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# Search for $Z'$ gauge boson predicted by lepton flavor and lepton flavor universality violating models with the CMS experiment at LHC

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The standard model conserves lepton flavor and lepton flavor universality although these do not follow from an underlying gauge symmetry. However, the discovery of neutrino oscillations and anomalies observed in B-meson decays indicate violation of lepton flavor and lepton flavor universality, respectively. Various scenarios beyond the standard model have been studied extensively by different experiments at the LHC. This talk presents recent searches for a new $Z'$ boson predicted in the context of lepton flavor violation and lepton flavor universality violation models. The searches use a 13 TeV $pp$ collision data sample, collected by the CMS experiment at the CERN LHC.

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PoS(LHCP2018)272

The standard model (SM) of particle physics includes the conservation of lepton number and lepton flavor, though they are not related to an underlying gauge symmetry. However, the observation of neutrino oscillations, which allows mixing between neutrinos belonging to different lepton families, implies that lepton number is violated, which is a clear indication of new physics (NP) beyond the SM. But, lepton flavor violation (LFV) in the charged sector induced by neutrino oscillations is heavily suppressed due to small neutrino and heavy gauge boson masses making its discovery extremely unlikely. Various extensions of the SM are able to enhance the branching fractions of such decays to levels observable at the LHC. Recently, the LHCb collaboration observed a deviation from the SM predictions in the neutral-current b→s transition hinting at lepton flavor universality violation (LFUV) [1]. Here, recent searches done in area of LFV and LFUV using proton-proton ($pp$) collision data collected by the CMS experiment [2] at the CERN LHC are presented.



## 1. Search for lepton flavor violating decays of heavy resonances to the $e\mu$ final states

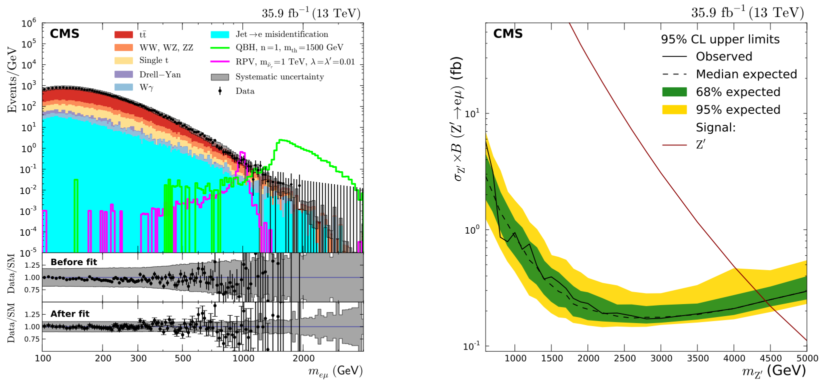
A search for LFV decays of heavy resonances into final states involving a muon and an electron has been performed using 13 TeV $pp$ collision data collected by the CMS detector in the year 2016, and corresponding to an integrated luminosity of 35.9 fb$^{-1}$ [3]. The analysis is designed in a model-independent way by only requiring events with two prompt well-identified and isolated leptons: a muon and an electron. The main sources of background are $t\bar{t}$, W$\gamma$, WW and jet backgrounds (W+jets, QCD multijets). The backgrounds consisting of real and isolated leptons are taken from MC simulations while the one with jets and photons misidentified as leptons, known as "fake background", is extracted from the classic fake rate method. No evidence for physics beyond the SM is observed in the invariant mass spectrum of selected $e\mu$ pairs as shown in Figure 1(a). Therefore, upper limits are calculated on the product of the resonance production cross section ($\sigma$) and the branching fraction ($\mathcal{B}$) to the $e\mu$ final state as a function of the resonance mass using a bayesian binned-likelihood approach at 95% confidence level (CL), assuming a uniform prior for the signal cross section. To interpret the results, various signal models with LFV decays have been chosen, as described below.

### 1.1 Lepton flavor violating decays of a $Z'$ resonance

Extensions of the SM including an additional U(1) gauge symmetry typically predict the existence of a heavy $Z'$ vector boson. A benchmark model considers the couplings of the $Z'$ boson to be the same as the ones of the SM $Z$ boson, but it can also decay to $e\mu$ final states with a branching fraction of 10%, resulting in its width to mass ratio of approximately 3%. The observed and expected limits on the $Z'$ mass at 95% CL are presented in Figure 1(b) and exclude a $Z'$ boson with mass less than 4.4 TeV.

### 1.2 R-parity violating SUSY models with $\widetilde{\nu}_\tau$ as Lightest Supersymmetric Particle

Some R-parity violating (RPV) models including lepton number and flavor violation, predict the existence of a narrow resonant tau s-neutrino ($\widetilde{\nu}_\tau$), as the lightest supersymmetric particle (LSP) which can be produced at the LHC, via a s-channel $q\bar{q}$ interactions. These resonances decay promptly to pairs of electron and muon via $\lambda_{132}$ and $\lambda_{231}$ couplings. The RPV couplings considered




(a) (b)

Figure 1: (a) The invariant mass distribution for $e\mu$ pairs in data (represented by black points), and stacked histograms showing standard model expectations before the fit. The expectations for quantum black hole, RPV signals are also shown. The two lower panels show the ratio of data to background expectations before and after the fit with the systematic uncertainties in gray bands. (b) The upper limits at 95% CL on the product of signal cross section and branching fraction, assuming $\mathcal{B} = 10\%$ for the decay to $e\mu$ final states as a function of $m_{Z'}$. The 68% and 95% CL intervals on the median are represented by the inner green and outer yellow bands [3].

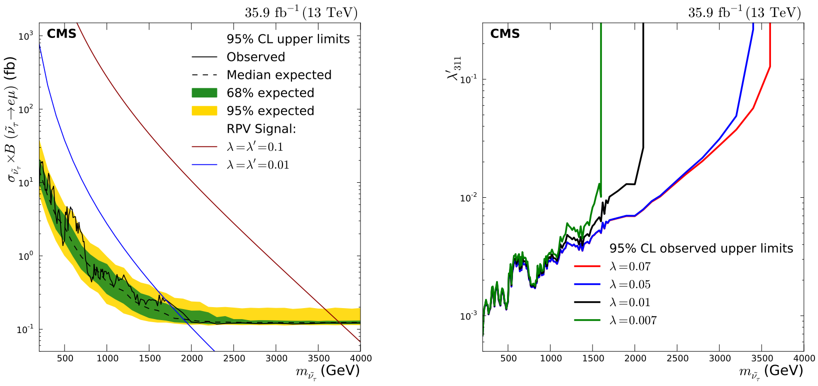
in this model are $\lambda_{132}$ = $\lambda_{231}$ and $\lambda'_{311}$ while others are considered to be zero. The observed and expected limits of 1.7 TeV and 1.9 TeV on the $\tilde{\nu}_\tau$ mass are obtained using coupling values of $\lambda_{132}$ = $\lambda_{231}$ = $\lambda'_{311}$ = 0.01; while for the coupling value of 0.1, the observed and expected limits are 3.8 TeV and 3.8 TeV, as presented in Figure 2(a). Moreover, using the narrow width approximation, $\sigma\mathcal{B}$ can be parameterized in terms of coupling constants as given in equation:

$$\sigma\mathcal{B} \propto (\lambda'_{311})^2[(\lambda_{132})^2 + (\lambda_{231})^2]/[3(\lambda'_{311})^2 + (\lambda_{132})^2 + (\lambda_{231})^2].$$

Using this expression and the observed upper bounds, limit contour plots in the parameter plane of $(m_{\tilde{\nu}_\tau}, \lambda'_{311})$ have been obtained for several values of $\lambda_{231} = \lambda_{132}$ and are represented in Figure 2(b).

### 1.3 LFV decays of Quantum Black Holes

Several theoretical models propose the possibility of the production of quantum black holes (QBH) at the LHC by lowering the effective fundamental Planck scale with the addition of extra spatial dimensions. In such models, these microscopic black holes are non-thermal objects that can decay to a pairs of leptons. These QBH are spin-0, colorless and charge neutral, with LFV decays and have a broader signal shape with a sharp edge at the threshold mass m$_{th}$. In absence of any significant excess, 95% CL limits are derived on $\sigma\mathcal{B}$ calculated for QBH predicted by the Randall-Sundrum (RS) brane-world model [4] having number of extra dimensions i.e. n = 1 and the Arkani-Hamed-Dimopoulous-Dvali (ADD) models [5] with n $>$ 1. Figure 3 shows the observed and expected limits of 3.6, 5.3, 5.5, and 5.6 TeV obtained for RS and ADD models, respectively.




(a) (b)

Figure 2: (a) Upper limits at 95% CL on the product of the signal cross section and branching fraction for the $\widetilde{\nu}_\tau$ signal, as a function of the mass of the RPV resonance for the two values of the coupling parameter. (b) Upper limits at 95% CL on the RPV $\widetilde{\nu}_\tau$ signal in the $(m_{\widetilde{\nu}_\tau}, \lambda'_{311})$ parameter plane, for different values of $\lambda = \lambda_{132} = \lambda_{231}$, where the regions to the left of and above the limits are excluded [3].

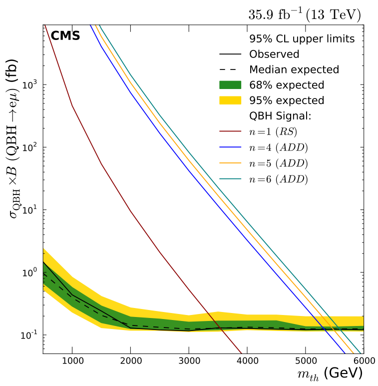
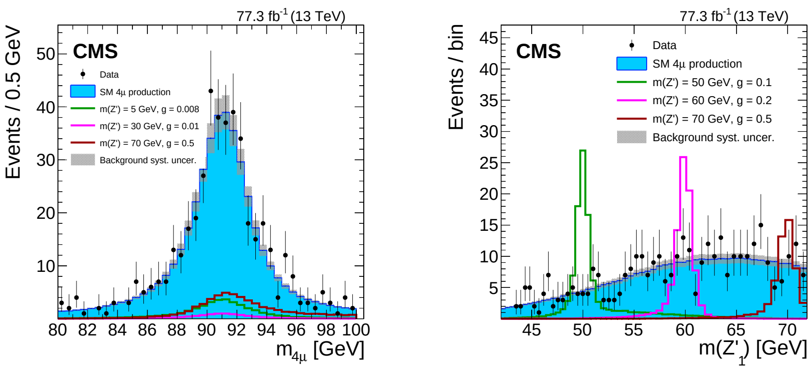



Figure 3: Upper limits at 95% CL on the signal cross section and branching fraction for QBH decay to $e\mu$ as a function of threshold mass $m_{\rm th}$. Solid lines represent predictions for several models with large extra spatial dimensions (n) such as RS for n = 1 and ADD for n= 4, 5, and 6 [3].

## 2. Search for $L_\mu - L_\tau$ gauge boson $Z'$ decaying to muons

This analysis proposes the search for $Z'$ gauge bosons with a mass in the range [5, 70] GeV, predicted by models including a U(1)$'$ gauge symmetry based on the difference between two family lepton numbers of the SM gauge group. Such gauge symmetries are anomaly free and do not require new fermionic particles in the model. The model based on the $L_\mu - L_\tau$ gauge symmetry [6] is less constrained experimentally as it couples to only the second and third generation leptons. Additionally, it provides an answer to anomalies observed in various experimental measurements such as the anomalous magnetic moment by the muon g-2 collaboration [7], the non-observation of dark matter, and anomalies in angular distributions of B $\to$ K$^*\mu^+\mu^-$ decay products [1, 8, 9, 10, 11]. A $Z'$ boson predicted by this model can be observed at the LHC as it couples to only the second and third lepton generations. In particular, it can be produced as a final state radiation product of muons originating from the decay of a SM $Z$ bosons. This $Z'$ further decays to two muons, leading to a final state with four muons. The main background which can mimic the signal process is the Drell-Yan production with a final state $\gamma^*$ radiation that converts into a muon pair, leading to the process: $q\bar{q}/gg \to Z \to 4\mu$. This analysis uses LHC delivered $pp$ collision data recorded by the CMS detector in the years 2016 and 2017, corresponding to an integrated luminosity of 77.3 fb$^{-1}$ [12]. Events triggered by one, two or three muons have been selected for the offline analysis with an efficiency of 99%. A dedicated algorithm has been used to recover final state radiation photons from muons. Events consisting of four well-identified and isolated muons with at least two muons having $p_{\mathrm{T}} > 10$ GeV and at least one with $p_{\mathrm{T}} > 20$ GeV are selected. The dimuon candidates are formed from oppositely charged muon pairs passing $4 < \mathrm{m}_{\mu^+\mu^-} < 120$ GeV and then these candidates are paired up to form $Z \to 4\mu$ candidates. The dimuon candidate with mass closer to $Z$ boson mass is defined as $\mathrm{Z}_1$ and the other pair as $\mathrm{Z}_2$. Additionally, these $Z \to 4\mu$ candidates are required to pass further cuts. The mass of $\mathrm{Z}_1$ candidate should be $> 12$ GeV and all the muons should be separated using $\Delta R(\mu_i, \mu_j) > 0.02$ requirement. The four-muon invariant mass $\mathrm{m}_{4\mu}$ is required to be in the range [80,100] GeV. The discriminating variable is $\mathrm{m}(\mathrm{Z}_1)$ or $\mathrm{m}(\mathrm{Z}_2)$ depending upon the mass hypothesis of the $Z'$ resonance. For $\mathrm{m}(Z') < 42.65$ GeV, $\mathrm{m}(\mathrm{Z}_2)$ is required to be within 2% of $\mathrm{m}(Z')$, while for $\mathrm{m}(Z') > 42.65$ GeV, $\mathrm{m}(\mathrm{Z}_1)$ is required to be within 2% of $\mathrm{m}(Z')$. Both the relevant experimental and theoretical uncertainties are considered for the estimation of the final results. The $\mathrm{m}_{4\mu}$ distribution after the final selections and the reconstructed mass $\mathrm{m}(\mathrm{Z}_1)$ are shown in Figures 4(a) and (b), respectively. As it can be seen, the observed distributions agree with the SM expectations within the statistical and systematic uncertainties. Therefore, upper limits at 95% CL are obtained on the product of the $Z'$ production cross section and the branching fraction $\mathcal{B}(Z' \to \mu\mu)$, and the product of branching fractions $\mathcal{B}(Z \to Z'\mu\mu) \times \mathcal{B}(Z' \to \mu\mu)$, using the CL$_s$ method and the asymptotic approximation as shown in Figure 5(a).



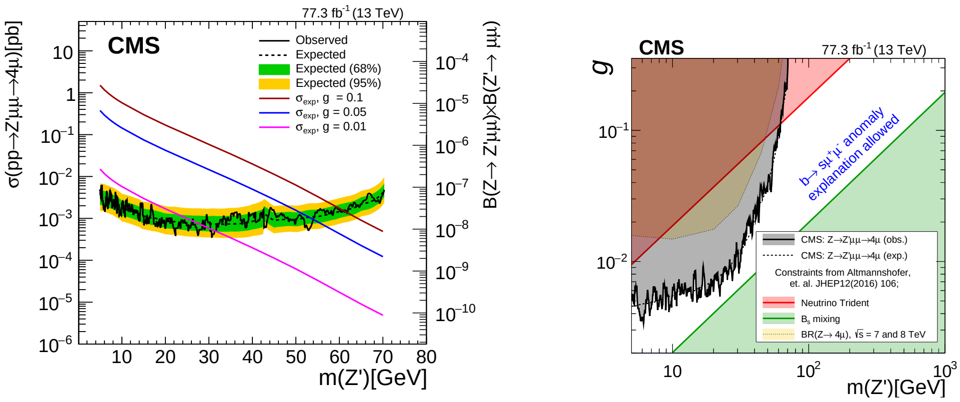

(a) (b)

Figure 4: Distributions of (a) four muon invariant mass and (b) reconstructed $\mathrm{m}(Z_1)$ mass showing comparisons of data with the predicted $q\bar{q}/gg \to Z \to 4\mu$ background. Solid lines show predictions from $Z'$ signal hypotheses with different masses and couplings [12].

Upper limits are also derived on the gauge coupling strength $g$ and are compared to other experimental constraints, as shown in Figure 5(b). These limits assume the branching fraction $\mathcal{B}(Z' \to \mu\mu)$ to be equal to 1/3 and the additional constraints are adapted from Ref. [10]. The



PoS(LHCP2018)272




(a) (b)

Figure 5: Expected and observed limits at 95% CL (a) on the product of the production cross section and the branching fraction on the left y-axis and on the branching fraction $\mathcal{B}(Z \to Z'\mu\mu) \times \mathcal{B}(Z' \to \mu\mu)$ on the right y-axis, and (b) on the gauge coupling strength ($g$) as a function of the resonance mass [12].

shaded yellow region represents constraints from ATLAS $Z \to 4\mu$ branching fraction measurements [13] while the red region is excluded by neutrino trident cross section measurements from the CCFR Collaboration [14, 15]. The region in green is excluded by a global analysis of $B_s$ mixing measurements [10]. The region in between these constraints with m($Z'$) $>$ 10 GeV is a region to explain LHCb B-decay anomalies. For the explanation of these anomalies, additional couplings of vector bosons to b and s quarks are required so $B_s$ mixing measurements are not 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. Upper limits of $10^{-8}$–$10^{-7}$ at 95% CL are set on the product of branching fractions which excludes a $Z'$ boson coupling strength to muons above 0.004–0.3, depending on the $Z'$ mass.

## 3. Summary

Searches for LFV decays of heavy resonances ($Z'$ and $\tilde{\nu}_\tau$) and quantum black holes in $e\mu$ final states are presented. In the absence of a significant excess, upper limits are placed on the production cross section and branching fraction to $e\mu$ pairs as a function of these resonance or QBH masses. Additionally, a search for an $L_\mu - L_\tau$ gauge boson $Z'$ decaying to muons, using $Z \to 4\mu$ events is presented. Upper limits of $10^{-8}$–$10^{-7}$ are placed on $\mathcal{B}(Z \to Z'\mu\mu) \times \mathcal{B}(Z' \to \mu\mu)$ which exclude $Z'$ couplings to muons above 0.004–0.3 depending upon the mass. These limits are the first ever dedicated limits on the $L_\mu - L_\tau$ model at the LHC.

## References


[1] R. Aaij *et al.* [LHCb Collaboration], JHEP **1708**, 055 (2017) doi:10.1007/JHEP08(2017)055 [arXiv:1705.05802 [hep-ex]].

[2] S. Chatrchyan *et al.* [CMS Collaboration], JINST **3**, S08004 (2008). doi:10.1088/1748-0221/3/08/S08004

[3] A. M. Sirunyan *et al.* [CMS Collaboration], JHEP **1804**, 073 (2018) doi:10.1007/JHEP04(2018)073 [arXiv:1802.01122 [hep-ex]].

[4] L. Randall and R. Sundrum, Phys. Rev. Lett. **83**, 3370 (1999) doi:10.1103/PhysRevLett.83.3370 [hep-ph/9905221].

[5] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, Phys. Lett. B **429**, 263 (1998) doi:10.1016/S0370-2693(98)00466-3 [hep-ph/9803315].

[6] X. G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D **44**, 2118 (1991). doi:10.1103/PhysRevD.44.2118

[7] G. W. Bennett *et al.* [Muon g-2 Collaboration], Phys. Rev. D **73**, 072003 (2006) doi:10.1103/PhysRevD.73.072003 [hep-ex/0602035].

[8] R. Aaij *et al.* [LHCb Collaboration], JHEP **1602**, 104 (2016) doi:10.1007/JHEP02(2016)104 [arXiv:1512.04442 [hep-ex]].

[9] S. Baek, N. G. Deshpande, X. G. He and P. Ko, Phys. Rev. D **64**, 055006 (2001) doi:10.1103/PhysRevD.64.055006 [hep-ph/0104141].

[10] W. Altmannshofer, S. Gori, S. Profumo and F. S. Queiroz, JHEP **1612**, 106 (2016) doi:10.1007/JHEP12(2016)106 [arXiv:1609.04026 [hep-ph]].

[11] K. Harigaya, T. Igari, M. M. Nojiri, M. Takeuchi and K. Tobe, JHEP **1403**, 105 (2014) doi:10.1007/JHEP03(2014)105 [arXiv:1311.0870 [hep-ph]].

[12] A. M. Sirunyan *et al.* [CMS Collaboration], [arXiv:1808.03684 [hep-ex]].

[13] G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. Lett. **112**, 231806 (2014) doi:10.1103/PhysRevLett.112.231806 [arXiv:1403.5657 [hep-ex]].

[14] W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, Phys. Rev. Lett. **113**, 091801 (2014) doi:10.1103/PhysRevLett.113.091801 [arXiv:1406.2332 [hep-ph]].

[15] S. R. Mishra *et al.* [CCFR Collaboration], Phys. Rev. Lett. **66**, 3117 (1991). doi:10.1103/PhysRevLett.66.3117

PoS(LHCP2018)272