

Constraining ultralight vector bosons via solar neutrino oscillations: The gauged $L_\mu - L_\tau$ model and prospects for JUNO and XLZD

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We present an extension of the Standard Model based upon the gauged $U(1)_{L_\mu - L_\tau}$ symmetry, featuring an ultralight vector boson that couples to the difference of muon and tau lepton numbers. This anomaly-free construction, whilst historically motivated by the muon's anomalous magnetic moment, is here employed as an independent phenomenological framework for solar neutrino physics. Through kinetic mixing with the photon, the Z' boson generates an effective matter potential within the solar interior, thereby modifying neutrino flavor oscillations via the Mikheyev-Smirnov-Wolfenstein mechanism. Utilizing recent solar neutrino measurements from Borexino, SNO, and Super-Kamiokande, together with an up-to-date solar standard model, we constrain the boson mass to be below 5.7×10^{-17} eV, positioning it as a potential ultralight dark matter candidate. The optimal model, corresponding to a coupling parameter $\eta_o \approx -2$, yields $\chi^2_\nu = 2.7$, which compares favorably with the standard three-flavor scenario ($\chi^2_\nu = 3.1$). This best-fit configuration corresponds to an effective four-fermion coupling $g_{Z'}^2 \epsilon / m_{Z'}^2 \approx 6.6 \times 10^{-23}$ eV⁻², approximately 5.7 times the Fermi constant, which for $\epsilon \approx 1$ and a reference mediator mass of 1 eV is equivalent to a gauge coupling $g_{Z'} \approx 8 \times 10^{-12}$. We furthermore present projections for forthcoming experiments. The Jiangmen Underground Neutrino Observatory (JUNO), which commenced operations in August 2025 and has already achieved world-leading precision in oscillation parameter measurements, together with the XLZD consortium, should substantially refine these constraints. Such ultralight particles may address long-standing discrepancies in galaxy simulations within the cold dark matter paradigm, and recent theoretical developments demonstrate their compatibility with nonthermal dark matter production mechanisms. Additionally, terrestrial long-baseline neutrino experiments provide complementary probes of this parameter space.

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I. INTRODUCTION

In recent years, our comprehension of the Universe has been subjected to rigorous scrutiny, driven by breakthroughs in particle physics experiments alongside cosmological and astrophysical observations. Within this context, the standard model of elementary particles and fundamental interactions finds itself under considerable examination, motivating physicists to explore theoretical frameworks that extend beyond the conventional paradigm.

The dark matter problem remains amongst the most compelling motivations for physics beyond the Standard

Model [1–5]. Despite decades of experimental effort, the fundamental nature of dark matter remains elusive, and its existence is inferred solely through gravitational effects on cosmological and galactic scales. Ultralight bosonic particles represent a particularly intriguing class of dark matter candidates, capable of addressing several outstanding puzzles in structure formation [6].

The present study focuses on neutrinos, which occupy a rather singular position amongst fundamental particles owing to their distinctive behavior and the many unresolved mysteries they present [see, e.g., [7–9]]. It is precisely for this reason that a new generation of diverse neutrino experiments is now underway [9,10], with the aim of determining neutrino parameters and characteristics to unprecedented accuracy, particularly those pertaining to the three-neutrino flavor oscillation model. This unique experimental landscape positions neutrino physics as an invaluable instrument for exploring new particles and interactions beyond the standard model.

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In light of these experimental advancements, the scientific community has been motivated to formulate a considerable variety of neutrino models [see, e.g., [11–17]], commonly referred to as nonstandard interaction (NSI) models. These theoretical constructions are poised for rigorous evaluation by the forthcoming generation of neutrino detectors [9,10].

This article presents a nonstandard interaction model based on the gauged $U(1)_{L_\mu-L_\tau}$ symmetry, featuring a vector boson whose mass may range from ultralight to massive. Unlike models that rely on complex baryon-number-dependent charge assignments, the $L_\mu - L_\tau$ gauge symmetry is naturally anomaly free without requiring new fermions or *ad hoc* charge assignments [18]. The charge assignments under this symmetry are elegantly simple: the muon sector (ν_μ, μ) carries charge +1, the tau sector (ν_τ, τ) carries charge −1, whilst the electron sector and all quarks remain uncharged. This model was historically motivated by hints of lepton-flavor-universality violation in B -meson decays and the muon’s anomalous magnetic moment. It is worth noting, however, that the experimental and theoretical landscape has evolved considerably since these anomalies were first identified. The LHCb Collaboration’s improved measurements of R_K and R_{K^*} , announced in December 2022, are now consistent with the Standard Model within 1σ [19]. Similarly, the Fermilab Muon $g-2$ experiment’s final measurement, combined with advances in lattice QCD calculations, has essentially eliminated the previously reported discrepancy between theory and experiment [20]. Consequently, whilst these historical anomalies provided the original impetus for the model, its current utility lies in its unique ability to explain dark matter phenomenology and potential long-range forces in the neutrino sector. Our present analysis examines its application to neutrino-plasma interactions in the Sun’s interior, thereby establishing an independent phenomenological testing ground.

Through our investigation, we determine the ideal mass range for these bosons that ensures alignment with existing solar neutrino experimental measurements [see, e.g., [9,21]]. Our analysis identifies the boson as an ultralight particle. We furthermore project the potential constraints on this model by drawing upon the expected accuracy of forthcoming solar neutrino experiments [e.g., [22]], most notably those from the DARWIN/XLZD [23,24] and JUNO [25–27] Collaborations.

The identification of the boson as an ultralight particle constitutes a significant finding, one that offers potential solutions to several outstanding astrophysical and cosmological problems. Such a boson presents itself as a promising dark matter candidate [6], with implications for the cosmic evolution of the Universe. Additionally, it may contribute towards resolving the solar abundance problem [see, e.g., [28,29]], a persistent inconsistency amongst solar models, observed neutrino fluxes, and helioseismic

observations that has resisted resolution despite considerable effort over the past two decades. Furthermore, recent phenomenological developments have demonstrated that the $L_\mu - L_\tau$ model can accommodate nonthermal dark matter production and leptogenesis [30], potentially explaining the baryon asymmetry of the Universe.

II. MODEL OVERVIEW

Here, we expand upon the Lagrangian of the standard model by introducing the gauged $U(1)_{L_\mu-L_\tau}$ symmetry, accompanied by a lightweight gauge boson Z' that couples to the difference of muon and tau lepton numbers. Since the first generation of leptons and all quarks have zero charge under this symmetry, the Z' boson does not directly couple to the dominant matter in the Sun. To generate a matter potential relevant for solar neutrinos, this model relies on *kinetic mixing* between the Z' field tensor and the electromagnetic field tensor. The interaction Lagrangian is given by [18]

$$\mathcal{L}_{Z'} = g_{Z'} Z'_\alpha (\bar{\mu} \gamma^\alpha \mu - \bar{\tau} \gamma^\alpha \tau + \bar{\nu}_\mu \gamma^\alpha \nu_\mu - \bar{\nu}_\tau \gamma^\alpha \nu_\tau) + \frac{\epsilon}{2} F^{\mu\nu} Z'_{\mu\nu}, \quad (1)$$

where $g_{Z'}$ is the coupling constant and ϵ is the kinetic mixing parameter. Due to the kinetic mixing term, the Z' boson acquires a coupling to the electromagnetic current proportional to ϵe . Consequently, the dense plasma of protons and electrons in the Sun generates a nonzero potential for the neutrinos. This potential distinguishes clearly between ν_μ and ν_τ , generating a diagonal potential matrix $\text{diag}(0, V, -V)$ in the flavor basis. For a light mediator, finite-size effects of the matter distribution are captured by the convolution $W_i(r)$ ($i = e, p$) in Eq. (2) [31,32].

The $L_\mu - L_\tau$ gauge symmetry is naturally anomaly free without requiring new fermions or *ad-hoc* baryonic charge assignments [18,33]. Our focus is on how this nonstandard interaction (NSI) shapes the neutrino flavor oscillation through the kinetic mixing portal. Consequently, neutrinos in this model interact coherently with the solar plasma [34]. It is important to note that since the neutron content of the Sun does not contribute to the kinetic mixing potential, only the proton (and electron) density enters the effective potential calculation.

In this study, we investigate neutrino propagation through both vacuum and matter, following the standard three-flavor neutrino oscillation model. This approach extends existing work, as referenced in various studies [e.g., [35–37]]. Our research builds upon the well-established Mikheyev-Smirnov-Wolfenstein effect (MSW) [38,39], whilst taking into consideration the presence of a Z' vector boson mediator as introduced by Lopes [40]. In the $L_\mu - L_\tau$ model, neutrinos interact with the solar plasma

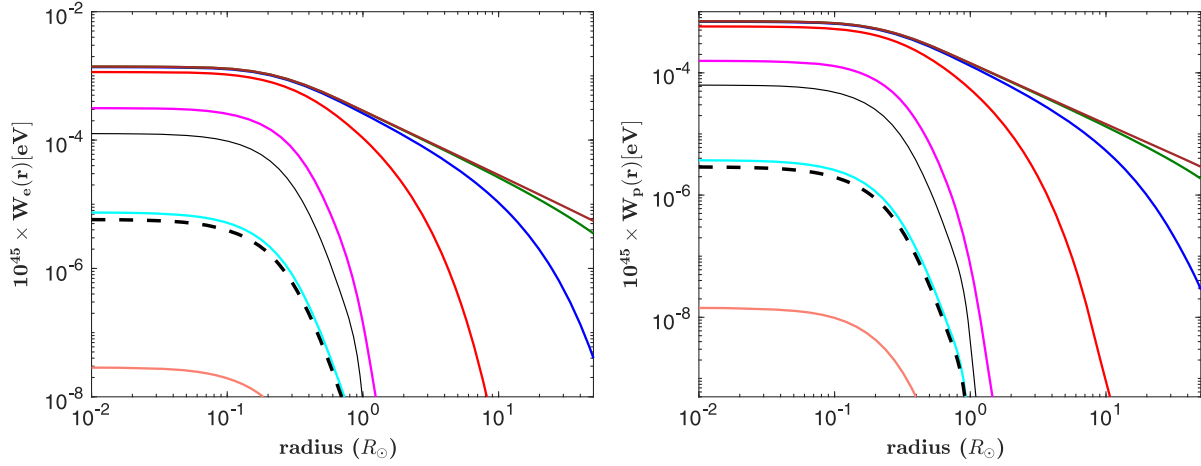


FIG. 1. The electron (left panel) and proton (right panel) potential functions, $W_e(r)$ and $W_p(r)$, inside the Sun as a function of distance from the solar center, expressed in units of the solar radius $R_\odot$. The curves correspond to a range of $\lambda_{Z'}/R_\odot$ values, with colors transitioning from salmon (lowest curves) to brown (uppermost curves); these correspond to $\lambda_{Z'}/R_\odot = 10^{-3}, 10^{-2}, 10^{-1}, 1, 10, 10^2$, and 10^3 , respectively. The dashed black line serves as a reference, representing the scaled internal electron density ($10^{-3}n_e$) in the left panel and proton density ($10^{-3}n_p$) in the right panel, as obtained from the standard solar model.

through the kinetic mixing portal. Due to the kinetic mixing, the Z' boson couples to the electromagnetic current, and consequently, the local potential of charged particles within the solar medium influences neutrino scattering, as characterized by the functions $W_i(\mathbf{r})$ with $i = e, p$ [31,41]. Assuming spherical symmetry within the Sun, $W_i(\mathbf{r})$ simplifies to $W_i(r)$,

$$W_i(r) = \frac{2\pi\lambda_{Z'}}{r} \int_0^{R_\odot} r' n_i(r') \left[e^{-\frac{|r'-r|}{\lambda_{Z'}}} - e^{-\frac{|r'+r|}{\lambda_{Z'}}} \right] dr', \quad (2)$$

where $i = e, p$ denotes electrons and protons, respectively, and $\lambda_{Z'} = 1/m_{Z'}$ delineates the range of the interaction. In the $L_\mu - L_\tau$ model with kinetic mixing, only the proton density $n_p(r)$ contributes to the effective potential, as the neutron content of the Sun does not couple to the electromagnetic current. Crucially, $W_p(r)$ captures the modulation of the matter potential attributable to the finite interaction range of the Z' vector boson, thereby differentiating from the conventional contact interaction. Complementary constraints on light-mediator NSI arise from neutrino scattering, in particular, coherent elastic neutrino-nucleus scattering, and can be combined with oscillation data [32,42]. Figure 1 shows the influence of the parameter $\lambda_{Z'}$ on $W_e(r)$ and $W_p(r)$.

Here, we express the influence of non-standard interactions (NSI) on neutrino propagation as a contribution to the potential, as follows:

$$V_{\text{eff}} = V_e(r) - V_p(r) = \sqrt{2}G_F n_{\text{eff}}(r), \quad (3)$$

where $V_e = \sqrt{2}G_F n_e$ and $V_p = \sqrt{2}G_F \zeta_{Z'}$. In this context, $n_{\text{eff}} \equiv n_e(r) - \zeta_{Z'}(r)$, G_F is the Fermi constant, $n_e(r)$ is the

radial profile of electron density, and $\zeta_{Z'}(r)$ represents the NSI strength term. In the $L_\mu - L_\tau$ model with kinetic mixing, only the proton density contributes

$$\zeta_{Z'}(r) = \eta_o W_p(r). \quad (4)$$

Here, $\eta_o = g_{Z'}^2 \epsilon / (2\sqrt{2}G_F m_{Z'}^2)$ is a dimensionless parameter that captures the relationship between the gauge coupling $g_{Z'}$, the kinetic mixing ϵ , and the mediator mass $m_{Z'}$; here $W_p(r)$ denotes the effective (mediator-smeared) proton number density, so that $\zeta_{Z'}(r)$ carries the dimensions of a number density. Conveniently, and following Gonzalez-Garcia *et al.* [41], the associated potential is $V_p = g_{Z'}^2 \epsilon W_p(r) / (2m_{Z'}^2)$, the factor of one half arising directly from the definition of η_o .

We are examining the probability of electron neutrinos surviving in different models with varying values of η_o . We then compare these findings with the latest solar neutrino experiment data. If you are interested in more standard calculations, see the recent particle physics review [43,44], specifically the “Neutrino Masses, Mixing, and Oscillations” section from the August 2024 update [45]. In simple terms, we use a formula to predict how likely electron neutrinos are to survive: $P_e(E) \approx \cos^4(\theta_{13}) P_e^{2\nu_e} + \sin^4(\theta_{13})$. We calculate the survival probability of electron neutrinos in a two neutrino flavor model as $P_e^{2\nu_e}(E) = 0.5 + (0.5 - P_\gamma) \cos(2\theta_{12}) \cos(2\theta_m)$. Here, P_γ accounts for probability jumps due to the nonadiabatic correction, and θ_m is the matter mixing angle [46], calculated at the neutrino source region in the Sun [e.g., [47,48]]. The matter mixing angle, θ_m , is computed as $\cos(2\theta_m) = A_m / (A_m^2 + \sin^2(2\theta_{12}))^{1/2}$. A_m depends on the initial mixing angle θ_{12} , the neutrino energy E , and the effective matter

potential V_{eff} [Eq. (3)], in combination with the squared-mass difference Δm_{21}^2 . We compute A_m as $A_m = \cos(2\theta_{12}) - 2EV_{\text{eff}}/\Delta m_{21}^2$, the energy factor rendering the second term dimensionless, as required. For a detailed discussion, refer to Lopes [40].

The probability of an electron neutrino surviving various nuclear reactions depends on where it originates within the Sun. For more on how the source location affects the survival probability $P_e(E)$, see Lopes [49,50]. The mean survival probability for each nuclear reaction in the Sun's interior, denoted as $P_{e,k}$, is calculated as follows:

$$P_{e,k}(E) = A_k^{-1} \int_0^{R_\odot} P_e(E, r) \phi_k(r) 4\pi \rho(r) r^2 dr. \quad (5)$$

In this equation, A_k serves as a normalization constant. The variable k denotes the solar neutrino sources, including pp , pep , ${}^8\text{B}$, ${}^7\text{Be}$, ${}^{13}\text{N}$ and ${}^{15}\text{O}$. Several factors, such as vacuum and matter oscillations and the Sun's internal physics, affect whether electron-neutrinos change flavor. Local solar plasma conditions have a significant role in this flavor conversion.

III. PRESENT CONSTRAINT

Figure 2 compares our predictions for the survival probability of electron neutrinos from several nonstandard interaction (NSI) models to the current solar neutrino data. The data analysis was conducted using the high- Z solar standard model, which is a well-validated model of the Sun's interior [e.g., [51,52], and references therein]. Each data point in the figure represents the observed survival probability of electron neutrinos as measured by three major solar neutrino detectors: SNO, Super-Kamiokande, and Borexino. The uncertainty associated with each data point is a combination of experimental error and theoretical uncertainty, which arises from modeling the Sun's interior [e.g., [22,51], and references therein]. More specifically, Borexino data include measurements from various solar neutrino reactions, such as pp (yellow diamond), ${}^7\text{Be}$ (red upward-triangle), pep (blue downward-triangle), and ${}^8\text{B}$ in the high-energy region (HER), denoted by circles in salmon (HER), orange (HER-I), and magenta (HER-II) colors; SNO's ${}^8\text{B}$ measurements are indicated by a cyan square; and the joint KamLAND/SNO ${}^7\text{Be}$ measurements are represented by a green square. Please refer to Borexino Collaboration *et al.* [53], Agostini *et al.* [54], Bellini *et al.* [55], Abe *et al.* [56,57], Aharmim *et al.* [58], Cravens *et al.* [59], and associated references for more in-depth understanding of this experimental data. For reference, the range of the MSW-LMA solution (within the $1\text{-}\sigma$ variation) is significantly smaller than the uncertainties associated with the current data points, as indicated by Capozzi *et al.* [60].

To strengthen our analysis, we introduce a test analogous to the chi-squared test, denoted as χ_ν^2 . This test

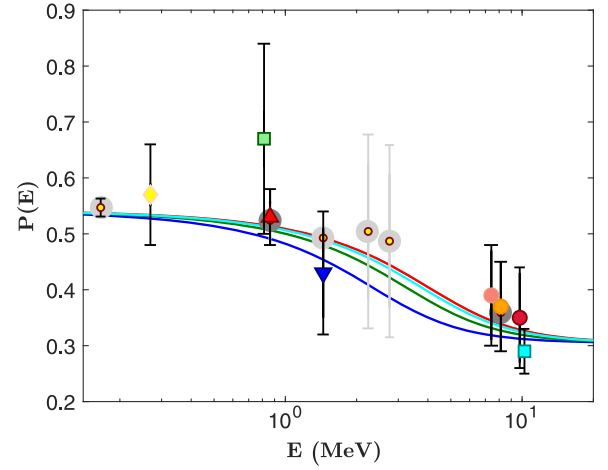


FIG. 2. The plot illustrates the survival probability of electron neutrinos for various models. The red curve represents the standard solar neutrino model ($\eta_o = 0$). NSI models are depicted as follows: $\lambda_{Z'}/R_\odot = 1$ with $\eta_o = -6$ (blue curve) and $\eta_o = -2$ (green curve), and $\lambda_{Z'}/R_\odot = 0.1$ with $\eta_o = -2$ (cyan curve). The colored markers signify the measured survival probabilities from three solar neutrino detectors (SNO, Super-Kamiokande, and Borexino) based on the prevailing standard solar model. The gray-yellow markers forecast the anticipated measurements from the upcoming DARWIN/XLZD and JUNO collaborations. Error bars for current and anticipated data reflect uncertainties inherent in the measurements and those arising from the current standard solar model. Further details and data source references are provided in the main text.

leverages the relationship of the electron neutrino survival probability with the solar background structure. The test is formulated as

$$\chi_\nu^2 = \sum_{i,k} \left(\frac{P_{e,k}^{\text{obs}}(E_i) - P_{e,k}^{\text{th}}(E_i)}{\sigma_{\text{obs}}(E_i)} \right)^2, \quad (6)$$

where this metric juxtaposes our theoretical models against empirical data accumulated from diverse neutrino experiments. Within this framework, different energy levels, denoted by E , are used to ascertain the survival probability function $P_{e,k}(E)$, detailed further in Eq. (5). Here, “obs” represents the observed readings, and “th” stands for the theoretical predictions for the neutrino energy E_i . The indices i and k , respectively, signify particular experimental data points and the corresponding solar neutrino sources. The term $\sigma_{\text{obs}}(E_i)$ designates the associated measurement error for the i^{th} entry. The values $P_{e,k}^{\text{obs}}(E_i)$ emanate from empirical findings of solar neutrino experiments.

Figure 3 showcases how χ_ν^2 varies for a selected group of NSI models with respect to η_o and $\lambda_{Z'}$. Based on Eq. (6), the standard neutrino flavor model (where $\eta_o = 0$) gives a χ_ν^2 of 3.1, which is denoted by a yellow circle in the figure. The plotted curves correspond to diverse values of $\lambda_{Z'}$ (or its inverse, $m_{Z'}$), spanning from 0.05 to 1000. We discern two pronounced asymptotic trends:

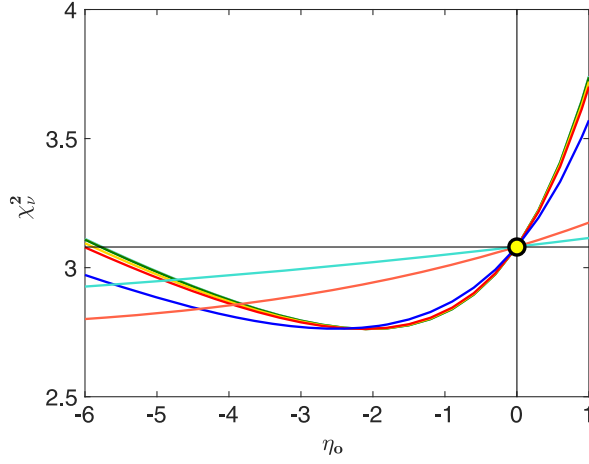


FIG. 3. Graph depicting the χ^2_ν test values versus the coupling constant η_o across various NSI neutrino models. Continuous lines indicate the χ^2_ν values for distinct $\lambda_{Z'}/R_\odot$ values, with color coding as follows: 0.05 (turquoise), 0.1 (tomato), 1 (blue), 5 (red), 10 (gold), 50 (green), 100 (light brown), and 1000 (cyan). The vertical line corresponding to $\eta_o = 0$ represents the standard model, while the horizontal line at $\chi^2_\nu = 3.1$ indicates the quality of fit for the current data. The yellow circle represents the χ^2_ν of the current neutrino flavor oscillation model.

- (1) For diminished values of $\lambda_{Z'}$ (or elevated values of $m_{Z'}$), the influence recedes. As shown in Eq. (3), the contribution from Eq. (4) renders the χ^2_ν function for a constant $\lambda_{Z'}$ virtually linear, with V_i decreasing proportional to $m_{Z'}^{-2}$.
- (2) Conversely, the effect amplifies for augmented values of $\lambda_{Z'}$ (or reduced values of $m_{Z'}$), until it reaches a χ^2_ν saturation function.

These results follow directly from the contribution of W_p to $\zeta_{Z'}(r)$, as specified in Eq. (4). Figure 1 illustrates that the magnitude of W_p , given by Eq. (2), diminishes as $\lambda_{Z'}$ decreases, a consequence of the finite interaction range imposed by the mediator mass, whilst approaching a constant value in the limit of large $\lambda_{Z'}$, where the Compton wavelength of the Z' boson substantially exceeds the solar radius. For completeness, we also display the magnitude of $W_e(r)$, although this function does not enter into the present calculation.

We found that NSI models with $\chi^2_\nu \leq 3.1$ are viable candidates for explaining solar neutrino data, as they perform at least as well as the standard neutrino flavor oscillation model (see Fig. 3). These models are characterized by η_o values between -4.8 and 0 and $\lambda_{Z'}/R_\odot \geq 5$. The best-fitting model has $\chi^2_\nu = 2.7$ for $\eta_o = -2$ and $\lambda_{Z'}/R_\odot \geq 5$, which corresponds to a Z' mass of $m_{Z'} \leq 5.7 \times 10^{-17}$ eV.

IV. FUTURE CONSTRAINT

It is worth considering what improvements might reasonably be expected from the forthcoming generation of

solar neutrino experiments, in particular, the Jiangmen Underground Neutrino Observatory (JUNO) [25–27], and the XLZD consortium (which now unifies the XENON, LZ, and DARWIN Collaborations) [23,24,61]. The experimental landscape has evolved rather more quickly than anticipated: JUNO commenced physics data acquisition in August 2025 and has already, within a mere 59 days of operation, achieved measurements of the solar neutrino oscillation parameters θ_{12} and Δm_{21}^2 with precision surpassing all previous experiments combined by a factor of 1.6. A development that is both gratifying and rather unexpected [62].

Our projections had anticipated neutrino flux measurements from multiple solar reactions, and it transpires that JUNO’s early performance exceeds these expectations. The Collaboration’s status report had foreseen a ^8B flux precision below 2.5% after six years of operation [63], representing a considerable improvement upon the approximately 3.8% achieved by SNO [[58] and references therein]. For the purposes of this analysis, we retain the original six-year targets: 0.15% precision for ^7Be and 3.1% for pep [27], though these may well prove conservative. We also anticipate JUNO measuring CNO neutrinos, focusing on the reactions $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$ and $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$, whilst sensibly setting aside the rather troublesome ^{17}F neutrinos. For ^{13}N and ^{15}O neutrino measurements, we assume a relative error of 20% owing to their complexity. A figure that experience suggests may prove optimistic when dealing with nuclear physics at these energies. By contrast, Borexino achieved 2.7% precision for ^7Be , 17% for pep , and 30% for CNO [53].

Furthermore, our analysis integrates a virtual XLZD data point alongside the extant data. All these projected data points are illustrated in Fig. 2 using yellow-gray markers. Based upon the standard neutrino oscillation model, we set these virtual data points at one quarter of the distance between current measurements and future predictions. For the XLZD data point specifically, we fix its position at one quarter of the distance between Borexino’s pp neutrino detection and the theoretical prediction (for $\eta_o = 0$) in the analogous energy range. This approach aligns with the predictions of Darwin Collaboration *et al.* [24], which inform our calculations. It bears mentioning that the LUX-ZEPLIN experiment achieved, in December 2025, the first statistically significant observation of solar ^8B neutrinos via coherent elastic neutrino-nucleus scattering at 4.5σ significance, thereby entering what colleagues have rather evocatively termed the “neutrino fog”. A development that bodes well for future pp neutrino measurements [64]. Our analyses integrate both experimental and theoretical uncertainties, as outlined by Orebi Gann *et al.* [51], Capelo and Lopes [22]. These uncertainties are combined in quadrature, following the methodology detailed by Lopes [49], Lopes and Turck-Chièze [65].

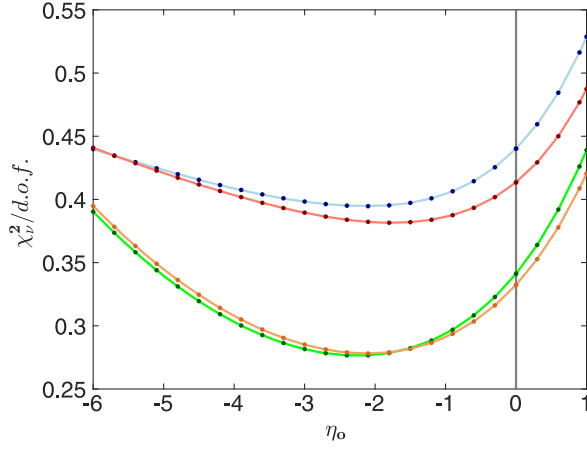


FIG. 4. Comparison of $\chi^2_{\nu}/\text{d.o.f.}$ across various NSI models for $\lambda_{Z'}/R_{\odot} = 5.0$ as a function of η_o . The curves represent the anticipated $\chi^2_{\nu}/\text{d.o.f.}$ precision based upon distinct datasets: (i) current data (blue); (ii) current data augmented with expected DARWIN/XLZD pp measurements (red); (iii) current data enriched with forthcoming JUNO measurements (green); and (iv) a comprehensive set including current data, DARWIN/XLZD pp , and JUNO measurements (orange). A detailed discussion is provided in the main text.

Figure 4 demonstrates that incorporating projected JUNO measurements into the analysis produces a gratifying reduction in $\chi^2_{\nu}/\text{d.o.f.}$ For the standard neutrino flavor oscillation model ($\eta_o = 0$), this quantity is expected to diminish from 0.45 to 0.34. Within our preferred model class ($\lambda_{Z'}/R_{\odot} = 5$) and in the region corresponding to the current best-fit model ($\eta_o = -2$), one anticipates a reduction from 0.41 to 0.27. Whilst the improvement in $\chi^2_{\nu}/\text{d.o.f.}$ attributable to XLZD alone appears modest, its capability to measure pp neutrinos at energies where the MSW effect remains negligible, that is to say, in the vacuum-dominated oscillation regime below approximately 1 MeV, underscores its considerable value, not least because such measurements furnish a largely model-independent probe of the solar core.

In Figs. 5 and 6, we present analogous plots to Fig. 3. These figures illustrate the potential model constraints based upon six years of JUNO data, as well as the combined dataset from both JUNO and XLZD experiments. For scenarios where $\lambda_{Z'}/R_{\odot} \geq 5$, the optimal model range is expected to narrow from $-6.0 \leq \eta_o \leq 0$ (based upon current data) to $-4.5 \leq \eta_o \leq 0$ when incorporating the full JUNO and XLZD dataset.

V. SUMMARY AND CONCLUSION

In this paper, we have presented what one hopes is a nuanced adaptation of the traditional particle physics model, crafted to address observed phenomena in solar neutrino physics. Central to this framework is the gauged $U(1)_{L_{\mu}-L_{\tau}}$ symmetry, a naturally anomaly-free extension of

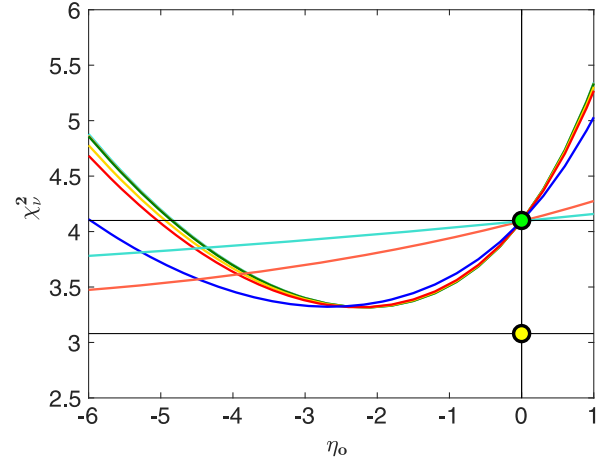


FIG. 5. The χ^2_{ν} test values as a function of the coupling constant η_o for various nonstandard interaction (NSI) neutrino models. This analysis incorporates all experimental data together with projected JUNO measurements (see Fig. 2). The color scheme follows that employed in Fig. 3. The green circle denotes the χ^2_{ν} value for the standard neutrino flavor model when evaluated against both present and anticipated JUNO data. Further particulars may be found in the main text.

the Standard Model that couples to the difference of muon and tau lepton numbers. We theorize that the Z' boson interacts with the solar plasma through kinetic mixing with the photon, thereby generating an effective matter potential for neutrinos. This addition complements (rather than supplants) the conventional three-neutrino flavor oscillation framework. Our preliminary results suggest that this

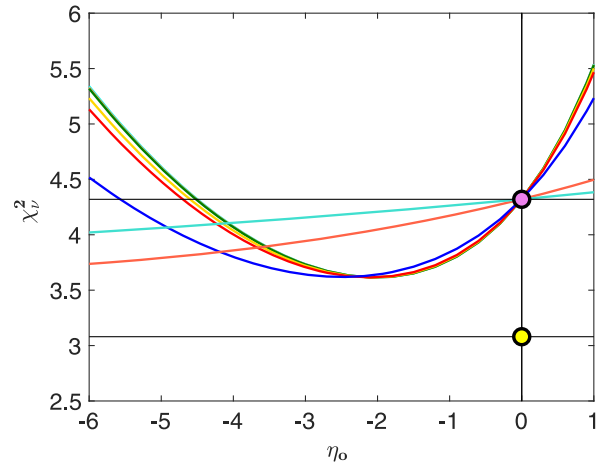


FIG. 6. The χ^2_{ν} test values versus the coupling constant η_o across various non-standard interaction (NSI) neutrino models. This analysis mirrors that of Fig. 5, but now incorporates projected data from both JUNO and XLZD (see Fig. 2). The color scheme follows Fig. 3. The violet circle indicates the χ^2_{ν} for the standard neutrino flavor model, when combining extant data with projected JUNO and XLZD data. Further details are provided in the main text.

model matches the current benchmark set by the standard neutrino flavor oscillation model in fitting solar neutrino data and may indeed exceed it. Though one must, of course, remain appropriately cautious about such claims.

The $L_\mu - L_\tau$ gauge symmetry was historically motivated by the anomalous magnetic dipole moment of the muon and related flavor anomalies [18]. It is important to acknowledge, in the interest of scientific candor, that the landscape regarding these anomalies has been fundamentally transformed. The B-meson anomalies in R_K and R_{K^*} , which had excited considerable theoretical speculation, were resolved following improved background modeling by the LHCb Collaboration in December 2022 [19]. More significantly, the Fermilab Muon g-2 experiment released its final measurement in June 2025 [66], achieving an unprecedented precision of 127 parts per billion. Concurrently, the Muon g-2 Theory Initiative published an updated Standard Model prediction [20] incorporating mature lattice QCD calculations for the hadronic vacuum polarization contribution. The resulting comparison reveals no statistically significant tension between theory and experiment at current precision levels. These developments, whilst perhaps disappointing for enthusiasts of new physics via the g-2 route, do not diminish the independent validity of our model when constrained by solar neutrino data. Indeed, they underscore the importance of diverse experimental probes such as the solar neutrino measurements we employ here, for testing extensions of the Standard Model. The $L_\mu - L_\tau$ model remains a highly attractive candidate for future study due to its ability to address terrestrial long-baseline force searches [67,68] and nonthermal dark matter phenomenology [30].

Employing the most recent solar neutrino data in conjunction with the current solar standard model, we have placed constraints on this nonstandard interaction model. Our results indicate that the best agreement with solar neutrino data arises when the intermediate boson is ultralight. In particular, the mass of the Z' boson should be less than 5.7×10^{-17} eV (or equivalently, $\lambda_{Z'}/R_\odot \geq 5$) for optimal alignment with current solar neutrino measurements.

Additionally, models with $-6.0 \leq \eta_o \leq 0$ achieve a fit to the current solar neutrino data that is comparable to, and in some cases marginally better than the standard flavor oscillation scenario. It is worth remarking that the best-fit model corresponds to a coupling parameter $\eta_o = g_{Z'}^2 \epsilon / (2\sqrt{2} G_F m_{Z'}^2) \approx -2$, where $g_{Z'}$ denotes the gauge coupling constant, ϵ the kinetic mixing parameter, and G_F the Fermi constant. This model yields $\chi_\nu^2 = 2.7$, which stands in contrast to the $\chi_\nu^2 = 3.1$ obtained for the standard case ($\eta_o = 0$). The value $\eta_o = -2$ corresponds to an effective four-fermion coupling $g_{Z'}^2 \epsilon / m_{Z'}^2 = 2\sqrt{2} G_F |\eta_o| \approx 6.6 \times 10^{-23} \text{ eV}^{-2}$, that is, approximately 5.7 times the Fermi constant, which is precisely why the induced

potential is able to compete with the standard MSW term. Assuming $\epsilon \approx 1$ and adopting a reference mediator mass $m_{Z'} = 1 \text{ eV}$, this corresponds to a gauge coupling $g_{Z'} \approx 8 \times 10^{-12}$, comfortably within the range anticipated for ultralight mediators (see below). It bears noting that whilst the individual values of the gauge coupling $g_{Z'}$ and kinetic mixing parameter ϵ are not separately constrained by this analysis, existing bounds from neutrino scattering experiments and cosmological considerations suggest that both parameters may span several orders of magnitude. For instance, cosmological constraints permit $g_{Z'} \simeq (3 - 8) \times 10^{-4}$ for MeV-scale Z' bosons, whilst for ultralight mediators ($m_{Z'} \sim 1 \text{ eV}$ to MeV) the coupling may lie in the range $g_{Z'} \sim 10^{-13}$ to 10^{-9} [69]. Similarly, the kinetic mixing parameter ϵ is scale dependent and may effectively vanish at low momentum transfer [70]. The product $g_{Z'}^2 \epsilon$ nonetheless remains the physically relevant combination for solar neutrino phenomenology.

Furthermore, our findings suggest that the forthcoming generation of solar neutrino detectors, JUNO and XLZD in particular, can significantly refine $\chi_\nu^2/\text{d.o.f.}$. Indeed, we anticipate that the standard case's value of 0.45 may be reduced to 0.34 when utilizing combined data from these collaborations. This advancement paves the way for either validating the standard scenario, or confirming this (or similar) nonstandard interaction models. Given that JUNO has already commenced operations and delivered results of remarkable precision, one is cautiously optimistic that these projections may be realized sooner than originally anticipated.

The implication that the intermediary boson is an ultralight particle, with mass constrained to be less than $5.7 \times 10^{-17} \text{ eV}$, suggests that it may, in principle, address several outstanding challenges in astrophysics and cosmology. We highlight a few scenarios potentially linked to such particles:

- (i) If stable, this boson emerges as a viable dark matter candidate. Ultralight dark matter particles offer notable potential in refining galaxy simulations within the CDM paradigm. Such particles serve as a bridge to resolve numerous discrepancies between numerical predictions and cosmological observations, including the core versus cusp issue, the missing satellites dilemma, the too-big-to-fail problem, galaxy rotation curve anomalies, and complications in high-redshift galaxy formation [e.g., [6,71]]. Recent constraints from dwarf galaxy kinematics suggest that ultralight bosonic dark matter must have masses exceeding approximately $2.2 \times 10^{-21} \text{ eV}$ [72]; our candidate, being considerably lighter still, occupies a distinct region of parameter space that would require different phenomenological signatures. Importantly, recent theoretical developments have demonstrated that the $L_\mu - L_\tau$ model can accommodate nonthermal dark matter production via

the decay of heavy right-handed neutrinos [30], potentially explaining both the dark matter relic density and the baryon asymmetry of the Universe through leptogenesis.

- (ii) It is worth remarking that the kinetic mixing inherent to this model gives rise to long-range forces that are, in principle, constrained by tests of the weak equivalence principle. Through kinetic mixing with the photon, the Z' boson acquires an effective coupling to the electromagnetic current proportional to ϵe , which can mediate composition-dependent interactions between macroscopic bodies. The MICROSCOPE satellite experiment has placed stringent bounds on new long-range forces coupled to linear combinations of baryon and lepton numbers, with constraints at the level of $|\epsilon| \lesssim 10^{-24}$ for forces coupled to total lepton number L or $B - L$ [73]. For the $L_\mu - L_\tau$ model under consideration here, however, neither electrons nor quarks carry any direct charge under the gauge symmetry, and consequently fifth-force signatures arise only through the kinetic mixing portal, a qualitatively different and suppressed mechanism compared to models such as $L_e - L_\mu$ or $L_e - L_\tau$, where electrons couple directly to the new gauge boson and planetary perihelion precession measurements yield constraints of order $g \lesssim 10^{-25}$ [74]. Importantly, the *physical* kinetic mixing relevant for low-energy processes is not simply the bare Lagrangian parameter ϵ , but rather receives radiative corrections from μ and τ loops that render it momentum dependent. In the low-momentum regime pertinent to fifth-force experiments, this effective mixing approaches an infrared boundary value that constitutes a free parameter of the model [70]. If this boundary value lies in proximity of zero, constraints from solar neutrino experiments, coherent elastic neutrino-nucleus scattering, and stellar cooling can be substantially relaxed, potentially by orders of magnitude. Nevertheless, any viable parameter space must remain consistent with these complementary probes. This phenomenological situation is distinct from baryon-coupled models, where the electron sector plays no mediating role whatsoever.
- (iii) The introduction of a new ultralight boson necessitates reevaluating pivotal processes in stellar evolution. One anticipates that nuclear reactions, the equation of state, and opacities in the Sun and other stars are amongst these processes. This perspective could provide critical insights into the solar

abundance problem [e.g., [28,75]], a persistent inconsistency amongst solar models, observed neutrino fluxes, and helioseismic observations that has resisted resolution despite considerable effort over the past two decades. Such alterations hold promise for predicting a seismic structure more consistent with observational data.

- (iv) Complementary tests of this model arise from terrestrial long-baseline neutrino experiments. Studies by Singh *et al.* [67] and Agarwalla *et al.* [68] have demonstrated that a combined analysis of DUNE and T2HK data is required to claim a statistical discovery of flavor-dependent long-range forces. Furthermore, high-energy astrophysical neutrinos offer a lever arm to probe coupling constants as small as 10^{-30} , far below solar sensitivity.

Finally, the forthcoming generation of ultralight dark matter detectors, as detailed in reviews such as Garcon *et al.* [76], Agrawal *et al.* [77], and Ferreira [71] is poised to probe this class of particle with increasing rigor. The bosons discussed in this work, characterized by masses below 5.7×10^{-17} eV and an effective four-fermion coupling $g_{Z'}^2 \epsilon / m_{Z'}^2 \approx 6.6 \times 10^{-23}$ eV⁻² (about $5.7 G_F$), represent a compelling target for experimental investigation. It bears noting, however, that such extraordinarily light mediators lie at the frontier of current detection capabilities, with gravitational-wave interferometers, pulsar timing arrays, and precision atomic spectroscopy amongst the most promising avenues for exploration [see, e.g., [78,79]]. The detection of ultralight bosons and further theoretical refinements could furnish important insights into the interplay between dark matter and leptonic interactions, potentially reshaping our understanding of the Universe's underlying structure. One remains, as ever, cautiously hopeful.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the author upon reasonable request.

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