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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 $\sqrt{s} = 13$ TeV

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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 ($\tilde{\tau}$) in supersymmetric models that exhibit coannihilation between the $\tilde{\tau}$ and the lightest neutralino ($\tilde{\chi}_1^0$), 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 (Δm) between the chargino ($\tilde{\chi}_1^\pm$) or next-to-lightest neutralino ($\tilde{\chi}_2^0$), and the $\tilde{\chi}_1^0$. The mass of the $\tilde{\tau}$ is assumed to be the average of the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ masses. The data are consistent with standard model background predictions. Upper limits at 95% confidence level are set on the sum of the $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$, and $\tilde{\tau}$ production cross sections for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 50 \text{ GeV}$, resulting in a lower limit of 290 GeV on the mass of the $\tilde{\chi}_1^\pm$, 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 potentially solve the gauge hierarchy problem. In SUSY models assuming $\mathcal{R}$ parity [8] conservation, if the lightest neutralino ($\tilde{\chi}_1^0$) is the lightest SUSY particle, it is neutral, stable, and could have undergone annihilation-production interactions with SM particles in the early universe so as to give the DM relic density observed today [9, 10]. In models with a bino (Z-like) $\tilde{\chi}_1^0$, these interactions alone are not sufficient to produce the correct DM relic abundance. In these cases, a model of coannihilation (CA) can be introduced, where CA refers to the interaction of $\tilde{\chi}_1^0$ 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 τ lepton, considering scenarios where the mass difference (Δm) between the $\tilde{\chi}_1^0$ and $\tilde{\tau}$ is ≤ 50 GeV. These scenarios are motivated by models including $\tilde{\tau}$ - $\tilde{\chi}_1^0$ CA [12–19], where the calculated relic DM density is consistent with the one measured by the WMAP and Planck Collaborations [9, 10]. The $\tilde{\tau}$ - $\tilde{\chi}_1^0$ CA cross section is exponentially enhanced by small $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$.

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 subsequently decay to a τ lepton and $\tilde{\chi}_1^0$. The analysis described in this Letter requires an extra jet (j) from initial-state radiation (ISR). The recoil effect created by the ISR jet facilitates the detection of momentum imbalance and identification of the low-energy (soft) τ lepton decay products [18–26]. Therefore, this analysis focuses on $pp \rightarrow \tilde{\tau}\tilde{\tau}j$ production and indirect $\tilde{\tau}$ production via decays of the lightest chargino ($\tilde{\chi}_1^\pm$) or the next-to-lightest neutralino ($\tilde{\chi}_2^0$) in processes such as $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp j \rightarrow \tilde{\tau}\tilde{\tau}\nu_\tau\nu_\tau j \rightarrow \tau\tilde{\chi}_1^0\tau\tilde{\chi}_1^0\nu_\tau\nu_\tau j$ and $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 j \rightarrow \tilde{\tau}\nu_\tau\tilde{\tau}\tau j \rightarrow \tau\tilde{\chi}_1^0\nu_\tau\tau\tilde{\chi}_1^0\tau j$, which can be the dominant production mechanisms for $\tilde{\tau}$ via the decay of heavier SUSY particles. While the above processes result in 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 $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) \leq 50$ GeV scenarios considered. The visible decay products of the τ leptons have lower p_T than the decaying particles, and it is therefore 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. For these reasons, 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 outlined above allows this analysis to probe the $\tilde{\tau}$ - $\tilde{\chi}_1^0$ CA region with $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) \leq 50$ GeV. This is the first collider search for compressed SUSY spectra using this strategy. Earlier searches performed by 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]. The analysis is performed using data collected in 2016 and 2017 with the CMS experiment [38] in pp collisions at $\sqrt{s} = 13$ TeV. 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 (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 two-tiered trigger system is used to filter events of interest [39]. 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 [40]. 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 [41, 42] with a distance parameter of 0.4. Identification criteria are applied to jet candidates to remove anomalous effects from the calorimeters [43]. For jets with $p_T > 30$ GeV and $|\eta| < 2.4$, the identification efficiency is $>99\%$ [44].

The jet energy scale and resolution are corrected depending on the p_T and η of the jet [45]. Jets originating from the hadronization of b quarks are identified using the combined secondary vertex algorithm [46]. 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 [47]. Muons are reconstructed using the tracker and muon chambers. A track in the central tracker is required to be consistent with measurements in the muon chambers and low-energy measurements in the calorimeters [48]. 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 τ leptons are reconstructed and identified using the hadrons-plus-strips algorithm [49], 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 the kinematic range used in 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 [49]. 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 $\vec{p}_T^{\text{miss}}$ is the negative vector p_T sum of all PF candidates. Its magnitude is p_T^{miss} . The production of undetected particles such as SM neutrinos and the SUSY $\tilde{\chi}_1^0$ is inferred from the measured p_T^{miss} [50, 51]. The jet corrections described above are propagated as corrections to p_T^{miss} , which improves the agreement in p_T^{miss} between simulated events 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 ($t\bar{t}$), and quantum chromodynamics (QCD) multijet processes. The contributions of W+jets and Z+jets events contain genuine τ_h candidates, energetic jets, and p_T^{miss} from neutrinos. Background from $t\bar{t}$ events is characterized by two b quark jets in addition to a genuine τ_h . The QCD multijet events are characterized by jets misidentified as τ_h , and the estimated yield of the QCD multijet background is derived from data.

Simulated samples for Z+jets, W+jets, $t\bar{t}$ +jets, and single top quark events are produced with the MADGRAPH5_aMC@NLO 2.6.0 program [52] 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 [53] with a left-handed $\tilde{\tau}$, $\mathcal{B}(\tilde{\chi}_2^0 \rightarrow \tau \tilde{\tau} \rightarrow \tau \tau \tilde{\chi}_1^0) = \mathcal{B}(\tilde{\chi}_1^\pm \rightarrow$

$\nu_\tau \tilde{\tau} \rightarrow \nu_\tau \tau \tilde{\chi}_1^0 = 100\%$, and $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_2^0)$. This set of signal samples is motivated by the importance of the chargino-neutralino sector in establishing the connection between SUSY models and DM. We will 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 $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0) \leq 50$ GeV is challenging because of the small production cross section and low signal acceptance, this second set of signal samples is included to highlight the improved sensitivity in this analysis, compared to previous non-ISR searches. This second set of signal samples allows for reinterpretation in other scenarios with $\tilde{\tau}$ -like particles. We will refer to this model as SUSY signal model 2 (SSM2). The MADGRAPH5_aMC@NLO generator is interfaced with PYTHIA 8.212 [54] using the CUETP8M1 and CP5 tunes [55, 56] for parton shower and fragmentation in the 2016 and 2017 simulated samples, respectively. The NNPDF3.0 LO and NLO [57] parton distribution functions (PDFs) are used in the event generation. The CMS detector response is simulated using the GEANT4 [58] package for the background samples, and the CMS fast simulation package [59] for the signal samples. To model the effect of additional pp interactions (pileup) 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. The 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 the signal production cross sections are calculated at NLO with next-to-leading logarithmic (NLL) soft-gluon resummation calculations [60–63].

Events are recorded using a p_T^{miss} trigger. The trigger efficiency is measured using data events with one muon, which results in a sample enriched in W+jets events, with 95% purity according to simulation. Selected events are required to have $p_T^{\text{miss}} > 230$ GeV, where the trigger is fully efficient, and exactly one identified τ_h candidate with $|\eta| < 2.1$. The p_T of the τ_h candidate is restricted to $20 < p_T(\tau_h) < 40$ GeV. The requirement of exactly one τ_h candidate and the upper limit on p_T reduce the W+jets, Z+jets, and $t\bar{t}$ +jets backgrounds. The highest- p_T jet is referred to as the ISR jet (j_{ISR}) and is required to satisfy $p_T > 100$ GeV and $|\eta| < 2.4$. The absolute difference in the azimuthal angle (ϕ) between the ISR jet and $\vec{p}_T^{\text{miss}}$ is required to be greater than 0.7 radians ($|\Delta\phi(j_{\text{ISR}}, \vec{p}_T^{\text{miss}})| > 0.7$ radians) in order to reduce the contribution from QCD multijet events containing large p_T^{miss} from jet mismeasurements. To reduce background processes with top quarks, events with b-tagged jets are rejected. Finally, 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 τ_h candidate and the $\vec{p}_T^{\text{miss}}$, defined as

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

is the main observable used 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 contamination from signal events. MC simulations are used to extrapolate the W/Z+jets and $t\bar{t}$ +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_T^{miss} . To calculate the correction factor, the contribution from nontargeted backgrounds is subtracted from data. The uncertainty in these background processes is propagated to the final systematic uncertainty

in the background predictions. The 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 the requirement of an ISR jet. This modeling is studied using a $Z(\rightarrow \mu\mu)$ +jets CR in data. The use of 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^{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, which range from 0.79 to 1.12. The correction factors are validated using a $W(\rightarrow \mu\nu_\mu)$ +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 $Z(\rightarrow \tau_h \tau_h)$ +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 $p_T > 60$ GeV and $|\eta| < 2.1$, selected by a dedicated $\tau_h \tau_h$ trigger [31, 64–66]. 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 $Z(\rightarrow \tau_h \tau_h)$ +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 $m(\tau_h \tau_h) > 100$ GeV. Correction factors of 0.92 ± 0.05 and 0.95 ± 0.04 for $Z(\rightarrow \tau_h \tau_h)$ +jets are measured in this CR for the 2016 and 2017 data sets, respectively. The quoted uncertainties are purely statistical. These correction factors are used to scale the $Z(\rightarrow \tau\tau)$ +jets prediction in the SR.

The contribution from $t\bar{t}$ 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 $t\bar{t}$ CR sample with high purity. The correction factor is applied to scale the prediction of $t\bar{t}$ 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 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 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 $W(\rightarrow \mu\nu_\mu)+\tau_h$ 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 $\Delta\phi(j_{\text{ISR}}, \vec{p}_T^{\text{miss}})$ requirement.

A major source of systematic uncertainty is the closure of the background estimation methods, where closure refers to tests (performed 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. The background estimation uncertainty from the closure tests for the QCD multijet background is determined by the deviation of the tight-to-loose ratios obtained in a $Z(\rightarrow \mu\mu)+\tau_h$ CR, where the τ_h is a misidentified jet, from those in the $W(\rightarrow \mu\nu_\mu)+\tau_h$ region. This uncertainty depends on $p_T(\tau_h)$ and varies from

4 to 29%. Shape-based systematic uncertainties resulting 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 procedure 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 [49]. 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 [47, 48, 67], with a resulting uncertainty of $\leq 1\%$. The p_T^{miss} scale uncertainties contribute via the jet energy scale (2–5% depending on η and p_T) and 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 [68] by comparing results using the CTEQ6.6L, MSTW08, and NNPDF10 PDF sets [69–71] 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 [72] and 2.3% [73] for the 2016 and 2017 data, respectively.

Figure 1 shows the $m_T(p_T^{\text{miss}}, \tau_h)$ distribution for events in the SR. The binning used in Fig. 1 has been 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 $m(\tilde{\chi}_1^\pm) = 200$ 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 .

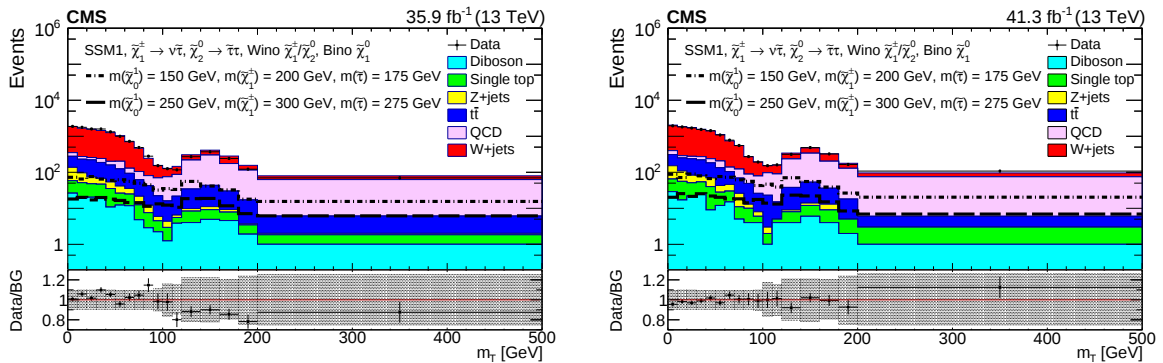


Figure 1: The m_T distribution for SR events with 2016 data (left) and 2017 data (right). In the upper panels of the figures, the solid colors correspond to the expected background processes, the black dots to the observed data, and the dashed lines to the expected signal from simulation. The lower panels of the figures show 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.

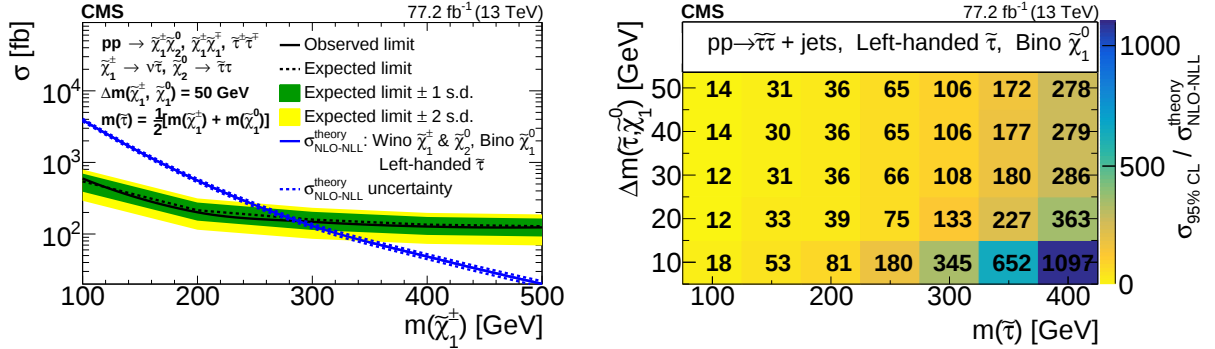


Figure 2: (left) The 95% confidence level (CL) upper limits on the SSM1 production cross sections ($\sigma_{95\% \text{ CL}}$) as a function of $m(\tilde{\chi}_1^\pm)$. The solid blue line corresponds to the theoretical cross section, and the dashed blue line to its uncertainty. The observed limit is shown with the solid black line, while the expected limit is represented 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 $\Delta m(\tilde{\tau}, \tilde{\chi}_1^0)$.

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 $m(\tilde{\chi}_1^\pm)$ 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 choice of 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 result in a DM relic density consistent with experimental measurements [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 [74–76]. Maximum likelihood fits are performed by using the final m_T distributions for the 2016 and 2017 data to construct a combined profile likelihood ratio test statistic [74] 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. [77]. Correlations among the signal and backgrounds have been considered in the calculation of the limits. For example, the uncertainty in the integrated luminosity is treated as fully correlated across signal and backgrounds, while uncertainties due to the 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. The uncertainties from the closure tests are treated as uncorrelated. It is noted, however, that the sensitivity is dominated by the statistical uncertainties.

For SSM1, we exclude $\tilde{\chi}_2^0/\tilde{\chi}_1^\pm$ with masses falling below 290 GeV for $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 50$ GeV and $\Delta m(\tilde{\chi}_1^\pm, \tilde{\tau}) = 25$ 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], and thus the search presented in this Letter provides the first results from the LHC to surpass the LEP bounds. 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.

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 in 2016 and 2017 with the CMS detector in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. This search targets compressed mass spectra where the mass difference (Δm) between the stau ($\tilde{\tau}$) particle and the lightest neutralino ($\tilde{\chi}_1^0$) is $\leq 50 \text{ GeV}$. This is motivated by models considering $\tilde{\tau}\text{-}\tilde{\chi}_1^0$ CA to maintain consistency in the estimation of 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 $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = 50 \text{ GeV}$ and a branching fraction of 100% for $\tilde{\chi}_1^\pm \rightarrow \tilde{\tau}\nu_\tau \rightarrow \tau\tilde{\chi}_1^0\nu_\tau$, $\tilde{\chi}_1^\pm$ 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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References

- [1] P. Ramond, “Dual theory for free fermions”, *Phys. Rev. D* **3** (1971) 2415, doi:10.1103/PhysRevD.3.2415.
- [2] Y. A. Gol’fand and E. P. Likhtman, “Extension of the algebra of Poincare group generators and violation of P invariance”, *JETP Lett.* **13** (1971) 323.
- [3] S. Ferrara and B. Zumino, “Supergauge invariant Yang-Mills theories”, *Nucl. Phys. B* **79** (1974) 413, doi:10.1016/0550-3213(74)90559-8.
- [4] J. Wess and B. Zumino, “Supergauge transformations in four dimensions”, *Nucl. Phys. B* **70** (1974) 39, doi:10.1016/0550-3213(74)90355-1.

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- [5] A. H. Chamseddine, R. Arnowitt, and P. Nath, “Locally supersymmetric grand unification”, *Phys. Rev. Lett.* **49** (1982) 970, doi:10.1103/PhysRevLett.49.970.
 - [6] R. Barbieri, S. Ferrara, and C. A. Savoy, “Gauge models with spontaneously broken local Supersymmetry”, *Phys. Lett. B* **119** (1982) 343, doi:10.1016/0370-2693(82)90685-2.
 - [7] L. Hall, J. Lykken, and S. Weinberg, “Supergravity as the messenger of supersymmetry breaking”, *Phys. Rev. D* **27** (1983) 2359, doi:10.1103/PhysRevD.27.2359.
 - [8] S. Dimopoulos and G. F. Giudice, “Naturalness constraints in supersymmetric theories with nonuniversal soft terms”, *Phys. Lett. B* **357** (1995) 573, doi:10.1016/0370-2693(95)00961-J, arXiv:hep-ph/9507282.
 - [9] WMAP Collaboration, “First year wilkinson microwave anisotropy probe (WMAP) observations: determination of cosmological parameters”, *Astrophys. J. Suppl.* **148** (2003) 175, doi:10.1086/377226, arXiv:astro-ph/0302209.
 - [10] Planck Collaboration, “Planck 2015 results. XIII. Cosmological parameters”, *Astron. Astrophys.* **594** (2016) A13, doi:10.1051/0004-6361/201525830, arXiv:1502.01589.
 - [11] K. Griest and D. Seckel, “Three exceptions in the calculation of relic abundances”, *Phys. Rev. D* **43** (1991) 3191, doi:10.1103/PhysRevD.43.3191.
 - [12] R. L. Arnowitt et al., “Detection of SUSY signals in stau neutralino co-annihilation region at the LHC”, *AIP Conf. Proc.* **903** (2007) 229, doi:10.1063/1.2735167, arXiv:hep-ph/0611089.
 - [13] V. Khotilovich, R. L. Arnowitt, B. Dutta, and T. Kamon, “The stau neutralino co-annihilation region at an international linear collider”, *Phys. Lett. B* **618** (2005) 182, doi:10.1016/j.physletb.2005.04.078, arXiv:hep-ph/0503165.
 - [14] M. Carena et al., “Light stau phenomenology and the Higgs $\gamma\gamma$ rate”, *JHEP* **07** (2012) 175, doi:10.1007/JHEP07(2012)175, arXiv:1205.5842.
 - [15] A. Aboubrahim, P. Nath, and A. B. Spisak, “Stau coannihilation, compressed spectrum, and SUSY discovery potential at the LHC”, *Phys. Rev. D* **95** (2017) 115030, doi:10.1103/PhysRevD.95.115030, arXiv:1704.04669.
 - [16] G. H. Duan et al., “Vacuum stability in stau-neutralino coannihilation in MSSM”, *Phys. Lett. B* **788** (2019) 475, doi:10.1016/j.physletb.2018.12.001, arXiv:1809.10061.
 - [17] R. Arnowitt et al., “Determining the dark matter relic density in the minimal supergravity stau-neutralino coannihilation region at the Large Hadron Collider”, *Phys. Rev. Lett.* **100** (2008) 231802, doi:10.1103/PhysRevLett.100.231802, arXiv:hep-ph/0802.2968.
 - [18] B. Dutta et al., “Vector boson fusion processes as a probe of supersymmetric electroweak sectors at the LHC”, *Phys. Rev. D* **87** (2013) 035029, doi:10.1103/PhysRevD.87.035029, arXiv:1210.0964.

- [19] A. G. Delannoy et al., “Probing dark matter at the LHC using vector boson fusion processes”, *Phys. Rev. Lett.* **111** (2013) 061801, doi:10.1103/PhysRevLett.111.061801, arXiv:1304.7779.
- [20] A. Florez et al., “Probing the stau-neutralino coannihilation region at the LHC with a soft tau lepton and an ISR jet”, *Phys. Rev. D* **94** (2016) 073007, doi:10.1103/PhysRevD.94.073007, arXiv:hep-ph/1606.08878.
- [21] B. Dutta et al., “Probing compressed bottom squarks with boosted jets and shape analysis”, *Phys. Rev. D* **92** (2015) 095009, doi:10.1103/PhysRevD.92.095009, arXiv:1507.01001.
- [22] B. Dutta et al., “Probing compressed top squarks at the LHC at 14 TeV”, *Phys. Rev. D* **90** (2014) 095022, doi:10.1103/PhysRevD.90.095022, arXiv:1312.1348.
- [23] B. Dutta et al., “Probing compressed sleptons at the LHC using vector boson fusion processes”, *Phys. Rev. D* **91** (2015) 055025, doi:10.1103/PhysRevD.91.055025, arXiv:1411.6043.
- [24] A. Flórez et al., “Searching for new heavy neutral gauge bosons using vector boson fusion processes at the LHC”, *Phys. Lett. B* **767** (2017) 126, doi:10.1016/j.physletb.2017.01.062, arXiv:1609.09765.
- [25] A. Flórez et al., “Expanding the reach of heavy neutrino searches at the LHC”, *Phys. Lett. B* **778** (2018) 94, doi:10.1016/j.physletb.2018.01.009, arXiv:1708.03007.
- [26] A. Flórez et al., “Probing heavy spin-2 bosons with $\gamma\gamma$ final states from vector boson fusion processes at the LHC”, *Phys. Rev. D* **99** (2019) 035034, doi:10.1103/PhysRevD.99.035034, arXiv:1812.06824.
- [27] CMS Collaboration, “Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2018) 160, doi:10.1007/JHEP03(2018)160, arXiv:1801.03957.
- [28] CMS Collaboration, “Search for new physics in events with two soft oppositely charged leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *Phys. Lett. B* **782** (2018) 440, doi:10.1016/j.physletb.2018.05.062, arXiv:1801.01846.
- [29] ATLAS Collaboration, “Search for the direct production of charginos and neutralinos in final states with tau leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector”, *Eur. Phys. J. C* **78** (2018) 154, doi:10.1140/epjc/s10052-018-5583-9, arXiv:1708.07875.
- [30] ATLAS Collaboration, “Search for electroweak production of supersymmetric states in scenarios with compressed mass spectra at $\sqrt{s} = 13$ TeV with the ATLAS detector”, *Phys. Rev. D* **97** (2017) 052010, doi:10.1103/PhysRevD.97.052010, arXiv:1712.08119.
- [31] CMS Collaboration, “Search for supersymmetry in the vector-boson fusion topology in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JHEP* **11** (2015) 189, doi:10.1007/JHEP11(2015)189, arXiv:1508.07628.

-
- [32] CMS Collaboration, “Search for supersymmetry with a compressed mass spectrum in the vector boson fusion topology with 1-lepton and 0-lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **08** (2019) 150, doi:10.1007/JHEP08(2019)150, arXiv:1905.13059.
- [33] CMS Collaboration, “Search for direct pair production of supersymmetric partners to the τ lepton in proton-proton collisions at $\sqrt{s} = 13$ TeV”, (2019). arXiv:1907.13179. Submitted to *Eur. Phys. J. C*.
- [34] ALEPH Collaboration, “Search for scalar leptons in e^+e^- collisions at center-of-mass energies up to 209 GeV”, *Phys. Lett. B* **526** (2002) 206, doi:10.1016/S0370-2693(01)01494-0, arXiv:hep-ex/0112011.
- [35] DELPHI Collaboration, “Searches for supersymmetric particles in e^+e^- collisions up to 208 GeV and interpretation of the results within the MSSM”, *Eur. Phys. J. C* **31** (2003) 421, doi:10.1140/epjc/s2003-01355-5, arXiv:hep-ex/0311019.
- [36] L3 Collaboration, “Search for scalar leptons and scalar quarks at LEP”, *Phys. Lett. B* **580** (2004) 37, doi:10.1016/j.physletb.2003.10.010, arXiv:hep-ex/0310007.
- [37] OPAL Collaboration, “Search for anomalous production of dilepton events with missing transverse momentum in e^+e^- collisions at $\sqrt{s} = 183$ GeV to 209 GeV”, *Eur. Phys. J. C* **32** (2004) 453, doi:10.1140/epjc/s2003-01466-y, arXiv:hep-ex/0309014.
- [38] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [39] CMS Collaboration, “The CMS trigger system”, *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
- [40] CMS Collaboration, “Particle-flow reconstruction and global event description with the CMS detector”, *JINST* **12** (2017) P10003, doi:10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
- [41] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_T jet clustering algorithm”, *JHEP* **04** (2008) 063, doi:10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
- [42] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet user manual”, *Eur. Phys. J. C* **72** (2012) 1896, doi:10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.
- [43] CMS Collaboration, “Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector”, *JINST* **14** (2019) P07004, doi:10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.
- [44] CMS Collaboration, “Jet algorithms performance in 13 TeV data”, CMS Physics Analysis Summary CMS-PAS-JME-16-003, 2016.
- [45] CMS Collaboration, “Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV”, *JINST* **12** (2017) P02014, doi:10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
- [46] CMS Collaboration, “Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV”, *JINST* **13** (2018) P05011, doi:10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

- [47] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *JINST* **10** (2015) P06005, doi:10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
- [48] CMS Collaboration, “Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P06015, doi:10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.
- [49] CMS Collaboration, “Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV”, *JINST* **13** (2018) P10005, doi:10.1088/1748-0221/13/10/P10005, arXiv:1809.02816.
- [50] CMS Collaboration, “Search for dark matter and supersymmetry with a compressed mass spectrum in the vector boson fusion topology in proton-proton collisions at $\sqrt{s} = 8$ TeV”, *Phys. Rev. Lett.* **118** (2017) 021802, doi:10.1103/PhysRevLett.118.021802, arXiv:1605.09305.
- [51] A. Flórez et al., “Anapole dark matter via vector boson fusion processes at the LHC”, *Phys. Rev. D* **100** (2019) 016017, doi:10.1103/PhysRevD.100.016017, arXiv:1902.01488.
- [52] J. Alwall et al., “The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations”, *JHEP* **07** (2014) 079, doi:10.1007/JHEP07(2014)079, arXiv:1405.0301.
- [53] LHC New Physics Working Group Collaboration, “Simplified models for LHC new physics searches”, *J. Phys. G* **39** (2012) 105005, doi:10.1088/0954-3899/39/10/105005, arXiv:1105.2838.
- [54] T. Sjöstrand et al., “An introduction to PYTHIA 8.2”, *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
- [55] CMS Collaboration, “Event generator tunes obtained from underlying event and multiparton scattering measurements”, *Eur. Phys. J. C* **76** (2016) 155, doi:10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
- [56] CMS Collaboration, “Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements”, (2019). arXiv:1903.12179. Submitted to *Eur. Phys. J. C*.
- [57] NNPDF Collaboration, “Parton distributions for the LHC Run II”, *JHEP* **04** (2015) 040, doi:10.1007/JHEP04(2015)040, arXiv:1410.8849.
- [58] GEANT4 Collaboration, “GEANT4—a simulation toolkit”, *Nucl. Instrum. Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.
- [59] CMS Collaboration, “The fast simulation of the CMS detector at LHC”, *J. Phys. Conf. Ser.* **331** (2011) 032049, doi:10.1088/1742-6596/331/3/032049.
- [60] J. Debove, B. Fuks, and M. Klasen, “Threshold resummation for gaugino pair production at hadron colliders”, *Nucl. Phys. B* **842** (2011) 51, doi:10.1016/j.nuclphysb.2010.08.016, arXiv:1005.2909.

-
- [61] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Gaugino production in proton-proton collisions at a center-of-mass energy of 8 TeV”, *JHEP* **10** (2012) 081, doi:10.1007/JHEP10(2012)081, arXiv:1207.2159.
 - [62] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, “Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO”, *Eur. Phys. J. C* **73** (2013) 2480, doi:10.1140/epjc/s10052-013-2480-0, arXiv:1304.0790.
 - [63] J. Fiaschi and M. Klasen, “Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II”, *Phys. Rev. D* **98** (2018) 055014, doi:10.1103/PhysRevD.98.055014, arXiv:1805.11322.
 - [64] CMS Collaboration, “Search for heavy neutrinos or third-generation leptoquarks in final states with two hadronically decaying tau leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2017) 077, doi:10.1007/JHEP03(2017)077, arXiv:1612.01190.
 - [65] CMS Collaboration, “Search for heavy neutrinos and third-generation leptoquarks in hadronic states of two τ leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **03** (2019) 170, doi:10.1007/JHEP03(2019)170, arXiv:1811.00806.
 - [66] CMS Collaboration, “Search for heavy resonances decaying to tau lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV”, *JHEP* **02** (2017) 048, doi:10.1007/JHEP02(2017)048, arXiv:1611.06594.
 - [67] CMS Collaboration, “Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **10** (2011) 132, doi:10.1007/JHEP10(2011)132, arXiv:1107.4789.
 - [68] J. Butterworth et al., “PDF4LHC recommendations for LHC Run II”, *J. Phys. G* **43** (2016) 023001, doi:10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
 - [69] P. M. Nadolsky et al., “Implications of CTEQ global analysis for collider observables”, *Phys. Rev. D* **78** (2008) 013004, doi:10.1103/PhysRevD.78.013004, arXiv:0802.0007.
 - [70] A. D. Martin, W. J. Stirling, R. S. Thorne, and G. Watt, “Update of parton distributions at NNLO”, *Phys. Lett. B* **652** (2007) 292, doi:10.1016/j.physletb.2007.07.040, arXiv:0706.0459.
 - [71] M. Ubiali, “NNPDF1.0 parton set for the LHC”, *Nucl. Phys. Proc. Suppl.* **186** (2009) 62, doi:10.1016/j.nuclphysbps.2008.12.020, arXiv:0809.3716.
 - [72] CMS Collaboration, “CMS luminosity measurements for the 2016 data-taking period”, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, 2017.
 - [73] CMS Collaboration, “CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV”, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, 2018.
 - [74] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, “Asymptotic formulae for likelihood-based tests of new physics”, *Eur. Phys. J. C* **71** (2011) 1554, doi:10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727. [Erratum: doi:10.1140/epjc/s10052-013-2501-z].

-
- [75] T. Junk, “Confidence level computation for combining searches with small statistics”, *Nucl. Instrum. Meth. A* **434** (1999) 435, doi:10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
- [76] A. L. Read, “Presentation of search results: the CL_s technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [77] R. J. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comput. Phys. Commun.* **77** (1993) 219, doi:10.1016/0010-4655(93)90005-w.

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- 25: Also at Shoolini University, Solan, India
- 26: Also at University of Hyderabad, Hyderabad, India
- 27: Also at University of Visva-Bharati, Santiniketan, India
- 28: Also at Isfahan University of Technology, Isfahan, Iran
- 29: Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy
- 30: Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- 31: Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- 32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 33: Also at Riga Technical University, Riga, Latvia, Riga, Latvia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at Imperial College, London, United Kingdom
- 42: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 43: Also at California Institute of Technology, Pasadena, USA
- 44: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 45: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 46: Also at Università degli Studi di Siena, Siena, Italy
- 47: Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy, Pavia, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Universität Zürich, Zurich, Switzerland
- 50: Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria, Vienna, Austria
- 51: Also at Burdur Mehmet Akif Ersoy University, BURDUR, Turkey
- 52: Also at Adiyaman University, Adiyaman, Turkey
- 53: Also at Şırnak University, Sirnak, Turkey
- 54: Also at Tsinghua University, Beijing, China
- 55: Also at Beykent University, Istanbul, Turkey, Istanbul, Turkey
- 56: Also at Istanbul Aydın University, Istanbul, Turkey
- 57: Also at Mersin University, Mersin, Turkey
- 58: Also at Piri Reis University, Istanbul, Turkey
- 59: Also at Gaziosmanpasa University, Tokat, Turkey

- 60: Also at Ozyegin University, Istanbul, Turkey
- 61: Also at Izmir Institute of Technology, Izmir, Turkey
- 62: Also at Marmara University, Istanbul, Turkey
- 63: Also at Kafkas University, Kars, Turkey
- 64: Also at Istanbul Bilgi University, Istanbul, Turkey
- 65: Also at Hacettepe University, Ankara, Turkey
- 66: Also at Vrije Universiteit Brussel, Brussel, Belgium
- 67: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 68: Also at IPPP Durham University, Durham, United Kingdom
- 69: Also at Monash University, Faculty of Science, Clayton, Australia
- 70: Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA
- 71: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
- 72: Also at Bingol University, Bingol, Turkey
- 73: Also at Georgian Technical University, Tbilisi, Georgia
- 74: Also at Sinop University, Sinop, Turkey
- 75: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 76: Also at Texas A&M University at Qatar, Doha, Qatar
- 77: Also at Kyungpook National University, Daegu, Korea, Daegu, Korea