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

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A search for heavy narrow resonances decaying into four-lepton final states has been performed using proton–proton collision data at $\sqrt{s} = 8\,\mathrm{TeV}$ collected by the CMS experiment, corresponding to an integrated luminosity of $19.7\,\mathrm{fb}^{-1}$. 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 $\mathrm{t\bar{t}}$ [25–28] final states. The dilepton channel provides a clean signal compared with the dijet and $\mathrm{t\bar{t}}$ 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 $\ell' = \mathrm{e}$ 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.

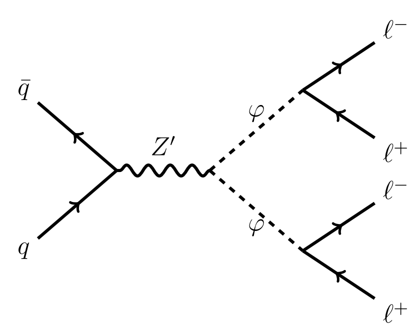

Fig. 1. Leading order Feynman diagram for the production and cascade decay of a Z′ resonance to a four-lepton final state.

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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