Measurement of the Z boson differential production cross section using its invisible decay mode \((Z \to \nu \bar{\nu})\) in proton-proton collisions at \(\sqrt{s} = 13\) TeV

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Abstract

Measurements of the total and differential fiducial cross sections for the Z boson decaying into two neutrinos are presented at the LHC in proton-proton collisions at a center-of-mass energy of 13 TeV. The data were collected by the CMS detector in 2016 and correspond to an integrated luminosity of 35.9 fb\(^{-1}\). In these measurements, events are selected containing an imbalance in transverse momentum and one or more energetic jets. The fiducial differential cross section is measured as a function of the Z boson transverse momentum. The results are combined with a previous measurement of charged-lepton decays of the Z boson.

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1 Introduction

The precision measurements of the production of neutrino pairs via the Z boson is an important aspect of the LHC program for testing the standard model (SM) of particle physics. They provide a reference for various other measurements in the high energy regime, especially when searching for contributions beyond the SM, where the Z boson production constitutes an important background process. Expectations for the Z boson cross section have been calculated up to next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD) and up to next-to-leading order (NLO) in electroweak (EW) production, which correspond to a full NLO EW theory \[1\text{-}4\] supplemented by two-loop Sudakov EW logarithms \[5\text{-}8\]. The calculations are limited by the uncertainties in parton distribution functions (PDFs), and higher-order QCD and EW corrections \[9\].

Measurements of the differential Z boson production cross sections have been reported by both ATLAS \[10\text{-}13\] and CMS \[14\text{-}17\] at the CERN LHC using charged leptons (electrons or muons) in the final states. However, no differential measurement of the Z bosons identified via their decays to a pair of neutrinos have yet been reported at a hadron collider. The Z boson branching fraction to neutrinos is about a factor of six times that to electrons or muons, which leads to a smaller statistical uncertainty. This can only be fully exploited at large transverse momenta of the Z boson \((p_T^Z)\), above \(\approx 500\text{ GeV}\), where the measurement of the missing transverse momentum \((p_T^{\text{miss}})\) is sufficiently accurate. This measurement therefore complements those using the charged lepton final states and improves their precision at a higher energy scale. A significant deviation, in particular at large \(p_T^Z\), could reveal signs of physics beyond the SM \[18\text{-}20\].

This paper presents the first inclusive, differential, and normalized fiducial cross section measurements as functions of \(p_T^Z\), where the Z boson is identified via its decay to a pair of neutrinos. The neutrinos are not detected by the CMS detector, but are reconstructed indirectly through the transverse momentum imbalance in the event. We use events with energetic jets and large \(p_T^{\text{miss}}\), where the jets mainly arise from the fragmentation and hadronization of quarks or gluons that are produced in the hard scattering process as initial-state radiation. The analysis is based on a data sample of proton-proton (pp) collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of \(35.9 \pm 0.9\text{ fb}^{-1}\) collected with the CMS detector at the LHC in 2016.

This paper is organized as follows. A brief overview of the CMS detector is given in Section 2. Information about the definition of objects used in the analysis and the event selection is summarized in Section 3. Event simulations with various Monte Carlo (MC) generators are discussed in Section 4. Section 5 explains the signal-extraction strategy and Section 6 discusses the total, differential, and normalized fiducial cross section measurements. A combined analysis of the current measurements with those from charged leptons is presented in Section 7. Finally, we summarize our results in Section 8.

2 The CMS detector and event reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end sections reside within the solenoid volume. Forward calorimeters extend the pseudorapidity \((\eta)\) coverage provided by the barrel and end-section detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return
yoke outside the solenoid. A more detailed description of the CMS detector, together with a
definition of the coordinate system and kinematic variables, can be found in Ref. \[21\]. Events of
interest are selected using a two-tiered trigger system \[22\]. The first level, composed of custom
hardware processors, uses information from the calorimeters and muon detectors at an output
rate of \(\approx 100 \text{ kHz} \) within a fixed latency of about 4 \(\mu\text{s} \). The second level, known as the high-
level trigger, consists of a farm of processors running a version of the full event reconstruction
software optimized for fast processing, that reduces the event rate to \(\approx 1 \text{ kHz} \) before data stor-
age. Additional pp interactions to the studied collision that take place in the same or nearby
bunch crossings are referred to as pileup.

Events are reconstructed using a particle-flow (PF) algorithm \[23\], which combines information
from the tracker, calorimeters, and muon systems to reconstruct and identify charged and neu-
tral hadrons, photons, muons, and electrons. Jets are reconstructed by clustering PF candidates
using the anti-\(k_T\) algorithm \[24, 25\] with a distance parameter \(R = 0.4\). The jet energies are
calibrated in the simulation, and separately in data, accounting for energy deposits of neutral
particles from pileup and any nonlinear detector response \[26, 27\]. A charged-hadron substrac-
tion technique, which removes the energy of charged hadrons not originating from the event
primary vertex (PV) \[28\], is applied to mitigate the effect of pileup. The PV is defined as the
vertex with the largest value of summed physics-object \(p_T^2\). Here, the physics objects are the
jets clustered using the jet finding algorithm \[24, 25\] with the tracks assigned to the vertex as
inputs, and the associated \(p_T^{\text{miss}}\), which is the negative vector \(p_T\) sum of those jets. The estima-
tion of \(p_T^{\text{miss}}\) is improved by propagating the energy correction to the jet four vectors into the
sum, as described in Ref. \[29\].

3 Event selection

We define a signal region (SR) and two control regions (CR) using single-lepton events. While
the number of signal events is extracted from the SR, the CRs are used to constrain the domi-
nant \(W(\ell\nu) + \text{jets}\) background. The data from the SR are based on a set of dedicated triggers
designed to select events with large \(p_T^{\text{miss}}\) and \(H_T^{\text{miss}}\) as calculated with PF algorithm in the
trigger. The observable \(p_T^{\text{miss}}\) corresponds to the magnitude of the vector \(\vec{p}_T\) sum of all PF
candidates reconstructed at the trigger level, while the \(H_T^{\text{miss}}\) is the scalar sum of jet \(p_T\)s with
\(p_T > 20 \text{ GeV}\) and \(|\eta| < 5.0\) reconstructed at the trigger level. The energy fraction attributed
to neutral hadrons in these jets is required to be smaller than 0.9 to suppress events with jets
originating from detector noise. In this dedicated trigger algorithm, which provides events
for the single-muon CR, the identified PF muons are not considered in the computations of
\(p_T^{\text{miss}}\) and \(H_T^{\text{miss}}\). The trigger efficiency is measured to be 97\% for events passing the analysis
selection with \(p_T^{\text{miss}} > 250 \text{ GeV}\), and becomes 100\% for events with \(p_T^{\text{miss}} > 350 \text{ GeV}\) \[18\]. The
single-electron CR is selected from a different data set based on isolated and non isolated single-
electron triggers. The trigger efficiency for the single-electron CR is measured to be \(\approx 90\%\) for
events passing the selection for electrons with \(p_T > 40 \text{ GeV}\), and becomes fully efficient for
events with electron at \(p_T > 100 \text{ GeV}\). The definitions in the following analysis are based on
the reconstructed PF candidates, and incorporate additional algorithms and requirements to
optimize the selected objects.

Jets originating from b quarks are identified (b-tagged) using a multivariate algorithm, referred
to as the combined secondary vertex algorithm (CSVv2) \[30\]. The b tagging working point
used in this analysis has a tagging efficiency of \(\approx 65\%\) as measured for jets originating from the
hadronization of b quarks in top quark pair (tt) events, with a corresponding mistag rate for
jets that originate from the hadronization of light flavor quarks of \( \approx 1\% \) [30].

Electron candidates are reconstructed by matching clusters of energy in the ECAL to tracks in the silicon tracker [31]. Clusters compatible with electromagnetic deposition become seeds for electron tracks by back-propagating their trajectories from the calorimeter to the tracker. Tracker seeds are also created from existing tracks by extrapolating their trajectories to the ECAL surface and associating them to PF clusters. After seeds are created, track reconstruction is performed using a dedicated fitting algorithm that includes bremsstrahlung photons that are compatible with originating from an electron track. Additional requirements are applied to reject electrons created in photon conversions in tracker material or jets misreconstructed as electrons. Electron identification criteria rely on observables sensitive to bremsstrahlung along the electron trajectory, the geometrical and momentum-energy matching between the electron trajectory and the associated energy deposit in ECAL, as well as the distribution of energy in the shower and its association with the PV.

Muon candidates are reconstructed in the central tracking system alone or by combining charged tracks in the muon detector with trajectories in the central tracker [32]. Identification criteria based on the number of measurements in the tracker and in the muon system, the fit quality of the muon track, and its consistency with its origin from the PV are imposed on the muon candidates to reduce the misidentification rate.

Prompt charged leptons are usually isolated, whereas misidentified leptons and leptons from QCD production, such as jets, are often accompanied by charged hadrons or neutral particles. Leptons also arise from a secondary vertex if they are decay products of bottom or charm hadrons. To identify prompt charged leptons we require electrons and muons to satisfy an isolation criterion. An isolation variable is defined by the \( p_T \) sum over charged PF candidates associated to the PV and neutral PF particles within a cone around the lepton of radius \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.4 \), excluding the lepton. Here \( \Delta \phi \) and \( \Delta \eta \) refer to the differences in the \( \phi \) (azimuth) and \( \eta \) variables of the PF candidate to the charged-lepton candidate. Isolation cannot be larger than a given maximum value [18]. To mitigate the effect of pileup on this variable, a correction is implemented based on the total event occupancy [33].

The \( \tau \) leptons that decay to hadrons (\( \tau_h \)) are identified using the “hadron-plus-strips” algorithm [34]. This algorithm constructs candidates seeded by PF jets that are consistent with \( \tau \) lepton decay with one or three charged pions. In the single charged pion decay mode, the presence of neutral pions is detected by reconstructing their photonic decays. Mistagged jets originating from non-\( \tau \) decays are rejected by a discriminator that takes into account the pileup contribution to the neutral component of the \( \tau_h \) decay [35]. In addition, decay candidates are, in similarity to electron and muon candidates, required to satisfy an isolation criterion as described in Ref. [34].

Photon candidates are reconstructed [36] from clusters in the ECAL that are required to be isolated. The energy deposition in the HCAL tower closest to the seed of the ECAL supercluster [31] assigned to the photon is required to contain \( <5\% \) of the energy deposited in the ECAL. The photon isolation is defined by the sum over scalar \( p_T \) in a cone centered around the photon momentum vector with a radius of \( \Delta R = 0.3 \), that excludes the contribution of the photon candidate itself. Corrections for pileup effects are applied to the isolation criteria and depend on the \( \eta \) of the photon.
3.1 Signal region

Events in the SR are selected using triggers with thresholds of 110 or 120 GeV on $p_T^{\text{miss}}$ and $H_T^{\text{miss}}$ that depend on the data-taking period. Events are required to have $p_T^{\text{miss}} > 250$ GeV, and the leading jet in the event is required to have $p_T > 100$ GeV and $|\eta| < 2.5$. The leading jet is also required to have at least 10% of its energy associated with charged particles and less than 80% to neutral hadrons. This selection helps to reduce beam-induced background events. In addition, the analysis employs various event filters to reduce large misreconstructed $p_T^{\text{miss}}$ backgrounds not originating from beam-beam collisions [29]. The background from $W(\ell\nu) +$ jets is suppressed by imposing a veto on events containing one or more loosely identified electron or muon with $p_T > 10$ GeV, or $\tau$ leptons with $p_T > 18$ GeV. Events that contain an isolated photon with $p_T > 15$ GeV and $|\eta| < 2.5$ are also vetoed to reduce the $\gamma +$ jets background. To reduce the contamination from top quark backgrounds, events are rejected if they contain an identified b quark jet candidate with $p_T > 20$ GeV and $|\eta| < 2.4$. Finally, production of multijet background events from QCD processes with $p_T^{\text{miss}}$ arising from mismeasurements of the jet momenta is suppressed by requiring the minimum azimuthal angle between the $p_T^{\text{miss}}$ direction and each of the first four jets with $p_T$ greater than 30 GeV ($\Delta \phi(p_T^{\text{jet}}, p_T^{\text{miss}})$) to be larger than 0.5 radians. The selection requirements in the SR are summarized in Table 1.

![Table 1: Summary of the signal region definition.](image)

| Variable          | Selection                        | Against background from |
|-------------------|----------------------------------|-------------------------|
| Electron veto     | $p_T > 10$ GeV, $|\eta| < 2.5$ | $Z \rightarrow \ell\ell +$ jets, $W(\ell\nu) +$ jets |
| Muon veto         | $p_T > 10$ GeV, $|\eta| < 2.4$  | $Z \rightarrow \ell\ell +$ jets, $W(\ell\nu) +$ jets |
| $\tau$ veto       | $p_T > 18$ GeV, $|\eta| < 2.3$  | $Z \rightarrow \ell\ell +$ jets, $W(\ell\nu) +$ jets |
| Photon veto       | $p_T > 15$ GeV, $|\eta| < 2.5$  | $\gamma +$ jets         |
| b jet veto        | CSVv2 < 0.8484, $p_T > 20$ GeV, | Top quark               |
|                   | $|\eta| < 2.4$                    | QCD multijet, top quark, $Z \rightarrow \ell\ell +$ jets |
| $p_T^{\text{miss}}$ | $> 250$ GeV                      | QCD multijet            |
| $\Delta \phi(p_T^{\text{jet}}, p_T^{\text{miss}})$ | > 0.5 radians                  | All                     |
| Leading jet       | $p_T > 100$ GeV, $|\eta| < 2.4$ |                         |

3.2 Single-muon control region

The single-muon CR is enriched in $W(\mu\nu) +$ jets events and is defined using the SR criteria with two modifications. First, the muon veto is not applied, and exactly one tightly identified and isolated muon with $p_T > 20$ GeV is required [32]. No additional loosely identified electrons or muons with $p_T > 10$ GeV are accepted. Second, the transverse mass of the muon-$p_T^{\text{miss}}$ system, given by $m_T = \sqrt{2p_T^{\text{miss}} p_T^{\mu}(1 - \cos \Delta \phi)}$, where $p_T^{\mu}$ is the $p_T$ of the muon, and $\Delta \phi$ is the azimuthal angle between $p_T^{\mu}$ and $p_T^{\text{miss}}$, is required to be less than 160 GeV. This suppresses background from QCD multijet events.

3.3 Single-electron control region

The single-electron CR is enriched in $W(e\nu) +$ jets events and is defined using the trigger selection described above. Events in the single-electron CR are required to contain exactly one tightly identified and isolated electron with $p_T > 40$ GeV [31], and no additional loosely identified electrons or muons with $p_T > 10$ GeV. Finally, the contamination from QCD multijet events is suppressed by requiring $p_T^{\text{miss}} > 50$ GeV and having the $m_T$ of the electron-$p_T^{\text{miss}}$ system satisfy $m_T < 160$ GeV.
4 Signal and background simulation

Multiple MC event generators are used to simulate the signal and background processes in this analysis. The simulated events are used to optimize selections, evaluate selection efficiencies and systematic uncertainties, and compute expected yields.

Simulated MC samples are produced for the $Z + \text{jets}$ and $W + \text{jets}$ processes at next-to-leading order (NLO) in QCD using the MadGraph5_aMC@NLO 2.2.2 \cite{madgraph} generator with up to two additional partons in the matrix element calculations. These events are corrected by vector boson $p_T$-dependent higher-order EW terms using the multiplicative prescription given in Refs. \cite{ew_matching, ew_matching_2, ew_matching_3, ew_matching_4}.

The QCD multijet processes are generated using MadGraph5_aMC@NLO at leading order (LO) in QCD with up to four additional partons in the matrix element calculations. The $t\bar{t}$ and single top quark backgrounds are generated at NLO using POWHEG 2.0 and 1.0, respectively \cite{powheg, powheg_2}, and the diboson (WW, WZ, and ZZ) processes are generated at LO in QCD using PYTHIA 8.205 \cite{pythia}.

The MC samples generated using MadGraph5_aMC@NLO and POWHEG are interfaced to PYTHIA 8.212 \cite{pythia} using the CUETP8M1 tune \cite{cuet} for the fragmentation, hadronization, and underlying event. The MadGraph5_aMC@NLO generator provides jets from matrix-element calculations matched to the parton-shower description following the MLM \cite{mlm} (FxFx \cite{fxfx}) method for LO (and NLO). We use the NNPDF 3.0 \cite{nnpdf30} PDFs in all generated samples or NNPDF 3.1 \cite{nnpdf31} for the theoretical calculations. All MC events are processed through a simulation of the CMS detector based on GEANT4 \cite{geant4} and are reconstructed with the same algorithms used for data. Additional pileup interactions are also simulated. The distribution of the number of pileup interactions in the simulation is adjusted to match the one observed in the data. The average number of pileup interactions in 2016 was 23.

5 Signal extraction

The largest background contribution in this analysis, about 85%, arises from the $W(\ell\nu) + \text{jets}$ process in events where the charged lepton is either not reconstructed or falls outside the detector acceptance, and is estimated using data from the mutually exclusive CRs selected from single-muon and single-electron final states. The hadronic recoil $p_T$ from the jets is used as an estimator for $p_T^{\text{miss}}$ in these control samples, and is defined by excluding any identified electrons or muons from its calculation.

A binned maximum-likelihood fit to the data is performed simultaneously in the SR and the two CRs to estimate the signal and the $W(\ell\nu) + \text{jets}$ background rates in each $p_T^{\text{miss}}$ bin. The $W(\ell\nu) + \text{jets}$ background normalization in each $p_T^{\text{miss}}$ bin is therefore a free parameter of the fit along with the signal yield:

$$\mathcal{L}(\mu_W^{W\rightarrow\ell\nu}, \mu, \theta) = \prod_i \text{Poisson} \left( d_i^W | B_i^W(\theta) + \frac{\mu_i^{W\rightarrow\ell\nu}}{R_i^W(\theta)} \right) \times \prod_i \text{Poisson} \left( d_i^i | B_i(\theta) + \mu_i^{W\rightarrow\ell\nu} + \mu S_i(\theta) \right).$$

In the above fit, $d_i$ and $d_i^W$ are the observed number of events in each bin of the SRs and single-lepton CRs, respectively. The expected contributions from background processes in these SRs and CRs are denoted as $B_i$ and $B_i^W$, respectively. The systematic uncertainties ($\theta$) enter the
likelihood as additive perturbations to the transfer factors $R^W_i$, and are modeled with Gaussian priors. The parameter $\mu^W_{\ell \nu}$ represents the yield of the $W(\ell \nu)$ + jets background in the $i^{th}$ $p_T^{\text{miss}}$ bin, and is left freely floating in the fit. The yields of our signal process $Z \rightarrow \nu \nu$ is represented as $S_i$. The transfer factors $R^W_i$ are constructed from the $W \rightarrow \mu \nu$ and $W \rightarrow e \nu$ simulated event yields in the respective single-lepton CRs and used to constrain the $W(\ell \nu)$ + jets backgrounds estimated in the SR [18]. These transfer factors are defined as the ratio of expected yields of the target process in the signal region and the process being measured in the control sample. They include the impacts from lepton acceptance and efficiency, lepton-veto efficiency, and the differences in trigger efficiencies in the CRs relative to the SR. The systematic uncertainties in these transfer factors are modeled in the maximum-likelihood fit as constrained-nuisance parameters that include both experimental and theoretical components. Finally, the signal strength, $\mu$, is left freely floating in the fit, and is the observed cross section relative to the predicted value.

Theoretical uncertainties of the $W(\ell \nu)$ + jets contributions include the effects from the modeling of uncertainties in the PDFs [52] because of higher-order corrections. Experimental uncertainties, including the lepton reconstruction, selection, and veto efficiencies are incorporated into the transfer factors. Lepton veto efficiencies are estimated by propagating them through the uncertainty in the tagging-scale factor to the vetoed selections, whereas the lepton flavor composition of the $W(\ell \nu)$ + jets process is constrained by the CRs. These experimental uncertainties are only applicable to the leptons in the SR that are not identified, and therefore passed the veto requirement but fall into the detector acceptance. The overall magnitude of the lepton veto uncertainty is determined to be $\approx 2\%$ and is dominated by the $\tau$ lepton veto uncertainty. The uncertainties in the efficiency of the electron and $p_T^{\text{miss}}$ triggers are also included in the transfer factors. All uncertainties discussed are within 1–2% range and are fully correlated across all the bins of hadronic recoil $p_T$. The full list of uncertainties in the transfer factors are summarized in Table 2.

Table 2: Experimental uncertainties affecting transfer factors in the analysis that is used to estimate the $W \rightarrow \ell \nu$ background in the SR. The number of $W$ boson events are denoted as $W_{\text{SR}}$ for the SR and in analogy as $W_{\mu \nu}$ ($W_{e \nu}$) for the single-muon (single-electron) CR.

| Source                  | Process            | Uncertainty (%) |
|-------------------------|--------------------|-----------------|
| Electron trigger        | $W_{\text{SR}}/W_{e \nu}$ | 1               |
| $p_T^{\text{miss}}$ trigger | $W_{\text{SR}}/W_{\mu \nu}$ | 0–2 (shape)    |
| Muon reconstruction efficiency | $W_{\text{SR}}/W_{\mu \nu}$ | 1               |
| Muon identification efficiency | $W_{\text{SR}}/W_{\mu \nu}$ | 1               |
| Electron reconstruction efficiency | $W_{\text{SR}}/W_{e \nu}$ | 1.5             |
| Electron identification efficiency | $W_{\text{SR}}/W_{e \nu}$ | <1 (shape)     |
| Muon veto               | $W_{\text{SR}}/W_{e \nu}$ | <1 (shape)     |
| Electron veto           | $W_{\text{SR}}/W_{e \nu}$ | 1–2 (shape)    |
| $\tau$ veto            | $W_{\text{SR}}/W_{e \nu}$ | 1–2 (shape)    |
| PDF                     | $W_{\text{SR}}/W_{e \nu}$ | 1–2 (shape)    |

The remaining backgrounds that contribute to the total event yield in the SR are much smaller than those from $W(\ell \nu)$ + jets. These backgrounds include QCD multijet events, that are measured by extrapolating data from CR defined by $\Delta \phi(\vec{p}_{T}^{\text{jet}}, \vec{p}_{T}^{\text{miss}}) < 0.5$. Top quark, diboson, and $Z \rightarrow \ell \ell$ + jets (when both leptons are out of acceptance) production are obtained directly from simulation.

Uncertainties assigned to processes estimated from simulation include the uncertainties in the
efficiency of the $b$ jet veto, which are estimated to be 3.0 (1.0)% for the top quark (diboson) background. A systematic uncertainty of 10% is included in the top quark background normalization from the modeling of the top quark $p_T$ distribution [53, 54]. Systematic uncertainties of 10 and 20% are included in the normalizations of the top quark [55] and diboson backgrounds [56, 57], respectively, to account for the uncertainties in their cross sections in the relevant kinematic phase space. A systematic uncertainty of 20% is also used to account for the rate of the $Z \rightarrow \ell\ell +$ jets process. Finally, an uncertainty in the QCD multijet background of 50–150% is assigned to cover differences in the jet response and the statistical uncertainty in the extrapolation from the CR to the SR. These uncertainties are summarized in Table 3.

Table 3: Uncertainties assigned to simulation-based processes in SR and CRs.

| Source                        | Process                                | Uncertainty (%) |
|-------------------------------|----------------------------------------|-----------------|
| Luminosity [58]               | All                                    | 2.3             |
| Electron trigger              | All in single-electron CR              | 1.0             |
| $p_T^{\text{miss}}$ trigger   | All in SR and single-muon CR           | 0–2.0 (shape)   |
| Jet/$p_T^{\text{miss}}$ scale | All                                    | 4.0             |
| Pileup                        | All                                    | 1.0–2.0 (shape) |
| Muon reconstruction efficiency| All in single-muon CR                 | 1.0             |
| Muon identification efficiency| All in single-electron CR             | 1.0             |
| Electron reconstruction efficiency| All in single-electron CR         | 1.0             |
| Electron identification efficiency| All in single-electron CR       | 1.5             |
| $b$ jet veto                  | Top quark in SR and all CR            | 3.0             |
|                               | All remaining in SR and all CR        | 1.0             |
| $p_T$ reweighting of top quark| Top quark                              | 10              |
| Top quark normalization       | Top quark                              | 10              |
| Normalization of diboson      | Diboson                                | 20              |
| $Z \rightarrow \ell\ell +$ jets normalization | $Z \rightarrow \ell\ell +$ jets in SR | 20              |
| Normalization of QCD multijets| QCD multijets in SR                  | 50–150 (shape)  |

6 Fiducial cross section measurements

This analysis provides the $Z$ boson production cross section in a restricted fiducial region and compares with the theoretical predictions. The data selection defined at the reconstruction level is summarized in Table 3. The fiducial phase space, for which theoretical predictions are computed, is defined at the generator level without considering the detector response. The detector resolution leads to a difference between the observables at the reconstruction and the analogous generator level quantities. To minimize discrepancies, the selection criteria imposed at the generator level are defined to mimic the definition at the reconstructed level as much as possible. For this analysis, the fiducial phase space is defined by requiring $p_T^{\text{miss}} > 200 \text{GeV}$ without any other requirements placed on the $Z$ boson kinematics or the transverse momentum of the leading jet. The $p_T^{\text{miss}}$ is the reconstructed $p_T$ of the neutrino pair emitted in $Z$ boson decays.

The differences between fiducial and analysis requirements at the reconstructed level, specifically the requirements on $p_T^{\text{miss}} > 250 \text{GeV}$ and $p_T^{\text{jet}} > 100 \text{GeV}$, introduces a small, ≈0.9%, theoretical uncertainty from PDFs and missing higher orders in renormalization and factorization scales (QCD scales). These uncertainties are computed by comparing the ratio of theoretical uncertainties in the tighter to the looser analysis phase space requirements.
bution arising from events reconstructed within the fiducial phase space, but not originating from there, is treated as background.

To measure the total and differential production cross sections, events in the SR are divided into ten bins of $p_T^{\text{miss}}$, where each bin width is chosen to be at least equal to the $p_T^{\text{miss}}$ resolution at the given $p_T^{\text{miss}}$ range. A detailed description of the performance of the $p_T^{\text{miss}}$ resolution is presented in Ref. [29] using Z + jets and $\gamma$+jets events. Based on these $p_T^{\text{miss}}$ measurements, the minimum bin width is chosen to be 25 GeV at the lower end of the spectrum and is gradually increased to 350 GeV at the highest $p_T^{\text{miss}}$. The width of the highest $p_T^{\text{miss}}$ bin is also chosen to reflect the statistical precision of the sample.

As explained above, to extract the signal and the background, a maximum-likelihood fit is performed using the SR and the CRs. Figure 1 shows the comparison between data and expectations in the SR and CRs before (pre-fit) and after (post-fit) the fit to the data. Pre-fit distributions for the Z + jets and W + jets processes are based on simulated MC samples produced at NLO in QCD and are corrected using vector boson $p_T$-dependent higher-order EW corrections extracted from theoretical calculations. We verified that the measured cross sections are not sensitive to these corrections.

The measured total fiducial cross section is $3000^{+180}_{-170}$ fb. The corresponding likelihood scan is shown in Fig. 2, together with the predicted value $\sigma_{Z\rightarrow\nu\nu} = 2700 \pm 440$ fb from MADGRAPH5_aMC@NLO using the NNPDF 3.0 [49] NLO PDFs. The theoretical uncertainties for MADGRAPH5_aMC@NLO include statistical, PDF, and QCD-scale uncertainties. The PDF uncertainties are estimated by taking the one standard deviation band of the predictions from the replicas available for samples [50]. The QCD-scale uncertainties are estimated by changing the renormalization ($\mu_R$) and factorization ($\mu_F$) scales independently up and down by a factor of two from their nominal values (excluding the two extreme values) and taking the largest changes in the cross section as the uncertainty. The dominant sources of uncertainty are associated with the jet and $p_T^{\text{miss}}$ momentum scales and the integrated luminosity.

The extracted differential cross sections are obtained by combining two neighboring bins in the reconstructed $p_T^{\text{miss}}$ spectra into a single bin. This stabilizes the fit and ensures that at least 65% of the events in the reconstructed $p_T^{\text{miss}}$ bin are also in the same bin in terms of the true $p_T$ of the decaying Z boson. Each fiducial bin is then measured separately and all contributions are allowed to float in the binned fit. The differential cross section measurements as functions of $p_T^Z$ are shown in Fig. 3 (left) with predictions from MADGRAPH5_aMC@NLO at NLO in QCD and with or without the higher-order EW corrections. These corrections are important at high $p_T^Z$ with expected correction factors of $\approx 0.9$ at $p_T^Z = 500$ GeV and $\approx 0.8$ at $p_T^Z = 1000$ GeV [9, 59].

The $p_T^Z$ distribution is also compared to the fixed-order expectation from FEWZ 3.1 [60–63] at NNLO accuracy in QCD ($O(\alpha_S^3)$, where $\alpha_S$ is the strong coupling) using the NNPDF 3.1 [50] NNLO PDFs. The EW corrections are included at NLO [63]. The central values of the $\mu_F$ and $\mu_R$ are chosen to be $\sqrt{q_T^2 + m_Z^2}$, where $m_Z$ is the nominal Z boson mass [64] and $q_T$ is the value of the lower edge of the corresponding bin in $p_T^Z$. The uncertainties in FEWZ include statistical, PDF, and QCD-scale uncertainties, calculated the same way as for MADGRAPH5_aMC@NLO.

Finally, the data are compared with the NNLO predictions of vector boson production in association with a jet [65] at $O(\alpha_S^3)$ accuracy using the NNPDF 3.1 [50] NNLO PDFs (referred as NNLOJET in the figures). The central values of the $\mu_F$ and $\mu_R$ are chosen to be $\sqrt{(p_T^Z)^2 + m_Z^2}$. The uncertainties for Z+1 jet at NNLO include PDF and QCD-scales, calculated the same way as for MADGRAPH5_aMC@NLO, and they are largely reduced with respect to other calculations.
Figure 1: Comparison of data and simulation in the single-muon (upper left), single-electron (upper right) CRs and in the SR (lower), before and after performing the simultaneous fit across all the signal and control regions. The hadronic recoil $p_T$ in single lepton events is used as an estimator for $p_{T\text{miss}}$ in the SR. For the distributions in the CRs, the other backgrounds include top quark, diboson, and QCD multijet events. Ratios of data with the pre-fit expectation (red points) and post-fit prediction (blue points) are shown. The gray band in the ratio panel indicates the post-fit uncertainty after combining all systematic uncertainties. The distribution of the pulls, defined as the difference between data and the post-fit expectation relative to the quadratic sum of the post-fit uncertainties in the expectation, and statistical uncertainty in data, are shown in the lower panel.
Figure 2: The likelihood scan for the fiducial Z boson production cross section in the $Z \rightarrow \nu\nu$ channel $Z \rightarrow \nu\nu$.

Similar to the inclusive measurement, the dominant source of uncertainties are associated with the jet and $p_T^{\text{miss}}$ scales and the integrated luminosity. Whereas the systematic uncertainties dominate in the first four fiducial regions, statistical uncertainty dominates in the last signal bin.

The ratio of the differential cross section relative to the total fiducial cross section (normalized cross section) is also measured using the same binning. In this measurement, the total and individual cross sections are evaluated simultaneously, and therefore, the systematic uncertainties in the individual cross sections are largely reduced. While each fiducial bin is measured separately, only four of these contributions are used to float in the binned maximum-likelihood fit, along with their sum. In this way, the normalized cross section has the same number of degrees of freedom as the differential measurement. The differential cross section measurements normalized to the total cross section are presented in Fig. 3 (right), as well as cross section ratios with respect to the predicted $p_T^Z$ measurements.

7 Combination of cross section measurements using charged leptons and neutrinos

Measurements of differential Z boson production cross section have also been performed with Z bosons decaying to dielectrons or dimuons [17], and these are combined with our new measurements to improve the precision at large $p_T^Z$. In both analyses, the signal samples are generated with MADGRAPH5_aMC@NLO implemented with the NLO EW corrections applied.

While the analysis selection is identical, the fiducial region of the charged-lepton case is modified compared to Ref. [17], to match the definition in Section 6. Specifically, the requirement on the dilepton mass to lie within 15 GeV of the Z boson mass is kept to reduce the photon propagator contribution, but no requirements on the generator-level $p_T^\ell$ and $\eta^\ell$ are applied. The removal of the fiducial requirements on lepton kinematics introduces a small, $\approx 2\%$, theoretical extrapolation uncertainty from PDF and QCD-scale changes in the $Z \rightarrow \ell\ell$ channel because the reconstruction-level selection requires $p_T^\ell > 25$ GeV and $|\eta^\ell| < 2.4$. 
The leading systematic uncertainties between the two analyses are rather different. For the final state with neutrinos, the jet and $p_{T}^{\text{miss}}$ momentum scales uncertainties are dominant, whereas for the charged-lepton final states they originate from lepton identification. These sources are kept uncorrelated between the two analyses. The only correlated uncertainty is the integrated luminosity.

The signal cross section is extracted through a simultaneous binned maximum-likelihood fit to the signal and background $p_{T}^{\text{miss}}$ spectra in the SR and CRs of the neutrino channel, as described in Section 6, and to the $p_{T}^{\ell\ell}$ spectra in the SRs of the charged lepton channel. The individual analyses and the combined differential cross sections are summarized in Table 4.

The combined result leads to a reduction in uncertainties compared with either of the two channels. In the lower-$p_{T}^{Z}$ regime, the combination is systematically limited and dominated by the charged-lepton channels. At the same time, at higher $p_{T}^{Z}$, the statistical limitation of the charged-lepton channel is mitigated by the $Z \rightarrow \nu\nu$ channel, yielding improved sensitivity.

The measured experimental distributions are compared with the theoretical predictions from the \textsc{MadGraph5\_aMC@NLO} generator with and without NLO EW corrections. These distributions are shown in Fig. 4. The uncertainty in the theoretical predictions includes uncertainties both from PDF and from renormalization and factorization scales, together with the statistical precision of the available samples.

The combined cross sections normalized to the total cross section are presented in Fig. 5 and Table 5. The uncertainties because of the jet and $p_{T}^{\text{miss}}$ momentum scales have a smaller $p_{T}^{Z}$ distribution dependence than the lepton efficiency uncertainties. Therefore, by evaluating the ratio of cross sections, the uncertainties in the $Z \rightarrow \nu\nu$ channel are more reduced than the ones from the $Z \rightarrow \ell\ell$ channels. While predictions are consistent with data within the experimental

Figure 3: The measured absolute (left) and normalized (right) fiducial cross sections as a function of $p_{T}^{Z}$ compared with \textsc{MadGraph5\_aMC@NLO} and fixed-order calculations. The shaded bands around the data points correspond to the total experimental uncertainty. The vertical bars around the predictions correspond to the combined statistical, PDF, and QCD-scale uncertainties.
Table 4: Cross sections (fb) at large $p_T^Z$ values in the $Z \to \ell\ell$ and $Z \to \nu\nu$ channels, and their combination. The theoretical predictions from MADGRAPH5_aMC@NLO at NLO in QCD and corrected to NLO in EW [9] using the NNPDF 3.0 are also reported. With the exception of the largest $p_T^Z$ bin, the statistical uncertainties in the measurements are much smaller than the systematic uncertainties. Both measurements and predictions correspond to $\sigma B(Z \to \ell\ell)$, where $\sigma$ is the total fiducial cross section, $B$ is the branching fraction, and $\ell$ is a charged lepton. The $Z \to \nu\nu$ measurement corresponds to $\sigma B(Z \to \ell\ell)/B(Z \to \nu\nu)$.

| $p_T^Z$ (GeV) | $Z \to e^+e^-$ | $Z \to \mu^+\mu^-$ | $Z \to \ell\ell$ | $Z \to \nu\nu$ | $Z \to \ell+\nu\nu$ | Theory |
|--------------|---------------|-------------------|----------------|----------------|------------------|--------|
| 200–300      | 2500±140      | 2400±120          | 2500±100       | 2500±150       | 2500±82          | 2200±350|
| 300–400      | 390±22        | 400±22            | 400±17         | 420±24         | 410±17           | 390±69 |
| 400–500      | 97±6.4        | 100±4.4           | 97±5.6         | 97±5.6         | 97±5.4           | 90±18  |
| 500–800      | 47±3.0        | 41±3.7            | 45±2.3         | 44±2.7         | 44±2.6           | 41±9.0 |
| 800–1500     | 3.9±0.6       | 3.2±0.7           | 3.7±0.4        | 3.2±0.3        | 3.3±0.2          | 3.3±0.9 |
| 200–1500     | 3000±160      | 3000±150          | 3000±150       | 3000±180       | 3000±100         | 2700±440|

and theoretical uncertainties across the $p_T^Z$ spectra, a deviation up to 15% at the highest-$p_T^Z$ regime is observed.

Table 5: Cross sections normalized to the total cross section measurements at high $p_T^Z$ values in the $Z \to \ell\ell$ and $Z \to \nu\nu$ channels, and in their combination.

| $p_T^Z$ (GeV) | $Z \to \ell\ell$ | $Z \to \nu\nu$ | $Z \to \ell+\nu\nu$ |
|--------------|----------------|----------------|------------------|
| 200–300      | 1.012±0.008    | 1.019±0.009    | 1.011±0.004      |
| 300–400      | 0.943±0.025    | 0.979±0.015    | 0.963±0.015      |
| 400–500      | 1.006±0.031    | 0.963±0.019    | 0.971±0.017      |
| 500–800      | 0.993±0.036    | 0.942±0.024    | 0.949±0.021      |
| 800–1500     | 1.036±0.099    | 0.869±0.059    | 0.914±0.052      |

8 Summary

Total, differential, and normalized fiducial cross section measurements for a Z boson produced in association with one or more jets in proton-proton collisions at a center-of-mass energy of 13 TeV at high Z boson $p_T$ in the invisible decay channel ($Z \to \nu\nu$) have been presented. The data collected with the CMS detector at the LHC correspond to an integrated luminosity of 35.9 fb$^{-1}$. The precision of this result is improved by combining the cross section measured with those extracted from charged-lepton final states. The results agree within uncertainties with the theoretical predictions from MADGRAPH5_aMC@NLO, FEWZ and Z+1 jet at next-to-next-to-leading order in perturbative quantum chromodynamics. These are the most precise measurements of the $p_T^Z$ spectrum to date in proton-proton collisions at 13 TeV.

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Figure 4: Measured $p_T^Z$ absolute cross section for $Z \rightarrow \ell^+\ell^-$ (left), and the combination (right) being compared with MADGRAPH5_aMC@NLO and fixed-order calculations. The shaded bands around the data points correspond to the total experimental uncertainty. The vertical bars around the predictions correspond to the combined statistical, PDF, and QCD-scale uncertainties.

Figure 5: Measured $p_T^Z$ normalized cross section for $Z \rightarrow \ell^+\ell^-$ (left), and the combination (right) compared with MADGRAPH5_aMC@NLO and fixed-order calculations. The shaded bands correspond to the total systematic uncertainty. The vertical bars around the predictions correspond to the combined statistical, PDF, and QCD-scale uncertainties.
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