Search for new physics in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV
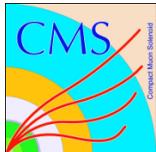
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ABSTRACT: A search is presented for physics beyond the standard model in final states with two opposite-sign, same-flavor leptons, jets, and missing transverse momentum. The data sample corresponds to an integrated luminosity of $2.3\,\text{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV collected with the CMS detector at the LHC in 2015. The analysis uses the invariant mass of the lepton pair, searching for a kinematic edge or a resonant-like excess compatible with the Z boson mass. Both search modes use several event categories in order to increase the sensitivity to new physics. These categories are based on the rapidity of the leptons, the multiplicity of jets and b jets, the scalar sum of jet transverse momenta, and missing transverse momentum. The observations in all signal regions are consistent with the expectations from the standard model, and the results are interpreted in the context of simplified models of supersymmetry.

Contents

1 Introduction

Supersymmetry (SUSY) [1–8] is one of the most appealing extensions of the standard model (SM), assuming a new fundamental symmetry that assigns a new fermion (boson) to every SM boson (fermion). SUSY resolves the hierarchy problem of the SM by stabilizing the Higgs boson mass via additional quantum loop corrections from the top super-partner (top squark), which compensate the correction due to the top quark. If R-parity [9] is conserved the lightest state predicted by the theory is stable and potentially massive, providing a candidate for Dark Matter. Many SUSY models also lead to the unification of the electroweak and strong forces at high energies.

This paper presents a search for signatures of SUSY in events with two opposite-sign, same-flavor leptons (electrons or muons), jets, and missing transverse momentum. A

dataset of pp collisions collected with the CMS detector at the CERN LHC at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$ in 2015 was used, corresponding to an integrated luminosity of 2.3 fb^{-1}. The dilepton topology is expected to occur in SUSY models where a neutralino decays to either an on-shell Z boson or a virtual Z/γ boson which in turn decays to leptons and the lightest SUSY particle (LSP), or into a lepton and its supersymmetric partner (slepton), the latter decaying into another lepton and the LSP. Decays involving an on-shell Z boson are expected to produce an excess of events compatible with the Z boson mass, while decays involving off-shell Z bosons or sleptons are expected to produce a characteristic edge shape in the invariant mass distribution of the dilepton system [10].

The CMS Collaboration published a version of this analysis using a $\sqrt{s} = 8\,\text{TeV}$ dataset, observing a $2.6\,\sigma$ local significance excess compatible with an edge shape located at a dilepton invariant mass of $78.7 \pm 1.4\,\text{GeV}$ [11]. The ATLAS collaboration reported the absence of any excess in a similar signal region, but observed a $3.0\,\sigma$ excess in dilepton events compatible with the Z boson mass [12]. Both of these excesses warrant scrutiny using the 13 TeV dataset and are analyzed here with minor changes with respect to the 8 TeV searches.

2   The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, that provides an axial magnetic field of 3.8 T. The bore of the solenoid is outfitted with various particle detection systems. Charged-particle trajectories are measured by silicon pixel and strip trackers, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity η is defined as $\eta = -\log[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the beam direction. A crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter surround the tracking volume. The calorimetry provides high resolution energy and direction measurements of electrons and hadronic jets. A preshower detector consisting of two planes of silicon sensors interleaved with lead is located in front of the ECAL at $|\eta| > 1.479$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing for energy balance measurements in the plane transverse to the beam direction. A two-tier trigger system selects the most interesting pp collision events for use in physics analysis. A more detailed description of the CMS detector, its coordinate system, and the main kinematic variables used in the analysis can be found elsewhere [13].

3   Datasets, triggers, and object selection

Events are collected with a set of isolated dilepton triggers that require a transverse momentum $p_\text{T} > 17\,\text{GeV}$ for the leading lepton and $p_\text{T} > 12\,(8)\,\text{GeV}$ for the subleading electron (muon), and $|\eta| < 2.5\,(2.4)$ for electrons (muons). In order to retain high signal efficiency, in particular for Lorentz-boosted dilepton systems, non-isolated dilepton triggers with $p_\text{T} > 33\,(27)\,\text{GeV}$ for the first electron (muon) and $p_\text{T} > 33\,(8)\,\text{GeV}$ for the second

electron (muon) are also used. The trigger efficiencies are measured in data using events selected by a suite of jet triggers.

Events are selected by requiring two opposite-charge, same flavor leptons ($e^{\pm}e^{\mp}$ or $\mu^{\pm}\mu^{\mp}$) with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and pseudorapidity $|\eta| < 2.4$. The distance between the leptons is requested to be at least $\sqrt{\Delta\phi^2 + \Delta\eta^2} = \Delta R > 0.3$ to avoid reconstruction efficiency differences between electrons and muons in events with very collinear leptons. This requirement is relaxed to $\Delta R > 0.1$ when the mass of the dilepton system is consistent with a Z boson to preserve acceptance for Z bosons with large transverse momentum. To ensure symmetry in acceptance between electrons and muons, all events with one of these two leptons in the barrel-endcap transition region of the ECAL, $1.4 < |\eta| < 1.6$, are rejected. A control sample of different flavor leptons ($e\mu$ or μe) is defined using the same lepton selection criteria. All the parameters above have been chosen in order to maximize the lepton selection efficiency while keeping the electron and muon efficiencies similar.

Electrons, reconstructed by associating tracks with ECAL clusters, are identified using a multivariate approach based on information on the cluster shape in the ECAL, track quality, and the matching between the track and the ECAL cluster [14]. Additionally, electrons from photon conversions are rejected. Muons are reconstructed from tracks found in the muon system associated with tracks in the tracker. They are identified based on the quality of the track fit and the number of associated hits in the tracking detectors. For both lepton flavors, the impact parameter with respect to the reconstructed vertex with the largest p_{T}^2 sum of associated tracks (primary vertex) is required to be within $0.5\,\mathrm{mm}$ in the transverse plane and below $1\,\mathrm{mm}$ along the beam direction. The lepton isolation, defined as the scalar p_{T} sum of all particle candidates, excluding the lepton itself, in a cone around the lepton, divided by the lepton p_{T}, is required to be smaller than $0.1\,(0.2)$ for electrons (muons). A cone-size, varying with lepton p_{T}, is chosen to be $\Delta R = 0.2$ for $p_{\mathrm{T}} < 50\,\mathrm{GeV}$, $\Delta R = 10\,\mathrm{GeV}/p_{\mathrm{T}}$ for $50 < p_{\mathrm{T}} < 200\,\mathrm{GeV}$, and $\Delta R = 0.05$ for $p_{\mathrm{T}} > 200\,\mathrm{GeV}$.

A particle flow (PF) technique [15, 16] is used to reconstruct particle candidates in the event. Jets are clustered from these candidates, excluding charged hadrons not associated to the primary vertex, using the anti-k_{T} clustering algorithm [17] implemented in the FASTJET package [18, 19] with a distance parameter of 0.4. Each jet is required to have $p_{\mathrm{T}} > 35\,\mathrm{GeV}$ where the p_{T} is corrected for non-uniform detector response and multiple collision (pileup) effects [20, 21], and $|\eta| < 2.4$. A jet is removed from the event if it lies within $\Delta R < 0.4$ of any of the selected leptons. The scalar sum of all jet transverse momenta is referred to as H_{T}. The magnitude of the negative vector p_{T} sum of all the PF candidates is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. Corrections to the jet energy are propagated to the $E_{\mathrm{T}}^{\mathrm{miss}}$ using the procedure developed for $7\,\mathrm{TeV}$ data [20]. Identification of jets originating from b-quarks is performed with the combined secondary vertex algorithm, using a working point in which the typical efficiency for b quarks is around 65% and the mistagging rate for light-flavor jets is around 1.5% [22].

While the main SM backgrounds are estimated using data control samples, simulated events are used to estimate uncertainties and minor SM background components. Next-to-leading order (NLO) and next-to-NLO cross sections [23–28] are used to normalize the simulated background samples, while NLO plus next-to-leading-logarithm (NLL) calcula-

tions [29] are used for the signal samples. Simulated samples of Drell-Yan (DY) production associated with jets (DY + jets), γ + jets, V + V, and t$\bar{\text{t}}$V (V = W, Z) events are generated with the MadGraph mc@nlo v2.2.2 event generator [23], while powheg v1 [30] is used for t$\bar{\text{t}}$ and single top quark production. The matrix element calculations performed with these generators are interfaced with pythia 8 [31] for the simulation of parton showering and hadronization. The NNPDF3.0 parton distribution functions (PDF) [32] are used for all samples. The detector response is simulated with a Geant4 model [33] of the CMS detector. The simulation of new physics signals is performed using the MadGraph5_aMC@NLO program at LO precision with up to 2 additional partons in the matrix elements calculations. Events are then interfaced with pythia 8 for fragmentation and hadronization, and simulated using the CMS fast simulation package [34]. Multiple pp interactions are superimposed on the hard collision and the simulated samples are reweighted to reflect the beam conditions. Normalization scale factors are applied to the simulated samples to account for differences between simulation and data in the trigger and reconstruction efficiencies.

4   Signal models

This search targets different modes of neutralino decays into final states with two opposite-sign, same-flavor leptons, jets, and $E_{\text{T}}^{\text{miss}}$ originating from the LSPs. In order to study these processes, two simplified models have been considered for the two search modes: one producing a resonant lepton signature through an on-shell Z boson for the "on-Z" search, and another producing an edge-like distribution in the invariant mass of the leptons, for the "edge" search.

The first of these simplified models represents gauge mediated supersymmetry breaking SUSY models [35] and is referred to as the GMSB scenario. The model assumes the production of a pair of gluinos ($\widetilde{\text{g}}$) that decay into a pair of quarks (u, d, s, c, or b) and the lightest neutralino $\widetilde{\chi}_1^0$. This neutralino decays into an on-shell Z boson and a massless gravitino ($\widetilde{\text{G}}$) as seen in figure 1 (left). At least one of the Z bosons decays into a pair of leptons producing the signature targeted by the on-Z search.

The signal model for the edge search, referred to as slepton-edge, assumes the production of a pair of bottom squarks, which decay to the next-to-lightest neutralino $\widetilde{\chi}_2^0$ and a b-quark. Two decay modes of the $\widetilde{\chi}_2^0$ are considered each with 50% probability. In the first one, the $\widetilde{\chi}_2^0$ decays to a Z boson and the lightest neutralino $\widetilde{\chi}_1^0$, which is stable. The Z boson can be on or off-shell, depending on the mass difference between the neutralinos, and decays according to its SM branching fractions. The second one features subsequent two-body decays with an intermediate slepton $\widetilde{\ell}$: $\widetilde{\chi}_2^0 \to \widetilde{\ell}\ell \to \ell\ell\widetilde{\chi}_1^0$. The masses of the sleptons ($\widetilde{\text{e}},\widetilde{\mu}$) are assumed degenerate and equal to the average of the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$. The masses of the $\widetilde{\text{b}}$ and $\widetilde{\chi}_2^0$ are free parameters, while $m_{\widetilde{\chi}_1^0}$ is fixed at 100 GeV. This scheme allows the position of the signal edge to vary along the invariant mass distribution according to the mass difference between the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$. The mass of the $\widetilde{\chi}_1^0$ has been chosen in such a way that the difference to the $\widetilde{\chi}_2^0$ mass is above 50 GeV, setting the minimum possible edge position at 50 GeV. An example for one of the possible decays is shown in figure 1 (right).
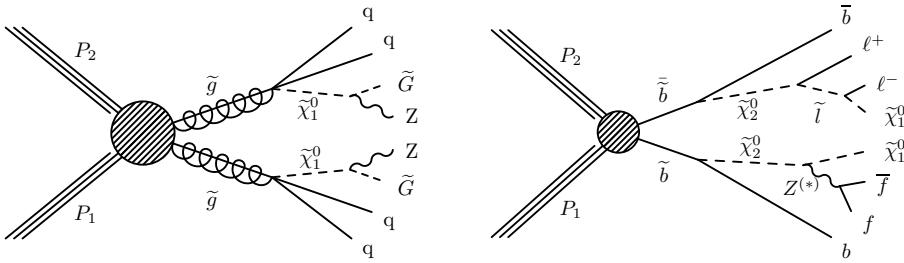
Figure 1. Diagrams for gluino and $\widetilde{b}$ pair production and decays realized in the simplified models. The GMSB model targeted by the on-Z search is shown on the left. On the right, the slepton-edge model features characteristic edges in the $m_{\ell\ell}$ spectrum given by the mass difference of the $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$.

5 Signal regions

Signal regions for the on-Z and edge searches follow two principles: first, they are designed to provide sensitivity to a range of new physics models, including the simplified models defined above, and second, they are designed to investigate excesses in the 8 TeV datasets reported by the ATLAS and CMS Collaborations [11, 12]. The selections described below are applied in addition to the dilepton selection described in section 3.

5.1 On-Z signal regions

The on-Z search is divided into a total of three signal region (SR) categories with dilepton invariant mass ($m_{\ell\ell}$) in the range $81 < m_{\ell\ell} < 101$ GeV. The first two, referred to as "SRA" (2–3 jets and $H_T > 400$ GeV) and "SRB" (≥ 4 jets), focus on events with low and high jet multiplicity. These categories are further divided according to the number of b-tagged jets and E_T^{miss}. One additional signal region, namely "ATLAS SR", is defined corresponding to the region showing a $3.0\,\sigma$ excess in the 8 TeV dataset of the ATLAS Collaboration [12]. The selection details are specified in section 7.

5.2 Edge search signal regions

The signal regions in the edge search remain largely unchanged with respect to the search performed with the 8 TeV dataset [11]. The requirements on the jet multiplicity and E_T^{miss} are similar to the previous analysis, namely $E_T^{\text{miss}} > 100\,(150)$ GeV if at least three (two) jets are present. The relative centrality expected in the decays of heavy particles, combined with the performance of the detector in the barrel region compared to the endcaps, motivates a division of the event sample depending on the $|\eta|$ of the leptons. The signal region is defined as central if both leptons lie within $|\eta| < 1.4$ and as forward if at least one of the leptons is located outside of this $|\eta|$ range. Furthermore, two exclusive bins are defined in the number of b-tagged jets, one without and one with at least one such jet.

The improvements in the CMS reconstruction algorithms for the 13 TeV data taking lead to a few differences between the 8 and 13 TeV signal regions. The lepton identification

algorithms have been updated for the 13 TeV data taking, with the most relevant improvement being the use of a new electron identification algorithm based on a multivariate discriminator [14]. The jet momentum threshold has been lowered from 40 GeV to 35 GeV given the improved pile-up rejection achieved at $\sqrt{s} = 13$ TeV, and the maximum $|\eta|$ has been reduced from to 3.0 to 2.4, to match the tracker acceptance. The isolation definition has also been modified to include a variable cone size. The rejection of non-prompt leptons has been improved as a consequence of all these changes. Finally, additional non-isolated double-lepton triggers have been added to recover efficiency for very boosted dilepton systems, although the increase in efficiency for the edge signal regions has been found to be small ($<4\%$).

A counting experiment is performed in five distinct regions of the $m_{\ell\ell}$ spectrum with events split among the four exclusive (0 or >=1 b-tagged jet, central or forward) and two inclusive (central or forward) categories. The five mass regions include the three that were present in the 8 TeV analysis (the low-mass region: $20 < m_{\ell\ell} < 70$ GeV, the on-Z region: $81 < m_{\ell\ell} < 101$ GeV, and the high-mass region: $m_{\ell\ell} > 120$ GeV), as well as the two regions immediately adjacent to the Z peak ($70 < m_{\ell\ell} < 81$ GeV and $101 < m_{\ell\ell} < 120$ GeV). The mass spectrum in the current analysis thus covers all $m_{\ell\ell}$ values above 20 GeV.

In order to directly compare the result obtained at 13 TeV with those obtained at 8 TeV, results for the signal regions are also given inclusively in the number of b-tagged jets, $N_{\text{b-jets}} \geq 0$. A summary of all signal regions is given along with the experimental results in section 7.

6 Standard model background predictions

The backgrounds from SM processes are divided into two types. Those that produce opposite-flavor (OF) pairs ($e^{\pm}\mu^{\mp}$) as often as same-flavor (SF) pairs ($\mu^{\pm}\mu^{\mp}$, $e^{\pm}e^{\mp}$) are referred to as flavor-symmetric (FS) backgrounds. Among them, the dominant contribution arises from top quark-antitop quark production; sub-leading contributions from WW, $Z/\gamma^{*}(\to \tau\tau)$, tW single-top quark production, and leptons from hadron decays are also present. The other category of backgrounds includes flavor-correlated lepton production and only contributes with SF leptons. The dominant contributions arise from DY production in association with jets, where the $E_{\text{T}}^{\text{miss}}$ arises from mismeasurement of the jet energies. Smaller contributions come from WZ and ZZ production, as well as rare processes such as t$\bar{\text{t}}$Z. These backgrounds are referred to as "Other SM" in this paper.

6.1 Flavor-symmetric backgrounds

The contribution of flavor-symmetric processes in the SF channels is estimated from the OF control sample. While there is a production symmetry between the two channels at particle level, it can be distorted by the different trigger, reconstruction, and identification efficiencies for electrons and muons. The background estimate is therefore obtained from the observed OF yield by applying a multiplicative correction factor, $R_{\text{SF/OF}}$. This factor is determined by two independent methods, a direct measurement in a control region enriched

	Central		Forward	
	Data	MC	Data	MC
$(1/2)(r_{\mu/e} + r_{\mu/e}^{-1})$	1.01 ± 0.01	1.01 ± 0.01	1.02 ± 0.04	1.03 ± 0.05
R_T	1.00 ± 0.07	1.02 ± 0.06	1.04 ± 0.09	1.04 ± 0.06
$R_{\mathrm{SF/OF}}$				
From factorization	1.01 ± 0.07	1.03 ± 0.06	1.06 ± 0.10	1.05 ± 0.08
Direct measurement	1.05 ± 0.06	1.05 ± 0.03	1.10 ± 0.09	1.08 ± 0.04
Weighted average	1.03 ± 0.05	1.04 ± 0.03	1.08 ± 0.07	1.07 ± 0.04

Table 1. Summary of $R_{\mathrm{SF/OF}}$ values obtained in data and simulation using the direct and factorized methods, and the final combination.

in FS backgrounds, and from the measurement of lepton efficiencies, factorized into the effects of reconstruction, identification, and trigger.

The direct measurement is performed in the region with $N_{\mathrm{jets}} = 2$ and $100 < E_T^{\mathrm{miss}} < 150\,\mathrm{GeV}$, excluding the mass range $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$ to reduce background contributions from resonant Z-boson production. Here, $R_{\mathrm{SF/OF}}$ is evaluated using the observed yield of SF and OF events, $4R_{\mathrm{SF/OF}} = N_{\mathrm{SF}}/N_{\mathrm{OF}}$. The applicability of this value in the signal region is confirmed by comparing it with the $R_{\mathrm{SF/OF}}$ value obtained in the signal region for $t\bar{t}$ simulated events. The difference between both values is found to be smaller than its statistical uncertainty (3%). The latter value is assigned as the systematic uncertainty in the measurement.

For the factorized approach, the ratio of muon to electron reconstruction and identification efficiencies, $r_{\mu/e}$, is measured in a DY-enriched region with $N_{\mathrm{jets}} \geq 2$ and $E_T^{\mathrm{miss}} < 50\,\mathrm{GeV}$ and requiring $60 < m_{\ell\ell} < 120\,\mathrm{GeV}$, resulting in a large sample of $e^{\pm}e^{\mp}$ and $\mu^{\pm}\mu^{\mp}$ events with similar kinematics to the signal region in terms of jet multiplicity. Assuming the factorization of lepton efficiencies in an event, the efficiency ratio is measured as $r_{\mu/e} = \sqrt{N_{\mu^+\mu^-}/N_{e^+e^-}}$. A systematic uncertainty of 10% (20%) is assigned to $r_{\mu/e}$ in the central (forward) lepton rapidity selection based on studies of its dependency on the lepton kinematics, the amount of E_T^{miss}, and the jet multiplicity. The trigger efficiencies for the three different flavor combinations are used to define the factor $R_T = \sqrt{\epsilon_{\mu^{\pm}\mu^{\mp}}^T \epsilon_{e^{\pm}e^{\mp}}^T}/\epsilon_{e^{\pm}\mu^{\mp}}^T$, which takes into account the difference between SF and OF channels at the trigger level. The final correction is $R_{\mathrm{SF/OF}} = (1/2)(r_{\mu/e} + r_{\mu/e}^{-1})\,R_T$. Here, $r_{\mu/e}$ is summed with its inverse, leading to a large reduction of the associated uncertainty.

The results of the direct measurement and the factorization method are shown in table 1. Since the results are in agreement and are obtained on independent data samples, they are combined using the weighted average. The resulting correction is $R_{\mathrm{SF/OF}} = 1.03 \pm 0.05$ (1.08 ± 0.07) for the central (forward) lepton rapidity selection.

6.2 Drell-Yan-like backgrounds

The E_T^{miss} from the DY background is estimated from E_T^{miss} templates obtained from a data control region. The main premise of this estimate based on data is that E_T^{miss} in

Z + jets events originates from the limited detector resolution when measuring the objects making up the hadronic system that recoils against the Z boson. We estimate the shape of the $E_\mathrm{T}^\mathrm{miss}$ distribution from a control sample of $\gamma +$ jets events where the jet system recoils against a photon instead of a Z boson. Signal regions requiring at least one b-tagged jet can lead to a small amount of additional $E_\mathrm{T}^\mathrm{miss}$ due to the neutrinos in semileptonic b quark decays. To account for this effect, the $E_\mathrm{T}^\mathrm{miss}$ templates are extracted from a control sample of $\gamma +$ jets events with at least one b-tagged jet.

The $\gamma +$ jets events in data are selected with a suite of single-photon triggers with p_T thresholds varying from 22 to 165 GeV. The triggers with thresholds below 165 GeV are prescaled such that only a fraction of accepted events are recorded, and the events are weighted by the trigger prescales to match the integrated luminosity collected with the signal dilepton triggers. In order to account for kinematic differences between the hadronic systems in the $\gamma+$jets and the Z+jets sample, the $\gamma+$jets sample is reweighted such that the boson p_T distribution matches that of the Z + jets sample. This reweighting is performed for each signal region, where the same requirements are applied to the Z + jets and the $\gamma +$ jets samples. The resulting $E_\mathrm{T}^\mathrm{miss}$ distribution is then normalized to the observed data yield in the region $E_\mathrm{T}^\mathrm{miss} < 50$ GeV where Z + jets is the dominant background.

The control sample used to estimate this background does not need to have a high purity of photons, since the $E_\mathrm{T}^\mathrm{miss}$ is assumed to originate from jet mismeasurement. However, it is required that the photon-like object be well measured so as to not contribute to the $E_\mathrm{T}^\mathrm{miss}$ mismeasurement. The stability of the photon selection is tested by repeating this background measurement after tightening the photon ID requirements, and it is found that the results are consistent with the measurement done using the looser selection. In order to ensure the photon-like object is sufficiently well-measured and that the $E_\mathrm{T}^\mathrm{miss}$ in the $\gamma +$ jets sample comes primarily from the mismeasurement of the jet system, the following conditions are required: $\Delta\phi(E_\mathrm{T}^\mathrm{miss}, \gamma) > 0.4$, a veto on events where the photon can be connected to a pattern of hits in the pixel detector, and the photon to be matched to a jet within a cone of $\Delta R = 0.4$. The requirement $\Delta\phi(E_\mathrm{T}^\mathrm{miss}, \gamma) > 0.4$ protects against under-measurement of the photon energy, which is much more likely for calorimeter-based quantities than over-measurement. Finally, the electromagnetic fraction of the matched jet (fraction of jet energy deposited in the electromagnetic calorimeter with respect to the total energy deposited in both, the electromagnetic and hadronic calorimeter) is required to be >0.7.

The dominant uncertainties in the $E_\mathrm{T}^\mathrm{miss}$ template prediction come from the limited size of the samples used. The uncertainty in the prediction takes into account the statistical uncertainty of the $\gamma +$ jets sample in the signal $E_\mathrm{T}^\mathrm{miss}$ regions, which ranges from 10–50%. The statistical uncertainty of the normalization for $E_\mathrm{T}^\mathrm{miss} < 50$ GeV is included and ranges from 4–10%, as shown in table 2. A closure test of the method is performed in simulation, using $\gamma +$ jets to predict the yield of Z + jets. An uncertainty is assigned from the results of this test as either the largest discrepancy between the $\gamma +$ jets prediction and the Z + jets yield for each $E_\mathrm{T}^\mathrm{miss}$ region, or the MC statistical uncertainty, whichever is larger. The values are listed in table 3 and vary between 4 and 50%, depending on the $E_\mathrm{T}^\mathrm{miss}$ region. Finally, the impact of photon purity on the estimate is studied in data by repeating the prediction with

Signal region	SRA		SRB		ATLAS SR
b tagging	b-jet veto	≥ 1 b tag	b-jet veto	≥ 1 b tag	–
Uncertainty	4 %	10 %	3 %	6 %	3 %

Table 2. Statistical uncertainties in the normalization of the $E_{\mathrm{T}}^{\mathrm{miss}}$ template prediction in the $E_{\mathrm{T}}^{\mathrm{miss}} < 50\,\mathrm{GeV}$ range, for each signal region. These are taken as a systematic uncertainty in the background prediction. The definitions of SRA, SRB, and ATLAS SR are found in section 5.1 and table 4.

$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	0–50	50–100	100–150	150–225	225–300	≥ 300
SRA, b-jet veto	1	4	4	5	15	35
SRA, $\geq$1 b tag	1	3	5	10	30	40
SRB, b-jet veto	1	2	4	10	20	25
SRB, $\geq$1 b tag	2	3	10	10	50	50
ATLAS SR	2	2	10	10	10	

Table 3. Systematic uncertainties in percentage for the $E_{\mathrm{T}}^{\mathrm{miss}}$ template method from the MC closure test, shown for all the on-Z signal regions. The definitions of SRA, SRB, and ATLAS SR are found in section 5.1 and table 4.

a tighter photon selection. Since the difference from the nominal prediction was smaller than the statistical uncertainty in all regions, no additional uncertainty was assigned.

6.2.1 Other standard model processes with a Z boson

The method using $E_{\mathrm{T}}^{\mathrm{miss}}$ templates only predicts instrumental $E_{\mathrm{T}}^{\mathrm{miss}}$ from jet mismeasurement and thus does not include the genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos expected in processes like $\mathrm{W}(\ell\nu)\mathrm{Z}(\ell\ell)$, $\mathrm{Z}(\ell\ell)\mathrm{Z}(\nu\nu)$, or rarer processes such as $\mathrm{t\bar{t}Z}$. These processes contribute a small fraction of the overall background and are determined with MC simulation. The MC prediction is compared to data in 3- and 4-lepton control regions. Agreement is observed, and a conservative uncertainty of 50% is assigned based on the limited statistics of these regions at higher jet multiplicities.

6.2.2 Drell-Yan background in the edge search

A procedure was designed to propagate the estimations obtained using the $E_{\mathrm{T}}^{\mathrm{miss}}$ templates for the on-Z regions to the off-Z mass regions. For this reason, a ratio $r_{\mathrm{out/in}}$ is measured in the DY-dominated control region where $r_{\mu/e}$ is also obtained. The numerator of this ratio is the number of SF events outside of the Z boson mass window, while the denominator is the SF yield within this window. Opposite-flavor yields in both the numerator and denominator are subtracted from the respective same-flavor yields in order to correct for FS contributions in the region where $r_{\mathrm{out/in}}$ is measured. The final ratio is unity for the mass region between 81 and 101 GeV, and varies between 2% and 7% for the other mass ranges, with values decreasing as a function of the invariant mass. The final contribution to the edge-like signal regions is then the on-Z prediction multiplied by this ratio for each

$N_{\text{jets}}/\ H_{\text{T}}$	$N_{\text{b-jets}}$	$E_{\text{T}}^{\text{miss}}$ (GeV)	Predicted	Observed
SRA 2–3 jets and $H_{\text{T}} > 400\,\text{GeV}$	0	100–150	$29.1\ ^{+5.3}_{-4.7}$	28
		150–225	$9.1\ ^{+3.2}_{-1.9}$	7
		225–300	$3.4\ ^{+2.5}_{-1.0}$	6
		>300	$2.1\ ^{+1.4}_{-0.7}$	6
	≥ 1	100–150	$14.3\ ^{+4.4}_{-3.2}$	21
		150–225	$6.9\ ^{+3.6}_{-2.3}$	6
		225–300	$6.1\ ^{+3.6}_{-2.3}$	1
		>300	$1.5\ ^{+2.4}_{-0.9}$	3
SRB ≥ 4 jets	0	100–150	$23.6\ ^{+4.9}_{-3.7}$	20
		150–225	$8.2\ ^{+3.4}_{-2.1}$	10
		225–300	$0.8\ ^{+1.2}_{-0.2}$	2
		>300	$1.5\ ^{+2.4}_{-0.9}$	0
	≥ 1	100–150	$44.7\ ^{+7.7}_{-6.6}$	45
		150–225	$16.8\ ^{+5.1}_{-3.9}$	23
		225–300	$0.6\ ^{+1.2}_{-0.3}$	4
		>300	$1.5\ ^{+2.4}_{-0.9}$	3
ATLAS–SR:				
$H_{\text{T}} + p_{\text{T}}^{\ell_1} + p_{\text{T}}^{\ell_2} > 600\,\text{GeV}$	$E_{\text{T}}^{\text{miss}} > 225\,\text{GeV}$	$\Delta\phi_{E_{\text{T}}^{\text{miss}},j_1,j_2} > 0.4$	$12.3^{+4.0}_{-2.8}$	14

Table 4. Observed and predicted yields for the on-Z search. The signal regions SRA and SRB are binned as a function of the b jet multiplicity and the missing transverse momentum. In the ATLAS SR, the transverse momenta of the two highest p_{T} leptons are included when calculating H_{T}, and an additional requirement is imposed on the angle between the $E_{\text{T}}^{\text{miss}}$ and the two leading jets $\Delta\phi_{E_{\text{T}}^{\text{miss}},j_1,j_2} > 0.4$.

of the signal regions. An uncertainty of 25% is assigned to $r_{\text{out/in}}$ to cover its dependencies on $E_{\text{T}}^{\text{miss}}$ and the jet multiplicity.

7 Results

The observed number of events in the different signal regions is compared with the background estimates obtained with the methods explained above for the on-Z and the edge searches. The results for the 16 exclusive signal regions of the on-Z search and the additional ATLAS signal region are presented in table 4. A graphical representation of these results can be seen in figure 2 (upper), where the background prediction has been divided into its three components: FS, DY, and other processes with a Z boson, in order to illustrate their relative contributions in the different signal regions.

The edge-like search features two distinct $m_{\ell\ell}$ spectra according to the centrality of the leptons, each of which is divided into five bins. This leads to a total of 10 mutually

| | | $N_{\text{b-jets}} \geq 0$ | | $N_{\text{b-jets}} = 0$ | | $N_{\text{b-jets}} \geq 1$ | |
	$m_{\ell\ell}$ range (GeV)	Pred.	Obs.	Pred.	Obs.	Pred.	Obs.
Central	20–70	477 ± 30 (4.8 ± 1.4)	445	130 ± 13 (3.6 ± 1.1)	135	347 ± 24 (1.2 ± 0.3)	310
	70–81	134 ± 13 (2.7 ± 0.8)	131	40 ± 6 (2.1 ± 0.6)	33	94 ± 10 (0.7 ± 0.2)	98
	81–101	254 ± 18 (62 ± 8)	275	95 ± 11 (46 ± 8)	107	160 ± 14 (16 ± 2)	168
	101–120	166 ± 15 (2.1 ± 0.6)	165	48 ± 7 (1.6 ± 0.5)	43	118 ± 12 (0.5 ± 0.2)	122
	>120	477 ± 30 (1.6 ± 0.5)	518	112 ± 12 (1.2 ± 0.4)	144	365 ± 25 (0.4 ± 0.1)	374
Forward	20–70	111 ± 12 (1.6 ± 0.4)	136	36 ± 6 (1.2 ± 0.4)	45	75 ± 10 (0.4 ± 0.1)	91
	70–81	47 ± 7 (1.2 ± 0.3)	50	15 ± 4 (0.9 ± 0.3)	14	32 ± 6 (0.3 ± 0.1)	36
	81–101	100 ± 10 (24 ± 3)	92	45 ± 6 (18 ± 3)	39	55 ± 8 (6.0 ± 1.2)	53
	101–120	78 ± 10 (1.0 ± 0.3)	51	22 ± 5 (0.7 ± 0.2)	15	55 ± 8 (0.2 ± 0.1)	36
	>120	308 ± 25 (0.7 ± 0.2)	306	85 ± 10 (0.5 ± 0.2)	95	223 ± 20 (0.2 ± 0.1)	211

Table 5. Results for the edge-like search in all 30 signal regions. The non-FS component of the total background is given separately in the brackets. All signal regions require $E_{\text{T}}^{\text{miss}} > 150\,(100)\,\text{GeV}$ if $N_{\text{jets}} \geq 2\,(3)$.

exclusive signal regions that are further divided according to the presence or absence of any b-tagged jet in the event. To be consistent with the 8 TeV search, the information without any selection on the number of b-tagged jets is also provided. Table 5 summarizes the SM predictions and the observations in all these signal regions. A graphical representation of these results is shown in figure 2 (lower), including the relative contributions of the different backgrounds.

The agreement between the observation and the prediction is found to be better than $1\,\sigma$ in most of the regions. The largest deviation found corresponds to a local significance of $1.8\,\sigma$. This result is compatible with the null hypothesis provided the large number of signal regions.

Figure 3 (upper) shows the $E_{\text{T}}^{\text{miss}}$ distribution for the on-Z ATLAS signal region, while figure 3 (lower), shows the $m_{\ell\ell}$ distribution for the edge region without any selection on the number of b-tagged jets and with central leptons, as in the region where CMS reported the excess at $\sqrt{s} = 8\,\text{TeV}$. The comparison between the observation and prediction in
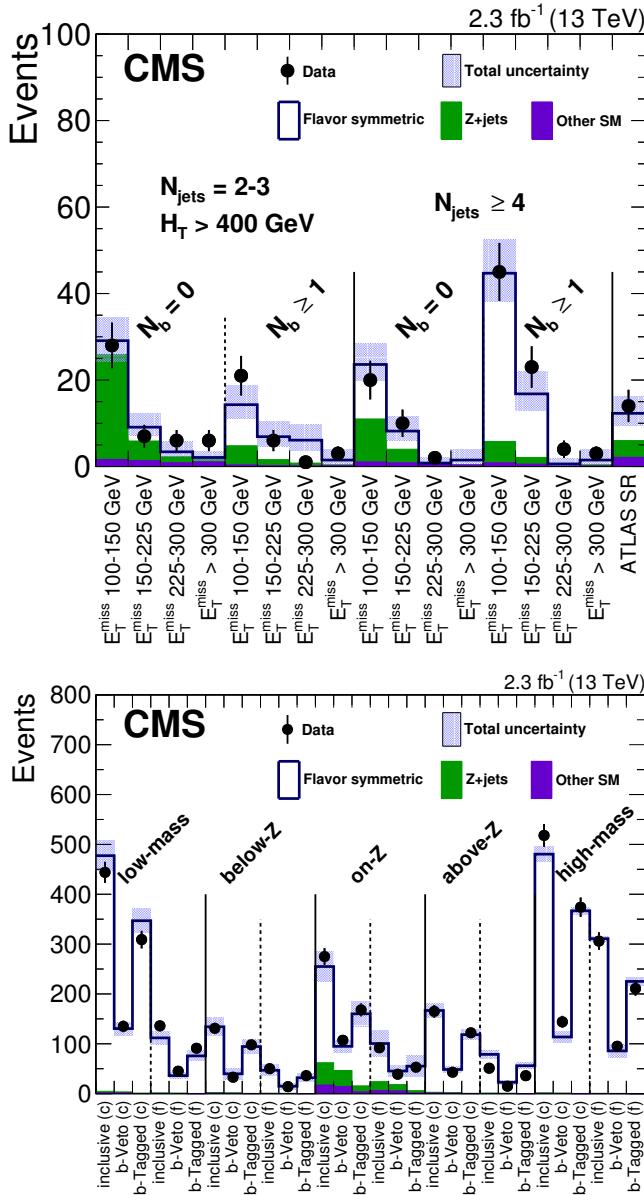
Figure 2. Overview of the results in all signal regions of the on-Z search (upper) and edge search (lower). The labels (c) and (f) refer to central and forward leptons. The data points in black are compared to the background expectation, which is shown as a solid blue line, together with its uncertainty, shown as a light blue band. The background components are shown as a stacked histogram with solid white color for the FS background, solid dark green for DY and dark purple for others.

these two regions of interest does not indicate the presence of any excess with respect to the SM expectation. The $3.0\,\sigma$ discrepancy between observation and prediction in the first bin of the $m_{\ell\ell}$ distribution in figure 3 (lower), has been studied in detail in several control regions with similar kinematic properties, and also by modifying the trigger, identification and isolation parameters of the leptons. Since no sign of any systematic effect has been found, we conclude this to be consistent with a statistical fluctuation.
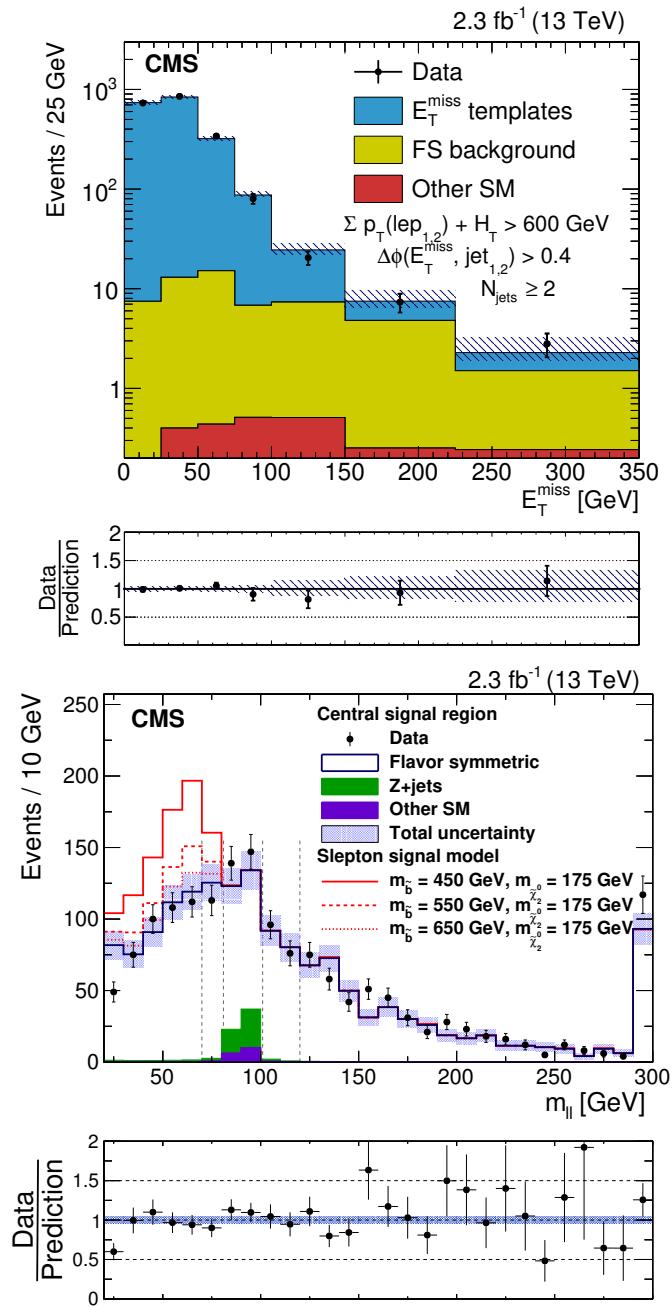
Figure 3. The E_T^{miss} and $m_{\ell\ell}$ distributions are shown for data and background predictions in the on-Z ATLAS signal region (upper) and for the region where CMS reported an excess in Run 1 (lower). The "Other SM" category includes WZ, ZZ, and other rare SM backgrounds taken from MC. The red lines in the $m_{\ell\ell}$ distribution correspond to three different slepton-edge signal hypotheses overlaid on top of the background distribution.

8 Interpretation

The results of the analysis are interpreted in terms of simplified models. In order to quantify the sensitivity of the on-Z and edge searches, two simulated samples with a scan of mass points of the GMSB and slepton-edge models have been produced. Upper limits on the cross section multiplied by the branching ratio have been calculated at a 95% confidence level (CL) using the CL_S criterion and an asymptotic formulation [36–39], taking into account the statistical and systematic uncertainties in the signal yields and the background predictions.

8.1 Systematic uncertainty in the signal yield

The systematic uncertainties in the signal yield have been evaluated by comparing the yields obtained after making a variation on the source of the systematic effect and the nominal yields. The uncertainty related to the measurement of the integrated luminosity is 2.7% [40]. The uncertainty in the corrections used to account for lepton identification and isolation efficiency differences between data and simulation is 2–4% in the signal acceptance. The uncertainty in the b tagging efficiency and mistag probability are 2–5% except for the edge signal regions without b tags, where they can range up to 20%. A further systematic uncertainty of 1–6% is considered on the scale factors correcting for the differences between fast and GEANT4 simulations for leptons. Dilepton trigger efficiencies ranging between 87% and 96%, and depending on the lepton flavor, are measured in data and applied as an overall scale factor to the signal simulation with a systematic uncertainty of 5%. The uncertainty in the jet energy scale varies between 0% and 8% depending on the signal kinematics. The uncertainty associated with the modeling of initial-state radiation (ISR) is 1–3%. The uncertainty in the correction to account for the pileup in the simulation is evaluated by shifting the inelastic cross section by $\pm 5\%$ and amounts to less than 6% on signal acceptance. Finally the statistical uncertainty on the number of simulated events is also considered and found to be in the range 1–20%, where the regions with low population of signal due to the acceptance in E_T^{miss} and/or b-tag multiplicity are most affected. These uncertainties are summarized in table 6.

8.2 Interpretation using simplified models

Since the GMSB model leads to a signature containing at least 6 jets in the final state, most of the sensitivity of the on-Z search is provided by the high jet multiplicity signal regions defined within the SRB category. We only consider the number of observed and predicted events in these regions to set limits on this model. The expected and observed limits are presented in figure 4. We exclude gluino masses up to 1.28 (1.03) TeV for large (small) neutralino masses. These results show an improvement with respect to the 8 TeV result where we obtained an observed and expected limits for gluino masses from 1.0 to 1.1 TeV.

The edge search is interpreted using the slepton-edge model, combining all the invariant mass, $|\eta|$, and mutually exclusive b tag regions. Figure 5 shows the exclusion contour in the plane of the masses of the bottom squark and the second neutralino. We exclude bottom squark masses up to 620 GeV at low $\widetilde{\chi}_2^0$ masses. The slight decrease in sensitivity at a

– 14 –

Source of uncertainty	Uncertainty (%)
Luminosity	2.7
Pileup	0–6
b tag modeling	2–20
Lepton reconstruction and isolation	2–4
Fast simulation scale factors	1–6
Trigger modeling	5
Jet energy scale	0–8
ISR modeling	1–3
Statistical uncertainty	1–20
Total uncertainty	7–32

**Table 6**. List of systematic uncertainties taken into account for the signal yields and typical values.
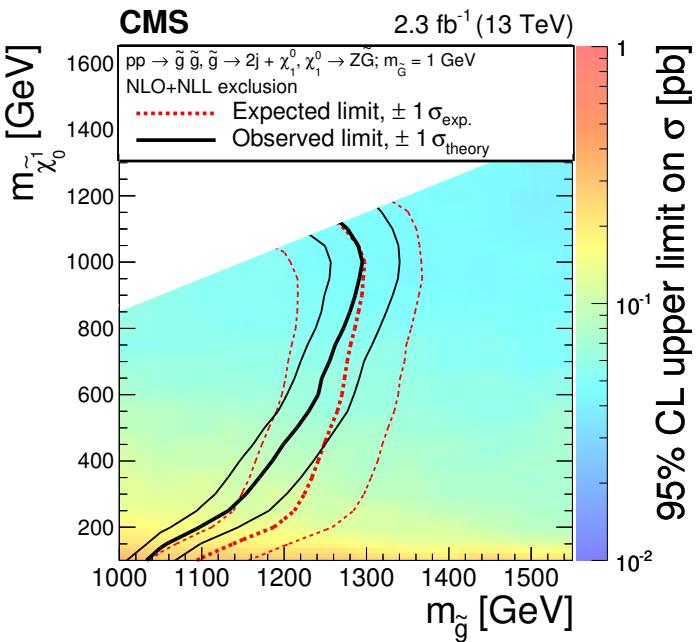
Figure 4. Cross section upper limits and exclusions contours at 95% CL with the results of the on-Z search interpreted in the GMSB model. The region to the left of the red dotted (black solid) line shows the masses which are excluded by the expected (observed) limit.

neutralino mass of ∼250 GeV corresponds to a kinematic edge located at ∼150–200 GeV. In this case the signal is spread evenly across all mass regions, while in the case of low (high) $\widetilde{\chi}_2^0$ masses, the majority of signal events fall into the low- (high-) mass bin, which increases the sensitivity for these mass points. The expected upper limits in the bottom squark/neutralino mass plane are similar to the limits set by the 8 TeV analysis. In two parameter regions the expected limits are slightly improved due to the introduction of new signal regions. The introduction of the below-Z and above-Z signal region increases the
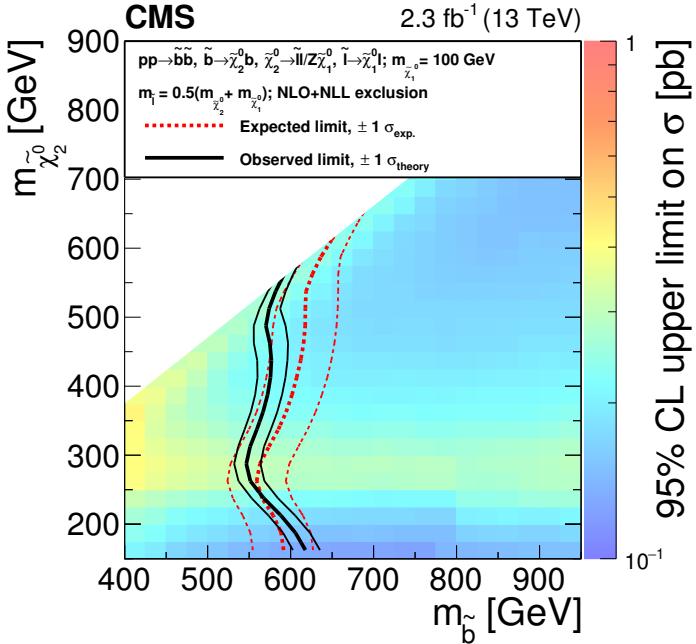
Figure 5. Cross section upper limits and exclusion contours at 95% CL with the results of the edge search interpreted in the slepton-edge model. The region to the left of the red dotted (black solid) line shows the masses which are excluded by the expected (observed) limit.

sensitivity of the analysis for sbottom masses of about 550 GeV and neutralino masses of around 250 GeV. The second improvement is the categorization according to the number of b-tagged jets that gives additional sensitivity close to the sbottom and neutralino mass diagonal where events with zero b-tagged jets become important since the produced b jets have less energy and are often not identified. The observed upper limits in the region with small neutralino masses have been largely improved with respect to the 8 TeV results from 500 to approximately 620 GeV.

9   Summary

A search for physics beyond the standard model has been presented in the opposite-sign, same-flavor lepton final state using a data sample of pp collisions collected at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 2.3 fb^{-1}, recorded with the CMS detector in 2015. Searches are performed for signals that either produce a kinematic edge, or a peak at the Z boson mass, in the dilepton invariant mass distribution. Comparing the observation to estimates for SM backgrounds obtained from data control samples, no statistically significant evidence for a signal has been observed. Notably, this is true for the two event selections where excesses of 2.6 and 3.0 σ significance had been observed by the CMS and ATLAS collaborations in their respective 8 TeV results [11, 12].

The search for events containing an on-shell Z boson is interpreted in a model of gauge-mediated supersymmetry breaking, where the Z bosons are produced in decay chains initiated through gluino pair production, and where the branching ratios have been fixed

to 100% to produce the desired topology. Gluino masses below 1.28 TeV for high neutralino masses and 1.03 TeV for low neutralino masses have been excluded, extending the previous exclusion limits derived from a similar analysis at 8 TeV by almost 200 GeV.

The search for an edge is interpreted in a simplified model based on bottom squark pair production, where dilepton mass edges are produced in decay chains containing the two lightest neutralinos and a slepton, where again the branching ratios have been fixed to produce the desired topology. Bottom squark masses below 550 and 620 GeV have been excluded, depending on the $\widetilde{\chi}_2^0$ mass. These limits are similar to previous exclusion limits except for low $\widetilde{\chi}_2^0$ masses where the excluded limits have been extended by about 100 GeV.

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33: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia

34: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico

35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland

36: Also at Institute for Nuclear Research, Moscow, Russia

37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia

39: Also at University of Florida, Gainesville, U.S.A.

40: Also at P.N. Lebedev Physical Institute, Moscow, Russia

41: Also at California Institute of Technology, Pasadena, U.S.A.

42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia

43: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy

44: Also at National Technical University of Athens, Athens, Greece

45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy

46: Also at National and Kapodistrian University of Athens, Athens, Greece

47: Also at Riga Technical University, Riga, Latvia

48: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

49: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

50: Also at Adiyaman University, Adiyaman, Turkey

51: Also at Mersin University, Mersin, Turkey

52: Also at Cag University, Mersin, Turkey

53: Also at Piri Reis University, Istanbul, Turkey

54: Also at Ozyegin University, Istanbul, Turkey

55: Also at Izmir Institute of Technology, Izmir, Turkey

56: Also at Marmara University, Istanbul, Turkey

57: Also at Kafkas University, Kars, Turkey

58: Also at Istanbul Bilgi University, Istanbul, Turkey

59: Also at Yildiz Technical University, Istanbul, Turkey

60: Also at Hacettepe University, Ankara, Turkey

61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom

62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom

63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain

64: Also at Utah Valley University, Orem, U.S.A.

65: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

66: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy

67: Also at Argonne National Laboratory, Argonne, U.S.A.

68: Also at Erzincan University, Erzincan, Turkey

69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey

70: Also at Texas A&M University at Qatar, Doha, Qatar

71: Also at Kyungpook National University, Daegu, Korea