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Probing the muon $g_\mu - 2$ anomaly, $L_\mu - L_\tau$ gauge boson and Dark Matter in dark photon experiments

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ABSTRACT

In the $L_\mu - L_\tau$ model the 3.6 σ discrepancy between the predicted and measured values of the anomalous magnetic moment of positive muons can be explained by the existence of a new dark boson Z' with a mass in the sub-GeV range, which is coupled at tree level predominantly to the second and third lepton generations. However, at the one-loop level the Z' coupling to electrons or quarks can be induced via the $\gamma - Z'$ kinetic mixing, which is generated through the loop involving the muon and tau lepton. This loophole has important experimental consequences since it opens up new possibilities for the complementary searches of the Z' with high-energy electron beams, in particular in the ongoing NA64 and incoming dark photon experiments. An extension of the model able to explain relic Dark Matter density is also discussed.

1. Introduction

At present there are several signals that new physics beyond the standard model (SM) exists. The most striking is the observation of Dark Matter (DM). Among the many models of DM, for a review, see e.g. [1–4], those that motivate the existence of light vector (scalar) bosons with a mass $m_d \leq O(1)$ GeV are rather popular now [5,6]. The main idea is that in addition to gravity a new interaction between visible and dark sector exists which is mediated by this gauge boson [6]. Another possible hint in favour of new physics is the muon $g_\mu - 2$ anomaly, which is the 3.6 σ discrepancy between the experimental values [7,8] and the SM predictions [9–12] for the anomalous magnetic moment of the muon.

Among several extensions of the SM explaining the anomaly, the models predicting the existence of a weak leptonic force mediated by a sub-GeV gauge boson Z' that couples predominantly to the difference between the muon and tau lepton numbers, $L_\mu - L_\tau$, are of general interest. The abelian symmetry $L_\mu - L_\tau$ is an anomaly-free global symmetry within the SM [13–15]. Breaking $L_\mu - L_\tau$ is crucial for the appearance of a new relatively light, with a mass $m_{Z'} \leq 1$ GeV, vector boson (Z') which couples very weakly to muon and tau-lepton with the coupling constant $\alpha_\mu \sim O(10^{-8})$ [16–29]. The Z' interaction with $L_\mu - L_\tau$ vector current given by

$$L_{Z'} = e_\mu Z'_\nu [\bar{\mu}\gamma^\nu\mu - \bar{\tau}\gamma^\nu\tau + \bar{\nu_\mu}\gamma^\nu\nu_\mu - \bar{\nu_\tau}\gamma^\nu\nu_\tau] \tag{1}$$

leads to additional contribution to the muon anomalous magnetic moment [30]

$$\delta a = \frac{\alpha_\mu}{2\pi} F(\frac{m_{Z'}}{m_\mu}), \tag{2}$$

where

$$F(x) = \int_0^1 dz \frac{[2z(1-z)^2]}{[(1-z)^2 + x^2 z]} \tag{3}$$

and $\alpha_\mu = \frac{e_\mu^2}{4\pi}$. The use of the formulae (2), (3) allows to determine the coupling constant α_μ which explains the value of the $g_\mu - 2$ anomaly [16–29] and it does not contradict to existing experimental bounds for $m_{Z'} \leq 2m_\mu$ [29]. Namely, for $m_{Z'} \ll m_\mu$ [30]

$$\alpha_\mu = (1.8 \pm 0.5) \times 10^{-8}. \tag{4}$$

For another limiting case $m_{Z'} \gg m_\mu$ the α_μ value is

$$\alpha_\mu = (2.7 \pm 0.7) \times 10^{-8} \times \frac{m_{Z'}^2}{m_\mu^2}. \tag{5}$$

In addition to the case of the $g_\mu - 2$ anomaly, there are also other implications of Z' [16–29]. For example, in neutrino sector,

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the $L_\mu - L_\tau$ model can provide a natural explanation of a zeroth-order approximation for neutrino mixing with a quasi-degenerate mass spectrum predicting a maximal atmospheric and vanishing reactor neutrino mixing angle [31–33], small masses of neutrinos and its oscillations by extending the model with the left-right gauge symmetry [34], the R_K puzzle in LHCb data and the $g_\mu - 2$ anomaly can be simultaneously explained with the $\simeq 10$ MeV Z' which also induces the nonstandard matter interactions (NSI) of neutrinos [35]. The later could also provide LMA-Dark solution to solar anomaly, which also requires NSI [36]. Recently, it has been pointed out that specific features of cosmic neutrino spectrum reported by the IceCube Collaboration can be explained by a mass of the MeV scale [37,38], which can be of interest for the search at Belle II [39]. Probing of the Z' in neutrino trident production and in neutrino experiments has been also discussed in [40,41].

In this letter we show that in the $L_\mu - L_\tau$ model nonzero $\gamma - Z'$ mixing generated at the one-loop level strongly motivates the complementary searches of the light Z' with high-energy electron beams. This open up an intriguing possibility for probing the $L_\mu - L_\tau$ gauge boson Z' in the near future with ongoing NA64 experiment with the statistics increased by a factor $\simeq 100$. The Z' searches can be as well performed in the incoming dark photon experiments, e.g. such as AWAKE, Belle-II, BDX, and LDMX. Moreover an extension of the $L_\mu - L_\tau$ model allows to explain relic Dark Matter density for $m_{Z'} \simeq O(10)$ MeV, which strengthen motivation for the experimental search of the $L_\mu - L_\tau$ mediator of the DM production in invisible decay mode.

2. The $\gamma - Z'$ mixing and $Z' \to invisible$ decays

It is generally assumed that searches for the $L_\mu - L_\tau$ gauge boson are difficult as it couples only to the muon and tau lepton family. The relevant bounds can be extracted from the measurements of the neutrino trident production $\nu_\mu N \to \nu_\mu \mu^+ \mu^- N$ [20, 21], from the search for a muonic dark force at BABAR [22], and from the data of the Borexino experiment [23]. Currently, the allowed Z' mass region for the explanation of the $g_\mu - 2$ anomaly is constrained to $m_{Z'} \lesssim 400$ MeV from by the neutrino trident production [42,43], while the BABAR search excluded masses $m_{Z'} \gtrsim$ 200 MeV. Besides this, the mass of the light Z' is constrained to be $m_{Z'} \geq 5\ MeV$ from the cosmology and astrophysical considerations [44–46]. To search for the Z' in the still unconstrained mass region $5 \lesssim m_{Z'} \lesssim 200$ MeV is challenging as the Z' dominant decay $Z' \to \nu\bar{\nu}$ is invisible. The direct search for such Z' by using the reaction $\mu Z \to \mu Z Z'; Z' \to invisible$ of the Z' production in high-energy muon scattering off heavy nuclei at the CERN SPS was proposed in Ref. [51]. The experiment is expected to improve the sensitivity to the coupling α_μ by a few orders of magnitude and fully cover the parameter region referred with Eqs. (4) and (5).

Let us now discuss the mixing between the Z' and ordinary photons. An account of one-loop diagrams, which is in our case propagator diagrams with virtual μ- and τ-leptons in the loop, leads to nonzero $\gamma - Z'$ kinetic mixing $\frac{\epsilon}{2} F^{\mu\nu} Z^{\mu\nu}$ where ϵ is the finite mixing strength given by [19]

$$\epsilon = \frac{8}{3} \frac{e e_\mu}{16\pi^2} \ln(\frac{m_\tau}{m_\mu}) = 1.43 \cdot 10^{-2} e_\mu \,. \qquad (6)$$

Here e is the electron charge and $m_\mu,\ m_\tau$ are the muon and tau-lepton masses respectively. It should be stressed that we assume that possible tree level mixing $\frac{\epsilon_{tree}}{2} F^{\mu\nu} Z^{\mu\nu}$ is absent or much smaller than one-loop mixing $\frac{\epsilon}{2} F^{\mu\nu} Z^{\mu\nu}$. To be precise, we assume that there is no essential cancellation between tree level and one loop mixing terms $|\epsilon_{tree} + \epsilon| \geq |\epsilon|$. For $m_{Z'} \ll m_\mu$ the value $e_\mu = (4.75 \pm 0.8) \cdot 10^{-4}$ from Eq. (4) leads to the prediction of the corresponding mixing value

$$\epsilon = (6.8 \pm 1.1) \cdot 10^{-6} \qquad (7)$$

Thus, one can see that the Z' interaction with the $L_\mu - L_\tau$ current induces at one-loop level the $\gamma - Z'$ mixing of Z' with ordinary photon which allows the Z' to couple to electrons. This loophole opens up the new possibility of searching the weak leptonic force mediated by the Z' in the complementary experiments looking for dark photons (A'). Indeed, the currently ongoing experiment NA64 at CERN [47,48] aimed at the direct search for invisible decay of sub-GeV A''s in the reaction $e^- + Z \to e^- + Z + A';\ A' \to invisible$ of high energy electron scattering off heavy nuclei [49,50]. The experimental signature of the invisible decay of Z' produced in the reaction $e^- + Z \to e^- + Z + Z';\ Z' \to invisible$ due to mixing of Eq. (6) is the same – it is an event with a large missing energy carried away by the Z'. Thus, by using Eq. (6) and bounds on the $\gamma - A'$ mixing, the NA64 can also set constraints on the coupling e_μ. The current NA64 bounds on the parameter ϵ for the dark photon mass region $1 \lesssim m_{A'} \lesssim 10$ MeV are in the range $10^{-5} \lesssim \epsilon \lesssim 10^{-4}$ for the number of accumulated electrons on target (EOT) $n_{EOT} \simeq 4.3 \cdot 10^{10}$ [48]. Taking into account that the sensitivity of the experiment scales as $\epsilon \sim 1/\sqrt{n_{EOT}}$, results in required increase of statistics by a factor $\simeq$100 in order to improve sensitivity up to the mixing value of Eq. (7) for the Z' with a mass in this region. This would allow either to discover the Z', or exclude it as an explanation of the $g_\mu - 2$ anomaly for the substantial part of the mass region $m_{Z'} \lesssim 2m_\mu$. The direct search for the Z' in missing-energy events in the reaction $\mu Z \to \mu Z Z'; Z' \to invisible$ in the dedicated experiment NA64 of Ref. [51] with the CERN muon beam would then be an important cross check of results obtained with the electron beam.

The mixing given by the Eq. (6) would also lead to an extra contribution to the elastic $\nu e \to \nu e$ scattering [38]. The BOREXINO solar neutrino data [23] and measurements in the LSND experiment [24] lead to the lower mass bound $m_{Z'} \geq (5 - 10)\ MeV$ and a similar bound to the e_μ coupling for $m_{Z'} \lesssim 10$ MeV [38], respectively, assuming that the muon anomaly is explained by the existence of a light Z' boson interacting with $L_\mu - L_\tau$ current and there is no tree level mixing between photon and Z', i.e. $\epsilon_{tree} = 0$. The expected 90% C.L. NA64 exclusion regions in the $(m_{Z'}, e_\mu)$ plane from the measurements with the election beam for $\simeq 4 \cdot 10^{12}$ and $\simeq 4 \cdot 10^{13}$ EOT [47,48,50] and muon beams for $\simeq 10^{12}$ muons on target (MOT) [51] are shown in Fig. 1, together with constraints from the BOREXINO [38], CCFR [43], and BABAR [22] experiments, and the BBN exclusion area [38,52]. The parameter space shown in Fig. 1 could also be probed by other electron experiments such as Belle II [39], BDX [53], and LDMX [54], which would provide important complementary results.

3. Search for the $Z' \to e^+e^-$ decay

Another possible way to search for the Z' is based on the production and detection of its visible decay mode, $Z' \to e^+e^-$, which can also occur at the one-loop level. The flux of Z's would be generated in a high intensity beam dump experiment through the mixing with photon produced either directly in the dump [55] or, e.g., in the $\pi^0,\ \eta,\ \eta'$ decays [56]. The Z's would then penetrate the dump without significant interaction and decay in flight into e^+e^- pairs which can be observed in a far detector. For a given flux $d\Phi(m_{Z'}, E_{Z'}, N_{POT})/dE_{Z'}$ of Z''s from the dump the expected number of $Z' \to e^+e^-$ decays occurring within the fiducial length L of a far detector located at a distance L' from the beam dump is given by

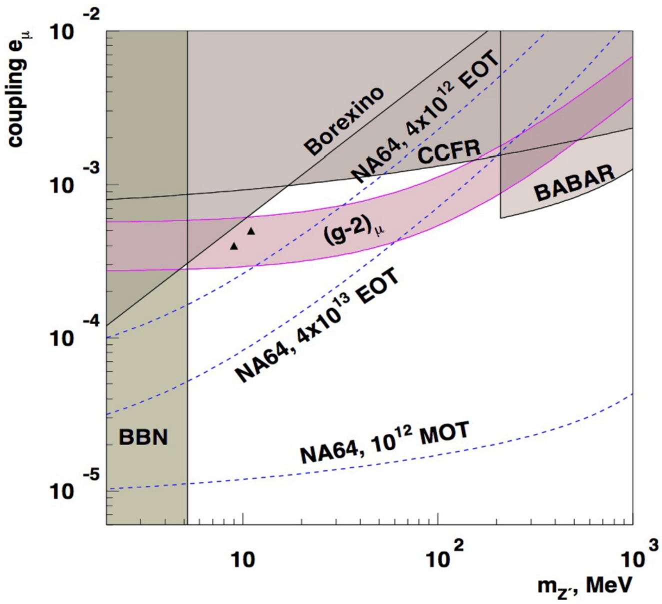

Fig. 1. The NA64 90% C.L. expected exclusion regions in the $(m_{Z'}, e_\mu)$ plane (dashed curves) from the measurements with the election (NA64, $\simeq 4\times10^{12}$ EOT and $\simeq 4\times10^{13}$ EOT) [47,48,50] and muon (NA64, $\simeq 10^{12}$ MOT) [51] beams. Constraints from the BOREXINO [38], CCFR [43], and BABAR [22] experiments, as well as the BBN excluded area [38,52] are also shown. Two triangles indicate reference points corresponding to the mass $m_{Z'}=9$ and 11 MeV, and coupling $e_\mu = 4\times10^{-4}$ and 5×10^{-4}, respectively, which are used to explain the IceCube results, see Ref. [38] for details.

$$N_{Z'\to e^+e^-} = Br(Z'\to e^+e^-)\int \frac{d\Phi}{dE_{Z'}} exp\Big(-\frac{L' m_{Z'}}{P_{Z'}\tau_{Z'}}\Big) \cdot\Big[1-exp\Big(-\frac{L m_{Z'}}{P_{Z'}\tau_{Z'}}\Big)\Big]\epsilon_{eff} A dE_{Z'} \quad (8)$$

where $E_{Z'}$, $P_{Z'}$, and $\tau_{Z'}$ are the Z' energy, momentum and the lifetime at rest, respectively, ϵ_{eff}, A are the e^+e^- pair reconstruction efficiency and acceptance, N_{POT} is the number of primary particles on target (dump). For the mass region $1 \lesssim m_{Z'} \lesssim 200$ MeV the branching fraction $Br(Z'\to e^+e^-)$ is given by

$$Br(Z'\to e^+e^-) = \frac{\Gamma(Z'\to e^+e^-)}{\Gamma(Z'\to e^+e^-)+\Gamma(Z'\to \nu\nu)} \quad (9)$$

where the decay rate of the Z' into neutrino, $\Gamma(Z'\to\nu\nu)$ ($\nu = \nu_\mu,\ \nu_\tau$) and e^+e^- pairs, $\Gamma(Z'\to e^+e^-)$ is given by

$$\Gamma(Z'\to\nu\nu) = \frac{e_\mu^2}{24\pi} m_{Z'} \quad (10)$$

and

$$\Gamma(Z'\to e^+e^-) = \frac{\alpha}{3}\epsilon^2 m_{Z'}\sqrt{1-\frac{4m_e^2}{m_{Z'}^2}}\Big(1+\frac{2m_e^2}{m_{Z'}^2}\Big), \quad (11)$$

respectively. Using Eqs. (9)–(11) we found the Z' lifetime to be in the range $10^{-15} \lesssim \tau_{Z'} \lesssim 10^{-13}$ s. This results in a short Z' decay length $0.3 \lesssim c\tau_{Z'}\gamma \lesssim 30$ cm even for the $m_{Z'} \simeq 10$ MeV and $E_{Z'} \simeq 50$ GeV. Thus, the attenuation of the Z' flux due to Z' decays in flight which is given by the term $exp\Big(-\frac{L' m_{Z'}}{P_{Z'}\tau_{Z'}}\Big)$ in Eq. (8), give a suppression factor $\ll 10^{-15}$ for any beam dump experiment searching for an excess of e^+e^- pairs from dark photon decays [8], as they typically used $L' \gtrsim 100$ m and Z' energy range $E_{Z'} \lesssim 50$ GeV. Here, the γ-factor is $\gamma = E_{Z'}/m_{Z'}$. Because the effective coupling of Z_μ to electrons (or quarks) due to the mixing of Eq. (6) is suppressed by a factor $\approx 10^{-2}$, the branching fraction $Br(Z'\to e^+e^-)$ is estimated to be $\simeq O(10^{-4})$. Taking all these into account makes current constraints $10^{-8} \lesssim \epsilon \lesssim 10^{-4}$ [8] from the beam dump experiments searching for visible $A'\to e^+e^-$ decays of dark photons in the mass range $1 \lesssim m_{A'} \lesssim 200$ MeV inapplicable to the Z' case and much more weaker than the value of Eq. (7) as they were obtained under the assumption that this decay mode is dominant.

Thus, the advantage of searching for Z' in a missing-energy type experiment, e.g. such as NA64, is that its sensitivity is roughly proportional to the mixing squared, ϵ^2 associated with the Z' production in the primary reaction and its subsequent invisible decay, while for the visible case it is proportional to $\epsilon^2 \times Br(Z'\to e^+e^-)$. The factor ϵ^2 is coming from the Z' production process and another suppression factor $Br(Z'\to e^+e^-) = O(10^{-4})$ from the $Z'\to e^+e^-$ decay in the detector. Similar arguments are also valid for the experiments that searched for the visible A' in particle decays and provided exclusion area $\epsilon \gtrsim 10^{-4} - 10^{-3}$ for the mass range $1 \lesssim m_{A'} \lesssim 200$ MeV [8]. As a consequence, taking into account the previous discussions, in any beam dump or decay experiment using electrons or quarks as a source of Z's through the mixing of (6), the number of visible $Z'\to e^+e^-$ signal events would be highly suppressed resulting in a weak bound on α_μ. Similar considerations results in rather modest constraints on invisible decays of Z' which one can extract from the present bounds of dark-photon experiments searching for the invisible A' decays [8]. For example, the limit on the coupling α_μ from the $K^+\to\pi^+ + missing\ energy$ decay is at the level $\alpha_\mu \le O(10^{-3})$, which is several orders of magnitude below the value from Eq. (4).

Finally, note that in order to cover the range $\epsilon \lesssim 10^{-5}$ for the $Z'\to e^+e^-$ decays the trick would be to run a corresponding experiment in a very short-length beam dump mode. A good example of such approach is the AWAKE experiment at CERN, which plan to search for dark photon decays $A'\to e^+e^-$ with a $\simeq 50$ GeV electron beam by using short W-dump and a detector located at a distance $L' \simeq$ a few meter [57]. This experiment would be very complementary to the Z' searches in invisible decay mode provided the accumulation of $\gtrsim 10^{16}$ EOT. The feasibility of this search is under study and will be reported elsewhere. Another experiment, which potentially might be sensitive to the values around of those from Eq. (7) is the HPS [58], which currently aims at reaching the sensitivity $\epsilon \simeq 10^{-5}$ for the $A'\to e^+e^-$ decays with the masses $\lesssim 100$ MeV by using a thin W target.

4. Dark matter in the $L_\mu - L_\tau$ model

Let us show now that an extension of the $L_\mu - L_\tau$ model is able to explain today DM density in the Universe. Consider the simplest SM extension with an additional complex scalar field ϕ_d.[1] The charged dark matter field ϕ_d interaction with the Z' field is

$$L_{\phi Z'} = (\partial^\mu\phi - ie_d Z'^\mu\phi)^*(\partial_\mu\phi - ie_d Z'_\mu\phi) - m_{DM}^2\phi^*\phi - \lambda_\phi(\phi^*\phi)^2 \quad (12)$$

The annihilation cross section $\phi_d\bar\phi_d \to \nu_\mu\bar\nu_\mu, \nu_\tau\bar\nu_\tau$ for $s\approx 4m_{DM}^2$ has the form[2]

$$\sigma v_{rel} = \frac{8\pi}{3}\frac{\epsilon^2\alpha\alpha_d m_{DM}^2 v_{rel}^2}{(m_{Z'}^2 - 4m_{DM}^2)^2}, \quad (13)$$

[1] The annihilation cross-section for scalar DM has p-wave suppression that allows to escape CMB bound [59].

[2] Here we consider the case $m_{Z'} > 2m_{DM}$.

We use standard assumption that in the hot early Universe DM is in equilibrium with ordinary matter. During the Universe expansion the temperature decreases and at some point the thermal decoupling of the Dark Matter starts to work. Namely, at some freeze-out temperature the cross-section of annihilation $DM\ particles \rightarrow\ SM\ particles$ becomes too small to obey the equilibrium of DM particles with the SM particles and DM decouples. The experimental data are in favour of scenario with cold relic for which the freeze-out temperature is much lower than the mass of the particle. In other words DM particles decouple in the non-relativistic regime. The value of the DM annihilation cross-section at the decoupling epoch determines the value of the current DM density in the Universe. Too big annihilation cross-section leads to small DM density and vice versa too small annihilation cross section leads to DM overproduction. The observed value of the DM density $\frac{\rho_{DM}}{\rho_c} \approx 0.23$ allows to estimate the DM annihilation cross-section into the SM particles and hence to estimate the discovery potential of light dark matter both in direct underground and accelerator experiments.

The dark matter relic density can be numerically estimated as [60]

$$\Omega_{DM}h^2 = 0.1\Big[\frac{(n+1)x_f^{n+1}}{(g_{*s}/g_*^{1/2})}\Big]\frac{0.856\cdot 10^{-9}\ \mathrm{GeV}^{-2}}{\sigma_0}\,, \qquad (14)$$

where $<\sigma v_{rel}> = \sigma_0 x_f^{-n}$, $x_f = \frac{m_{DM}}{T_{dec}}$ and

$$x_f = c - (n + \frac{1}{2})\ln(c)\,, \qquad (15)$$

$$c = \ln\Big[0.038(n+1)\frac{g}{\sqrt{g_*}}M_{Pl}m_{DM}\sigma_0\Big]. \qquad (16)$$

For the case where dark matter consists of dark matter particles and dark matter antiparticles $\sigma = \frac{\sigma_{an}}{2}$. Numerically we find that

$$k(m_{DM})\cdot 10^{-6}(\frac{m_{DM}}{\mathrm{GeV}})^2\Big[\frac{m^2_{A'}}{m^2_{DM}} - 4\Big]^2 = \epsilon^2\alpha_D\,. \qquad (17)$$

Here the coefficient $k(m_{DM})$ depends logarithmically on the dark matter mass m_{DM} and $k_{DM} \approx 0.5(0.8)$ for $m_{DM} = 1(100)\ MeV$. For instance, for $m_{A'} = 2.2\ m_{DM}$ we have

$$0.71k(m_{DM})\cdot 10^{-6}\Big[\frac{m_{DM}}{1\ \mathrm{GeV}}\Big]^2 = \epsilon^2\alpha_d\,. \qquad (18)$$

As a consequence of (18) we find that for $m_{Z'} \ll m_\mu$ the values $\epsilon^2 = (2.5 \pm 0.7)\cdot 10^{-6}$ and

$$\alpha_d = (0.28 \pm 0.08)k(m_{DM})\Big[\frac{m_{DM}}{1\ \mathrm{GeV}}\Big]^2 \qquad (19)$$

explain both the $g_\mu - 2$ muon anomaly and today DM density. We can rewrite the equation (19) in the form

$$\frac{e_d^2}{e_\mu^2} = (16 \pm 9)k(m_{DM})\Big[\frac{m_{DM}}{1\ \mathrm{MeV}}\Big]^2. \qquad (20)$$

So we see that for $m_{DM} \geq 1$ MeV we have $e_d \gg e_\mu$, i.e. the Z' must interact much more strongly with light DM than with the SM matter.

5. Summary

In summary, the $L_\mu - L_\tau$ model with the light vector boson Z' interacting with $L_\mu - L_\tau$ current is a well-motivated SM extension, with impressive indirect support from the possible explanation of the muon $g_\mu - 2$ anomaly and several observations in neutrino sector and astrophysics. While the model can be effectively tested with the direct high-energy muon experiment at the CERN SPS [51], we show that nonzero $\gamma - Z'$ mixing generated in the model at the one-loop level strongly motivates the complementary searches of the light Z' with high-energy electron beams. This open up an intriguing possibility for probing the $L_\mu - L_\tau$ gauge boson Z' in the near future with ongoing NA64 experiment with the statistics increased by a factor $\simeq 100$. The Z' searches can be as well performed in the incoming dark photon experiments, e.g. such as AWAKE, Belle-II, BDX, and LDMX. Moreover an extension of the $L_\mu - L_\tau$ model allows to explain relic Dark Matter density for $m_{Z'} \simeq O(10)$ MeV, which strengthen motivation for the experimental search of the $L_\mu - L_\tau$ mediator of the DM production in invisible decay mode. Finally, we note that if the Z' couples to light DM, then an additional contribution from the invisible decay mode $Z' \rightarrow dark\ matter$ increases the $Z' \rightarrow invisible$ decay rate as a consequence for $m_{Z'} > 2m_\mu$ visible decay $Z' \rightarrow \mu^+\mu^-$ is suppressed.

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