# Search for resonances in the dilepton mass distribution in pp collisions at $\sqrt{s} = 7$ TeV

**The CMS collaboration**

ABSTRACT: A search for narrow resonances at high mass in the dimuon and dielectron channels has been performed by the CMS experiment at the CERN LHC, using pp collision data recorded at $\sqrt{s} = 7$ TeV. The event samples correspond to integrated luminosities of 40 pb$^{-1}$ in the dimuon channel and 35 pb$^{-1}$ in the dielectron channel. Heavy dilepton resonances are predicted in theoretical models with extra gauge bosons (Z′) or as Kaluza-Klein graviton excitations (G$_{KK}$) in the Randall-Sundrum model. Upper limits on the inclusive cross section of Z′(G$_{KK}$) $\to \ell^+\ell^-$ relative to Z $\to \ell^+\ell^-$ are presented. These limits exclude at 95% confidence level a Z′ with standard-model-like couplings below 1140 GeV, the superstring-inspired Z′$_\psi$ below 887 GeV, and, for values of the coupling parameter $k/\overline{M}_{\mathrm{Pl}}$ of 0.05 (0.1), Kaluza-Klein gravitons below 855 (1079) GeV.

# Contents

# 1 Introduction

Many models of new physics predict the existence of narrow resonances, possibly at the TeV mass scale, that decay to a pair of charged leptons. This Letter describes a search for resonant signals that can be detected by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) [1] at CERN. The Sequential Standard Model $Z'_{\rm SSM}$ with standard-model-like couplings, the $Z'_\psi$ predicted by grand unified theories [2], and Kaluza-Klein graviton excitations arising in the Randall-Sundrum (RS) model of extra dimensions [3, 4] were used as benchmarks. The RS model has two free parameters: the mass of the first graviton excitation and the coupling $k/\overline{M}_{\rm Pl}$, where $k$ is the curvature of the extra dimension and $\overline{M}_{\rm Pl}$ is the reduced effective Planck scale. Two values of the coupling parameter were considered: $k/\overline{M}_{\rm Pl} = 0.05$ and $0.1$. For a resonance mass of $1\,\mathrm{TeV}$, the widths are 30, 6 and 3.5 (14) GeV for a $Z'_{\rm SSM}$, $Z'_\psi$, and $G_{\rm KK}$ with $k/\overline{M}_{\rm Pl} = 0.05$ (0.1), respectively.

The results of searches for narrow $Z' \to \ell^+\ell^-$ and $G_{KK} \to \ell^+\ell^-$ resonances in $p\bar{p}$ collisions at the Tevatron with over $5\,\text{fb}^{-1}$ of integrated luminosity at centre-of-mass energy of $1.96\,\text{TeV}$ have previously been reported [5–8]. Indirect constraints have been placed on the mass of the virtual $Z'$ bosons by LEP-II experiments [9–12] by examining the cross sections and angular distribution of dileptons and hadronic final states in $e^+e^-$ collisions.

The results presented in this Letter were obtained from an analysis of data recorded in 2010, corresponding to an integrated luminosity of $40 \pm 4\,\text{pb}^{-1}$ in the dimuon channel, and $35 \pm 4\,\text{pb}^{-1}$ in the dielectron channel, obtained from pp collisions at a centre-of-mass energy of $7\,\text{TeV}$. The total integrated luminosity used for the electron analysis is smaller than that for the muon analysis because of the tighter quality requirements imposed on the data. The search for resonances is based on a shape analysis of dilepton mass spectra, in order to be robust against uncertainties in the absolute background level. By examining the dilepton-mass spectrum from below the Z resonance to the highest mass events recorded, we obtain limits on the ratio of the production cross section times branching fraction for high-mass resonances to that of the Z. Using further input describing the dilepton mass dependence on effects of parton distribution functions (PDFs) and $k$-factors, mass bounds are calculated for specific models. In addition, model-independent limit contours are determined in the two-parameter $(c_d, c_u)$ plane [13]. Selected benchmark models for $Z'$ production are illustrated in this plane, where where $c_u$ and $c_d$ are model-dependent couplings of the $Z'$ to up- and down-type quarks, respectively allowing lower bounds to be determined.

## 2 The CMS detector

The central feature of the CMS [14] apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Within the field volume are the silicon pixel and strip trackers, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). The endcap hadronic calorimeters are segmented in the z-direction. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry.

CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the $x$-axis pointing to the centre of the LHC, the $y$-axis pointing up (perpendicular to the LHC plane), and the $z$-axis along the anticlockwise-beam direction. The polar angle, $\theta$, is measured from the positive $z$-axis and the azimuthal angle, $\phi$, is measured in the $x$-$y$ plane.

Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes based on one of three technologies: drift tubes in the barrel region, cathode strip chambers in the endcaps, and resistive plate chambers in the barrel and part of the endcaps. The inner tracker (silicon pixels and strips) detects charged particles within the pseudorapidity range $|\eta| < 2.5$.

The electromagnetic calorimeter consists of nearly 76 000 lead tungstate crystals which provide coverage in pseudorapidity $|\eta| < 1.479$ in the barrel region (EB, with crystal size $\Delta\eta = 0.0174$ and $\Delta\phi = 0.0174$) and $1.479 < |\eta| < 3.0$ in the two endcap regions (EE, with

somewhat larger crystals.). A preshower detector consisting of two planes of silicon sensors interleaved with a total of $3\,X_0$ of lead is located in front of the EE.

The first level (L1) of the CMS trigger system, composed of custom hardware processors, selects the most interesting events using information from the calorimeters and muon detectors. The High Level Trigger (HLT) processor farm further decreases the event rate employing the full event information, including the inner tracker. The muon selection algorithms in the HLT use information from the muon detectors and the silicon pixel and strip trackers. The electromagnetic (EM) selection algorithms use the energy deposits in the ECAL and HCAL; the electron selection in addition requires tracks matched to clusters. Events with muons or electromagnetic clusters with $p_T$ above L1 and HLT thresholds are recorded.

## 3 Electron and muon selection

### 3.1 Triggers

The events used in the dimuon channel analysis were collected using a single-muon trigger. The algorithm requires a muon candidate to be found in the muon detectors by the L1 trigger. The candidate track is then matched to a silicon tracker track, forming an HLT muon. The HLT muon is required to have $p_T > 9$ to $15\,\text{GeV}$, depending on the running period.

A double EM cluster trigger was used to select the events for the dielectron channel. ECAL clusters are formed by summing energy deposits in crystals surrounding a "seed" that is locally the highest-energy crystal. The clustering algorithm takes into account the emission of bremsstrahlung. This trigger requires two clusters with the ECAL transverse energy $E_T$ above a threshold of 17 to $22\,\text{GeV}$, depending on the running period. For each of these clusters, the ratio $H/E$, where $E$ is the energy of the ECAL cluster and $H$ is the energy in the HCAL cells situated behind it, is required to be less than 15%. At least one of these clusters must have been associated with an energy deposit identified by the L1 trigger.

### 3.2 Lepton reconstruction

The reconstruction, identification, and calibration of muons and electrons follow standard CMS methods [15]. Combinations of test beam, cosmic ray muons, and data from proton collisions have been used to calibrate the relevant detector systems for both muons and electrons.

Muons are reconstructed independently as tracks in both the muon detectors and the silicon tracker [16]. The two tracks can be matched and fitted simultaneously to form a "global muon". Both muons in the event must be identified as global muons, with at least 10 hits in the silicon tracker and with $p_T > 20\,\text{GeV}$. All muon candidates that satisfy these criteria are classified as "loose" muons. At least one of the two muons in each event must be further classified as a "tight" muon by passing the following additional requirements: a transverse impact parameter with respect to the collision point less than 0.2 cm; a $\chi^2$ per degree of freedom less than 10 for the global track fit; at least one hit in the pixel detector; hits from the muon tracking system in at least two muon stations on the track; and correspondence with the single-muon trigger.

Electrons are reconstructed by associating a cluster in the ECAL with a track in the tracker [17]. Track reconstruction, which is specific to electrons to account for bremsstrahlung emission, is seeded from the clusters in the ECAL, first using the cluster position and energy to search for compatible hits in the pixel detector, and then using these hits as seeds to reconstruct a track in the silicon tracker. A minimum of five hits is required on each track. Electron candidates are required to be within the barrel or endcap acceptance regions, with pseudorapidities of $|\eta| < 1.442$ and $1.560 < |\eta| < 2.5$, respectively. A candidate electron is required to deposit most of its energy in the ECAL and relatively little in the HCAL ($H/E < 5\%$). The transverse shape of the energy deposit is required to be consistent with that expected for an electron, and the associated track must be well-matched in $\eta$ and $\phi$. Electron candidates must have $E_{\mathrm{T}} > 25\,\mathrm{GeV}$.

In order to suppress misidentified leptons from jets and non-prompt muons from hadron decays, both lepton selections impose isolation requirements. Candidate leptons are required to be isolated within a narrow cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, centred on the lepton. Muon isolation requires that the sum of the $p_{\mathrm{T}}$ of all tracks within the cone, excluding the muon, is less than 10% of the $p_{\mathrm{T}}$ of the muon. For electrons, the sum of the $p_{\mathrm{T}}$ of the tracks, excluding the tracks within an inner cone of $\Delta R = 0.04$, is required to be less than $7\,\mathrm{GeV}$ for candidates reconstructed within the barrel acceptance and $15\,\mathrm{GeV}$ within the endcap acceptance. The calorimeter isolation requirement for electron candidates within the barrel acceptance is that, excluding the $E_{\mathrm{T}}$ of the candidate, the sum of the $E_{\mathrm{T}}$ resulting from deposits in the ECAL and the HCAL within a cone of $\Delta R = 0.3$ be less than $0.03E_{\mathrm{T}} + 2\,\mathrm{GeV}$. For candidates within the endcap acceptance, the segmentation of the HCAL in the $z$-direction is exploited. For candidates with $E_{\mathrm{T}}$ below $50\,\mathrm{GeV}$ (above $50\,\mathrm{GeV}$), the isolation energy is required to be less than $2.5\,\mathrm{GeV}$ ($0.03(E_{\mathrm{T}} - 50) + 2.5\,\mathrm{GeV}$), where $E_{\mathrm{T}}$ is determined using the ECAL and the first layer of the segmented HCAL. The $E_{\mathrm{T}}$ in the second layer of the HCAL is required to be less than $0.5\,\mathrm{GeV}$. These requirements ensure that the candidate electrons are well-measured and have minimal contamination from jets.

The performance of the detector systems for the data sample presented in this paper is established using measurements of standard model (SM) W and Z processes with leptonic final states [15] and using traversing cosmic ray muons [18].

Muon momentum resolution varies from 1% at momenta of a few tens of GeV to 10% at momenta of several hundred GeV, as verified with measurements made with cosmic rays. The alignment of the muon and inner tracking systems is important for obtaining the best momentum resolution, and hence mass resolution, particularly at the high masses relevant to the Z′ search. An additional contribution to the momentum resolution arises from the presence of distortion modes in the tracker geometry that are not completely constrained by the alignment procedures. The dimuon mass resolution is estimated to have an rms of 5.8% at $500\,\mathrm{GeV}$ and 9.6% at $1\,\mathrm{TeV}$.

The ECAL has an ultimate energy resolution of better than 0.5% for unconverted photons with transverse energies above $100\,\mathrm{GeV}$. The ECAL energy resolution obtained thus far is on average 1.0% for the barrel and 4.0% for the endcaps. The mass resolution is estimated to be 1.3% at $500\,\mathrm{GeV}$ and 1.1% at $1\,\mathrm{TeV}$. Electrons from W and Z bosons were

used to calibrate ECAL energy measurements. For both muons and electrons, the energy scale is set using the Z mass peak, except for electrons in the barrel section of the ECAL, where the energy scale is set using neutral pions, and then checked using the Z mass peak. The ECAL energy scale uncertainty is 1% in the barrel and 3% in the endcaps.

## 3.3 Efficiency estimation

The efficiency for identifying and reconstructing lepton candidates is measured with the tag-and-probe method [15]. A tag lepton is established by applying tight cuts to one lepton candidate; the other candidate is used as a probe. A large sample of high-purity probes is obtained by requiring that the tag-and-probe pair have an invariant mass consistent with the Z boson mass ($80 < m_{\ell\ell} < 100\,\text{GeV}$). The factors contributing to the overall efficiency are measured in the data. They are: the trigger efficiency, the reconstruction efficiency in the silicon tracker, the electron clustering efficiency, and the lepton reconstruction and identification efficiency. All efficiencies and scale factors quoted below are computed using events in the Z mass region.

The trigger efficiencies are defined relative to the full offline lepton requirements. For the dimuon events, the efficiency of the single muon trigger with respect to loose muons is measured to be $89\% \pm 2\%$ [15]. The overall efficiency, defined with respect to particles within the physical acceptance of the detector, for loose (tight) muons is measured to be $94.1\% \pm 1.0\%$ ($81.2\% \pm 1.0\%$). Within the statistical precision allowed by the current data sample, the dimuon efficiency is constant as a function of $p_{\text{T}}$ above 20 GeV, as is the ratio of the efficiency in the data to that in the Monte Carlo (MC) of $0.977 \pm 0.004$. For dielectron events, the double EM cluster trigger is 100% efficient (99% during the early running period). The total electron identification efficiency is $90.1\% \pm 0.5\%$ (barrel) and $87.2\% \pm 0.9\%$ (endcap). The ratio of the electron efficiency measured from the data to that determined from MC simulation at the Z resonance is $0.979 \pm 0.006$ (EB) and $0.993 \pm 0.011$ (EE). To determine the efficiency applicable to high-energy electrons in the data sample, this correction factor is applied to the efficiency found using MC simulation. The efficiency of electron identification increases as a function of the electron transverse energy until it becomes flat beyond an $E_{\text{T}}$ value of about 45 GeV. Between 30 and 45 GeV it increases by about 5%.

## 4 Event samples and selection

Simulated event samples for the signal and associated backgrounds were generated with the PYTHIA v6.422 [19] MC event generator, and with MADGRAPH [20] and POWHEG v1.1 [21–23] interfaced with the PYTHIA parton-shower generator using the CTEQ6L1 [24] PDF set. The response of the detector was simulated in detail using GEANT4 [25]. These samples were further processed through the trigger emulation and event reconstruction chain of the CMS experiment.

For both dimuon and dielectron final states, two isolated same flavour leptons that pass the lepton identification criteria described in section 3.2 are required. The two charges are required to have opposite sign in the case of dimuons (for which a charge misassignment

implies a large momentum measurement error), but not in the case of dielectrons (for which charge assignment is decoupled from the ECAL-based energy measurement). An opposite-charge requirement for dielectrons would lead to a loss of signal efficiency of a few percent.

Of the two muons selected, one is required to satisfy the "tight" criteria. The electron sample requires at least one electron candidate in the barrel because events with both electrons in the endcaps will have a lower signal-to-background ratio. For both channels, each event is required to have a reconstructed vertex with at least four associated tracks, located less than 2 cm from the centre of the detector in the direction transverse to the beam and less than 24 cm in the direction along the beam. This requirement provides protection against cosmic rays. Additional suppression of cosmic ray muons is obtained by requiring the three-dimensional opening angle between the two muons to be smaller than $\pi - 0.02$ radians.

## 5 Backgrounds

The most prominent SM process that contributes to the dimuon and dielectron invariant mass spectra is Drell-Yan production ($Z/\gamma^*$); there are also contributions from the $t\bar{t}$, tW, WW, and $Z \to \tau\tau$ channels. In addition, jets may be misidentified as leptons and contribute to the dilepton invariant mass spectrum through multi-jet and vector boson + jet final states.

### 5.1 $Z/\gamma^*$ backgrounds

The shape of the dilepton invariant mass spectrum is obtained from Drell-Yan production using a MC simulation based on the PYTHIA event generator. The simulated spectrum at the invariant mass peak of the Z boson is normalized to the data. The dimuon analysis uses the data events in the Z mass interval of 60–120 GeV; the dielectron analysis uses data events in the narrower interval of 80–100 GeV in order to obtain a comparably small background contamination.

A contribution to the uncertainty attributed to the extrapolation of the event yield and the shape of the Drell-Yan background to high invariant masses arises from higher order QCD corrections. The next-to-next-to-leading order (NNLO) $k$-factor is computed using FEWZz v1.X [26], with PYTHIA v6.409 and CTEQ6.1 PDF [27] as a baseline. It is found that the variation of the $k$-factor with mass does not exceed 4% where the main difference arises from the comparison of PYTHIA and FEWZz calculations. A further source of uncertainty arises from the PDFs. The LHAGLUE [28] interface to the LHAPDF-5.3.1 [29] library is used to evaluate these uncertainties, using the error PDFs from the CTEQ6.1 and the MRST2006nnlo [30] uncertainty eigenvector sets. The uncertainty on the ratio of the background in the high-mass region to that in the region of the Z peak is below 4% for both PDF sets and masses below 1 TeV. Combining the higher order QCD and PDF uncertainties in quadrature, the resulting uncertainty in the number of events normalized to those expected at the Z peak is about 5.7% for masses between 200 GeV and 1 TeV.
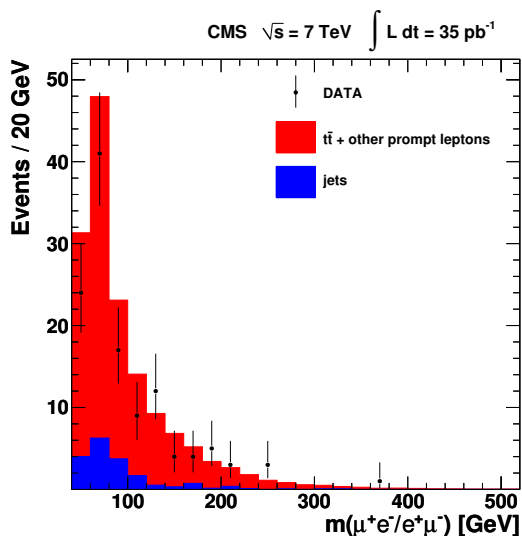
**Figure 1**. The observed opposite-sign $e^{\pm}\mu^{\mp}$ dilepton invariant mass spectrum (data points). The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means. Filled histograms show contributions to the spectrum from $t\bar{t}$, other sources of prompt leptons (tW, diboson production, $Z \to \tau\tau$), and the multi-jet background (from Monte Carlo simulation).

## 5.2 Other backgrounds with prompt lepton pairs

The dominant non-Drell-Yan electroweak contribution to high $m_{\ell\ell}$ masses is $t\bar{t}$; in addition there are contributions from tW and diboson production. In the Z peak region, $Z \to \tau\tau$ decays also contribute. All these processes are flavour symmetric and produce twice as many $e\mu$ pairs as ee or $\mu\mu$ pairs. The invariant mass spectrum from $e^{\pm}\mu^{\mp}$ events is expected to have the same shape as that of same flavour $\ell^+\ell^-$ events but without significant contamination from Drell-Yan production.

Figure 1 shows the observed $e^{\pm}\mu^{\mp}$ dilepton invariant mass spectrum from a dataset corresponding to $35\,\mathrm{pb}^{-1}$, overlaid on the prediction from simulated background processes. This spectrum was obtained using the same single-muon trigger as in the dimuon analysis and by requiring oppositely charged leptons of different flavour. Using an electron trigger, a very similar spectrum is produced. Differences in the geometric acceptances and efficiencies result in the predicted ratios of $\mu^+\mu^-$ and ee to $e^{\pm}\mu^{\mp}$ being approximately 0.64 and 0.50, respectively. In the data, shown in figure 1, there are 32 (7) $e^{\pm}\mu^{\mp}$ events with invariant mass above 120 (200) GeV. This yields an expectation of about 20 (4) dimuon events and 16 (4) dielectron events. A direct estimate from MC simulations of the processes involved predicts 20.1±3.6 (5.3±1.0) dimuon events and 13.2±2.4 (3.5±0.6) dielectron events. The uncertainty includes both statistical and systematic contributions, and is dominated by the theoretical uncertainty of 15% on the $t\bar{t}$ production cross section [31, 32]. The agreement between the observed and predicted distributions provides a validation of the estimated contributions from the backgrounds from prompt leptons obtained using MC simulations.

## 5.3 Events with misidentified and non-prompt leptons

A further source of background arises when objects are falsely identified as prompt leptons. The misidentification of jets as leptons, the principle source of such backgrounds, is more likely to occur for electrons than for muons.

Backgrounds arising from jets that are misidentified as electrons include $W \to e\nu$ + jet events with one jet misidentified as a prompt electron, and also multi-jet events with two jets misidentified as prompt electrons. A prescaled single EM cluster trigger is used for collecting a sample of events to determine the rate of jets misreconstructed as electrons and to estimate the backgrounds from misidentified electrons. The events in this sample are required to have no more than one reconstructed electron, and missing transverse energy of less than 20 GeV, to suppress the contribution from Z and W events respectively. The probability for an EM cluster with $H/E < 5\%$ to be reconstructed as an electron is determined in bins of $E_T$ and $\eta$ from a data sample dominated by multi-jet events and is used to weight appropriately events which have two such clusters passing the double EM trigger. The estimated background contribution to the dielectron mass spectrum due to misidentified jets is 8.6±3.4 (2.1±0.8) for $m_{ee} > 120\,(200)\,\mathrm{GeV}$.

In order to estimate the residual contribution from background events with at least one non-prompt or misidentified muon, events are selected from the data sample with single muons that pass all selection cuts except the isolation requirement. A map is created, showing the isolation probability for these muons as a function of $p_T$ and $\eta$. This probability map is corrected for the expected contribution from events with single prompt muons from $t\bar{t}$ and W decays and for the observed correlation between the probabilities for two muons in the same event. The probability map is used to predict the number of background events with two isolated muons based on the sample of events that have two non-isolated muons. This procedure, which has been validated using simulated events, predicts a mean background to $m_{\mu\mu} > 120\,(200)\,\mathrm{GeV}$ of $0.8 \pm 0.2\,(0.2 \pm 0.1)$.

As the signal sample includes the requirement that the muons in the pair have opposite electric charge, a further cross-check of the estimate is performed using events with two isolated muons of the same charge. There are no events with same-charge muon pairs and $m_{\mu\mu} > 120\,\mathrm{GeV}$, a result which is statistically compatible with both the figure of $1.6 \pm 0.3$ events predicted from SM process using MC simulation and the figure of $0.4 \pm 0.1$ events obtained using methods based on data.

## 5.4 Cosmic ray muon backgrounds

The $\mu^+\mu^-$ data sample is susceptible to contamination from traversing cosmic ray muons, which may be misreconstructed as a pair of oppositely charged, high-momentum muons. Cosmic ray events can be removed from the data sample because of their distinct topology (collinearity of two tracks associated with the same muon), and their uniform distribution of impact parameters with respect to the collision vertex. The residual mean expected background from cosmic ray muons is measured using sidebands to be less than 0.1 events with $m_{\mu\mu} > 120\,\mathrm{GeV}$.

## 6 Dilepton invariant mass spectra

The measured dimuon and dielectron invariant mass spectra are displayed in figures 2(left) and (right) respectively, along with the expected signal from $Z'_{SSM}$ with a mass of 750 GeV. In the dimuon sample, the highest invariant mass event has $m_{\mu\mu} = 463$ GeV, with the $p_T$ of the two muons measured to be 258 and 185 GeV. The highest invariant mass event in the dielectron sample has $m_{ee} = 419$ GeV, with the electron candidates having $E_T$ of 125 and 84 GeV.

The expectations from the various background sources, $Z/\gamma^*$, $t\bar{t}$, other sources of prompt leptons (tW, diboson production, $Z \to \tau\tau$) and multi-jet events are also overlaid in figure 2. For the dielectron sample, the multi-jet background estimate was obtained directly from the data. The prediction for Drell-Yan production of $Z/\gamma^*$ is normalized to the observed $Z \to \ell\ell$ signal. All other MC predictions are normalized to the expected cross sections. Figures 3(left) and (right) show the corresponding cumulative distributions of the spectra for the dimuon and dielectron samples. Good agreement is observed between data and the expectation from SM processes over the mass region above the Z peak.

Searches for narrow resonances at the Tevatron [6, 8] have placed lower limits in the mass range 600 GeV to 1000 GeV. The region with dilepton masses $120$ GeV $< m_{\ell\ell} < 200$ GeV is part of the region for which resonances have been excluded by previous experiments, and thus should be dominated by SM processes. The observed good agreement between the data and the prediction in this control region gives confidence that the SM expectations and the detector performance are well understood.

In the Z peak mass region defined as $60 < m_{\ell\ell} < 120$ GeV, the number of dimuon and dielectron candidates are 16 515 and 8 768 respectively, with very small backgrounds. The difference in the electron and muon numbers is due to the higher $E_T$ cut in the electron analysis and lower electron identification efficiencies at these energies. The expected yields in the control region (120–200 GeV) and high invariant mass regions ($> 200$ GeV) are listed in table 1. The agreement between the observed data and expectations, while not used in the shape-based analysis, is good.

## 7 Limits on the production cross section

The observed invariant mass spectrum agrees with expectations based on standard model processes, therefore limits are set on the possible contributions from a narrow heavy resonance. The parameter of interest is the ratio of the products of cross sections and branching fractions:

$$R_\sigma = \frac{\sigma(\text{pp} \to Z' + X \to \ell\ell + X)}{\sigma(\text{pp} \to Z + X \to \ell\ell + X)}. \tag{7.1}$$

By focusing on the ratio $R_\sigma$, we eliminate the uncertainty in the integrated luminosity, reduce the dependence on experimental acceptance, trigger, and offline efficiencies, and generally obtain a more robust result.

For statistical inference about $R_\sigma$, we first estimate the Poisson mean $\mu_Z$ of the number of $Z \to \ell\ell$ events in the sample by counting the number of events in the Z peak mass region
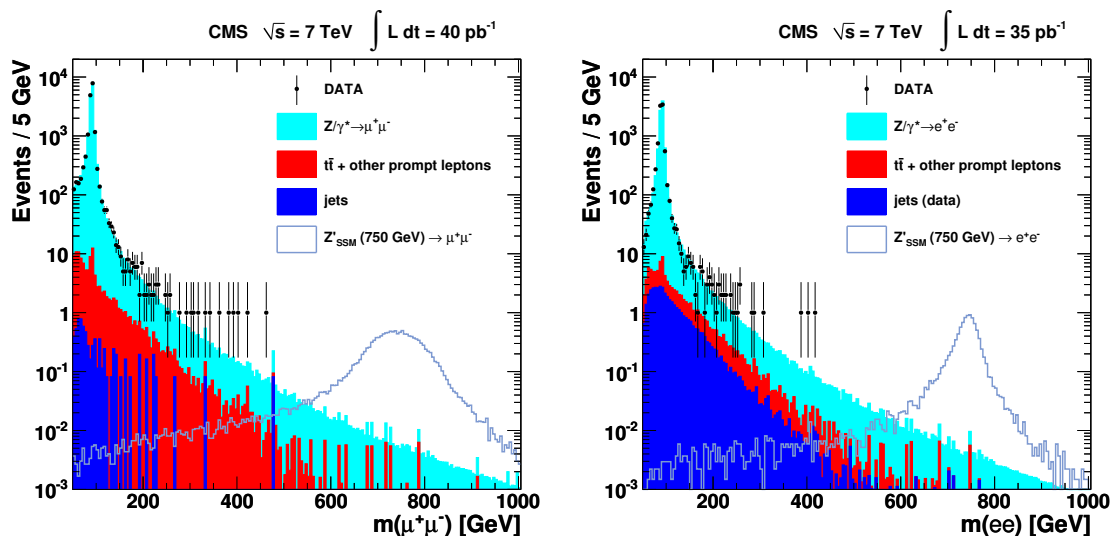
**Figure 2**. Invariant mass spectrum of $\mu^+\mu^-$ (left) and ee (right) events. The points with error bars represent the data. The uncertainties on the data points (statistical only) represent 68% confidence intervals for the Poisson means. The filled histograms represent the expectations from SM processes: $Z/\gamma^*$, $t\bar{t}$, other sources of prompt leptons (tW, diboson production, $Z \to \tau\tau$), and the multi-jet backgrounds. The open histogram shows the signal expected for a $Z'_{\rm SSM}$ with a mass of 750 GeV.
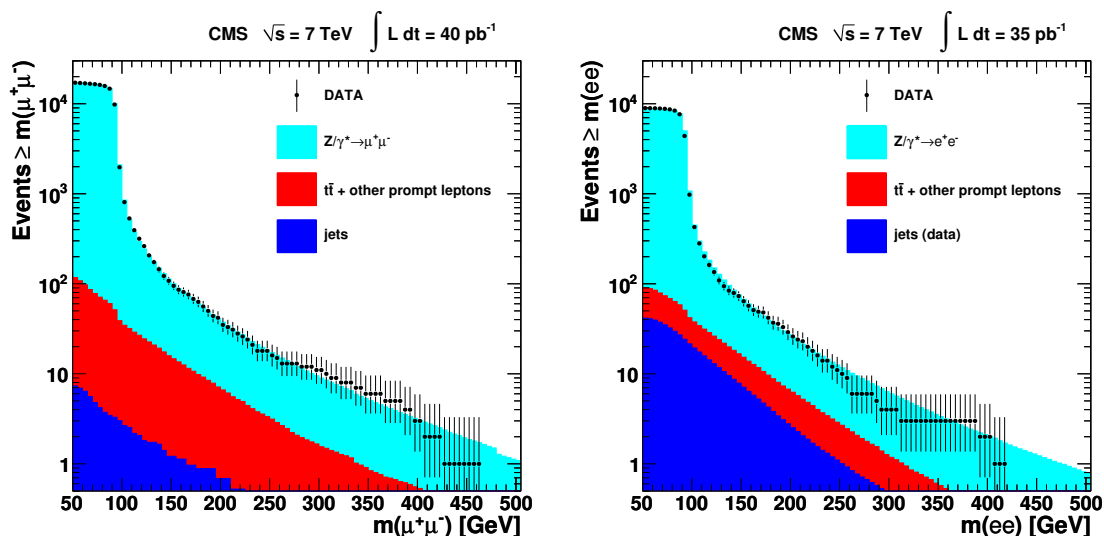


**Figure 3**. Cumulative distribution of invariant mass spectrum of $\mu^+\mu^-$ (left) and ee (right) events. The points with error bars represent the data, and the filled histogram represents the expectations from SM processes.

and correcting for a small ($\sim 0.4\%$) background contamination (determined with MC simulation). The uncertainty on $\mu_Z$ is about 1% (almost all statistical) and contributes

| Source | Number of events | | | |
|--------|:----------------:|:--:|:--:|:--:|
| | Dimuon sample | | Dielectron sample | |
| | $(120 - 200)\,\text{GeV}$ | $>200\,\text{GeV}$ | $(120 - 200)\,\text{GeV}$ | $>200\,\text{GeV}$ |
| CMS data | 227 | 35 | 109 | 26 |
| $\text{Z}'_{\text{SSM}}$ (750 GeV) | — | $15.0 \pm 1.9$ | — | $8.7 \pm 1.1$ |
| Total background | $204 \pm 23$ | $36.3 \pm 4.3$ | $120 \pm 14$ | $24.4 \pm 3.0$ |
| $\text{Z}/\gamma^*$ | $187 \pm 23$ | $30.2 \pm 3.6$ | $104 \pm 14$ | $18.8 \pm 2.3$ |
| $t\bar{t}$ | $12.3 \pm 2.3$ | $4.2 \pm 0.8$ | $7.6 \pm 1.4$ | $2.7 \pm 0.5$ |
| Other prompt leptons | $4.4 \pm 0.5$ | $1.7 \pm 0.2$ | $2.1 \pm 0.2$ | $0.8 \pm 0.1$ |
| Multi-jet events | $0.6 \pm 0.2$ | $0.2 \pm 0.1$ | $6.5 \pm 2.6$ | $2.1 \pm 0.8$ |

**Table 1.** Number of dilepton events with invariant mass in the control region $120 < m_{\ell\ell} < 200\,\text{GeV}$ and the search region $m_{\ell\ell} > 200\,\text{GeV}$. The expected number of Z′ events is given within ranges of 328 GeV and 120 GeV for the dimuon sample and the dielectron sample respectively, centred on 750 GeV. The total background is the sum of the SM processes listed. The MC yields are normalized to the expected cross sections. Uncertainties include both statistical and systematic components added in quadrature.

negligibly to the uncertainty on $R_\sigma$.

We then construct an extended unbinned likelihood function for the spectrum of $\ell\ell$ invariant mass values $m$ above 200 GeV, based on a sum of analytic probability density functions (pdfs) for the signal and background shapes.

The pdf $f_{\text{S}}(m|\Gamma, M, w)$ for the resonance signal is a Breit-Wigner of width $\Gamma$ and mass $M$ convoluted with a Gaussian resolution function of width $w$ (section 3.2). The width $\Gamma$ is taken to be that of the $\text{Z}'_{\text{SSM}}$ (about 3%); as noted below, the high-mass limits are insensitive to this width. The Poisson mean of the yield is $\mu_{\text{S}} = R_\sigma \cdot \mu_{\text{Z}} \cdot R_\epsilon$, where $R_\epsilon$ is the ratio of selection efficiency times detector acceptance for Z′ decay to that of Z decay; $\mu_{\text{B}}$ denotes the Poisson mean of the total background yield. A background pdf $f_{\text{B}}$ was chosen and its shape parameters fixed by fitting to the simulated Drell-Yan spectrum in the mass range $200 < m_{\ell\ell} < 2000\,\text{GeV}$. Two functional forms for the dependence of $f_{\text{B}}$ on shape parameters $\alpha$ and $\kappa$ were tried: $f_{\text{B}}(m|\alpha, \kappa) \sim \exp(-\alpha m^\kappa)$ and $\sim \exp(-\alpha m)m^{-\kappa}$. Both yielded good fits and consistent results for both the dimuon and dielectron spectra. For definiteness, this Letter presents results obtained with the latter form.

The extended likelihood $\mathcal{L}$ is then

$$\mathcal{L}(\boldsymbol{m}|R_\sigma, M, \Gamma, w, \alpha, \kappa, \mu_{\text{B}}) = \frac{\mu^N e^{-\mu}}{N!} \prod_{i=1}^{N} \left( \frac{\mu_{\text{S}}(R_\sigma)}{\mu} f_{\text{S}}(m_i|M, \Gamma, w) + \frac{\mu_{\text{B}}}{\mu} f_{\text{B}}(m_i|\alpha, \kappa) \right),$$
(7.2)

where $\boldsymbol{m}$ denotes the dataset in which the observables are the invariant mass values of the lepton pairs, $m_i$; $N$ denotes the total number of events observed above 200 GeV; and $\mu = \mu_{\text{S}} + \mu_{\text{B}}$ is the mean of the Poisson distribution from which $N$ is an observation.

Starting from eq. 7.2, confidence/credible intervals are computed using more than one approach, both frequentist (using profile likelihood ratios) and Bayesian (multiplying $\mathcal{L}$ by prior pdfs including a uniform prior for the signal mean). With no candidate events

in the region of small expected background above 465 GeV, the result is insensitive to the statistical technique, and also with respect to the width of the $Z'$ and to changes in systematic uncertainties and their functional forms, taken to be log-normal distributions with fractional uncertainties.

For $R_\epsilon$, we assign an uncertainty of 8% for the dielectron channel and 3% for the dimuon channel. These values reflect our current understanding of the detector acceptance and reconstruction efficiency turn-on at low mass (including PDF uncertainties and mass-dependence of $k$-factors), as well as the corresponding values at high mass, where cosmic ray muons are available to study muon performance but not electron performance. The uncertainty in the mass scale affects only the mass region below 500 GeV where there are events in both channels extrapolating from the well-calibrated observed resonances. For the dielectron channel, it is set to 1% based on linearity studies. For the dimuon channel, it is set to zero, as a sensitivity study showed negligible change in the results up to the maximum misalignment consistent with alignment studies (corresponding to several percent change in momentum scale). The acceptance for $G_{KK}$ (spin 2) is higher than for $Z'$ (spin 1) by less than 8% over the mass range 0.75–1.1 TeV. This was conservatively neglected when calculating the limits.

In the frequentist calculation, the mean background level $\mu_B$ is the maximum likelihood estimate; in the fully Bayesian calculation a prior must be assigned to the mean background level, but the result is insensitive to reasonable choices (i.e., for which the likelihood dominates the prior).

The upper limits on $R_\sigma$ (eq. 7.1) from the various approaches are similar, and we report the Bayesian result (implemented with Markov Chain Monte Carlo in RooStats [33]) for definiteness. From the dimuon and dielectron data, we obtain the upper limits on the cross section ratio $R_\sigma$ at 95% confidence level (C.L.) shown in figures 4(upper) and (middle), respectively.

In figure 4, the predicted cross section ratios for $Z'_{\rm SSM}$ and $Z'_\psi$ production are superimposed together with those for $G_{KK}$ production with dimensionless graviton coupling to SM fields $k/\overline{M}_{\rm Pl} = 0.05$ and 0.1. The leading order cross section predictions for $Z'_{\rm SSM}$ and $Z'_\psi$ from PYTHIA using CTEQ6.1 PDFs are corrected for a mass dependent $k$-factor obtained using ZWPRODP [34–37] to account for NNLO contributions. For the RS graviton model, a constant NLO $k$-factor of 1.6 is used [38]. The uncertainties due to the QCD scale parameter and PDFs are indicated as a band. The NNLO prediction for the Z production cross section is $0.97 \pm 0.04$ nb [26].

Propagating the above-mentioned uncertainties into the comparison of the experimental limits with the predicted cross section ratios, we exclude at 95% C.L. $Z'$ masses as follows. From the dimuon only analysis, the $Z'_{\rm SSM}$ can be excluded below 1027 GeV, the $Z'_\psi$ below 792 GeV, and the RS $G_{KK}$ below 778 (987) GeV for couplings of 0.05 (0.1). For the dielectron analysis, the production of $Z'_{\rm SSM}$ and $Z'_\psi$ bosons is excluded for masses below 958 and 731 GeV, respectively. The corresponding lower limits on the mass for RS $G_{KK}$ with couplings of 0.05 (0.10) are 729 (931) GeV.

## 7.1 Combined limits on the production cross section using dimuon and dielectron events

The above statistical formalism is generalized to combine the results from the dimuon and dielectron channels, by defining the combined likelihood as the product of the likelihoods for the individual channels with $R_\sigma$ forced to be the same value for both channels. The combined limit is shown in figure 4 (bottom).

By combining the two channels, the following 95% C.L. lower limits on the mass of a Z$'$ resonance are obtained: 1140 GeV for the Z$'_{\rm SSM}$, and 887 GeV for Z$'_\psi$ models. RS Kaluza-Klein gravitons are excluded below 855 (1079) GeV for values of couplings 0.05 (0.10). Our observed limits are more restrictive than or comparable to those previously obtained via similar direct searches by the Tevatron experiments [5–8], or indirect searches by LEP-II experiments [9–12], with the exception of Z$'_{\rm SSM}$, where the value from LEP-II is the most restrictive.

The distortion of the observed limits at $\sim$400 GeV visible in figure 4 is the result of a clustering of several dimuon and dielectron events around this mass. We have tested for the statistical significance of these excesses ($p$-values expressed as equivalent $Z$-values, i.e. effective number of Gaussian sigma in a one-sided test), using the techniques described in [39]. For the dimuon sample, the probability of an enhancement at least as large as that at 400 GeV occurring anywhere above 200 GeV in the observed sample size corresponds to $Z < 0.2$; for the electron sample, it is less. For the combined data sample, the corresponding probability in a joint peak search is equivalent to $Z = 1.1$.

In the narrow-width approximation, the cross section for the process pp $\rightarrow$ Z$' + X \rightarrow \ell\ell + X$ can be expressed [13, 34] in terms of the quantity $c_u w_u + c_d w_d$, where $c_u$ and $c_d$ contain the information from the model-dependent Z$'$ couplings to fermions in the annihilation of charge 2/3 and charge $-1/3$ quarks, respectively, and where $w_u$ and $w_d$ contain the information about PDFs for the respective annihilation at a given Z$'$ mass.

The translation of the experimental limits into the $(c_u, c_d)$ plane has been studied in the context of both the narrow-width and finite width approximations. The procedures have been shown to give the same results. In figure 5 the limits on the Z$'$ mass are shown as lines in the $(c_d, c_u)$ plane intersected by curves from various models which specify $(c_d, c_u)$ as a function of a model mixing parameter. In this plane, the thin solid lines labeled by mass are iso-contours of cross section with constant $c_u + (w_d/w_u)c_d$, where $w_d/w_u$ is in the range 0.5–0.6 for the results relevant here. As this linear combination increases or decreases by an order of magnitude, the mass limits change by roughly 500 GeV. The point labeled SM corresponds to the Z$'_{\rm SSM}$; it lies on the more general curve for the Generalized Sequential Standard Model (GSM) for which the generators of the U(1)$_{T_{3L}}$ and U(1)$_Q$ gauge groups are mixed with a mixing angle $\alpha$. Then $\alpha = -0.072\pi$ corresponds to the $Z'_{SSM}$ and $\alpha = 0$ and $\pi/2$ define the $T_{3L}$ and $Q$ benchmarks, respectively, which have larger values of $(c_d, c_u)$ and hence larger lower bounds on the masses. Also shown are contours for the E$_6$ model (with $\chi$, $\psi$, $\eta$, $S$, and $N$ corresponding to angles 0, $0.5\pi$, $-0.29\pi$, $0.13\pi$, and $0.42\pi$, respectively) and Generalized LR models (with $R$, $B-L$, $LR$, and $Y$ corresponding to angles 0, $0.5\pi$, $-0.13\pi$, and $0.25\pi$, respectively) [34] .
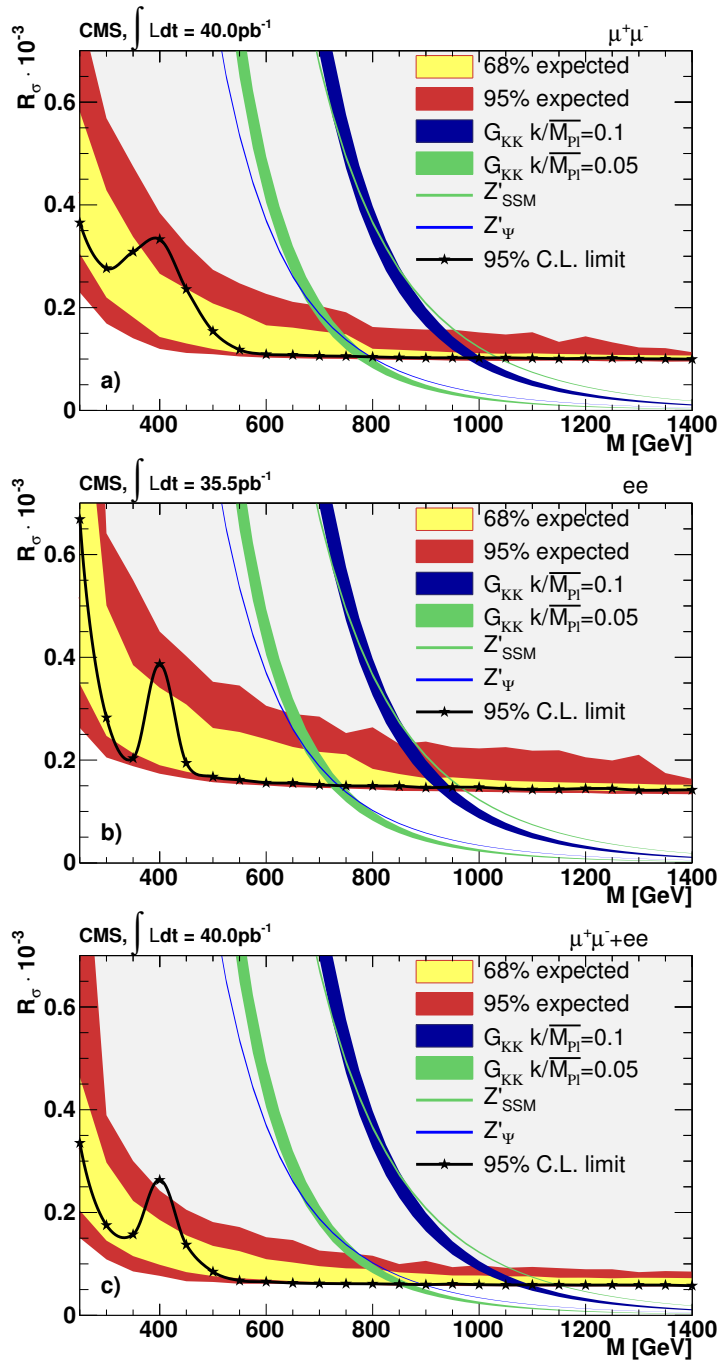
**Figure 4**. Upper limits as a function of resonance mass $M$, on the production ratio $R_\sigma$ of cross section times branching fraction into lepton pairs for $\mathrm{Z}'_{\mathrm{SSM}}$ and $\mathrm{G}_{\mathrm{KK}}$ production and $\mathrm{Z}'_\psi$ boson production. The limits are shown from (top) the $\mu^+\mu^-$ final state, (middle) the ee final state and (bottom) the combined dilepton result. Shaded yellow and red bands correspond to the 68% and 95% quantiles for the expected limits. The predicted cross section ratios are shown as bands, with widths indicating the theoretical uncertainties.
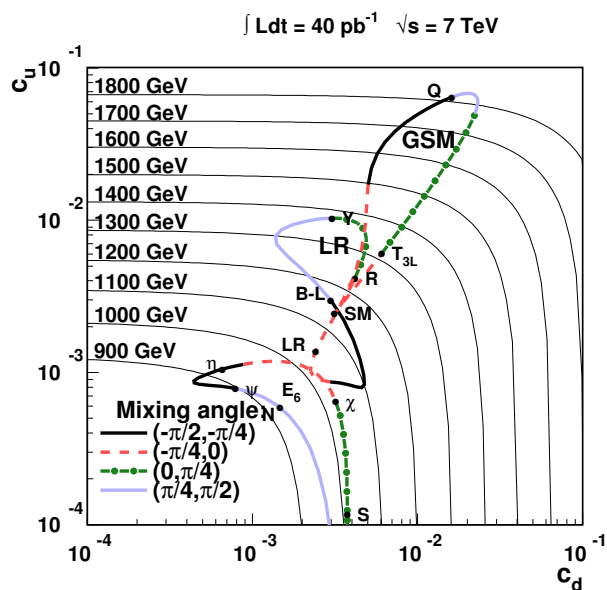
**Figure 5**. 95% C.L. lower limits on the Z′ mass, represented by the thin continuous lines in the $(c_d, c_u)$ plane. Curves for three classes of model are shown. Colours on the curves correspond to different mixing angles of the generators defined in each model. For any point on a curve, the mass limit corresponding to that value of $(c_d, c_u)$ is given by the intersected contour.

## 8 Summary

The CMS Collaboration has searched for narrow resonances in the invariant mass spectrum of dimuon and dielectron final states in event samples corresponding to an integrated luminosity of $40 \, \mathrm{pb}^{-1}$ and $35 \, \mathrm{pb}^{-1}$, respectively. The spectra are consistent with standard model expectations and upper limits on the cross section times branching fraction for Z′ into lepton pairs relative to standard model Z boson production have been set. Mass limits have been set on neutral gauge bosons Z′ and RS Kaluza-Klein gravitons $G_{\mathrm{KK}}$. A Z′ with standard-model-like couplings can be excluded below $1140 \, \mathrm{GeV}$, the superstring-inspired $Z'_\psi$ below $887 \, \mathrm{GeV}$, and RS Kaluza-Klein gravitons below $855$ $(1079) \, \mathrm{GeV}$ for couplings of $0.05$ $(0.10)$, all at 95% C.L. The higher centre of mass energy used in this search, compared to that of previous experiments, has resulted in limits that are comparable to or exceed those previously published, despite the much lower integrated luminosity accumulated at the LHC thus far.

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