

Standard Model Tested with Neutrinos

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(Received 14 April 2025; revised 4 November 2025; accepted 18 November 2025; published 4 December 2025)

The standard model (SM) of particle physics effectively explains most observed phenomena, though some anomalies, especially in the neutrino sector, suggest the need for extensions. In this Letter, we perform the first global fit of elastic neutrino-nucleus and neutrino-electron scattering data to further test the SM within a consistent framework. Our results on the neutrino charge radius, the only nonzero electromagnetic property of neutrinos in the SM, show no significant deviation, indicating no large beyond the SM flavor-dependent effects for electron and muon neutrinos. By incorporating solar neutrino data from dark matter direct detection experiments, we also place the most stringent constraints on the tau neutrino charge radius obtained from neutrino scattering experiments. Additionally, we determine updated constraints on the vector and axial-vector neutrino-electron neutral current couplings, adjusting for flavor-dependent effects and for the different experimental momentum transfers. The global analysis reveals two allowed solutions: one close to the SM prediction, and a degenerate solution that is favored. We show that future dark matter detectors could achieve sufficient precision to resolve the degeneracy. As we move toward the precision era, this Letter demonstrates the crucial need to properly account for flavor- and momentum-dependent effects to avoid misinterpretations of the data.

DOI: [10.1103/dplq-dvc8](https://doi.org/10.1103/dplq-dvc8)

Over time, the electroweak theory of the standard model (SM) has been extensively investigated, both theoretically and experimentally, to precisely determine the interactions between particles. The quest for increasingly higher precision led to the introduction of the so-called radiative corrections [1–10], due to higher-order vertex contributions. Existing formalisms have been designed so that most radiative corrections in low-energy neutral current interactions are largely universal, meaning they remain independent of the specific particles participating in the process. In this Letter, we discuss neutrino interactions, focusing in particular on the elastic neutrino electron (ν ES) and the coherent neutrino-nucleus scattering (CE ν NS) processes,

for which another nonuniversal radiative correction, the so-called neutrino charge radius (NCR), has to be accounted for. The latter, being the only nonzero neutrino electromagnetic property predicted by the SM, provides a unique way for testing the theory and looking for possible hints of flavor-dependent effects beyond the SM (BSM). Moreover, neutral current neutrino-electron couplings provide another way for testing the SM. Unfortunately, up to now the degeneracy between the vector and axial-vector neutral current couplings [11] has prevented attainment of a clear test of the electroweak theory. As a result, verifying the SM consistency has required combination of neutrino data with e^+e^- measurements.

In this Letter, we refine the conventional description of the neutrino charge-radius radiative correction by incorporating its momentum dependence [10]. Additionally, we explicitly account for flavor- and momentum-dependent effects in the neutral current neutrino-electron couplings when combining constraints from available data. We perform the first comprehensive global analysis within a unified framework, reevaluating a vast amount of ν ES and CE ν NS data, to precisely test the SM using neutrinos, extending the scope of previous analyses [12–15].

In the SM the ν ES cross section is obtained by multiplying the single electron cross section with the effective electron

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charge of the target atom $Z_{\text{eff}}(T_e)$ [16–18], and for each neutrino flavor ν_ℓ ($\ell = e, \mu, \tau$) it is given by [11]

$$\begin{aligned} \frac{d\sigma_{\nu_\ell e}}{dT_e}(E, T_e) = Z_{\text{eff}}(T_e) \frac{G_F^2 m_e}{2\pi} & \left[(g_V^{\nu_\ell e} + g_A^{\nu_\ell e})^2 \right. \\ & + (g_V^{\nu_\ell e} - g_A^{\nu_\ell e})^2 \left(1 - \frac{T_e}{E} \right)^2 \\ & \left. - \left((g_V^{\nu_\ell e})^2 - (g_A^{\nu_\ell e})^2 \right) \frac{m_e T_e}{E^2} \right], \quad (1) \end{aligned}$$

where G_F is the Fermi constant, E is the neutrino energy, m_e is the electron mass, T_e is the electron recoil energy, and $g_V^{\nu_\ell e}$ and $g_A^{\nu_\ell e}$ are the neutrino-electron vector and axial-vector couplings, respectively. To analyze the νES process, it is necessary to study in detail the calculation of the couplings beyond tree level, thus accounting for the radiative corrections [2,8], such as the WW and ZZ box diagrams as well as the NCR contribution (for more information see Supplemental Material [19]). The latter enters the vector coupling and represents the only flavor-dependent radiative correction. Thus, we can define the neutrino-electron couplings as

$$g_V^{\nu_\ell e} = \tilde{g}_V^{\nu_\ell e} + 2\phi_{\nu_\ell W} + \delta_{\ell e}, \quad (2)$$

$$g_A^{\nu_\ell e} = g_A^{\nu_\ell e} + \delta_{\ell e}, \quad (3)$$

where $\tilde{g}_V^{\nu_\ell e}$ and $g_A^{\nu_\ell e}$ are the neutral current flavor-independent couplings, and include only the flavor-independent radiative corrections. The Kronecker delta, $\delta_{\ell e}$, accounts for the charge current contribution, which is present only for $\ell = e$, while for antineutrinos, $g_A^{\nu_\ell e} \rightarrow -g_A^{\nu_\ell e}$. For the full definition of the vector and axial-vector couplings please refer to Refs. [8,19]. The remaining $\phi_{\nu_\ell W}$ term in Eq. (2) represents the NCR radiative contribution, which is defined as [2]

$$\phi_{\nu_\ell W} = -\frac{\alpha}{6\pi} \left(\ln \frac{M_W^2}{m_\ell^2} + \frac{3}{2} \right), \quad (4)$$

at zero-momentum transfer. Here, α is the low-energy limit of the electromagnetic coupling, M_W is the W boson mass, and m_ℓ is the mass of the charged lepton with flavor ℓ . Clearly, this radiative contribution depends on the neutrino flavor and is generated by a loop insertion into the ν_ℓ line, where W boson(s) and charged lepton(s) ℓ enter. These diagrams' contribution can be calculated, and according to Refs. [23–25], the NCR corresponds to a physical observable, being finite and gauge invariant. In particular, the SM calculation renders [7]

$$\langle r_{\nu_\ell}^2 \rangle_{\text{SM}} = -\frac{G_F}{2\sqrt{2}\pi^2} \left[3 - 2 \ln \left(\frac{m_\ell^2}{M_W^2} \right) \right], \quad (5)$$

which corresponds to the numerical values

$$\langle r_{\nu_e}^2 \rangle \simeq -0.83 \times 10^{-32} \text{ cm}^2, \quad (6)$$

$$\langle r_{\nu_\mu}^2 \rangle \simeq -0.48 \times 10^{-32} \text{ cm}^2, \quad (7)$$

$$\langle r_{\nu_\tau}^2 \rangle \simeq -0.30 \times 10^{-32} \text{ cm}^2. \quad (8)$$

The numerical values for the neutrino-electron couplings in the low-energy limit are

$$g_V^{\nu_e e} = 0.9524, \quad g_A^{\nu_e e} = 0.4938, \quad (9)$$

$$g_V^{\nu_\mu e} = -0.0394, \quad g_A^{\nu_\mu e} = -0.5062, \quad (10)$$

$$g_V^{\nu_\tau e} = -0.0350, \quad g_A^{\nu_\tau e} = -0.5062, \quad (11)$$

when including radiative corrections [2,8] and the latest weak mixing angle calculation [11].

Given that the NCR contributes not only to the νES process, but also to $\text{CE}\nu\text{NS}$ by entering into the neutrino-proton coupling (since it affects the scattering of neutrinos with charged particles [10]) the complementarity between νES and $\text{CE}\nu\text{NS}$ is pivotal to fully leveraging the data.

Although measuring the NCR would serve as a fundamental test of the SM, the available data remain insufficient to provide a first determination. So far, only constraints have been put on its value [16,26–29]. When considering BSM effects on the NCR, one should also consider possible off-diagonal flavor-changing contributions, known as transition charge radii [7]. Constraints on these have been derived from existing data (see, e.g., Refs. [16,30]). Here, however, we focus solely on the diagonal NCRs, which allows us to probe their SM values.

As discussed recently in Ref. [10], the neutrino charge radius radiative correction depends also on the momentum transfer, which therefore should be carefully corrected for. For this purpose, we include a “neutrino charge radius form factor,” which is defined by isolating the momentum-dependent NCR with respect to the SM picture, so basically as

$$\mathcal{F}_{\nu_\ell}(q^2) = \frac{\langle r_{\nu_\ell}^2 \rangle^{\text{eff}}(q^2)}{\langle r_{\nu_\ell}^2 \rangle^{\text{eff}}(0)} \equiv \frac{\langle r_{\nu_\ell}^2 \rangle^{\text{eff}}(q^2)}{\langle r_{\nu_\ell}^2 \rangle^{\text{SM}}}, \quad (12)$$

where we introduced an effective NCR definition [10]. The neutrino-electron vector neutral coupling can then be defined as

$$g_V^{\nu_\ell e} = \tilde{g}_V^{\nu_\ell e} + \frac{\sqrt{2}\pi\alpha}{3G_F} \langle r_{\nu_\ell}^2 \rangle \mathcal{F}_{\nu_\ell}(q^2) + \delta_{\ell e}. \quad (13)$$

The impact of the momentum dependence of the NCR form factor becomes relevant for momenta larger than the mass of the corresponding charged lepton ℓ that enters the loops.

We can profit from the large amount of available ν ES data to extract the value of the NCRs and combine them with the constraints set by us using the available CE ν NS data in Ref. [31], namely from COHERENT CsI [32], COHERENT Ar [33,34], CONUS + [35], and TEXONO Ge [36]. For completeness, we also updated such constraints including the latest ν GEN [37] data. Moreover, in this Letter, we analyze the reactor $\bar{\nu}_e - e$ data from the TEXONO collaboration [27] using a recent antineutrino flux parametrization [38]. We also consider the results on the $\nu_e - e$ integrated cross section measured by the LSND [39] and LAMPF [40] collaborations. Similarly, we analyze the integrated cross section results reported by BNL-E734 for the $\nu_\mu(\bar{\nu}_\mu) - e$ processes [28]. We also include the $\nu_\mu(\bar{\nu}_\mu) - e$ differential cross section measurement reported by the CHARM-II experiment [41–43]. Lastly, to incorporate also the data from the CCFR collaboration [44], we converted the constraint on the weak mixing angle into a determination of the muonic NCR, which can be done given the fact that the neutrino charge radius acts as an effective shift of the weak mixing angle inside the vector neutrino-electron neutral current coupling [e.g., see Eq. (1) of Ref. [7]].

The strength of this Letter lies in the development of a global fit that, for the first time, incorporates all the most relevant ν ES and CE ν NS data within a consistent theoretical and phenomenological framework. Specifically, we build upon previous analyses which either neglected radiative corrections altogether or included them only

partially, typically considering only the neutrino charge radius correction. In contrast, our Letter incorporates the full set of relevant radiative contributions (as detailed in Supplemental Material [19]), applies a consistent treatment across all experimental datasets, ensuring uniformity across experiments and allowing for a more accurate and meaningful comparison of different data, uses the most up-to-date constants and a consistent antineutrino flux description for reactor data, and, most importantly, includes the momentum dependence that was pioneered in Ref. [10].

The results from our analysis of the individual aforementioned data are shown in Fig. 1 for the electron and muon neutrino charge radii, along with their combination, obtained by keeping $\tilde{g}_V^{\nu e}$ fixed to its SM value and varying $\langle r_{\nu_e}^2 \rangle$. The 1σ confidence level (CL) NCR values obtained from the global fit are

$$\langle r_{\nu_e}^2 \rangle = 2.2_{-2.3}^{+2.4} \times 10^{-32} \text{ cm}^2, \quad (14)$$

$$\langle r_{\nu_\mu}^2 \rangle = -0.19_{-0.56}^{+0.55} \times 10^{-32} \text{ cm}^2, \quad (15)$$

which are fairly in agreement with the SM prediction. These represent the most precise determinations of such quantities. Note that none of the individual datasets is able to select the SM region alone [45], which only emerges through the global fit.

While putting less precise constraints on $\langle r_{\nu_e}^2 \rangle$ and $\langle r_{\nu_\mu}^2 \rangle$, solar neutrino data from dark matter direct detection experiments (DMDD) are uniquely sensitive also to the

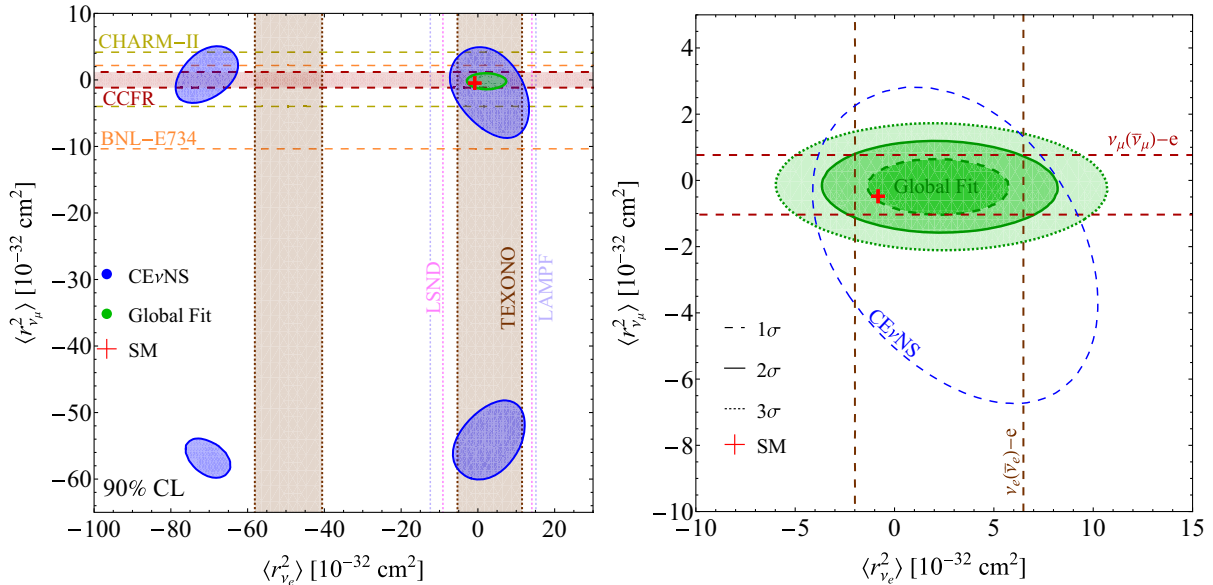


FIG. 1. Left: contours at 90% CL for 2 degrees of freedom ($\Delta\chi^2 \simeq 4.61$) obtained from the analysis of ν ES data from TEXONO [27], LSND [39], LAMPF [40], CHARM-II [41,42], BNL-E734 [28], and CCFR [44] along with the constraints obtained by combining the available CE ν NS data [10,31] with the addition of ν GEN data [37], and their combination (green contour). The red cross indicates the SM value of the NCRs. Right: the same constraints shown around the SM prediction and at different CLs. The dashed vertical band indicates the combined $\nu_e - e$ and $\bar{\nu}_e - e$ result, while the horizontal one the combined $\nu_\mu - e$ and $\bar{\nu}_\mu - e$ one at 1σ CL for 2 degrees of freedom ($\Delta\chi^2 \simeq 2.30$).

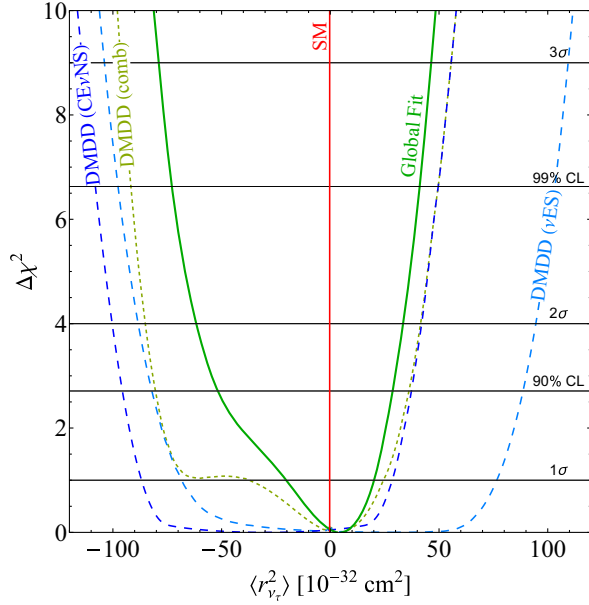


FIG. 2. Marginal $\Delta\chi^2$'s obtained from the analysis of direct detection dark matter experiments (DMDDs) [8,30,51,52] analyzing the signals due to solar neutrino CE ν NS and ν ES. The solid green curve indicates the result from the global fit.

τ flavor both through CE ν NS [46,47] and ν ES [48–50]. Including solar neutrino data in the global analysis yields the most stringent constraint on the τ flavor obtained from CE ν NS and ν ES experiments. For the solar neutrino analysis we closely follow Refs. [51,52] for CE ν NS data and Refs. [8,30] for the ν ES case. The results from the several analyses are shown in Fig. 2. The 1σ CL from the global fit corresponds to

$$-20 \leq \langle r_{\nu_e}^2 \rangle [10^{-32} \text{ cm}^2] \leq 20. \quad (16)$$

Note that even though the previously discussed experiments do not measure $\langle r_{\nu_e}^2 \rangle$ directly, their inclusion helps to break degeneracies, improving the overall bound on the τ flavor as shown in the figure. The bound is still less precise than the ones for the other neutrino flavors, although excellent prospects are awaited considering next-generation experiments [30].

Restricting ourselves only to the ν ES data, we can constrain the value of the vector and axial-vector neutrino-electron neutral current couplings to test the prediction of the electroweak theory. In the literature, the constraints are obtained by directly fitting $\tilde{g}_{V,e}^{\nu_e}$ and $\tilde{g}_{A,e}^{\nu_e}$ inside the neutrino-electron cross section. Due to the radiative corrections and the charge current contribution, the vector coupling naturally depends on the neutrino flavor, as shown in Eq. (2). Thus, to correctly compare the available data, we restrict our analysis to the flavor-independent neutral current couplings, $\tilde{g}_{V,\text{SM}}^{\nu_e}$ and $\tilde{g}_{A,\text{SM}}^{\nu_e}$, while keeping the neutrino charge radius contributions fixed to

their SM predictions. However, $\tilde{g}_V^{\nu_e}$ also depends on the experimental energy scale, e.g., due to the effect of the running of the weak mixing angle, which enters only the vector coupling. To combine correctly the different measurements, we thus correct for the dependence on the energy scale, and compare the value of the couplings at a common scale, chosen to be the Z boson mass, M_Z , as often done in the context of the weak mixing angle [11].

To this aim, we introduce a term, $\delta\tilde{g}_V$, in the definition of the coupling in Eq. (13) which accounts for the running of the weak mixing angle as predicted by the SM. Namely, $\delta\tilde{g}_V$ has been defined as the difference between the coupling constant at a certain energy scale q^2 with respect to its value at M_Z ,

$$\delta\tilde{g}_{V,\text{SM}}(q^2) = \tilde{g}_{V,\text{SM}}^{\nu_e}(q^2) - \tilde{g}_{V,\text{SM}}^{\nu_e}(M_Z), \quad (17)$$

so that the flavor-independent coupling at a generic scale q^2 can be written in terms of its value at M_Z ,

$$\tilde{g}_V^{\nu_e}(q^2) = \tilde{g}_V^{\nu_e}(M_Z) + \delta\tilde{g}_{V,\text{SM}}(q^2). \quad (18)$$

By substituting the above definition inside Eq. (13), we can measure directly $\tilde{g}_V^{\nu_e}(M_Z)$, which in this way is a universal quantity independent of the particular experiment. The correction $\delta\tilde{g}_{V,\text{SM}}^{\nu_e}(q^2)$ has a larger impact for low energy data. Indeed, $\delta\tilde{g}_{V,\text{SM}}^{\nu_e}(q^2 = 0)$ is about 50% of $\tilde{g}_{V,\text{SM}}^{\nu_e}(q^2 = 0)$.

In Fig. 3 (left), we show the results at 1σ CL on the neutral current couplings obtained accounting for such a momentum dependence in the considered ν ES experiments along with their combination. Differently from the results reported by the latest PDG electroweak review, in Fig. 10.1 of Ref. [11], we separate the flavor-dependent contribution due to the NCR and correct for the different experimental momentum transfer, to extract the neutral current flavor-independent coupling evaluated at M_Z . The global fit indicates a preference for the degenerate solution (obtained by swapping $\tilde{g}_{V,\text{SM}}^{\nu_e}$ and $\tilde{g}_{A,\text{SM}}^{\nu_e}$), while the SM prediction, as visible in the inset, lies just outside the 1σ contour. The difference in chi square between the two solutions is about $\Delta\chi^2 \simeq 2.1$, while the allowed values at 90% CL are

$$\tilde{g}_V^{\nu_e}(M_Z) = [-0.53, -0.45] \cup [-0.08, -0.03], \quad (19)$$

$$\tilde{g}_A^{\nu_e} = [-0.52, -0.48] \cup [-0.13, -0.03], \quad (20)$$

to be compared with the SM values $\tilde{g}_{V,\text{SM}}^{\nu_e}(M_Z) = -0.0433$ and $\tilde{g}_{A,\text{SM}}^{\nu_e} = -0.5062$.

If such a preference persists, new and more precise ν ES measurements would be needed. In Fig. 3 (left), we overlay the obtained contours with the sensitivity expected from a future xenon-based DMDD experiment with an exposure of 300 ton years [30,53]. It is interesting to notice that the

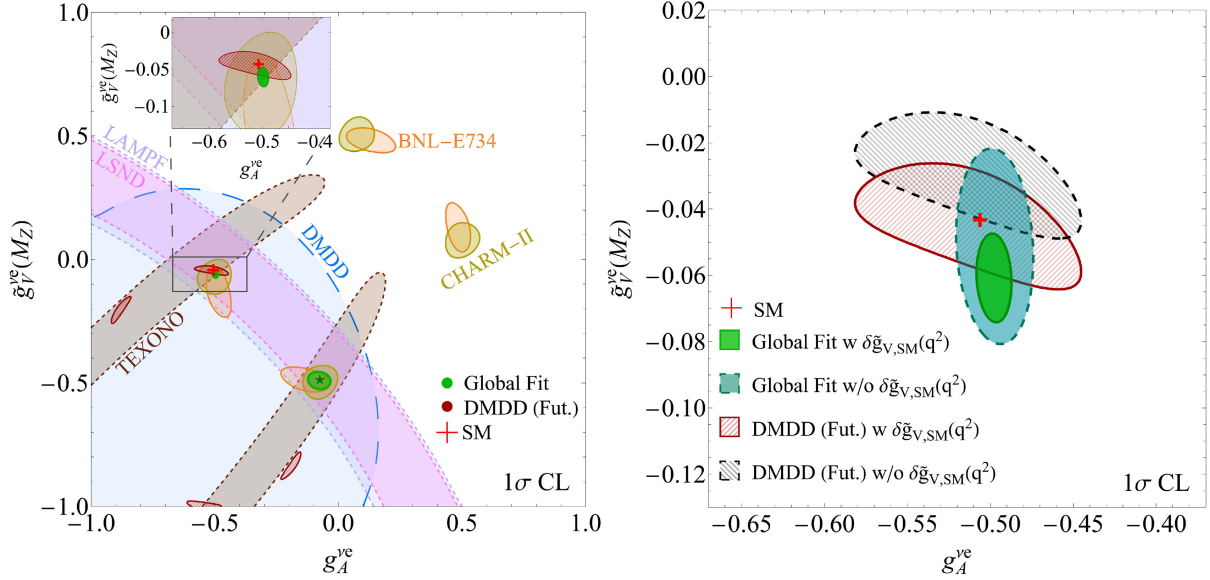


FIG. 3. Left: constraints at 1σ CL on the flavor-independent neutral current couplings $\tilde{g}_V^{\nu e}(M_Z)$ and the $g_A^{\nu e}$ from the different ν ES data along with their combination. The red cross indicates the SM prediction while the green star indicates the best fit. The dark red striped contour shows the potentiality of a future DMDD experiment [53]. In the inset, we show an enlargement of the contours around the SM prediction. Right: comparison of the global fit results with the sensitivity from a future DMDD experiment, including (solid) or not (dashed) the correction due to the momentum transfer.

expected precision will reach the level of our current global fit, thus showing the capability of discriminating the SM solution with respect to the degenerate one, without the need of including e^+e^- data with additional assumptions [11]. Thus, future DMDD experiments will play a crucial role in testing the standard model with neutrinos only. However, such a level of precision requires one to carefully account for the effects investigated in this Letter. In fact, even if the effect of the momentum transfer plays a small but nonnegligible role in the global fit of the current data, in the future it will be mandatory to account for it. This is shown in Fig. 3 (right), where, restricting ourselves around the SM values for the couplings, the result of the global fit performed by correcting for the momentum transfer is compared to the case in which no correction is included. We superimposed the contours obtained by the sensitivity study of a future DMDD in the same two scenarios. Neglecting the effect of momentum transfer results in a significant shift, as large as 50%, on $\tilde{g}_V^{\nu e}(M_Z)$. Future proposed measurements with high precision such as DUNE [54], future ultranear reactor experiments [55], and the LHC Forward Physics Facility [56] will provide similar crucial information for testing the SM with neutrinos.

To conclude, in this Letter we present the state-of-the-art of a global fit of neutrino data, in particular reanalyzing a vast sample of neutrino-electron and neutrino-nucleus scattering data, to extract the most stringent constraints on the neutrino charge radius, which show no significant evidence for flavor-dependent deviations from the SM

picture. Moreover, we set stringent constraints on the vector and axial-vector neutral current couplings to perform a robust test of the electroweak theory. The available data are not sufficient to exclude the degenerate solution, which remains the preferred one. Thus, we emphasize the importance of radiative corrections and momentum-dependent effects, highlighting their critical role in future precision measurements.

Data availability—The data that support the findings of this article are not publicly available because they are owned by a third party and the terms of use prevent public distribution. The data are available from the authors upon reasonable request.

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