Erratum: Non-standard neutrino interactions and low energy experiments

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ABSTRACT: We correct the constraints on non-standard neutrino interactions (NSI) from deep inelastic scattering. We also provide a detailed derivation of the Borexino bounds on Rayleigh operators, while the original manuscript relied on a naive estimate. The updated Borexino constraints are weaker than the ones presented in the original manuscript.

6.3   Constraints on NSI from deep inelastic scattering

The bounds listed in equations (6.22) and (6.23) of section 6.3 of the original manuscript [1] contain typographical errors. The correct bounds are

$$\mathcal{C}^{(6)}_{1,u(d,s)}: \quad \Lambda > 669(713,275)\,\text{GeV} \quad (\nu_e), \quad \Lambda > 1402(1540,780)\,\text{GeV} \quad (\nu_\mu), \quad (6.22)$$

$$\mathcal{C}^{(6)}_{2,u(d,s)}: \quad \Lambda > 419(451,322)\,\text{GeV} \quad (\nu_e), \quad \Lambda > 1048(628,472)\,\text{GeV} \quad (\nu_\mu). \quad (6.23)$$

6.4   Other constraints

The second part of section 6.4 of the original manuscript [1], which describes the bounds on Rayleigh operators from Borexino, relied on a naive estimate that led to an overestimate of the bounds. The paragraph after equation (6.30), up to and including equation (6.32), should be replaced with the text below:

The measured neutrino scattering rates in Borexino also bound Rayleigh operators $\mathcal{C}_{1,2}^{(7)}$. These contribute at 1-loop to the $\nu e \to \nu e$ scattering and at tree level to $\nu e \to \nu e \gamma$, i.e., to the neutrino scattering with an emission of an extra photon. In Borexino both processes result in the same detector response and thus need to be added, giving the total scattering cross section $\sigma_{\nu_\alpha e}$ for neutrino flavor ν_α (defined to include also the SM contributions). We calculate the tree-level $\nu e \to \nu e \gamma$ scattering numerically by implementing the Rayleigh operator in `MadGraph` [2]. For the much smaller 1-loop induced $\nu e \to \nu e$ scattering we use a simple NDA estimate, taking $\sigma \simeq \left(|\hat{\mathcal{C}}_1^{(7)}|^2 + 3|\hat{\mathcal{C}}_2^{(7)}|^2/2 \right) \alpha^4 s^2/(48\pi^4)$, where $s = m_e^2 + 2 m_e E_\nu$ is the center of mass energy of the scattering process.

The event rate per day per 100 tons of detector is given by

$$
\begin{aligned}
R_i(\hat{C}_1^{(7)}, \hat{C}_2^{(7)}) = T N_e \int dE_\nu \, \phi_i(E_\nu) \Big[& P_i^e \sigma_{\nu_e e} \left(E_\nu, \hat{C}_{1,e}^{(7)}, \hat{C}_{2,e}^{(7)} \right) \\
& + P_i^\mu \sigma_{\nu_\mu e} \left(E_\nu, \hat{C}_{1,\mu}^{(7)}, \hat{C}_{2,\mu}^{(7)} \right) \Big] ,
\end{aligned}
\tag{6.31}
$$

with $T = 1\,\mathrm{day} = 8.64 \cdot 10^4\,\mathrm{s}$ the exposure time and $N_e = 3.307 \cdot 10^{31}$ the number of target electrons in 100 tons of detector mass, and $\ell = e, \mu$ denote the incoming neutrino flavor for the $C_{j,\ell}^{(7)}$, $j = 1, 2$ Wilson coefficients. The main components of the solar neutrino flux on Earth, $\phi_i(E_\nu)$, ref. [3], are due to proton-proton fusion ($i = pp$), Berillium 7 electron capture ($i = {}^7\mathrm{Be}$), and proton electron capture ($i = pep$). The ν_e from pp have a continuous energy spectrum with the maximal energy $E_{\nu,\max} = 0.423\,\mathrm{MeV}$, while ${}^7\mathrm{Be}$ and pep neutrinos have an almost monochromatic spectrum with energy $E_{{}^7\mathrm{Be}} = 0.863\,\mathrm{MeV}$ and $E_{pep} = 1.445\,\mathrm{MeV}$. The lower integration limit $E_{\nu,\min} = 0.139\,\mathrm{MeV}$ in (6.31) is the minimum incoming neutrino energy that can still produce $T = T_{th} \sim 50\,\mathrm{keV}$ recoil in Borexino, while the upper integration limit is $E_{\nu,\max}$. The ν_e produced in the Sun undergo flavor oscillations while propagating to Earth, giving the ν_e survival probabilities $P_{pp}^e = 0.554\,, P_{{}^7\mathrm{Be}}^e = 0.536\,, P_{pep}^e = 0.529\,,$ once matter effects are taken into account [4], while $P_i^\mu = (1 - P_i^e)/2$, assuming for simplicity maximal θ_{23}.

We derive the bounds on the experimentally allowed values of the Rayleigh operators $\hat{C}_{j,\ell}^{(7)}$ from the chi-squared function

$$
\chi^2(\vec{\alpha}, \hat{C}_j) = \sum_i \frac{\left[R_{\mathrm{meas},i} - R_i(\hat{C}_1^{(7)}, \hat{C}_2^{(7)})(1 + \alpha_i) \right]^2}{\sigma_i^2} + \left(\frac{\alpha_i}{\sigma_{\alpha_i}} \right)^2 ,
\tag{6.32}
$$

where the sum is over the three types of solar neutrino fluxes, with the corresponding SM rates in Borexino phase-II given by $R_{pp}(0) = 131.4$, $R_{{}^7\mathrm{Be}}(0) = 48.1$, $R_{pep}(0) = 2.8$. The parameters α_i are marginalized over, and account for theoretical errors on the predictions, $\sigma_{\alpha_{pp}} = 1.1\%, \sigma_{\alpha_{{}^7\mathrm{Be}}} = 5.8\%, \sigma_{\alpha_{pep}} = 1.5\%$, while $R_{\mathrm{meas},pp} = 134 \pm 10$, $R_{\mathrm{meas},{}^7\mathrm{Be}} = 48.3 \pm 1.1$, $R_{\mathrm{meas},pep} = 2.43 \pm 0.36$ are the masured event rates and their statistical uncertainties, $R_{\mathrm{meas},i} \pm \sigma_i$. We convert the 1σ allowed ranges on $\hat{C}_{j,\ell}^{(7)}$

(switching on one at a time) to the bounds on the effective scale, Λ

$$\mathcal{C}_1^{(7)}: \qquad \Lambda > 86\,\mathrm{MeV} \quad (\nu_e), \qquad \Lambda > 55\,\mathrm{MeV} \quad (\nu_\mu), \tag{6.33}$$

$$\mathcal{C}_2^{(7)}: \qquad \Lambda > 98\,\mathrm{MeV} \quad (\nu_e), \qquad \Lambda > 63\,\mathrm{MeV} \quad (\nu_\mu), \tag{6.34}$$

by setting the corresponding dimensionless Wilson coefficient $C_{j,\ell}^{(7)} = 1$ in (2.1).

Our previous estimates of the modified neutrino scattering rates in Borexino resulted in the strongest bounds on the Rayleigh operators. The corrected bounds from Borexino are substantially weaker and insignificant compared to the bounds from COHERENT and CHARM.

The corrected bounds from deep inelastic scattering and from Borexino affect the plots in figures 6 and 7. The updated figures are shown below.
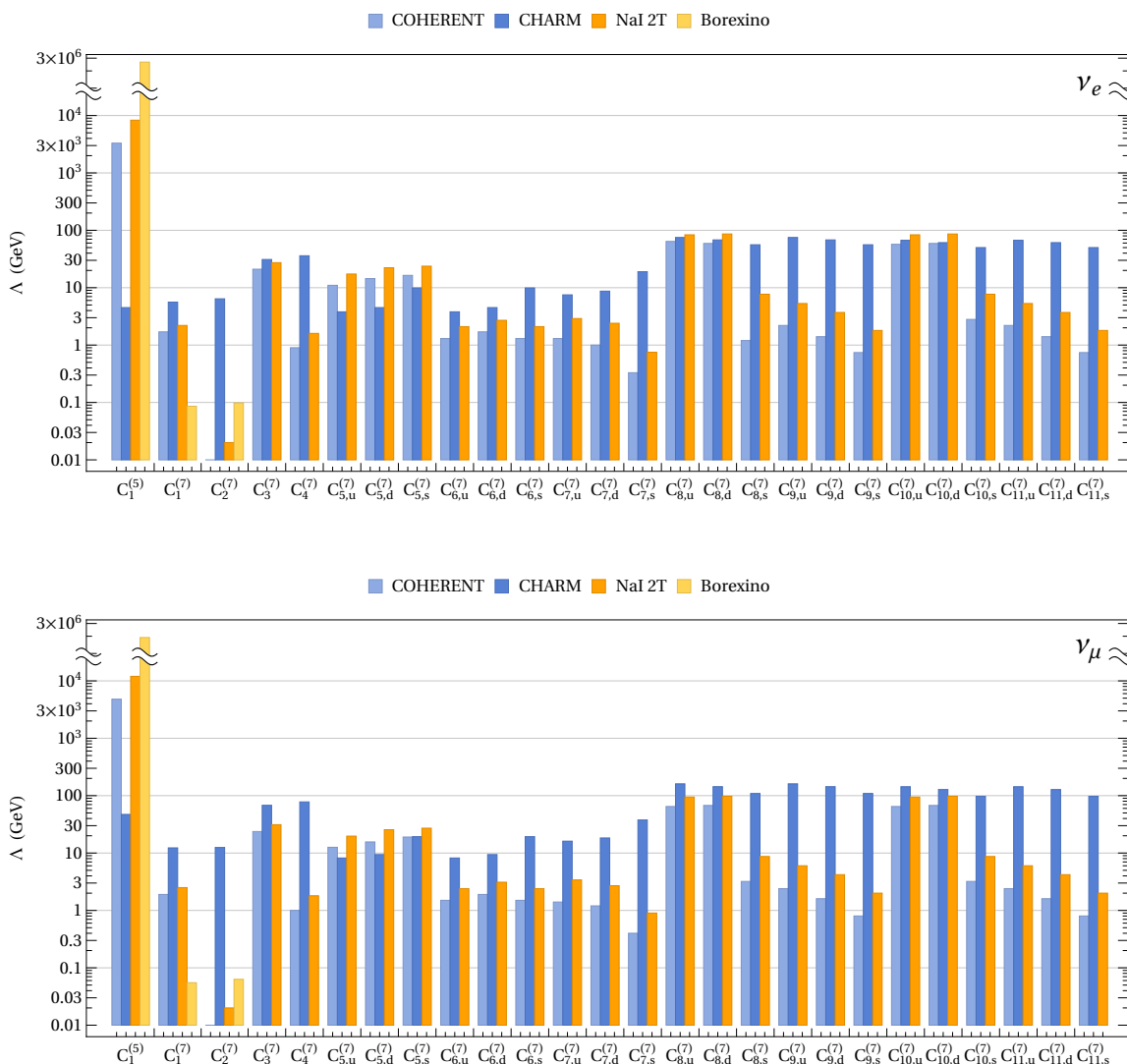

Figure 6. Limits from COHERENT, CHARM, Borexino, and projected limits from a NaI 2T experiment on the scale Λ of dimension 5 and dimension 7 NSI operators for electron neutrinos (top) and muon neutrinos (bottom).
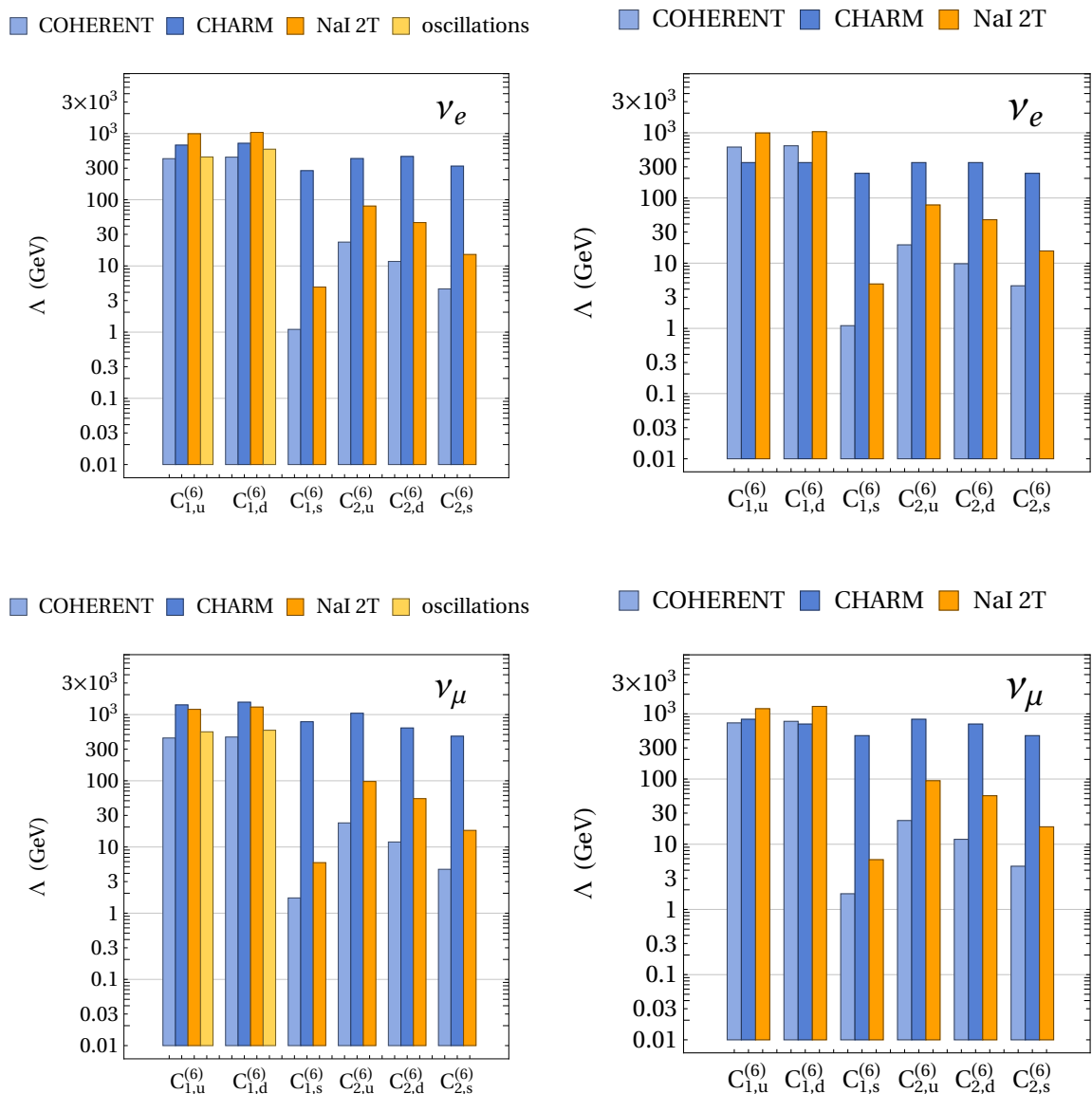
Figure 7. Limits from COHERENT, CHARM, neutrino oscillations and projected limits from a NaI 2T experiment on the scale Λ of dimension 6 operators for electron neutrinos (top) and muon neutrinos (bottom). The two panels on the left correspond to lepton flavor conserving operators $(\nu_i \to \nu_i)$, the ones on the right to lepton flavor violating operators $(\nu_i \to \nu_j, i \neq j)$.

References

[1] W. Altmannshofer, M. Tammaro and J. Zupan, *Non-standard neutrino interactions and low energy experiments*, *JHEP* **09** (2019) 083 [`arXiv:1812.02778`] [ɪɴSPIRE].

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[3] E. Vitagliano, I. Tamborra and G. Raffelt, *Grand unified neutrino spectrum at Earth: Sources and spectral components*, *Rev. Mod. Phys.* **92** (2020) 045006.

[4] A.N. Khan, W. Rodejohann and X.-J. Xu, *Borexino and general neutrino interactions*, *Phys. Rev. D* **101** (2020) 055047 [`arXiv:1906.12102`] [ɪɴSPIRE].