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Lepton universality tests and searches for charged lepton flavor violation with the CMS experiment

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Lepton families and lepton flavours are central pillars of the standard model (SM). However, these fundamental symmetries are explained but not motivated. The observation of neutrino oscillations indicates that lepton flavour (LF) is not conserved in the SM, and it is possible that LF violating decays could also be observed in the charged lepton sector. Charged LF violating decays are allowed in the SM although they are extremely rare and inaccessible at current colliders. Recent measurements provide a consistent tension of lepton flavour universality (LFU) in processes that include B-decays. These could either be due to simple fluctuations or indicate first hints of the breaking of the SM. If confirmed, LFU violation would imply physics beyond the SM, such as new fundamental interactions. Here, tests of charged LFU and searches for charged LFU violating decays at the CERN LHC with the CMS experiment are presented and discussed.

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1. Introduction

The standard model (SM) of particle physics currently provides the best description of Nature. Measurements show excellent agreement with theory predictions over 10 orders of magnitude. However, despite its success, the SM has unresolved mysteries, e.g. mass hierarchy, neutrino masses, dark matter, and more. Among other things, it predicts that, in their interactions, the different leptons (electron, muon, τ) have the same coupling strengths, a property known as lepton flavour universality (LFU). Recent measurements indicating possible violation of LFU motivated a renewed interest in a yet unresolved matter. What is at the origin of lepton flavour? The origin of lepton flavour remains an open problem.

Here, we focus on tests of LFU and searches for charged lepton flavour violation. There is no fundamental symmetry that enforces lepton flavour conservation. Lepton flavour violation (LFV) has been observed in the neutrino sector, via neutrino oscillations. Therefore, one could expect that LFV effects be also be visible in the charged lepton sector. In fact, charged LFV decays are allowed in the SM but the branching ratios are extremely small, e.g. $B(Z \to e\mu) \sim 10^{-60}$, $B(\tau \to 3\mu) \sim 10^{-55}$. These rates are inaccessible at current experiments.

Significant progress was made in the understanding of the lepton families and flavour symmetry breaking, accessible at low energies through flavour-changing neutral-current processes. Several models that include sources of significant LFV at the TeV scale have been ruled out. Several small but consistent deviations from SM predictions have been observed in rare semi-leptonic decays of B mesons [1–4], although their interpretation is hindered by QCD uncertainties. In particular, the studies can be grouped into two categories: 1) $b \to s\ell^+\ell^-$, neutral-current processes showing deviations from $\mu - e$ universality, 2) $b \to c\ell\nu$, charged-current processes with deviations from $\tau - \mu$ and $\tau - e$ universality. Measurements of exclusive decays of branching ratios and angular observables have been performed. Deviations of up to 4.6σ from SM expectations have been estimated [5]. While these deviations could be a first sign of New Physics, one cannot exclude effects due to statistical fluctuations or some underestimated systematic uncertainties. Moreover, the current measured anomaly of the muon magnetic moment (g-2) reinforces the tension with SM expectations [6] among the lepton families.

LFU can be studied at the CMS experiment in both low- and high-p_T processes. Some of the most recent results are summarized below. Object identification, with a particular attention to τ lepton, comes first.

2. Tau lepton identification

In order to improve the sensitivity to the understanding of LFU, it is crucial to optimize event identification and reconstruction, with a particular focus on all lepton families. The study of final states involving τ leptons may provide strong indications of the presence of New Physics if couplings are proportional to the mass. While electrons and muons have traditionally been used as main probes of the leptonic final states, the identification of hadronic τ decays at hadron colliders is challenging and was achieved for the first time only in the decays of top quarks [7]. Since then, important steps have been made.

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The τ lepton is the only lepton sufficiently massive to decay into hadrons and neutrinos, with a branching fraction of about 65%. Hadronic τ decays are reconstructed by combining information from charged hadrons, using tracks, and π^0 candidates, obtained by clustering photon and electron candidates. In the remaining 35%, τ leptons decay into an electron or a muon, and two neutrinos. In their leptonic decays, electrons and muons are detected through the standard techniques.

A fully inclusive particle-flow reconstruction algorithm [8] tuned to the detector was developed to combine the information from all sub-detectors and reconstruct particles produced in the collision. For each collision, a comprehensive list of final-state particles identified and reconstructed by the algorithm provides a global event description that leads to an excellent performance for jet and hadronic τ decay reconstruction, missing transverse momentum determination, and electron and muon identification. Reconstruction and identification of τ leptons in their hadronic decays (τ_h) has been significantly improved [9]. A newly developed algorithm uses a deep neural network. It uses grids in pseudorapidity and azimuthal angle coordinates, the $\eta - \phi$ space centered around the τ_h axis. A finer grid closer to the center defines the signal cone with a radius of up to 0.1, and an outer grid that contains the isolation cone with a radius of 0.5. For a given working point, the efficiency for genuine τ_h identification is 60% while it is 0.5% for jets mis-identified as τ_h. The performance is extended to also reconstruct highly boosted τ leptons.

3. Precision measurements at the electroweak scale

The study of the W boson decay branching fractions provides a relevant test of the SM. The W bosons are expected to equally couple to the three lepton families. Experimental evidence of a departure from this assumption would be a sign of New Physics. A clean test of LFU can be carried out by comparing the three leptonic branching fractions of the W boson in the electron, muon, and τ decay modes. A combined measurement of the $B(W \to \ell\nu)$ fractions was performed by the LEP experiments and the ratio between the τ and the light leptons (electron and muon) branching fractions, $R_{\tau/\ell} = 1.066 \pm 0.025$ [10], indicated a 2.6σ disagreement with SM predictions. A more precise measurement is required in order to confirm or recuse the earlier result. At the LHC, the large production cross section of top quark pairs, each decaying into a W boson and a b quark, offers an abundant sample of W bosons. A recent measurement exploited a similar strategy to measure $R_{\tau/\ell}$ by fitting the impact parameter distribution of muons in the final state. The result, $R_{\tau/\ell} = 0.992 \pm 0.013$, is in agreement with SM expectations [11].

A precise measurement of the three leptonic as well as of the inclusive hadronic W boson branching fractions was carried out [12]. The analysis is based on final states consistent with the production of two W bosons, or a W plus jets, that decay leptonically. Different event categories sensitive to signal processes and defined on the presence of leptons, number of hadronic and b-tagged jets were defined. A maximum-likelihood estimate of the W branching fractions is performed by fitting each event category simultaneously to the data. The results support the hypothesis of LFU for the weak interactions. Under the assumption of LFU, three SM quantities are also measured: the sum squared of the first two rows of the CKM matrix elements, the CKM element $|V_{cs}|$, and the strong coupling constant at the W mass scale, $\alpha_S(m_W)$.

A test of LFU can also be performed by measuring the cross section of top quark pair production in dilepton final states containing one τ lepton[13]. The $t \to \tau\nu b$ decay involves exclusively third-generation leptons and quarks which, due to their large masses, could be particularly sensitive to beyond SM contributions. For example, a charged Higgs boson may give rise to anomalous τ lepton production that could be observed in this decay channel. If the top quark plays a special role in the electroweak symmetry breaking mechanism, couplings to the W boson may also change. The τ lepton is identified through its visible decay products. In this measurement, the signal includes only τ leptons that decay hadronically. The cross section is measured by performing a profile likelihood ratio fit to the transverse mass distribution of the system containing the light lepton ($\ell = e, \mu$) and the missing transverse momentum. The ratio of the cross sections in the $\ell\tau$ and light dilepton final states, $\sigma_{t\bar{t}}(\ell\tau)/\sigma_{t\bar{t}}(\ell\ell)$, and the ratio of the partial to the total decay width of the top quark are also evaluated. Results are in agreement with SM expectations.

4. The Higgs sector

The discovery of the Higgs boson with a mass of approximately 125 GeV marked an important milestone in the understanding of the electroweak sector of the SM. The observation was followed by precision measurements of the mass, couplings, and CP quantum numbers of the Higgs, which were found to be consistent with the SM predictions.

The SM predicts that the coupling strengths of the Higgs boson to fermions and bosons are proportional to their masses. The measurements are consistent with SM predictions. Due to the small masses, the Yukawa couplings to fermions of the first and second generation have yet to be firmly established experimentally. Evidence for Higgs boson decay to a pair of muons was recently reported, with a coupling strength consistent with SM expectations [14].

LFV in the decays of the Higgs boson is forbidden in the SM. However, there are extension of the SM that allow that. A common feature of many of those models is the inclusion of additional neutral Higgs bosons that would allow LFV decays. A direct search for lepton flavour violating decays of a neutral non-SM Higgs boson, $H \to e\tau$ and $H \to \mu\tau$, was performed [15]. The τ leptons are reconstructed in their leptonic (τ_e, τ_μ) and hadronic (τ_h) decay modes. There are some significant kinematic differences. The primary difference is that the electron (muon) in the LFV $H \to e(\mu)\tau$ decay is produced promptly, and tends to have a higher momentum than in the $H \to \tau_e(\tau_\mu)\tau$ decay. Events are divided into categories based on the number of jets and event kinematics to enhance different Higgs boson production mechanisms. The search uses BDT discriminants to improve separation between signal and background events. No significant excess is found for the LFV Higgs boson decays, and limits were set on the off-diagonal $e\tau$ and $\mu\tau$ Yukawa couplings. Results have a dominant contribution from systematic uncertainties.

Several extensions of the SM, predict a Higgs sector with several Higgs fields with different masses, charges, and other properties. The existence of a charged Higgs boson would provide unequivocal evidence for New Physics. The production mechanism depends on the charged Higgs boson mass. If the charged Higgs boson mass is less than the top quark mass, $m_{H^\pm} < m_t$, it is produced in top quark decays. If it is heavy, i.e. $m_{H^+} > m_t$, the charged Higgs is produced in association with a top quark as $pp \to tbH^\pm$. A light $H^\pm$ decays almost exclusively to a τ lepton and a neutrino, while a heavy $H^\pm$ decays into top and bottom quarks. However, even in the case of a heavy $H^\pm$, the branching fraction to a τ and a neutrino remains sizeable. A direct search for the process $H^\pm \to \tau^\pm\nu$ was performed in the hadronic final state and in final states with an electron or a muon. Three different final states are sought: the hadronic final state (τ_h+jets), the leptonic final state with a τ_h ($\ell + \tau_h$), and the leptonic final state without a τ_h(ℓ + no τ_h). Events are further classified into different categories and a transverse mass distribution is reconstructed in each category of each final state and used in a maximum-likelihood fit to search for a signal. The mass range from 80 GeV to 3 TeV is covered in the search, and the observed limit ranges from 6 pb at 80 GeV to 5 fb at 3 TeV [16].

Extended Higgs sectors with additional SU(2) doublets or triplets introduce couplings of gauge bosons to heavy neutral or charged Higgs bosons [17, 18]. An excess of events with respect to the SM predictions would indicate the presence of new resonances, such as $H^\pm$ or $H^{\pm\pm}$, decaying to WZ boson pairs or same-sign WW boson pairs, respectively. This was investigated by searching for a charged Higgs produced in vector boson scattering (VBS) processes and decaying to vector bosons. Although with a small cross section, VBS processes are sensitive to BSM effects [19, 20]. Events are selected by requiring two or three electrons or muons, missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. Model independent limits are derived as a function of the $H^\pm$ mass, from 200 GeV to 3000 GeV [21].

5. Searches for New Physics processes

Searches for new phenomena that include signatures with leptons are of special interest, as an asymmetric response could signal the presence of New Physics processes. In particular, studies of final states including τ leptons have gained interest, as enhancements in the couplings to τ leptons can be large. **Supersymmetry (SUSY)** is a promising extension of the SM with the potential to solve some of the outstanding problems by introducing a new symmetry between fermions and bosons. The inclusion of a new set of particles, the supersymmetric particles, would fix the hierarchy problems by canceling the large loop corrections to the mass of the Higgs boson. It features the presence of superpartners of SM particles with the same quantum numbers except for the spin, which is different by half a unit. In SUSY models with R-parity conservation, the lightest supersymmetric particle (LSP) is stable and could be a dark matter (DM) candidate. Searches for SUSY particles have extensively been carried out in several final states. Here, we report on a few recent searches that focus on some of the lightest and therefore most accessible supersymmetric particle candidates.

Charginos and neutralinos

A direct search for electroweak production of **charginos and neutralinos**, the SUSY equivalent of Ws and νs in the SM, was performed in final states with multiple leptons (including τs). Whether the decays are more likely to result in τ leptons than the other lepton flavours depends on the combination of gauge eigenstates making up charginos and neutralinos, and their masses. Events are categorized according to lepton flavours and charges to focus on various signal hypotheses. Search regions are defined based on the event kinematics to further separate signal events from the SM backgrounds. A parametric neural network is used. Results are interpreted in terms of different models and represent a broad range of production and decay scenarios for charginos and neutralinos. Depending on the model hypotheses, charginos and neutralinos with masses up to values between 300 and 1450 GeV are excluded at 95% C.L. [24].

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The τ slepton

The τ **slepton** ($\tilde{\tau}$), the superpartner of the τ lepton, would provide a mechanism that could explain the observed DM relic density through $\tilde{\tau}$-neutralino annihilation. The existence of a light $\tilde{\tau}$ as the next-to-lightest supersymmetric particle (NLSP) would lead to an enhanced production rate of final states with τ leptons in collider experiments. A search for the direct production of a pair of τ sleptons was carried out in events with two hadronically decaying τ leptons [23]. In addition to scenarios in which the τ sleptons decay promptly, the search also addresses scenarios in which the τ sleptons have macroscopic lifetimes, giving rise to displaced τ leptons. The search strategy relies on a simultaneous maximum likelihood fit of the event yields observed in 31 search regions. Limits on pair production of both promptly decaying and long-lived τ sleptons were obtained in the framework of simplified models in which the τ slepton decays to a τ lepton and the lightest supersymmetric particle (LSP), which is assumed to be stable.

The top squark

A search for pair production of the **supersymmetric partner of the top quark**, the top squark, was carried out in a final state containing hadronically decaying τ leptons and large missing transverse momentum. This final state is sensitive to high-$\tan\beta$ or higgsino-like scenarios and probes the parameter space of the minimal supersymmetric standard model (MSSM) in which the lightest charginos and neutralinos preferentially couple to third-generation fermions, such as τ leptons. No significant excess was observed and exclusion limits on the top squark mass as a function of the mass of the lightest neutralino were set at 95% C.L. [24].

Leptoquarks and heavy particles

Leptoquarks (LQs) have recently regained interest as they can explain the anomalies observed in the measurements of B meson decays. The models proposed to explain these anomalies favour couplings to the heavy third-generation fermions and may be accessible at the LHC. A model [25] predicts a LQ with a mass of $\mathcal{O}$(TeV) decaying with a 50% branching fraction to either a top quark and a neutrino ($t\nu$) or a bottom quark and a τ lepton ($b\tau$). Furthermore, the SM lacks the explanation for the symmetry between the quark and lepton families and LQs could provide a link between the families and an explanation of this symmetry. At hadron colliders, LQs can be produced in pairs or singly in association with a lepton. Searches for LQs were performed in the $t\tau\nu(b)$ signatures, in which both the top and the τ decay hadronically. Events were split in categories according to the number of b-jets and the topology of the top quark decay products (either "boosted" or "resolved"). Observations are in agreement with SM predictions [26]. Earlier searches for squarks and gluinos are also reinterpreted to constrain LQ production models. LQ pair production is considered with LQ decays to a neutrino and a top, bottom, or light quark, LQ$\rightarrow q\nu$ [27].

Neutrino oscillations provided experimental evidence for non-zero neutrino masses. However, they are extremely small when compared to those of other SM particles. The existence of **heavy neutral leptons (HNLs)** could provide an explanation of the small neutrino masses or, in the case of a stable HNL, be a DM candidate. HNLs can be produced through the mixing with an electron, muon, or τ neutrino. A search for long-lived HNLs with displaced vertices was also performed [28].

Extensions of the SM predict the existence of heavy particles that undergo lepton flavor violating decays. A search was carried out for **heavy resonances and quantum black holes** decaying into $e\mu$, $e\tau$, and $\mu\tau$ final states [29]. No excess of events was detected over the SM backgrounds.

6. Summary

Intriguing results in charged and neutral current decays of B mesons indicate possible anomalies in lepton flavour universality (LFU). With abundant data samples, and high energy proton collisions, the LHC experiments can perform tests of LFU and searches for charged lepton violation in several different processes. Those range from precision measurements at the electroweak scale to those in the Higgs sector and searches for New Physics processes. The latest results obtained at the CMS experiment have been discussed and summarized. No clear discrepancy from SM expectations is found. Large data samples are expected to be collected in the upcoming Run 3, starting in 2022, and in the following at the High-Luminosity LHC Phase 2.

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References

[1] R. Aaij *et al.* [LHCb], "Test of lepton universality in beauty-quark decays," [arXiv:2103.11769 [hep-ex]].

[2] R. Aaij *et al.* [LHCb], "Angular analysis of the $B^+ \to K^{*+}\mu^+\mu^-$ decay," Phys. Rev. Lett. **126**, no.16, 161802 (2021) doi:10.1103/PhysRevLett.126.161802 [arXiv:2012.13241 [hep-ex]].

[3] R. Aaij *et al.* [LHCb], "Measurement of CP-averaged observables in the $B^0 \to K^{*0}\mu^+\mu^-$ decay," Phys. Rev. Lett. **125**, no.1, 011802 (2020) doi:10.1103/PhysRevLett.125.011802 [arXiv:2003.04831 [hep-ex]].

[4] A. M. Sirunyan *et al.* [CMS], "Measurement of angular parameters from the decay $\mathrm{B}^0 \to \mathrm{K}^{*0}\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV," Phys. Lett. B **781**, 517 (2018) doi:10.1016/j.physletb.2018.04.030 [arXiv:1710.02846 [hep-ex]].

[5] C. Cornella, D. A. Faroughy, J. Fuentes-Martin, G. Isidori and M. Neubert, "Reading the footprints of the B-meson flavor anomalies," JHEP **08**, 050 (2021) doi:10.1007/JHEP08(2021)050 [arXiv:2103.16558 [hep-ph]].

[6] B. Abi *et al.* [Muon g-2], "Measurement of the positive muon anomalous magnetic moment to 0.46 ppm," Phys. Rev. Lett. **126**, no.14, 141801 (2021) doi:10.1103/PhysRevLett.126.141801 [arXiv:2104.03281 [hep-ex]].

[7] F. Abe *et al.* [CDF], "The $\mu\tau$ and $e\tau$ decays of top quark pairs produced in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.8 TeV," Phys. Rev. Lett. **79**, 3585-3590 (1997) doi:10.1103/PhysRevLett.79.3585 [arXiv:hep-ex/9704007 [hep-ex]].

[8] A. M. Sirunyan *et al.* [CMS], "Particle-flow reconstruction and global event description with the CMS detector," JINST **12**, no.10, P10003 (2017) doi:10.1088/1748-0221/12/10/P10003 [arXiv:1706.04965 [physics.ins-det]].

[9] A. M. Sirunyan *et al.* [CMS], "Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s}$ = 13 TeV," JINST **13**, no.10, P10005 (2018) doi:10.1088/1748-0221/13/10/P10005 [arXiv:1809.02816 [hep-ex]].

[10] S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL and LEP Electroweak], "Electroweak measurements in electron-positron collisions at W boson pair energies at LEP," Phys. Rept. **532**, 119-244 (2013) doi:10.1016/j.physrep.2013.07.004 [arXiv:1302.3415 [hep-ex]].

[11] G. Aad *et al.* [ATLAS], "Test of the universality of τ and μ lepton couplings in W-boson decays from $t\bar{t}$ events with the ATLAS detector," [arXiv:2007.14040 [hep-ex]].

[12] [CMS], "A precision measurement of the W boson decay branching fractions in pp collisions at $\sqrt{s}$ = 13 TeV," CMS-PAS-SMP-18-011.

[13] A. M. Sirunyan *et al.* [CMS], "Measurement of the top quark pair production cross section in dilepton final states containing one τ lepton in pp collisions at $\sqrt{s}$ = 13 TeV," JHEP **02**, 191 (2020) doi:10.1007/JHEP02(2020)191 [arXiv:1911.13204 [hep-ex]].

[14] A. M. Sirunyan *et al.* [CMS], "Evidence for Higgs boson decay to a pair of muons," JHEP **01**, 148 (2021) doi:10.1007/JHEP01(2021)148 [arXiv:2009.04363 [hep-ex]].

[15] A. M. Sirunyan *et al.* [CMS], "Search for lepton-flavor violating decays of the Higgs boson in the $\mu\tau$ and eτ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV," Phys. Rev. D **104**, no.3, 032013 (2021) doi:10.1103/PhysRevD.104.032013 [arXiv:2105.03007 [hep-ex]].

[16] A. M. Sirunyan *et al.* [CMS], "Search for charged Higgs bosons in the $\mathrm{H}^\pm \to \tau^\pm\nu_\tau$ decay channel in proton-proton collisions at $\sqrt{s}$ = 13 TeV," JHEP **07**, 142 (2019) doi:10.1007/JHEP07(2019)142 [arXiv:1903.04560 [hep-ex]].

[17] C. Englert, E. Re and M. Spannowsky, "Triplet Higgs boson collider phenomenology after the LHC," Phys. Rev. D **87**, no.9, 095014 (2013) doi:10.1103/PhysRevD.87.095014 [arXiv:1302.6505 [hep-ph]].

[18] H. Georgi and M. Machacek, "Doubly charged Higgs bosons," Nucl. Phys. B **262**, 463-477 (1985) doi:10.1016/0550-3213(85)90325-6

[19] M. Gallinaro, K. Long, J. Reuter, R. Ruiz, D. Bachas, *et al.* "Beyond the standard model in vector boson scattering signatures," [arXiv:2005.09889 [hep-ph]].

[20] D. Buarque, M. Gallinaro, R. Ruiz, T. K. Aarrestad, M. Chiesa, *et al.* "Vector boson scattering processes: Status and prospects," [arXiv:2106.01393 [hep-ph]].

[21] A. M. Sirunyan *et al.* [CMS], "Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s}$ = 13 TeV," Eur. Phys. J. C **81**, no.8, 723 (2021) doi:10.1140/epjc/s10052-021-09472-3 [arXiv:2104.04762 [hep-ex]].

[22] A. Tumasyan *et al.* [CMS], "Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s}$ = 13 TeV," [arXiv:2106.14246 [hep-ex]].

[23] [CMS], "Search for direct pair production of supersymmetric partners to the τ lepton in the all-hadronic final state at $\sqrt{s}$ = 13 TeV," CMS-PAS-SUS-21-001.

[24] A. Tumasyan *et al.* [CMS], "Search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s}$ = 13 TeV," [arXiv:2106.14246 [hep-ex]].

[25] D. Buttazzo, A. Greljo, G. Isidori and D. Marzocca, "B-physics anomalies: a guide to combined explanations," JHEP **11**, 044 (2017) doi:10.1007/JHEP11(2017)044 [arXiv:1706.07808 [hep-ph]].

[26] A. M. Sirunyan *et al.* [CMS], "Search for singly and pair-produced leptoquarks coupling to third-generation fermions in proton-proton collisions at $\sqrt{s}$ = 13 TeV," Phys. Lett. B **819**, 136446 (2021) doi:10.1016/j.physletb.2021.136446 [arXiv:2012.04178 [hep-ex]].

[27] A. M. Sirunyan *et al.* [CMS], "Constraints on models of scalar and vector leptoquarks decaying to a quark and a neutrino at $\sqrt{s}$ = 13 TeV," Phys. Rev. D **98**, no.3, 032005 (2018) doi:10.1103/PhysRevD.98.032005 [arXiv:1805.10228 [hep-ex]].

[28] [CMS], "Search for long-lived heavy neutral leptons with displaced vertices in pp collisions at $\sqrt{s}$ = 13 TeV with the CMS detector," CMS-PAS-EXO-20-009.

[29] [CMS], "Search for heavy resonances and quantum black holes in eμ, eτ, and $\mu\tau$ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV," CMS-PAS-EXO-19-014.