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Search for heavy narrow dilepton resonances in pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV

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ABSTRACT

An updated search for heavy narrow resonances decaying to muon or electron pairs using the CMS detector is presented. Data samples from pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV at the LHC, with integrated luminosities of up to 5.3 and 4.1 fb^{-1}, respectively, are combined. No evidence for a heavy narrow resonance is observed. The analysis of the combined data sets excludes, at 95% confidence level, a Sequential Standard Model Z'_{SSM} resonance lighter than 2590 GeV, a superstring-inspired Z'_{ψ} lighter than 2260 GeV, and Kaluza–Klein gravitons lighter than 2390 (2030) GeV, assuming that the coupling parameter $k/\overline{M}_{Pl}$ is 0.10 (0.05). These are the most stringent limits to date.

1. Introduction

A number of scenarios for physics beyond the standard model predict the existence of heavy narrow resonances that decay to lepton pairs. In this Letter, we report on a search for resonances with the Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) [1]. We consider the following three benchmark scenarios: the Sequential Standard Model Z'_{SSM} with standard-model-like couplings [2], the Z'_{ψ} predicted by grand unified theories [3], and Kaluza–Klein graviton excitations in the Randall–Sundrum (RS) model of extra dimensions [4,5]. The RS model has two free parameters. One parameter is the mass of the first graviton excitation, and the other is the coupling $k/\overline{M}_{Pl}$, where k is the curvature of the extra dimension and $\overline{M}_{Pl}$ is the reduced Planck scale.

Previous searches for narrow $Z' \to \ell^+\ell^-$ ($\ell = \mu, e$) resonances have been reported by the CMS [6] and ATLAS [7] Collaborations, each based on integrated luminosities of 5 fb^{-1} at $\sqrt{s} = 7$ TeV. The CDF and D0 experiments have published results based on integrated luminosities exceeding 5 fb^{-1} of p$\bar{\text{p}}$ collisions at $\sqrt{s} = 1.96$ TeV [8–13]. The best previous direct lower limits on the Z'_{SSM} and Z'_{ψ} masses are 2330 GeV and 2000 GeV [6], respectively. The best previous direct limits on RS graviton (G_{KK}) production are 2160 GeV for $k/\overline{M}_{Pl} = 0.1$ [7] and 1810 GeV for $k/\overline{M}_{Pl} = 0.05$ [6]. Indirect constraints [14–17] are less stringent.

We use data samples from pp collisions at center-of-mass energy $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 3.6 ± 0.2 fb^{-1} for the dielectron channel. The dimuon channel does not use information from the calorimeters and incorporates additional data from running periods when the calorimeters were not fully operational. This increases the integrated luminosity of the sample to 4.1 ± 0.2 fb^{-1}. We combine the analysis of these data with previous results from the analysis based on an integrated luminosity of 5 fb^{-1} at $\sqrt{s} = 7$ TeV [6]. The reconstruction, selection criteria, efficiencies, and systematics for the two data sets are very similar. The results are applicable to any model with a narrow resonance that has equal dimuon and dielectron branching fractions. A resonance is considered narrow if the experimental width is dominated by the detector resolution.

We perform a shape-based analysis of the dilepton mass spectra searching for a peak on a smoothly falling distribution with the overall background normalization determined by an unbinned maximum likelihood fit. The data are consistent with expectations from the standard model. We report limits on the ratio (R_σ) of the production cross sections times branching fractions of a heavy narrow resonance to that of the Z boson, at the 95% confidence level (CL). Many experimental and theoretical uncertainties cancel in this ratio. We further translate these limits into lower limits on the masses of new heavy narrow resonances, using next-to-next-to-leading-order (NNLO) cross section calculations [18] for the Z boson production.

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2. The CMS detector

A detailed description of the CMS detector can be found in Ref. [19]. We briefly discuss the systems most relevant to this analysis. The central feature of the CMS detector is an all-silicon inner tracker system, composed of silicon pixel and strip detectors. The tracker is surrounded by a lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass-scintillator hadron calorimeter (HCAL). The finely segmented ECAL consists of nearly 76 000 lead-tungstate crystals which provide coverage up to pseudorapidity $|\eta| = 3.0$. It is divided in the barrel ($|\eta| < 1.479$) and endcap ($1.479 < |\eta| < 3.0$) detectors. We define pseudorapidity as $\eta = -\ln[\tan(\theta/2)]$. Here, θ is the polar angle with respect to the direction of the counterclockwise proton beam. We use ϕ for the azimuthal angle of a track's momentum at the point of closest approach to the beamline. The tracker and calorimeter systems reside within a 6 m diameter superconducting solenoid, which produces a 3.8 T axial magnetic field. Muons are detected by gas-ionization chambers embedded in the steel flux-return yoke.

The CMS experiment utilizes a two-level trigger system. The first level of the trigger (L1) selects events of interest using custom hardware processors [20]. It uses information from the muon and calorimeter systems to reduce the readout rate from the 20 MHz bunch crossing rate to a maximum rate of 100 kHz. The software based high-level trigger (HLT) further reduces the recorded event rate to a few hundred Hz by adding information from the inner tracker and analyzing event information in greater detail [21].

3. Event selection and object reconstruction

The event selection closely mirrors the one used for the $\sqrt{s} = 7$ TeV analysis. We briefly review the procedure here. Dimuon events are triggered by requiring at least one muon to be reconstructed by the HLT and to have transverse momentum $p_T > 40$ GeV and $|\eta| < 2.1$. Dielectron events are accepted by a double-electron trigger requiring two clusters in the ECAL, each with transverse energy $E_T > 33$ GeV. The trigger allows only small deposits of energy in the HCAL to be associated with the ECAL clusters. HLT clusters are required to be loosely matched to the trajectories of tracks having hits in the pixel detector. The lepton trigger efficiencies are measured using a "tag-and-probe" technique at the Z resonance [6,22,23], up to transverse momenta of roughly 500 GeV for muons and 100 GeV for electrons. For higher transverse momenta, the electron efficiency is measured using a simple trigger which requires only an ECAL cluster with $E_T > 300$ GeV to directly monitor the trigger efficiency for selected high mass events. In order to have a consistent trigger between the low-mass control region and the high-mass signal region, the simple ECAL trigger is used only to validate the efficiency of the primary trigger. The muon trigger efficiency is 97% for events with both muons within the trigger acceptance, across the entire range of dimuon invariant masses of interest. The efficiency of the electron trigger for dielectron candidates passing the analysis selection requirements increases from 80% at electron $E_T = 35$ GeV to a 99% plateau at $E_T > 37$ GeV. The efficiency threshold curve of the trigger is measured using data collected by a lower threshold trigger that is applied to approximately every 5th event passing the L1 part of the trigger. Because the threshold behavior is well-determined, the offline E_T selection cut can be placed at 35 GeV, which improves the normalization to the Z peak. Both muon and electron trigger efficiencies are within 1–2% of those found in Ref. [6]. Standard CMS algorithms [6,23,24] are used to reconstruct and select muon and electron candidates. Muon candidates are formed by matching tracks in the silicon tracker to tracks in the muon systems. Muon tracks are required to have hits in nine or more layers of the tracker and include at least one hit from each of the pixel and muon systems.

Muon candidates are required to be isolated in a cone about the muon direction of $\Delta R < 0.3$ in the tracker and to have $p_T > 45$ GeV and $|\eta| < 2.4$. The quantity ΔR is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where $\Delta\phi$ is in radians. The combined fit of the muon trajectory through the tracker and muon systems provides a reliable measurement of muon momenta extending to order 1 TeV [23,25]. Electron candidates are formed by matching ECAL clusters to reconstructed tracks, and are required to have $|\eta| < 1.442$ and $1.560 < |\eta| < 2.5$ for the ECAL barrel and ECAL endcap regions, respectively. As in Ref. [6], electrons are additionally required to have little associated activity in the HCAL, have a shower shape consistent with that of an electromagnetic object, and be isolated in a cone about the electron direction of $\Delta R < 0.3$ in the calorimeter and tracker. To account for the contamination which varies with the number of additional proton–proton interactions per event, the calorimeter isolation of the electron is corrected for the average energy density in the event [26].

The ECAL is capable of measuring energies in a single crystal of up to approximately 1.7 TeV in the barrel region and 2.8 TeV in the endcap region. Saturation effects become an issue for resonance masses around 4 TeV, which are beyond the reach of the current analysis, within the framework of the models considered here. Occasionally, anomalously large signals are observed in the barrel ECAL due to the direct deposition of energy into the avalanche photo-diodes (APDs) by particles transiting the detector [27]. Since the APDs are normally used to detect the scintillation light produced by the crystals, the equivalent energies of these signals can reach into the TeV range. The deposits are generally in a single channel and have different pulse timings from scintillation signals. They are rejected by cutting on the timing of the pulse and the amount of energy recorded in neighboring crystals.

More than 99% of the anomalous clusters are rejected with a negligible loss of real electrons [27]. When combined with the requirement of a compatible track in the silicon tracker, this requirement reduces background from anomalous clusters to a negligible level. However, the energy deposit pattern of all selected high energy electrons is scrutinized even further. There is no evidence that any of the remaining events is due to these anomalous signals.

Previously established techniques [6,22,23] are used to measure event reconstruction and selection efficiencies. The efficiencies for reconstructing and selecting leptons are roughly 90%, for both muons and electrons with $p_T > 100$ GeV. The efficiencies include the isolation requirements and are measured with total uncertainties of a few percent. Part of the systematic uncertainty cancels in the ratio of high-mass dilepton cross section to the Z boson cross section. Studies with Monte Carlo simulated samples predict both lepton reconstruction and selection efficiencies to be constant within 1% for transverse momenta $p_T \geqslant 100$ GeV.

Each dilepton candidate is required to have two isolated leptons of the same flavor that pass the identification criteria described above. When multiple dilepton candidates are present, the most energetic pair in the bunch crossing is selected. For dimuon events, one muon must have $|\eta| < 2.1$ to satisfy the trigger requirements. For dielectron events, at least one electron must have $|\eta| < 1.442$. This removes events in which both electrons are in the endcap, a topology where little signal is expected but which has a significant background arising from misidentified jets. Muons are required to have opposite charge, since a charge mis-assignment implies a large mismeasurement of momentum. The energy estimate for electrons is dominated by electromagnetic calorimeter information and is not sensitive the momentum mis-measurement indicated by a charge mis-assignment. The charge requirement would also result in a few percent efficiency loss in a region with little background and would degrade the sensitivity of the analysis. Therefore, we do not impose a charge requirement for dielectron candidates at high mass. Muon candidates are additionally required to originate from the same vertex. The χ^2 per degree of freedom for the fit to a common vertex is required to be less than 10. The tracker-measured transverse impact parameter with respect to the beam spot must be less than 2 mm for each muon. The mass resolution of a dielectron candidate is predicted by Monte Carlo simulation to be approximately 1.8% for masses above 800 GeV. The dimuon mass resolution is 5% (9%) at 1 TeV (2 TeV) and increases linearly with dimuon mass.

The opening angle of the muon pair is required to be less than $\pi - 0.02$ radians. This requirement greatly reduces the cosmic ray background associated with muons traversing the detector.

4. Backgrounds

The dilepton background in pp collisions at $\sqrt{s} = 8$ TeV is very similar to that found in $\sqrt{s} = 7$ TeV collisions [6] even though there were significantly more interactions per bunch crossing at the higher energy. The effect of this "event pileup" is included in our simulations of background processes and our data-driven estimates of the background from misidentified jets. The dominant standard model background is due to Drell–Yan production. The shape of this contribution is determined from Monte Carlo simulation using the PYTHIA v6.4 [28] event generator. The background contribution is normalized to the event count at the Z peak by counting same-flavor dilepton candidates within the mass window $60 < m_{\ell\ell} < 120$ GeV. The next largest background contribution is due to other standard model processes that produce isolated dileptons. We consider the lepton flavor symmetric processes of $t\bar{t}$, tW, $Z \to \tau^+\tau^-$, and diboson (WW, WZ, and ZZ) production when estimating this background component. The absolute normalization and shape for these backgrounds is taken directly from Monte Carlo simulation generated using MadGraph 5 [29], POWHEG [30–33], and PYTHIA. We validate this background prediction by comparing the eμ dilepton mass spectra for data and simulation.

Track-based lepton isolation strongly suppresses backgrounds from jets misreconstructed as leptons. This background is almost negligible for the dimuon channel but is a significant portion of the non-Drell–Yan background in the dielectron channel. Since misidentification of jets as leptons is more likely to occur for electrons than for muons, electrons have additional isolation and jet discrimination requirements. In the dielectron channel, the main contributing processes apart from Drell–Yan are dijet, W + jet, and photon + jet production (where the photon is misidentified as an electron). The probability that a jet is misidentified as an electron is measured in bins of E_T and η, using a jet-dominated sample. This probability is then used to weight events in which one electron satisfies all selection criteria and the other is a candidate for being a misidentified jet, to obtain the jet background prediction. The dimuon resonance search is susceptible to backgrounds from cosmic ray muons. The expected cosmic ray background for dimuons with $m_{\mu\mu} > 200$ GeV is determined from two complementary samples. For events in the first sample, the requirement on the dimuon opening angle is removed. In the second sample, the impact parameter requirement on the muon tracks is not applied. From the populations of these two samples, the remaining cosmic ray background contamination is estimated to be less than 0.2 events.

5. Results

The dilepton mass distributions for events passing all the selection criteria are shown in Fig. 1. The "jets" distribution illustrates

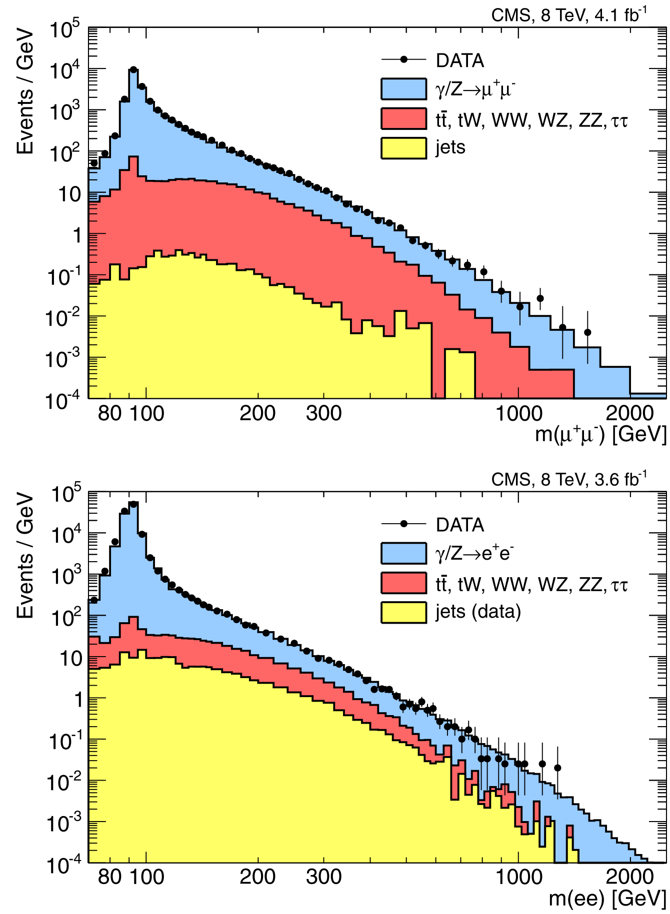

Fig. 1. The invariant mass spectrum of $\mu^+\mu^-$ (top) and ee (bottom) events for the $\sqrt{s} = 8$ TeV data set. The points with error bars represent the data. The solid histograms represent the standard model predicted background contributions.

the contribution of events in which at least one jet is misreconstructed as a lepton. This distribution is derived from data while all other components are derived from simulation. The relative fractions of the different background components are fixed to the ratios of their theoretical cross sections. The total simulated background is normalized to data at the Z peak ($60 < m_{\ell\ell} < 120$ GeV). The expected yields in the control region ($120 < m_{\ell\ell} < 200$ GeV) and in the search region ($m_{\ell\ell} > 200$ GeV) are compared with observed yields in Table 1. The observed mass spectra and event counts agree with standard model predictions both in shape and normalization.

We set a 95% CL limit on the ratio R_σ of the product of the cross section and branching fraction for each Z′ boson to that of the standard model Z boson. The cross section of the Z′ boson is calculated in a window of ±40% about the on-shell mass of the resonance, while for the Z boson it is calculated in the peak window defined above. We follow the Bayesian procedure of Ref. [6], which is based on an unbinned extended maximum likelihood analysis. We calculate the limits using the 8 TeV data alone, as well as from a combination of the 8 TeV and 7 TeV data sets. Mass-dependent ratios of parton distribution functions (PDF) at $\sqrt{s} = 7$ TeV and 8 TeV are used as an additional input to derive limits on R_σ at 8 TeV, $R_{\sigma,8\,\mathrm{TeV}}$, that combine both data sets. The CTEQ6.1 LO PDF set [34] was used to calculate these ratios, and the result was cross-checked with the MSTW2008 PDF set [35]. The CTEQ and MSTW calculations agreed well and the uncertainty in this ratio does not significantly contribute to the final result. The most significant uncertainty in the limit computation is associated

Table 1
The dilepton event count in the control region $120 < m_{\ell\ell} < 200$ GeV and in the search region $m_{\ell\ell} > 200$ GeV for the $\sqrt{s} = 8$ TeV data set. The total background is the sum of the events for the standard model processes listed. Uncertainties represent a quadrature sum of statistical and systematic uncertainties.

Source	Number of events			
	Dimuon sample		Dielectron sample	
	(120–200) GeV	>200 GeV	(120–200) GeV	>200 GeV
Data	13 831	3503	12 030	2904
Total background	$13\,010 \pm 590$	3630 ± 160	$12\,240 \pm 590$	2970 ± 260
Z/γ^*	$11\,700 \pm 570$	2920 ± 140	$10\,660 \pm 530$	2200 ± 220
$t\bar{t}$ + others	1280 ± 150	698 ± 78	1220 ± 180	560 ± 80
Jets	26 ± 3	10 ± 1	360 ± 180	210 ± 110

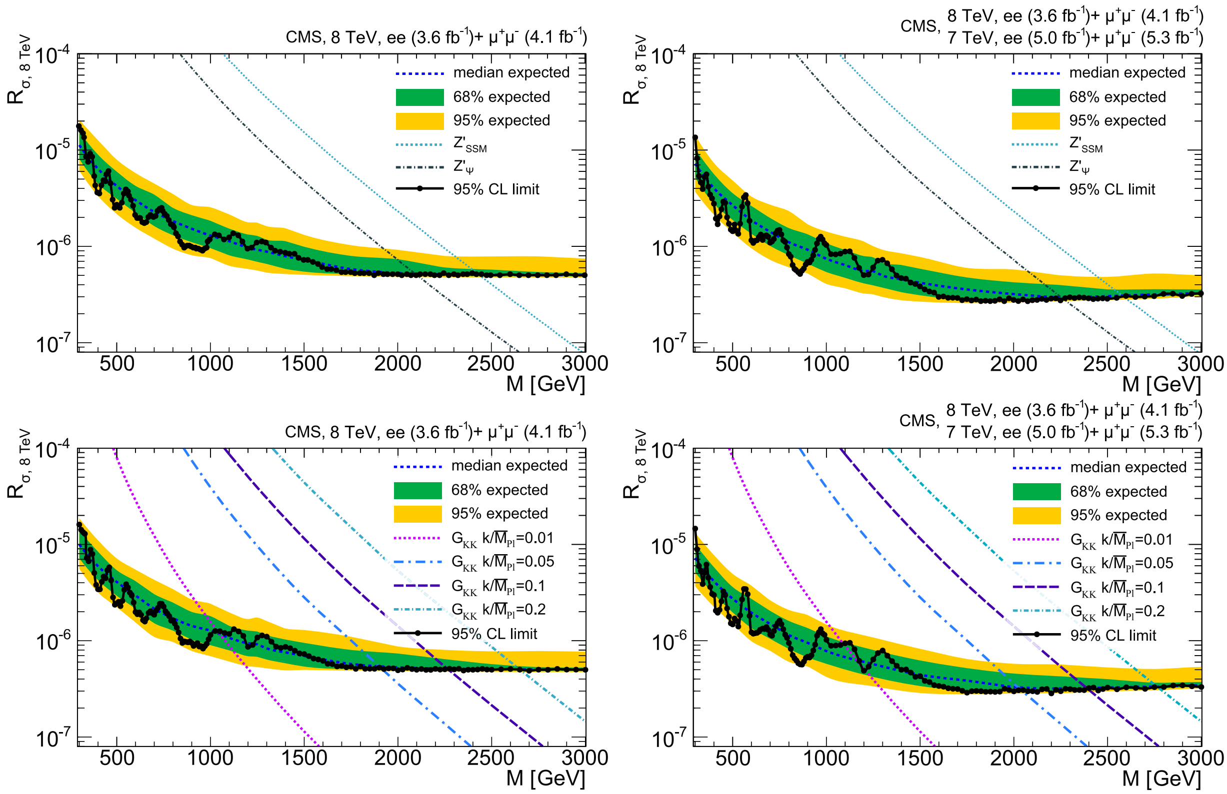

Fig. 2. Upper limits on the ratio R_σ of the production cross section times branching fraction into lepton pairs to the same quantity for Z bosons, as a function of resonance mass M for spin-1 (top) and spin-2 (bottom) boson production. The left plots are for the 8 TeV data set while the right plots are for the combination of the 7 and 8 TeV data sets. For the spin-2 case, the 7 and 8 TeV data set combination is only valid for models that have the same fraction of $q\bar{q}$ to coupling as an RS graviton. For the spin-1 case no coupling is considered. Shaded bands identified in the legend correspond to the 68% and 95% quantiles for the expected limits, respectively.

with our understanding of the selection efficiency and detector acceptance ratio for Z′ bosons relative to the Z, denoted R_ϵ. The uncertainty in the total lepton selection efficiency at high mass dominates the R_ϵ uncertainty. The lepton selection efficiencies are measured in data up to $p_T \sim 500$ GeV, but above 100 GeV the uncertainties in these measurements become large. This leads to a total uncertainty in R_ϵ of 3% for the dimuon channel and 8% for the dielectron channel after including PDF uncertainties in the acceptance. The effects of misalignment, higher order corrections to the background shape, and the uncertainty in backgrounds due to jets misidentified as leptons have only negligible impact on the limits. The upper limits on the ratio R_σ for spin-1 and spin-2 particles obtained from the dilepton combined mass spectra are shown in Fig. 2. Table 2 shows the limits on R_σ converted into mass limits on specific models. The resonance is assumed to be narrow, meaning that the detector resolution dominates the width of the peak. The Z'_ψ with a relative width of 0.6% is therefore considered narrow. A wider resonance, such as the Z'_{SSM}, which has a width of 3%, will have more background under the peak. Consequently, we would set weaker limits on its production cross sections. The two cases provide similar results when there is very little background after all selection criteria have been imposed. This occurs around 1.4 TeV. For a resonance below 1.4 TeV not to have been discovered, it must have a small coupling and therefore be narrow. For the spin-2 case an additional requirement is that the ratio of gg to $q\bar{q}$ production of the resonance must be the same as the ratio for an RS graviton. The combination of the 7 and 8 TeV data sets relies on this assumption, as gg and $q\bar{q}$ cross sections scale differently with $\sqrt{s}$. For the spin-1 case, no gg coupling is considered. The Z′ and RS Graviton cross sections are calculated using the PYTHIA event generator with the CTEQ6.1 PDF set. The LO cross sections are corrected for next-to-leading (NLO) or NNLO QCD contributions using the same k-factors as Ref. [6]. A mass dependent NNLO k-factor calculated with ZWPRODP [36–38] is used for the Z′ models. A flat NLO k-factor of 1.6 is applied to the RS graviton cross sections [39].

Table 2
Mass lower limits at the 95% CL on specific models obtained using dilepton data at $\sqrt{s} = 7$ and 8 TeV separately and combined. The 7 TeV results are taken from Ref. [6].

Model	Mass limits (GeV)		
	7 TeV	8 TeV	7 + 8 TeV
Z'_{SSM}	2330	2440	2590
Z'_{ψ}	2000	2110	2260
G_{KK} $(k/\overline{M}_{Pl} = 0.1)$	2140	2260	2390
G_{KK} $(k/\overline{M}_{Pl} = 0.05)$	1810	1900	2030

6. Summary

The CMS Collaboration has searched for heavy narrow resonances in dimuon and dielectron invariant mass spectra. The search combined data samples from pp collisions at $\sqrt{s} = 7$ TeV [6] and 8 TeV. The $\sqrt{s} = 8$ TeV data sets have integrated luminosities of 4.1 fb^{-1} (3.6 fb^{-1}) for the dimuon (dielectron) channel. The $\sqrt{s} = 7$ TeV data sets have integrated luminosities of 5.3 fb^{-1} (5.0 fb^{-1}) for the dimuon (dielectron) channel, and have been previously published [6]. The measured dilepton mass spectra are consistent with predictions from the standard model. Upper limits on the cross section times branching fraction for the production of new heavy narrow resonances relative to Z boson production are presented. The findings exclude, at 95% CL, a Z'_{SSM} with standard-model-like couplings below 2590 GeV and the superstring-inspired Z'_{ψ} below 2260 GeV. An RS graviton with $k/\overline{M}_{Pl}$ of 0.1 (0.05) is excluded below 2390 (2030) GeV. These are the most restrictive limits to date for the classes of models considered.

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