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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 $\sqrt{s} = 13\,\text{TeV}$

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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 $35.9\,\text{fb}^{-1}$. 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 ($\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_2^0$) 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 ($\widetilde{\text{t}}$), when the lightest neutralino and the top squark have similar masses. At 95% confidence level, wino-like $\widetilde{\chi}_1^{\pm}/\widetilde{\chi}_2^0$ 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 $\widetilde{\text{t}}$ 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 ($\widetilde{\chi}_1^0$). A stable LSP would escape undetected, yielding a characteristic signature of a large magnitude of missing transverse momentum ($p_{\text{T}}^{\text{miss}}$) 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 $p_{\text{T}}^{\text{miss}}$ 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 $p_{\text{T}}^{\text{miss}}$, 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 ($\widetilde{\text{t}}$). 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_T^{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_T^{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_T^{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_T^{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_T^{miss} trigger, which is used for signal regions (SRs) with an offline p_T^{miss} cut > 200 GeV and an additional trigger which requires two muons to lower the offline p_T^{miss} cut to 125 GeV. Both the muon p_T and the muon pair p_T have a trigger online cut of $p_T > 3$ GeV. The inclusive p_T^{miss} triggers correspond to an integrated luminosity of 35.9 fb^{-1}, whereas the events recorded with the dimuon + p_T^{miss} trigger correspond to 33.2 fb^{-1}.

Simulated signal and major background processes, such as $t\bar{t}$, 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. $t\bar{t}$W, $t\bar{t}$Z, WWW, ZZZ, WZZ, and WWZ) are also generated at NLO precision with MadGraph5_aMC@NLO 2.2.2 (2.3.2.2 for $t\bar{t}$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 $\widetilde{t}$-pair production, in which a heavy chargino mediates the decay of the $\widetilde{t}$ into leptons and $\widetilde{\chi}_1^0$, namely $\widetilde{t} \to b\widetilde{\chi}_1^{\pm} \to bW^*\widetilde{\chi}_1^0$. The mass of the $\widetilde{\chi}_1^{\pm}$ is set to $(m_{\widetilde{t}} + m_{\widetilde{\chi}_1^0})/2$, and the mass difference between $\widetilde{t}$ 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 $\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^{\pm}$ ($\widetilde{t}$ 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

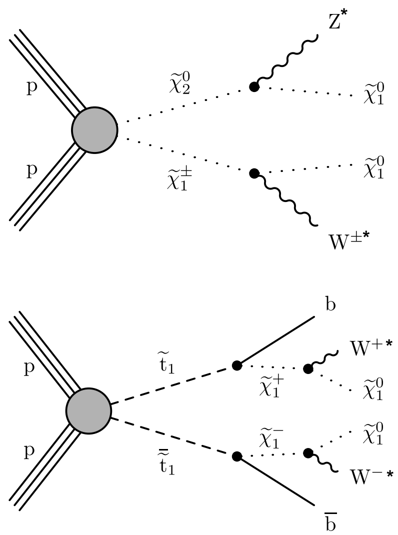

Fig. 1. Production and decay of an electroweakino pair (upper) and of a chargino-mediated $\widetilde{t}$ pair (lower).

models features associated $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^\pm$ production and as such corresponds to the same diagram as the one shown in Fig. 1 (upper). The second higgsino model considers associated $\widetilde{\chi}_2^0$-$\widetilde{\chi}_1^0$ production. In both cases, the mass of the chargino is given as $m_{\widetilde{\chi}_1^\pm} = (m_{\widetilde{\chi}_2^0} + m_{\widetilde{\chi}_1^0})/2$, and the $\widetilde{\chi}_2^0$ decays via an off-shell Z boson, and if applicable, the $\widetilde{\chi}_1^\pm$ decays via an off-shell W boson. The simplified models do not include any spin correlations in the decays. In the simplified higgsino model, this can lead to a different $M(\ell\ell)$ distribution that we do not account for.

In addition to the electroweakino models, we interpret the results in a phenomenological minimal supersymmetric model (pMSSM) [51], in which the higgsino (μ), bino (M_1), and wino (M_2) mass parameters are varied. There is only a small dependency on $\tan\beta$, which is set to 10. All other mass parameters are assumed to be decoupled. To reduce the parameter space to a two-dimensional grid, M_2 is set to $2M_1$. This convention is inspired by electroweakino mass unification at the grand unified theory scale. Since the focus is on electroweak production only, the gluino mass parameter M_3 is assumed to be decoupled. All trilinear couplings are discarded. In this model, the higgsino mass parameter μ is varied between 100 and 200 GeV, while M_1 varies between 300 GeV and 1 TeV. Events for this “higgsino pMSSM” are generated with MadGraph5_amc@nlo [52]. The NLO cross sections are computed using Prospino 2 [53]. Several additional packages [54–58] are used to calculate mass spectra and particle decays.

4. Object reconstruction

The analysis makes use of the particle-flow (PF) algorithm [59], which reconstructs and identifies each individual particle through an optimized combination of information from the various elements of the CMS detector. The difficulties in reconstructing the event of interest, because of the presence of the large average number of interactions per bunch crossing (pileup), are mitigated by a primary vertex selection and other methods described below. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [60,61] with the tracks assigned to the vertex as inputs, and the associated p_T^{miss}, taken as the negative vector p_T sum of those jets.

The leading and subleading muon (electron) are required to satisfy $p_T > 5$ GeV, $|\eta| < 2.4$ (2.5). A requirement of $p_T < 30$ GeV on the leptons is also applied; this threshold is identified as the p_T value below which the current analysis is more sensitive in the compressed regions compared to other CMS analyses. To increase the sensitivity in the compressed mass regime, the lower threshold on the p_T of the subleading muon is set to 3.5 GeV in the high-p_T^{miss} regions of the $\widetilde{t}$ search.

Muons are required to satisfy standard identification criteria [62], and to be isolated within a cone in η–ϕ space of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$: the p_T sum of other charged particle tracks within the cone, Iso_{abs}, is required to be less than 5 GeV. In addition, the quantity Iso_{rel}, which is the ratio of Iso_{abs} and the p_T of the muon, is required to be less than 0.5. Contamination from pileup within the isolation cone is subtracted using techniques that utilize charged particle deposits within the cone itself [62].

Electrons from prompt decays are selected using a multivariate discriminant based on the energy distribution in the shower and track quality variables. The loose working point employed by the $H \to ZZ^* \to 4\ell$ analysis [63] is used for $p_T < 10$ GeV, and a tighter one for $p_T > 10$ GeV. The same definition of isolation and the same isolation criteria are applied for electrons as used for muons.

To suppress nonprompt leptons, requirements on the three-dimensional impact parameter [64] relative to the primary vertex, IP_{3D}, and its significance, SIP_{3D}, are applied. Leptons are required to have $IP_{3D} < 0.01$ cm and $SIP_{3D} < 2$ standard deviations (s.d.).

The combined efficiency for reconstruction, selection and isolation depends on the p_T of the lepton. The efficiencies are in the range 70% (50%) for muons (electrons) at 5 GeV, up to 80% (60%) for muons (electrons) at 30 GeV.

Jets are clustered using the anti-k_T algorithm [60] with a distance parameter of 0.4 [65], as implemented in the FastJet package [61]. The momentum of a jet, which is determined by the vectorial sum of all particle momenta in the jet, is found from simulation to be within 5 to 10% of the true momentum over the full p_T spectrum and detector acceptance. An offset correction is applied to jet energies to take into account the contribution from pileup [66]. Jet energy corrections are obtained from simulation, and confirmed through in situ measurements of the energy balance in dijet and photon + jet events [67]. Jets are selected with $p_T > 25$ GeV and $|\eta| < 2.4$. In the following, the transverse hadronic energy, H_T, is defined as the scalar p_T sum of the selected jets.

Jets arising from the hadronization of b quarks are identified through the combined secondary vertex (CSV) tagger [68,69], which employs both secondary vertex and track-based information. In this analysis, a loose working point corresponding to a b tagging efficiency of about 80% is used with misidentification rates of 10% and 40% for light-quark or gluon jets and for c quark jets, respectively [68].

The $\vec{p}_T^{miss}$ is determined using the PF-reconstructed objects. A variety of event filters are applied to remove detector- and beam related noise [70].

5. Event selection

The analysis requires two oppositely charged leptons ($N_\ell = 2$), of either same (ee, $\mu\mu$) or different flavour (eμ), and moderate p_T^{miss} in the final state, together with at least one jet in the event.

The main backgrounds arise from events in which one of the leptons is not prompt (mainly from W + jets events), events from fully leptonic $t\bar{t}$ decays ($t\bar{t}(2\ell)$), and Drell–Yan (DY) processes with subsequent decays $\gamma/Z^* \to \tau\tau \to \ell\ell\nu_\ell\nu_\ell\nu_\tau\nu_\tau$. Smaller backgrounds are from tW production (tW) and the diboson processes

WW and ZZ*, with $Z^* \to \ell\ell$ and $Z \to \nu\nu$ (VV). Processes such as $t\bar{t}W$, $t\bar{t}Z$, WWW, ZZZ, WZZ and WWZ as well as processes including the Higgs boson have very small contributions, and are grouped together as "Rare". The following event selection shown in Table 1 includes a number of requirements designed to reduce these backgrounds:

- $0.6 < p_T^{miss}/H_T < 1.4$: this criterion is effective in rejecting SM events comprised uniquely of jets produced through the strong interaction, referred to as QCD multijet events, while remaining efficient for events with ISR, as in the case of the signal. The bounds on the ratio p_T^{miss}/H_T is determined from a study of a control region (CR) at low-p_T^{miss} and with dimuon mass close to that of the J/ψ meson. This requirement rejects such events while leaving the signal unaffected.
- b jet event veto: requiring events where no jet is tagged as originating from b quarks significantly reduces the $t\bar{t}$ background in which b jets originate from the decay of the top quarks. This requirement is applied to all jets with $p_T > 25$ GeV and uses the b tagging selection criteria described in Section 4. The efficiency for a potential signal from $\tilde{t}$ decays is not affected significantly since in the compressed $\tilde{t}$-LSP model, the b jets are expected to have small p_T and are therefore not tagged.
- $M(\tau\tau) < 0$ or $M(\tau\tau) > 160$ GeV: this requirement on the estimate of the ditau mass is designed to reject the large background from $Z \to \tau\tau$ decays, with the τ leptons decaying leptonically. The quantity $M(\tau\tau)$ [22] is computed as follows: since the τ leptons from the decay of a Z boson have large p_T compared to their mass, the direction of the outgoing lepton is approximately the same as that of the τ lepton (i.e. $\Delta R(\ell, \tau) \approx 0$). The magnitudes of the lepton momentum vectors are then rescaled so that the lepton pair balances the hadronic recoil. For $Z \to \tau\tau$ events, this leads to a fairly good approximation of the original τ momenta. The invariant mass of the two τ leptons, $M(\tau\tau)$, is estimated by the invariant mass of the two scaled leptons. In some events, the estimate of the magnitude of the τ momentum results in a negative value when the flight direction is opposite to the direction of the lepton. In such cases, $M(\tau\tau)$ is set to its negative value.
- $M_T(\ell_i, p_T^{miss}) < 70$ GeV, for $i = 1, 2$: the transverse mass M_T is defined as

$$M_T(\ell, p_T^{miss}) = \sqrt{2 p_T^{\ell} p_T^{miss} \left(1 - \cos\left[\Delta\phi\left(\ell, p_T^{miss}\right)\right]\right)},$$

  and ℓ_1 and ℓ_2 are the leading and subleading leptons, respectively. For the signal, the leading lepton is typically aligned with the boost direction of the LSP ($\Delta\phi(\ell, p_T^{miss}) \approx 0$). This requirement is effective in further suppressing the $t\bar{t}$ background for the electroweakino search, but not for the $\tilde{t}$ search. It is therefore only applied in the electroweakino search.
- J/ψ, and Υ veto: to suppress background contributions from J/ψ, low-mass γ^*, and Υ decays, the dilepton invariant mass $M(\ell\ell)$ is required to satisfy $M(\ell\ell) > 4$ GeV and to also lie outside the range $9 < M(\ell\ell) < 10.5$ GeV. This veto is only applied to same flavour lepton pairs.
- $p_T^{miss} > 125$ GeV: to ensure high trigger efficiency, both the p_T^{miss} and the muon corrected p_T^{miss}, which is computed from the vectorial sum of the p_T^{miss} and the p_T of the muons selected in the event, is required to be larger than 125 GeV. The region 125 GeV $< p_T^{miss} <$ 200 GeV is only accessible by the dimuon trigger and therefore only dimuon pairs are considered. The region $p_T^{miss} > 200$ GeV includes also electrons.
- Trigger acceptance: in the online selection, the lepton pair is required to have a small boost of $p_T > 3$ GeV, together with an upper bound on the dimuon invariant mass $M(\ell\ell) < 60$ GeV, to limit the trigger rate. To remain fully efficient after offline reconstruction, an upper bound of 50 GeV on $M(\ell\ell)$ and a lower requirement on the dilepton transverse momentum $p_T(\ell\ell) > 3$ GeV are imposed.
- $H_T > 100$ GeV: this requirement suppresses backgrounds with low hadronic activity in the event.

Table 1
Common selection requirements for the signal regions. The subleading lepton p_T threshold is reduced to 3.5 GeV for muons in the high-p_T^{miss}, $\tilde{t}$-like signal region.

Variable	SR selection criteria
N_ℓ	2 ($\mu\mu$, μe, ee)
$q(\ell_1)q(\ell_2)$	-1
$p_T(\ell_1)$, $p_T(\ell_2)$	[5, 30] GeV
$p_T(\mu_2)$ for high-p_T^{miss} $\tilde{t}$-like SR	[3.5, 30] GeV
$\|\eta_\mu\|$	<2.4
$\|\eta_e\|$	<2.5
IP_{3D}	<0.01 cm
SIP_{3D}	<2
$Iso_{rel}(\ell_{1,2})$	<0.5
$Iso_{abs}(\ell_{1,2})$	<5 GeV
p_T(jet)	>25 GeV
$\|\eta\|$(jet)	<2.4
N_b (p_T >25 GeV, CSV)	0
$M(\ell\ell)$	[4, 9] or [10.5, 50] GeV (for $\mu\mu$ and ee)
$p_T(\ell\ell)$	>3 GeV
p_T^{miss}	>125 GeV (for $\mu\mu$)
	>200 GeV (for μe, ee)
p_T^{miss} (muon corrected)	>125 GeV (for $\mu\mu$)
	>200 GeV (for μe, ee)
p_T^{miss}/H_T	[0.6, 1.4]
H_T	>100 GeV
$M(\tau\tau)$	veto [0, 160] GeV
$M_T(\ell_i, p_T^{miss})$, $i = 1, 2$	<70 GeV (electroweakino selection only)

For the selected events, a set of SRs are defined, based on the dilepton invariant mass and p_T^{miss}. For events with leptons of same flavour and opposite charge, four SRs are defined in $M(\ell\ell)$ ranges of 4–9, 10.5–20, 20–30, and 30–50 GeV. These SRs are intended for searches for $\tilde{\chi}_2^0 \to Z^*\tilde{\chi}_1^0$ events, where $M(\ell\ell)$ is related to the mass difference between the two electroweakinos. For events with leptons of different flavour and opposite charge, three SRs are defined in the leading lepton p_T ranges of 5–12, 12–20, and 20–30 GeV. The definition of the bins of the SRs can be found in Table 2.

To exploit the potential of the dimuon plus p_T^{miss} trigger, events are separated according to the value of p_T^{miss}: in total three ranges are used for the signal regions, namely $p_T^{miss} \in$ 125–200, 200–300, and >300 GeV for the $\tilde{t}$ search, and $p_T^{miss} \in$ 125–200, 200–250, and >250 GeV for the electroweakino search. Since the low-p_T^{miss} region contains events accessible only via the dimuon + p_T^{miss} trigger, only $\mu\mu$ pairs are considered. The muons need to be of opposite charge. Conversely, in the high-p_T^{miss} regions, both electron and muon flavours are considered. The electroweakino SRs are populated by ee and $\mu\mu$ pairs, where the leptons are oppositely charged. For the $\tilde{t}$ SRs, eμ pairs are also considered. For the latter, the p_T threshold on the trailing lepton is reduced to 3.5 GeV for muons in the high-p_T^{miss} region to gain sensitivity in the search for $\tilde{t}$ signal.

The acceptance times efficiency for the signal model TChi150/20 (T2tt350/330) in the electroweakino (stop) selection is between 3×10^{-5} (3×10^{-5}) and 7×10^{-5} (15×10^{-5}). The efficiency times acceptance for muons is about 2 to 5 times higher than for electrons in the electroweakino selection and about 1.5 to 3 times higher in the stop selection.

Table 2
Definition of bins in the two SRs. The lowest p_T^{miss} region includes only muon pairs, since it is only accessible by the dimuon trigger.

Electroweakino search region		$\tilde{t}$ search region	
p_T^{miss}[GeV]	$M(\ell\ell)$[GeV]	p_T^{miss}[GeV]	p_T^{lepton}[GeV]
[125, 200]	[4, 9] [10.5, 20] [20, 30] [30, 50]	[125, 200]	[5, 12] [12, 20] [20, 30]
[200, 250]	[4, 9] [10.5, 20] [20, 30] [30, 50]	[200, 300]	[5, 12] [12, 20] [20, 30]
>250	[4, 9] [10.5, 20] [20, 30] [30, 50]	>300	[5, 12] [12, 20] [20, 30]

Table 3
Summary of changes in selection criteria relative to Table 1 for CRs and the VV validation region (VR).

DY CR	$t\bar{t}$ (2ℓ) CR	VV VR
	No upper requirement on p_T (ℓ) $Iso_{rel} < 0.1$ as an or condition with the SR isolation	
$0 < M(\tau\tau) < 160$ GeV $IP_{3D} < 0.0175$ cm, $SIP_{3D} < 2.5$ s.d. $p_T(\ell_1) > 20$ GeV, or $IP_{3D} > 0.01$ cm, or $SIP_{3D} > 2$ s.d. M_T as for electroweakino SR	No requirements on M_T At least one b-tagged jet with $p_T > 40$ GeV	$p_T(\ell_1) > 20$ GeV |same flavour $M(\ell\ell) - M(Z)\| > 10$ GeV $M_T > 90$ GeV

6. Background estimation

Backgrounds with two prompt leptons are estimated using CRs chosen to be mostly free from signal but when possible, with similar kinematic characteristics as the events in the signal regions. Different CRs are employed for each SM process that contributes significantly to the signal region, i.e. the $t\bar{t}$ dilepton background and the DY + jets background. The normalization of the diboson background is cross checked in a validation region (VR).

For each background, the number of events in each SR is estimated using the number of events observed in the corresponding CR, and a transfer factor that is used to describe the expected ratio of events in the SR and CR for the process in question. The transfer factor for a specific process, F_{process}, is determined from Monte Carlo (MC) simulation of the process through the ratio

$$F_{\text{process}} = \frac{N^{\text{SR}}_{\text{MC process}}}{N^{\text{CR}}_{\text{MC process}}}.$$

Since a CR typically contains contributions from other physics processes, they need to be subtracted from the observed number of events in the CR, $N^{\text{CR}}_{\text{data}}$. These contributions, $N^{\text{CR}}_{\text{MC other}}$, are small compared to the main process for which the CR is defined, and are thus estimated using MC simulation. The estimate of the background from a specific physics process in the SR is then given by

$$N^{\text{SR}}_{\text{process}} = \left(N^{\text{CR}}_{\text{data}} - N^{\text{CR}}_{\text{MC other}}\right) F_{\text{process}}.$$

Systematic uncertainties in the value of F_{process} are included when determining the full uncertainty in $N^{\text{SR}}_{\text{process}}$. The total background in the SR is given as the sum of the backgrounds expected from each process.

The different CRs are split into two p_T^{miss} bins: The low p_T^{miss} bin with p_T^{miss} between 125 and 200 GeV is used to constrain the SRs with the same p_T^{miss} range, while the high p_T^{miss} bin with p_T^{miss} >200 GeV is used to constrain all SRs with p_T^{miss} above 200 GeV. The shapes for $M(\ell\ell)$ and the lepton p_T are taken directly from simulation. A summary of all CRs for prompt lepton backgrounds is given in Table 3. For the diboson background, a validation region enriched in VV (mainly WW events) is added. This region is used to establish how well the simulation agrees with data in order to validate the uncertainty assigned to the diboson simulation. About half of the events in this region stem from VV.

6.1. The DY + jets control region

The main difference between the CR for the DY + jets background and the SR lies in the requirement imposed on the $M_{\tau\tau}$ variable; the CR consists of events that are vetoed in the SR selection, namely those events with $M_{\tau\tau}$ in the range 0–160 GeV. To increase the efficiency for leptons from τ decays, the impact parameter requirements are relaxed to $IP_{3D} < 0.0175$ cm and $SIP_{3D} < 2.5$ s.d. The variation of the scale factors applied to simulation by changing the cuts on IP_{3D} and SIP_{3D} was found to be negligible. In addition, the 30 GeV upper bound on the lepton p_T is removed, and the region with lepton $p_T < 20$ GeV, $IP_{3D} < 0.01$ cm, and $SIP_{3D} < 2$ is also removed to reduce the presence of potential signal. The distributions in kinematic quantities of these events, including the variables used to define the signal regions, $M(\ell\ell)$ and the leading lepton p_T, are well described in simulation. The event yields estimated from simulation and the observed event yields are listed in Table 4.

6.2. The $t\bar{t}$ (2ℓ) control region

To obtain a sample enriched in $t\bar{t}$ events, at least one jet is required to be identified as originating from b quarks. To reduce potential signal contamination, the leading b-tagged jet is required to satisfy $p_T > 40$ GeV. To increase the number of events in the CR, while still avoiding potentially large signal contamination, the upper bound on the lepton p_T is also removed. The event yields estimated from simulation and the observed event yields are also shown in Table 4.

Table 4
Data and simulation yields for the DY and $t\bar{t}$ (2ℓ) CRs, corresponding to integrated luminosities of 35.9 fb^{-1} (high-p_T^{miss} region) and 33.2 fb^{-1} (low-p_T^{miss} region). The SR scale factors are derived by subtracting the other processes from the observed data count, and dividing this number by the expected event yields from simulation for the process in question. The uncertainties are statistical only.

p_T^{miss}	DY CR		$t\bar{t}$ (2ℓ) CR	
	125–200 GeV	>200 GeV	125–200 GeV	>200 GeV
DY + jets or $t\bar{t}$	70.1 ± 5.1	64.5 ± 3.3	1053.7 ± 9.4	535.7 ± 7.1
All SM processes	82.6 ± 5.5	75.2 ± 3.6	1170.0 ± 11.0	710.4 ± 11.1
Data	84	75	1157	680
SR scale factor	1.02 ± 0.13	0.99 ± 0.13	0.99 ± 0.03	0.94 ± 0.05

6.3. Nonprompt background

The background from nonprompt or misidentified leptons is evaluated using a "tight-to-loose" method. Events where at least one lepton fails the tight identification and isolation criteria but passes a looser selection define the "application region". Events in this region are weighted by a transfer factor based on the probability that nonprompt leptons passing the loose requirements also satisfy the tight ones. The resulting estimate is corrected for the presence of prompt leptons in the application region.

The probability for nonprompt or misidentified leptons to pass the tight selection criteria is referred to as the misidentification probability, which is determined as a function of lepton p_T and η. This probability is measured using a dedicated data sample, the "measurement region" (MR), which is enriched in the background from SM events containing only jets produced via strong interaction, referred to as QCD multijet events. This method has been used in several multilepton analyses at CMS and is described in more detail in Ref. [71]. The MR is defined through the presence of one loose lepton, obtained by relaxing the isolation and impact parameter requirements, and through a jet with $p_T > 30$ GeV, separated from the lepton by $\Delta R > 0.7$. For muons, events are selected through prescaled single-lepton triggers with no isolation requirements. For electrons, a mixture of prescaled jet triggers is used. The method includes a correction for the presence of prompt leptons in the MR, mostly due to W and Z boson production in association with jets. The probability for prompt leptons to pass the tight selection criteria is taken from simulation and is corrected with a data-to-simulation scale factor extracted from data enriched in $Z \to \ell\ell$ decays.

In this analysis, the misidentification probability measured in QCD multijet events is applied to loosely identified leptons in events that are dominated by W + jets and $t\bar{t}$ production. The latter can have both a different composition in terms of the flavour of the jets that give rise to the nonprompt leptons, as well as different kinematic properties, potentially resulting in a different effective misidentification probability. These effects are studied by comparing the misidentification probabilities measured in simulated events of these two processes in the kinematic regions probed by this analysis. A closure test is then performed by applying the misidentification probability measured in the QCD simulated multijet events to a sample of W + jets events. The yield of events passing the tight identification criteria is compared with the estimate obtained by applying the misidentification probability to events in the application region. The method is found to be consistent within a level of <40%; this value is used as a systematic uncertainty in the estimate of the normalization of the reducible background.

To further constrain the contribution of the nonprompt lepton background in the SR, a dedicated CR consisting of same-sign (SS) leptons is defined. Requiring the two lepton candidates to have the same sign increases significantly the probability that at least one of the two is a nonprompt or misidentified lepton. The SS CR is defined using the $\tilde{t}$ selection in the $p_T^{miss} > 200$ GeV region, where

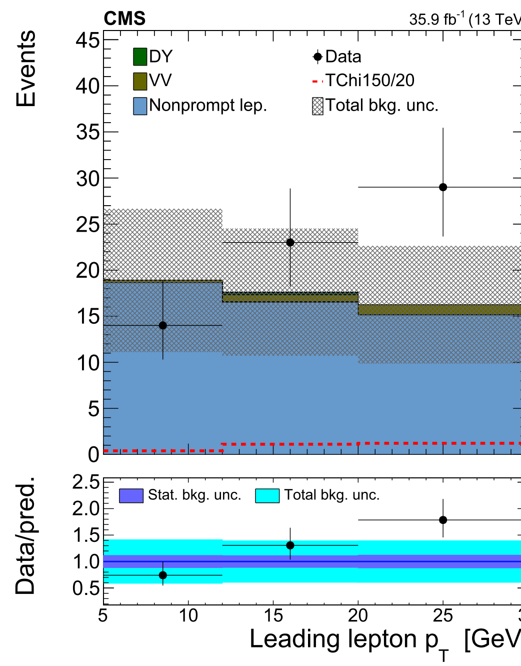

Fig. 2. Same-sign CR for $\tilde{t}$ selection and $p_T^{miss} > 200$ GeV. The distribution of the leading lepton p_T is used as input to the final signal extraction. A signal from neutralino–chargino ($\tilde{\chi}_2^0$–$\tilde{\chi}_1^{\pm}$) production is superimposed.

the opposite charge requirement of the two leptons is modified to same-sign. In the SS CR, the prediction of the nonprompt lepton background is derived from the "tight-to-loose" method and agrees with the data. Fig. 2 shows the leading lepton p_T distribution in the SS CR. It also shows the near absence of a signal. The distribution of the leading lepton p_T is used as input to the final fit that performs the signal extraction, as its constraining power is significant, given the significant uncertainty on the measured misidentification probability.

7. Systematic uncertainties

This section summarizes the systematic uncertainties in the estimate of the background from the various SM processes. For each source of systematic uncertainty, we present both the effect on the corresponding specific background and the overall effect on the total background predictions are listed in Table 5.

The uncertainty in the predicted nonprompt lepton background contains a statistical component due to the statistical uncertainty in the application region event yield, it ranges from 10% to 50%. When applied in the SR, the uncertainty is 4% to 20%. Another source of statistical uncertainty arises from limited statistics in data and simulation in the DY + jets and $t\bar{t}$ (2ℓ) CRs. The effect on the predicted yields in the SR, obtained using the transfer factor described in Section 6, is approximately 13% for the DY + jets background and 3% for the $t\bar{t}$ background.

Table 5
Relative uncertainties in the final total background predictions for each individual systematic source of uncertainty.

Systematic source of uncertainty	Typical uncertainty (%)
VV background normalization	3–25
Nonprompt lepton background normalization	4–20
DY + jets background normalization	4–20
$t\bar{t}$ background normalization	2–8
Rare background normalization	1–3
Jet energy scale	2–12
b tagging	2–6
Pileup	1–5
Lepton selection	1–4
Integrated luminosity	2.5
Trigger	1–2
$t\bar{t}$ modelling	<1

For the $t\bar{t}$ background, we have considered a set of systematic uncertainties arising from the modelling of the kinematic distributions in the simulation of this process. The spin correlation of the top quarks has been varied by 20%, based on the ATLAS and CMS [72,73] measurements and a comparison between different generators (MadGraph5_amc@nlo versus powheg). The helicity amplitudes of the W boson in top quark decays have been varied by 5%. A top quark p_T modelling uncertainty has also been derived by reweighting the simulated $t\bar{t}$ events based on the number of ISR jets ($N_{\text{jets}}^{\text{ISR}}$), so as to make the jet multiplicity agree with data. The reweighting factors range from 0.92 to 0.51 for $N_{\text{jets}}^{\text{ISR}}$ between 1 and 6. The systematic uncertainty in these reweighting factors is taken to be equal to one half of the deviation of the factor from unity. The combined effect of this set of $t\bar{t}$ modelling uncertainties on the total number of predicted $t\bar{t}$ background events is found to be in the range 3–5%.

For the DY + jets background, the uncertainty in the resolution of the p_T of the system recoiling against the two leptons is obtained from data dominated by $Z \to \mu\mu$ events. The uncertainty affects the DY estimate, which uses the efficiency of the requirements on $M_{\tau\tau}$ from simulation. The effect on the estimated yields of DY + jets is found to be negligible (<1%).

As presented in Section 6, the method used to estimate the background from nonprompt and misidentified leptons leads to a 40% uncertainty on the normalization. In the global fit this uncertainty is reduced to 25%.

A 50% uncertainty is assigned for the diboson background normalization, which is checked in the dedicated region described in Section 6. In this region, which is enriched in W W events with similar kinematic properties as the events in the SR, the simulation is found to agree, within the given uncertainty, with the data.

A conservative 100% uncertainty is assigned to the very small rare backgrounds that are dominated by the tW process.

The experimental uncertainties related to b tagging, trigger, lepton reconstruction, identification, and isolation criteria have been propagated and their effect on the final results ranges from 2% up to 12%. The jet energy scale corrections (JEC) are applied to match jet energies measured in data and simulation. The JEC are affected by an intrinsic uncertainty, which affects all simulated background, leading to typically 2–12% uncertainties in the final predictions.

An uncertainty of 2.5% is assigned to the integrated luminosity measured by CMS for the 2016 data taking period [74]. This affects the estimate of the rare SM backgrounds that rely on the measured data luminosity.

Finally, the uncertainty related to pileup has been estimated by varying the minimum-bias cross section by ±5% and reweighting the pileup distribution accordingly. The systematic uncertainty is found to be in the range 1–5%.

As the signal yields are from simulation, additional systematic uncertainties are applied in two categories. One arises from the systematic uncertainty in the inclusive NLO + NLL [48–50] cross section used for the normalization, determined by varying the renormalization and factorization scales and the PDF. The dependence on these QCD scales yields a total uncertainty of 3%. The other category arises from the uncertainty in the product of the signal acceptance and efficiency.

It is important to properly model the ISR that leads to the boost of the produced SUSY particles in the transverse plane. In particular, for the electroweakino benchmark, the modelling of the ISR with MadGraph5_amc@nlo affects the total transverse momentum p_T^{ISR} of the system of SUSY particles, which can be improved by reweighting p_T^{ISR} in the simulated signal events. This reweighting is based on p_T studies of events containing a Z boson [75], in which the factors range between 1.18 at p_T^{ISR} of 125 GeV, and 0.78 for $p_T^{\text{ISR}} > 600$ GeV. The deviation from 1.0 is taken as the systematic uncertainty of the reweighting procedure. For the $\widetilde{t}$ benchmark to improve the modelling of the multiplicity of additional jets from ISR, the events are reweighted based on the $N_{\text{jets}}^{\text{ISR}}$, using the same corrections used for the top background as described earlier in this section. The typical uncertainties on the final results from the ISR modelling are found to be in the range 2–7%.

We account for differences observed in p_T^{miss} reconstruction effects in full and fast simulation used for signal. The uncertainties vary between 3 and 5%. The uncertainties related to potential differences in b tagging between the full and fast simulation and in the JEC vary in the range 1–2%.

These uncertainties, together with those related to the predicted backgrounds described in Section 6, are included as log-normal distributed nuisance parameters in the likelihood approach.

8. Results

The estimated yields of the SM background processes and the data observed in the SRs are shown in Figs. 3 and 4. No significant excess has been observed. The estimates in the SR bins are extracted from a maximum likelihood fit of the data using the expected yields described in Section 6, namely the DY + jets, $t\bar{t}$ (2ℓ), and SS CRs. Log-normal distributions for nuisance parameters are used to describe the systematic uncertainties of Section 7. The uncertainties in the predicted yields quoted in the following are those determined from the fit.

The predicted yields along with the data are also summarized in Tables 6 and 7 for each bin of the SR.The total uncertainty in the yield for each SM process includes the systematic and statistical uncertainties described in Section 7, added in quadrature. The largest deviation from the SM expectation is seen in a bin of the electroweakino search region. The bin with $p_T^{\text{miss}} \in [200, 250]$ GeV and $M(\ell\ell) \in [10.5, 20]$ GeV has 3.5 ± 0.9 expected events but 0 observed. The smaller number of events observed in this bin drives the observed exclusion to higher values than expected, as can be seen in the next section. Overall, there is good agreement between expectation and observation.

9. Interpretation

The results are interpreted in terms of the simplified models with compressed mass spectra for $\widetilde{\chi}_2^0\widetilde{\chi}_1^\pm \to Z^*W^{\pm *}\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ and for $\widetilde{t}\widetilde{t} \to b\widetilde{\chi}_1^\pm b\widetilde{\chi}_1^\mp$ with the subsequent decay $\widetilde{\chi}_1^\pm \to W^{\pm *}\widetilde{\chi}_1^0$ as discussed in Section 3. A binned likelihood fit of signal and the background expectations to the data is performed. This fit takes as input the yields in the SRs (12 for the electroweakino interpretation and 9 for the top squark interpretation), together with those

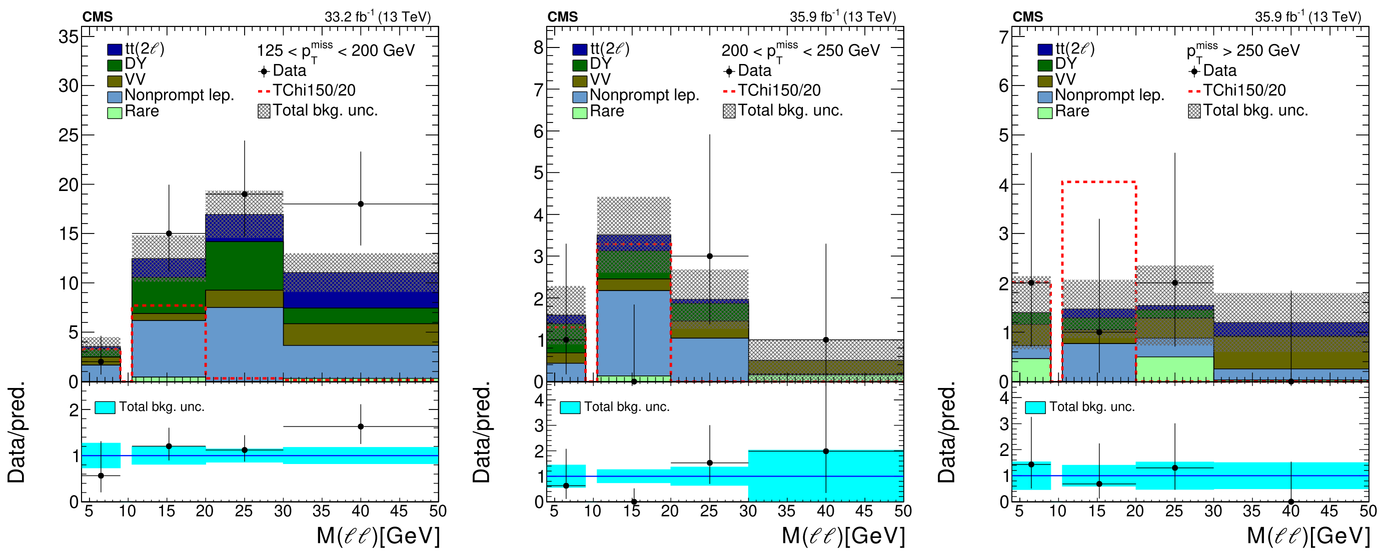

Fig. 3. Left: electroweakino search regions in bins of $M(\ell\ell)$ for $125 < p_T^{miss} < 200$ GeV (muon only channel) for 33.2 fb^{-1}; middle: $200 < p_T^{miss} < 250$ GeV (muon and electron channel) for 35.9 fb^{-1}; right: $p_T^{miss} > 250$ GeV (muon and electron channel) for 35.9 fb^{-1}. A signal from neutralino–chargino ($\widetilde{\chi}_2^0$–$\widetilde{\chi}_1^{\pm}$) production is superimposed. The gap between 9 and 10.5 GeV corresponds to the Υ veto.

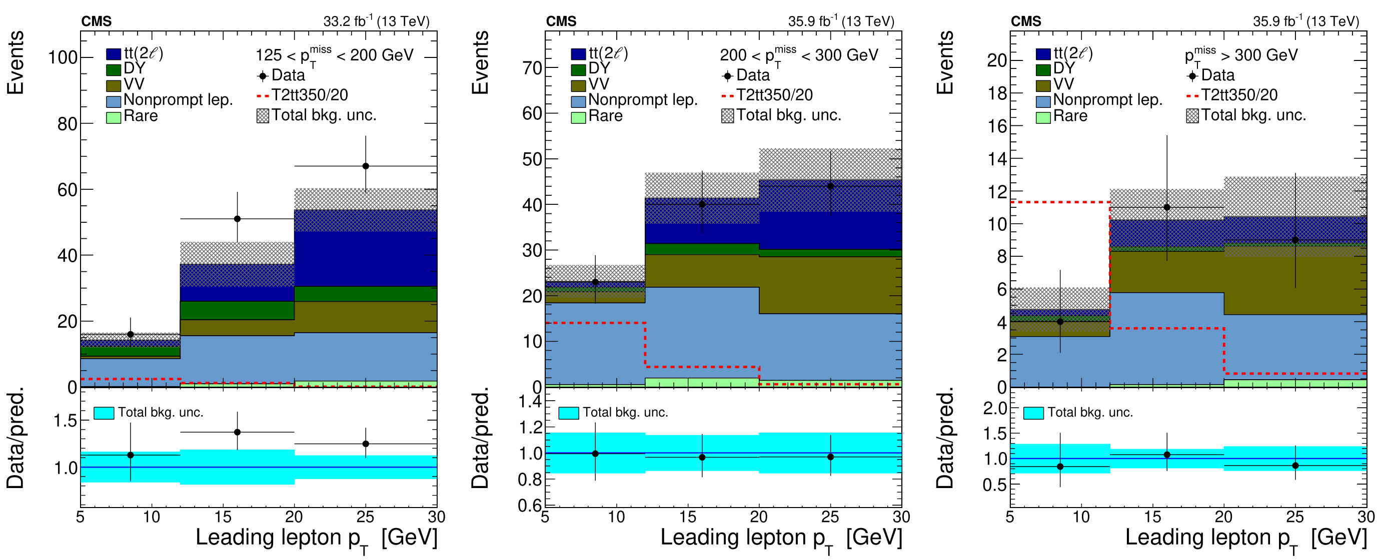

Fig. 4. Left: $\widetilde{t}$ search regions in bins of leading lepton p_T for $125 < p_T^{miss} < 200$ GeV (muon only channel) for 33.2 fb^{-1}; middle: $200 < p_T^{miss} < 300$ GeV (muon and electron channel) for 35.9 fb^{-1}; right: $p_T^{miss} > 300$ GeV (muon and electron channel) for 35.9 fb^{-1}. A signal from $\widetilde{t}$ pair production is superimposed.

in the two CRs ($125 < p_T^{miss} < 200$ GeV and $p_T^{miss} > 200$ GeV) for the $t\bar{t}$ and DY + jets estimates, and the three p_T bins for same-sign leptons for the $p_T^{miss} > 200$ GeV CR. These background-dominated bins also help to constrain the uncertainties in the background taken from simulation and the one predicted by the “tight-to-loose” method.

Upper limits on the cross sections in the benchmark models at 95% confidence level (CL) are extracted. We use asymptotic formulae [76] to derive the results. To set limits, the CL$_s$ criterion, as described in [77,78], is used. Figures 5 and 6 show the observed and expected upper limits on the electroweakino and $\widetilde{t}$ pair production cross sections for the benchmarks considered in this search.

For the electroweakino simplified model, the production cross sections are computed at NLO + NLL precision in the limit of a mass degenerate wino $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^{\pm}$, a light bino $\widetilde{\chi}_1^0$, and assuming all other SUSY particles to be heavy and decoupled [48–50]. Masses of $\widetilde{\chi}_2^0$ up to 230 GeV for a $\Delta m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0)$ of 20 GeV are excluded. The existence of $\widetilde{t}$ masses up to 450 GeV with a $\Delta m(\widetilde{t}, \widetilde{\chi}_1^0)$ of 40 GeV is ruled out for this specific model.

The expected and observed exclusion contours for the higgsino pMSSM are shown in Fig. 7. The higgsino mass parameter μ is excluded up to 160 GeV, when the bino mass parameter M_1 is 300 GeV and the wino mass parameter M_2 is 600 GeV. For larger values of M_1 and M_2, the mass splitting $\Delta m(\widetilde{\chi}_2^0, \widetilde{\chi}_1^0)$ becomes smaller and the sensitivity is reduced. For $M_1 = 700$ GeV, μ is excluded up to 100 GeV.

Fig. 8 shows the expected and observed exclusion contours and upper limits on cross sections at 95% CL in a higgsino simplified model. To calculate the cross sections in this model, a scan in $|\mu|$, M_1, M_2 and $\tan\beta$ is carried out. All parameters are required to be real, M_2 to be positive and $\tan\beta \in [1, 100]$. The remaining SUSY particle masses are decoupled, and all trilinear couplings are discarded. The parameter space is then scanned to achieve the

Table 6
The number of events observed in the data and the result of the fit of the backgrounds to the data in the electroweakino search regions. The uncertainty indicated is determined from the fit to the 33.2 and 35.9 fb^{-1} integrated luminosities. Values for the $M(\ell\ell)$ ranges are in GeV. Rare background event yields are omitted when they do not contribute to the SR bin.

	$125 < p_T^{miss} < 200$ GeV			
	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$t\bar{t}(2\ell)$	0.23 ± 0.16	1.9 ± 0.52	2.80 ± 0.65	3.60 ± 0.75
DY + jets	0.83 ± 0.63	3.7 ± 1.5	4.9 ± 1.5	1.60 ± 0.99
VV	0.82 ± 0.48	0.71 ± 0.65	1.7 ± 1.0	2.2 ± 1.2
Nonprompt lepton	1.7 ± 0.7	5.7 ± 1.5	7.5 ± 1.7	3.3 ± 1.1
Rare	–	$0.46^{+0.64}_{-0.45}$	–	$0.33^{+0.49}_{-0.32}$
Total SM prediction	3.5 ± 1.0	12.0 ± 2.3	17.0 ± 2.4	11.0 ± 2.0
Data	2	15	19	18
	$200 < p_T^{miss} < 250$ GeV			
	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$t\bar{t}(2\ell)$	0.21 ± 0.17	0.38 ± 0.18	$0.11^{+0.11}_{-0.10}$	–
DY + jets	0.69 ± 0.62	0.67 ± 0.32	0.42 ± 0.27	–
VV	$0.26^{+0.28}_{-0.25}$	$0.29^{+0.32}_{-0.28}$	0.42 ± 0.33	0.33 ± 0.29
Nonprompt lepton	0.44 ± 0.32	2.0 ± 0.7	1.0 ± 0.6	$0.03^{+0.14}_{-0.02}$
Rare	–	$0.14^{+0.39}_{-0.13}$	–	$0.17^{+0.37}_{-0.16}$
Total SM prediction	1.6 ± 0.7	3.5 ± 0.9	2.0 ± 0.7	$0.51^{+0.52}_{-0.50}$
Data	1	0	3	1
	$p_T^{miss} > 250$ GeV			
	$4 < M(\ell\ell) < 9$	$10.5 < M(\ell\ell) < 20$	$20 < M(\ell\ell) < 30$	$30 < M(\ell\ell) < 50$
$t\bar{t}(2\ell)$	–	0.19 ± 0.14	0.091 ± 0.091	0.27 ± 0.14
DY + jets	0.24 ± 0.19	0.24 ± 0.17	0.17 ± 0.16	$0.014^{+0.019}_{-0.013}$
VV	0.43 ± 0.35	$0.29^{+0.29}_{-0.28}$	0.41 ± 0.29	0.66 ± 0.45
Nonprompt lepton	$0.28^{+0.33}_{-0.27}$	0.77 ± 0.44	0.38 ± 0.30	0.23 ± 0.18
Rare	$0.45^{+0.57}_{-0.44}$	–	$0.49^{+0.62}_{-0.48}$	$0.04^{+0.28}_{-0.03}$
Total SM prediction	1.4 ± 0.7	1.5 ± 0.6	1.5 ± 0.8	1.2 ± 0.6
Data	2	1	2	0

Table 7
The number of events observed in the data and the result of the fit of the backgrounds to the data in the $\tilde{t}$ search regions. The uncertainty indicated is determined from the fit to the 33.2 and 35.9 fb^{-1} integrated luminosities. Values for the $p_T(\ell_1)$ ranges are in GeV. Rare background event yields are omitted when they do not contribute to the SR bin.

	$125 < p_T^{miss} < 200$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	1.9 ± 0.4	11.0 ± 1.9	23.0 ± 3.5
DY + jets	2.9 ± 1.4	5.6 ± 1.9	4.6 ± 1.7
VV	0.8 ± 0.7	$4.9^{+6.3}_{-4.8}$	9.4 ± 5.4
Nonprompt lepton	8.5 ± 1.9	15.0 ± 2.6	15.0 ± 2.6
Rare	$0.10^{+0.16}_{-0.09}$	$0.93^{+1.0}_{-0.92}$	1.8 ± 1.7
Total SM prediction	14.0 ± 2.3	37.0 ± 6.8	54.0 ± 6.5
Data	16	51	67
	$200 < p_T^{miss} < 300$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	1.3 ± 0.35	9.9 ± 1.2	15 ± 2.2
DY + jets	0.92 ± 0.83	2.4 ± 0.9	1.6 ± 0.6
VV	2.5 ± 1.4	7.1 ± 4.0	12.0 ± 6.2
Nonprompt lepton	18.0 ± 3.2	20.0 ± 3.4	15.0 ± 2.7
Rare	$0.52^{+0.54}_{-0.51}$	1.96 ± 1.46	1.45 ± 1.13
Total SM prediction	23.0 ± 3.5	41.0 ± 5.6	45.0 ± 7.0
Data	23	40	44
	$p_T^{miss} > 300$ GeV		
	$5 < p_T(\ell_1) < 12$	$12 < p_T(\ell_1) < 20$	$20 < p_T(\ell_1) < 30$
$t\bar{t}(2\ell)$	0.39 ± 0.25	1.6 ± 0.5	1.6 ± 0.4
DY + jets	0.33 ± 0.26	0.28 ± 0.18	0.19 ± 0.07
VV	0.93 ± 0.53	2.5 ± 1.4	4.2 ± 2.2
Nonprompt lepton	3.1 ± 1.1	5.6 ± 1.3	4.0 ± 1.3
Rare	–	$0.15^{+0.18}_{-0.14}$	$0.45^{+0.50}_{-0.44}$
Total SM prediction	4.7 ± 1.3	10.0 ± 1.9	10.0 ± 2.5
Data	4	11	9

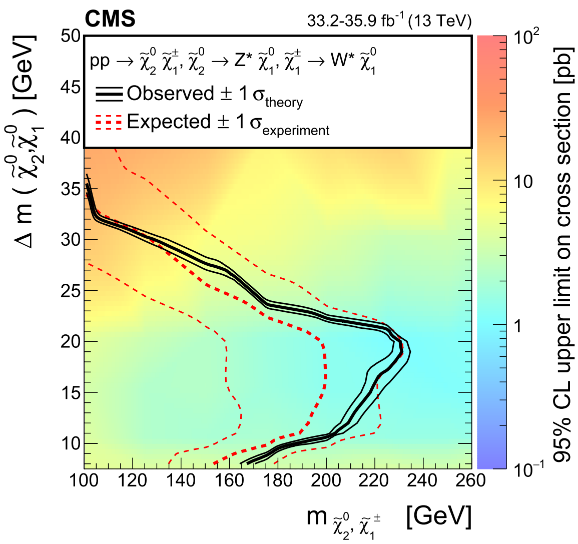

Fig. 5. The observed 95% CL exclusion contours (black curves) assuming the NLO + NLL cross sections, with the variations corresponding to the uncertainty in the cross section for electroweakino. The dashed (red) curves present the 95% CL expected limits with the band covering 68% of the limits in the absence of signal. Results are based on a simplified model of $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to Z^*W^*\tilde{\chi}_1^0\tilde{\chi}_1^0$ process with a pure wino production cross section. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

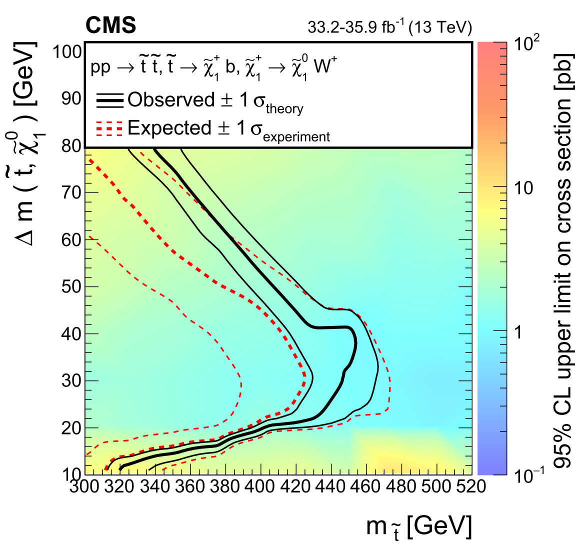

Fig. 6. The observed 95% CL exclusion contours (black curves) assuming the NLO + NLL cross sections, with the variations corresponding to the uncertainty in the cross section for $\tilde{t}$. The dashed (red) curves present the 95% CL expected limits with the band covering 68% of the limits in the absence of signal. A simplified model of the $\tilde{t}$ pair production, followed by the $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ and the subsequent $\tilde{\chi}_1^{\pm} \to W^*\tilde{\chi}_1^0$ decay is used for the $\tilde{t}$ search. In this latter model, the mass of the $\tilde{\chi}_1^{\pm}$ is set to be $(m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$.

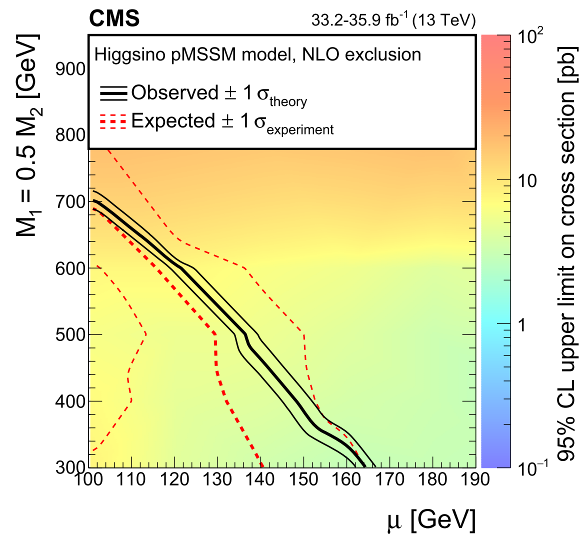

Fig. 7. The observed 95% CL exclusion contours (black curve) assuming the NLO cross sections, with the variations corresponding to the uncertainty in the cross sections for the higgsino pMSSM, which has been introduced in the text. The dashed (red) curves present the band covering 68% of the limits in the absence of signal. The model considers all possible production processes.

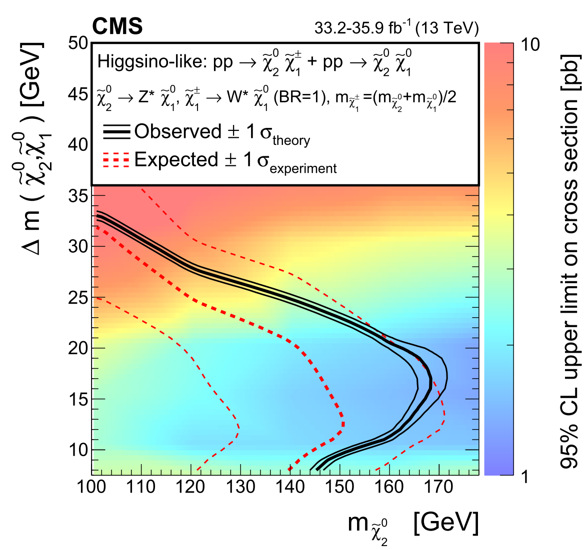

Fig. 8. The observed 95% CL exclusion contours (black curves) assuming the NLO + NLL cross sections, with the variations corresponding to the uncertainty in the cross sections for the higgsino simplified models. The dashed (red) curves present the expected limits with the associated band covering 68% of the limits in the absence of signal.

maximum higgsino content for $\tilde{\chi}_2^0$, $\tilde{\chi}_1^{\pm}$, and $\tilde{\chi}_1^0$ [79]. For a Δm between 15 and 20 GeV, the production model of $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^{\pm}$ and $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^0$ is excluded for masses up to $\tilde{\chi}_2^0 \sim 167$ GeV.

10. Summary

A search is presented for new physics in events with two low-momentum leptons of opposite charge and missing transverse momentum in data collected by the CMS experiment at a centre-of-mass energy of 13 TeV, corresponding to an integrated luminosity of up to 35.9 fb^{-1}. The data are found to be consistent with standard model expectations. The results are interpreted in the framework of supersymmetric simplified models targeting electroweakino mass-degenerate spectra and $\tilde{t}$-$\tilde{\chi}_1^0$ mass-degenerate benchmark models. For the $\tilde{t}$ chargino-mediated decay into $bW^*\tilde{\chi}_1^0$, top squark masses of up to 450 GeV are excluded in a simplified model for $\Delta m(\tilde{t}, \tilde{\chi}_1^0) = 40$ GeV. The search further probes the $\tilde{\chi}_2^0\tilde{\chi}_1^{\pm} \to Z^*W^*\tilde{\chi}_1^0\tilde{\chi}_1^0$ process for mass differences (Δm) between $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ of less than 20 GeV. Assuming wino production cross sections, $\tilde{\chi}_2^0$ masses up to 230 GeV are excluded for Δm of 20 GeV. The search is also sensitive to higgsino production; in a simplified higgsino model, $\tilde{\chi}_2^0$ masses up to 167 GeV are excluded for Δm of 15 GeV, while in a higgsino pMSSM, limits in the higgsino-bino mass parameters μ–M_1 plane are extracted.

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