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Search for an $L_{\mu} - L_{\tau}$ gauge boson using $Z \to 4\mu$ events in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

Abstract

A search for a narrow Z′ gauge boson with a mass between 5 and 70 GeV resulting from an $L_{\mu} - L_{\tau}$ $U(1)$ local gauge symmetry is reported. Events containing four muons with an invariant mass near the standard model Z boson mass are analyzed, and the selection is further optimized to be sensitive to the events that may contain $Z \to Z'\mu\mu \to 4\mu$ decays. A data sample of proton-proton collisions at a center-of-mass energy of 13 TeV is used, corresponding to an integrated luminosity of $77.3\,\text{fb}^{-1}$ recorded in 2016 and 2017 by the CMS detector at the LHC. Theories that predict such a particle have been proposed as an explanation of various experimental discrepancies, including the lack of a dark matter signal in direct-detection experiments, tension in the measurement of the anomalous magnetic moment of the muon, and reports of possible lepton flavor universality violation in B meson decays. The event yields are consistent with the standard model predictions. Upper limits of 10^{-8}–10^{-7} at 95% confidence level are set on the product of branching fractions $\mathcal{B}(Z \to Z'\mu\mu)\mathcal{B}(Z' \to \mu\mu)$, depending on the Z′ mass, which excludes a Z′ boson coupling strength to muons above 0.004–0.3. These are the first dedicated limits on $L_{\mu} - L_{\tau}$ models at the LHC and result in a significant increase in the excluded model parameter space.

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*See Appendix A for the list of collaboration members

1 Introduction

The standard model (SM) of particle physics [1–3] can not explain all experimental observations to date and is, therefore, generally believed to be an incomplete theory. Enlarging the SM gauge group to include an additional $U(1)$ symmetry is a simple and well-motivated extension [4], which leads to a prediction of a new vector particle, a Z' boson. In order for the extended gauge symmetry to be anomaly free, only certain generation-dependent couplings are allowed. The anomaly-free model we consider in this paper is the $L_\mu - L_\tau$ gauge symmetry [5], where L_μ and L_τ are the μ and τ lepton numbers, respectively. The interaction between the Z' and the second- and third-generation leptons can be described with the following Lagrangian [6]:

$$\mathcal{L}_{Z'} = -gZ'_\mu \left(\overline{L}_{L_\mu}\gamma^\mu L_{L_\mu} + \overline{l}_{R_\mu}\gamma^\mu l_{R_\mu} - \overline{L}_{L_\tau}\gamma^\mu L_{L_\tau} - \overline{l}_{R_\tau}\gamma^\mu l_{R_\tau} \right) \tag{1}$$

where g is an arbitrary dimensionless coupling to the SM left-handed and right-handed μ and τ multiplets, respectively, are

$$L_{L_{\mu(\tau)}} = \begin{pmatrix} \nu_{L_{\mu(\tau)}} \\ l_{L_{\mu(\tau)}} \end{pmatrix} \text{ and } l_{R_{\mu(\tau)}}. \tag{2}$$

Additional $U(1)$ gauge symmetries based on the difference in lepton family numbers are all anomaly free and require no new fermionic particle content. The model based on gauging $L_\mu - L_\tau$ in particular is the least constrained experimentally, since it is coupled only to second- and third-generation leptons.This model has gained popularity in recent years [7–13] as an explanation to several anomalous experimental measurements in particle physics. These anomalies include the measurement of the anomalous muon magnetic moment by the Muon g−2 Collaboration [14], which can be explained for certain values of the Z' mass and coupling strength (g) [7, 9]. In addition, if the Z' mediates an interaction between dark matter and ordinary matter, the bounds on the dark matter coupling strength from direct-detection experiments are less stringent [10, 11] since the Z' does not couple directly to quarks. Finally, if additional interactions beyond the minimal $L_\mu - L_\tau$ model are assumed, abnormalities in kinematic angular distributions and lepton flavor universality tests observed in $B \to K^*\mu^+\mu^-$ decays [15, 16] can be explained by this model, given its flavor non-universal couplings [8, 11].

The Z' gauge boson associated with the putative $L_\mu - L_\tau$ gauge symmetry can be sought at the CERN LHC. Since the Z' couples only to second- and third-generation leptons (μ, ν_μ, τ and ν_τ), it must be produced as a final state radiation product of a lepton originating from some other physics process. The $Z \to 4\mu$ decay provides an extremely clean source of muons with excellent mass resolution. The resonant signal decay $Z' \to \mu\mu$ that may be present in $Z \to 4\mu$ decays further reduces the background contamination. There are two types of irreducible background where the additional dimuon pair originates from annihilation or conversion topologies. The Feynman diagrams in Fig. 1 (left) for the signal and in Fig. 1 (right) for the background are examples of the annihilation topology, while the diagrams in Fig. 2 are examples of the conversion topology. The dominant background to the search comes from the annihilation diagram in Fig. 1 (right), while the background originating from the conversion diagrams in Fig. 2 are subdominant. The signal and background processes originating from the diagrams in Fig. 1 will hereafter be collectively referred to as the $Z \to 4\mu$ process since they have very similar kinematic properties. The background processes originating from the diagrams in Fig. 1 (right) and Fig. 2 (left) will be collectively referred to as $q\overline{q} \to 4\mu$, and the process originating from the diagram in Fig. 2 (right) will be referred to as $gg \to 4\mu$.

The $Z \to 4\mu$ process has been studied by the ATLAS and CMS Collaborations [17–19] and constraints on the $L_\mu - L_\tau$ parameter space have been derived. However, these measurements are not optimized for the presence of a Z′ particle. In particular, they do not utilize the fact that two of the four muons would form a resonant peak at the Z′ mass, providing a means to reduce the dominant background by several orders of magnitude. The subject of this paper is a dedicated counting experiment search with a final selection based on the reconstructed Z′ candidate mass.

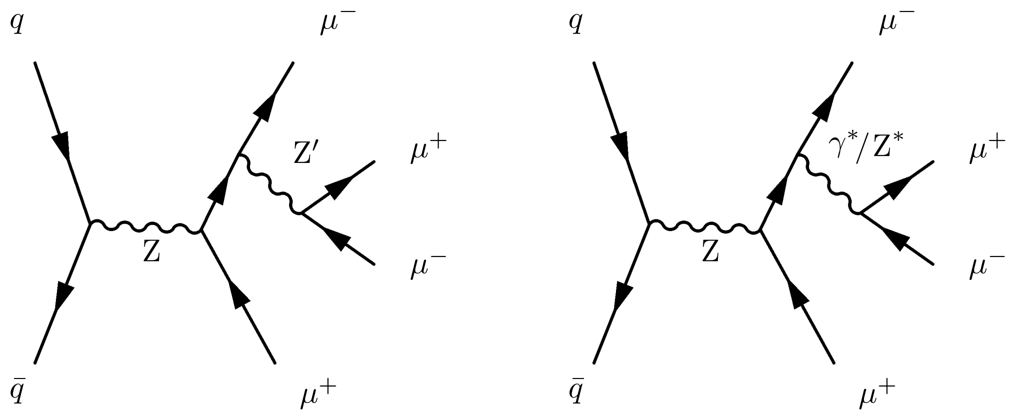

Figure 1: Leading order Feynman diagrams for the signal process (left) and the dominant background process (right), where in each diagram the additional dimuon pair originates from annihilation.

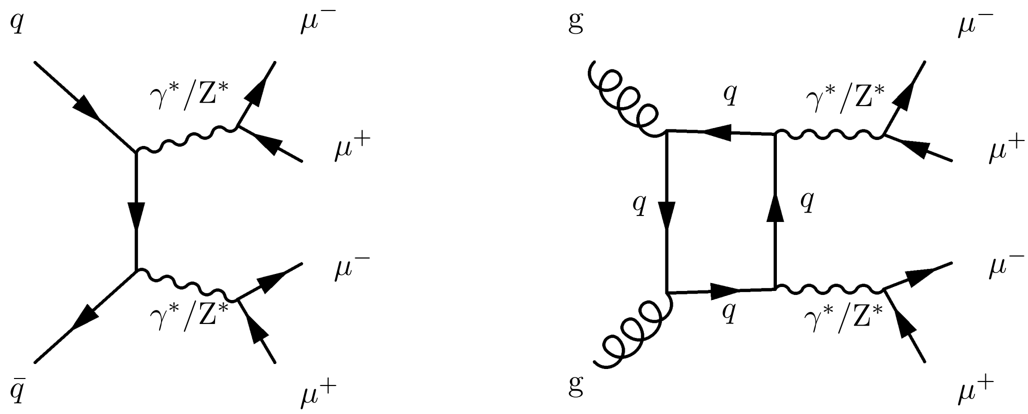

Figure 2: Leading order Feynman diagrams for the subdominant quark-initiated (left) and gluon-initiated (right) background processes, where in each diagram the dimuon pairs originate from conversion.

2 The CMS detector

A 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. [20]. 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, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η)

coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. The silicon tracker measures charged particles with $|\eta| < 2.5$. For nonisolated particles with transverse momentum (p_{T}) between 1 and 10 GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [21]. Muons are measured in the region $|\eta| < 2.4$, 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 $20 < p_{\mathrm{T}} < 100$ GeV of 1.3–2.0% in the barrel ($|\eta| < 0.9$) and better than 6% in the endcaps ($|\eta| > 0.9$). The first level of the CMS trigger system [22], composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to less than 1 kHz before data storage.

3 Data and simulated samples

This analysis makes use of proton-proton (pp) collision data recorded by the CMS detector in 2016 and 2017, corresponding to an integrated luminosity of 77.3 fb^{-1}. Collision events are selected by HLT algorithms that require the presence of one, two, or three muons passing loose identification and isolation requirements. The overall trigger efficiency for simulated signal events that pass the full selection chain of this analysis (described in Section 4) is greater than 99%. The trigger efficiency is measured in data with a method based on the "tag-and-probe" technique [23] using a sample of 4μ events collected by the single-muon triggers. Events with four muons contain predominantly prompt muons and, therefore, background subtraction is not necessary. Muons matched to the single-muon triggers are used as tags and the other three muons are used as probes. The probe muons are then matched to the triggering muon objects from any of the one, two, or three muon triggers, and the combined efficiency is extracted. The efficiency in data is found to be in agreement with the expectation from simulation.

Monte Carlo simulation samples for the Z′ signal and for the background coming from the $\mathrm{q\overline{q}} \to 4\mu$ and $\mathrm{gg} \to 4\mu$ processes are used to optimize the event selection, evaluate the signal acceptance, and estimate the background rate and systematic uncertainties. The signal is generated at leading order (LO) in perturbative quantum chromodynamics (pQCD) with MADGRAPH5_aMC@NLO (v2_4_2) [24] together with the Universal FEYNRULES Output (UFO) model from Ref. [6]. The signal samples are generated with $m(\mathrm{Z'})$ ranging from 5 to 70 GeV in steps of 5 GeV. For $m(\mathrm{Z'})$ below 5 GeV nonprompt muons become a challenging background, and for $m(\mathrm{Z'})$ above 70 GeV the Z boson starts to be produced off mass-shell, requiring a dedicated event selection. The $\mathrm{q\overline{q}} \to 4\mu$ process is generated at next-to-LO (NLO) in pQCD with POWHEG 2.0 [25–27], while the $\mathrm{gg} \to 4\mu$ process is generated at LO with MCFM 7.0 [28]. The default set of parton distribution functions (PDFs) used in all simulations is NNPDF30_nlo_as_0118 [29]. The fully differential cross section for the $\mathrm{q\overline{q}} \to 4\mu$ process has been computed at next-to-NLO (NNLO) [30], and the appropriate NNLO/NLO correction factor K of 1.03 at $m(4\mu) = m(\mathrm{Z})$ is used to correct the POWHEG sample. Because the signal production process is the same as that of the $\mathrm{q\overline{q}} \to 4\mu$ background, an analogous NNLO/LO K factor of 1.29 is used to correct the signal process. The $\mathrm{gg} \to 4\mu$ process contributes at NNLO in pQCD and is corrected by a K factor of 2.4 [31–37].

After the final selection, described in Section 5, the $\mathrm{gg} \to 4\mu$ background contribution is typically less than 1% (and at most 7%) of the the $\mathrm{q\overline{q}} \to 4\mu$ contribution. These simulations have been found to provide an accurate description of 4μ events in data by several previous publications [19, 38–40]. All the generated events are interfaced with PYTHIA 8.212 [41] tune CUETP8M1 [42] to simulate multiple parton interactions, the underlying event, and the fragmentation and hadronization effects. The generated events are processed through a detailed simulation of the CMS detector based on GEANT4 [43, 44] and reconstructed with the same algorithms that are used for the data. The simulated events include overlapping pp interactions (pileup) and have been reweighted so that the distribution of the number of interactions per LHC bunch crossing in simulation matches that observed in data.

4 Object reconstruction

The techniques of the object reconstruction and event selection are based largely on Refs. [19, 38–40]. Event reconstruction is based on the particle-flow (PF) algorithm [45], which exploits information from all the CMS subdetectors to identify and reconstruct individual particles in the event. Higher-level observables, such as muon isolation quantities, are built from the PF candidates classified as charged hadrons, neutral hadrons, photons, electrons, or muons.

Muons are reconstructed within the geometrical acceptance $|\eta| < 2.4$ by combining information from the silicon tracker and the muon system [46], and are required to satisfy $p_{\mathrm{T}} > 5\,\mathrm{GeV}$. The inner and outer tracks are matched using either an outside-in algorithm, starting from a track in the muon system, or an inside-out algorithm, starting from a track in the silicon tracker. In the latter case, some very low-p_{T} muons that may not have sufficient energy to penetrate the entire muon system are also collected by considering tracks that match track segments in only one or two planes of the muon system. Muons are identified from the reconstructed muon track candidates by applying minimal requirements on the inner and outer tracks, taking into account their compatibility with small energy deposits in the calorimeters.

Muons originating from nonprompt decays of hadrons are suppressed by requiring each muon track to have the ratio between its impact parameter in three dimensions, computed with respect to the chosen primary vertex position, and its uncertainty to be less than 4. The primary pp interaction vertex is taken to be the reconstructed vertex with the largest value of summed physics-object p_{T}^2. The physics objects are the jets, clustered using the jet finding algorithm [47, 48] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the p_{T} of those jets.

A relative isolation requirement of $\mathcal{I}^{\mu} < 0.35$ is imposed to discriminate between prompt muons from Z boson decays and those arising from electroweak decays of hadrons within jets, where the relative isolation is defined as

$$\mathcal{I}^{\mu} \equiv \left(\sum p_{\mathrm{T}}^{\text{charged}} + \max\left[0, \sum p_{\mathrm{T}}^{\text{neutral}} + \sum p_{\mathrm{T}}^{\gamma} - p_{\mathrm{T}}^{\mathrm{PU}}\right] \right) / p_{\mathrm{T}}^{\mu}. \tag{3}$$

The isolation sums involved are all restricted to PF candidates within a volume bounded by a cone of angular radius $\Delta R = 0.3$ around the muon direction at the primary vertex, where the angular distance between two particles i and j is $\Delta R(i,j) = \sqrt{(\eta^i - \eta^j)^2 + (\phi^i - \phi^j)^2}$, where ϕ is the azimuthal angle in radians. The quantity $\sum p_{\mathrm{T}}^{\text{charged}}$ is the scalar sum of the transverse momenta of charged hadrons originating from the chosen primary vertex of the event. The quantities $\sum p_{\mathrm{T}}^{\text{neutral}}$ and $\sum p_{\mathrm{T}}^{\gamma}$ are the scalar sums of the transverse momenta for neutral hadrons and photons, respectively. Energy deposits from pileup interactions, $p_{\mathrm{T}}^{\mathrm{PU}}$, are subtracted to make the isolation variable less sensitive to the number of pileup interactions. Here, we define $p_{\mathrm{T}}^{\mathrm{PU}} \equiv 0.5 \sum_i p_{\mathrm{T}}^{\mathrm{PU},i}$, where i runs over the momenta of the charged hadron PF candidates not originating from the primary vertex and the factor of 0.5 accounts for the different fractions of charged and neutral particles in the cone.

An algorithm is used to recover the final-state radiation (FSR) photons from muons. Photons reconstructed by the PF algorithm within $|\eta_\gamma| < 2.4$ are required to satisfy $p_T^\gamma > 2\,\text{GeV}$ and $\mathcal{I}^\gamma < 1.8$. The photon relative isolation $\mathcal{I}^\gamma$ is defined as for the muons in Eq. (3). Every FSR candidate is associated with the closest selected muon in the event, and we require FSR candidates to satisfy $\Delta R(\gamma,\mu)/(p_T^\gamma)^2 < 0.012\,\text{GeV}^{-2}$ and $\Delta R(\gamma,\mu) < 0.5$. Finally, for every muon we retain the FSR candidate, if any, with the lowest $\Delta R(\gamma,\mu)/(p_T^\gamma)^2$. About 5% of signal events are found to have one FSR photon attached. Any selected FSR photons are excluded from the corresponding muon isolation computation.

The decay products of known dimuon resonances (J/ψ meson, Z boson) are used to calibrate the muon momentum scale and resolution in bins of p_T and η. Muon momenta are calibrated using a Kalman filter approach [49]. A tag-and-probe technique [23, 50] is used to measure the efficiency of the reconstruction and selection for prompt muons in several bins of p_T and η. The difference between the efficiencies measured in simulation and data, which on average is 1.2% per muon, is used to correct the selection efficiency in the simulated samples. The combined muon reconstruction and identification efficiency for signal events, including these corrections, is about 92% per muon.

5 Event selection

Events are required to contain at least four well-identified and isolated muons, with at least two muons required to have $p_T > 10\,\text{GeV}$ and at least one to have $p_T > 20\,\text{GeV}$. The four selected muons must have zero net charge. Dimuon candidates are formed from muon pairs of opposite sign ($\mu^+\mu^-$) and are required to pass $4 < m_{\mu^+\mu^-} < 120\,\text{GeV}$. All recovered FSR photon candidates are included in the invariant mass computation. The dimuon candidates are then combined into $Z \to 4\mu$ candidates, and we define Z'_1 to be the dimuon candidate with an invariant mass closest to the nominal Z boson mass (m_Z) [51], and Z'_2 as the other one. In events with more than four muons, the $Z \to 4\mu$ candidate with $m(Z'_1)$ closest to m_Z is selected. If several $Z \to 4\mu$ candidates have the same $m(Z'_1)$, the Z'_2 candidate formed from the two muons with the highest scalar sum of p_T is chosen.

To be considered for the analysis, $Z \to 4\mu$ candidates have to pass a set of kinematic requirements. The Z'_1 invariant mass must be larger than 12 GeV and all muons must be separated in angular space by at least $\Delta R(\mu_i,\mu_j) > 0.02$. To further suppress events with muons originating from hadron decays in jet fragmentation or from the decay of low-mass hadronic resonances, all four opposite sign muon pairs that can be constructed with the four muons are required to satisfy $m_{\mu^+\mu^-} > 4\,\text{GeV}$, where selected FSR photons are disregarded in the invariant mass computation. Finally, the four-muon invariant mass $m(4\mu)$ must be between 80 and 100 GeV. The Z' candidate is most often reconstructed as Z'_2 for $m(Z') < 42.65\,\text{GeV}$ and as Z'_1 for $m(Z') > 42.65\,\text{GeV}$. The search is a counting experiment with a sliding mass window, and a final selection made on either $m(Z'_1)$ or $m(Z'_2)$ values, depending on the Z' mass hypothesis. The exclusion limit for $m(Z') = 42.65\,\text{GeV}$ using either $m(Z'_2)$ or $m(Z'_1)$ as an observable is about the same. For $m(Z') < 42.65\,\text{GeV}$, $m(Z'_2)$ is required to be within 2% of the $m(Z')$. While for $m(Z') > 42.65$ GeV, the same requirement is applied on $m(Z'_1)$. The search window size of 2% was chosen to simultaneously optimize the expected significance and exclusion limit for different Z' mass hypotheses. The efficiency of this requirement varies with Z mass and is 60% for $m(Z') = 5\,\text{GeV}$, 25% for $m(Z') = 40\,\text{GeV}$, and 75% for $m(Z') = 70\,\text{GeV}$. The low efficiency for $m(Z') \approx m_Z/2$ is due the combinatoric ambiguity in selecting the correct Z'

candidate from the four possible dimuon candidates. The selection is, however, still extremely beneficial, as it eliminates approximately 99.8% of the SM $Z\gamma^*$ background for $m(Z') = 40\,\text{GeV}$. Additional backgrounds to the signal that can arise from processes in which heavy-flavor jets produce secondary muons, and from processes in which decays of heavy-flavor hadrons or nonprompt decays of light mesons within jets are misidentified as prompt muons, are found to be negligible after the final event selection.

6 Systematic uncertainties

Experimental uncertainties that equally affect the signal and background estimations include the uncertainty in the integrated luminosity measurement of 2.5% [52] and 2.3% [53] for the 2016 and 2017 data sets, respectively, and the uncertainty in the muon identification and reconstruction efficiency (4.9% on the overall event yield). An uncertainty in the signal and background yields due to the muon momentum scale is determined using $Z \to 4\mu$ events in data and simulation and found to be negligible (0.1%). An uncertainty in the signal and background yields of 2% coming from the determination of the muon momentum resolution is obtained by smearing the dimuon mass resolution by 20% [40] with respect to the nominal resolution and recomputing the expected yields. The uncertainties due to the finite sizes of the simulated samples amount to 3% for the background estimation and 1.4% for the signal estimation.

Theoretical uncertainties that affect both the signal and background estimations include uncertainties in the finite-order perturbative calculations and the choice of the PDF set. The uncertainties arising from finite-order perturbative calculations are estimated by varying the renormalization and factorization scales between 0.5 and 2 times their nominal value, while keeping their ratios between 0.5 and 2. This uncertainty is found to be 3.5 (3.9)% for the $q\bar{q} \to 4\mu$ ($gg \to 4\mu$) process and is taken to be correlated between the signal and the dominant $q\bar{q} \to 4\mu$ background process. Following Ref. [31] and taking into account differences in selection, an additional uncertainty of 10% in the K factor used for the $gg \to 4\mu$ prediction described in Section 3 is applied to account for the fact that the K factor was computed for the closely related $gg \to H$ process. The uncertainty from the PDF set is determined following the PDF4LHC recommendations [54] and is found to be 3.1 (3.5)% for the $q\bar{q} \to 4\mu$ ($gg \to 4\mu$) process. This uncertainty is also taken to be correlated between the signal and the dominant $q\bar{q} \to 4\mu$ background process.

To estimate the effect of the interference between the signal and background processes, three types of samples, $pp \to 4\mu$ (inclusive), $pp \to Z'\mu\mu \to 4\mu$ (signal only), and $pp \to 4\mu$ (background only), are generated using MADGRAPH5_aMC@NLO (v2_4_2), with g varied from 0.01 to 0.5. The inclusive sample contains background, signal, and interference contributions. The effect of the interference on the normalization of the signal is estimated by taking the difference between the inclusive sample's cross section and the sum of the signal and background sample's cross sections. This difference is at most 5% after the final event selection, and additional 5% uncertainty in the signal yield is applied to account for this effect.

7 Results

The number of candidates observed in data and the expected yields for the backgrounds and the different Z' signals after the full event selection are reported in Table 1. The reconstructed four-muon invariant mass distributions are shown in Fig. 3 and compared with the expectations from signal and background processes. Fig. 4 shows the reconstructed $m(Z'_1)$ and $m(Z'_2)$ distributions.

Table 1: The numbers of expected background and signal events and the numbers of observed candidate events after the full selection with $80 < m_{4\mu} < 100\,\mathrm{GeV}$. The signal and $\mathrm{q\bar{q}/gg} \to 4\mu$ background rates are both estimated from simulation. The signal predictions are reported with systematic uncertainties only, while the background predictions are reported with statistical and systematic uncertainties, respectively. Also shown are the numbers of expected background and signal events and the numbers of observed candidate events in the relevant mass windows for three $m(\mathrm{Z'})$ hypotheses. The values of the coupling strengths are chosen for the purpose of illustration.

	Background	$m(\mathrm{Z'}) = 5\,\mathrm{GeV}$ $g = 0.008$	$m(\mathrm{Z'}) = 15\,\mathrm{GeV}$ $g = 0.01$	$m(\mathrm{Z'}) = 70\,\mathrm{GeV}$ $g = 0.5$	Observed Data
$80 < m_{4\mu} < 100\,\mathrm{GeV}$	$423.0 \pm 20.6 \pm 33.4$	37.1 ± 3.7	31.4 ± 3.1	53.8 ± 5.4	441
$4.9 < m(\mathrm{Z'_2}) < 5.1\,\mathrm{GeV}$	$9.2 \pm 3.0 \pm 0.7$	23.3 ± 2.3	—	—	13
$14.7 < m(\mathrm{Z'_2}) < 15.3\,\mathrm{GeV}$	$7.7 \pm 2.8 \pm 0.6$	—	18.9 ± 1.9	—	6
$68.6 < m(\mathrm{Z'_1}) < 71.4\,\mathrm{GeV}$	$34.9 \pm 5.9 \pm 2.8$	—	—	36.0 ± 3.6	35

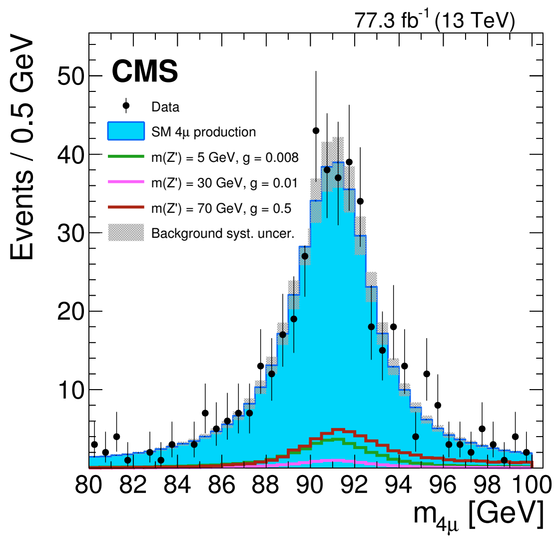

Figure 3: Distribution of the reconstructed four-muon invariant mass $m_{4\mu}$ in the full mass range and a comparison to the predicted $\mathrm{q\bar{q}/gg} \to 4\mu$ background. The blue histogram represents the expected SM 4μ background distribution and the gray band shows the systematic uncertainty in its prediction. For illustration, three Z′ signal hypotheses with different masses and coupling strengths are shown by colored lines.

In all cases, the observed distributions agree with the expectations within the assigned uncertainties. Upper limits at 95% confidence level (CL) are derived on the product of the $\mathrm{Z'}\mu\mu$ production cross section and the branching fraction $\mathcal{B}(\mathrm{Z'} \to \mu\mu)$ using the $\mathrm{CL_s}$ method [55, 56] with the test statistic described in Ref. [57], in the asymptotic approximation [58]. The asymptotic approximation was verified to be valid by computing limits with the full $\mathrm{CL_s}$ method using pseudo-experiments for several $m(\mathrm{Z'})$ hypotheses. A linear interpolation of the expected event yields between generated signal MC samples is assumed in the limit calculations. Systematic uncertainties are incorporated into the likelihood as nuisance parameters with log-normal prior constraints. Due to the low number of events passing the final selection, the statistical uncertainty is always larger than 22% within the entire $m(\mathrm{Z'})$ search region, and dominates the sensitivity of this analysis. These limits are shown in Fig. 5. The upper limits on the $\mathcal{B}(\mathrm{Z} \to \mathrm{Z'}\mu\mu)\mathcal{B}(\mathrm{Z'} \to \mu\mu)$ are also shown. For the derivation of branching fraction limits, the Z boson production cross section prediction computed at NNLO in pQCD with the program FEWZ 2.1 [59–61] is used.

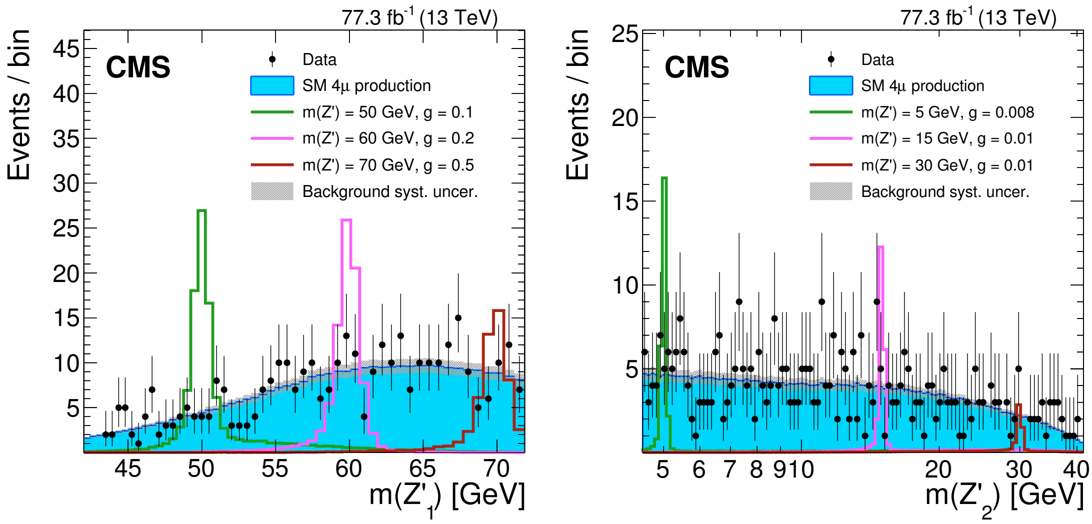

Figure 4: Distributions of the reconstructed $m(\mathrm{Z}'_1)$ and $m(\mathrm{Z}'_2)$ observables and a comparison to the predicted $\mathrm{q\overline{q}/gg} \to 4\mu$ background. The variable bin width has been chosen according to the expected mass resolution. The blue histogram represents the expected SM 4μ background distributions and the gray band shows the systematic uncertainty in its prediction. For illustration, three Z' signal hypotheses with different masses and coupling strengths are also shown by colored lines.

Upper limits are also derived on the gauge coupling strength g and compared to other experimental constraints, shown in Fig. 6. These limits assume the $\mathcal{B}(\mathrm{Z}' \to \mu\mu)$ is equal to 1/3 as in the minimal $L_\mu - L_\tau$ model with equal left- and right-handed coupling strengths, and the additional constraints are adapted from Ref. [11]. The mass of the dark matter candidate in the model from Ref. [11] is assumed to be much larger than the largest Z' mass considered and the gauge coupling strengths to other particles, such as b- and s-quarks, are taken to be much smaller than the coupling strength to leptons so that $\mathcal{B}(\mathrm{Z}' \to \mu\mu)$ is constant. The natural width of the Z' is also assumed to be less than the detector resolution, which is a valid approximation in the minimal $L_\mu - L_\tau$ model when $g^2/4\pi < 0.01$. The shaded yellow region shows constraints derived in Ref. [11] from the ATLAS $\mathcal{B}(\mathrm{Z} \to 4\mu)$ measurement at $\sqrt{s} = 7$ and 8 TeV [18]. The shaded red region is excluded by the measurement of the so-called neutrino trident cross section by the CCFR Collaboration [62, 63]. The green region is excluded by a global analysis of $\mathrm{B_s}$ mixing measurements performed in Ref. [11]. The region in between those two constraints and for $m(\mathrm{Z}') > 10\,\mathrm{GeV}$ is a candidate region to explain the LHCb B decay anomalies. It is important to note that in order to explain these anomalies, additional assumptions on the couplings of the Z' boson to b- and s-quarks are required, and the constraints from $\mathrm{B_s}$ mixing measurements are therefore not generally applicable to the minimal $L_\mu - L_\tau$ model. It can be seen that this search is able to exclude a significant portion of the previously allowed parameter space.

8 Summary

The first dedicated search at the LHC for a Z' gauge boson resulting from an $L_\mu - L_\tau$ $U(1)$ local gauge symmetry has been presented. Events containing four muons with an invariant mass near the standard model Z boson mass are analyzed, and the selection is further optimized to be sensitive to the events that may contain $\mathrm{Z} \to \mathrm{Z}'\mu\mu \to 4\mu$ decays. A data sample of proton-proton collisions at a center-of-mass energy of 13 TeV is used, corresponding to an

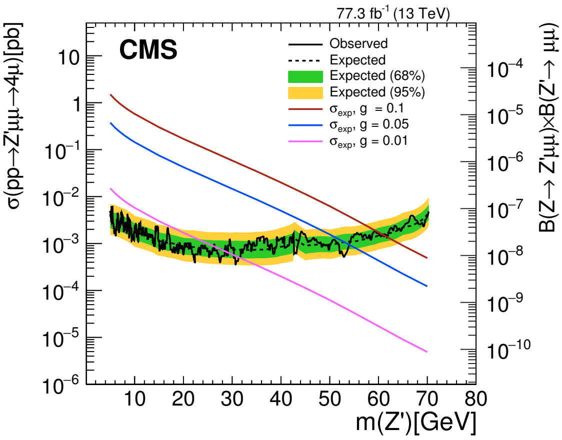

Figure 5: Expected and observed 95% CL limits on the product of the Z$'$ production cross section and branching fraction (left y-axis) and $\mathcal{B}(\mathrm{Z} \to \mathrm{Z}'\mu\mu)\mathcal{B}(\mathrm{Z}' \to \mu\mu)$ (right y-axis). The dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in green and yellow, respectively. The solid black curve is the observed upper limit. The colored lines show the predicted cross section times branching fraction (left y-axis) and $\mathcal{B}(\mathrm{Z} \to \mathrm{Z}'\mu\mu)\mathcal{B}(\mathrm{Z}' \to \mu\mu)$ (right y-axis) as a function of $m(\mathrm{Z}')$ for three different coupling strengths, chosen for illustration.

integrated luminosity of 77.3 fb^{-1} recorded in 2016 and 2017 by the CMS detector at the LHC. The search places strong constraints on theories that attempt to explain various experimental anomalies including the lack of a dark matter signal in direct-detection experiments, tension in the measurement of the anomalous magnetic moment of the muon, and reports of possible lepton flavor universality violation in B meson decays. The event yields are consistent with the standard model predictions. Upper limits of 10^{-8}–10^{-7} at 95% confidence level are set on the product of branching fractions $\mathcal{B}(\mathrm{Z} \to \mathrm{Z}'\mu\mu)\mathcal{B}(\mathrm{Z}' \to \mu\mu)$, depending on the Z$'$ mass, which excludes a Z$'$ boson coupling strength to muons above 0.004–0.3. These are the first dedicated limits on $L_\mu - L_\tau$ models at the LHC and result in a significant increase in the excluded model parameter space.

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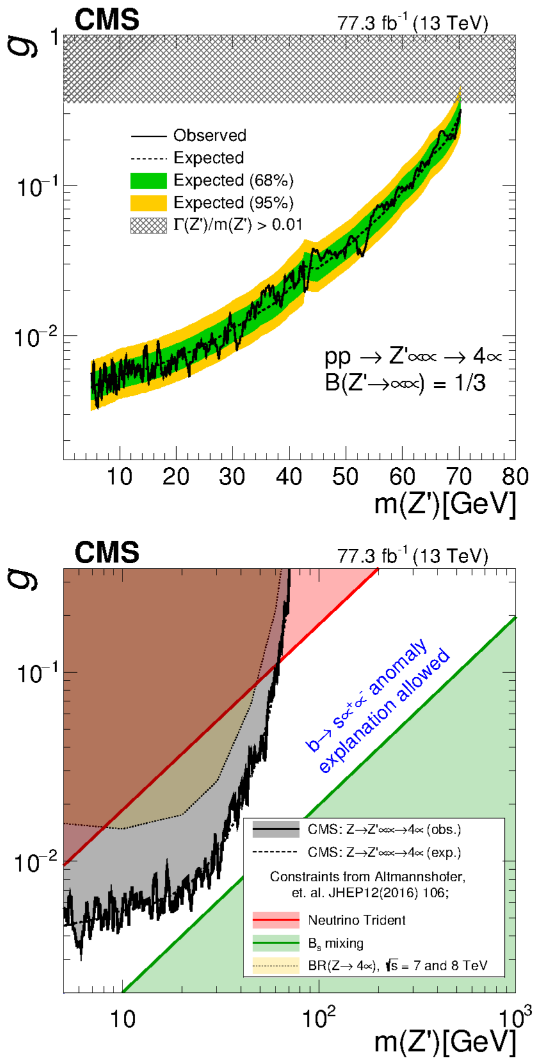

Figure 6: Top: Expected and observed 95% CL limits on the gauge coupling strength g as a function of $m(Z')$. The dashed black curve is the expected upper limit, with one and two standard-deviation bands shown in green and yellow, respectively. The solid black curve is the observed upper limit. The $\mathcal{B}(Z' \to \mu\mu) = 1/3$ is used to derive the upper limits. The hatched area shows the region where the narrow width approximation is no longer valid. Bottom: comparison with other experiments sensitive to the same parameter space, with shaded regions being excluded as described in the text. These three constraints are adapted from Ref. [11].

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14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
15: Also at Tbilisi State University, Tbilisi, Georgia
16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany

19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
24: Also at Institute of Physics, Bhubaneswar, India
25: Also at Shoolini University, Solan, India
26: Also at University of Visva-Bharati, Santiniketan, India
27: Also at Isfahan University of Technology, Isfahan, Iran
28: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
29: Also at Università degli Studi di Siena, Siena, Italy
30: Also at Kyunghee University, Seoul, Korea
31: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
32: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
33: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
34: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
35: Also at Institute for Nuclear Research, Moscow, Russia
36: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
37: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
38: Also at University of Florida, Gainesville, USA
39: Also at P.N. Lebedev Physical Institute, Moscow, Russia
40: Also at California Institute of Technology, Pasadena, USA
41: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy
44: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Riga Technical University, Riga, Latvia
48: Also at Universität Zürich, Zurich, Switzerland
49: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
50: Also at Adiyaman University, Adiyaman, Turkey
51: Also at Istanbul Aydin University, Istanbul, Turkey
52: Also at Mersin University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Gaziosmanpasa University, Tokat, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul University, Faculty of Science, Istanbul, Turkey
60: Also at Istanbul Bilgi University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
63: Also at School of Physics and Astronomy, University of Southampton, Southampton,

United Kingdom
64: Also at Monash University, Faculty of Science, Clayton, Australia
65: Also at Bethel University, St. Paul, USA
66: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
67: Also at Utah Valley University, Orem, USA
68: Also at Purdue University, West Lafayette, USA
69: Also at Beykent University, Istanbul, Turkey
70: Also at Bingol University, Bingol, Turkey
71: Also at Sinop University, Sinop, Turkey
72: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
73: Also at Texas A&M University at Qatar, Doha, Qatar
74: Also at Kyungpook National University, Daegu, Korea