

Cosmic horizon of neutrinos

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The persistent discrepancy between the experimental measurement and the Standard Model (SM) prediction of the muon's anomalous magnetic moment $(g-2)_\mu$ remains one of the most intriguing hints of physics beyond the SM. A well-motivated explanation involves a light Z' gauge boson associated with a broken $U(1)_{L_\mu-L_\tau}$ symmetry. Such a boson not only resolves the $(g-2)_\mu$ anomaly, but also induces resonant interactions between high-energy cosmic neutrinos and the cosmic neutrino background (CνB), potentially shaping the observable neutrino flux at Earth. In this work, we explore the implications of such interactions for the cosmic propagation of high-energy neutrinos. We compute the optical depth for neutrino attenuation via Z' -mediated scattering, accounting for neutrino masses, hierarchies, and thermal distributions. We delineate the regions in $(m_{Z'}, m_\nu)$ space where the optical depth exceeds unity, defining a “neutrino cosmic horizon” beyond which high-energy neutrinos are significantly attenuated. We confront these results with the parameter space required to simultaneously explain the muon $g-2$ anomaly and ease the Hubble tension via an additional contribution to the effective number of relativistic degrees of freedom, $\Delta N_{\text{eff}} \simeq 0.2-0.5$. Our analysis reveals a consistent region in parameter space where all three phenomena [$(g-2)_\mu$, N_{eff} , and high-energy neutrino attenuation] can be explained by the same light mediator. These findings motivate future searches for spectral features in IceCube and its next-generation successors as indirect probes of new physics in the neutrino sector.

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I. INTRODUCTION

The anomalous magnetic moment of the muon, defined as $a_\mu \equiv (g_\mu - 2)/2$, has long stood as a precise test of the Standard Model (SM) of particle physics. Recent measurements by the Fermilab Muon $g-2$ experiment [1] continue to show a persistent deviation from SM predictions. When compared to the latest theoretical estimates—including both traditional data-driven and modern lattice QCD approaches—the experimental value exhibits a discrepancy of over 4σ and potentially as high as 5σ depending on the theoretical treatment of the hadronic vacuum polarization (HVP) contribution [2,3]. This anomaly offers tantalizing evidence for physics beyond the SM.

Among the most compelling extensions is the introduction of a new light vector boson, the Z' , arising from a

spontaneously broken $U(1)_{L_\mu-L_\tau}$ gauge symmetry. This model stands out for several reasons: it preserves SM gauge invariance, avoids tight constraints from electron couplings, and naturally generates loop-level contributions to $(g-2)_\mu$ consistent with the observed discrepancy [4,5]. The same Z' boson also mediates interactions in the neutrino sector, potentially leading to observable effects in both astrophysical and cosmological settings.

High-energy astrophysical neutrinos, as observed by IceCube [6], offer a unique probe of such new physics. Unlike photons, which are attenuated over cosmological distances via pair production with background radiation fields, neutrinos typically propagate unimpeded due to their feeble interactions. However, in the presence of a light mediator, high-energy neutrinos may resonantly scatter off the relic cosmic neutrino background (CνB), leading to attenuation features or spectral dips in the observed flux [7,8]. These features are sensitive to both the mediator mass and the absolute neutrino mass scale, offering a rare window into otherwise inaccessible regions of parameter space.

In addition to its particle physics motivations, the $U(1)_{L_\mu-L_\tau}$ model also holds cosmological appeal. A light Z' boson in thermal equilibrium with neutrinos in the early Universe can alter the effective number of relativistic

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degrees of freedom N_{eff} . In particular, values of $\Delta N_{\text{eff}} \simeq 0.2\text{--}0.5$ can alleviate the current tension between early- and late-time measurements of the Hubble constant H_0 [9].

In this work, we investigate whether a single light Z' boson can simultaneously explain the muon $g - 2$ anomaly, the observed high-energy neutrino flux, and the Hubble tension. We focus on the resulting attenuation of PeV-scale neutrinos via resonant scattering on the $C\nu B$, computing the neutrino optical depth as a function of the mediator and neutrino masses. We examine how this attenuation interacts with the allowed regions from $(g - 2)_\mu$ and cosmological constraints, identifying viable parameter space that links together these three seemingly disconnected observations. Our results provide guidance for future searches for spectral features in IceCube and its successors and offer new motivation for exploring the high-energy neutrino sky as a portal to new physics.

II. HIGH-ENERGY ASTROPHYSICAL NEUTRINOS AND IMPLICATIONS FOR NEW PHYSICS

In 2013, the IceCube Neutrino Observatory reported the first observation of high-energy astrophysical neutrinos, marking a significant milestone in neutrino astronomy [6]. Utilizing a cubic-kilometer array of photomultiplier tubes embedded in Antarctic ice, IceCube detected 28 neutrino events with energies ranging from 30 TeV to 1.2 PeV over a two-year period. The statistical significance of this observation exceeded 4σ , effectively ruling out atmospheric backgrounds and confirming the extraterrestrial origin of these neutrinos.

This discovery has spurred extensive theoretical investigations into potential new physics scenarios that could manifest in the high-energy neutrino spectrum. One such avenue involves the introduction of a light Z' gauge boson associated with a broken $U(1)_{L_\mu - L_\tau}$ symmetry. This model not only offers a solution to the longstanding $(g - 2)_\mu$ anomaly but also predicts resonant interactions between high-energy cosmic neutrinos and the cosmic neutrino background. Such interactions could lead to observable features, like dips, in the neutrino energy spectrum detected by IceCube [10].

Further studies have explored the implications of these models for cosmology and neutrino physics. For instance, a gauged $L_\mu - L_\tau$ model with a MeV-scale Z' boson has been proposed to simultaneously address the $(g - 2)_\mu$ discrepancy and the Hubble tension. This model predicts resonance scattering effects that could be probed by current and future neutrino telescopes, such as IceCube-Gen2 [11].

Additionally, alternative explanations involving long-range muon spin forces mediated by axionlike particles have been considered. These models suggest that such forces could influence neutrino oscillations, providing another potential link between high-energy neutrino observations and the $(g - 2)_\mu$ anomaly. Constraints from neutrino

experiments like IceCube, Super-Kamiokande, and SNO have been used to test these scenarios, offering complementary insights into the parameter space of these new physics models [12].

III. THE MUON ANOMALOUS MAGNETIC MOMENT: CURRENT STATUS AND IMPLICATIONS

The anomalous magnetic moment of the muon, defined as $a_\mu = (g_\mu - 2)/2$, serves as a sensitive probe of quantum corrections from both the SM and potential new physics. The most precise experimental measurement to date comes from the Fermilab Muon $g - 2$ experiment (E989), which reported a combined result with the earlier Brookhaven E821 experiment as [13]

$$a_\mu^{\text{exp}} = 116592033(62) \times 10^{-11}, \quad (3.1)$$

showing a deviation from the Standard Model prediction at the level of approximately 4σ .

On the theoretical side, the SM prediction has been refined using two complementary approaches to the HVP contribution:

- (i) Data-driven dispersive methods based on updated $e^+e^- \rightarrow \text{hadrons}$ cross sections now include new CMD-3 results for the $\pi^+\pi^-$ channel. These adjustments have, in fact, increased the tension among previously consistent datasets, ultimately resulting in a slightly larger SM prediction and worsening the discrepancy to over 5σ [2,3],

$$a_\mu^{\text{SM,data}} = 116592070.5(14.8) \times 10^{-11}, \quad (3.2)$$

leading to a persistent excess,

$$\Delta a_\mu^{\text{data}} = a_\mu^{\text{exp}} - a_\mu^{\text{SM,data}} \approx (38.5 \pm 63.7) \times 10^{-11}, \quad (3.3)$$

still significant at more than 4σ and potentially above 5σ when CMD-3-valued cross sections are fully incorporated [2].

- (ii) *Ab initio* lattice QCD calculations have advanced substantially: the latest results from AMD/BMW/DMZ and Mainz report a total leading-order HVP contribution that aligns closely with the experimental value, effectively eliminating the tension. For instance, a recent lattice determination yields $a_\mu^{\text{HVP}} = (724.5 \pm 7.2) \times 10^{-10}$, corresponding to

$$a_\mu^{\text{SM,lattice}} \approx 116592030(10) \times 10^{-11}, \quad (3.4)$$

which lies within 1σ of the experimental measurement [14]. These results significantly reduce or remove the experimental-theory discrepancy while

remaining in tension with the updated data-driven estimates [14,15].

Thus, new lattice results substantially reduce (or even eliminate) the muon $g-2$ anomaly, while data-driven approaches continue to exhibit significant tension due to shifts in the HVP input. Reconciling these divergent methods remains a major challenge. If the discrepancy holds—particularly favoring one method over another—it could suggest physics beyond the Standard Model (BSM). Among the most widely studied BSM scenarios are those involving additional $U(1)$ gauge symmetries, such as $U(1)_{L_\mu-L_\tau}$, which predict a light Z' boson coupling preferentially to muons. These models can explain the observed Δa_μ with a mediator mass in the MeV–GeV range and have implications for neutrino scattering and astrophysical observations [4].

Other viable explanations include scalar leptoquarks, supersymmetric models with light sleptons and neutralinos, and contributions from axionlike particles that couple preferentially to muons (see, e.g., [10] for a review). Each scenario offers distinct experimental signatures at current and future colliders, low-energy fixed-target experiments, and high-precision neutrino observatories. As both experimental and theoretical efforts converge, the muon $g-2$ anomaly remains a compelling target in the search for new physics.

IV. THE NEUTRINO COSMIC HORIZON

The cosmic horizon for high-energy neutrinos is governed by their interactions with the relic neutrino background and other diffuse photon fields. Unlike photons, which are strongly attenuated by interactions with the cosmic microwave background (CMB) and extragalactic background light, neutrinos interact only via weak interactions, resulting in extremely long mean free paths even at PeV–EeV energies.

The dominant energy-loss process for high-energy photons is pair production off background photons, particularly, $\gamma + \gamma_{\text{CMB}} \rightarrow e^+ + e^-$. This sets a horizon of ~ 100 Mpc for TeV–PeV photons, beyond which the Universe becomes effectively opaque [16]. In contrast, the mean free path for neutrinos due to scattering off the C ν B, such as through the resonant process $\nu + \bar{\nu} \rightarrow Z$, known as the Glashow resonance, is many orders of magnitude larger—typically on the scale of gigaparsecs for neutrinos below $\sim 10^{22}$ eV [17,18].

The neutrino horizon is further modified in new physics scenarios involving secret neutrino interactions or light mediators, which can introduce resonant absorption features in the neutrino spectrum [8]. In such models, the neutrino mean free path can be significantly reduced, leading to observable distortions in the flux measured by detectors like IceCube. This has been proposed as a potential explanation for dips or cutoffs in the observed spectrum and even as a probe of neutrino mass generation mechanisms [7].

While both photons and neutrinos experience energy-dependent attenuation from cosmological backgrounds, their interaction cross sections differ by many orders of magnitude. High-energy neutrinos can reach us from redshifts $z \gtrsim 1$, providing a unique window into the high-energy Universe, including sources inaccessible to photons due to electromagnetic opacity.

V. NEUTRINO MASSES AND MIXING

The discovery of neutrino oscillations provided the first clear evidence that neutrinos have mass, requiring an extension of the SM, which originally assumed them to be massless. Oscillations arise from a misalignment between flavor and mass eigenstates, encoded in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. The unitary PMNS matrix is parametrized by three mixing angles ($\theta_{12}, \theta_{23}, \theta_{13}$), one Dirac CP -violating phase δ_{CP} , and, if neutrinos are Majorana particles, two additional Majorana phases.

Oscillation experiments measure mass-squared differences and mixing angles, but not the absolute neutrino mass scale. The best-fit values from global analyses yield the following parameters for the normal mass ordering [19]:

$$\Delta m_{21}^2 = (7.42 \pm 0.21) \times 10^{-5} \text{ eV}^2, \quad (5.1)$$

$$\Delta m_{31}^2 = (2.517 \pm 0.028) \times 10^{-3} \text{ eV}^2, \quad (5.2)$$

$$\sin^2 \theta_{12} = 0.304 \pm 0.012, \quad (5.3)$$

$$\sin^2 \theta_{23} = 0.573^{+0.016}_{-0.020}, \quad (5.4)$$

$$\sin^2 \theta_{13} = 0.02219 \pm 0.00062. \quad (5.5)$$

The CP -violating phase δ_{CP} is weakly constrained, with a best-fit near 195° , although large uncertainties remain [19].

While oscillation data determine the differences in the squared masses, the absolute neutrino mass scale remains unknown. Constraints arise from β decay end point experiments, such as KATRIN, which reports an upper limit of $m_\beta < 0.8$ eV at 90% C.L. [20], and from cosmological observations. The *Planck* satellite, combined with baryon acoustic oscillation data, sets an upper bound on the sum of neutrino masses $\sum m_\nu < 0.12$ eV at 95% C.L. [21].

From a theoretical perspective, the smallness of neutrino masses is naturally explained via the seesaw mechanism, in which heavy right-handed neutrinos (or other sterile states) couple to left-handed neutrinos through Yukawa interactions, generating light Majorana masses after electroweak symmetry breaking. Several variants exist, including type-I, type-II, and inverse seesaw models, each with distinct implications for lepton number violation and collider phenomenology [22,23].

Ongoing and upcoming experiments, such as JUNO, DUNE, and Hyper-Kamiokande, aim to determine the neutrino mass ordering, improve sensitivity to δ_{CP} , and further constrain the mixing parameters, potentially opening a window into physics beyond the Standard Model.

VI. RESULTS

To determine the survival probability of high-energy neutrinos, we compute their optical depth τ_ν , defined in Eq. (6.2). The optical depth is calculated based on the integrated neutrino- Z' scattering cross section, assuming a thermal distribution for the $C\nu B$.

We sum over final-state spins and flavors. Since both the high-energy neutrinos and the $C\nu B$ are nearly flavor universal, and the Z' couples only to the μ and τ sectors, we consider $i = j = \mu, \tau$ in Eq. (6.7). This introduces a multiplicity factor of 2 in the relevant cross section,

$$\sigma_{\nu_i} = \sum_j \sigma(\nu_i \bar{\nu}_j \rightarrow \nu \bar{\nu}). \quad (6.1)$$

The total optical depth is then given by

$$\tau_\nu = \left(\frac{n_\nu}{H_0} \right) \sum \sigma_{\nu_i}, \quad (6.2)$$

where n_ν is the number density of the background neutrinos and H_0 is the Hubble parameter today. We assume both normal and inverted neutrino mass hierarchies. For each value of the neutrino mass scale m_ν , the individual masses are given by

$$\begin{aligned} \text{normal hierarchy: } m_1 &= m_\nu, & m_2 &= m_1 + \sqrt{\Delta m_{21}^2}, \\ m_3 &= m_2 + \sqrt{\Delta m_{31}^2}, \end{aligned} \quad (6.3)$$

$$\begin{aligned} \text{inverted hierarchy: } m_1 &= m_\nu, & m_2 &= m_1 + \sqrt{\Delta m_{31}^2}, \\ m_3 &= m_2 + \sqrt{\Delta m_{21}^2}. \end{aligned} \quad (6.4)$$

Note that our mass parametrization differs from the standard physics convention: In our Eqs. (6.3) and (6.4), we define m_ν as the lightest mass in both hierarchies and use additive relationships for simplicity. The resulting *Planck* constraints [21] then are, explicitly,

For normal hierarchy (6.3): $m_1 = m_\nu$, $m_2 = m_1 + \sqrt{\Delta m_{21}^2}$, $m_3 = m_2 + \sqrt{\Delta m_{31}^2}$,

$$\begin{aligned} \sum m_\nu &= m_\nu + \left(m_\nu + \sqrt{\Delta m_{21}^2} \right) \\ &\quad + \left(m_\nu + \sqrt{\Delta m_{21}^2} + \sqrt{\Delta m_{31}^2} \right) \\ &= 3m_\nu + 2\sqrt{\Delta m_{21}^2} + \sqrt{\Delta m_{31}^2} \\ &\approx 3m_\nu + 2(0.0086) + 0.050 = 3m_\nu + 0.067 \text{ eV}. \end{aligned} \quad (6.5)$$

This gives $m_\nu < (0.12 - 0.067)/3 = 0.018 \text{ eV}$.

For inverted hierarchy (6.4): $m_1 = m_\nu$, $m_2 = m_1 + \sqrt{\Delta m_{31}^2}$, $m_3 = m_2 + \sqrt{\Delta m_{21}^2}$,

$$\begin{aligned} \sum m_\nu &= m_\nu + \left(m_\nu + \sqrt{\Delta m_{31}^2} \right) \\ &\quad + \left(m_\nu + \sqrt{\Delta m_{31}^2} + \sqrt{\Delta m_{21}^2} \right) \\ &= 3m_\nu + 2\sqrt{\Delta m_{31}^2} + \sqrt{\Delta m_{21}^2} \\ &\approx 3m_\nu + 2(0.050) + 0.0086 = 3m_\nu + 0.109 \text{ eV}. \end{aligned} \quad (6.6)$$

This gives $m_\nu < (0.12 - 0.109)/3 = 0.004 \text{ eV}$.

In our framework, the independent parameter is the lightest neutrino mass eigenvalue $m_{\nu,\min}$, while the remaining two eigenmasses are reconstructed using the measured mass splittings. The impact of this constraint on the optical depth is twofold. First, it removes portions of the parameter space where large values of τ_ν might otherwise appear attainable at very small m_ν . Second, because the resonance condition for neutrino-neutrino scattering depends on the center-of-mass kinematics, which, in turn, depends on the target neutrino mass through $s = m_j^2 + 2E_\nu(E_j - p \cos \theta)$, the cosmological lower bound effectively limits how far into the relativistic-target regime one can move. In practice, this truncation reduces the extent of the region where $\tau_\nu > 1$ is realized, particularly at lower mediator masses.

We emphasize that our choice of parametrizing the neutrino sector in terms of the lightest eigenvalue is made for consistency with the optical-depth calculation, which explicitly sums over mass eigenstates with fixed splittings. An alternative and commonly used cosmological parametrization would impose bounds directly on the sum of masses, $\sum m_\nu$. While such a treatment would modify the precise shape of the excluded region—and would typically yield slightly less restrictive horizontal bounds in the $(m_{Z'}, m_\nu)$ plane—it would not alter our qualitative conclusions regarding the structure of the viable parameter space or the location of the $\tau_\nu \sim 1$ contours.

The Z' -mediated neutrino scattering cross section (neglecting PMNS rotation) is given by

$$\sigma(\nu_i \bar{\nu}_j \rightarrow \nu \bar{\nu}) = \frac{2g_{Z'}^4 s}{3\pi[(s - m_{Z'}^2)^2 + m_{Z'}^2 \Gamma_{Z'}^2]}, \quad (6.7)$$

where s is the center-of-mass energy squared, $m_{Z'}$ is the Z' mass, and $\Gamma_{Z'}$ is its decay width [10]. The latter is given by

$$\Gamma_{Z'} = \frac{g_{Z'}^2 m_{Z'}}{12\pi} \sum_{i=\mu,\tau} \left(1 + 2 \frac{m_i^2}{m_{Z'}^2}\right) \sqrt{1 - 4 \frac{m_i^2}{m_{Z'}^2}} \Theta(m_{Z'} - 2m_i), \quad (6.8)$$

where the sum runs over muon and τ flavors, and Θ is the Heaviside step function ensuring kinematically allowed decays. For the parameter ranges considered in this work, the Z' boson can decay to both muon and τ neutrino pairs, with $\Gamma_{Z'} \approx g_{Z'}^2 m_{Z'}/(6\pi)$.

A crucial technical point in the optical-depth calculation concerns the nonzero temperature of the C ν B. At the smallest neutrino masses, neglecting the thermal motion of the background neutrinos leads to an incorrect determination of the center-of-mass energy and, consequently, of the resonant scattering rate.

Today the C ν B temperature is $T_{\nu,0} \simeq 1.7 \times 10^{-4}$ eV, corresponding to typical thermal momenta $p_{\text{th}} \sim \mathcal{O}(3T_{\nu,0}) \sim 5 \times 10^{-4}$ eV. For neutrino masses in the sub-meV regime, the background neutrinos are therefore semirelativistic, and their momentum distribution cannot be approximated by a fixed target at rest. In this regime, the dominant contribution to the scattering rate arises from the convolution of the Breit-Wigner resonance structure with the full Fermi-Dirac momentum distribution.

The thermally averaged cross section for scattering between a high-energy neutrino of energy E and background neutrinos is

$$\langle \sigma \rangle = \frac{2g_{Z'}^4}{3\pi} I_{\text{thermal}}(m_{Z'}, \Gamma_{Z'}, E, T_{\nu,0}), \quad (6.9)$$

where

$$I_{\text{thermal}} = \frac{\int_0^\infty dp \int_{-1}^{+1} d\mu \frac{s(p,\mu)}{[s(p,\mu) - m_{Z'}^2]^2 + m_{Z'}^2 \Gamma_{Z'}^2} f(p) p^2}{\int_0^\infty f(p) p^2 dp}. \quad (6.10)$$

Here

$$s(p,\mu) = m_\nu^2 + 2E \left(\sqrt{p^2 + m_\nu^2} - p\mu \right),$$

$$f(p) = \frac{1}{e^{p/T_{\nu,0}} + 1}, \quad (6.11)$$

and $\mu = \cos \theta$ is the scattering angle. The angular integration can be performed analytically, while the momentum integral must be evaluated numerically.

The behavior of I_{thermal} is controlled by the relation between the resonance momentum

$$p_{\text{res}} \sim \frac{m_{Z'}^2}{2E} \quad (6.12)$$

and the thermal scale $T_{\nu,0}$. If $p_{\text{res}} \lesssim T_{\nu,0}$, the resonance lies within the bulk of the thermal distribution and the integral is unsuppressed. Conversely, when $p_{\text{res}} \gg T_{\nu,0}$, only the exponentially suppressed tail of the Fermi-Dirac distribution can contribute, and the cross section is strongly damped.

This feature implies that the optical depth does not depend primarily on the neutrino rest mass at small m_ν , but rather on the ratio $m_{Z'}^2/(ET_{\nu,0})$. In particular, naive estimates that replace the momentum integral by a fixed characteristic value (e.g., $p \sim 3T_{\nu,0}$) or that neglect the angular dependence can misestimate the scattering rate by many orders of magnitude. A proper thermal average over both momentum and angle is therefore essential for a consistent determination of the resonant structure and of the $\tau_\nu \sim 1$ contours in the parameter space.

Figure 1 presents the two-dimensional parameter space in the $(\log_{10} m_{Z'}, \log_{10} m_{\nu,\text{min}})$ plane, showing contours of the optical depth τ_ν computed using the full thermal average over the C ν B. As emphasized above, the relevant dynamical scale controlling resonant scattering is not the neutrino rest mass itself, but the ratio $m_{Z'}^2/(ET_{\nu,0})$, which determines whether the resonance lies within the thermally populated region of the background distribution. The white dashed horizontal lines indicate the cosmological upper bounds on the lightest neutrino mass for the normal and inverted hierarchies, respectively. These bounds remove the upper portions of the parameter space in Fig. 1, leaving only the lower-mass region phenomenologically viable. Note that the figure would shift if different neutrino energies were chosen, as we show in Fig. 2 explicitly: For a neutrino energy E_ν , the center-of-mass energy squared is approximately $s \approx 2E_\nu m_\nu$ (for $E_\nu \gg m_\nu$), so the resonance occurs when $m_{Z'} \approx \sqrt{2E_\nu m_\nu}$. Higher energies would shift the resonance bands to higher Z' masses for fixed neutrino mass.

Figure 3 provides one-dimensional cutouts of $\log_{10}(\tau_\nu)$ as a function of $m_{Z'}$ for fixed values of the lightest neutrino mass, shown separately for the normal and inverted hierarchies. These curves make explicit the resonant structure responsible for the contours seen in Fig. 1. For small $m_{Z'}$, the resonance occurs at momenta comparable to or below the thermal scale $T_{\nu,0}$, leading to large optical depths. As $m_{Z'}$ increases, the required resonance momentum $p_{\text{res}} \simeq m_{Z'}^2/(2E)$ moves into the exponentially suppressed tail of the Fermi-Dirac distribution, and τ_ν decreases rapidly. The sharp peaks visible in Fig. 3 correspond to the narrow range where the resonance condition overlaps with the thermally populated region.

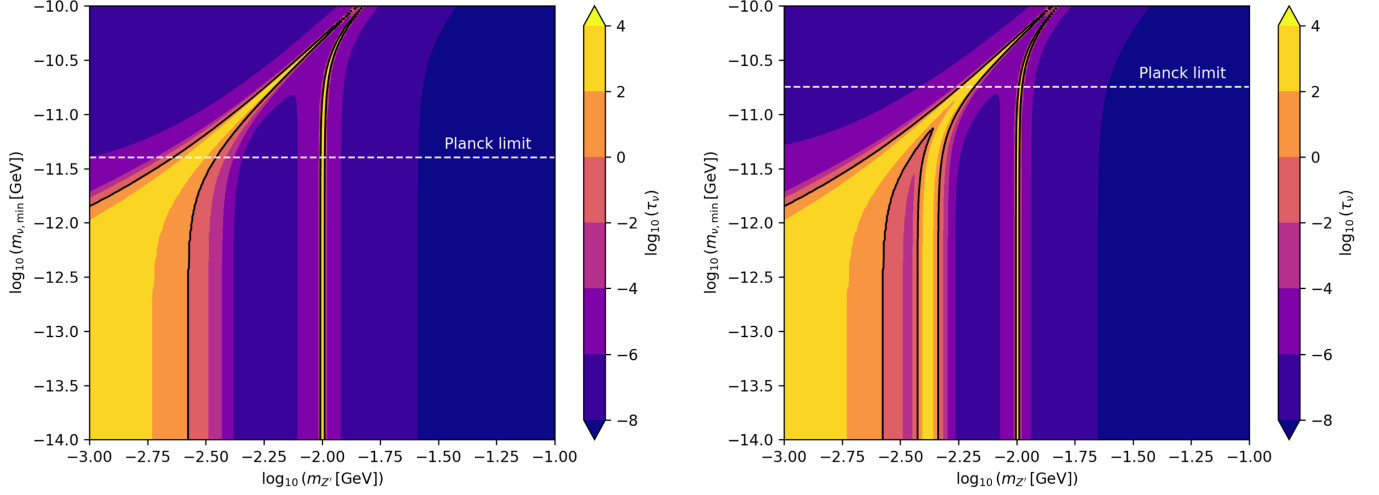


FIG. 1. Optical depth $\log_{10}(\tau_\nu)$ as a function of $m_{Z'}$ and m_ν for the normal (left) and inverted (right) neutrino mass hierarchies. We computed the optical depth for PeV-scale neutrinos ($E_\nu \sim 10^{15}$ eV), which corresponds to the energy range of the highest-energy neutrinos observed by IceCube. Yellow bands correspond to regions where $\tau_\nu \gtrsim 1$. The regions above the white dashed lines are ruled out by cosmology [21].

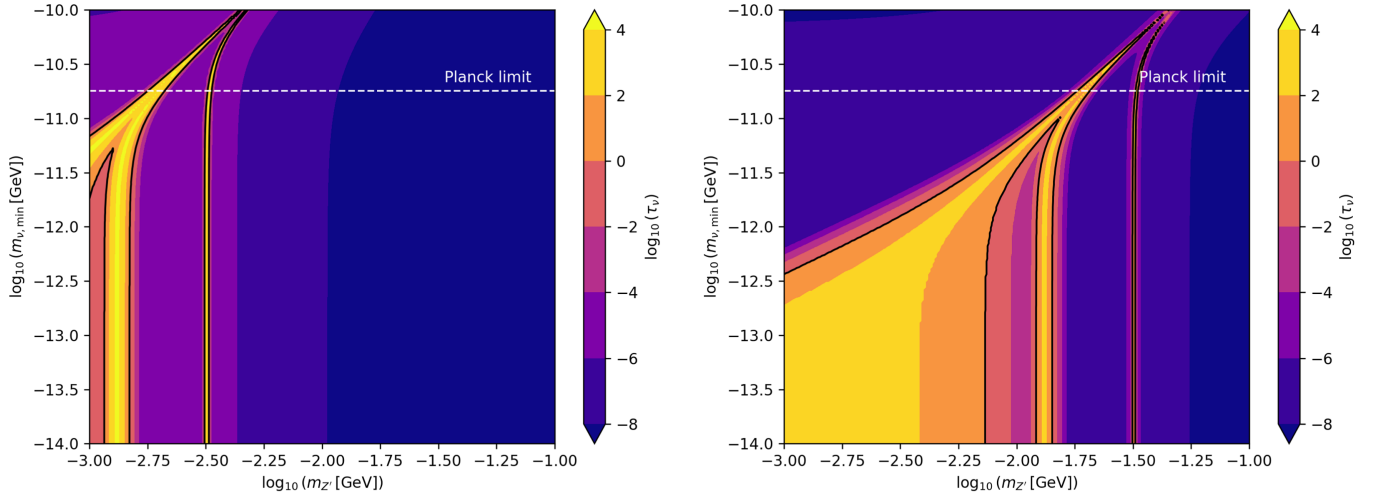


FIG. 2. As in Fig. 1, but for an impinging neutrino energy of 0.1 PeV (left) and 10 PeV (right), for the normal hierarchy.

Importantly, the comparison between Figs. 1 and 3 demonstrates that the optical depth is controlled, at small masses, by the thermal distribution rather than by a naive scaling with the neutrino mass. While m_ν still enters through the kinematics and the hierarchy-dependent mass splittings, its role is secondary once the full thermal averaging is implemented. The dominant physical effect is instead the interplay between the mediator mass, the neutrino energy, and the CMB temperature. This clarifies the origin of the resonant structure and resolves the concern raised regarding the treatment of the background temperature.

We compare these results to constraints and preferred regions from other cosmological and particle physics observations. In particular, we compute the gauge coupling $g_{Z'}$ required to explain the observed muon anomalous

magnetic moment Δa_μ as a function of $m_{Z'}$ using

$$\Delta a_\mu(m_{Z'}, g_{Z'}) = \frac{g_{Z'}^2 m_\mu^2}{4\pi^2 m_{Z'}^2} \int_0^1 \frac{x^2(1-x)dx}{1-x + \left(\frac{m_\mu^2}{m_{Z'}^2}\right)x^2}, \quad (6.13)$$

which can be inverted to express the required coupling,

$$g_{Z'}(m_{Z'}, \Delta a_\mu) = \left(\frac{m_\mu^2}{4\pi^2 m_{Z'}^2 \Delta a_\mu} \int_0^1 \frac{x^2(1-x)dx}{1-x + \left(\frac{m_\mu^2}{m_{Z'}^2}\right)x^2} \right)^{-1/2}. \quad (6.14)$$

Figure 4 synthesizes the various constraints in the $(\log_{10} m_{Z'}, \log_{10} g_{Z'})$ plane and illustrates explicitly the

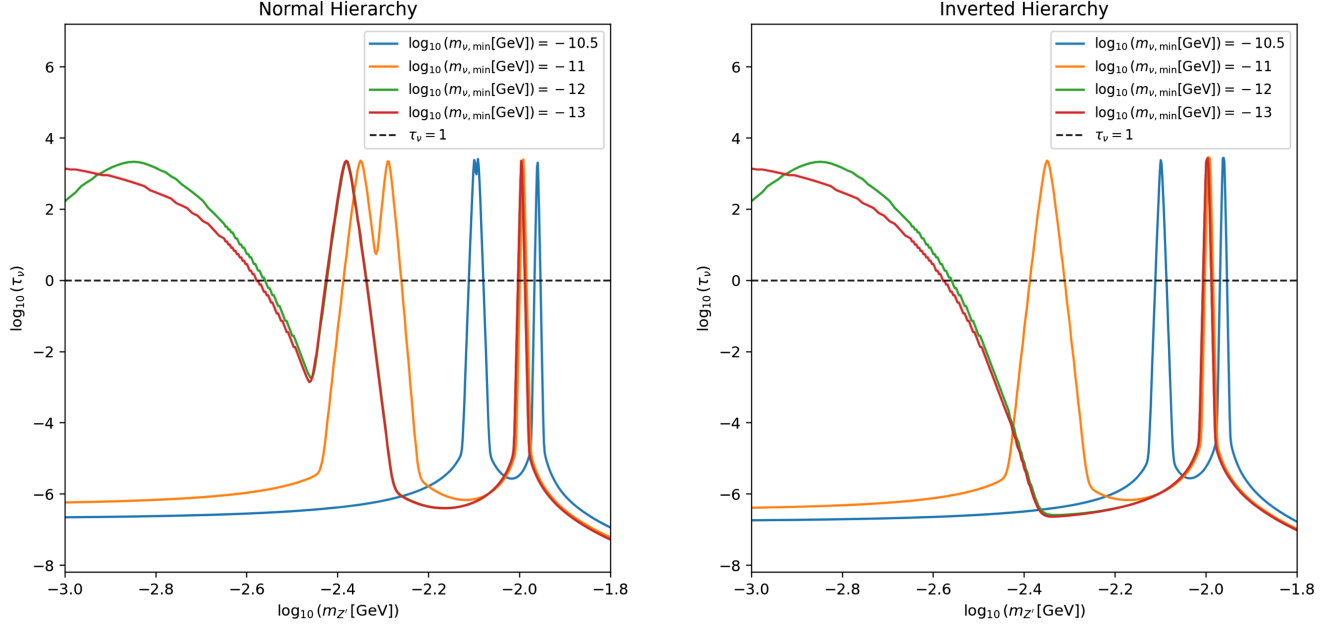


FIG. 3. Cutouts of the optical depth $\log_{10}(\tau_\nu)$ as a function of $\log_{10}(m_{Z'}[\text{GeV}])$ for fixed values of the lightest neutrino mass. The normal hierarchy is shown on the left, and the inverted hierarchy is shown on the right. Colored curves correspond to $\log_{10}(m_{\nu,\text{min}}[\text{GeV}]) = -10.5, -11, -12$, and -13 , as indicated in the legend. The horizontal dashed line denotes $\tau_\nu = 1$. Sharp peaks arise when the resonance condition $m_{Z'}^2 \simeq 2Ep$ is satisfied within the thermally populated region of the cosmic neutrino background. For sufficiently small $m_{Z'}$, the resonance momentum lies below the thermal scale and the optical depth becomes large; whereas for larger $m_{Z'}$ the required resonance momentum exceeds the characteristic thermal momentum, leading to exponential suppression from the tail of the Fermi-Dirac distribution. The position and width of the peaks therefore reflect the interplay between the mediator mass, the neutrino energy, and the $C\nu B$ thermal scale rather than a simple dependence on the neutrino rest mass alone.

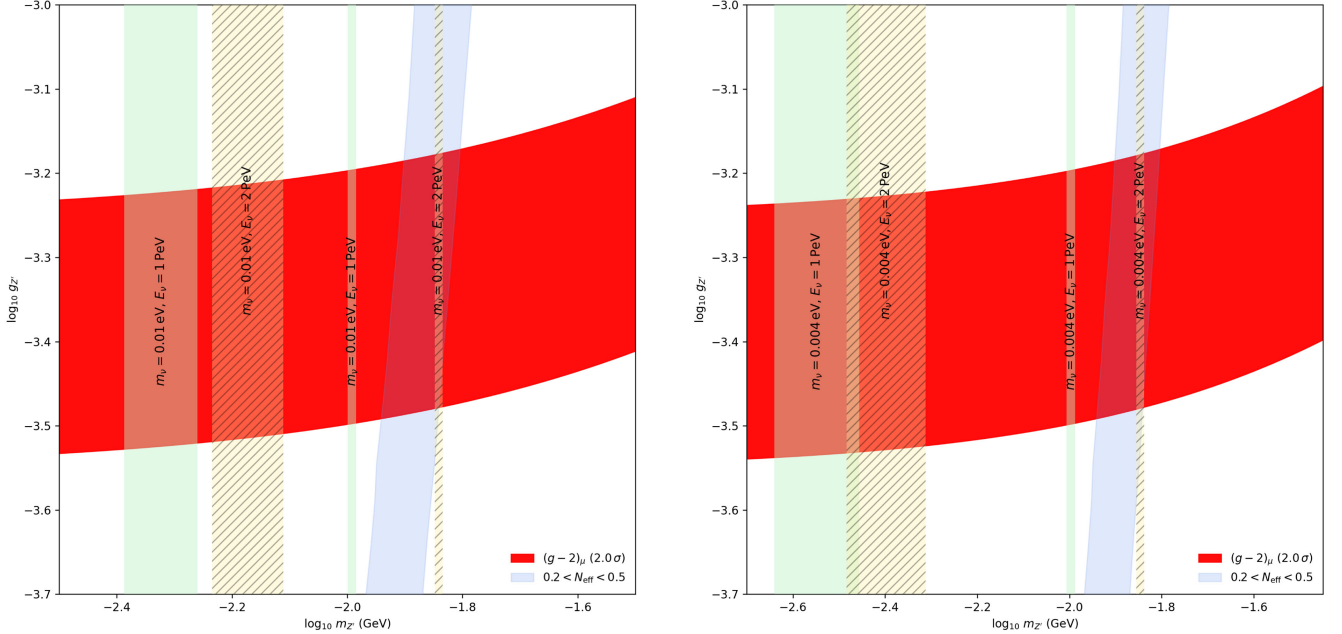


FIG. 4. Parameter space in the $(\log_{10} m_{Z'}, \log_{10} g_{Z'})$ plane showing the $(g-2)_\mu$ 2σ preferred region (red) and the region where $0.2 < \Delta N_{\text{eff}} < 0.5$ (light blue). Superimposed vertical bands indicate the ranges of mediator mass $m_{Z'}$ for which the optical depth satisfies $\tau_\nu > 1$ for selected values of the lightest neutrino mass and representative neutrino energies. The band widths reflect the resonance condition and the full thermal averaging over the cosmic neutrino background. The overlap (or lack thereof) between these bands and the $(g-2)_\mu$ region illustrates the degree to which efficient high-energy neutrino attenuation can occur within phenomenologically viable couplings.

interplay between neutrino attenuation, the $(g-2)_\mu$ anomaly, and the ΔN_{eff} region. The red band denotes the $(g-2)_\mu$ preferred region at 2σ , obtained by inverting the measured Δa_μ for each value of $m_{Z'}$. The light blue band corresponds to the region where $0.2 < \Delta N_{\text{eff}} < 0.5$, which is of interest for alleviating the Hubble tension.

Superimposed on these regions are vertical bands indicating the ranges of $m_{Z'}$ for which the optical depth satisfies $\tau_\nu > 1$ for selected values of the lightest neutrino mass and representative neutrino energies, respectively, 1 and 2 PeV. The bands are vertical because, once $g_{Z'}(m_{Z'})$ is fixed by the $(g-2)_\mu$ inversion, the optical-depth condition effectively selects a restricted interval in mediator mass. The width of each band reflects the resonant condition together with the thermal averaging over the cosmic neutrino background.

Several features are apparent. First, for $E_\nu \sim \mathcal{O}(\text{PeV})$, the $\tau_\nu > 1$ bands lie at mediator masses near $m_{Z'} \sim 10^{-2} \text{ GeV}$, corresponding to resonance momenta $p_{\text{res}} \simeq m_{Z'}^2/(2E_\nu)$ that fall within the thermally populated region of the background distribution. As E_ν increases, the resonance condition shifts to larger $m_{Z'}$, and the corresponding vertical bands move accordingly.

Second, the overlap between the $\tau_\nu > 1$ bands and the red $(g-2)_\mu$ region is highly sensitive to both the neutrino mass and the neutrino energy. For some combinations, the attenuation region partially intersects the $(g-2)_\mu$ preferred band, implying that efficient high-energy neutrino absorption can occur within phenomenologically viable couplings. In other cases, the $\tau_\nu > 1$ bands lie entirely outside the red region, indicating that significant attenuation would require couplings incompatible with the muon anomalous magnetic moment constraint.

Third, the comparison with the light blue ΔN_{eff} region shows that the parameter space capable of modifying early-Universe radiation content does not generically coincide with the region where high-energy neutrino attenuation is efficient. The degree of overlap depends on the hierarchy and on the assumed neutrino mass. This demonstrates that the cosmological and astrophysical effects probe complementary, and in some cases disjoint, regions of parameter space.

Overall, Fig. 4 highlights the nontrivial interplay between laboratory constraints, cosmological considerations, and high-energy astrophysical observables. The vertical structure of the attenuation bands reflects the thermal origin of the resonance, controlled primarily by the ratio $m_{Z'}^2/(E_\nu T_{\nu,0})$, rather than by the neutrino rest mass alone. This reinforces the importance of the full thermal averaging procedure in determining the viable regions of the model.

VII. DISCUSSION AND CONCLUSIONS

In this work, we have revisited resonant neutrino scattering in a $U(1)_{L_\mu-L_\tau}$ framework, focusing on its

implications for the optical depth of high-energy neutrinos propagating through the CMB. While similar mediator scenarios have been studied previously (e.g., Ref. [11]), our analysis introduces several technical refinements and presents the results in a framework that clarifies the role of absolute neutrino mass and thermal effects.

The central methodological improvement of this work is the implementation of a fully thermal-averaged cross section. Instead of approximating the center-of-mass energy using $s \simeq 2m_\nu E_\nu$, we perform the complete integration over the Fermi-Dirac momentum distribution and the angular dependence of the background neutrinos. This correction becomes essential when the neutrino rest mass is comparable to or smaller than the thermal momentum scale $T_{\nu,0}$. In this regime, the resonance structure is governed not by m_ν alone but by the ratio $m_{Z'}^2/(E_\nu T_{\nu,0})$, and the cross section can be exponentially suppressed when the required resonance momentum lies in the high-momentum tail of the distribution.

As a result, the optical depth at small m_ν behaves qualitatively differently from naive treatments that neglect thermal motion. This modifies both the scaling of τ_ν and the interpretation of the allowed parameter space. In particular, we find that the resonance structure in Fig. 1 is controlled by thermal kinematics at small mass, while at larger m_ν the conventional rest-mass scaling is recovered.

Our presentation emphasizes the optical depth τ_ν itself as the primary observable quantity. Figure 1 maps τ_ν in the $(\log_{10} m_{Z'}, \log_{10} m_{\nu,\text{min}})$ plane for fixed energies, revealing structure that is not immediately visible in traditional $(m_{Z'}, g_{Z'})$ plots. Figures 2 and 3 provide complementary energy-resolved visualizations and cutouts, illustrating how the resonance position and width shift with neutrino energy and absolute mass scale. The comparison between normal and inverted hierarchies shows that the hierarchy dependence is modest at small masses once thermal averaging is included, but becomes more pronounced at larger m_ν .

Figure 4 synthesizes these ingredients by overlaying the regions favored by $(g-2)_\mu$, those consistent with $0.2 < \Delta N_{\text{eff}} < 0.5$, and the bands where $\tau_\nu > 1$ for representative neutrino masses and energies. We find that nonempty regions of parameter space exist where all three conditions can be simultaneously satisfied. However, the existence and location of such regions depend sensitively on both the lightest neutrino mass and the energy of the propagating neutrino. For smaller lightest neutrino masses m_ν , thermal suppression shifts or narrows the $\tau_\nu > 1$ bands, while increasing the neutrino energy moves the resonance condition and can restore overlap with the cosmologically and $(g-2)_\mu$ preferred regions.

In this sense, the viability of a significant cosmic neutrino opacity is not a universal prediction of the model, but rather a conditional statement tied to the absolute neutrino mass scale and the energy spectrum of astrophysical neutrinos. The parameter space compatible with

$(g-2)_\mu$, ΔN_{eff} , and $\tau_\nu > 1$ is therefore structured and energy dependent, rather than generic.

We have also incorporated updated cosmological limits on the sum of neutrino masses and made explicit how they intersect the optical-depth structure. These constraints further restrict the allowed parameter space in a hierarchy-dependent manner.

Taken together, our results demonstrate that a consistent thermal treatment of the C ν B is essential for interpreting resonant neutrino scattering in the sub-eV mass regime. While the underlying mediator framework overlaps with earlier work, the combination of (i) a complete thermal average, (ii) a systematic mapping of optical depth as a function of absolute neutrino mass, (iii) explicit hierarchy comparisons, (iv) energy-resolved analyses, and (v) updated cosmological overlays yields quantitatively distinct

conclusions and a clearer picture of the physically viable parameter space.

Future improvements in measurements of the absolute neutrino mass scale, together with high-statistics observations of PeV-scale astrophysical neutrinos, will be essential in further testing this scenario and refining the interplay between particle physics, cosmology, and neutrino astronomy.

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DATA AVAILABILITY

No data were created or analyzed in this study.

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