Lepton flavor violation with light vector bosons

Julian Heeck

Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium

A B S T R A C T

New sub-GeV vector bosons with couplings to muons but not electrons have been discussed in order to explain the muon's magnetic moment, the gap of high-energy neutrinos in IceCube or the proton radius puzzle. If such a light Z' not only violates lepton universality but also lepton flavor, as expected for example from the recent hint for $h \to \mu \tau$ at CMS, the two-body decay mode $\tau \to \mu Z'$ opens up and for $M_{Z'} < 2m_\mu$ gives better constraints than $\tau \to 3\mu$ already with 20-year-old ARGUS limits. We discuss the general prospects and motivation of light vector bosons with lepton-flavor-violating couplings.

© 2016 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

1. Introduction

The search for physics beyond the Standard Model (SM) follows two complementary paths: on the one hand we have the high-energy-frontier experiments, most importantly ATLAS and CMS at the LHC, which can probe new particles with TeV-scale masses if they interact sufficiently strong; on the other hand we have the high-precision frontier, which aims at minute deviations in low-energy observables. New physics can typically fall into either regime depending on the parameters involved; for example, a new gauge boson Z' which acquires its mass $M_{Z'}$ from a TeV-scale vacuum expectation value $\langle \phi \rangle = M_{Z'}/g'$ can be discovered at the LHC for gauge couplings $g' = \mathcal{O}(1)$. For smaller gauge couplings, say $g' = 10^{-6}$, the same model would however only be testable at the precision frontier, which can probe MeV-scale masses. If the Z' has flavor-violating couplings, the strongest constraints typically arise from rare decays such as $\mu \to e\gamma$. Studies are usually concerned with very heavy Z' masses [1–3], even though one can again consider rather light Z' with a small coupling constant. It is precisely this region of parameter space we are interested in here. (Similar studies can be (and have been) performed for light (pseudo-)scalar bosons, e.g. Majorons, axions or familons [4–10].)

Motivations for a light Z' are plentiful. There is the long-standing $\sim 3\sigma$ discrepancy $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (236 \pm 87) \times 10^{-11}$ [11] of the muon's anomalous magnetic moment $a_\mu \equiv (g-2)_\mu/2$, which can be resolved with a sufficiently muon-philic Z' [12–14] with

mass below GeV [15].[1] The same light Z' can explain the gap of high-energy neutrinos in IceCube [18–21]. An MeV-scale Z' has also been proposed to resolve the proton radius puzzle [22,23], which requires couplings to protons and muons [24].

Interestingly, the Z' violates lepton *universality* in all cases in order to avoid strong bounds on electron couplings. (A popular UV-complete model is based on gauged $U(1)_{L_\mu - L_\tau}$, which is not only free of anomalies [25–27] but also motivated by neutrino mixing angles [28–30].) From lepton non-universality it is but a small stretch to imagine lepton-flavor violating (LFV) couplings of the light Z'. This holds true in particular considering the tantalizing 2.5σ hint for the LFV scalar decay $h \to \mu\tau$ at CMS [31] and ATLAS [32], which has been shown in Ref. [33] to fit perfectly into a $U(1)_{L_\mu - L_\tau}$ model with LFV Z' couplings. Here we show that by simply taking the gauge coupling g' to be small, the very same model can resolve the muon's magnetic moment and lead to a large LFV decay rate $\tau \to \mu Z'$.

We will focus on Z' couplings to muons and taus, heavily inspired by $U(1)_{L_\mu - L_\tau}$ models and the observation that all experimental hints for lepton non-universality or LFV reside in the muon sector. An additional coupling to quarks can lead to further interesting effects and can be readily constructed, see e.g. Refs. [34–36]. While a light Z' can not resolve the accumulating anomalies in B-meson decays [37], it can lead to non-standard neutrino interactions, as recently discussed in Ref. [38,39]. One sure source of additional couplings is kinetic mixing of our Z' with the photon, which unavoidably arises in models with several $U(1)$ gauge groups [40].

E-mail address: Julian.Heeck@ulb.ac.be.

[1] Note that the lepton-universal "hidden photon" solution of $(g-2)_\mu$ has recently been excluded experimentally [16,17].

We will neglect this coupling here and refer to Ref. [41] for a thorough discussion.

2. Couplings

We consider flavor-violating Z' couplings in the μ–τ sector as parametrized by the effective Lagrangian

$$\mathcal{L} = (\overline{\mu}, \overline{\tau}) \, \slashed{Z}' \left[\begin{pmatrix} \nu_{\mu\mu} & \nu_{\mu\tau} \\ \nu_{\mu\tau} & \nu_{\tau\tau} \end{pmatrix} - \begin{pmatrix} a_{\mu\mu} & a_{\mu\tau} \\ a_{\mu\tau} & a_{\tau\tau} \end{pmatrix} \gamma_5 \right] \begin{pmatrix} \mu \\ \tau \end{pmatrix}. \qquad (1)$$

We will assume these couplings to be real and often collectively denote $\nu_{\alpha\beta}$ and $a_{\alpha\beta}$ as $g_{\alpha\beta}$. Typically one would assume the off-diagonal entries to be generated from a small rotation, so that $|g_{\alpha\beta}| \ll |g_{\alpha\alpha}|$ [33,42]. This does not necessarily have to be the case, as one can also build models with purely off-diagonal entries [43]. We remain agnostic about the origin for now, and furthermore do not introduce a coupling to electrons in order to simplify the discussion. We do, however, expect a coupling to the neutrinos, which will be relevant for the neutrino trident production (NTP) bound of the $(g - 2)_\mu$ resolution [15]. Without introducing right-handed neutrinos, $SU(2)_L$ gauge invariance enforces the neutrino couplings

$$\mathcal{L} = \left(\overline{\nu}_\mu, \overline{\nu}_\tau \right) \slashed{Z}' \begin{pmatrix} \nu_{\mu\mu} + a_{\mu\mu} & \nu_{\mu\tau} + a_{\mu\tau} \\ \nu_{\mu\tau} + a_{\mu\tau} & \nu_{\tau\tau} + a_{\tau\tau} \end{pmatrix} P_L \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}, \qquad (2)$$

with left-handed projector $P_L = (1 - \gamma_5)/2$. Right-handed neutrinos introduce a model dependence, but could have the same $U(1)'$ charges as the other leptons, e.g. in $L_\mu - L_\tau$ models. In that case one has to assume neutrinos to be Majorana particles, because Dirac neutrinos coupled to a light Z' would severely modify Big Bang nucleosynthesis (BBN) and exclude our region of interest to explain $(g - 2)_\mu$ [44]. Majorana masses can be obtained easily enough by means of a seesaw mechanism at the scale $M_{Z'}/g'$, see e.g. Refs. [33,42], which makes the heavy seesaw partners of the neutrinos unimportant for our study.

2.1. Flavor conserving processes

Let us first review the effects of $g_{\alpha\beta}$ on flavor conserving processes. The most important constraint—and motivation—for this kind of model comes from the muon's magnetic moment. The one-loop contribution can be readily calculated following e.g. Ref. [45]. In the limit $M_{Z'} \gg m_\mu$, we find the simple expression

$$\Delta a_\mu \simeq \frac{\nu_{\mu\mu}^2 + \nu_{\mu\tau}^2 \left(\frac{3m_\tau}{m_\mu} - 2 \right) - 5a_{\mu\mu}^2 - a_{\mu\tau}^2 \left(\frac{3m_\tau}{m_\mu} + 2 \right)}{12\pi^2 M_{Z'}^2 / m_\mu^2}, \qquad (3)$$

whereas the opposite limit $M_{Z'} \ll m_\mu$ gives

$$\Delta a_\mu \simeq + \frac{\nu_{\mu\mu}^2}{8\pi^2} + \frac{\nu_{\mu\tau}^2}{16\pi^2} \frac{m_\mu m_\tau}{M_{Z'}^2} \left(1 - \frac{5m_\mu}{3m_\tau} \right)$$
$$- \frac{a_{\mu\mu}^2}{4\pi^2} \frac{m_\mu^2}{M_{Z'}^2} - \frac{a_{\mu\tau}^2}{16\pi^2} \frac{m_\mu m_\tau}{M_{Z'}^2} \left(1 + \frac{5m_\mu}{3m_\tau} \right). \qquad (4)$$

A positive contribution—in order to resolve the discrepancy—requires *vector* couplings, so we will mostly neglect $a_{\alpha\beta}$ in the following. (Constraints on $a_{\mu\mu}$ from parity violation have been derived in Ref. [46].) See Fig. 1 for the preferred region in the $\nu_{\mu\mu}$–$M_{Z'}$ plane. Note that all contributions except for the diagonal vector coupling are enhanced by $1/M_{Z'}^2$ in the limit of light Z'.

As pointed out in Refs. [15,34], any muon-philic Z' solution to $(g - 2)_\mu$ is constrained by measurements of NTP $\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$, most importantly from CCFR [48]. This essentially excludes the Z' mass range above 900 MeV for a solution of
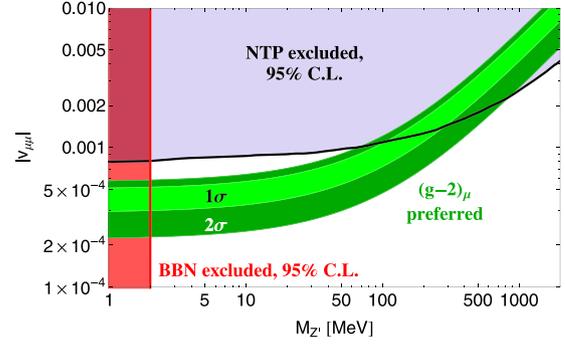

Fig. 1. Limits on a gauge boson Z' with only vector-like couplings $\nu_{\mu\mu}$ to muons and muon-neutrinos. The (light) green area is the preferred (1σ) 2σ region to resolve the muon's anomalous magnetic moment, gray is the NTP bound ($\nu_\mu N \to \nu_\mu N \mu^+ \mu^-$) from CCFR [15], and red the BBN bound corresponding to $\Delta N_{\text{eff}} \leq 1$ from $\nu\bar{\nu} \to Z'$ production [47]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$(g - 2)_\mu$, see Fig. 1. (We use an updated and fairly conservative value for $(g - 2)_\mu$ from Ref. [11], so our numerical values differ from e.g. Ref. [15].) The remaining parameter space of interest for $(g - 2)_\mu$ can be covered with future searches [49].

A very light Z' will contribute to the relativistic degrees of freedom in the early Universe and severely modify BBN. Even if the Z' couples only to neutrinos, one can obtain 95% C.L. limits $M_{Z'} > 2$ MeV for $g_{\alpha\alpha} > 10^{-9}$ [47]. (We will not entertain the possibility of even smaller couplings and masses [50].) Similar qualitative conclusions have been obtained in Refs. [21,39]. Kaon decay $K^- \to \mu^- \bar{\nu} Z'$ followed by the invisible decay $Z' \to \nu\nu$ gives additional constraints in particular on the axial couplings $a_{\alpha\beta}$ [51,52], but are not relevant here.

2.2. Flavor violating processes

Having identified the preferred region of parameters to explain $(g - 2)_\mu$ as $M_{Z'} \simeq 1$ MeV–1 GeV with $\nu_{\mu\mu} = \mathcal{O}(5 \times 10^{-4})$, we study the impact of LFV couplings on the model. These arise in particular in $U(1)_{L_\mu - L_\tau}$ models that try to explain $h \to \mu\tau$ [33,35,36], but are of course of more general interest. For heavy Z', the most constraining LFV decay is typically $\tau \to 3\mu$, with current upper limit Br$(\tau \to 3\mu) < 1.2 \times 10^{-8}$ at 90% C.L. [53]. This limit can most likely be improved by an order of magnitude to 10^{-9} in the future [54,55]. For large $M_{Z'} \gg m_\tau \gg m_\mu$, we obtain the well-known expression

$$\Gamma(\tau \to 3\mu) \simeq \frac{m_\tau^5}{768\pi^3 M_{Z'}^4}$$
$$\times \left[4\nu_{\mu\mu}\nu_{\mu\tau}a_{\mu\mu}a_{\mu\tau} + 3(\nu_{\mu\mu}^2 + a_{\mu\mu}^2)(\nu_{\mu\tau}^2 + a_{\mu\tau}^2) \right], \qquad (5)$$

whereas the formulae are much more complicated for small $M_{Z'}$. For vector interactions, $a_{\mu\mu} = 0$, the longitudinal Z' polarization drops out when coupled to the muon current $\overline{\mu}\gamma^\alpha\mu$, so the rate is constant for $M_{Z'} \to 0$

$$\Gamma(\tau \to 3\mu) \simeq \frac{m_\tau^3 \nu_{\mu\mu}^2}{900\pi^3 m_\mu^2} (\nu_{\mu\tau}^2 + a_{\mu\tau}^2) + \mathcal{O}\left(\frac{M_{Z'}^2}{m_\tau} \right), \qquad (6)$$

but for a non-zero axial current there is an enhancement for small $M_{Z'}$ of the form

$$\Gamma(\tau \to 3\mu) \simeq \frac{a_{\mu\mu}^2 (\nu_{\mu\tau}^2 + a_{\mu\tau}^2)}{128\pi^3} \frac{m_\tau^3 m_\mu^2}{M_{Z'}^4} \log^2\left(\frac{m_\mu}{m_\tau} \right), \qquad (7)$$
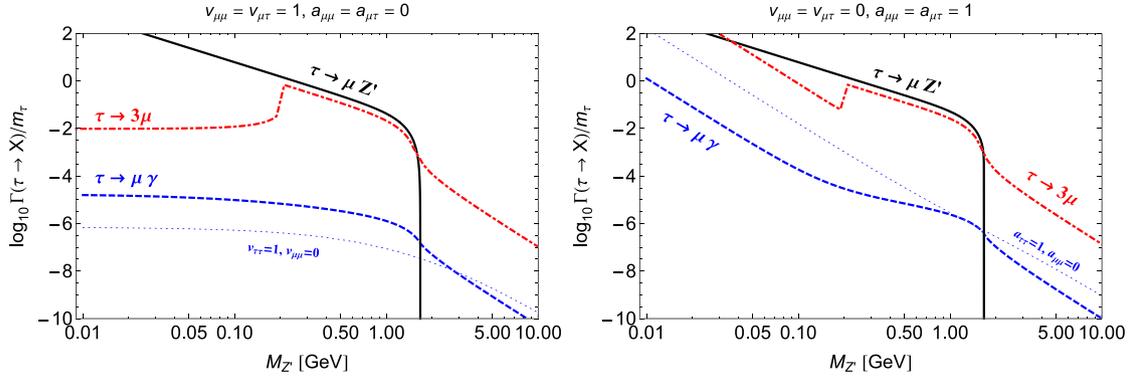
Fig. 2. $M_{Z'}$ dependence of the decay modes $\tau \to \mu Z'$ (black), $\tau \to 3\mu$ with $\mathrm{Br}(Z' \to \mu\mu) = 1/2$ (red, dotdashed), and $\tau \to \mu\gamma$ (blue, dashed) for vector (left) and axial couplings (right). $\tau \to \mu\gamma$ is also shown for $g_{\tau\tau} = 1$, $g_{\mu\mu} = 0$ in blue (dotted) for $g = v$ (left) and $g = a$ (right). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

for $M_{Z'} \ll m_\mu$. In the intermediate region $2m_\mu < M_{Z'} < m_\tau - m_\mu$ the Z' can be produced on-shell, and the rate in the narrow-width approximation takes the form

$$\Gamma(\tau \to 3\mu) \simeq \Gamma(\tau \to \mu Z') \, \mathrm{Br}(Z' \to \mu\mu) \,. \tag{8}$$

Assuming only the decays into $\nu_{\mu,\tau}$ from our effective Lagrangian, we have $\mathrm{Br}(Z' \to \mu\mu) = \mathcal{O}(1)$. The decay width $\tau \to 3\mu$ is shown in Fig. 2 for both vector and axial couplings. In order for the experimental limits from BaBar and Belle on $\tau \to 3\mu$ to be applicable, we have to require the $Z' \to \mu\mu$ decay to occur well inside the relevant detector, which is the case for the region of interest from Fig. 1. A future discovery of $\tau \to 3\mu$, e.g. at Belle II, could reveal the underlying light mediator if enough spectral information can be collected.

The Z' contributes at one loop to $\tau \to \mu\gamma$ [56], which is constrained to a similar level as $\tau \to 3\mu$ [53]. The rate is however suppressed by α_{EM} compared to $\tau \to 3\mu$ and thus typically gives much weaker bounds on the underlying parameters. Assuming only $v_{\mu\mu}$ and $v_{\mu\tau}$ to be non-zero, the rate for $M_{Z'} \ll m_\mu$ is approximately

$$\Gamma(\tau \to \mu\gamma) \simeq \alpha_{\mathrm{EM}} \frac{v_{\mu\mu}^2 v_{\mu\tau}^2}{128\pi^3} m_\tau \log^2\left(\frac{m_\mu}{m_\tau}\right), \tag{9}$$

see Fig. 2. While typically much smaller than the $\tau \to 3\mu$ rate, the loop-induced $\tau \to \mu\gamma$ depends also on the coupling $g_{\tau\tau}$, and hence can dominate if $g_{\tau\tau} \gg g_{\mu\mu}$. As a result, $\tau \to \mu\gamma$ is in our setup only useful to obtain limits on $g_{\tau\tau}$ for non-zero $g_{\mu\tau}$.

As hinted at before, for $M_{Z'} < m_\tau - m_\mu$, which includes our region of interest (Fig. 1), the couplings allow for the two-body decay $\tau \to \mu Z'$ [43,58], followed by $Z' \to \nu\nu$ or $Z' \to \mu\mu$ (see Eq. (8)). This rarely considered decay turns out to give the best limits on our LFV couplings for $M_{Z'} < 2m_\mu$. A short calculation gives

$$\Gamma(\tau \to \mu Z') = \frac{v_{\mu\tau}^2}{8\pi} \frac{m_\tau^2}{M_{Z'}^2} \left[\left(1 - \frac{m_\mu}{m_\tau}\right)^2 - \frac{M_{Z'}^2}{m_\tau^2} \right] \\ \times \left[\left(1 + \frac{m_\mu}{m_\tau}\right)^2 + \frac{2M_{Z'}^2}{m_\tau^2} \right] \sqrt{\boldsymbol{p}_\mu^2} \,, \tag{10}$$

with muon momentum (squared) defined by

$$\boldsymbol{p}_\mu^2 = \frac{\left[m_\tau^2 - (M_{Z'} + m_\mu)^2\right]\left[m_\tau^2 - (M_{Z'} - m_\mu)^2\right]}{4m_\tau^2} \,. \tag{11}$$

The decay rate via the axial coupling can be obtained from Eq. (10) by replacing $v_{\mu\tau} \to a_{\mu\tau}$ and $m_\mu \to -m_\mu$. The rate features a

$1/M_{Z'}^2$ enhancement for small $M_{Z'}$ that is known from e.g. top decays $t \to bW$ and can be understood with help of the Goldstone boson equivalence theorem. In particular it means that the longitudinal Z' polarization dominates in the decay for small $M_{Z'}$.

Experimental constraints on the LFV two-body decay $\tau \to \mu Z'$ with an invisibly decaying Z' have been derived 1995 by AR-GUS [57] (see also older limits in Refs. [59,60]). Testing seven values of $M_{Z'}$ from 0 to 1.6 GeV, limits on $\mathrm{Br}(\tau \to \mu Z')$ at the per-mille level have been obtained, which we will naively interpolate for Z' masses in between. (The limits were actually obtained for pseudo-scalars, but we expect them to be approximately valid for vector bosons as well, especially because the longitudinal part of Z' dominates for small $M_{Z'}$.) For the sub-GeV masses of interest for us, this leads to the 95% C.L. limit $\mathrm{Br}(\tau \to \mu Z') \lesssim 5 \times 10^{-3}$ [57].

Notice that we are looking at $\tau \to \mu + \mathrm{inv}$, which is similar to the SM decay mode $\tau \to \mu\nu\nu$. However, here it is a *two-body* decay, so the resulting muon spectrum is different and allows for an experimental test of this mode (similar to analyses of Michel parameters). This is of course still harder to look for than visible modes such as $\tau \to \mu\gamma$, but Belle and BaBar should be able to improve ARGUS' limit using their ~ 3000 times larger set of τ events. Future B factories such as Belle II can of course improve these limits even further (or discover the decay). As pointed out long ago in Ref. [61] (for muon decay), the process $\tau \to \mu\gamma Z'$ can give competitive limits to $\tau \to \mu Z'$ and should also be considered. To our knowledge, there are no limits on $\tau \to \mu\gamma + \mathrm{inv}$ yet.

3. Discussion

As discussed above, the relevant region to explain the muon's magnetic-moment anomaly via $v_{\mu\mu}$ requires Z' masses below GeV and thus leads to $\tau \to \mu Z'$ if a LFV μ–τ coupling $g_{\mu\tau}$ exists. For $M_{Z'} > 2m_\mu$, the decay $\tau \to 3\mu$ is resonantly enhanced and will generally give the strongest limits on $g_{\mu\tau}$, unless $\mathrm{Br}(Z' \to \mu\mu) \ll 1$. For $M_{Z'} < 2m_\mu$—which holds for most of the relevant parameter space—on the other hand, the LFV two-body decay $\tau \to \mu Z'$ followed by $Z' \to \nu\nu$ gives the strongest bounds on $g_{\mu\tau}$, namely $M_{Z'}/|g_{\mu\tau}| > 3.1 \times 10^6$ GeV (Fig. 3).

In principle one can also consider dominantly off-diagonal couplings, i.e. $g_{\mu\mu} \ll g_{\mu\tau}$, as constructed in Ref. [43]. A resolution of $(g-2)_\mu$ then requires $M_{Z'}/|v_{\mu\tau}| \simeq 1.4$ TeV with $M_{Z'} > m_\tau - m_\mu$ in order to evade the $\tau \to \mu Z'$ bound. Note that neither the NTP bound nor $\tau \to 3\mu, \mu\gamma$ apply for $g_{\mu\mu,\tau\tau} = 0$, so it is indeed possible to resolve $(g-2)_\mu$ via $v_{\mu\tau}$ [43].

Having focused on the μ–τ sector so far, we will now briefly discuss Z' couplings to electrons, which are much more constrained. Let us replace the taus in Eqs. (1) and (2) by electrons,
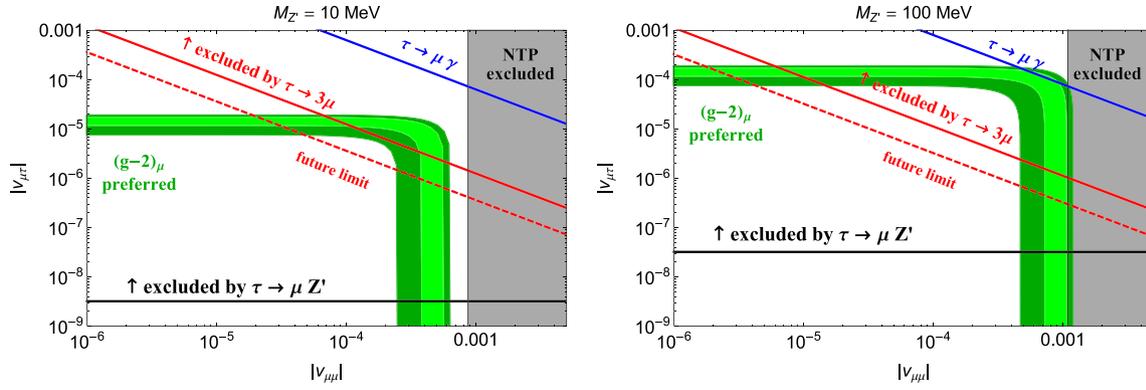
Fig. 3. Limits on the Z' couplings $v_{\mu\mu,\mu\tau}$ with $M_{Z'} = 10$ MeV (left) and 100 MeV (right). The preferred region for a_μ at (1σ) 2σ shown in (light) green, the 95% C.L. constraint from NTP [15] in gray. Blue and (dashed) red show (future) 90% C.L. constraints from $\tau \to \mu\gamma$ and $\tau \to 3\mu$, respectively, far surpassed by the 95% C.L. limit from $\tau \to \mu Z'$ [57] (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

so that we still have $v_{\mu\mu}$ to resolve $(g-2)_\mu$ (Fig. 1). The electron coupling g_{ee} is required to be far smaller than the muon coupling in order to survive electron experiments [16,17]. The relevant LFV decays are $\mu \to 3e$, $\mu \to e\gamma$, and, if $M_{Z'} < m_\mu - m_e$, $\mu \to eZ'$. 90% C.L. limits on $\text{Br}(\mu \to ef)$ of order 10^{-5} [62] and 10^{-6} [63] have been obtained for Majoron-like scalars f, as well as $\text{Br}(\mu \to e\gamma f) < 1.1 \times 10^{-9}$ at 90% C.L. [61,64]. Since BBN requires at least $M_{Z'} > 2m_e$, we are however unavoidably in the resonantly enhanced mode of $\mu \to 3e$ should $\mu \to eZ'$ exist,

$$\text{Br}(\mu \to 3e) \simeq \text{Br}(\mu \to eZ') \, \text{Br}(Z' \to ee) , \qquad (12)$$

which is limited to 10^{-12} [65]. For realistic models we expect $\text{Br}(Z' \to ee)$ to be of order one, so the two-body decay $\mu \to eZ'$ can never compete with the well-constrained $\mu \to 3e$. (A loophole being again purely off-diagonal couplings.)

The third possible combination is a Z' coupling to electrons and taus, leading to the LFV decays $\tau \to 3e$, $\tau \to e\gamma$, and potentially $\tau \to eZ'$. Without $(g-2)_\mu$ as a guiding principle, we can still conclude that the decay rate $Z' \to ee$ can not be turned off kinematically due to the BBN bound, so it will again be generically impossible for $\tau \to eZ'$ to be observable without violating $\tau \to 3e$ constraints. As such, $\tau \to \mu Z'$ is really the standout LFV two-body decay of light new gauge bosons, as it can easily be dominant while respecting existing bounds from e.g. $\tau \to 3\mu$. Furthermore, the relevant couplings—$v_{\mu\mu}$ and $v_{\mu\tau}$—are motivated by the muon's magnetic moment and the hint for $h \to \mu\tau$.

4. Conclusion

If the muon's magnetic-moment anomaly is resolved by a new light gauge boson Z' coupled to muons, its mass is restricted to be between MeV and GeV. Its couplings necessarily violate lepton universality, so it is not far fetched to also assume lepton flavor violation, additionally motivated by the recent hint for $h \to \mu\tau$. We have shown here that the constraints on the LFV Z' couplings do not only come from the usual candidates $\tau \to 3\mu$ or $\tau \to \mu\gamma$, but also from the two-body decay $\tau \to \mu Z'$, courtesy of the small Z' mass, followed by $Z' \to \nu\nu$. The current limit on $\tau \to \mu Z'$ comes from the 5×10^5 τ events studied by ARGUS 20 years ago, and can certainly be improved using Belle's 10^9 τ events.

Acknowledgements

References

[1] P. Langacker, M. Plümacher, Flavor changing effects in theories with a heavy Z' boson with family nonuniversal couplings, Phys. Rev. D 62 (2000) 013006, arXiv:hep-ph/0001204.

[2] B. Murakami, The impact of lepton flavor violating Z' bosons on muon $g-2$ and other muon observables, Phys. Rev. D 65 (2002) 055003, arXiv:hep-ph/0110095.

[3] C.-W. Chiang, Y.-F. Lin, J. Tandean, Probing leptonic interactions of a family-nonuniversal Z' boson, J. High Energy Phys. 1111 (2011) 083, arXiv:1108.3969.

[4] F. Wilczek, Axions and family symmetry breaking, Phys. Rev. Lett. 49 (1982) 1549–1552.

[5] B. Grinstein, J. Preskill, M.B. Wise, Neutrino masses and family symmetry, Phys. Lett. B 159 (1985) 57.

[6] J.L. Feng, T. Moroi, H. Murayama, E. Schnapka, Third generation familons, B factories, and neutrino cosmology, Phys. Rev. D 57 (1998) 5875–5892.

[7] M. Hirsch, A. Vicente, J. Meyer, W. Porod, Majoron emission in muon and tau decays revisited, Phys. Rev. D 79 (2009) 055023, arXiv:0902.0525.

[8] J. Jaeckel, A family of WISPy dark matter candidates, Phys. Lett. B 732 (2014) 1–7, arXiv:1311.0880.

[9] A. Celis, J. Fuentes-Martín, H. Serôdio, An invisible axion model with controlled FCNCs at tree level, Phys. Lett. B 741 (2015) 117–123, arXiv:1410.6217.

[10] A. Celis, J. Fuentes-Martín, H. Serôdio, A class of invisible axion models with FCNCs at tree level, J. High Energy Phys. 12 (2014) 167, arXiv:1410.6218.

[11] A. Crivellin, J. Heeck, P. Stoffer, A perturbed lepton-specific two-Higgs-doublet model facing experimental hints for physics beyond the Standard Model, Phys. Rev. Lett. 116 (2016) 081801, arXiv:1507.07567.

[12] S.N. Gninenko, N.V. Krasnikov, The muon anomalous magnetic moment and a new light gauge boson, Phys. Lett. B 513 (2001) 119, arXiv:hep-ph/0102222.

[13] S. Baek, N.G. Deshpande, X.G. He, P. Ko, Muon anomalous $g-2$ and gauged $L_\mu - L_\tau$ models, Phys. Rev. D 64 (2001) 055006, arXiv:hep-ph/0104141.

[14] C.D. Carone, Flavor-nonuniversal dark gauge bosons and the muon $g-2$, Phys. Lett. B 721 (2013) 118–122, arXiv:1301.2027.

[15] W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, Neutrino trident production: a powerful probe of new physics with neutrino beams, Phys. Rev. Lett. 113 (2014) 091801, arXiv:1406.2332.

[16] BaBar Collaboration, J.P. Lees, et al., Search for a dark photon in e^+e^- collisions at BaBar, Phys. Rev. Lett. 113 (2014) 201801, arXiv:1406.2980.

[17] NA48/2 Collaboration, J.R. Batley, et al., Search for the dark photon in π^0 decays, Phys. Lett. B 746 (2015) 178–185, arXiv:1504.00607.

[18] T. Araki, F. Kaneko, Y. Konishi, T. Ota, J. Sato, et al., Cosmic neutrino spectrum and the muon anomalous magnetic moment in the gauged $L_\mu - L_\tau$ model, Phys. Rev. D 91 (2015) 037301, arXiv:1409.4180.

[19] A. DiFranzo, D. Hooper, Searching for MeV-scale gauge bosons with IceCube, Phys. Rev. D 92 (2015) 095007, arXiv:1507.03015.

[20] T. Araki, F. Kaneko, T. Ota, J. Sato, T. Shimomura, MeV scale leptonic force for cosmic neutrino spectrum and muon anomalous magnetic moment, Phys. Rev. D 93 (2016) 013014, arXiv:1508.07471.

[21] A. Kamada, H.-B. Yu, Coherent propagation of PeV neutrinos and the dip in the neutrino spectrum at IceCube, Phys. Rev. D 92 (2015) 113004, arXiv:1504.00711.

[22] R. Pohl, et al., The size of the proton, Nature 466 (2010) 213–216.

[23] R. Pohl, R. Gilman, G.A. Miller, K. Pachucki, Muonic hydrogen and the proton radius puzzle, Annu. Rev. Nucl. Part. Sci. 63 (2013) 175–204, arXiv:1301.0905.

[24] D. Tucker-Smith, I. Yavin, Muonic hydrogen and MeV forces, Phys. Rev. D 83 (2011) 101702, arXiv:1011.4922.

[25] X. He, G.C. Joshi, H. Lew, R. Volkas, New Z-prime phenomenology, Phys. Rev. D 43 (1991) 22–24.

[26] R. Foot, New physics from electric charge quantization?, Mod. Phys. Lett. A 6 (1991) 527–530.

[27] X.-G. He, G.C. Joshi, H. Lew, R. Volkas, Simplest Z-prime model, Phys. Rev. D 44 (1991) 2118–2132.

[28] P. Binetruy, S. Lavignac, S.T. Petcov, P. Ramond, Quasidegenerate neutrinos from an Abelian family symmetry, Nucl. Phys. B 496 (1997) 3–23, arXiv:hep-ph/9610481.

[29] N.F. Bell, R.R. Volkas, Bottom up model for maximal ν_μ–ν_τ mixing, Phys. Rev. D 63 (2001) 013006, arXiv:hep-ph/0008177.

[30] S. Choubey, W. Rodejohann, A flavor symmetry for quasi-degenerate neutrinos: $L_\mu - L_\tau$, Eur. Phys. J. C 40 (2005) 259–268, arXiv:hep-ph/0411190.

[31] CMS Collaboration, V. Khachatryan, et al., Search for lepton-flavour-violating decays of the Higgs boson, Phys. Lett. B 749 (2015) 337–362, arXiv:1502.07400.

[32] ATLAS Collaboration, G. Aad, et al., Search for lepton-flavour-violating $H \to \mu\tau$ decays of the Higgs boson with the ATLAS detector, J. High Energy Phys. 11 (2015) 211, arXiv:1508.03372.

[33] J. Heeck, M. Holthausen, W. Rodejohann, Y. Shimizu, Higgs $\to \mu\tau$ in abelian and non-abelian flavor symmetry models, Nucl. Phys. B 896 (2015) 281–310, arXiv:1412.3671.

[34] W. Altmannshofer, S. Gori, M. Pospelov, I. Yavin, Quark flavor transitions in $L_\mu - L_\tau$ models, Phys. Rev. D 89 (2014) 095033, arXiv:1403.1269.

[35] A. Crivellin, G. D'Ambrosio, J. Heeck, Explaining $h \to \mu^\pm \tau^\mp$, $B \to K^* \mu^+ \mu^-$ and $B \to K \mu^+ \mu^- / B \to K e^+ e^-$ in a two-Higgs-doublet model with gauged $L_\mu - L_\tau$, Phys. Rev. Lett. 114 (2015) 151801, arXiv:1501.00993.

[36] A. Crivellin, G. D'Ambrosio, J. Heeck, Addressing the LHC flavor anomalies with horizontal gauge symmetries, Phys. Rev. D 91 (2015) 075006, arXiv:1503.03477.

[37] K. Fuyuto, W.-S. Hou, M. Kohda, Z'-induced FCNC decays of top, beauty, and strange quarks, Phys. Rev. D 93 (2016) 054021, arXiv:1512.09026.

[38] Y. Farzan, A model for large non-standard interactions of neutrinos leading to the LMA-Dark solution, Phys. Lett. B 748 (2015) 311–315, arXiv:1505.06906.

[39] Y. Farzan, I.M. Shoemaker, Lepton flavor violating non-standard interactions via light mediators, arXiv:1512.09147.

[40] P. Galison, A. Manohar, Two Z's or not two Z's?, Phys. Lett. B 136 (1984) 279.

[41] R. Essig, et al., Working group report: new light weakly coupled particles, in: Community Summer Study 2013: Snowmass on the Mississippi, CSS2013, Minneapolis, MN, USA, July 29–August 6, 2013, 2013, arXiv:1311.0029.

[42] J. Heeck, W. Rodejohann, Gauged $L_\mu - L_\tau$ symmetry at the electroweak scale, Phys. Rev. D 84 (2011) 075007, arXiv:1107.5238.

[43] R. Foot, X. He, H. Lew, R. Volkas, Model for a light Z' boson, Phys. Rev. D 50 (1994) 4571–4580, arXiv:hep-ph/9401250.

[44] J. Heeck, Unbroken B–L symmetry, Phys. Lett. B 739 (2014) 256–262, arXiv:1408.6845.

[45] J.P. Leveille, The second order weak correction to $(g - 2)$ of the muon in arbitrary gauge models, Nucl. Phys. B 137 (1978) 63.

[46] S.G. Karshenboim, D. McKeen, M. Pospelov, Constraints on muon-specific dark forces, Phys. Rev. D 90 (2014) 073004, arXiv:1401.6154.

[47] B. Ahlgren, T. Ohlsson, S. Zhou, Comment on "Is dark matter with long-range interactions a solution to all small-scale problems of Λ cold dark matter cosmology?", Phys. Rev. Lett. 111 (2013) 199001, arXiv:1309.0991.

[48] CCFR Collaboration, S. Mishra, et al., Neutrino tridents and W–Z interference, Phys. Rev. Lett. 66 (1991) 3117–3120.

[49] S.N. Gninenko, N.V. Krasnikov, V.A. Matveev, Muon $g - 2$ and searches for a new leptophobic sub-GeV dark boson in a missing-energy experiment at CERN, Phys. Rev. D 91 (2015) 095015, arXiv:1412.1400.

[50] J. Heeck, W. Rodejohann, Gauged $L_\mu - L_\tau$ and different muon neutrino and anti-neutrino oscillations: MINOS and beyond, J. Phys. G 38 (2011) 085005, arXiv:1007.2655.

[51] V. Barger, C.-W. Chiang, W.-Y. Keung, D. Marfatia, Constraint on parity-violating muonic forces, Phys. Rev. Lett. 108 (2012) 081802, arXiv:1109.6652.

[52] R. Laha, B. Dasgupta, J.F. Beacom, Constraints on new neutrino interactions via light abelian vector bosons, Phys. Rev. D 89 (2014) 093025, arXiv:1304.3460.

[53] HFAG Heavy Flavor Averaging Group, Y. Amhis, et al., Averages of b-hadron, c-hadron, and τ-lepton properties as of summer 2014, arXiv:1412.7515.

[54] T. Aushev, W. Bartel, A. Bondar, J. Brodzicka, T. Browder, et al., Physics at super B factory, arXiv:1002.5012.

[55] S. Alekhin, et al., A facility to search for hidden particles at the CERN SPS: the SHiP physics case, arXiv:1504.04855.

[56] L. Lavoura, General formulae for $f_1 \to f_2 \gamma$, Eur. Phys. J. C 29 (2003) 191–195, arXiv:hep-ph/0302221.

[57] ARGUS Collaboration, H. Albrecht, et al., A search for lepton flavor violating decays $\tau \to e\alpha$, $\tau \to \mu\alpha$, Z. Phys. C 68 (1995) 25–28.

[58] K.L. McDonald, B. McKellar, Systematic study of leptonic mixing in a class of $SU(2)_H$ models, Phys. Rev. D 73 (2006) 073004, arXiv:hep-ph/0603129.

[59] MARK-III Collaboration, R. Baltrusaitis, et al., τ leptonic branching ratios and a search for goldstone decay, Phys. Rev. Lett. 55 (1985) 1842.

[60] ARGUS Collaboration, H. Albrecht, et al., Determination of the Michel parameter in tau decay, Phys. Lett. B 246 (1990) 278–284.

[61] J.T. Goldman, A. Hallin, C. Hoffman, L. Piilonen, D. Preston, et al., Light boson emission in the decay of the μ^+, Phys. Rev. D 36 (1987) 1543–1546.

[62] TWIST Collaboration, R. Bayes, et al., Search for two body muon decay signals, Phys. Rev. D 91 (2015) 052020, arXiv:1409.0638.

[63] A. Jodidio, B. Balke, J. Carr, G. Gidal, K. Shinsky, et al., Search for right-handed currents in muon decay, Phys. Rev. D 34 (1986) 1967.

[64] R. Bolton, M. Cooper, J. Frank, A. Hallin, P. Heusi, et al., Search for rare muon decays with the crystal box detector, Phys. Rev. D 38 (1988) 2077.

[65] SINDRUM Collaboration, U. Bellgardt, et al., Search for the decay $\mu^+ \to e^+ e^+ e^-$, Nucl. Phys. B 299 (1988) 1.

[66] H.H. Patel, Package-X: a mathematica package for the analytic calculation of one-loop integrals, Comput. Phys. Commun. 197 (2015) 276–290, arXiv:1503.01469.