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Search for supersymmetry in proton-proton collisions at $\sqrt{s} = 13$ TeV in events with high-momentum Z bosons and missing transverse momentum

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Abstract

A search for new physics in events with two highly Lorentz-boosted Z bosons and large missing transverse momentum is presented. The analyzed proton-proton collision data, corresponding to an integrated luminosity of 137 fb^{-1} , were recorded at $\sqrt{s} = 13$ TeV by the CMS experiment at the CERN LHC. The search utilizes the substructure of jets with large radius to identify quark pairs from Z boson decays. Backgrounds from standard model processes are suppressed by requirements on the jet mass and the missing transverse momentum. No significant excess in the event yield is observed beyond the number of background events expected from the standard model. For a simplified supersymmetric model in which the Z bosons arise from the decay of gluinos, an exclusion limit of 1920 GeV on the gluino mass is set at 95% confidence level. This is the first search for beyond-standard-model production of pairs of boosted Z bosons plus large missing transverse momentum.

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1 Introduction

The discovery of a Higgs boson in 2012 by the ATLAS and CMS experiments [1–3] at the CERN LHC fulfilled the predicted particle content of the standard model (SM). However, within the SM as a quantum field theory, the measured Higgs boson mass of around 125 GeV presents a special challenge as the calculated mass is unstable against corrections from loop processes when the theory is extended to higher mass scales. In the absence of extreme fine tuning [4–7] that would precisely cancel the divergent terms, the mass value can run up to the ultraviolet cutoff of the model at the Planck scale. This instability of the Higgs boson mass and the entire electroweak scale is known as the gauge hierarchy problem.

One widely studied extension of the SM is supersymmetry (SUSY) [8–10], which posits a partner for each SM particle differing in spin by one-half unit. For example, squarks \tilde{q} and gluinos \tilde{g} are the SUSY partners of quarks and gluons, respectively. Depending on the mass hierarchy of these new particles, they could resolve the gauge hierarchy problem by providing necessary radiative corrections to partly cancel the SM contributions. Furthermore, in R -parity conserving models [11, 12], SUSY particles are produced in pairs, while the lightest of them is neutral, stable, and weakly interacting. This lightest SUSY particle (LSP) provides a suitable candidate for dark matter [12], which is not described in the SM. The typical experimental signatures of pair-produced SUSY particles with R -parity conserving decay chains are jets, leptons, and large missing transverse momentum (p_T^{miss}).

As gluinos and squarks carry color charge, like their SM partners, they can be produced via the strong interaction; therefore among SUSY particles they have the highest production cross sections at hadron colliders for a given mass. Searches for direct decays of gluinos to quarks and the LSP have excluded $m(\tilde{g}) \lesssim 2$ TeV [13–16], depending on the model. The search described in this paper focuses on gluino decay cascades to Z bosons and the LSP via the next-to-lightest SUSY particle (NLSP). We consider a picture in which the NLSP and LSP are respectively the neutralinos $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$, mixed states of SUSY partners of the neutral Higgs and gauge bosons. Such a situation arises in SUSY scenarios like those described in Ref. [17] that seek to preserve “naturalness,” that is, minimal fine tuning of the SM to solve the gauge hierarchy problem, by admitting large mass splittings among the neutralinos (and charginos), leading to experimental signatures with vector bosons and p_T^{miss} in the final state. Figure 1 shows our signal process, expressed within the framework of simplified models [18–21], and referred to as T5ZZ. We further assume a heavy $\tilde{\chi}_2^0$, (with mass below that of the \tilde{g}), and a light $\tilde{\chi}_1^0$. This gives rise to energetic Z bosons along with large p_T^{miss} and additional soft quarks in the final state. In our model calculations we set the branching fraction for $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$ to 100%, the $\tilde{\chi}_1^0$ mass to 1 GeV, and the difference in mass between the \tilde{g} and $\tilde{\chi}_2^0$ to 50 GeV, though any set of mass parameters with a large [$\mathcal{O}(\text{TeV})$] mass difference between the $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ will result in highly energetic Z bosons. For the dominant $Z \rightarrow q\bar{q}$ decay at large momentum, the decay products can be contained in a single reconstructed jet with a large angular radius (wide-cone jet).

In this paper, we present a search in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV for events with two highly Lorentz-boosted, hadronically decaying Z bosons and large p_T^{miss} . The analysis is based on the LHC Run 2 data set with an integrated luminosity of 137 fb^{-1} , recorded by the CMS experiment during 2016–2018. The signature for a signal is a pair of wide-cone jets, each having a reconstructed mass consistent with the Z boson mass. This selection, in combination with large p_T^{miss} , greatly suppresses backgrounds from SM processes.

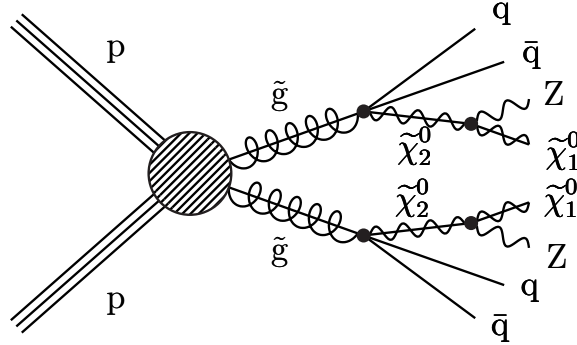


Figure 1: Signal diagram for the T5ZZ simplified model process. The assumed small mass splitting between the \tilde{g} and $\tilde{\chi}_2^0$ implies a massive $\tilde{\chi}_2^0$. We further assume a 100% branching fraction for the $\tilde{\chi}_2^0$ decay to the Z boson and $\tilde{\chi}_1^0$, leading to an energetic Z boson and large p_T^{miss} .

2 The CMS detector and trigger

A detailed description of the CMS detector and the associated coordinate system and kinematic variables is given in Ref. [22]. The main components of the apparatus are briefly discussed here. The core of CMS is a cylindrical superconducting solenoid with an inner diameter of 6 m that provides a 3.8 T axial magnetic field. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter are placed within the volume enclosed by the solenoid. Gas-ionization detectors are embedded in the steel flux-return yoke outside the solenoid to identify muons. The detector is nearly hermetic, permitting accurate measurements of p_T^{miss} .

The CMS trigger system is described in Ref. [23]. For this analysis, signal candidate events were recorded by requiring p_T^{miss} at the trigger level to exceed a threshold that varied between 100 and 120 GeV, depending on the LHC instantaneous luminosity. The efficiency of this trigger is measured in data to be greater than 97% for events satisfying the selection criteria described in Section 5. Additional triggers based on an isolated lepton or photon are used to select control samples for the background predictions.

3 Simulated event samples

The estimation of yields for the most prominent backgrounds is based on data in orthogonal signal-depleted control regions and is described in Section 6. Samples of Monte Carlo (MC) simulated events are used to test the background estimation, as well as to optimize the selection criteria. These samples include events with top quark pair production ($t\bar{t}$), and photon, W boson, or Z boson production accompanied by jets, denoted γ +jets, W +jets, or Z +jets, respectively.

The SM production of $t\bar{t}$, γ +jets, W +jets, Z +jets, and quantum chromodynamics (QCD) multijet events is simulated using the MADGRAPH5_aMC@NLO 2.2.2 [24, 25] generator for 2016 samples and MADGRAPH5_aMC@NLO 2.4.2 for 2017 and 2018 samples, all with leading order (LO) precision. The $t\bar{t}$ events are generated with up to three additional partons in the matrix element calculations, while the γ +jets, W +jets, and Z +jets events are generated with up to four additional partons. Single top quark events produced via the s channel, diboson events originating from WW , ZZ , or ZH production, and events from $t\bar{t}W$, $t\bar{t}Z$, and WWZ production, are generated with MADGRAPH5_aMC@NLO 2.2.2 at next-to-leading order (NLO) [26], except that WW events in which both W bosons decay leptonically are generated using POWHEG 2.0 [27–31] at NLO. The POWHEG generator is also used to describe t -channel production of single top quarks

as well as tW events. Normalization of the simulated background samples is derived from the most accurate cross section calculations available [24, 30–40], which generally correspond to NLO or next-to-NLO (NNLO) precision.

Samples of simulated signal events are generated at LO using MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) for the 2016 (2017 and 2018) samples, with up to two additional partons included in the matrix element calculations. The production cross sections are normalized to approximate NNLO plus next-to-next-to-leading logarithmic (NNLL) precision [41–52].

All simulated samples make use of PYTHIA 8.205 (2016) or 8.230 (2017 and 2018) [53] to describe parton showering and hadronization. The CUETP8M1 [54] tune was used to simulate both the SM background and signal samples for the 2016 simulation. To generate the 2017 and 2018 samples, PYTHIA was used, with the CP5 tune [55] for the backgrounds and the CP2 tune [55] for signals. Simulated samples generated at LO (NLO) with the CUETP8M1 tune use the NNPDF3.0LO (NNPDF3.0NLO) [56] PDF set, while those generated with the CP2 or CP5 tune use the NNPDF3.1LO (NNPDF3.1NNLO) [57] PDF set. Here PDF refers to the parton distribution function. The detector response is modeled with GEANT4 [58]. The simulated events are generated with a distribution of pp interactions per bunch crossing (“pileup”) that is adjusted to match the corresponding distribution measured in data.

To improve the description of initial-state radiation (ISR), the MADGRAPH5_aMC@NLO prediction of the jet multiplicity distribution is compared with data in a control sample enriched in $t\bar{t}$ events [13]. A correction factor derived therefrom is subsequently applied to the simulated $t\bar{t}$ and signal events. The correction is found to be unnecessary for $t\bar{t}$ samples that are generated with the CP5 tune, so it is not applied to those samples.

4 Event reconstruction

Individual particles are reconstructed with the CMS particle-flow (PF) algorithm [59], which identifies them as photons, charged or neutral hadrons, electrons, or muons. These objects are characterized kinematically by their transverse momentum p_T , pseudorapidity η , and azimuthal angle ϕ . Photon and electron candidates are required to satisfy $|\eta| < 2.5$, and muon candidates $|\eta| < 2.4$, within the fiducial coverage of the tracking and muon system, respectively.

The missing transverse momentum vector \vec{p}_T^{miss} is computed as the negative vector sum of the p_T of all of the PF candidates in an event, and its magnitude is denoted as p_T^{miss} [60]. The \vec{p}_T^{miss} is modified to account for corrections to the energy scale of the reconstructed jets in the event.

The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex, where the physics objects are the jets, clustered using the anti- k_T algorithm [61, 62] with the charged particle tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector p_T sum of those jets. Charged particle tracks associated with vertices other than the primary vertex are removed from further consideration.

Jets are defined as clusters of PF candidates formed by the anti- k_T algorithm with a distance parameter of 0.4 or 0.8. Quality criteria [63, 64] are imposed to suppress jets from spurious sources such as electronics noise in the calorimeters. The jet energies are corrected for the nonlinear response of the detector [65]. Jets with $p_T > 30$ GeV, $|\eta| < 2.4$, and a distance parameter of 0.4 (AK4) are used as specified in Section 5 to calculate some of the selection variables. For these jets, charged particles that emerge from vertices other than the primary one

are removed from the list of PF candidates used for the jet clustering. The expected contribution from neutral particles from pileup is removed using the effective area technique [64, 66].

The hadronically decaying Z boson candidates are reconstructed as wide-cone jets with a distance parameter of 0.8 (AK8). These AK8 jets are reclustered from their original constituents using the “soft drop” method [67] to remove soft, wide-angle radiation that can adversely impact the mass measurement of the jet. Contributions from pileup in these jets are removed with the PUPPI technique [68]. The soft drop mass m_{jet} is then used to identify jets from $Z \rightarrow q\bar{q}$ decays. No requirements on their flavor content are imposed.

The identification of b jets (b jet tagging) is performed by applying, to the AK4 jets, a version of the combined secondary vertex algorithm based on deep neural networks [69] (DeepCSV). A working point (“medium”) of this algorithm is used that has a tagging efficiency for b jets of 68%, and a misidentification probability of approximately 1% for gluon and light-flavor quark jets and 12% for charm quark jets.

As described in Section 5, events with leptons or photons are vetoed in the search sample selection. Electron and muon candidates are identified as described in Refs. [70] and [71], respectively. To suppress jets erroneously identified as leptons or genuine leptons from hadron decays, electron and muon candidates are subjected to an isolation requirement. The isolation criterion is based on a variable I , which is the scalar p_T sum of charged hadron, neutral hadron, and photon PF candidates within a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ around the lepton direction, divided by the lepton p_T . The expected contributions of neutral particles from pileup are subtracted [64, 66]. The radius of the cone, in radians, is 0.2 for lepton $p_T < 50$ GeV, $10 \text{ GeV}/p_T$ for $50 \leq p_T \leq 200$ GeV, and 0.05 for $p_T > 200$ GeV. The decrease in cone size with increasing lepton p_T accounts for the increased collimation of the decay products from the lepton’s parent particle as the Lorentz boost of the latter increases [72]. The isolation requirement is $I < 0.1$ (0.2) for electrons (muons).

To further suppress events with leptons from hadron decays and single-prong hadronic τ lepton decays, the event selection veto is extended to include isolated charged-particle tracks not identified as electrons or muons by the criteria of the previous paragraph. For these candidates the scalar p_T sum of all other charged-particle tracks within $\Delta R = 0.3$ around the track direction, divided by the track p_T , is required to be less than 0.2 if the track is identified as a PF electron or muon, and less than 0.1 otherwise. Isolated tracks are required to satisfy $|\eta| < 2.4$.

Photon candidates are identified as described in Ref. [73], using the “loose” working point, and with an isolation requirement based on the individual sums of energy from charged and neutral hadrons and electromagnetically interacting particles, excluding the photon candidate itself, within $\Delta R = 0.3$ around the direction of the photon candidate. Each of the three individual sums, corrected for pileup, is required not to exceed a threshold that depends on the calorimeter geometry.

5 Event selection

We select events with large jet activity and p_T^{miss} , no leptons or photons, and wide-cone jets from Lorentz-boosted, hadronically decaying Z bosons. Control regions for the determination of backgrounds are also defined.

The observables used to characterize candidate events are:

- N_{jet} , the number of AK4 jets in the event;

- p_T^{miss} ;
- $H_T = \sum_{\text{AK4 jets}} |\vec{p}_T|$;
- $\Delta\phi_{j, \vec{H}_T^{\text{miss}}}$, the azimuthal angle between the \vec{p}_T of the j^{th} AK4 jet and $\vec{H}_T^{\text{miss}} = -\sum_{\text{AK4 jets}} \vec{p}_T$;
- m_T^i , the transverse mass [74] of a system comprising the i^{th} isolated track and \vec{p}_T^{miss} ;
- $\Delta R_{Z,b}$, the angular separation between a wide-cone jet and a b-tagged jet.

The following requirements define the event selection:

1. $N_{\text{jet}} \geq 2$;
2. $p_T^{\text{miss}} > 300 \text{ GeV}$;
3. $H_T > 400 \text{ GeV}$;
4. $|\Delta\phi_{j, \vec{H}_T^{\text{miss}}}| > 0.5$ (0.3) for the first two (up to next two, if $N_{\text{jet}} > 2$) AK4 jets ranked in descending order of p_T ;
5. no identified isolated photon, electron, or muon candidate with $p_T > 10 \text{ GeV}$;
6. no isolated track with $m_T < 100 \text{ GeV}$ and

$$p_T > \begin{cases} 5 \text{ GeV} & \text{if the track is identified as a PF electron or muon,} \\ 10 \text{ GeV} & \text{otherwise.} \end{cases}$$
7. at least two AK8 jets with $p_T > 200 \text{ GeV}$;
8. m_{jet} of the two highest p_T AK8 jets between 40 and 140 GeV;
9. $\Delta R_{Z,b} > 0.8$, for the second-highest p_T AK8 jet and any b-tagged jet.

The $\Delta\phi_{j, \vec{H}_T^{\text{miss}}}$ requirements suppress background from QCD multijet events, as well as those from hadronic Z and W boson decay, for which \vec{H}_T^{miss} is usually aligned along a jet direction. The m_T requirement restricts the isolated track veto to situations consistent with a W boson decay.

The first six requirements define an inclusive ‘‘hadronic baseline’’ selection, and the last three specify the further selection of events with jet pairs that include pairs of hadronically decaying Z boson candidates. The accepted range in m_{jet} is chosen to reject the bulk of nonresonant SM processes on the low side, and the peak from boosted top quark jets on the high side, while including sidebands around the Z boson peak to facilitate the determination of the background. The $\Delta R_{Z,b}$ requirement suppresses backgrounds from $t\bar{t}$ and single top quark events in which a top quark is reconstructed as a b-tagged jet together with a W boson reconstructed as an AK8 jet.

Figure 2 shows the simulated SM background components and two example signal mass points for events selected without and with the three Z boson requirements. The main sources of SM background are Z+jets, W+jets, and $t\bar{t}$, which can yield large p_T^{miss} accompanied by AK8 jets formed from random combinations of hadrons. In the case of Z+jets, large p_T^{miss} comes from the $Z \rightarrow \nu\bar{\nu}$ decay. For W+jets and $t\bar{t}$, p_T^{miss} arises from a leptonically decaying W boson where the charged lepton is undetected. Smaller background contributions arise from the QCD multijet

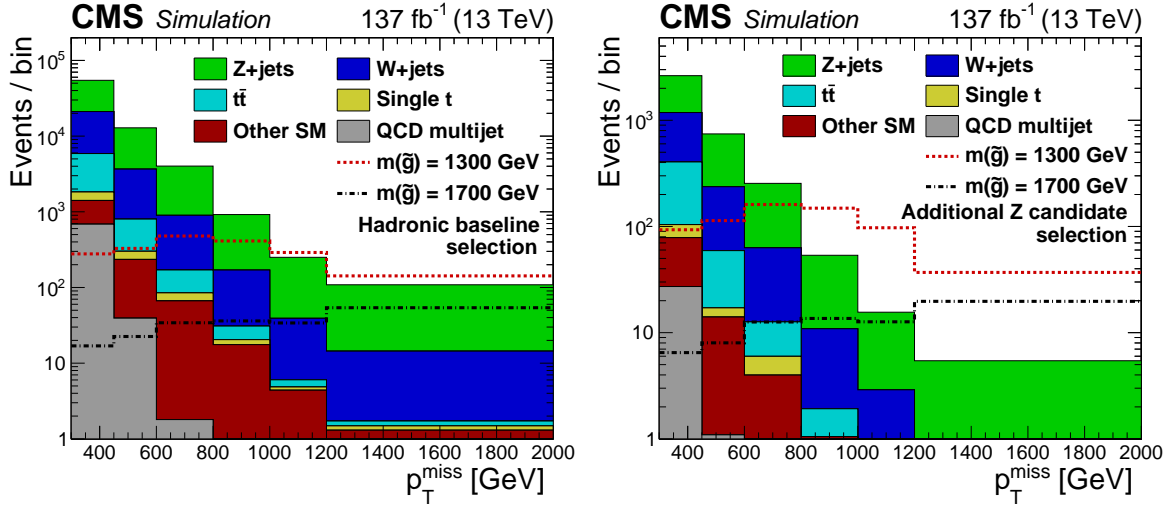


Figure 2: Distributions of p_T^{miss} for simulated SM backgrounds (stacked histograms), with only the hadronic baseline selection (left), and after the additional Z candidate selection (right). Expected signal contributions for two example mass points (dotted lines) are also shown. The last bin includes the overflow events.

events in which the measurement of a jet's energy suffers a large fluctuation, production of single top quarks, and other SM processes, such as diboson production and $t\bar{t}$ pairs accompanied by vector bosons.

An event satisfying the above criteria lies in the search region (SR) if, in addition, both of the two highest p_T AK8 jets have m_{jet} values in the range $[70, 100]$ GeV (as discussed in Section 6.1). Relative to the hadronic baseline selection, about 21% of signal events are retained in the SR, along with 0.5% of background events. The p_T^{miss} distribution in the SR is divided into six bins, with lower boundaries at 300, 450, 600, 800, 1000, and 1200 GeV.

6 Background estimation

This section focuses on the estimation of SM backgrounds in each p_T^{miss} bin. We first describe the method based on control samples in data, then follow with a description of the performance of the method in simulation (MC closure), and lastly deal with the uncertainty in the p_T^{miss} dependence (shape uncertainty) based on the data observed in the validation samples.

6.1 Background estimation method

Control regions (CRs) are formed from the events in which one or both of the highest p_T (leading) and second-highest p_T (subleading) jets lie in the m_{jet} sideband $[40, 70] \cup [100, 140]$ GeV. Figure 3 shows the definition of the SR and CRs in the plane of jet masses of the leading and subleading jets. In addition, validation samples are selected by inverting the lepton or photon veto requirement.

The first step of the method is to determine the background normalization $\mathcal{B}_{\text{norm}}$ integrated over all p_T^{miss} bins above 300 GeV. We fit the m_{jet} distribution for the leading jet in the leading-jet mass sideband, defined as the sample having the subleading jet m_{jet} within, and the leading jet m_{jet} outside, the Z signal window. The bulk of the background is from nonresonant SM contributions, which can be modeled with a smoothly falling shape. The nominal fit is performed with a linear function, as shown in Fig. 4.

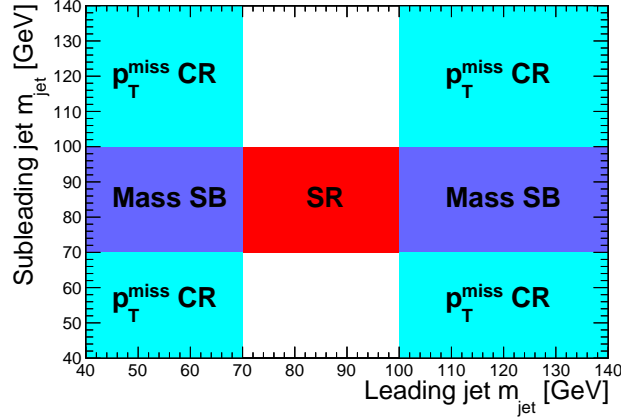


Figure 3: Definition of the search and control regions in the plane of subleading vs. leading jet mass. The search region (red central box), with both m_{jet} values lying within the Z signal window, defines the acceptance for potential signal; the leading-jet mass sideband (dark blue), with subleading jet within and leading jet outside the signal window, is used to measure the background normalization; the $p_{\text{T}}^{\text{miss}}$ CR (light blue), with both leading- and subleading-jet m_{jet} values lying outside the signal window, is used to derive the $p_{\text{T}}^{\text{miss}}$ shape in the search region.

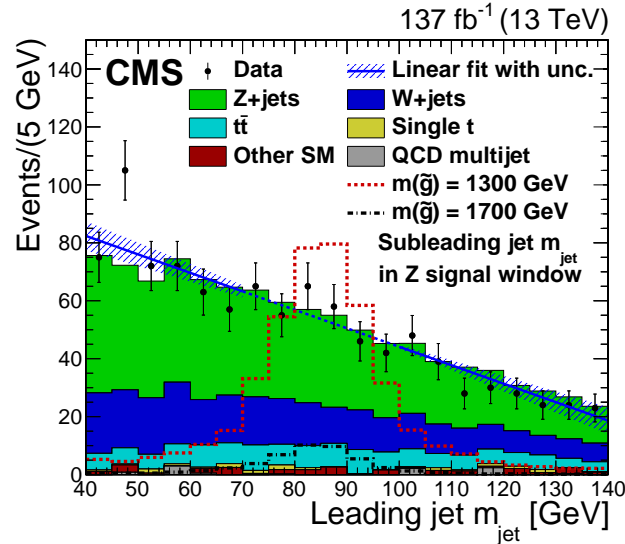


Figure 4: Leading AK8 jet m_{jet} shape fit in the mass sidebands. The Z candidate selection is applied and the subleading AK8 jet m_{jet} value is required to lie in the Z signal window. The blue hatched region represents the ± 1 standard deviation uncertainty in the fit to the mass sideband performed with a linear function, which is indicated by the blue line. The stacked histogram shows the background from simulation scaled to the data. Expected signal contributions for two example mass points are also shown.

The uncertainties in $\mathcal{B}_{\text{norm}}$ include a statistical component from the fit, and a systematic one due to the choice of the fitting function. To obtain the statistical uncertainty due to the interpolation of the fit into the SR, pseudo-experiments generated from the background model are fitted using a linear function with free slope and normalization. The Gaussian width of the resulting distribution of the yields in the Z signal window, 10.7 events, is taken as the statistical uncertainty in the total background prediction.

To test if the linear function is adequate to represent the m_{jet} distribution, we consider higher-order polynomials as alternative functions. We check Chebyshev polynomials of up to the fourth order. The largest variation in the fitted yield with respect to the nominal one, 10.9 events, comes from a fit with a third-order Chebyshev polynomial, and is taken as an additional uncertainty attributable to the fit shape. Considering the statistical uncertainty described above, this results in $\mathcal{B}_{\text{norm}} = 325 \pm 15$.

To determine the distribution of background events in the $p_{\text{T}}^{\text{miss}}$ bins, we rely on an underlying assumption that $p_{\text{T}}^{\text{miss}}$ and m_{jet} have minimal correlation. To derive the $p_{\text{T}}^{\text{miss}}$ shape in the SR, a nonoverlapping CR is used in which both leading and subleading AK8 jets have m_{jet} in the mass sideband. This is referred to as the $p_{\text{T}}^{\text{miss}}$ CR (Fig. 3). In each of the six $p_{\text{T}}^{\text{miss}}$ bins, we calculate the background prediction as

$$\mathcal{B}_i = \mathcal{T} N_i^{\text{CR}}, \quad (1)$$

where N_i^{CR} is the yield in $p_{\text{T}}^{\text{miss}}$ bin i in the $p_{\text{T}}^{\text{miss}}$ CR, and the transfer factor,

$$\mathcal{T} \equiv \frac{\mathcal{B}_{\text{norm}}}{\sum_i N_i^{\text{CR}}} = 0.198 \pm 0.009, \quad (2)$$

scales the $p_{\text{T}}^{\text{miss}}$ CR yield to that of the SR. The uncertainty in \mathcal{T} includes both statistical and systematic uncertainties in $\mathcal{B}_{\text{norm}}$.

6.2 Background closure in simulation

The background estimation method based on control samples in data is tested by applying the procedure to MC simulation. We perform this closure test in two steps.

The main assumption to verify is the lack of correlation between the AK8 jet mass and $p_{\text{T}}^{\text{miss}}$ shape. Figure 5 shows the results of a test of this assumption, where the simulated sample size permits a distribution in relatively fine steps. The plots compare the $p_{\text{T}}^{\text{miss}}$ shape in the search and control regions, for the two main background processes. In both cases we see that the $p_{\text{T}}^{\text{miss}}$ shapes are consistent between the two regions.

For the closure test of the background estimation method we calculate the background prediction in each $p_{\text{T}}^{\text{miss}}$ bin [Eq. (1)] and compare these predictions with the background yields taken directly from simulation. The results of this test, shown in Fig. 6, demonstrate good agreement within the statistical precision of the test. To account for the uncertainties in the comparison, we assign the relative difference between the prediction and direct observation as a nonclosure systematic uncertainty in the $p_{\text{T}}^{\text{miss}}$ shape. This difference ranges from 1 to 20%, where the variations in the four lower $p_{\text{T}}^{\text{miss}}$ bins are treated as being anti-correlated with those in the higher $p_{\text{T}}^{\text{miss}}$ bins to give a systematic uncertainty in the $p_{\text{T}}^{\text{miss}}$ shape that does not affect the overall normalization of the background estimation.

6.3 The $p_{\text{T}}^{\text{miss}}$ shape uncertainty

While the background estimation method is shown to close well in simulation, we additionally verify in data how well the $p_{\text{T}}^{\text{miss}}$ CR models the $p_{\text{T}}^{\text{miss}}$ shape in the Z signal window. In

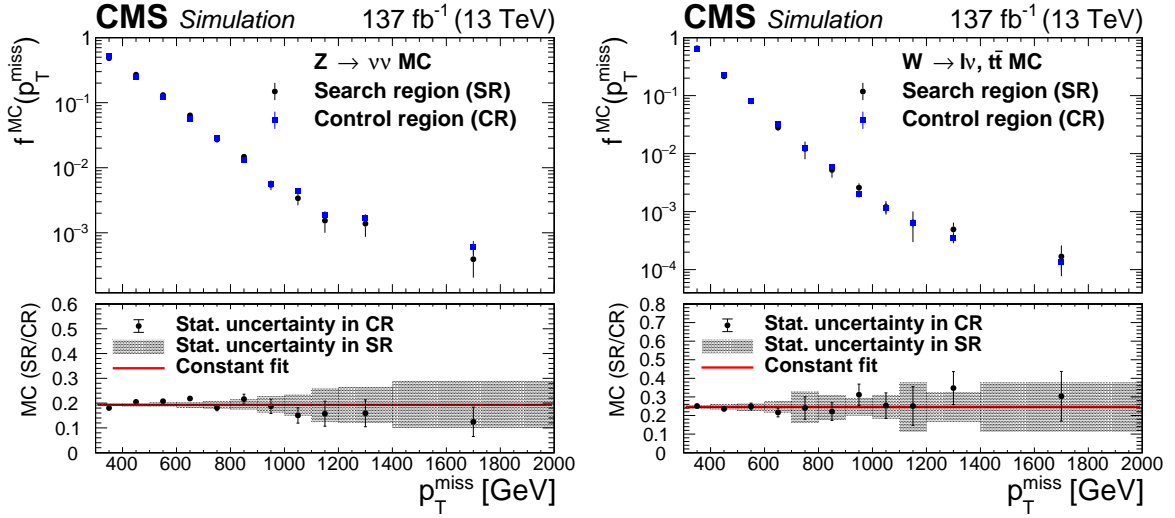


Figure 5: Comparison of the p_T^{miss} shape in the search and control regions in simulation. The upper panels show the unit-normalized p_T^{miss} distributions $f^{\text{MC}}(p_T^{\text{miss}})$ in the two regions, while the lower panels show the ratio of the number of events in the search region to that in the control region. This comparison is done for two main background components: $Z \rightarrow \nu\bar{\nu}$ (left) and $t\bar{t}$ plus W +jets (right). In the lower panel the statistical uncertainties in the search and control region yields are denoted by the shading and vertical bars, respectively, and a fit to a constant is included to show the average ratio.

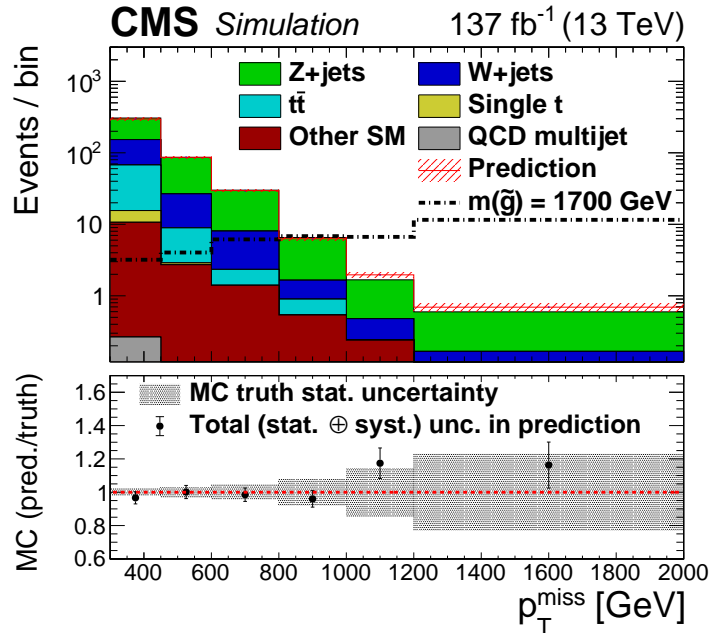


Figure 6: Results of the closure test in which the background estimation method based on control samples in data is applied to simulation and compared with the direct yield, in the analysis search bins. Expected signal contribution for one example mass point is also shown. The lower panel shows the ratio of the prediction to the direct yield. The gray band shows the statistical uncertainty in the direct yield, and the error bars on the points represent the total uncertainty in the prediction.

particular, two validation samples are used to compare the p_T^{miss} shape obtained from the p_T^{miss} CR with the one obtained in the Z signal window, used to define our SR, for the main background components. A photon validation sample is used as a proxy for the Z+jets background component, while a single-lepton sample is used to validate the modeling of $t\bar{t}$ and W+jets combined.

We select the photon validation sample from events recorded with a single-photon trigger, replacing the photon veto with the requirement of exactly one photon, defined as in Section 4. The photon p_T is used to emulate the p_T^{miss} from the Z boson when the latter decays to neutrinos. The lower- p_T trigger threshold for the photon compared with the p_T^{miss} threshold in the signal trigger allows us to consider the photon validation sample down to 200 GeV in photon p_T as a proxy for p_T^{miss} . To enhance the event count in this sample, we do not require a threshold on $\Delta R_{Z,b}$ since there is a low risk of heavy flavor contamination. All other event selection requirements are the same as for the SR of the analysis.

For the single-lepton sample, the same p_T^{miss} trigger is used as for the SR. The same offline criteria are also applied, with the exception that the p_T^{miss} requirement is relaxed to 200 GeV to gain a longer lever arm for the p_T^{miss} shape comparison, and the lepton vetoes are applied only after selecting exactly one electron or muon.

Figure 7 shows the p_T^{miss} shape comparison for the photon and single-lepton data. Both ratios are consistent with being independent of p_T^{miss} , as expected from the MC closure test, albeit within the limited statistical precision of the data. To account for possible shape differences between the search and control regions, we apply a systematic uncertainty in the p_T^{miss} shape calculated using the photon and single-lepton samples. The uncertainty is the difference with respect to a uniform distribution of a fit to the SR/CR distribution with a linear function having a free slope parameter. This results in uncertainties ranging from 0–33% in the Z+jets background based on the photon validation sample, and 1–14% in the combined $t\bar{t}$ and W+jets background based on the single-lepton validation sample. Weighting these by the proportions of those components in the total background yields uncertainties of 2–30%, depending on the p_T^{miss} bin.

7 Systematic uncertainties

The uncertainties in the SM background prediction are described in Section 6, along with the description of the background estimation method. The uncertainties in the background normalization include the statistical uncertainty from the mass sideband fit interpolation as well as the systematic one derived from alternative fit functions. The uncertainties in the p_T^{miss} shape include the statistical uncertainties of the p_T^{miss} CR. The systematic uncertainties only affect the p_T^{miss} shape without changing the background normalization. These are derived from the MC closure test and data validation samples. All of these systematic uncertainties are summarized in the upper section of Table 1.

The sources of uncertainty in the signal efficiency affect the signal normalization, the signal p_T^{miss} shape, or both, as indicated in Table 1. The uncertainties in the integrated luminosity are 2.5% [75], 2.3% [76], and 2.5% [77] for 2016, 2017, and 2018, respectively. The trigger, lepton veto, and isolated-track veto efficiencies are measured in data validation samples and their statistical uncertainties propagated to the signal yields. The ISR modeling in the simulation is adjusted to match the efficiencies measured in data events enriched in dileptonic $t\bar{t}$ production and decay, and the uncertainty in this correction is propagated to the signal yields. To evaluate the uncertainty associated with the renormalization (μ_R) and factorization (μ_F) scales, each

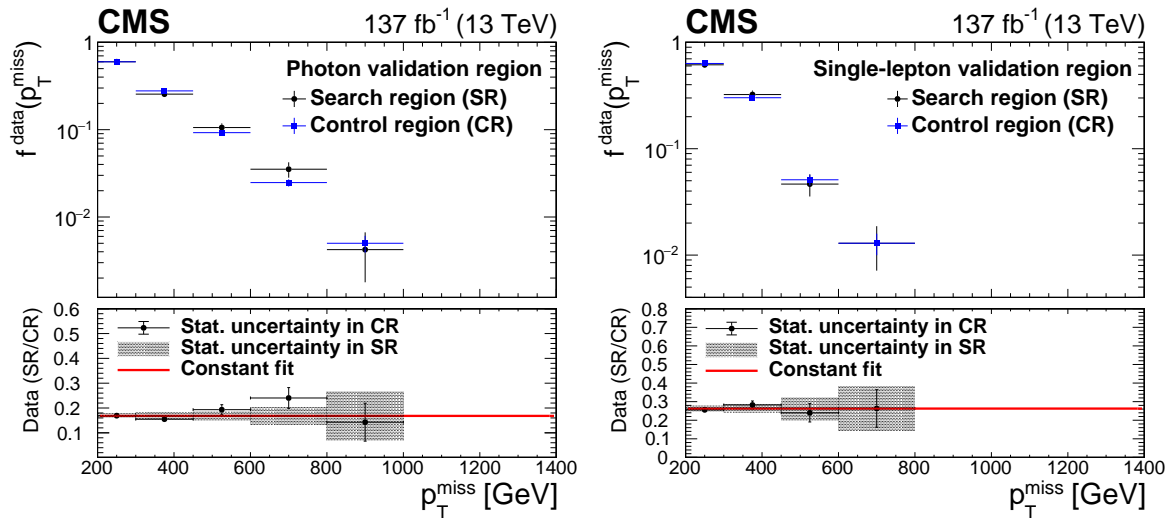


Figure 7: Comparison of the p_T^{miss} shape between the Z signal window and p_T^{miss} control region for the photon (left) and single-lepton (right) validation samples in data. The upper panels show the unit-normalized p_T^{miss} distributions $f^{\text{data}}(p_T^{\text{miss}})$ in the two regions, while the lower panels show the ratio of the number of events in the search region to that in the control region. A fit to a constant is included in the lower panels to show the average ratio. The horizontal bars on the markers indicate the widths of the search bins. In the lower panel the statistical uncertainties in the search and control region yields are denoted by the shading and vertical bars, respectively.

Table 1: Summary of systematic uncertainties, where the ranges refer to different p_T^{miss} bins. In the last column we distinguish uncertainties that affect the normalizations (“norm.”), the shapes of distributions, or both.

Source of uncertainty	Effect on yields (%)	norm. or shape
Uncertainties in the background predictions		
Fit, normalization	3.3	norm.
Fit, shape	3.4	norm.
m_{jet} CR statistics	3–100	shape
MC closure	2–13	shape
Data validation	2–30	shape
Uncertainties in the signal yields		
Integrated luminosity	2.3–2.5	norm.
Trigger efficiency	2.0	both
Isolated lepton and track vetoes	2.0	norm.
Jet quality requirements	1.0	norm.
ISR modeling	1–2	both
μ_R and μ_F scales	0.2–0.5	both
JEC	2–4	both
JER	5–6	both
MC statistics	1–2	both
m_{jet} resolution	1–3	norm.

scale is varied independently by a factor of 2.0 and 0.5 [78, 79]. Uncertainties in the simulation of pileup are found to be of the order of 0.02%; thus no associated uncertainty is applied.

The jet momenta in MC samples are smeared to match the jet energy resolution (JER) in data. The jet energy corrections (JECs) are varied using p_T - and η -dependent uncertainties. Both effects are propagated to the jet-dependent variables, including p_T^{miss} , H_T , and $\Delta\phi_{j, \vec{H}_T^{\text{miss}}}$, and are varied within the uncertainty of the corrections to derive a systematic uncertainty in the signal yields. The efficiency of the jet quality requirements used to suppress events with misreconstructed jets is found to differ by 1% between data and simulation, and this is applied as a systematic uncertainty. The difference in the resolution of m_{jet} between data and simulation is applied as a smearing factor to the MC events, and the statistical uncertainty in the size of the correction is included as a systematic uncertainty in the corresponding selection efficiency. Lastly, the statistical precision due to the limited event count in the simulated samples is accounted for as an uncertainty.

The systematic uncertainties associated with the signal yields are evaluated assuming that the contributions from the three years of data taking are fully correlated. The total systematic uncertainties in the signal yields range from 0.2 to 6%.

8 Results

The background predictions and observed yields for each p_T^{miss} bin are shown in Fig. 8 and Table 2. The table also gives the inputs to the prediction calculation, Eq. (1). The observations are found to be consistent with the SM predictions within uncertainties, and no evidence for SUSY is observed. We calculate upper limits on the gluino pair-production cross section using a maximum-likelihood fit in which the free parameters are the signal strength μ and the nuisance parameters associated with the systematic uncertainties in the background and signal model. The uncertainty in the normalization of the background is represented with a lognormal function correlated across all p_T^{miss} bins, while the p_T^{miss} CR statistical uncertainties are assigned as uncorrelated. The MC closure and data-MC agreement uncertainties are assigned as correlated across p_T^{miss} bins.

We evaluate 95% confidence level (CL) upper limits based on the asymptotic form of a likelihood ratio test statistic [80], in conjunction with the CL_s criterion described in Refs. [81–83]. The test statistic is $q(\mu) = -2 \ln(\mathcal{L}_\mu / \mathcal{L}_{\text{max}})$, where \mathcal{L}_μ is the maximum likelihood for fixed μ , and \mathcal{L}_{max} is the same determined by allowing all parameters, including μ , to vary.

Expected and observed 95% CL upper limits, and the predicted gluino pair-production cross sections, are shown in Fig. 9, taking $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ and $m(\tilde{g}) - m(\tilde{\chi}_2^0) = 50 \text{ GeV}$. The observed (expected) gluino mass limits reach as high as 1920 (2060) GeV. The observed limit is 1.4 standard deviations weaker than the expected one due to the mild excesses observed in the two highest p_T^{miss} bins. The sensitivity of the search is independent of $m(\tilde{\chi}_1^0)$ values that are small compared with $m(\tilde{\chi}_2^0)$, and of $m(\tilde{\chi}_2^0)$ values large enough to ensure Lorentz-boosted Z boson daughters. A gradual loss of signal efficiency occurs with increasing $\Delta m(\tilde{g}, \tilde{\chi}_2^0)$ as quarks from the gluino decay that form AK8 jets with p_T above the 200 GeV threshold displace Z jets as leading or subleading in p_T .

9 Summary

Results are presented of a search for events with two hadronically decaying, highly energetic Z bosons and large transverse momentum imbalance, in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$. The sample corresponds to an integrated luminosity of 137 fb^{-1} . The signature for a Z boson candidate is a wide-cone jet having a measured mass compatible with the Z boson mass. Yields

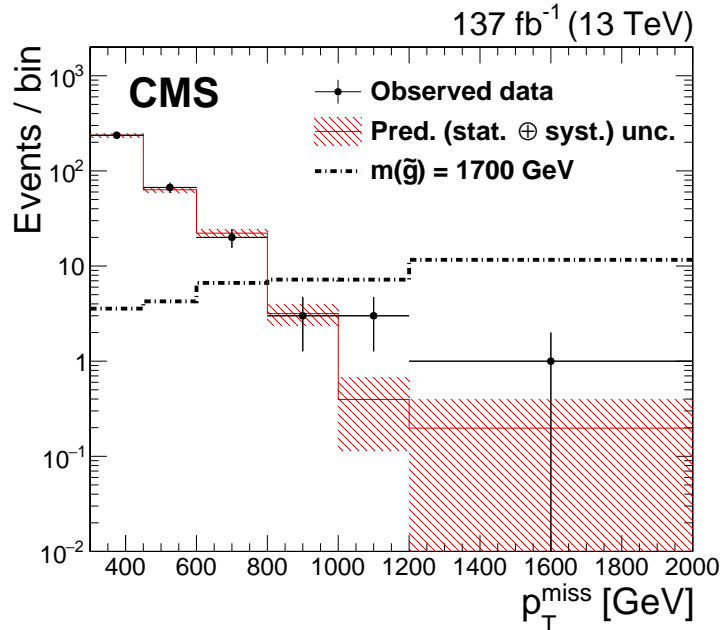


Figure 8: Observed data and background prediction as functions of p_T^{miss} . The horizontal bar associated with each data point represents the width of the corresponding bin. The red hatched region denotes the expected statistical and systematic uncertainties added in quadrature. Expected signal contribution for one example mass point is also shown.

Table 2: Number of events in the p_T^{miss} CR, transfer factor, background prediction, and observed yield in each of the six p_T^{miss} bins. Where two uncertainties are quoted, the first is statistical and the second systematic. The systematic uncertainties in the background prediction include the shape uncertainties in addition to the uncertainty in \mathcal{T} . Also listed in the last column is the number of expected signal events and corresponding statistical uncertainties for one example mass point.

p_T^{miss} bin (GeV)	p_T^{miss} CR yield N^{CR} (events)	Transfer factor \mathcal{T}	Background prediction \mathcal{B} (events)	Observed yield (events)	Exp. signal $m(\tilde{g}) = 1700$ GeV (events)
300–450	1191	0.198 ± 0.009	$236 \pm 7 \pm 16$	237	3.5 ± 0.1
450–600	320		$63.3 \pm 3.6 \pm 3.3$	67	4.3 ± 0.1
600–800	112		$22.2 \pm 2.0 \pm 1.9$	20	6.6 ± 0.1
800–1000	16		$3.2 \pm 0.8 \pm 0.5$	3	7.2 ± 0.1
1000–1200	2		$0.40 \pm 0.29 \pm 0.11$	3	7.2 ± 0.1
>1200	1		$0.20 \pm 0.20 \pm 0.06$	1	11.6 ± 0.1

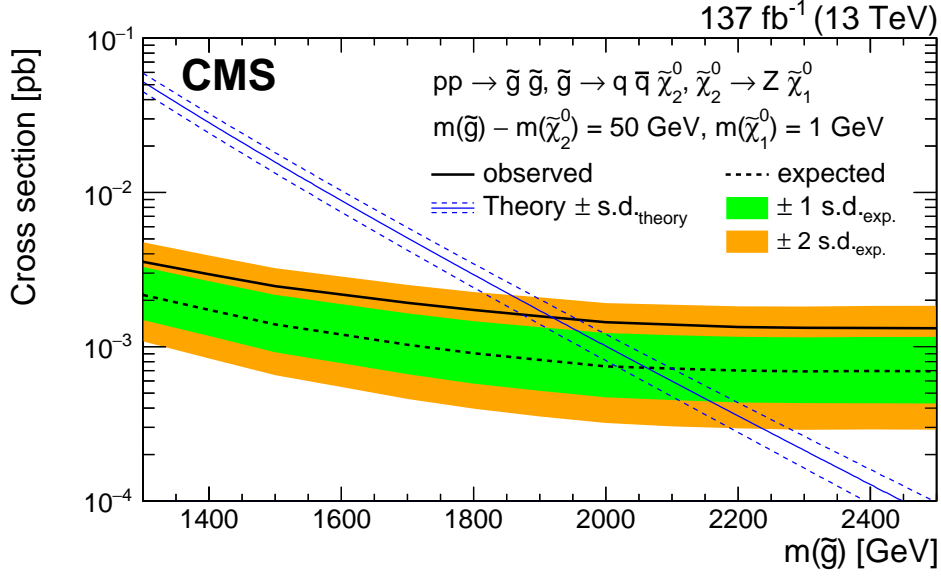


Figure 9: The 95% CL upper limit on the production cross section for the T5ZZ signal model as a function of the gluino mass. The solid black curve shows the observed exclusion limit. The dashed black curve presents the expected limit while the green and yellow bands represent the ± 1 and ± 2 standard deviation uncertainty ranges. The approximate-NNLO+NNLL cross sections [41–45] are shown in the solid blue curve while the dashed blue curves show their theoretical uncertainties [84]. The T5ZZ model assumes a 100% branching fraction for the $\tilde{\chi}_2^0$ to decay to the Z boson and $\tilde{\chi}_1^0$.

from standard model background processes, which are small for events with the largest transverse momentum imbalance, are estimated from the data in jet mass sidebands. No evidence for physics beyond the standard model is observed. The reach of the search is interpreted in a simplified supersymmetric model of gluino pair production in which each gluino decays to a low-momentum quark pair and the next-to-lightest supersymmetric particle (NLSP), and the latter decays to a Z boson and the lightest supersymmetric particle (LSP). With the further assumption of a large mass splitting between the NLSP and LSP, the data exclude gluino masses below 1920 GeV at 95% confidence level. This is the first search for beyond-standard-model production of pairs of boosted Z bosons plus large missing transverse momentum.

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