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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

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ABSTRACT

A search is presented for new physics in events with two low-momentum, oppositely charged leptons (electrons or muons) and missing transverse momentum in proton-proton collisions at a centre-of-mass energy of 13 TeV. The data collected using the CMS detector at the LHC correspond to an integrated luminosity of 35.9 fb^{-1}. The observed event yields are consistent with the expectations from the standard model. The results are interpreted in terms of pair production of charginos and neutralinos ($\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_2^0$) with nearly degenerate masses, as expected in natural supersymmetry models with light higgsinos, as well as in terms of the pair production of top squarks ($\tilde{t}$), when the lightest neutralino and the top squark have similar masses. At 95% confidence level, wino-like $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ masses are excluded up to 230 GeV for a mass difference of 20 GeV relative to the lightest neutralino. In the higgsino-like model, masses are excluded up to 168 GeV for the same mass difference. For $\tilde{t}$ pair production, top squark masses up to 450 GeV are excluded for a mass difference of 40 GeV relative to the lightest neutralino.

1. Introduction

Supersymmetry (SUSY) [1–5] is a widely considered extension of the standard model (SM) of particle physics, as it can provide solutions to several open questions in the SM, in particular those related to the hierarchy problem [6–8] and the nature of dark matter. SUSY predicts superpartners of SM particles whose spins differ by one-half unit with respect to their SM partners. In R-parity conserving models [9], SUSY particles are pair-produced and their decay chains end in the stable, lightest SUSY particle (LSP), which in many models corresponds to the lightest neutralino ($\tilde{\chi}_1^0$). A stable LSP would escape undetected, yielding a characteristic signature of a large magnitude of missing transverse momentum (p_T^{miss}) in collisions at the CERN LHC. As a stable, neutral and weakly interacting particle, the neutralino matches the properties required of a dark matter candidate [10].

The absence of SUSY signals in previous experiments, as well as at the LHC, can be interpreted as an indication that SUSY particles have very large mass, leading to the expectation that SUSY events have large visible energy and momentum. As a result, the many searches that yield the most stringent limits on the masses of the SUSY particles are based on events with large p_T^{miss} and energetic final-state objects such as leptons and jets. Another interpretation for the absence of a SUSY signal is that the SUSY particles are in a part of the parameter space that is not easily accessible. One such scenario, where previously mentioned searches would not be sensitive, is where the mass spectrum is compressed, i.e. the mass splitting between the produced SUSY particles and the LSP is small. When the mass splittings between SUSY particles are small, the visible energy in the event, and also potentially the p_T^{miss}, is relatively low, which motivates searches in events with low-momentum objects.

Compressed mass spectra arise in several SUSY models, including natural SUSY, i.e. SUSY models that solve the hierarchy problem with little fine tuning. It has been pointed out in several studies, for example in Refs. [6–8,11–15], that naturalness imposes constraints on the masses of higgsinos, top squarks, and gluinos. Natural SUSY is generally considered to require at least one coloured SUSY particle of mass below approximately one TeV. Further, it is often assumed that this particle is the top squark ($\tilde{t}$). More recently, however, the hypothesis of natural SUSY requiring a light top squark has been disputed as arising from oversimplified assumptions [16–18]. Irrespective of the top squark, higgsinos remain a complementary window to natural SUSY as they are generally expected to be light. As pointed out in Refs. [19–22], light

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higgsinos are likely to have a compressed mass spectrum, potentially leading to signatures with soft leptons and moderate $p_{\mathrm{T}}^{\mathrm{miss}}$. Thus far, the most sensitive searches in this model have been carried out by experiments at LEP [23,24] and ATLAS [25]. The LEP experiments excluded $\widetilde{\chi}_1^{\pm}$ masses up to 103.5 GeV for a mass splitting between the $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_1^{0}$ of at least 3 GeV.

The search described in this letter is designed for neutralinos and charginos, which are collectively referred to as “electroweakinos”, in a model where these electroweakinos form a compressed mass spectrum [19,21,22,26]. Two models are considered where the electroweakinos are either pure wino/bino-like or where the lightest electroweakinos are of mostly higgsino nature. The search has discovery potential also when a light top squark and the LSP are nearly degenerate in mass and the top squark decays to four fermions. A more detailed discussion of such models can be found in Ref. [27]. The near-degeneracy in mass of the top squark and the LSP is typical of the so-called “co-annihilation region”, in which the LSP is the sole source of dark matter [28].

In the models considered in this analysis, the visible decay products in the SUSY signal have low momentum, which can be distinguished from SM processes when a jet with large transverse momentum (p_{T}) from initial-state radiation (ISR) leads to a large boost of the SUSY particle pair. This boost also enhances the $p_{\mathrm{T}}^{\mathrm{miss}}$ in the event. A similar search has previously been reported by the ATLAS Collaboration [25]. For the signal studied in this letter, SUSY particles can decay leptonically, and the presence of low-p_{T} leptons can be used to discriminate against otherwise dominant SM backgrounds, such as multijet production through quantum chromodynamics (QCD) and Z + jets events with invisible Z boson decays.

The current strategy is similar to that in the previous publication based on 8 TeV data [29], with the main difference being the deployment of a new trigger selection that improves the sensitivity of the search in events with two muons and low $p_{\mathrm{T}}^{\mathrm{miss}}$. In addition, the selection has further been optimized for electroweakinos with a compressed mass spectrum. At least one jet is required in the final state; in the case of the signal, this jet must arise from ISR, which provides the final-state particles with a boost in the transverse plane, and thereby the potential for moderate or large $p_{\mathrm{T}}^{\mathrm{miss}}$ in the event. Unlike the 8 TeV analysis, there is no upper limit on the number of jets in the event.

2. CMS detector

The central feature of the CMS apparatus 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 (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [30]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [31].

3. Data and simulated samples

The data used in this search correspond to an integrated luminosity of 35.9 fb^{-1} of proton–proton (pp) collisions at a centre-of-mass energy of 13 TeV, recorded in 2016 using the CMS detector. The data are selected using two triggers: an inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger, which is used for signal regions (SRs) with an offline $p_{\mathrm{T}}^{\mathrm{miss}}$ cut > 200 GeV and an additional trigger which requires two muons to lower the offline $p_{\mathrm{T}}^{\mathrm{miss}}$ cut to 125 GeV. Both the muon p_{T} and the muon pair p_{T} have a trigger online cut of $p_{\mathrm{T}} > 3$ GeV. The inclusive $p_{\mathrm{T}}^{\mathrm{miss}}$ triggers correspond to an integrated luminosity of 35.9 fb^{-1}, whereas the events recorded with the dimuon + $p_{\mathrm{T}}^{\mathrm{miss}}$ trigger correspond to 33.2 fb^{-1}.

Simulated signal and major background processes, such as $\mathrm{t\bar{t}}$, W + jets, and Z + jets are generated with the MadGraph5_aMC@NLO 2.2.2 [32,33] event generator at leading order (LO) precision in perturbative QCD using the MLM merging scheme [34]. Additional partons are modelled in these samples. The diboson processes WW, ZZ, and Wγ are generated with the MadGraph5_aMC@NLO 2.2.2 event generator at next-to-leading order (NLO) precision using the FxFx merging scheme [33], while the WZ process is generated at NLO with powheg v2.0 [35–39]. Rare background processes (e.g. $\mathrm{t\bar{t}W}$, $\mathrm{t\bar{t}Z}$, WWW, ZZZ, WZZ, and WWZ) are also generated at NLO precision with MadGraph5_aMC@NLO 2.2.2 (2.3.2.2 for $\mathrm{t\bar{t}Z}$) [32,33]. The rare background from single top quarks produced in association with a W boson is generated at NLO precision with powheg v1.0 [40]. The NNPDF3.0 [41] LO and NLO parton distribution functions (PDF) are used for the simulated samples generated at LO and NLO. Showering, hadronization and the underlying event description are carried out using the pythia 8.212 package [42] with the CUETP8M1 underlying event tune [43,44]. A detailed simulation of the CMS detector is based on the Geant4 [45] package. A fast detector simulation [46] is used for the large number of signal samples, corresponding to different SUSY particle masses. The trigger, lepton identification, and b tagging efficiencies are corrected in the simulation through application of scale factors measured in dedicated data samples [47]. Corrections for the use of the fast detector simulation are also applied.

For the signal, we consider the neutralino–chargino ($\widetilde{\chi}_2^0$–$\widetilde{\chi}_1^{\pm}$) pair production where the mass degenerate $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ are assumed to decay to the LSP via virtual Z and W bosons. The decays of electroweakinos are carried out using pythia, assuming a constant matrix element. The SM branching fractions are assumed for the decays of the virtual Z and W bosons. The simulation of the $\widetilde{\chi}_2^0$ ($\widetilde{\chi}_1^{\pm}$) decay takes into account the Breit–Wigner shape of the Z (W) boson mass. The production cross sections correspond to those of pure wino production [48–50] computed at NLO plus next-to-leading-logarithmic (NLL) precision. A second mass scan simulates a simplified model of $\widetilde{\mathrm{t}}$-pair production, in which a heavy chargino mediates the decay of the $\widetilde{\mathrm{t}}$ into leptons and $\widetilde{\chi}_1^0$, namely $\widetilde{\mathrm{t}} \to \mathrm{b}\widetilde{\chi}_1^{\pm} \to \mathrm{bW}^*\widetilde{\chi}_1^0$. The mass of the $\widetilde{\chi}_1^{\pm}$ is set to $(m_{\widetilde{\mathrm{t}}} + m_{\widetilde{\chi}_1^0})/2$, and the mass difference between $\widetilde{\mathrm{t}}$ and $\widetilde{\chi}_1^0$ is set to be less than 80 GeV, thus b jets are expected to have a p_{T} below 25 GeV. Fig. 1 shows diagrams for these two simplified models. We denote the upper diagram in Fig. 1 as TChi and the lower diagram as T2tt. The masses are given with the model name, i.e. TChi150/20 (T2tt150/20) denotes a $\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$ ($\widetilde{\mathrm{t}}$ pair) production, where the produced particles have a mass of 150 GeV and a mass difference to the LSP of 20 GeV.

We interpret the results of this search in two variations of the electroweakino model. While the model described above uses pure wino cross sections with the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$ mass degenerate, these additional models resemble a scenario where the electroweakinos are of higgsino nature. The first of these higgsino simplified