for Nuclear Research, Dubna</td>
<td>Russia</td>
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<tr>
<td>Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia</td>
<td>Russia</td>
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<tr>
<td>Institute for Nuclear Research, Moscow, Russia</td>
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<td>Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC ‘Kurchatov Institute’, Moscow, Russia</td>
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<td>Moscow Institute of Physics and Technology, Moscow, Russia</td>
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<tr>
<td>National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia</td>
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<td>P.N. Lebedev Physical Institute, Moscow, Russia</td>
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<tr>
<td>Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia</td>
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<td>Novosibirsk State University (NSU), Novosibirsk, Russia</td>
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<tr>
<td>Institute for High Energy Physics of National Research Centre ‘Kurchatov Institute’, Protvino, Russia</td>
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<td>National Research Tomsk Polytechnic University, Tomsk, Russia</td>
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<tr>
<td>University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia</td>
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<tr>
<td>Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain</td>
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<td>Universidad Autónoma de Madrid, Madrid, Spain</td>
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<td>Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain</td>
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<td>University of Colombo, Colombo, Sri Lanka</td>
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<td>University of Ruhuna, Department of Physics, Matura, Sri Lanka</td>
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<td>CERN, European Organization for Nuclear Research, Geneva, Switzerland</td>
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<td>Paul Scherrer Institut, Villigen, Switzerland</td>
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<tr>
<td>ETH Zurich—Institute for Particle Physics and Astrophysics (IPF), Zurich, Switzerland</td>
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<td>Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand</td>
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<td>University of California at Santa Barbara—Department of Physics, Santa Barbara, California, USA</td>
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<td>California Institute of Technology, Pasadena, California, USA</td>
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<td>Carnegie Mellon University, Pittsburgh, Pennsylvania, USA</td>
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<td>University of Colorado at Boulder, Boulder, Colorado, USA</td>
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<td>Cornell University, Ithaca, New York, USA</td>
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<td>Fermi National Accelerator Laboratory, Batavia, Illinois, USA</td>
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<td>University of Florida, Gainesville, Florida, USA</td>
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<td>University of Illinois at Chicago (UIC), Chicago, Illinois, USA</td>
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<td>The University of Iowa, Iowa City, Iowa, USA</td>
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<td>Johns Hopkins University, Baltimore, Maryland, USA</td>
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<td>The University of Kansas, Lawrence, Kansas, USA</td>
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Deceased.

Also at Vienna University of Technology, Vienna, Austria.

Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

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Also at UFMS, Campo Grande, Brazil.

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Also at Suez University, Suez, Egypt.

Also at Purdue University, West Lafayette, Indiana, USA.

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Also at Erzincan Binali Yıldırım University, Erzincan, Turkey.

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Also at Institute of Physics, Bhubaneswar, India.

Also at Shoolini University, Solan, India.

Also at University of Hyderabad, Hyderabad, India.

Also at University of Visva-Bharati, Santiniketan, India.

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Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development.

Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.

Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.