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Observation of Z decays to four leptons with the CMS detector at the LHC

The CMS Collaboration*

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Abstract

The first observation of the Z boson decaying to four leptons in proton-proton collisions is presented. The analyzed data set corresponds to an integrated luminosity of 5.02 fb^{-1} at $\sqrt{s} = 7$ TeV collected by the CMS detector at the Large Hadron Collider. A pronounced resonance peak, with a statistical significance of $9.7\,\sigma$, is observed in the distribution of the invariant mass of four leptons (electrons and/or muons) with mass and width consistent with expectations for Z boson decays. The branching fraction and cross section reported here are defined by phase space restrictions on the leptons, namely, $80 < m_{4\ell} < 100$ GeV, where $m_{4\ell}$ is the invariant mass of the four leptons, and $m_{\ell\ell} > 4$ GeV for all pairs of leptons, where $m_{\ell\ell}$ is the two-lepton invariant mass. The measured branching fraction is $\mathcal{B}(Z \to 4\ell) = \left(4.2^{+0.9}_{-0.8}(\text{stat.}) \pm 0.2(\text{syst.})\right) \times 10^{-6}$ and agrees with the standard model prediction of 4.45×10^{-6}. The measured cross section times branching fraction is $\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell) = 112^{+23}_{-20}(\text{stat.})^{+7}_{-5}(\text{syst.})^{+3}_{-2}(\text{lumi.})$ fb, also consistent with the standard model prediction of 120 fb. The four-lepton mass peak arising from $Z \to 4\ell$ decays provides a calibration channel for the Higgs boson search in the $H \to ZZ \to 4\ell$ decay mode.

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*See Appendix A for the list of collaboration members

1 Introduction

We present the first observation of $Z \to 4\ell$ decays in pp collisions at $\sqrt{s} = 7\,\text{TeV}$, and measurements of the production cross section times branching fraction for Z decays into four leptons $\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell)$ and the branching fraction $\mathcal{B}(Z \to 4\ell)$. In this paper, ℓ denotes an electron or muon. Previously, all four LEP collaborations reported observations of final states with four fermions, $e^+e^- \to 4f$, which include $e^+e^- \to Z \to 4f$ [1–4]. However, the observation of $Z \to 4\ell$ decays in pp collisions is of special interest. The clean resonant peak in the four-lepton invariant mass distribution at $m_{4\ell} = m_Z$ can be used for direct calibration of the four-lepton mass scale, the four-lepton mass resolution, and the overall four-lepton reconstruction efficiency in phase space similar to the light Higgs boson four-lepton decays, $H \to ZZ \to 4\ell$. The $pp \to Z \to 4\ell$ process and its implications for the $H \to ZZ \to 4\ell$ search at the Large Hadron Collider (LHC) were first studied in Ref. [5].

These results are based on the data collected in 2010 and 2011 by the Compact Muon Solenoid (CMS) detector [6] at the LHC. The data set used in the analysis corresponds to a total integrated luminosity of $5.02 \pm 0.11\,\text{fb}^{-1}$.

2 CMS detector

The central feature of the CMS apparatus is a superconducting solenoid 13 m in length and 6 m in diameter providing an axial magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Charged particle trajectories are measured by the tracker, covering $0 < \phi < 2\pi$ in azimuth and $|\eta| < 2.5$, where the pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle of the trajectory of the particle with respect to the anticlockwise beam direction. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum (p_T) resolution of about 2% in the muon p_T range relevant for the analysis presented in this paper (from a few to a few tens of GeV). The ECAL consists of nearly 76 000 lead tungstate crystals distributed in the barrel region (EB, $|\eta| < 1.479$) and two endcap regions (EE, $1.479 < |\eta| < 3$), and has an ultimate energy resolution better than 0.5% for unconverted photons with transverse energies above 100 GeV. The electron energy resolution is 3% or better for the range of energies relevant for the measurement reported in this paper. A two-level trigger system selects the most interesting events for use in the offline physics analyses. A more detailed description of the CMS detector can be found in Ref. [6].

3 Signal definition

The leading-order (LO) Feynman diagram for the Z production and decay into four leptons, $q\bar{q} \to Z \to 4\ell$, is presented in Fig. 1 (left). This process is sometimes referred to as single-resonant four-lepton production.

We define signal events as those with four leptons, $e^+e^-e^+e^-$ (4e), $\mu^+\mu^-\mu^+\mu^-$ (4μ), or $e^+e^-\mu^+\mu^-$ (2e2μ), with four-lepton invariant mass satisfying $80 < m_{4\ell} < 100\,\text{GeV}$ and dilepton masses $m_{\ell\ell} > 4\,\text{GeV}$ for all six possible pairings of leptons. The lower limit on $m_{\ell\ell}$ reduces background that rises rapidly as $m_{\ell\ell}$ decreases. The branching fraction and cross section reported here are defined by these phase space restrictions.

Predicted partial widths and branching fractions for Z boson decays to 4e, 4μ, and 2e2μ final states are summarized in Table 1. The results are obtained at LO using CalcHEP 3.2 [7], which takes quantum mechanical interferences into account. The partial width for the 2e2μ channel is different from twice the width in either the 4e or 4μ channel because decays to four leptons of the same flavour involve additional Feynman diagrams with permutations of same-sign leptons. We do not have a sufficient number of events to measure the differences between decay rates for the three four-lepton final states. We therefore measure the overall branching fraction $\mathcal{B}(Z \to 4\ell)$ and assume the 4e, 4μ, and 2e2μ relative branching fractions predicted by theory (Table 1). The main irreducible background is the process $q\bar{q} \to Z\gamma^* \to 4\ell$, for which the LO Feynman diagram is shown in Fig. 1 (right). Events are simulated with the next-to-leading-order generator POWHEG [8]. The effects of multiple pp collisions within each bunch crossing are taken into account in all simulated samples.

Table 1: Partial widths and branching fractions for Z boson decays to 4e, 4μ, 2e2μ final states with $m_{\ell\ell} > 4$ GeV for all lepton pairs. The branching fractions are calculated with CalcHEP 3.2 [7] at LO using the total Z boson width $\Gamma_{\text{tot}} = 2.4952$ GeV [9]. Theoretical uncertainties are smaller than experimental uncertainties and are not shown in the table.

Quantity of interest	4e	4μ	2e2μ	4ℓ
Partial width, Γ_i (keV)	2.95	2.95	5.21	11.12
Branching fractions, $\Gamma_i/\Gamma_{\text{tot}}$	1.18×10^{-6}	1.18×10^{-6}	2.09×10^{-6}	4.45×10^{-6}
Relative fractions, $f_i = \Gamma_i/\Gamma_{4\ell}$	0.2655	0.2655	0.4690	-

4 Signal extraction

The trigger and selection criteria used in this analysis closely follow the $H \to ZZ \to 4\ell$ search by CMS [10]. We use data collected with dielectron and dimuon triggers selecting events with at least two electrons or two muons with transverse momentum $p_T > 17$ and 8 GeV. To match the trigger selection, we require that at least two leptons reconstructed offline have $p_T > 20$ and 10 GeV. In this phase-space region, we expect and observe a high trigger efficiency of 96–99%, depending on the final state.

Muon candidates are reconstructed using two algorithms, one in which tracks in the silicon strip tracker are matched to hits in the muon detectors, and another in which a combined fit is performed to signals in both the silicon strip tracker and the muon system [11]. The muon

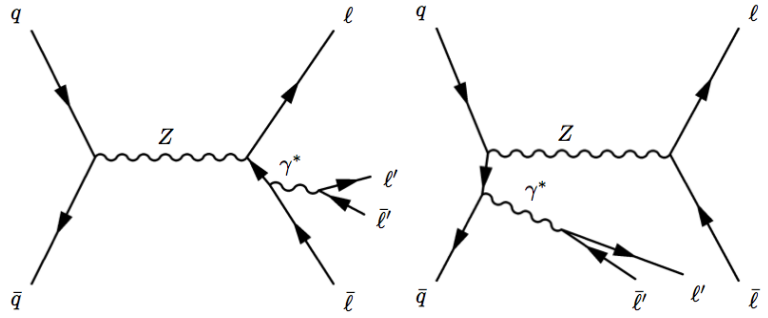

Figure 1: (Left) Diagram of the $Z \to 4\ell$ process. (Right) Diagram of the $Z\gamma^* \to 4\ell$ process for the irreducible background of $Z \to 2\ell$ production with the initial-state radiation undergoing an internal conversion $\gamma^* \to 2\ell$. Both Z and γ^* are present in all propagators. The choice of propagators shown in the figures corresponds to the dominant contributions in the phase space $80 < m_{4\ell} < 100$ GeV.

candidates are required to be successfully reconstructed by both algorithms. Other identification criteria (the number of measurements in the tracker and muon systems, the fit quality of the muon track, and the consistency of the track with the primary vertex) are also imposed on the muon candidates to reduce the misidentification rate. The vertex with the largest value of $\sum p_T^2$ for the associated tracks is chosen to be the primary vertex. According to simulation, this requirement provides the correct assignment for the primary vertex in more than 99% of both signal and background events. The average number of reconstructed vertices per event in 2011 data is approximately 7.

Electron reconstruction also involves two algorithms, one in which energy clusters in the electromagnetic calorimeter are matched to signals in the silicon pixel detector and another in which tracks in the silicon strip tracker are matched to ECAL clusters [12]. The electron candidates used in the analysis are reconstructed by either algorithm. Additional identification criteria (the spatial distribution of the shower in the ECAL, matching of the electron track with a cluster in the ECAL, and consistency of the track with the primary vertex) are imposed on the electron candidates to reduce the misidentification rate. Requirements are imposed on the geometrical properties of the electron track with respect to the primary vertex and neighbouring tracks, as well as requirements on the number of missing hits in the innermost tracker layers in order to remove electrons produced by photon conversions in the detector material.

Electrons are required to satisfy $p_T > 7$ GeV and $|\eta| < 2.5$, while muons are required to satisfy $p_T > 5$ GeV and $|\eta| < 2.4$.

Leptons produced in the decay of Z (or γ^*) bosons are typically isolated from hadronic activity in the event. The scalar sum of transverse energy deposits in the calorimeters and the transverse momenta of tracks in a cone of radius $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ in η-ϕ space around each lepton is computed. This sum is corrected for the contribution from the other lepton candidates as well as for the average hadronic activity in an event. The ratio of this corrected sum to the lepton p_T is required to be smaller than 0.275.

To suppress background events with leptons originating from secondary vertices (such as heavy quark decays or misidentified pions), the significance of the impact parameter of each lepton relative to the primary vertex, $s_{3D} = d_{3D}/\sigma_{3D}$, is required to satisfy $|s_{3D}| < 4$, where d_{3D} is the impact parameter in three dimensions and σ_{3D} is its associated uncertainty.

Events are selected with at least four leptons satisfying the above criteria. The same-flavour, opposite-charge lepton pair with mass closest to the nominal Z boson mass is identified. A second pair is constructed from the remaining leptons with the highest p_T satisfying the requirement of the same flavour and opposite charge. We require all six dilepton combinations constructed from the four selected leptons to satisfy $m_{\ell\ell} > 4$ GeV and the four-lepton invariant mass must be in the range $80 < m_{4\ell} < 100$ GeV. The overall reconstruction and selection efficiencies for simulated signal events are found to be 25%, 59%, and 33% for the 4e, 4μ and 2e2μ channels, respectively. The overall theoretical acceptance efficiencies (per channel, in the same order) are 8.9%, 14%, and 11.1%.

We estimate the irreducible four-lepton background from simulation using selection efficiencies corrected for differences between the simulated efficiencies and those measured in data.

Processes with one or more misidentified or nonprompt leptons contributing to the signal region $80 < m_{4\ell} < 100$ GeV are dominated by Z + X production. Their rate is measured in data using control regions and is found to be negligible. The methodology used is identical to that used in the $H \to ZZ \to 4\ell$ search [13].

We use $pp \to Z \to 2\mu$ events as a control sample in order to cancel systematic uncertainties in the measurement of the branching fraction $\mathcal{B}(Z \to 4\ell)$. The muon selection criteria are identical to those in the $Z \to 4\ell$ event selection with p_T thresholds $p_T > 20$ and 10 GeV applied to the higher and lower p_T muons, respectively.

5 Results

5.1 Observation of $Z \to 4\ell$ decays

Figure 2 shows the four-lepton mass distribution for events that pass all the selection criteria except the invariant mass requirement. Events with all three final states, 4e, 4μ, and $2e2\mu$, are included. The prominent peak at $m_{4\ell} = m_Z$ constitutes the first observation of $pp \to Z \to 4\ell$. The number of events with $80 < m_{4\ell} < 100$ GeV is 28, in good agreement with the standard model expectation of 30.0 events. Table 2 shows good agreement between the expected and observed events in each of the 4e, 4μ, and $2e2\mu$ channels. The probability for a background fluctuation to be at least as large as the observed maximum excess can be evaluated by generating sets of simulated data incorporating all statistical and systematic uncertainties. This probability can be expressed as a corresponding number of standard deviations using the one-sided Gaussian tail convention. The results presented in this paper are obtained using asymptotic formulae [14] and include the systematic uncertainties described in the next subsection. The statistical significance of the peak in Fig. 2 is 9.7σ.

Table 2: Numbers of expected and observed events with $80 < m_{4\ell} < 100$ GeV. The yields are determined by means of fits described in the text; the fit results in the 4e channel are not meaningful because only two events are selected.

Final state channels	4e	4μ	$2e2\mu$	4ℓ
Irreducible background ($pp \to Z\gamma^* \to 4\ell$)	0.07	0.25	0.14	0.46 ± 0.05
Other (reducible) backgrounds	0.01	0.01	0.05	0.07 ± 0.1
Expected signal ($pp \to Z \to 4\ell$)	3.8	13.6	12.0	29.4 ± 2.6
Total expected (simulation)	3.9	13.9	12.2	30.0 ± 2.6
Observed events	2	14	12	28
Yield from fit to the observed mass distribution	-	13.6 ± 3.8	11.5 ± 3.1	27.3 ± 5.4

5.2 Measurement of $\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell)$ and $\mathcal{B}(Z \to 4\ell)$

The numbers of $Z \to 4\ell$ (signal) and $Z \to 2\mu$ (control) events passing the selection may be expressed as follows:

$$N^{4\ell} - N^{4\ell}_{\text{bkg}} = \sum_i L\,\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell)\,f_i\,\epsilon_i^{\text{acc}}\,\epsilon_i^{\text{exp}}\,c_i \quad (i = 4e, 4\mu, 2e2\mu), \tag{1}$$

$$N^{2\mu} - N^{2\mu}_{\text{bkg}} = L\,\sigma(pp \to Z)\,\mathcal{B}(Z \to 2\mu)\,\epsilon^{\text{acc}}_{Z\to 2\mu}\,\epsilon^{\text{exp}}_{Z\to 2\mu}\,c_{Z\to 2\mu}, \tag{2}$$

where

- L denotes the integrated luminosity;
- $\sigma(pp \to Z) = 26.9$ nb is the theoretical Z boson production cross section ($80 < m_{4\ell} < 100$ GeV), calculated with FEWZ [15] at NNLO level;
- $\mathcal{B}(Z \to 4\ell)$ is the signal decay branching fraction (for $m_{\ell\ell} > 4$ GeV);

- $\mathcal{B}(\mathrm{Z} \to 2\mu) = 0.03366 \pm 0.00002$ is the $\mathrm{Z} \to 2\mu$ branching fraction [9];
- f_i is the relative fraction of all 4ℓ events in the ith channel ($i = 4\mathrm{e}, 4\mu, 2\mathrm{e}2\mu$) from Table 1;
- $\epsilon_i^{\mathrm{acc}}$ is the theoretical acceptance of the lepton p_{T} and η requirements used in the analysis;
- $\epsilon_i^{\mathrm{exp}}$ is the experimental efficiency, as obtained from the simulation, to reconstruct events within the acceptance;
- c_i is the data-to-simulation correction factor for the experimental efficiency derived from Monte Carlo events. The c_i are within one percent of unity.

Equation (1) allows the extraction of the production cross section times branching fraction $\sigma(\mathrm{pp} \to \mathrm{Z})\,\mathcal{B}(\mathrm{Z} \to 4\ell) = 112^{+23}_{-20}\,(\mathrm{stat.})\,\mathrm{fb}$, while the ratio of Eqns. (1) and (2) allows extraction of the branching fraction $\mathcal{B}(\mathrm{Z} \to 4\ell) = \left(4.2^{+0.9}_{-0.8}\,(\mathrm{stat.})\right) \times 10^{-6}$ with cancellation of several systematic uncertainties.

The signal and the irreducible background have the following systematic uncertainties:

- Interference between the signal and background production is less than 0.2% in the range $80 < m_{4\ell} < 100\,\mathrm{GeV}$, and is accounted for as a source of systematic uncer-

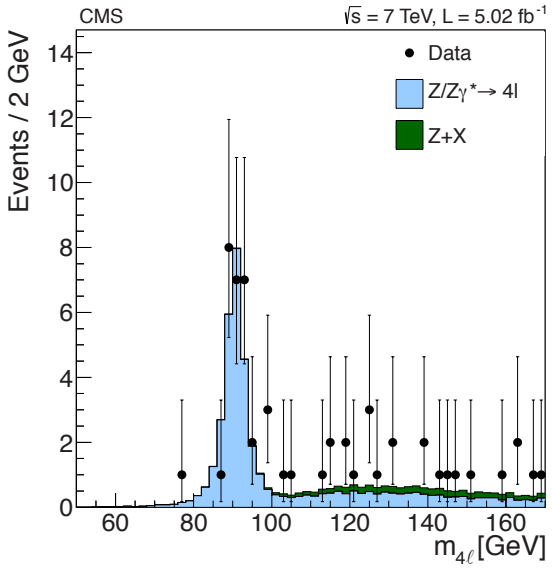

Figure 2: Four-lepton invariant mass distribution for events passing all selection requirements except that on $m_{4\ell}$. The data are shown by points. The filled histograms represent standard model expectations for $\mathrm{pp} \to \mathrm{Z}/\mathrm{Z}\gamma^* \to 4\ell$ and for reducible backgrounds. The three final states, 4e, 4μ, and $2\mathrm{e}2\mu$, are combined.

tainty.

- Uncertainties in parton distribution functions lead to uncertainties in the total cross section and acceptance. For $pp \to Z\gamma^* \to 4\ell$ and $pp \to Z \to 2\mu$, these uncertainties are 4% [10] and 1% [16]. For $pp \to Z \to 4\ell$ we obtain an uncertainty of 4% by following the same procedure as in Ref. [10].
- The theoretical uncertainties related to the choice of QCD renormalization/factorization scales are evaluated by varying these scales up and down by a factor of two. For $pp \to Z\gamma^* \to 4\ell$ and $pp \to Z \to 2\mu$, these uncertainties are both 2% [10, 16]. For $pp \to Z \to 4\ell$ we obtain an uncertainty of 1% by following the same procedure as in Ref. [10].
- The effect of bremsstrahlung radiation on event acceptance is estimated to be negligible.
- Lepton reconstruction, isolation, and impact parameter uncertainties as well as uncertainties associated with the high-level trigger efficiency are determined using a "tag-and-probe" method [16] where efficiencies and uncertainties are measured in samples of $Z \to 2\ell$ events. The statistical uncertainties on the lepton efficiencies obtained in different (p_T, η) bins are propagated to four-lepton reconstruction uncertainties for $Z \to 4\ell$ and $Z\gamma^* \to 4\ell$ events. These uncertainties range from 1% to 6%. Correlation between the "tag-and-probe" efficiency measurement at the $Z \to 2\ell$ calibration signal are taken into account.
- The uncertainty on the integrated luminosity is 2.2% [17].

The reducible background is estimated directly from data. The predicted yield of the reducible backgrounds is approximately 0.1 event (less than one percent of the signal yield, as shown in Table 2) and has a total uncertainty, also evaluated from data, of 130%.

To account for systematic uncertainties, including correlations among different channels, as well as between signal and background, we construct the likelihood for the four observed final states (4e, 4μ, 2e2μ, and 2μ). Using the full likelihood in conjunction with the profile likelihood method [14], we measure the production cross section times branching fraction and the branching fraction for $Z \to 4\ell$ to be

$$\begin{aligned} \sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell) &= 112^{+23}_{-20}\,(\text{stat.})^{+7}_{-5}(\text{syst.})^{+3}_{-2}\,(\text{lum.})\,\text{fb}, \\ \mathcal{B}(Z \to 4\ell) &= \left(4.2^{+0.9}_{-0.8}\,(\text{stat.}) \pm 0.2\,(\text{syst.})\right) \times 10^{-6}. \end{aligned}$$

These measurements agree with the standard model predictions, 120 ± 5 fb and 4.45×10^{-6}, respectively.

5.3 $Z \to 4\ell$ decays as a calibration channel in the $H \to ZZ \to 4\ell$ search

The $Z \to 4\ell$ decays give a narrow resonant peak in the four-lepton invariant mass distribution, which can be used as a calibration channel in the context of the Higgs boson search in the $H \to ZZ \to 4\ell$ decay mode. Figure 3 (left) shows that the number of events in the $Z \to 4\ell$ peak at $m_{4\ell} = m_Z$ is approximately an order of magnitude larger than the expected number of events for the SM Higgs boson with a mass $m_H = 125$ GeV [13, 18]. The $Z \to 4\ell$ peak can be used for a direct calibration of the four-lepton mass scale, the four-lepton mass resolution, and the overall four-lepton reconstruction efficiency in a phase space similar to the Higgs boson four-lepton decays. Such a direct calibration using the $Z \to 4\ell$ peak is complementary to the current

indirect tag-and-probe method making use of $Z \to 2\ell$ events, with the benefit that $Z \to 4\ell$ has similar kinematics to $H \to ZZ \to 4\ell$.

Figure 3 (right) shows the results of an unbinned maximum-likelihood fit to the four-lepton mass distribution for the observed events. The fitted signal yield is shown in the last line of Table 2, along with the results of separate fits to the mass distributions in the three channels. The background shape comes from a simulation of $pp \to ZZ \to 4\ell$ events with the overall normalization floating in the fit. Differences in shape between the reducible and irreducible backgrounds are ignored because of the small contribution of the former. The signal shape is a convolution of the Breit–Wigner and Crystal Ball [19] functions. The central value and width of the Breit–Wigner function are fixed at the Z boson mass and width [9]. The Crystal Ball parameters are free to vary in the fit. Data used for this analysis is only a (lower energy) subset of that used in the recent discovery paper [13].

From the fit results, as shown in Fig. 3 (right), one can see that the offset of the peak is 0.4 ± 0.4 GeV (to the right) (the "mean" value of the Crystal Ball function represents an offset with respect to the fixed Breit–Wigner function peak position), or, in relative units, $0.4 \pm 0.4\%$. These numbers can be used to constrain the possible systematic uncertainty of the four-lepton mass scale. With the current data there is no evidence for a statistically significant bias.

The Crystal Ball width (sigma of the Gaussian core) returned by the fit is 1.1 ± 0.5 GeV, consistent with the simulation-based expectations of 1.0% for 4μ and 1.4% for $2e2\mu$ (which for a Higgs boson with mass 125 GeV corresponds to 1.3 GeV and 1.8 GeV) for a Higgs signal in this mass range. There are only two 4e events, so the mass resolution of 4e events cannot be constrained. With the current data, we can measure the average four-lepton mass resolution with about 45% statistical uncertainty. (For completeness, the other two parameters of the Crystal Ball function from the fit are $N = 0.4 \pm 1.7$ and $\alpha = 12 \pm 10$.)

6 Summary

The first observation of the Z boson decaying to four leptons (electrons and/or muons) in proton-proton collisions has been presented. The data set analyzed corresponds to an integrated luminosity of $5.02\,\text{fb}^{-1}$ at $\sqrt{s} = 7\,\text{TeV}$. A pronounced resonance peak, with a statistical significance of $9.7\,\sigma$, is observed in the distribution of the invariant mass of four leptons with mass and width consistent with expectations for Z boson decays. The event yields, branching fraction, and cross section reported here are defined by phase space restrictions on the leptons, namely, $80 < m_{4\ell} < 100\,\text{GeV}$, where $m_{4\ell}$ is the invariant mass of the four leptons, and $m_{\ell\ell} > 4\,\text{GeV}$ for all pairs of leptons, where $m_{\ell\ell}$ is the two-lepton invariant mass. We observe 28 events, in agreement with the expectation of 30.0 ± 2.6 events, comprised of 29.4 ± 2.6 $Z \to 4\ell$ events and 0.6 ± 0.2 events from backgrounds. The measured branching fraction is $\mathcal{B}(Z \to 4\ell) = \left(4.2^{+0.9}_{-0.8}\,(\text{stat.}) \pm 0.2\,(\text{syst.})\right) \times 10^{-6}$, in agreement with the standard model prediction of 4.45×10^{-6}. The measured cross section times branching fraction is $\sigma(pp \to Z)\,\mathcal{B}(Z \to 4\ell) = 112^{+23}_{-20}\,(\text{stat.})^{+7}_{-5}\,(\text{syst.})^{+3}_{-2}\,(\text{lumi.})\,\text{fb}^{-1}$, also consistent with the standard model prediction of 120 fb. The four-lepton mass peak arising from $Z \to 4\ell$ decays provides a calibration channel for the Higgs boson search in the $H \to ZZ \to 4\ell$ decay mode.

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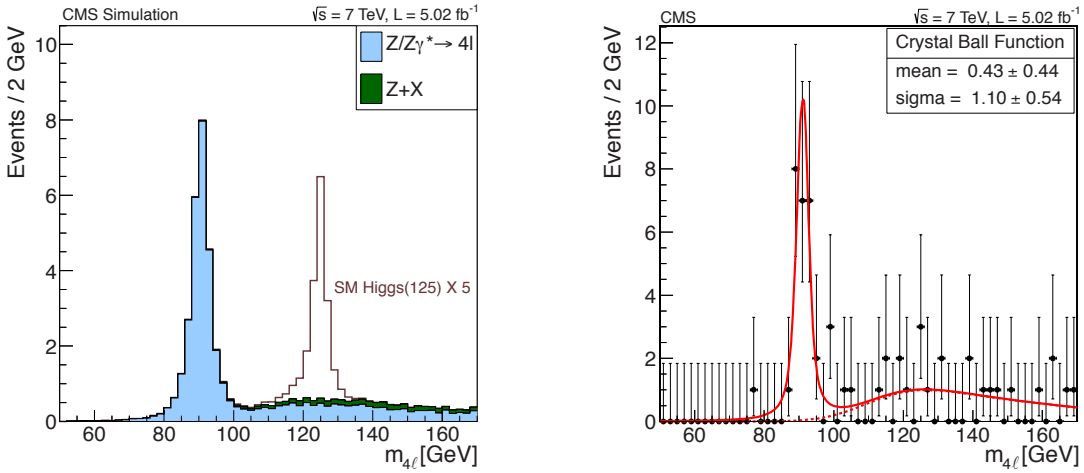

Figure 3: (Left) Four-lepton mass distribution in simulation for pp $\to 4\ell$, without the Higgs boson (light shaded histogram), Z + X background (dark shaded histogram), and pp $\to$ H $\to$ ZZ $\to 4\ell$ for a Higgs boson mass $m_{\mathrm{H}} = 125\,\mathrm{GeV}$. The three contributions are stacked. The standard model cross section for the Higgs boson is scaled up by a factor of 5. (Right) Four-lepton mass distribution with data represented by the points with error bars. The three final states, 4e, 4μ, and 2e2μ, are combined. The solid line represents a simultaneous fit to the background and Z boson peak.

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