

Search for Z' bosons decaying into charginos in final states with two oppositely charged leptons and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract

Massive leptophobic Z' bosons decaying to a pair of charginos are searched for in proton-proton collisions at $\sqrt{s} = 13$ TeV, using data samples collected by the CMS experiment in 2016, 2017, and 2018, corresponding to a total integrated luminosity of 138 fb^{-1} . The Z' bosons originate from an additional $U(1)'$ gauge symmetry extended to the minimal supersymmetric standard model. The final state consists of two oppositely charged leptons and missing transverse momentum. The signal extraction is performed with a parametrized neural network. The measurements are found to be consistent with the standard model expectations. Upper limits are set on the Z' boson production cross sections as a function of the Z' and chargino masses. The analysis excludes Z' boson masses up to about 3.5 TeV for the specific case of Z' bosons decaying exclusively to charginos, with the charginos decaying to W bosons and neutralinos.

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1 Introduction

Searches for a heavy neutral gauge boson Z' have been performed by the ATLAS and CMS Collaborations since the beginning of data taking at the CERN LHC. These searches primarily focused on direct resonance decays into standard model (SM) particles: lepton pairs, jet pairs, and dibosons [1–5]. The most stringent limits so far have been set by the dilepton searches, the other channels imposing relatively mild constraints.

There are well-motivated theoretical frameworks beyond the SM (BSM), also consistent with the current experimental constraints, suggesting scenarios where resonances decay into new particles. One example is the $U(1)'$ -extended minimal supersymmetric SM (UMSSM) scenario [6–9], derived from embedding the minimal supersymmetric SM (MSSM) [10] in the unified gauge group E_6 . This scenario offers several advantages: a scalar singlet introduced in the model can induce both supersymmetry (SUSY) [10] breaking and the dynamical generation of the μ parameter [9], which would otherwise be introduced unnaturally at the electroweak scale in the MSSM. It also forbids rapid proton decay, without the need to introduce an ad hoc discrete R -parity symmetry.

The $U(1)'$ extension leads to an extra gauge boson, the Z' . In certain charge scenarios, this leads to leptophobic Z' bosons, suppressing the decays of the Z' boson to leptons [9, 11, 12] and circumventing the stringent experimental constraints set by dilepton resonance searches. Instead, the Z' boson decays are dominated by other channels, including decays to SM final states with quark pairs, boson pairs (such as W^+W^- or HZ), neutrino pairs, or SUSY final states with chargino or neutralino pairs, where charginos (neutralinos) are the mass eigenstates of the charged (neutral) superpartners of the SM gauge and Higgs bosons.

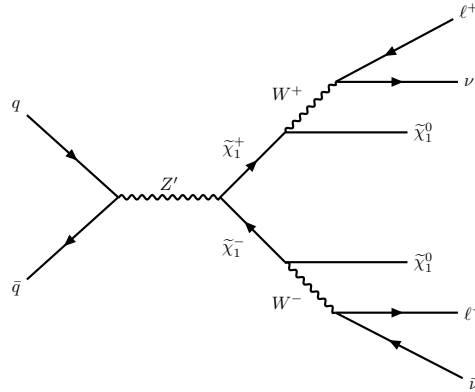


Figure 1: Diagram showing the signal process studied in this analysis: a leptophobic Z' boson decaying into two charginos, each subsequently decaying into a lepton, a neutrino, and a neutralino.

This paper reports a search for leptophobic Z' bosons that decay into two charginos, $\tilde{\chi}_1^\pm$, each of them decaying into a W boson and the lightest neutralino, $\tilde{\chi}_1^0$ (the lightest supersymmetric particle, which is a dark matter candidate and is stable under R -parity conservation, given the $U(1)'$ gauge structure of the UMSSM scenario), with the W bosons decaying leptonically. This process, illustrated in Fig. 1, leads to a distinct signature with two oppositely charged high-momentum leptons (e^+e^- , $\mu^+\mu^-$, or $e^\pm\mu^\mp$) and high missing transverse momentum (p_T^{miss}). Previously reported searches have not addressed this specific scenario. For example, the Z' boson searches in the dilepton channel described in Refs. [1, 2] have neither applied an explicit requirement on p_T^{miss} nor considered the kinematic properties imposed by the intermediate charginos. Moreover, direct chargino pair production searches, such as those reported in

Refs. [13, 14], have not explored the kinematic properties imposed by the assumption that they are produced in the decay of a heavy particle.

The leptophobic Z' boson production cross section is similar to that of the Z' bosons predicted in other models, such as the sequential SM or those from non-supersymmetric E_6 gauge groups [1–4]. In the full UMSSM scenario, including the complete SUSY particle content with their predicted properties, the branching fractions of the Z' boson decay into charginos and of the subsequent decays of the charginos into leptonically decaying W bosons are both of the order of a few percent [9, 11]. In order to extract such small signal from the dominant SM backgrounds, the analysis employs a multivariate analysis approach.

2 The CMS apparatus and event samples

The CMS apparatus is a multipurpose detector [15] designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons [16–18]. A superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a 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 coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors (drift tubes, cathode strip chambers, and resistive plate chambers) embedded in the steel flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of 100 kHz within a fixed latency of 4 μ s [19]. The second level, consisting of a farm of processors running a faster version of the full event reconstruction software, reduces the rate to around 1 kHz, before data storage [20, 21]. 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 Refs. [15, 22].

The proton-proton (pp) event samples used in the analysis were collected at a center-of-mass energy of 13 TeV in 2016, 2017, and 2018, with integrated luminosities of 36.3, 41.5, and 59.8 fb^{-1} , respectively [23–25], leading to a total integrated luminosity of 138 fb^{-1} .

The analysis also relies on Monte Carlo (MC) simulated event samples, to evaluate the SM backgrounds and extract the signal yields. The signal events are generated for the exclusive process $pp \rightarrow Z' \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ \tilde{\chi}_1^0 W^- \tilde{\chi}_1^0 \rightarrow \ell^+ \nu \tilde{\chi}_1^0 \ell^- \nu \tilde{\chi}_1^0$. The hard process is generated at leading order (LO) precision using the MADGRAPH5_aMC@NLO v2.6.5 generator [26], with the NNPDF3.1 LO parton distribution functions (PDFs) [27] and assuming the strong coupling constant $\alpha_S(m_Z) = 0.13$, where m_Z is the mass of the Z boson. The masses of the Z' boson and of the chargino are scanned, respectively, from 1.7 to 4.1 TeV in steps of 400 GeV and from 345 to 1845 GeV in steps of 250 GeV. The neutralino mass is taken to be half of the chargino mass, which arises from the assumption of gaugino mass unification at the grand unified theory (GUT) scale [10, 28]. The events are generated in a theoretical framework that assumes a negligible Z' boson width. The effective cross sections are calculated by setting the $Z' \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ \tilde{\chi}_1^0 W^- \tilde{\chi}_1^0$ branching fraction to 100%.

The POWHEG v2 [29–32] event generator is used to simulate, at next-to-leading order (NLO) precision in perturbative quantum chromodynamics (QCD), the following SM background processes: $t\bar{t}$ pair production; single top quark production in association with a W boson, and W plus Z boson pair production. The MADGRAPH5_aMC@NLO event generator is used to simulate, at NLO precision, these other SM background processes: Drell–Yan (DY), WZ , $t\bar{t}W$, $t\bar{t}Z$,

WWW, and WWZ. For the SM backgrounds, the NNPDF3.1 NNLO PDF sets are used [27].

To model the fragmentation and parton showering processes, the generated events are processed through PYTHIA [33], using version 8.240. For multi-jet NLO samples, partons in the matrix element calculation are merged with the parton shower using the FxFx prescription [34]. The MC samples are simulated with the CP2 (for the signal, consistent with the LO matrix element) and CP5 (for the SM backgrounds) underlying-event tunes [35]. The simulated events are processed through a detailed simulation of the CMS detector, based on the GEANT4 package [36], using the same trigger and reconstruction algorithms as used to collect and process the data.

3 Object reconstruction, identification, and selection

The objects used in this analysis are reconstructed starting with a particle-flow (PF) algorithm [37], which aims to reconstruct and identify each individual particle in an event, through an optimized combination of information from the various elements of the CMS detector. The energy of the photons is directly obtained from the ECAL measurements. The electron's energy is determined by combining the electron momentum at the primary interaction vertex (as determined by the silicon tracker), the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding tracks. The energy of each charged hadron is computed by combining the momentum measured in the tracker with the matching ECAL and HCAL energy deposits, corrected using the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies.

Electrons are reconstructed by associating a track in the silicon layers with a cluster of energy in the ECAL. Their momentum is evaluated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. Electrons from $Z \rightarrow ee$ decays, with transverse momentum $p_T \approx 45$ GeV, have a momentum resolution between 1.6% and 5%; it is generally better in the barrel than in the endcaps and also depends on the bremsstrahlung radiation emitted by the electrons [16, 38, 39]. Electrons are identified by an algorithm based on a boosted decision tree (BDT), selecting a working point with identification efficiency approximately 90%. Isolation variables [16] are included in the BDT training. The electrons are required to have $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.5$, excluding the $1.44 < |\eta| < 1.57$ transition region, situated between the barrel and endcap detectors. They are also required to have relative isolation, I_{PF}^{rel} , smaller than 0.08, computed as the ratio between the sum of the p_T of all PF particles within a cone of radius $\Delta R = 0.3$ around the electron trajectory and the electron p_T , with corrections applied to mitigate the contribution from pileup (i.e., additional pp interactions within the same or nearby bunch crossings).

Muons are measured in the $|\eta| < 2.4$ range, by associating a track in the silicon tracker with a track in the muon detectors, and are required to have $p_T > 25$ GeV. The single-muon trigger efficiency exceeds 90% over the full η range and the efficiency to reconstruct and identify muons is larger than 96%. Muons with p_T up to 100 GeV have a relative transverse momentum resolution of 1% in the barrel and 3% in the endcaps [17]. Muons are identified by applying a set of quality criteria to the candidates, using a working point with an identification efficiency of 95%. Their relative isolation, computed using a cone of radius 0.4, is required to be $I_{PF}^{rel} < 0.15$.

Jets are reconstructed from the PF particles using the infrared- and collinear-safe anti- k_T algorithm [40, 41] with a distance parameter $\Delta R = 0.4$. The jet momentum is determined as the

vectorial sum of all particle momenta in the jet. Simulation studies show that this value is, on average, within 5–10% of the momentum of the jet at the particle level (that is, prior to its detection), over the entire p_T spectrum and detector coverage. Pileup interactions increase the number of tracks and calorimetric energy deposits, thereby increasing the apparent jet momentum.

To mitigate this effect, tracks identified as originating from pileup vertices are discarded and an offset is applied to correct for remaining contributions [42]. The jet energy corrections are derived, from simulation studies, so that the measured (average) jet energy is identical to the particle-level jet energy. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to evaluate residual differences between the jet energy scale in measured and simulated events, so that appropriate corrections can be applied [43]. Additional selection criteria are applied to each jet, to remove jets potentially dominated by instrumental effects or reconstruction failures [42]. Jets overlapping with selected leptons, within a cone of $\Delta R = 0.4$, are rejected. To select true jets and reject instrumental noise, tight selection criteria are imposed on variables related to the energy fractions and relative multiplicities of the various PF candidate types clustered in the jet. The selected jets must have $p_T > 30 \text{ GeV}$ and $|\eta| < 2.4$.

Some of the jets passing the above selection criteria are identified by the DeepCSV algorithm [44] as originating from the hadronization of bottom quarks; they are referred to as b-tagged jets. The chosen working point of the algorithm has an average b tagging efficiency of 70%, for a gluon and light flavor jet misidentification rate of 1% [44].

The missing transverse momentum vector \vec{p}_T^{miss} (of magnitude p_T^{miss}) is computed, for each event, as the projection, in the plane perpendicular to the beam axis, of the negative vector sum of the momenta of all reconstructed PF objects [45]. The contribution from particles from pileup interactions, which degrades the p_T^{miss} resolution, is mitigated using the pileup per particle identification algorithm [46]. Events with anomalous p_T^{miss} , originating from reconstruction or detector failures, are filtered out [45].

4 Analysis method and signal selection

The events are selected using single-electron triggers with electron p_T thresholds of 27 or 32 GeV, and single-muon triggers with muon p_T thresholds of 24 or 27 GeV, depending on the year of data taking. The efficiencies for the single-electron (single-muon) triggers are about 80% (90%) at the p_T efficiency plateau [16, 47]. The events are required to have exactly two oppositely charged leptons (electrons or muons), the leading (trailing) lepton having $p_T > 80$ (40) GeV. The dilepton invariant mass, $m_{\ell\ell}$, is required to be larger than 100 GeV, to suppress backgrounds with on-shell Z bosons. To eliminate most of the DY+jets and $t\bar{t}$ backgrounds, p_T^{miss} is required to be larger than 100 GeV. To further suppress the $t\bar{t}$ background, events with b-tagged jets are rejected. The events passing these criteria are then distributed in three classes, defined by their lepton flavor combinations: e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$. The selection is summarized in Table 1.

These event selection criteria reject most of the SM backgrounds, while retaining a high signal selection efficiency. However, the remaining irreducible backgrounds, primarily from the $t\bar{t}$, tW , and WW processes, exhibit features that resemble those of the signal events, so that no single variable exists that effectively discriminates the signal from the backgrounds. Therefore, a multivariate analysis approach is adopted, combining information from the kinematical and topological features that characterize the signal and background processes.

Table 1: Signal event selection and search channels.

Selection variables	Selection criteria
Number of leptons	=2
Opposite charge lepton pairs	= 1 (e^+e^- , $\mu^+\mu^-$, $e^\pm\mu^\mp$)
Leading lepton p_T	>80 GeV
Trailing lepton p_T	>40 GeV
Dilepton invariant mass ($m_{\ell\ell}$)	>100 GeV
Missing transverse momentum (p_T^{miss})	>100 GeV
Number of b jets	=0

The analysis employs a fully connected parametrized neural network (PNN), to overcome the limitations of traditional training approaches. When training a neural network (NN) to extract a signal model with free parameters, such as the particle masses, several approaches can be considered. One of the most common approaches is to train a dedicated NN for a selected set of individual mass points in the signal model. While this method is expected to provide an optimal performance for each of those specific mass points, it does not guarantee a good performance for other mass points. The PNN approach [48] addresses this limitation by including the free model parameters as inputs in the NN training. In our specific analysis, the additional training parameters are the masses of the Z' boson and of the chargino.

The PNN learns nontrivial correlations among the relevant variables and provides a model that maps the input variables to signal- or background-like scores. These PNN scores (ranging between 0 and 1) are then used in a binned likelihood fit that provides the results of the analysis. The PNN training is performed using half of the simulated events (signal and all SM backgrounds considered in this analysis, randomly sampled) that pass the selection criteria described above, except for the b-tagged jet veto requirement. Since the PNN score is not expected to be strongly affected by the b-tagged jet requirement, the training is performed on b-tagged jet inclusive events, thereby increasing the number of events available for training. The remaining half of the events, which are not used for training, are used for the validation of the PNN performance. The training is done independently for each of the search channels, taking into account the cross section of each process along with event reweighting, such that the effective event yields of each signal and the total background are balanced.

The PNN training uses the variables listed below. The variables are selected because they exhibit a good discriminating power between the signal and the SM background processes. For example, the signal features higher average lepton p_T values because of the high mass of the Z' boson and higher p_T^{miss} because the final state includes two massive neutralinos.

- The p_T of the leading (ℓ_1) and trailing (ℓ_2) leptons.
- The dilepton invariant mass, $m_{\ell\ell}$.
- The p_T^{miss} .
- The magnitude of the vectorial sum of the dilepton p_T and \vec{p}_T^{miss} , $|\vec{p}_T(\ell\ell) + \vec{p}_T^{\text{miss}}|$.
- $|\vec{p}_T(\ell\ell) + \vec{p}_T^{\text{miss}}| - p_T(\ell\ell)$, where $p_T(\ell\ell)$ is the magnitude of the dilepton p_T .
- The transverse mass,

$$m_T = 2 p_T(\ell\ell) p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{\ell\ell}, \vec{p}_T^{\text{miss}})], \quad (1)$$

where $\Delta\phi(\vec{\ell\ell}, \vec{p}_T^{\text{miss}})$ is the azimuthal distance between the dilepton and \vec{p}_T^{miss} .

- The “stransverse mass” [49, 50],

$$M_{T2} = \min_{\vec{p}_T^{\text{miss}(1)} + \vec{p}_T^{\text{miss}(2)} = \vec{p}_T^{\text{miss}}} \left[\max \left(m_T(\ell_1, \vec{p}_T^{\text{miss}}), m_T(\ell_2, \vec{p}_T^{\text{miss}}) \right) \right], \quad (2)$$

where $\vec{p}_T^{\text{miss}(1,2)}$ are the vector p_T of two invisible objects whose momentum sum is \vec{p}_T^{miss} and $m_T(\ell_{1,2}, \vec{p}_T^{\text{miss}})$ are the transverse masses obtained by pairing $\vec{p}_T^{\text{miss}(i)}$ with either of the two leptons. The stransverse mass is a discriminating variable particularly useful in events with more than one invisible particle in the final state. For example, in $t\bar{t}$ events that decay leptonically, M_{T2} exhibits an endpoint at the W boson mass.

These variables are complemented with variables representing angular distances between the various event objects. In the azimuthal dimension, we have the distances between the two leptons, $\Delta\phi(\ell_1, \ell_2)$, between \vec{p}_T^{miss} and the dilepton, $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T(\ell_1\ell_2))$, and between \vec{p}_T^{miss} and each of the two leptons, $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T(\ell_1))$ and $\Delta\phi(\vec{p}_T^{\text{miss}}, \vec{p}_T(\ell_2))$. For each of these variables, the signal distribution peaks at π , while the background processes have flatter distributions. There is also the angular distance in η and azimuth, $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, between the two leptons, $\Delta R(\ell_1, \ell_2)$. The signal distribution peaks close to 3 and reaches higher values, while the background processes have broader distributions and mostly populate lower values.

While the set of the most important variables slightly depends on the search channel and assumed signal scenario, the top-ranked variables typically include $p_T(\ell)$, $m_{\ell\ell}$, p_T^{miss} , m_T , and M_{T2} . Figure 2 shows the distributions measured for some variables.

The analysis uses the TensorFlow [51] framework, interfaced with the Keras [52] library. The gradient descent algorithm [53] employed in the PNN assumes that the input variables follow normal Gaussian distributions, while, in reality, they span a wide variety of numerical ranges. Therefore, each variable x is transformed into $(x - \bar{x})/\sigma_x$, where \bar{x} and σ_x are the mean and standard deviation of its distribution. Model structure parameters (e.g., the number of hidden layers) and training process parameters are scanned in a grid search and by using Bayesian optimization methods [54].

Figure 3 shows the performance of the PNN approach with that of an NN model trained on a specific signal point ($m_{Z'} = 2.5$ TeV and $m_{\tilde{\chi}_1^+} = 345$ GeV), using MC simulations of the $e\mu$ search channel with the 2017 integrated luminosity. The comparison uses the Asimov significance (Z_A) [55], defined as

$$\begin{aligned} Z_A^2 &= -2 \ln \frac{\mathcal{L}(\mu = 0 \mid D(s+b))}{\mathcal{L}(\mu = 1 \mid D(s+b))} \\ &= -2 \ln \frac{\prod_i^{\text{bins}} \mathcal{P}(s_i + b_i \mid b_i)}{\prod_i^{\text{bins}} \mathcal{P}(s_i + b_i \mid s_i + b_i)} \\ &= \sum_i^{\text{bins}} 2 \left[(s_i + b_i) \ln \frac{s_i + b_i}{b_i} - s_i \right]. \end{aligned} \quad (3)$$

where μ represents the signal strength (the ratio of the signal yield to the predicted signal yield, where $\mu = 1$ corresponds to the full prediction), $D(s+b)$ denotes pseudo-data assuming the full signal and background yields, \mathcal{P} represents the Poisson distribution, and s_i (b_i) is the number of signal (background) counts in the i^{th} bin of the PNN scores. The two significances coincide at the signal point used in the NN training ($m_{Z'} = 2.5$ TeV and $m_{\tilde{\chi}_1^+} = 345$ GeV), as expected, but the NN significance degrades as the masses deviate from that point. For example,

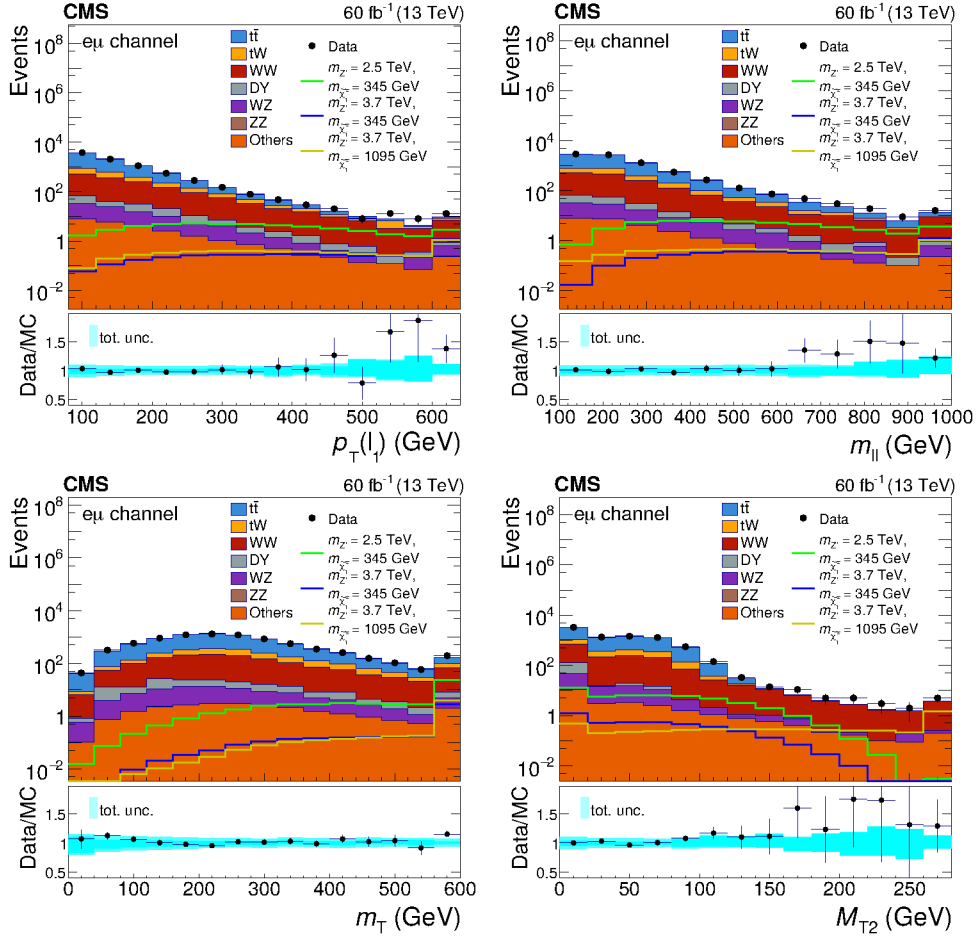


Figure 2: Distributions measured from the $e^\pm\mu^\mp$ sample collected in 2018, for $p_T(\ell_1)$ (upper left), $m_{\ell\ell}$ (upper right), m_T (lower left), and M_{T2} (lower right). Several benchmark signal distributions are overlaid (colored lines), illustrating the separation power between signal and background. The panel under each plot shows the data-to-background ratio, along with the corresponding total uncertainty band (in cyan).

when $m_{Z'}$ = 4.1 TeV, the PNN significance is higher by 11 (17)% for a chargino mass of 345 (845) GeV.

5 Background evaluation

The dominant irreducible SM backgrounds in the signal region (SR) are the $t\bar{t}$, WW, and DY processes, whose shapes in the signal region are evaluated using the simulated events for each process. These backgrounds are normalized using factors obtained by fitting the PNN score distributions in the SR and, simultaneously, in three control regions (CRs) defined so that they are dominated by each of the three SM processes, with negligible signal contamination. The three search channels are analyzed separately and then combined in a fit. The $t\bar{t}$ CR is considered in all three channels, the WW CR is only considered in the $e^\pm\mu^\mp$ channel as its yield is negligible in the other channels, and the DY CR is only considered in the e^+e^- and $\mu^+\mu^-$ channels.

Table 2 lists the selection criteria that define the SRs and CRs. Events with at least one b-tagged jet are used to define the $t\bar{t}$ CR, while those with $40 < m_{\ell\ell} < 100$ GeV define the WW CR. The

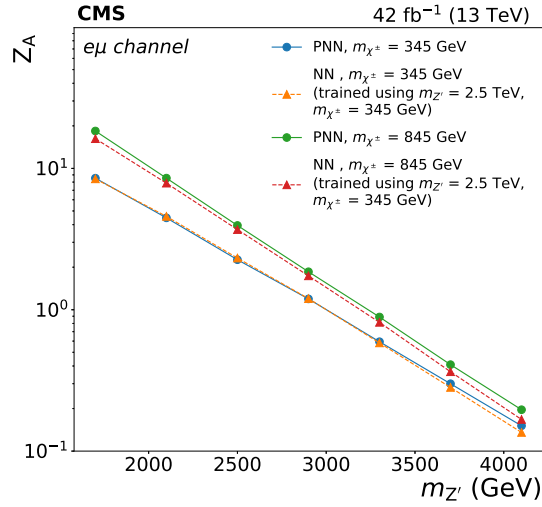


Figure 3: Asimov significance, Z_A , vs. $m_{Z'}$ for the PNN model (circles) and for a NN model trained on a specific signal point (triangles) for the 2017 simulated event sample, in the $e^\pm \mu^\mp$ channel. Two chargino masses have been considered, as indicated.

Table 2: Definitions of the signal and control regions used in the analysis.

Region	p_T^{miss} (GeV)	$m_{\ell\ell}$ (GeV)	b jets	Channels
SR	>100	>100	0	$e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$
$t\bar{t}$ CR	>100	>100	≥ 1	$e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$
WW CR	>100	40–100	0	$e^\pm\mu^\mp$
DY CR	30–100	>100	0	$e^+e^-, \mu^+\mu^-$

DY CR is defined by requiring p_T^{miss} to be between 30 and 100 GeV. The same PNN model is deployed in all regions.

Figure 4 shows the PNN score distributions of the measured (merging the three data-taking periods) and simulated SM background events, for the PNN model with $m_{Z'} = 2.5$ TeV and $m_{\tilde{\chi}_1^\pm} = 345$ GeV, for three combinations of CRs and search channels: $t\bar{t}$ and WW CRs for $e^\pm \mu^\mp$ and DY CR for the merged e^+e^- and $\mu^+\mu^-$ channels. The SM distributions in the colored stack show the fitted yields (“Bkg. fit”). The data-to-background ratios are shown using both the raw (“Pre-fit”) and fitted SM yields. The measured distributions are in agreement with the fitted SM backgrounds.

The remaining, subdominant, background processes have a negligible impact in the analysis sensitivity and, therefore, are evaluated from the simulated samples.

6 Systematic uncertainties

Several sources of theoretical and experimental systematic uncertainties listed below affect the shape or normalization of the PNN signal and background distributions. These uncertainties are taken into account through nuisance parameters in the final profile likelihood fit. Effects from a single source of uncertainty are treated as fully correlated across the PNN score bins, whereas independent sources of uncertainty are treated as uncorrelated.

The uncertainties associated with the renormalization (μ_R) and factorization (μ_F) scales are

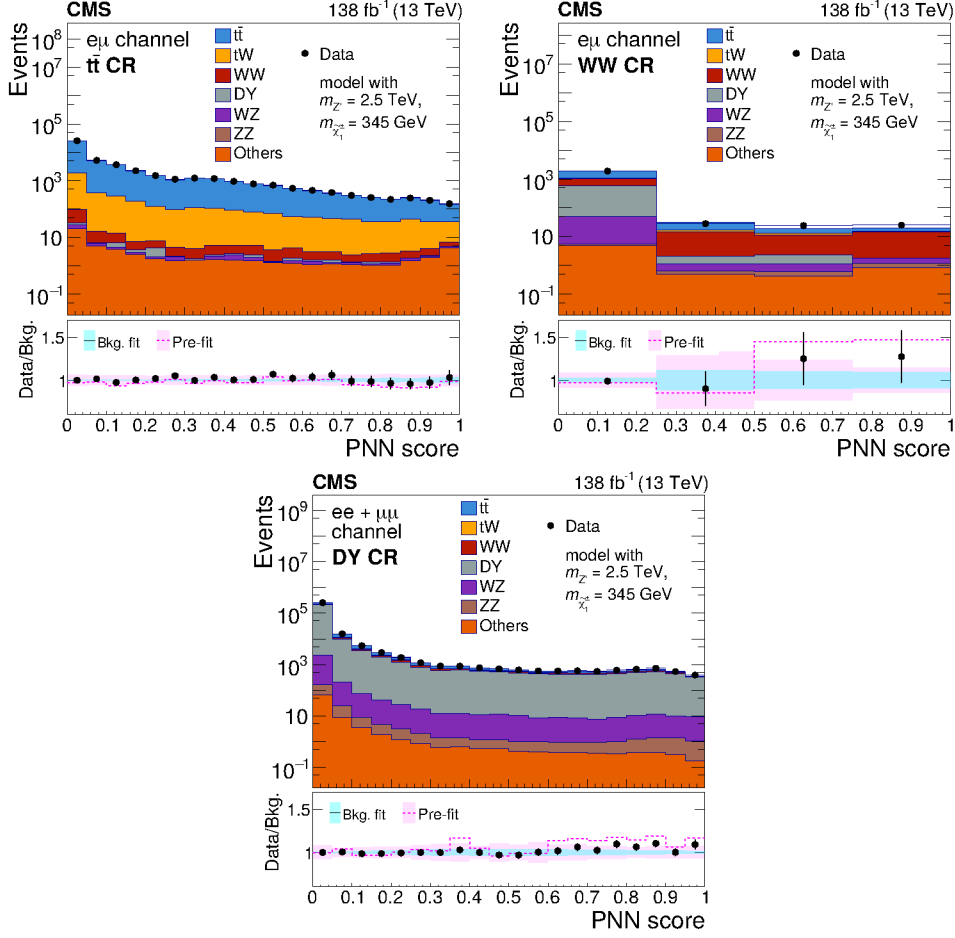


Figure 4: Measured and simulated SM PNN score distributions for a model with $m_{Z'} = 2.5$ TeV and $m_{\tilde{\chi}_1^\pm} = 345$ GeV, for the $t\bar{t}$ (upper left) and WW (upper right) CRs in the $e^\pm\mu^\mp$ channel and for the DY CR in the $e^+e^- + \mu^+\mu^-$ channel (lower). The panel under each plot shows the data-to-background ratios using either a background-only fit (black circles and cyan band) or a pre-fit (magenta dashed line and band). The uncertainties are displayed around the unity line.

evaluated by independently varying μ_R and μ_F by a factor of 2 and 0.5, excluding the two extreme combinations. The uncertainty associated with the PDFs and α_S value is evaluated by reweighting the simulated events using the variations provided by the NNPDF3.1 [27] and PDF4LHC [56] sets, respectively, for the SM backgrounds and signal. The uncertainty from the matching between the matrix element generator and the parton shower in the POWHEG and PYTHIA simulation is evaluated with simulation studies, varying the parameter (h_{damp}) that regulates the first high- p_T emission. Uncertainties in the simulation of the underlying event are estimated by varying the tune settings [35]. To improve the agreement between the measured and simulated top quark p_T spectra in $t\bar{t}$ events, weights are applied to the NLO events to match the p_T distribution predicted at next-to-next-to-leading order (NNLO) [57]. The resulting variation in the prediction after applying the reweighting is taken as the corresponding uncertainty. The backgrounds normalized using factors obtained from the fit ($t\bar{t}$, WW, and DY) are assigned a normalization uncertainty corresponding to the fit uncertainty. The backgrounds directly estimated from the simulated samples (all but $t\bar{t}$, WW, and DY) have a normalization uncertainty equal to twice their theoretical uncertainty.

The integrated luminosities of the 2016, 2017, and 2018 data taking periods have uncertainties

of 1.2%, 2.3%, and 2.5%, respectively [23–25]. These uncertainties are uniformly applied to the simulated events. The number of simulated pileup interactions is estimated assuming a total inelastic pp cross section of 69.2 mb. A corresponding uncertainty is evaluated by varying the total inelastic cross section by $\pm 4.6\%$ [42]. During the 2016 and 2017 data-taking periods, a gradual shift in the timing of the inputs of the ECAL L1 trigger in the forward endcap region ($|\eta| > 2.4$) led to an inefficiency. Also the muon detectors showed a similar trigger inefficiency effect, especially in 2016. Corrections for this effect are applied to simulated events; the corresponding uncertainties are around 1%. Scale factors are applied, as functions of lepton p_T and η , to account for differences between the measured and simulated samples regarding the lepton reconstruction, identification, and isolation efficiencies. The uncertainties associated with the calculation of these factors are propagated as systematic uncertainties. Uncertainties in the evaluation of the jet energy scale are taken into account by varying the jet momenta in simulated events, separately for the overall energy scale, differences in flavor response, residual differences between the energy scale measurements, etc. Uncertainties in the jet energy resolution are evaluated by varying the difference between the reconstructed and particle-level jet energies, or by smearing the measured jet energy if no matching particle-level jet could be found [43]. These jet energy scale and resolution variations are also propagated to \vec{p}_T^{miss} . Differences between the measured and simulated b jet tagging and light-quark or gluon jet mistagging scale factors are assigned as systematic uncertainties, as functions of p_T and η . Statistical uncertainties resulting from the finite size of the simulated samples are addressed using the Barlow–Beeston method [58]: in bins with more than 100 effective events a single Gaussian-constrained nuisance parameter is introduced for the sum of process yields, while for the other bins Poisson-constrained parameters are introduced for each process.

Among the systematic sources, the dominant contributions arise from the normalization uncertainty for backgrounds normalized using fit factors (around 12% of the fit uncertainty) and from the b jet tagging scale factor uncertainty (around 10% of the prior uncertainty). The other sources have a relatively mild impact on the results.

7 Results and interpretation

The search for the Z' signal is performed by fitting the measured PNN score distributions, in the SR for each of the three search channels. These distributions depend on the assumed Z' and $\tilde{\chi}_1^\pm$ masses. The CRs are combined and fitted simultaneously with the SRs, to determine the normalization factors for the dominant background processes.

Figure 5 presents the measured and estimated background PNN score distributions in the SR of each of the three search channels, for a model with $m_{Z'} = 2.5 \text{ TeV}$ and $m_{\tilde{\chi}_1^\pm} = 345 \text{ GeV}$. In each panel, the stack of SM background contributions corresponds to the background-only fit. The panels under each plot show the data-to-background ratios in both the “pre-fit” and “background-only fit” options, also displaying the total uncertainties, computed as the sum in quadrature of the statistical and systematic terms. The normalization factors of the dominant background processes are primarily determined from the CRs and the background-rich bins in the SRs. For the signal mass point hypothesis shown in Fig. 5, the fitted normalization factors are: 1.01 ± 0.03 for $t\bar{t}$, 1.12 ± 0.13 for WW , and 1.14 ± 0.04 for DY . The uncertainties (from the fit) are smaller for the processes with large yields in the CRs.

In the e^+e^- channel, the fit shows agreement between the measured PNN distribution and the SM expectation. In the $\mu^+\mu^-$ channel, a mild excess is observed in the signal-like bin (PNN score close to 1), with a local significance of 2 to 3 standard deviations, depending on

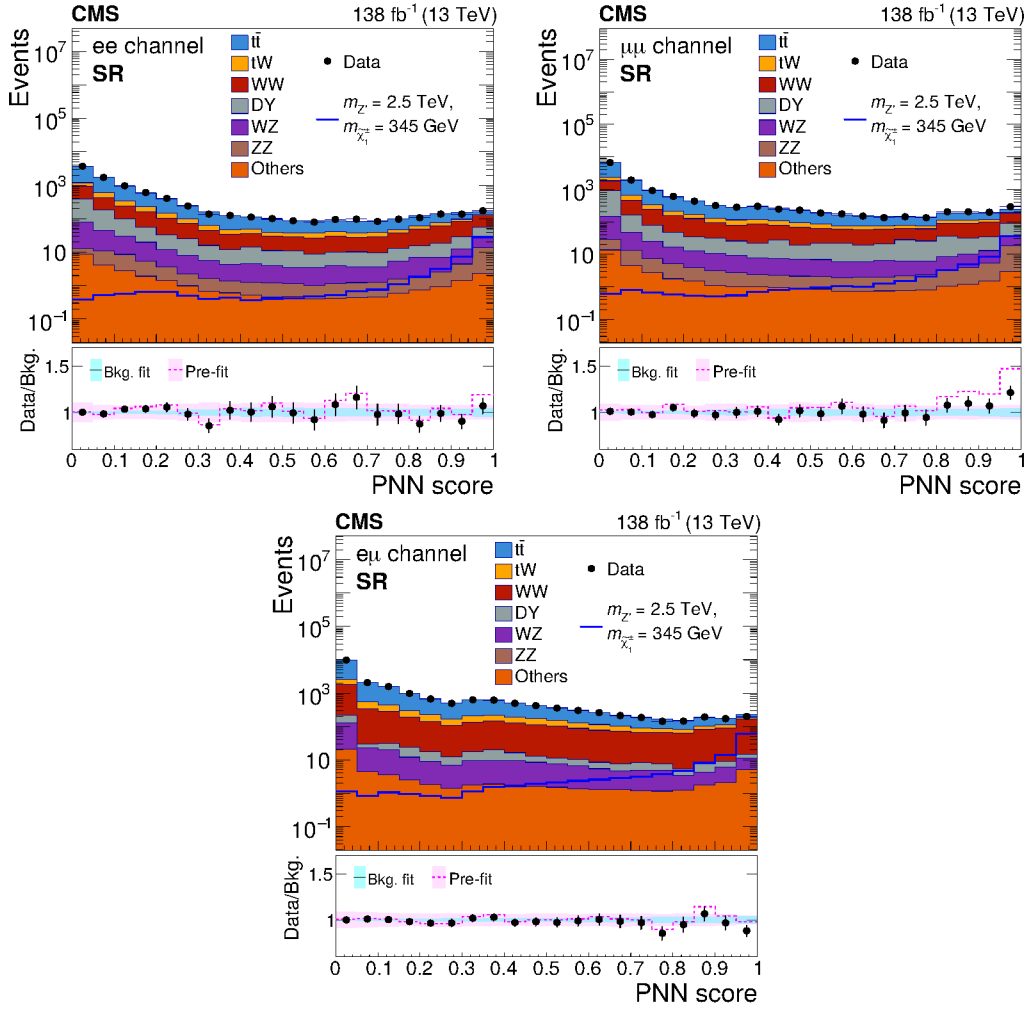


Figure 5: Measured and estimated background PNN score distributions, in the SRs of the three search channels. Signal distributions for a model with $m_{Z'} = 2.5$ TeV and $m_{\tilde{\chi}_1^\pm} = 345$ GeV are superimposed on the plots. The panel under each plot shows the data-to-background ratios using either a background-only fit (black circles and cyan band) or a pre-fit (magenta dashed line and band). The uncertainties are displayed around the unity line.

the assumed signal mass hypothesis. The $e^\pm\mu^\mp$ channel, instead, shows a mild deficit in the signal-like bin.

A statistical interpretation has been conducted by testing the SM hypothesis against the Z' boson hypothesis. Upper limits on the Z' boson production cross section are calculated at 95% confidence level (CL) using a modified frequentist approach and the CL_s criterion, implemented through an asymptotic approximation [55, 59–61]. The limits are computed using the COMBINE statistical analysis tool [62], which is based on the ROOFIT [63] and ROOSTATS [64] frameworks. Figure 6 shows the observed and expected $pp \rightarrow Z'$ cross section upper limits in the $m_{Z'}$ vs. $m_{\tilde{\chi}_1^\pm}$ plane, while Fig. 7 shows the corresponding limits as a function of $m_{Z'}$, for several $m_{\tilde{\chi}_1^\pm}$ values.

The cross section limits are computed for an integrated luminosity of 138 fb^{-1} and assuming that the $Z' \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ \tilde{\chi}_1^0 W^- \tilde{\chi}_1^0$ branching fraction is 100%. The Z' boson width is considered negligible and the neutralino mass is set to be half of the chargino mass. The obtained

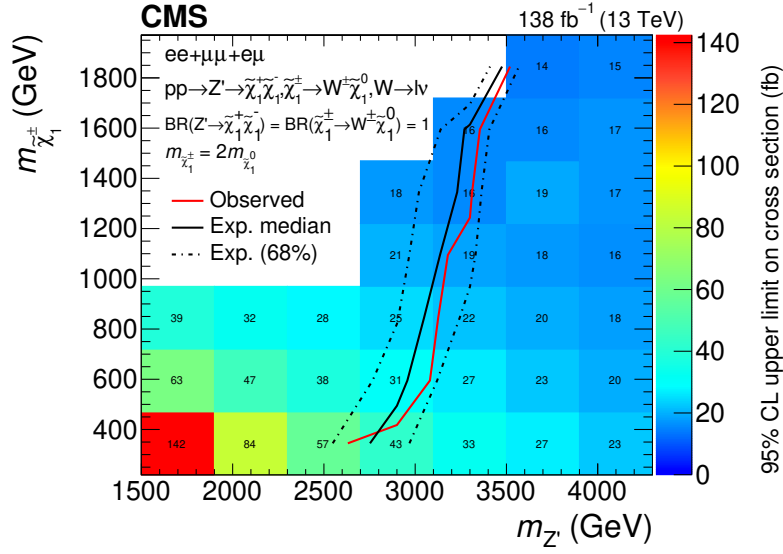


Figure 6: Upper limits, at 95% CL, on the $pp \rightarrow Z'$ cross section, in the Z' boson mass vs. $\tilde{\chi}_1^\pm$ mass plane, combining the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ channels, as determined from the measured data (red line) and as expected from the simulation studies (black lines: median exclusion in solid and 68% quantiles in dashed). The region to the left of the curves is excluded. The color grid shows median expected upper limits.

limits are mostly driven by the $e^\pm\mu^\mp$ channel, which has a better sensitivity because its signal (and background) event yields are higher than those of the same-flavor channels. For a fixed Z' boson mass, the sensitivity improves for higher $\tilde{\chi}_1^\pm$ masses, given the improved signal selection efficiency. Although the sensitivity is quoted for a narrow-width Z' resonance, it is expected to be similar for wider resonances with a width-to-mass ratio up to 20%, as the kinematic distributions are found to be comparable to those in the narrow-width case.

For the scenario with $m_{\tilde{\chi}_1^\pm} \approx 1.8$ TeV, the measurement excludes the existence of Z' bosons with mass up to 3.5 TeV. Assuming that the Z' boson has a mass of 2.9 TeV and only decays to a chargino pair, the observations exclude charginos in the 400–1400 GeV mass range.

Tabulated results are provided in the HEPData record for this analysis [65].

8 Summary

A search has been conducted for a leptophobic Z' boson decaying into two charginos, which subsequently decay into W bosons and neutralinos. A data sample of proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1} , was analyzed. This is the first search for this process using LHC data. An analysis was designed in the dilepton plus missing transverse momentum final state, in the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ channels. A parametrized neural network was employed to enhance the signal sensitivity. The analysis was interpreted using simplified model spectra featuring the production and decay process of the leptophobic Z' boson derived from the $U(1)'$ extension of the minimal supersymmetric standard model. The measurements were found to be consistent with the standard model expectations. Upper limits on the Z' boson production cross section were presented in the Z' boson mass vs. chargino mass plane, with $m_{\tilde{\chi}_1^\pm} = 2 m_{\tilde{\chi}_1^0}$. The analysis excludes Z' boson masses up to about 3.5 TeV for the specific case of Z' bosons decaying exclusively to

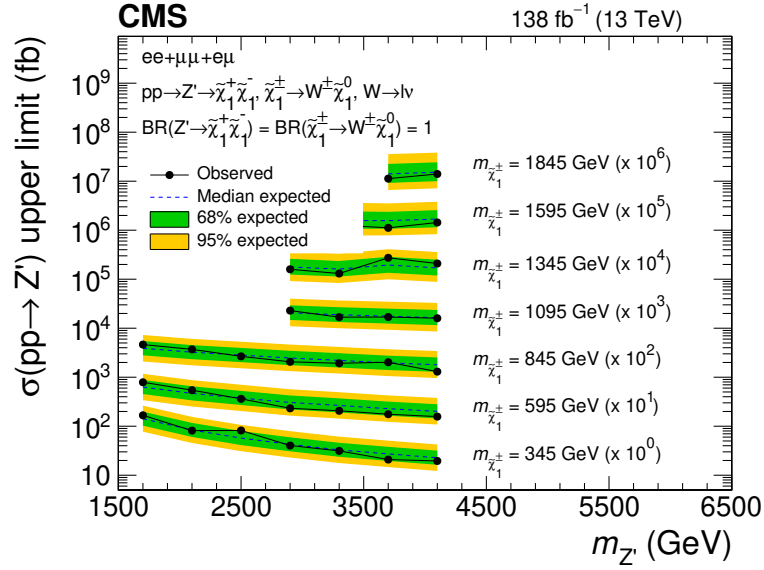


Figure 7: Upper limits, at 95% CL, on the $pp \rightarrow Z'$ cross section, vs. Z' boson mass for several $\tilde{\chi}_1^\pm$ mass values, combining the e^+e^- , $\mu^+\mu^-$, and $e^\pm\mu^\mp$ channels, as determined from the measured data (black circles) and as expected from the simulation studies (dashed lines with green and yellow uncertainty bands). The limits for different $m_{\tilde{\chi}_1^\pm}$ values are shifted vertically, for visibility purposes.

charginos, with the charginos decaying to W bosons and neutralinos. Under the assumption of 2.9 TeV Z' boson decaying exclusively to charginos, observations rule out chargino masses in the 400–1400 GeV range.

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

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










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












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
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



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






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




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








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






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












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









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






















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














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






















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























































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



















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


















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G. Steinbrück , R. Ward , B. Wiederspan, M. Wolf 









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


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



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




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









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






















































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























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
















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


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




















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

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























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








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








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

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




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






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





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
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


























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




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













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



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


























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
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









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











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













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L. Levchuk 









































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





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









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




















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


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







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



































































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














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



















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








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








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



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










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


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




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



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


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






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






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

G. Agarwal , R. Band , R. Bucci, S. Castells , A. Das , A. Ehnis, R. Goldouzian , M. Hildreth , K. Hurtado Anampa , T. Ivanov , C. Jessop , A. Karneyeu , K. Lannon

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















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








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


















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










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





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- ²⁵Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- ²⁶Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
- ²⁷Also at Brandenburg University of Technology, Cottbus, Germany
- ²⁸Also at Forschungszentrum Jülich, Juelich, Germany
- ²⁹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ³⁰Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary
- ³¹Now at Universitatea Babeş-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
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- ³³Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
- ³⁴Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
- ³⁵Also at The University of Kansas, Lawrence, Kansas, USA
- ³⁶Also at Punjab Agricultural University, Ludhiana, India
- ³⁷Also at University of Hyderabad, Hyderabad, India
- ³⁸Also at Indian Institute of Science (IISc), Bangalore, India
- ³⁹Also at University of Visva-Bharati, Santiniketan, India
- ⁴⁰Also at IIT Bhubaneswar, Bhubaneswar, India
- ⁴¹Also at Institute of Physics, Bhubaneswar, India
- ⁴²Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
- ⁴³Also at Isfahan University of Technology, Isfahan, Iran
- ⁴⁴Also at Sharif University of Technology, Tehran, Iran
- ⁴⁵Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
- ⁴⁶Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran
- ⁴⁷Also at Helwan University, Cairo, Egypt
- ⁴⁸Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
- ⁴⁹Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
- ⁵⁰Also at James Madison University, Harrisonburg, Maryland, USA
- ⁵¹Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- ⁵²Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
- ⁵³Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
- ⁵⁴Also at Lulea University of Technology, Lulea, Sweden
- ⁵⁵Also at Ain Shams University, Cairo, Egypt
- ⁵⁶Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
- ⁵⁷Also at UPES - University of Petroleum and Energy Studies, Dehradun, India
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- ⁶¹Also at Saegis Campus, Nugegoda, Sri Lanka
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- ⁶⁵Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
- ⁶⁶Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
- ⁶⁷Also at Konya Technical University, Konya, Turkey
- ⁶⁸Also at Izmir Bakircay University, Izmir, Turkey
- ⁶⁹Also at Adiyaman University, Adiyaman, Turkey
- ⁷⁰Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey
- ⁷¹Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey
- ⁷²Also at Marmara University, Istanbul, Turkey
- ⁷³Also at Milli Savunma University, Istanbul, Turkey
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