Constraining nonstandard neutrino interactions with electrons

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We update the phenomenological constraints of the nonstandard neutrino interactions (NSNI) with electrons including in the analysis, for the first time, data from LAMPF, Krasnoyarsk, and the latest Texono observations. We assume that NSNI modify the cross section of elastic scattering of (anti) neutrinos off electrons, using reactor and accelerator data, and the cross section of the electron-positron annihilation, using the four LEP experiments, in particular, new data from DELPHI. We find more restrictive allowed regions for the NSNI parameters: $-0.11 < \varepsilon_{ee}^{\text{FD}} < 0.05$ and $-0.02 < \varepsilon_{e\tau}^{\text{FD}} < 0.09$ (90% C.L.). We also recalculate the parameters of tauonic flavor obtaining $-0.35 < \varepsilon_{e\tau}^{\text{FD}} < 0.50$ and $-0.51 < \varepsilon_{\tau\tau}^{\text{FD}} < 0.34$ (90% C.L.). Although more severe than the limits already present in the literature, our results indicate that NSNI are allowed by the present data as a subleading effect, and the standard electroweak model continues consistent with the experimental panorama at 90% C.L. Further improvement on this picture will deserve a lot of engagement of upcoming experiments.

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I. INTRODUCTION

Observations of neutrinos coming from the Sun, from nuclear reactors, from cosmic ray collisions in the high atmospheric altitudes and neutrinos observed in accelerator beams offer compelling evidence in favor of the neutrino oscillation hypothesis (for a complete panorama of this subject, see [1] and references therein). The oscillation phenomenon requires an extension of the minimal version of the SM gauge principle at energies near the electroweak breaking, including new nonstandard bosons [3,4]. Whatever the origin of the new interactions, it is important to quantify its strength. New interactions have to be included without spoiling neutrino oscillations and several other SM predictions which are consistent with the present experimental picture. In particular, NSNI strength can be estimated from neutrino phenomenology.

The effective Lagrangian which parametrizes the NSNI is given by [5–8]:

$$\mathcal{L}^{\text{NSNI}}_{\text{eff}} = \varepsilon_{\alpha\beta}^{f} \sqrt{2} G_F \langle \bar{\nu}_\beta \gamma^{\mu} L \nu_\alpha \rangle \langle \bar{f} \gamma_{\rho} P f \rangle,$$

where $G_F$ is the Fermi constant, $\alpha$ and $\beta$ represent the leptonic flavor, $f$ refers to the fermions of the first family ($f = e, u, d$), and $\nu$ represents the chiral operators ($P = R, L$).

The NSNI strength is taken into consideration in the $\varepsilon_{\alpha\beta}^{fp}$ parameters. The NSNI could conserve the lepton flavor, in which case it is called flavor diagonal (FD) $\alpha = \beta$, or not, when it is called flavor changing $\alpha \neq \beta$.

In this work, we address the sensitivity of the present data on constraining the NSNI with electrons ($f = e$). We use LSND, Irvine, Rovno, and MUNU experimental data which have already been used to constrain NSNI [6] adding, for the first time in this kind of analysis, LAMPF [9], Krasnoyarsk [10] and, in particular, the latest Texono data [11] to find limits on FD parameters $\varepsilon_{\alpha\alpha}^{fp}$ ($P = R, L$). Also, we consider the cross section for the process $e^{+}e^{-} \rightarrow \nu\bar{\nu}\gamma$ measured in the LEP experiments: ALEPH, OPAL, and L3 (elsewhere in Refs. [8,12]) including new data from the DELPHI experiment [13] to constrain $\varepsilon_{\alpha\alpha}^{fp}$ ($P = R, L$) with $\alpha = e, \tau$.

Our analysis constrains NSNI in more stringent ranges than the ones found in the literature. These results indicate that NSNI are allowed by the present data as a subleading effect and the standard electroweak model continues consistent with the experimental at 90% C.L.

The present article is organized as follows: to constrain the FD NSNI $\varepsilon_{\alpha\alpha}^{fp}$ ($\alpha = e, \tau$) parameters, first, we will use neutrino elastic scattering cross section data in Sec. II. Second, we will calculate the NSNI constrains from the cross section for process $e^{+}e^{-} \rightarrow \nu\bar{\nu}\gamma$ using the four LEP experiments, in Sec. III. Then, we perform the global analysis for the $\varepsilon_{\alpha\alpha}^{fp}$ parameters in Sec. IV. The summary and conclusion are presented in Sec. V.

II. NEUTRINO ELASTIC SCATTERING

For low energies, the neutrino-electron elastic scattering can be described by a SM effective theory [5]:

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For neutrino interactions with electrons \( f = e \), the NSNI Lagrangian in Eq. (1) takes a form that looks like the SM one in Eq. (2) with the SM couplings replaced by the new parameters \( e_{\nu e}^{\nu e} \), in the form:

\[
-L_{\text{eff}}^{\text{NSNI}} = 2\sqrt{2}G_F \left( (\bar{\nu}_e \gamma^\mu L \nu_e)(\bar{e} \gamma_\mu L e) + (\bar{\nu}_\mu \gamma^\mu L \nu_\mu)(g_R^e \bar{e} \gamma_\mu L e + g_L^e \bar{e} \gamma_\mu L e) \right),
\]

(3)

Adding the effective SM theory in Eq. (2) to the NSNI Lagrangian in Eq. (3) for \( f = e \), we see the NSNI effect is given by the following form:

\[
\sigma(e_{\nu e}^{\nu e}, e_{\nu e}^{\nu e}) = \int_0^{E_{\nu, \text{max}}} dT \frac{d\sigma(E_{\nu}, T)}{dT} = \frac{2m_e G_F^2 E_{\nu}}{\pi} \left( \frac{g_R^e}{g_L^e} + \frac{1}{3} \frac{g_L^e}{g_R^e} \right).
\]

(6)

Calculating the antineutrino cross section involves the knowledge of the antineutrino production flux (spectrum), the energy resolution function and, in some cases, other reactor characteristics, for instance, the efficiency. In a previous analysis, the authors of Ref. [6] used a resolution function in the form of a Gaussian distribution with mean \( T \) and variance \( T^{0.7} \), only for the MUNU experiment [14]. We reanalyzed the MUNU experiment using the Gaussian resolution, also testing with another variance \( T^{0.57} \) [15], and we did not find a difference compared with our calculation, ignoring the resolution effects. In the last case, the cross section used has the following form:

\[
\sigma(e_{\nu e}^{\nu e}, e_{\nu e}^{\nu e}) = \int_{T_{\text{min}}}^{T_{\text{max}}} dT \int_{E_{\nu, \text{min}}}^{E_{\nu, \text{max}}} dE_{\nu} \lambda(E_{\nu}) \frac{d\sigma}{dT}(E_{\nu}, T),
\]

(7)

where \( \lambda(E_{\nu}) \) is the spectrum of the fission elements \( ^{235}\text{U}, ^{239}\text{Pu}, ^{241}\text{Pu}, \) and \( ^{238}\text{U} \), \( \phi_k(E_{\nu}) \) is the flux parameterization and \( \alpha_k \) the abundance for each element.

The integration limits in Eq. (7), \( T_{\text{min}} \) and \( T_{\text{max}} \), are the cinematic cuts fixed by the experiments. The energy limit \( E_{\nu, \text{max}} \) is essentially given by the end of the spectrum (\( \sim 9 \text{ MeV} \)), and \( E_{\nu, \text{min}}(T) = 0.5(T + \sqrt{T^2 + 2m_e T}) \) [16].

**B. Geometrical form of the restriction**

Comparing the theoretical cross sections with the experimental ones, and fixing the SM couplings \( g_{R}^e \) (or the value of \( \sin^2 \theta_W = 0.2326 \) including radiative corrections [7]), we obtain the restriction of the NSNI parameters \( e_{\nu e}^{\nu e} \).

We used LSND, Irvine, Rovno, and MUNU experiments from the literature [6]. And we added, up to our knowledge, for the first time in this kind of analysis, LAMPF [9], Krasnoyarsk [10], and the latest Texono data [11]. The new experimental results to be used in our analysis are shown in Table I.\(^1\)

\(^1\)In fact, these new experiments were used to leptonically determine the Weinberg angle (\( \sin^2 \theta_W \)) [17] or to constrain another NSNI parameter [18].

**Table I. Experiments added with respect to Ref. [6], in order to constrain the NSNI parameters \( e_{\nu e}^{\nu e} \).**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( T ) [MeV]</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAMPF ( \nu_e e )</td>
<td>7–60</td>
<td>( \sigma = [10.0 \pm 1.8]E_{\nu} \times 10^{-45} \text{ cm}^2 ) [9]</td>
</tr>
<tr>
<td>Krasnoyarsk ( \bar{\nu}_e e )</td>
<td>3.15–5.175</td>
<td>( \sigma = [4.5 \pm 2.4] \times 10^{-46} \text{ cm}^2 \text{ fis}^{-1} ) [10]</td>
</tr>
<tr>
<td>Texono ( \bar{\nu}_e e )</td>
<td>3–8</td>
<td>( R = [1.08 \pm 0.26] \times R_{\text{SM}}^{\text{NSNI}} ) [11]</td>
</tr>
</tbody>
</table>
For the antineutrino case, we used the theoretical flux parametrization from [19], for almost all experiments except for Rovno, in which case we used the parametrization from [20]. We also used the average abundances \( a_1 = a(\text{Bi}^{209}) = 54\%, \ a_2 = a(\text{Bi}^{208}) = 33\%, \ a_3 = a(\text{Bi}^{207}) = 6\%, \) and \( a_4 = a(\text{Bi}^{206}) = 7\% \) over an annual reactor cycle [14].

In the MUNU case, the available measurement is the event rate. Then, we calculate that rate including a normalization in the theoretical flux \( N \), with the purpose of parametrizing our ignorance on the reactor efficiency \( \bar{\epsilon} \) (\( N^{-1} \sim \bar{\epsilon} \)).

We define the integrals of the differential cross section in Eq. (7) in the form:

\[
I_i = \int_{T_{\text{min}}}^{T_{\text{max}}} dT \int_{E_{\text{min}}(T)}^{E_{\text{max}}(T)} \lambda(E) \sigma_i(E, T), \tag{8}
\]

where \( \sigma_i(E, T) \) is the differential cross section coefficient of the NSNI parameter. Then we find

\[
\sigma(e^{-}e^{-}, e^{-}e^{-}) = \frac{I_1 \bar{g}_R^2 + I_2 \bar{g}_L^2 - I_3 \bar{g}_R \bar{g}_L}{\text{C.L.}}. \tag{9}
\]

From Eqs. (6) and (9), we obtain ellipses in the NSNI parameters. The ellipses in the antineutrino case are rotated by an angle \( \tan(2\phi) = I_3/(I_1 - I_2) \), while for neutrino scattering, the ellipses are not, because in the approximation \( m_e \ll E_\nu \), the term \( I_3 \) is negligible.

To quantify the region for each parameter, we use the \( \chi^2 \) analysis in the way detailed in the next section.

**C. The \( \chi^2 \) analysis**

We use the usual definition for the \( \chi^2 \) function:

\[
\chi^2(e^{-}e^{-}, e^{-}e^{-}) = \sum_i \left[ \frac{[\sigma_i(e^{-}e^{-}, e^{-}e^{-}) - \sigma_{\text{exp}}^i]^2}{\Delta_i^2} \right], \tag{10}
\]

where \( \sigma_{\text{exp}}^i \) and \( \Delta_i \) are the measurement of the cross section and its error, respectively, for the \( i \) experiment. Minimizing Eq. (10) using the theoretical cross section from Eqs. (6) and (9), we obtain the regions of the right panel in Fig. 1.

These four regions are the result of the functional dependence of the cross section of Eq. (6), which are ellipses with horizontal main axes in the NSNI parameter space intercepted by ellipses with vertical main axes derived from the antineutrino cross section given by Eq. (9).

Each region of Fig. 1 is calculated from \( \chi^2_{\text{min}} + \Delta \chi^2 \). The fixed value for \( \Delta \chi^2 = 4.61, 5.99, 9.21 \) for two parameters, corresponds to 90%, 95%, and 99% C.L., respectively. We find \( \chi^2_{\text{min}} = 6.17 \) for 8 experiments so, we have 6 degrees of freedom (d.o.f).

Our regions are smaller than the corresponding one found in Ref. [8], which is significative from the contour at 99% C.L., now defining four separated regions. The SM point (0, 0) is included at 90%.

In Table II, we summarize our constraints for \( e^{-}e^{-} \) and \( e^{-}e^{-} \) and compare with previous limits around the SM region using only the scattering data [6]. In the first column, we show the largest range of \( e^{-}e^{-} \) regardless of the value of remaining parameter \( e^{-}e^{-} \) and vice-versa. In other words, this analysis allows the remaining parameter to freely varying.

We observe that our parameter constraints are more restricted than those ones presented in Ref. [6], shown in the second column of Table II.

**III. PAIR ANNIHILATION IN NEUTRINOS**

The first analysis to restrict the NSNI parameters with the process \( e^+e^- \rightarrow \nu\bar{\nu}\gamma \) was made by the authors of Ref. [5], and later, updated with more experiments in Ref. [8]. We follow both approaches adding even more data.

**A. Cross section**

Taking into consideration both SM and NSNI interactions, the total cross section can be written as \( \sigma = \sigma^{\text{SM}} + \sigma^{\text{NS}} \). In the “radiator” approximation to describe the photon emission, the cross section for the process \( e^+e^- \rightarrow \nu\bar{\nu}\gamma \) can be calculated as [5]

\[
\sigma(s) = \int dx \int dy H(x, y; s) \sigma_0(\delta), \tag{11}
\]
where \( x = \frac{2E_{\gamma}}{\sqrt{s}} \), \( \sqrt{s} \) is the center-of-mass energy, \( s = (1 - x)s \), \( y = \cos \theta_{\gamma} \) (photon angle), \( \sigma_0 \) is the “bare” cross section (without the photon vertex) and \( H(x, y; s) \) represents the probability to “radiate” a photon in a scale \( s \), the fraction energy \( x \) in the center-of-mass reference.

We use the radiation function \( H(x, y; s) \) from [21]

\[
H^{(a)}(x, y; s) = \frac{2\alpha}{\pi} \frac{1}{x} \frac{1}{1 - x^2} \left[ \left( 1 - \frac{x^2}{2} \right)^2 + \frac{x^2 y^2}{4} \right],
\]

where \( \alpha \) is the fine structure constant. The bare SM cross section is given by

\[
\sigma_{0\text{SM}}^{(s)} = \frac{N_g G_F^2}{6\pi} M_W^2 (g_R^g)^2 
\left[ \frac{s}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \right]
+ \frac{G_F^2}{\pi} \frac{M_W^2}{s} \left[ \frac{s + 2M_W^2}{2s} \left( \frac{M_W^2}{s} + \frac{M_W^2}{s} \right) \right]
\times \log \left( \frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} \left( \frac{M_W^2}{s} + \frac{M_W^2}{s} \right)
\times \left[ \frac{M_W^2}{s} \log \left( \frac{s + M_W^2}{M_W^2} \right) - \frac{M_W^2}{s} \left( \frac{3}{2} \right) \right],
\]

and the bare NSNI cross section is

\[
\sigma_{0\text{NSNI}}^{(s)} = \sum_{a=e, \mu, \tau} \frac{G_F^2}{6\pi} \left[ \frac{(e_{aR}^e)^2 + (e_{aR}^e)^2}{(s - M_Z^2)^2 + (M_Z \Gamma_Z)^2} \right]
- 2g_R^g (e_{aR}^e + (g_R^g e_{aR}^e)) \left[ \frac{M_Z^2}{s} \log \left( \frac{s + M_W^2}{M_W^2} \right) \right]
+ \frac{G_F^2}{\pi} \left[ \frac{(s + M_W^2)^2}{s^2} \log \left( \frac{s + M_W^2}{M_W^2} \right) \right]
- \frac{M_W^2}{s} \left( \frac{3}{2} \right).
\]

where \( N_{\nu} \) is the number of active neutrinos, \( M_W \) and \( M_Z \) are the boson \( W \) and \( Z \) masses, respectively, and \( \Gamma_Z \) is the total decay rate of \( Z \).

### Table III. DELPHI data [13].

| \( \sqrt{s} \) (GeV) | \( \sigma^{\text{exp}} \) (pb) | \( \sigma^{\text{MC}} \) (pb) | \( N_{\text{obs}} \) | \( E_{\gamma} \) (GeV) | \( |y| \) |
|---------------------|------------------|----------------|----------------|------------------|---------------|
| 187.1               | 1.78 ± 0.13      | 1.89           | 177            | \( x \geq 0.06 \) | \( \leq 0.71 \) |
| 196.8               | 1.41 ± 0.13      | 1.75           | 127            | \( x \geq 0.06 \) | \( \leq 0.71 \) |
| 205.4               | 1.50 ± 0.11      | 1.61           | 190            | \( x \geq 0.06 \) | \( \leq 0.71 \) |
| 187.1               | 1.98 ± 0.14      | 1.97           | 220            | 0.2 ≤ \( x \) ≤ 0.9 | 0.85 ≤ \( |y| \) ≤ 0.98 |
| 196.8               | 1.71 ± 0.14      | 1.76           | 175            | 0.2 ≤ \( x \) ≤ 0.9 | 0.85 ≤ \( |y| \) ≤ 0.98 |
| 205.4               | 1.71 ± 0.12      | 1.57           | 224            | 0.2 ≤ \( x \) ≤ 0.9 | 0.85 ≤ \( |y| \) ≤ 0.98 |
| 187.1               | 1.37 ± 0.14      | 1.44           | 126            | 0.3 ≤ \( x \) ≤ 0.9 | 0.99 ≤ \( |y| \) ≤ 0.990 |
| 196.8               | 1.22 ± 0.14      | 1.29           | 90             | 0.3 ≤ \( x \) ≤ 0.9 | 0.99 ≤ \( |y| \) ≤ 0.990 |
| 205.4               | 1.12 ± 0.11      | 1.18           | 114            | 0.3 ≤ \( x \) ≤ 0.9 | 0.99 ≤ \( |y| \) ≤ 0.990 |
The data. The form of the allowed regions shown in this figure is the result of the interception of the circles’ LEP data only.

Even before the global analysis, observe that LEP experiments constrain $-0.05 \leq e^{ee}_{e} \leq 0.15$ more than the $-0.35 \leq e^{ee}_{e} \leq 0.55$ parameter around SM point (0, 0). Because of the form of the constrained region (one region, left panel of Fig. 2) we expect in the global analysis (including the four regions of the scattering data, contours of Fig. 1) the decreasing of the number of regions appearing in Fig. 1.

The authors of Ref. [5] were the first to notice the importance of the process $e^{+}e^{-} \rightarrow \nu \bar{\nu} \gamma$ to constrain the $e^{\mu}_{L}$ parameters, due to the lack of cross section data for $\tau$ elastic scattering. To constrain those parameters we use a $\chi^2$ function analog as Eq. (10):

$$\chi^2(e^{R}_{\tau\tau}, e^{L}_{\tau\tau}) = \sum_{i} \left[ \sigma_{i}(e^{R}_{\tau\tau}, e^{L}_{\tau\tau}) - \sigma_{i}^{\text{exp}} \right]^2 / \Delta_{i}^2,$$

where $\sigma_{i}(e^{R}_{\tau\tau}, e^{L}_{\tau\tau})$ is given by Eq. (18).

In the right panel of Fig. 2 are shown the contours for these parameters, and the greatest constraints we obtain are $-0.35 < e^{R}_{\tau\tau} < 0.50$ and $-0.51 < e^{L}_{\tau\tau} < 0.34$ at 90% C.L. All the constraints on $e^{R}_{\tau\tau}$ are summarized in Table IV. Note that here we use the same procedure previously used to find Table II (see corresponding explanation in the text). Also shown in this Table are the results of the six parameter variation realized in Ref. [8]. Note that our results are systematically more restrictive.

### IV. GLOBAL ANALYSIS

Putting together the two main $\chi^2$ statistics we have made, from neutrino elastic scattering $\chi^2_{\text{elast}}$ and pair

| TABLE IV. Constraints of the FD NSNI parameters $e^{R}_{ee}$ and $e^{L}_{ee}$ at 90% C.L. Our results are found using the same procedure adopted to find the results shown in Table II. |
|---|---|
| From Fig. 2 (right) and Fig. 3 | 6-Parameters, Ref. [8] |
| $-0.11 < e^{R}_{ee} < 0.5$ | $-0.03 < e^{R}_{ee} < 0.18$ |
| $-0.02 < e^{L}_{ee} < 0.09$ | $-0.14 < e^{L}_{ee} < 0.09$ |
| $-0.35 < e^{R}_{\tau\tau} < 0.50$ | $-0.4 < e^{R}_{\tau\tau} < 0.6$ |
| $-0.51 < e^{L}_{\tau\tau} < 0.34$ | $-0.6 < e^{L}_{\tau\tau} < 0.4$ |

FIG. 2 (color online). Left panel: contours at 90% (darker internal part of each region), 95% (90% region plus wrapped region), and 99% (sum of all regions) of C.L for the $e^{R}_{ee}$ parameters, we find $\chi^2_{\text{min}} = 26.04$. Right panel: contours for the $e^{L}_{ee}$ parameters, we find $\chi^2_{\text{min}} = 25.83$. We use 37 experiments from [8,12] and Table III, then, we have 35 d.o.f.
From the pair annihilation cross section analysis, we obtain different regions than the one obtained by different authors. We can visualize that, from the LEP circles, the allowed region has to be qualitatively coincident with the one obtained by our analysis. Also, we are not surprised with the regions we obtain since they include the SM predictions. The difference between the regions for electronic and tauonic flavor are due to the numerical value for the coefficient $I_2$.

In Refs. [5,6] the analysis was done assuming a variation of one and two parameters simultaneously, and in Ref. [8] a six parameter variation was done. It is not clear which sort of variation is more convenient. In fact, only if one assumes a specific SM extension, this kind of question can be appropriately answered.

In our model independent approach, we perform a two parameter variation and our results are more restrictive than what is obtained for a six parameter variation.

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