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Search for leptophobic Z′ bosons decaying into four-lepton final states in proton–proton collisions at $\sqrt{s} = 8\,\text{TeV}$

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ABSTRACT

A search for heavy narrow resonances decaying into four-lepton final states has been performed using proton–proton collision data at $\sqrt{s} = 8\,\text{TeV}$ collected by the CMS experiment, corresponding to an integrated luminosity of $19.7\,\text{fb}^{-1}$. No excess of events over the standard model background expectation is observed. Upper limits for a benchmark model on the product of cross section and branching fraction for the production of these heavy narrow resonances are presented. The limit excludes leptophobic Z′ bosons with masses below 2.5 TeV within the benchmark model. This is the first result to constrain a leptophobic Z′ resonance in the four-lepton channel.

1. Introduction

Extensions of the standard model (SM) that incorporate one or more extra Abelian gauge groups predict the existence of one or more neutral gauge bosons [1,2]. These occur naturally in most grand unified theories. Heavy neutral bosons are also predicted in models with extra spatial dimensions [3,4], e.g. Randall–Sundrum models [5,6], where these resonances may arise from Kaluza–Klein excitations of a graviton. Searches for heavy neutral resonances at hadron colliders, and most recently at the CERN LHC, are typically performed using the dijet [7–10], dilepton [11–14], diphoton [15–17], diboson [18–24], and $t\bar{t}$ [25–28] final states. The dilepton channel provides a clean signal compared with the dijet and $t\bar{t}$ channels. However, in leptophobic Z′ models, where the Z′ does not couple to SM leptons, the dilepton limits are not applicable. Although searches based on the dijet final state remain applicable, they suffer from large dijet background produced by quantum chromodynamics (QCD) subprocesses. We extend the search for heavy neutral vector bosons by considering possible Z′ decays into new particles predicted by various theoretical extensions of the SM.

In this Letter, we report on a search for a leptophobic Z′ resonance that decays into four leptons via cascade decays as described in Ref. [29]. In this model, the Z′ is coupled to quark pairs but not to lepton pairs, and can be produced with a large cross section at the LHC. These non-standard Z′ resonances also decay to pairs of new scalar bosons (φ) each of which subsequently decays to pairs of leptons ($\varphi \to \ell\ell'$, where ℓ and $\ell' = \text{e}$ or μ). Fig. 1 shows the leading-order Feynman diagram for the production of four-lepton final states via a Z′ resonance at a hadron collider. The reconstruction of the φ bosons in the dilepton channel is inefficient if the difference between Z′ and φ masses is large and the two daughter leptons are consequently highly collimated. In the following sections we describe a technique to increase the selection efficiency.

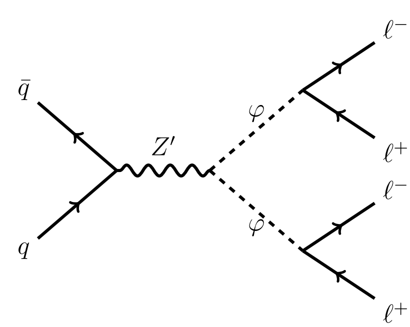

Fig. 1. Leading order Feynman diagram for the production and cascade decay of a Z′ resonance to a four-lepton final state.

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The analysis is a search for heavy narrow resonances decaying into four isolated final state leptons. The benchmark model [29] assumes ($\Gamma/M < 1\%$), corresponding to a natural width of the Z′ resonance that is much smaller than the detector resolution. The following final states are considered: $\mu\mu\mu\mu$, $\mu\mu\mu$e, $\mu\mu$ee, μeee, and eeee. The $\mu\mu$ee, $\mu\mu\mu$e and μeee channels are included to allow for the possibility of lepton flavor violation (LFV) [30–32] in the decays of the new scalar bosons. In this Letter, we set limits on the product of the cross section and branching fraction for production and decay to four leptons, and interpret the results in the context of the benchmark model described above [29].

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Each detector is composed of a barrel and two endcap sections. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors.

Muons are measured in the range $|\eta| < 2.4$ with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [33].

The ECAL consists of 75 848 crystals that provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region (EB) and $1.48 < |\eta| < 3.00$ in two endcap regions (EE). The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with transverse momentum $p_T \approx 45$ GeV from $Z \to e^+e^-$ decays ranges from 1.7% for nonshowering electrons (approximately 30%) in the barrel region to 4.5% for showering electrons (approximately 60%) in the endcaps [34].

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [35].

3. The simulated event samples

The Monte Carlo (MC) generator program used to produce the simulated event samples for the benchmark model is CalcHEP 3.4.1 [36] interfaced with pythia 6.4.24 [37]. These samples are divided into five decay channels ($\mu\mu\mu\mu$, $\mu\mu\mu$e, $\mu\mu$ee, μeee, eeee) for different Z′ boson masses ($m_{Z'}$) ranging from 250 to 3000 GeV in increments of 250 GeV. The benchmark model assumes that new particles other than Z′ and φ are heavy enough not to affect the production and decay of the Z′ boson. Signal MC samples are produced with six different values of the φ mass (m_φ), with $m_\varphi = 50$ GeV used as the reference mass value in the interpretation of the results. An important feature of this analysis is the presence of a "boosted signature" associated with the collimation of the two leptons coming from the same parent particle and resulting from the large difference between $m_{Z'}$ and m_φ. In addition, samples are generated with m_φ masses of 5, 10, 20, 30 and 40% of $m_{Z'}$, for which, in most cases, the contribution from the boosted signature is less important. The product of the leading order (LO) signal cross section and branching fraction in each channel varies with $m_{Z'}$ (from 250 to 3000 GeV) as follows: $\mu\mu\mu\mu$ and eeee from 0.8 pb to 3.0×10^{-6} pb, $\mu\mu$ee from 12.3 pb to 4.7×10^{-5} pb, and $\mu\mu\mu$e and μeee from 3.1 pb to 1.2×10^{-5} pb. The branching fraction of $\varphi \to \ell\ell'$ is set to 1 and therefore only the leptonic decay channels are considered. These signal MC samples are used to optimize event selection, evaluate signal efficiencies and calculate exclusion limits.

The dominant SM background is the production of ZZ decaying into four leptons. The $q\bar{q}$-induced ZZ production is generated using the pythia event generator and the gg-induced production using the gg2zz program [38]. Additional backgrounds from diboson production (WW and WZ) are generated with pythia, and from top quark production ($t\bar{t}$, tW, and $\bar{t}$W) are generated with powheg 1.0 [39]. Other processes, such as $t\bar{t}$Z and triboson production (WWγ, WWZ, WZZ, and ZZZ), are generated with MadGraph 5.1.3.30 [40]. Simulated event samples are normalized using the integrated luminosity and higher order theoretical cross sections: next-to-next-to-leading order for $t\bar{t}$ [41] and next-to-leading order for ZZ [42] and the other backgrounds.

The MC samples are generated using the CTEQ6L [43] set of parton distribution functions (PDFs) and the pythia Z2* tune [44,45] in order to model the proton structure and the underlying event. The samples are then processed with the full CMS detector simulation software, based on Geant4 [46,47], which includes trigger simulation and event reconstruction.

4. Event selection

The 2012 data set of proton–proton collisions at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}, is used for the analysis. Data are collected with lepton triggers with various p_T thresholds. The trigger used for the muon-enriched channels ($\mu\mu\mu\mu$, $\mu\mu\mu$e) requires the presence of at least one muon candidate with $p_T > 40$ GeV and $|\eta| < 2.1$. The trigger used for the electron-enriched channels (μeee, eeee) requires two clusters of energy deposits in the ECAL with transverse energy $E_T > 33$ GeV each. For the $\mu\mu$ee channel, the trigger requires both an electron and a muon with $p_T > 22$ GeV.

In the subsequent analysis, events are required to contain a reconstructed primary vertex (PV) with at least four associated tracks, and its r (z) coordinates are required to be within 2 (24) cm of the nominal interaction point. The PV is defined as the vertex with the highest sum of p_T^2 for the associated tracks. We select the events with four leptons in the final state, where the leptons are identified by the selection criteria described below. The two leading leptons are required to have $p_T > 45$ GeV to ensure that the trigger is fully efficient for the selected events. This requirement has a negligible effect on the signal acceptance. The two subleading leptons are required to have $p_T > 30$ GeV. This choice balances loss of efficiency against increased misidentification probability. All four leptons must satisfy $|\eta| < 2.4$. No charge requirement is applied to the lepton selection.

Muon candidates are reconstructed by a combined fit including hits in both tracking and muon detectors ("global muons") [33]. The tracks associated with global muons are required to have the following properties: at least one pixel detector hit, at least six strip tracker layers with hits, at least one muon chamber hit, at least two muon detector planes with muon segments, a transverse impact parameter of the tracker track $|d_{xy}| < 0.2$ cm with respect to the PV, a longitudinal distance of the tracker track $|d_z| < 0.5$ cm with respect to the PV, and $\delta p_T/p_T < 0.3$ where δp_T is the uncertainty in the measured p_T of the track. All muon candidates are required to be isolated. A muon is considered isolated if the scalar p_T sum of all tracks within a cone of $\Delta R < 0.3$ around the muon, excluding the muon candidate itself, does not exceed 10% of the muon p_T, where $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$. If there is a second lepton candidate within a cone $\Delta R < 0.3$, we remove its contribution.

An electron candidate is identified by matching a cluster in the ECAL to a track in the silicon tracker [34]. Identification criteria are applied to suppress jets misidentified as electrons. Electrons are required to pass the following criteria: the profile of energy deposition in the ECAL should be consistent with an electron, the sum of HCAL energy deposits behind the ECAL cluster should be less than 10% of the associated ECAL deposit, the track associated with the cluster should have no more than one hit missing in the pixel detector layers and $|d_{xy}|$ should be less than 0.02 cm with respect to the selected PV. All electron candidates are required to be isolated using the following definition: within a cone $\Delta R < 0.3$ around the track of the electron candidate, the p_T sum of all other tracks is required to be less than 5 GeV and the E_T sum of the energies of the calorimeter deposits that are not associated with the candidate is required to be less than 5% of the candidate's E_T. This differs from the isolation requirement of 3% in Ref. [13], because of the inefficiency (of approximately 6% at electron $E_T = 1$ TeV) caused by overlapping electrons due to the high Lorentz boost of the φ boson ($m_\varphi = 50$ GeV). In addition, if the direction of the second lepton candidate falls within the isolation cone of the first ($\Delta R < 0.3$), the contributions it makes to both p_T and E_T are subtracted when imposing the isolation requirements.

The kinematic distributions of the final-state particles are similar for all five channels. The final state consists of two leading leptons with high p_T and two subleading leptons with relatively low p_T. The two leptons from the same parent φ boson can be highly Lorentz boosted if m_φ is significantly smaller than $m_{Z'}$. This feature is generally found for high-mass ($m_{Z'} > 1$ TeV) samples in the case of $m_\varphi = 50$ GeV. This boosted signature introduces a significant inefficiency for the event selection except for the LFV case (φ decaying into eμ). To take into account the boosted signature for φ decaying into $\mu\mu$, one of the muon candidates selected by the above criteria is allowed to be reconstructed only as a tracker muon, a track in the tracker matched to track segments in the muon system ("tracker muons") [33], if the two muons are as close as $\Delta R < 0.4$. In such exceptional cases, the requirements of at least one muon chamber hit and at least two muon detector planes with muon segments are not applied to the tracker muon.

The boosted signature for a φ decaying into ee is much more complicated since the electrons can easily merge into a single cluster in the ECAL. In this case, only one electron candidate is reconstructed from the two original electrons. The probability for having a merged candidate is about 50% with $m_{Z'} = 3$ TeV and $m_\varphi = 50$ GeV. These events would be rejected by the four-lepton requirement, introducing a large signal inefficiency. To select such events, an electron candidate having a ratio of ECAL cluster energy to track momentum larger than 1.5 and a second track with $p_T > 30$ GeV within a cone of ΔR(electron, track) < 0.25, is considered as a "merged electron". Events are accepted with three (two) leptons if they contain one (two) merged electron(s), since each merged electron is considered to contribute two electrons to the total. In order to avoid significant misidentification, merged electrons are only considered if the ECAL cluster energy is bigger than 500 GeV.

The dominant background in this analysis arises from ZZ events decaying into four leptons. To suppress this background, events with two oppositely charged same-flavor lepton pairs are rejected if the mass of the lepton pair, $m_{\ell\ell}$, is in the range 89–93 GeV. The Z mass window is made as narrow as possible in order to minimise degradation of the signal efficiency in the case of $m_\varphi \approx m_Z$. This requirement results in negligible signal efficiency loss for $m_{Z'} > 500$ GeV. At lower masses, the efficiency loss increases and is approximately 20 (7)% at $m_{Z'} = 250$ GeV for the eeee ($\mu\mu\mu\mu$) channel. More than 70% (30%) of the ZZ background is rejected by the mass window veto requirement in the muon (electron) channel. This requirement is not applied to the merged electron case, thus accounting for the difference in rejection efficiency for the two channels.

The event selection efficiency is 50–70% ($\mu\mu\mu\mu$), 55–65% ($\mu\mu\mu$e and $\mu\mu$ee) and 45–65% (μeee and eeee) throughout the range $m_{Z'} > 1$ TeV for $m_\varphi = 50$ GeV. Below $m_{Z'} = 1$ TeV, the efficiency decreases rapidly because of the effect on the acceptance of the kinematic requirements. Heavier m_φ values correspond to a less boosted signature and therefore are selected with a higher efficiency. For $m_{Z'} > 2$ TeV, the efficiency for the other m_φ samples is approximately 10–15% (1–5%) higher in the electron (muon) channels than for the $m_\varphi = 50$ GeV scenario, where the range of values reflects the variation with $m_{Z'}$. For $m_{Z'} < 1$ TeV, the contribution from boosted events is not significant and the efficiency is similar for all values of m_φ considered.

5. Background estimation

Most of the SM backgrounds are suppressed by requiring four isolated high-quality lepton candidates. As discussed above, the dominant background is from ZZ events decaying into four leptons. Other backgrounds originate from top quark events with two genuine leptons and two lepton candidates arising from misidentified jets, and from WW (WZ) events that contain two (one) misidentified or nonprompt leptons from jets. In the case of triboson production, there may be four genuine leptons in the event. These backgrounds are estimated using MC simulation.

The contribution from events with more than two leptons arising from misidentified jets is expected to be small because this analysis requires four isolated leptons in the final state. This background is estimated using the "misidentification rate" method described in Ref. [13]. The misidentification rate measured as a function of electron E_T in the barrel and endcap is applied to events with electron candidates passing the trigger but failing the full selection. The contribution from jet backgrounds estimated using this procedure is found to be negligible.

Fig. 2 shows the four-lepton invariant mass ($m_{4\ell}$) distribution for selected events. The number of observed events and estimated backgrounds are summarized in Table 1. As shown in the figure and table, the distribution of observed events is in agreement with the expected backgrounds. The table shows two different mass ranges. In the region $m_{4\ell} > 1$ TeV, the backgrounds from SM processes are very small, typically less than one event.

6. Results

No excess of events is observed in the data sample compared to the SM expectations and exclusion limits at 95% confidence level (CL) are calculated in the context of the benchmark model. The signal region consists of events with four leptons (e or μ) with $|\eta| < 2.4$: the two leading (subleading) leptons are required to have $p_T > 45$ (30) GeV. A Bayesian approach is adopted with a likelihood function defined with a signal strength modifier, a prior probability, and a set of nuisance parameters. The prior probability distribution for the signal cross section is positive and uniform, since this is known to result in good frequentist coverage properties. The systematic uncertainties associated with the backgrounds, selection efficiency and luminosity are treated as nuisance parameters with log-normal prior distributions [48]. A limit on the signal contribution is derived by interpreting the likelihood function as a probability distribution and integrating over this. The coverage of the 95% CL assigned to the limit has been checked using a Markov chain Monte Carlo method.

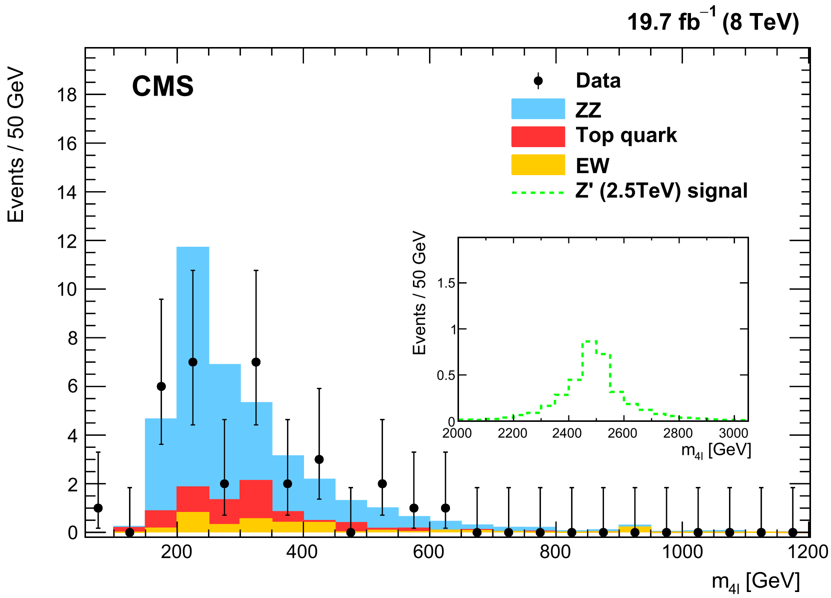

Fig. 2. The $m_{4\ell}$ spectrum for the combination of the five studied channels. The points with vertical bars represent the data and the associated statistical uncertainties; the histograms represent the expectations from SM processes; "Top quark" denotes the sum of the events for $t\bar{t}$, tW, $t\bar{t}Z$ processes; "EW" denotes the sum of the events from WW, WZ, WWγ, WWZ, WZZ, and ZZZ processes. The inset shows the expectation from the benchmark model for a signal at $m_{Z'} = 2.5$ TeV with $m_\varphi = 50$ GeV.

Table 1
Summary of the observed yield and expected backgrounds for all channels, where N_{obs} is the number of observed events in data. The total background (N_{tot}) is the sum of three different backgrounds that are estimated using MC simulations; N_{ZZ} refers to the background from ZZ events; N_t is the background from $t\bar{t}$, single top quark, and $t\bar{t}Z$ production; N_{EW} is the background from WW and WZ, and triple gauge boson production. The quoted uncertainties are statistical only.

Channel	$0.1 < m_{4\ell} < 1.0$ TeV					$m_{4\ell} > 1.0$ TeV	
	N_{obs}	SM backgrounds				N_{obs}	N_{tot}
		N_{ZZ}	N_t	N_{EW}	N_{tot}		
$Z' \to \mu\mu\mu\mu$	3	4.9 ± 0.3	0.9 ± 0.5	–	5.9 ± 0.6	0	–
$Z' \to \mu\mu\mu e$	6	0.4 ± 0.1	1.3 ± 0.6	1.2 ± 0.3	2.9 ± 0.7	0	–
$Z' \to \mu\mu ee$	12	9.3 ± 0.4	3.0 ± 1.5	1.2 ± 0.3	13.5 ± 1.6	0	0.1 ± 0.1
$Z' \to \mu eee$	2	0.2 ± 0.1	0.4 ± 0.1	0.6 ± 0.2	1.2 ± 0.2	0	0.1 ± 0.1
$Z' \to eeee$	9	15.0 ± 0.5	0.2 ± 0.1	0.2 ± 0.1	15.4 ± 0.5	0	0.2 ± 0.1
Combined	32	29.9 ± 0.7	5.7 ± 1.9	3.3 ± 0.5	38.9 ± 2.1	0	0.4 ± 0.2

The systematic uncertainties are dominated by the uncertainties in the background estimates and in the lepton selection efficiencies. The uncertainty in the MC estimation of the main background cross section (ZZ and $t\bar{t}$) arising from higher-order QCD corrections and choice of PDFs is 15%. In order to be conservative, we choose to double this figure and assign an uncertainty of 30% from this source. The systematic uncertainty in the muon selection efficiency including reconstruction, identification, and isolation is 0.5% [33]. The uncertainties in the electron selection efficiency are 0.7% (0.6%) for electrons below 100 GeV in EB (EE) and 1.4% (0.4%) for electrons above 100 GeV in EB (EE) [13]. The uncertainties due to the lepton efficiency in both signal and background yields vary between 2.2% and 2.7% as a function of $m_{4\ell}$. Including the effect of the merged lepton signature, a total uncertainty of 10% in the event selection efficiency is assigned for each channel. The impact of the uncertainty in the electron energy scale on signal (background) yield is 1% (0.5%) [13]. Uncertainties in the muon momentum scale and mass resolutions are below 0.1% [33]. The uncertainty in the integrated luminosity is assigned to be 2.6% [49]. In this analysis, the statistical uncertainties are dominant and the systematic uncertainties have a small impact on the results. We tested the robustness of the limits by doubling the values assumed for the systematic uncertainties. We observed a negligible change in the calculated limits, and conclude that the limits are insensitive to any underestimation of the systematic uncertainties.

Limits on the product of cross section and branching fraction are set in the context of the benchmark model as a function of $m_{4\ell}$. The natural width of the Z′ resonance is assumed to be smaller than the mass resolution of the detector in all channels. The detector resolution in the $\mu\mu\mu\mu$ channel varies from 1.1% at $m_{4\ell} = 250$ GeV to 7.5% at $m_{4\ell} = 3$ TeV, and it has a constant value of about 0.6% over this range in the eeee channel. In the limit calculation, we set the mass window to be six times the mass resolution centred around the signal mass point considered. A counting experiment is performed for the limit calculation. Fig. 3 shows the upper limits on the product of the cross section and branching fraction, for the combination of all five channels, for the mass range considered in the benchmark model of Ref. [29]. In the framework of this model, we translate these cross section upper limits into lower limits on the Z′ boson mass. For the combination of the five channels, the value obtained for this lower mass limit is 2.5 TeV. The black solid (dashed) line indicates the observed (expected) 95% CL upper limits, the inner (outer) band indicates the ±1 (2) standard deviation uncertainty in the expected limits, and the blue dashed line shows the theoretical Z′ cross section for $m_\varphi = 50$ GeV. This theoretical cross section is calculated under the benchmark model assumption that the branching fraction

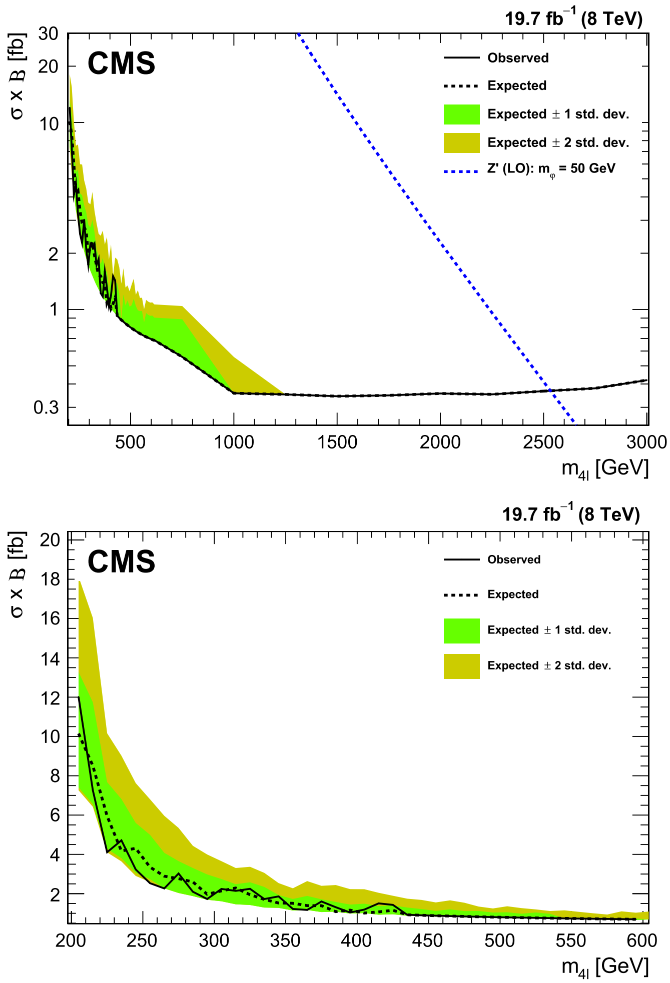

Fig. 3. The 95% CL upper limit on the cross section times branching fraction as a function of $m_{4\ell}$ for the combination of the five channels: full mass range (top) and expanded view of the low mass region (bottom). The shaded green (yellow) band indicates the one (two) sigma uncertainty in the expected limits. The blue dashed line represents the theoretical predictions for the benchmark model [29] for $m_\varphi = 50$ GeV. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The 95% CL lower limits (in TeV) on $m_{Z'}$ for the five separate channels and for their combination. Results are presented for the benchmark assumption $m_\varphi = 50$ GeV, and for the five different values of the ratio $m_\varphi/m_{Z'}$.

m_φ	50 GeV	$0.05m_{Z'}$	$0.1m_{Z'}$	$0.2m_{Z'}$	$0.3m_{Z'}$	$0.4m_{Z'}$
$\mu\mu\mu\mu$	1.7	1.6	1.7	1.7	1.7	1.7
$\mu\mu\mu$e	2.0	2.0	2.1	2.1	2.1	2.1
$\mu\mu$ee	2.4	2.4	2.5	2.5	2.5	2.5
μeee	2.0	2.0	2.1	2.1	2.1	2.1
eeee	1.7	1.7	1.7	1.7	1.7	1.7
Combined	2.5	2.6	2.6	2.6	2.6	2.6

$\mathcal{B}(\varphi \to \ell\ell') = 100\%$. In the region above the 1–1.5 TeV, the bands are not visible since backgrounds are negligible here.

Table 2 shows the exclusion limit on $m_{Z'}$ for the five separate channels and for the combination. Results are presented for the benchmark assumption $m_\varphi = 50$ GeV, and for the five different values of the ratio $m_\varphi/m_{Z'}$ assumed for the generated signal samples, taking into account the event selection efficiencies described above. The predicted cross sections decrease as the ratio $m_\varphi/m_{Z'}$ increases. The contribution of the merged lepton signature also decreases, resulting in an overall efficiency increase. Therefore the scenarios with $m_\varphi/m_{Z'} = 5$, 10, 20, 30 and 40% of $m_{Z'}$, give slightly higher limits than the $m_\varphi = 50$ GeV scenario.

7. Summary

Results have been presented from a search for heavy narrow resonances decaying into four-lepton final states via intermediate scalar particles φ, where the branching fraction of $\varphi \to \ell\ell$ ($\ell = $ e or μ) is set to 1. These results are based on a sample of proton–proton collision data at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. The four-lepton invariant mass spectra are consistent with the standard model predictions. Masses of Z' bosons have been excluded at 95% confidence level for a specific benchmark model with $m_\varphi = 50$ GeV, and for five different assumptions for the ratio $m_\varphi/m_{Z'}$ ($m_\varphi/m_{Z'} = 5$, 10, 20, 30 and 40%). Five decay channels ($\mu\mu\mu\mu$, $\mu\mu\mu$e, $\mu\mu$ee, μeee, eeee) are considered in this analysis. Combining all channels, a lower limit on the Z' mass of 2.5 TeV is obtained for the benchmark model, and 2.6 TeV for each of the models assuming a fixed ratio between m_φ and $m_{Z'}$. This is the first result to constrain a leptophobic Z' resonance in the four-lepton channel.

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