Search for narrow resonances in dilepton mass spectra in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

A search for narrow, high-mass resonances decaying to electron or muon pairs has been performed using pp collision data collected at $\sqrt{s} = 7$ TeV by the CMS experiment in 2011. The data sample corresponds to an integrated luminosity of approximately 5 fb^{-1}. The event yields observed in the signal regions are consistent with predictions of the standard model backgrounds, and upper limits on the cross section times branching fraction for a resonance decaying to dileptons are extracted from a shape analysis of the dilepton invariant mass distribution. The resulting mass limits at 95% confidence level are 2330 GeV for the Z′ in the Sequential Standard Model, 2000 GeV for the superstring-inspired Z′$_\psi$ resonance, 890 (540) GeV for the Stueckelberg extension Z′$_{St}$ with the mass parameter $\epsilon = 0.06$ (0.04), and 2140 (1810) GeV for Kaluza–Klein gravitons with the coupling parameter $k/\overline{M}_{Pl}$ of 0.10 (0.05). These limits are the most stringent to date.

1. Introduction

This Letter describes the results of a search for narrow resonances in the dilepton mass spectra using data collected by the Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) [1] at CERN during 2011.

Numerous models describing possible physics beyond the standard model (SM) predict the existence of narrow resonances at the TeV mass scale. The results of the search reported here are interpreted in the context of several such models. The narrow resonances predicted in these models include the Sequential Standard Model Z′$_{SSM}$ with standard model couplings [2], the Z′$_\psi$ expected in grand unified theories [3], the Z′$_{St}$ produced in the Stueckelberg extension to the standard model [4,5], and the Kaluza–Klein graviton (G$_{KK}$) excitations arising in the Randall–Sundrum (RS) model of extra dimensions [6,7]. For a resonance mass of 1 TeV, the widths of the Z′$_{SSM}$, Z′$_\psi$, Z′$_{St}$, and G$_{KK}$ are 30, 6, 0.06, and 3.5 (14) GeV, where the G$_{KK}$ coupling parameter $k/\overline{M}_{Pl}$ is taken to be 0.05 (0.1). In the case of the Z′$_{St}$ this width is evaluated at a value of 0.06 for the ϵ parameter. This parameter represents the ratio of the mass parameters of the gauge bosons before they mix to become the Z and Z′$_{St}$. The maximum allowed value of ϵ is approximately 0.06, as determined by the precision measurements of the Z parameters. If ϵ is equal to 0, there is no coupling to the Stueckelberg extension and the standard model is recovered.

Results of searches for narrow Z′ → $\ell^+\ell^-$ and G$_{KK}$ → $\ell^+\ell^-$ resonances have previously been reported by the ATLAS [8] and CMS [9] Collaborations, based on about 1 fb^{-1} and 40 pb^{-1} of data, respectively. The D0 and CDF experiments have published results with over 5 fb^{-1} of integrated luminosity in p$\bar{\text{p}}$ collisions, at a centre-of-mass energy of 1.96 TeV [10–15]. Indirect constraints have been placed on the mass of virtual Z′ bosons by LEP-II experiments [16–19], using the cross sections and angular distributions of dilepton and hadronic final states in e$^+$e$^-$ collisions.

The results presented in this Letter are obtained from an analysis of pp collision data at $\sqrt{s} = 7$ TeV corresponding to an integrated luminosity of 5.28 ± 0.12 fb^{-1} for the muon channel and 4.98 ± 0.11 fb^{-1} for the electron channel [20]. The analysis procedure reported here follows methods used in the earlier analysis of a smaller data set, described in Ref. [9]. The search for resonances is based on a shape analysis of the dilepton mass spectra, to be robust against uncertainties in the absolute background level. In the absence of a signal, limits are set on the ratio R_σ of the production cross section times branching fraction for high-mass resonances to that for the Z boson. In this approach, many experimental and theoretical uncertainties common to both measurements cancel. Using theoretical cross sections and including K factors and parton distribution functions (PDFs), lower mass limits are calculated for several models.

2. The CMS detector

The central feature of the CMS detector is a superconducting solenoid providing an axial magnetic field of 3.8 T and enclosing

the all-silicon inner tracker, the crystal electromagnetic calorimeter (ECAL), and the brass-scintillator hadronic calorimeter (HCAL). The inner tracker is composed of a pixel detector and a silicon strip tracker, and measures charged-particle trajectories in the pseudo-rapidity range $|\eta| < 2.5$.[1] The finely segmented ECAL consists of nearly 76 000 lead-tungstate crystals which provide coverage in pseudorapidity up to $|\eta| = 3.0$. The muon system covers the pseudorapidity region $|\eta| < 2.4$ and consists of up to four stations of gas-ionization muon detectors installed outside the solenoid and sandwiched between steel layers serving both as hadron absorbers and as a return yoke for the magnetic field. A detailed description of the CMS detector can be found elsewhere [21].

The CMS experiment uses a two-level trigger system. The Level-1 Trigger, composed of custom hardware processors, selects events of interest using information from the calorimeters and muon detectors [22]. The High-Level Trigger (HLT) is software-based and further decreases the event collection rate by using the full event information, including that from the inner tracker [23].

3. Electron and muon selection

The events used in the dimuon channel analysis were collected using a single-muon trigger with a transverse momentum (p_T) threshold of 40 GeV. In order to keep the trigger rate at an acceptable level, the acceptance of this trigger was restricted to the pseudorapidity range of $|\eta| < 2.1$. The muon candidates' tracks are formed in the trigger by combining standalone tracks reconstructed separately in the muon chambers and in the inner tracker.

The trigger used to select dielectron events requires the presence of two clusters in the ECAL, each with transverse energy $E_T > 33$ GeV and each matched to hits in the pixel detector. The trigger also requires the absence of significant energy deposits in the hadron calorimeter cells directly behind these two ECAL clusters.

Electrons and muons are reconstructed using standard CMS algorithms, described in more detail in [9,24,25]. Clusters in the ECAL are matched to reconstructed tracks to form electron candidates. These candidates must be within the barrel or endcap acceptance regions, with pseudorapidities of $|\eta| < 1.442$ and $1.560 < |\eta| < 2.5$, respectively. Electron candidates must have $E_T > 35$ GeV if they are within the barrel region and $E_T > 40$ GeV if they are within the endcap regions. As in the muon trigger, muon tracks are reconstructed separately in both the muon system and the inner tracker [24] and then matched and fitted simultaneously to form "global muons". Each of the muon candidates must have $p_T > 45$ GeV; the candidate must also have a transverse impact parameter with respect to the centre of the luminous region of less than 0.2 cm, at least one hit in the pixel detector, hits in at least nine silicon tracker layers, and matched segments in two or more muon stations. The muon candidates are required to come from the same vertex by performing a common-vertex fit and requiring the vertex χ^2 to be below 10.

To suppress the misidentification of jets as electrons, the sum of the p_T of all other tracks in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the electron candidate's track must be less than 5 GeV, and the sum of the E_T of calorimeter energy deposits in the same cone must be less than approximately 3% of the candidate's E_T. For the calculation of the p_T sum, tracks must pass within 0.2 cm (in the z direction) of the primary vertex with which the electron

candidates are associated. With respect to the earlier analysis [9] and as a consequence of the increase in the number of interactions per bunch crossing, the longitudinal segmentation of the HCAL in the endcaps is no longer used to identify electrons. To suppress both jets and non-prompt muon sources of misidentification for muons, the sum of the p_Ts of all other tracks within a cone of $\Delta R < 0.3$ about the muon candidate's track must be less than 10% of the candidate's p_T.

The data sample collected in 2011 has been used to improve the alignment of the muon chambers. The dimuon mass resolution, $\sigma(m_{\mu\mu})/m_{\mu\mu}$, is 6.5% at masses around 1 TeV, rising to 12% at 2 TeV. The fractional dielectron mass resolution, $\Delta m_{ee}/m_{ee}$, is approximately constant above 500 GeV. When both electrons are detected in the barrel, this mass resolution is 1.1%, and when one of the electrons is in the barrel and the other is in the endcaps it is 2.3%

While a knowledge of the overall triggering and identification efficiencies is required to set limits on specific models, only the energy dependence of these efficiencies needs to be evaluated for the measurement of R_σ. The triggering and particle identification efficiencies in the energy range up to about 150 GeV were measured from data using the "tag-and-probe" method [24,25]. Monte Carlo (MC) simulations were used to evaluate the evolution of efficiencies beyond this energy. For dielectron events, the combined efficiency of the first-level and high-level triggers is larger than 99% and requires no corrections. The data were used to measure the electron identification efficiency at the Z resonance, and the ratio of this efficiency to that found in the simulation is used to scale the efficiencies at high energies. This ratio is within 1% of unity. The efficiency at $p_T = 100$ GeV is (86 ± 2)% in the barrel and (84 ± 2)% in the endcaps. For simulated events, the variation in this efficiency is less than 2% for p_T above 100 GeV. A similar procedure was used to extract scale factors for the muon trigger efficiency and for muon identification. The trigger efficiency was found to be (91.3 ± 0.1)%, and the muon identification efficiencies were found to be (96.3 ± 0.2)% and (94.2 ± 0.2)% for the barrel and endcaps, respectively, where the uncertainties given are statistical only. These uncertainties remain uniform over the p_T region that was probed by applying the tag-and-probe method to the available data sample.

4. Event samples and event selection

Simulated event samples for the signal and background processes were variously generated with PYTHIA, MADGRAPH and POWHEG. The MADGRAPH [26] matrix-element generator was used for $t\bar{t}$, single top and W + jets samples and the POWHEG V1.1 framework [27–29] for Drell–Yan to electrons and muons and single top samples. Both of these were interfaced with the PYTHIA V6.424 (using the Z2 tune) [30,31] parton-shower generator. All other processes were generated using PYTHIA. The CTEQ6L1 [32] parton distribution function (PDF) set was used for all samples except the Drell–Yan where the CT10 [33] set was used. The response of the detector was simulated in detail using GEANT4 [34]. These samples were further processed through the trigger emulation and event reconstruction chain of the CMS experiment.

For both the dimuon and dielectron final states, two isolated, same-flavour leptons that pass the lepton identification criteria described in Section 3 were required. The two lepton charges were required to be of 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 (where charge assignment is decoupled from the ECAL-based energy measurement). An opposite-charge requirement for dielectrons would lead

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[1] A right-handed coordinate system is used in CMS, with the origin at the nominal collision point, the x axis pointing to the centre of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the anticlockwise-beam direction. The pseudorapidity η is defined as $\eta = -\ln\tan(\theta/2)$, where $\cos\theta = p_z/p$. The azimuthal angle ϕ is the angle relative to the positive x axis measured in the x–y plane.

to a loss of signal efficiency of a few percent and hence was not applied.

The electron event selection requires the presence of at least one electron candidate in the ECAL barrel because events with both electrons in the endcaps have a lower signal-to-background ratio as a result of a higher rate of jets being misidentified as electrons. For both channels, each event was 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 within 24 cm in the direction along the beam. This requirement supresses cosmic ray background. Additional suppression of cosmic ray muons was 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/γ^*), either directly or via $\tau\tau$; there are also contributions from $t\bar{t}$, tW, and diboson processes. In addition, jets may be misidentified as leptons and contribute to the dilepton invariant mass spectra through multijet and vector boson plus jets final states. The contamination from diphotons misidentified as dielectrons, as well possible contributions from $b\bar{b}$ and $c\bar{c}$ events, have been established to be negligible.

In the final dilepton spectra, the background component from standard model processes is found by fitting an appropriate function to the data. To find an appropriate functional form, trial variants were fitted to distributions obtained from MC simulations. The studies of the background components described below were performed in order to verify that the assumed background composition is correct and are not used directly to estimate the magnitude of the background.

5.1. Z/γ^* backgrounds

The shape of the dilepton invariant mass spectrum from Drell–Yan production was obtained using a MC simulation based on the POWHEG event generator. The simulated invariant mass spectrum was normalized to the data using the number of events in the mass interval 60–120 GeV. The shape of this spectrum can be modified by higher-order corrections and by variations in PDFs. An uncertainty due to these sources is assigned to the extrapolation of the background shape, from masses where no non-standard model contribution is expected, to higher masses. The procedure used is described in Ref. [9]. The uncertainty in the predicted number of events normalized to those expected in the Z peak ranges from approximately 5% at a mass of 400 GeV to 20% at a mass of 2 TeV.

5.2. Other backgrounds with prompt lepton pairs

Pairs of prompt leptons can arise from $t\bar{t}$, tW, and diboson production. These processes are lepton flavour symmetric, enabling the use of an eμ spectrum to assess the contribution of these processes to the same-flavour dilepton spectra. The invariant mass spectrum found using a trigger that requires the presence of both a photon (or electron) and a muon is shown in Fig. 1. Using a single-muon trigger, a very similar spectrum is found. The leptons in this figure are required to have opposite signs. The components of the background arising from real leptons are estimated from MC simulations. The background contribution arising from jets being misidentified and reconstructed as leptons is derived from data by using same-sign eμ spectrum. The observed number of eμ events
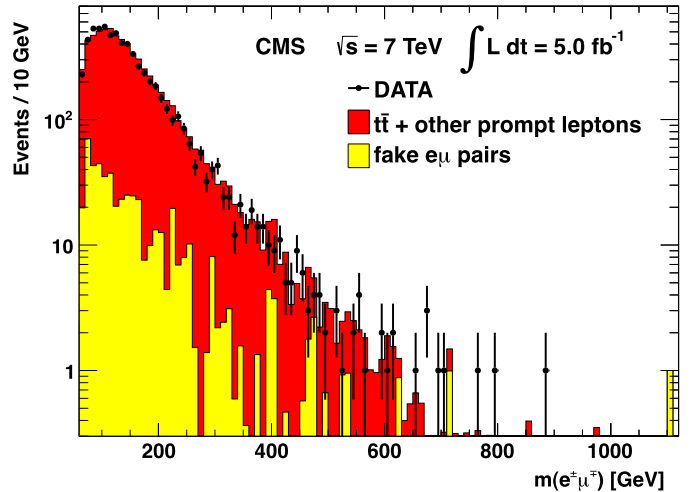

Fig. 1. The observed opposite-sign $e^{\pm}\mu^{\mp}$ dilepton invariant mass spectrum (data points). The filled red histogram shows the contribution to the spectrum from $t\bar{t}$ and other sources of prompt leptons (tW, diboson production, $Z \to \tau\tau$), as derived from simulations. The background where at least one of the reconstructed objects is not a real lepton is shown in yellow and estimated from the data using the same-sign $e^{\pm}\mu^{\pm}$ spectrum. (For interpretation of the references to colours in this figure legend, the reader is referred to the web version of this Letter.)

with any sign combination allowed is 3863 (1175) in the mass region above 120 (200) GeV. Using MC simulation, and the data for the contribution where at least one jet has been misreconstructed as a lepton, the expected number of events above 120 (200) GeV is 4081 ± 406 (1305 ± 123). The overall uncertainty in these numbers is dominated by the theoretical uncertainty of 15% on the $t\bar{t}$ production cross section [35,36]. Note that these numbers are not used to determine the final mass limits.

5.3. Events with misidentified or non-prompt leptons

Candidate prompt leptons can be misreconstructed from tracks and energy deposits that have not originated from a lepton. The misidentification of jets as leptons, the principal source of such backgrounds, is more likely to occur for electrons than for muons. The muon background from this source was determined as in Ref. [9] and verified to be negligible (less than 0.05 events above 600 GeV).

Both jets and photons can be misidentified as electrons. Potential sources of such backgrounds are $W \to e\nu + $ jet, $\gamma + $ jet events and multijet events. A single electromagnetic-cluster trigger collected a sample of events used to determine the fraction of jets passing the electromagnetic trigger criteria that are misreconstructed as electrons. To suppress the contribution from Z decays, events in this sample are required to have no more than one reconstructed electron passing less stringent than standard selection criteria. Contamination from genuine electrons in $W + $ jet events and from converted photons in $\gamma + $ jet events may affect the misidentification rate measurement. The contributions from these sources were estimated using MC simulations and subtracted from the data, to perform this measurement. The mass spectrum due to events with at least one misidentified electron was found by summing the multijet spectrum estimated from the data and the $W \to e\nu + $ jet and $\gamma + $ jet contributions estimated using MC simulations. The multijet spectrum was found by using an event sample passing the trigger used to collect signal events and applying the probability that both candidates are misidentified as electrons. The magnitude of this total contribution is illustrated in Fig. 2. The estimated background contribution to the dielectron mass spectrum
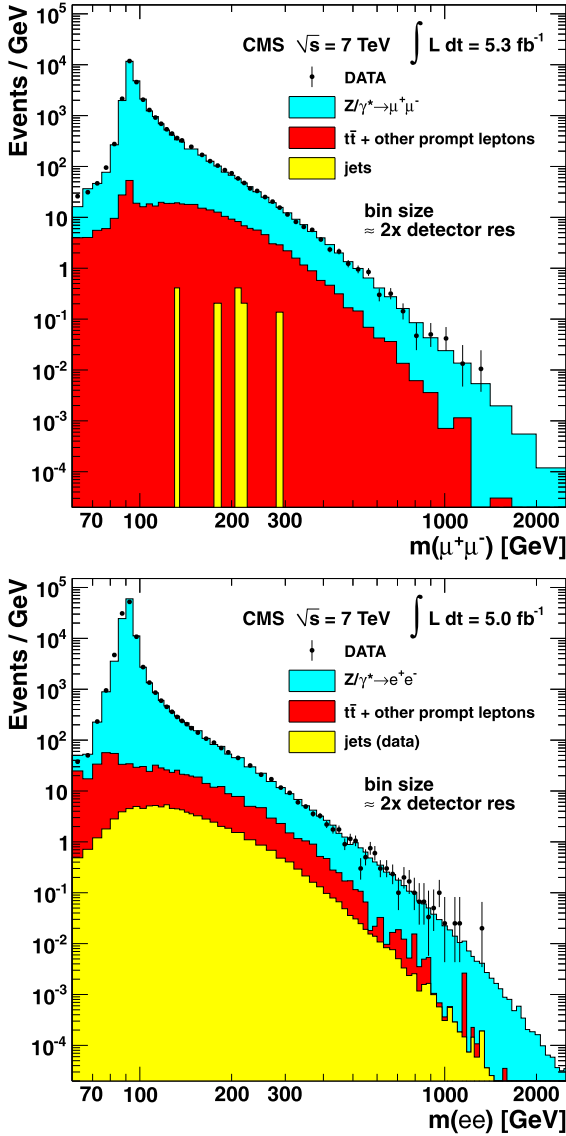
Fig. 2. The invariant mass spectrum of $\mu^+\mu^-$ (top) and ee (bottom) events. The points with error bars represent data. The uncertainties in the data points are statistical only. The histograms represent the expectations from SM processes: Z/γ^*, $t\bar{t}$ and other sources of prompt leptons (tW, diboson production, $Z \to \tau\tau$), and the multijet backgrounds. Multijet backgrounds contain at least one jet that has been misreconstructed as a lepton.

due to misidentified jets is 381 ± 153 (127 ± 51) for $m_{ee} > 120$ (200) GeV.

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 are removed from the data sample using selection criteria mentioned above, which eliminate events with two muons having collinear tracks and events with muons that have large impact parameters relative to the collision vertex. For the dimuon mass region $m_{\mu\mu} > 200$ GeV, the residual mean expected background was estimated using two event samples. Events in one sample were selected without imposing the requirement on the dimuon opening angle and in the other sample the requirements on muon impact parameter and on the existence of a good quality primary vertex were not applied. The efficiencies of the remaining cuts were esti-
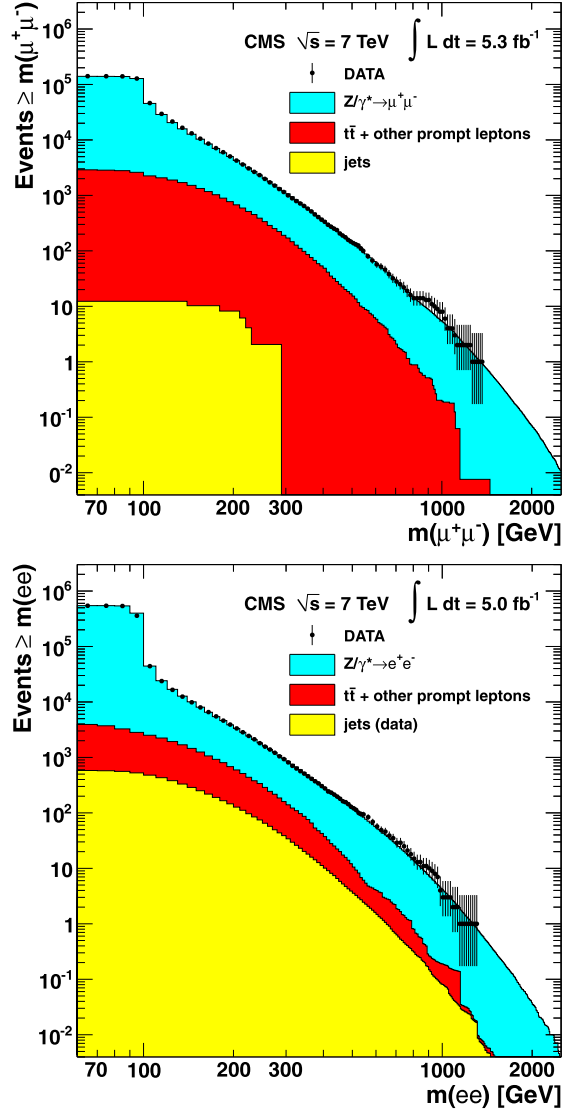

Fig. 3. The cumulative distribution of the invariant mass spectrum of $\mu^+\mu^-$ (top) and ee (bottom) events. The points with error bars represent data; the histograms represent the expectations from SM processes.

mated using these samples and treated as uncorrelated in order to determine the final total efficiency. This background was found to be less than 0.2 events.

6. Dilepton invariant mass spectra

Fig. 2 shows a comparison of data and expected backgrounds in both dimuon (top) and dielectron (bottom) mass spectra. The illustrated "jets" contribution includes events where at least one jet has been misreconstructed as a lepton. The component from events where two jets are misreconstructed as electrons was obtained from data. Contributions from $W \to e\nu$ + jet and γ + jet events were estimated from MC simulations, as were all other backgrounds illustrated. The relative fractions of backgrounds derived from simulation are determined using theoretical cross sections. Overall, these backgrounds are normalized to the data using the ratio of the number of observed to expected events within a window of 60–120 GeV, which includes the Z resonance peak. Fig. 3 shows the corresponding cumulative distributions of the spectra for the dimuon (top) and dielectron (bottom) samples. The expected yields in the control region (120–200 GeV) and in the high invariant mass

Table 1

The number of dilepton events with invariant mass in the control region $120 < m_{\ell\ell} < 200$ GeV and in the search region $m_{\ell\ell} > 200$ GeV. The total background is the sum of the events for the SM processes listed. The yields from simulation are relatively normalized using the expected cross sections, and overall the simulation is normalized to the data using the number of events in the mass window 60–120 GeV. Uncertainties include both statistical and systematic components added in quadrature.

Source	Number of events			
	Dimuon sample		Dielectron sample	
	(120–200) GeV	>200 GeV	(120–200) GeV	>200 GeV
Data	17 240	4250	13 207	3335
Total background	$16\,272 \pm 739$	4266 ± 185	$13\,286 \pm 625$	3209 ± 276
Z/γ^*	$15\,055 \pm 726$	3591 ± 170	$11\,945 \pm 597$	2615 ± 262
$t\bar{t}$ + other prompt leptons	1213 ± 145	667 ± 80	1087 ± 163	467 ± 70
Sources including at least one jet misreconstructed as a lepton	4 ± 3	8 ± 4	254 ± 102	127 ± 51

region (>200 GeV) are listed in Table 1. The observed data agree with the expectations. (It should be noted that such agreement is not critical to the shaped-based analysis discussed below.)

The cross check procedures and the event scrutiny described in Ref. [9] were performed for all events with an invariant mass above 800 GeV. No anomalies were found.

7. Statistical analysis and results

The observed invariant mass spectra agree with expectations based on standard model processes. Limits are set on the possible contributions from narrow heavy resonances as follows.

The procedure followed to set 95% confidence level (CL) limits is identical to that described in Ref. [9]. An extended unbinned likelihood function is used based on a signal shape, parametrized by a Breit–Wigner function convolved with a Gaussian resolution function, and a background function with approximately exponential behaviour. The functional form used for the background is $m^{-\kappa}e^{-\alpha m}$, where the shape parameters κ and α were determined from a fit to a simulated background mass spectrum. The agreement between this fit and the observed data over a range of mass bins is shown in Fig. 4. The width of the Breit–Wigner is conservatively taken to be that of the Z' boson in the Sequential Standard Model, which has the largest width of the resonances considered, namely 3.1%. The highest mass limits are insensitive to this width.

An upper limit on the ratio R_σ of the cross section times branching fraction of a Z' boson relative to that for a Z boson was found using the Bayesian technique described in Ref. [9]. The dominant uncertainty in this analysis is that in R_ϵ, the ratio of selection efficiency times detector acceptance for Z' decay to that for Z decay. This uncertainty is 8% for the dielectron channel and 3% for the dimuon channel. These values reflect the current understanding of the detector acceptance and the reconstruction efficiency turn-on at low mass (including PDF uncertainties on the acceptance), as well as their values at high mass. The largest contribution to the dielectron uncertainty comes from the uncertainty in the electron reconstruction efficiency at high mass as, unlike for muons where cosmic rays provide a high momentum sample, there is no available data sample of high energy electrons with high purity. For the dielectron channel, the mass scale uncertainty is 1%, derived from a study of the variation of the energy scale with time and a linearity study using different methods to calculate the ECAL cluster energies [9]. For the dimuon channel, the mass scale uncertainty for this analysis is set to zero. A sensitivity study showed negligible change in the limits up to the maximum detector misalignment consistent with alignment studies, a shift corresponding to a several percent change in the momentum scale. The effects of the uncertainties in the PDF and the higher-order corrections [37] on the shape of the background distribution, and hence on the fitting function used for the background, were examined. No further systematic uncertainties were found to be required to ac-
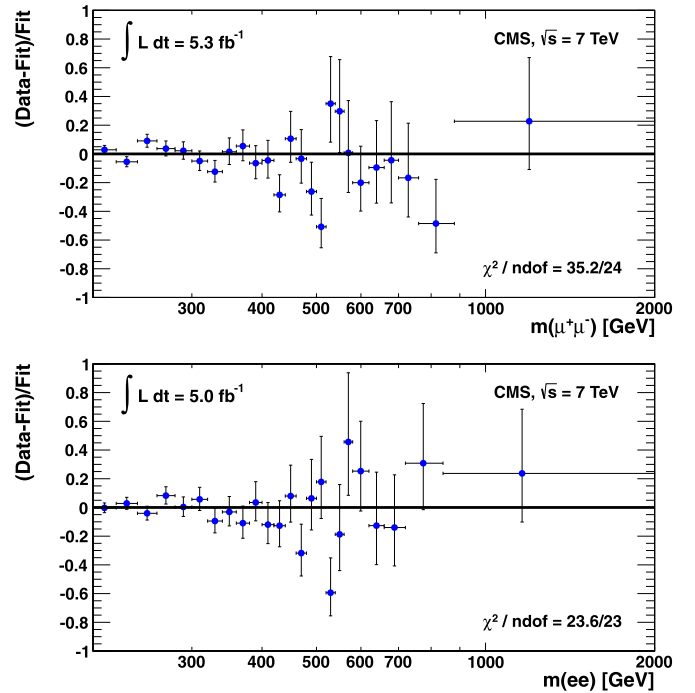

Fig. 4. The relative difference between the data and the fitted parametrization of the simulated background, where the latter is normalized to the data, is shown in a variety of mass bins for the muon (top) and electron (bottom) channels. The binning was chosen so that there is a minimum prediction of 10 events in each bin and a minimum bin size of 20 GeV was required. The horizontal error bars simply represent the bin width and should not be interpreted as an uncertainty.

commodate these effects on the background shape. In the electron channel the background from jets misidentified as electrons is very small, and the uncertainty in this background has a negligible effect on the limit determination. The acceptance for G_{KK} (spin 2) is higher than for Z' (spin 1) by less than 8% over the mass range 0.75–2.0 TeV. This difference in acceptance was conservatively neglected when calculating the corresponding limits.

In Fig. 5, the predicted cross section times branching fraction ratios for Z'_{SSM}, Z'_ψ, and Z'_{St} production are shown together with those for G_{KK} production, with the dimensionless graviton coupling to SM fields $k/\overline{M}_{Pl} = 0.05$ and 0.1. The leading-order cross section predictions for Z'_{SSM}, Z'_ψ, and Z'_{St} from PYTHIA using CTEQ6.1 PDFs are corrected for a mass dependent K factor obtained using ZWPRODP [38–40], to account for the next-to-next-to-leading order (NNLO) QCD contributions. For the RS graviton model, a constant next-to-leading order K factor of 1.6 is used [41]. The uncertainties due to factorization and renormalization scales and PDFs are indicated as a band. The calculated Z' and G_{KK} cross sections include generated dileptons with masses only within $\pm 40\%$ of the
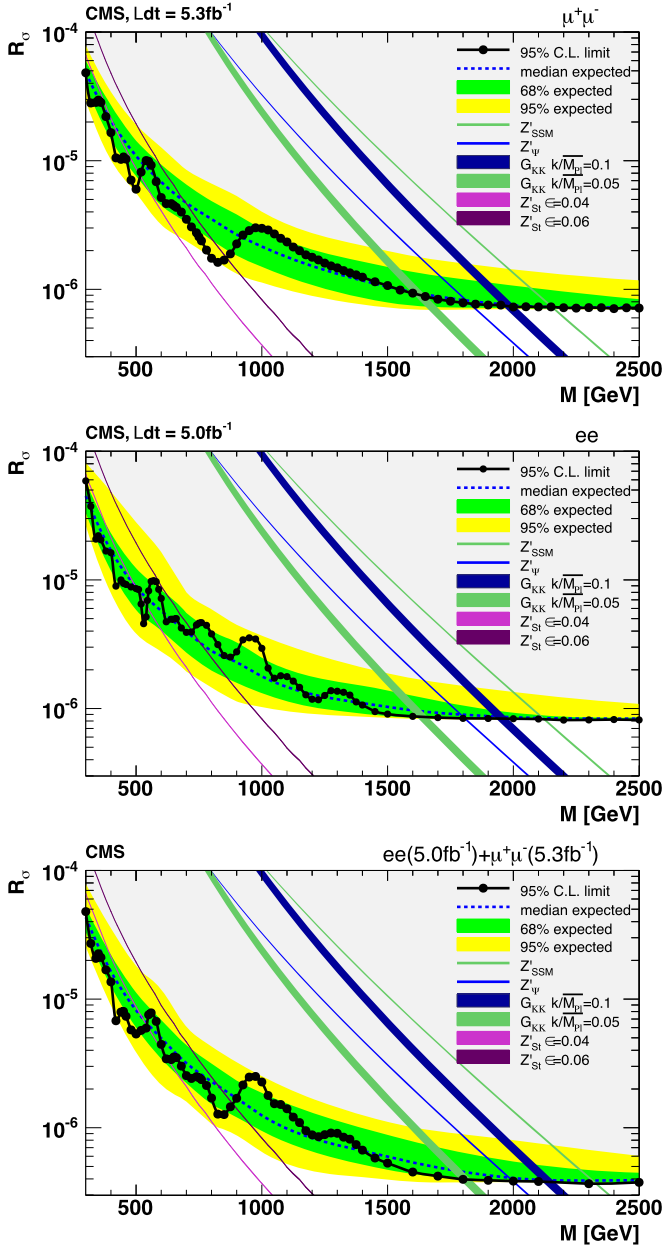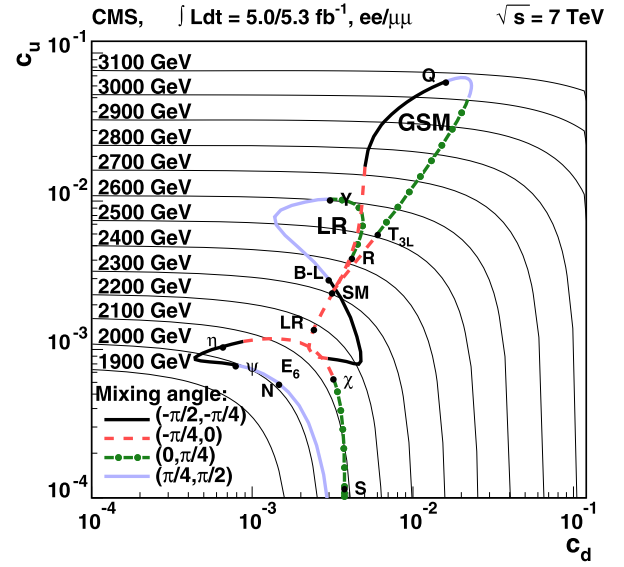
Fig. 6. The 95 % CL upper limits on the Z′ cross sections for given masses are equivalent to excluded regions in the (c_d, c_u) plane which are bounded by the thin black lines in the figure. They are compared with the predicted values of (c_d, c_u) in three classes of models. The colours on curves correspond to different mixing angles of the generators defined in each model. For any point on a model curve, the mass limit corresponding to that value of (c_d, c_u) is given by the intersecting experimental contour.

Fig. 5. Upper limits as a function of the resonance mass M on the production ratio R_σ of cross section times branching fraction into lepton pairs for Z'_{SSM}, Z'_ψ, Z'_{St}, and G_{KK} production to the same quantity for Z bosons. The limits are shown from (top) the $\mu^+\mu^-$ final state, (middle) the ee final state and (bottom) the combined dilepton result. Shaded green and yellow 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. The differences in the widths reflect the different uncertainties in the K factors used. (For interpretation of the references to colours in this figure legend, the reader is referred to the web version of this Letter.)

nominal resonance mass [9,38]. The NNLO prediction for the Z/γ^* production cross section in the mass window of 60 to 120 GeV is 0.97 ± 0.04 nb [37].

The uncertainties described above are propagated into a comparison of the experimental limits with the predicted cross section times branching fraction ratios (R_σ) to obtain 95% CL lower limits on Z′ masses in various models. No uncertainties on cross sections for the various theoretical models are included when determining the limits. As a result of the dimuon analysis, the Z'_{SSM} can be excluded below 2150 GeV, the Z'_ψ below 1820 GeV, and the RS G_{KK}

below 1990 (1630) GeV for couplings of 0.10 (0.05). For the dielectron analysis, the production of Z'_{SSM} and Z'_ψ bosons is excluded for masses below 2120 and 1810 GeV, respectively. The corresponding lower limits on the mass for RS G_{KK} with couplings of 0.10 (0.05) are 1960 (1640) GeV.

The combined limit, obtained by using the product of the likelihoods for the individual channels, is shown in Fig. 5 (bottom plot). The signal cross section is constrained to be the same in the two channels and lepton universality is assumed. The 95% CL lower limits on the mass of a Z′ resonance are 2330 GeV for Z'_{SSM}, 2000 GeV for Z'_ψ, and 890 (540) GeV for Z'_{St} with $\epsilon = 0.06$ (0.04). The RS Kaluza–Klein gravitons are excluded below 2140 (1810) GeV, for couplings of 0.10 (0.05). The observed limits are more restrictive than those previously obtained via similar direct searches by the Tevatron experiments [10–13,42,43] and indirect searches by LEP-II experiments [16–19], as well as those obtained by ATLAS [8] and CMS [9] using smaller data samples. The results are also presented in the (c_d, c_u) plane in Fig. 6 [9,44]. The parameters c_d and c_u contain all the information about the model-dependent couplings of the Z′ to fermions in the annihilations of charge $-1/3$ and $2/3$ quarks, respectively. The cross-section limits at any particular mass are contours in the (c_d, c_u) plane. The model classes are described in [9,38].

The largest deviation from SM expectations at high masses is around 1 TeV, in both spectra. The statistical significance of the observations is expressed in terms of Z-values, which are the effective numbers of Gaussian standard deviations in a one-sided test. For the dimuon sample, the maximum excess occurs at 1005 GeV, with local $Z = 1.2$, while for the dielectron sample, the maximum excess occurs at 960 GeV, with local $Z = 1.7$. In the combination of the two channels, the maximum excess is found at 965 GeV, with local $Z = 2.1$. The probability of an enhancement at least as large as the one found occurring anywhere between 600 and 2500 GeV in the observed sample size corresponds to $Z = -0.7$ for the dimuon sample and $Z = 0.3$ for the dielectron sample. For the combined data sample, the corresponding probability in a joint peak search is equivalent to $Z = 0.4$.

8. Summary

The CMS Collaboration has searched for narrow resonances in dimuon and dielectron invariant mass spectra using pp collision data collected at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of 5.28 ± 0.12 fb^{-1} for dimuons and 4.98 ± 0.11 fb^{-1} for dielectrons. The spectra are consistent with expectations from the standard model and upper limits have been set on the cross section times branching fraction for Z′ into lepton pairs relative to standard model Z boson production and decay. Lower mass limits have been set at 95% CL: a Sequential Standard Model Z′ can be excluded below 2330 GeV, the superstring-inspired Z′$_\psi$ below 2000 GeV, the Z′$_{St}$ with an ϵ parameter of 0.06 (0.04) below 890 (540) GeV, and Randall–Sundrum Kaluza–Klein gravitons below 2140 (1810) GeV for couplings of 0.10 (0.05). The constraints on these cross sections and masses are the most stringent to date.

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