Solar neutrino constraints on singly charged Higgs boson via EνES

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Outline

Introduction

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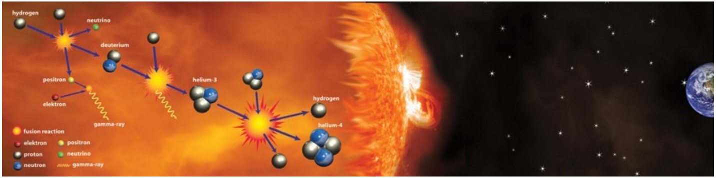
- Solar neutrinos rarely interact, intensively available, and well-directional messengers that have been one of the deriving sources of developments in neutrino physics for decades.
- Since the slow progress after the discovery of the SM Higgs at the energy frontier, shifting to other facility may provide alternative perspectives.
- Advancement of solar neutrino experiments and DD-DM facilities are being planned or under construction.

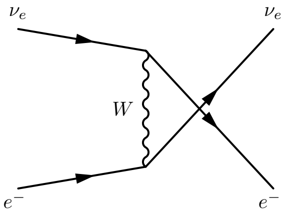


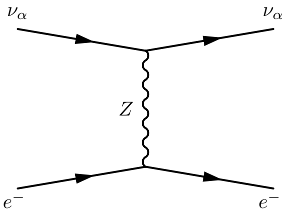
- Massive neutrinos is a strong moti- vation for searching BSM physics.
- We consider here the contribution of charged boson from the Higgs Triplet Model (HTM) (Cheng, Li, 1980).
- It provides an alternative way to introduce the smallness of neutrino masses through a mechanism called type-II see-saw.
- Previous studies have explored the model from various experiments: colliders, nuclear reactor, etc.
- Focusing on the singly charged Higgs, we consider the recent data from direct detection of dark matter experiments: PandaX-4T and XENONnT.

Elastic Neutrino-Electron Scattering ($E\nu ES$)

EνES Process

- It is is a pure leptonic process in the SM that provides one aspect of neutrino interaction with matter.
- The incoming neutrino can interact with the electron cloud in the target material in direct detection experiments .



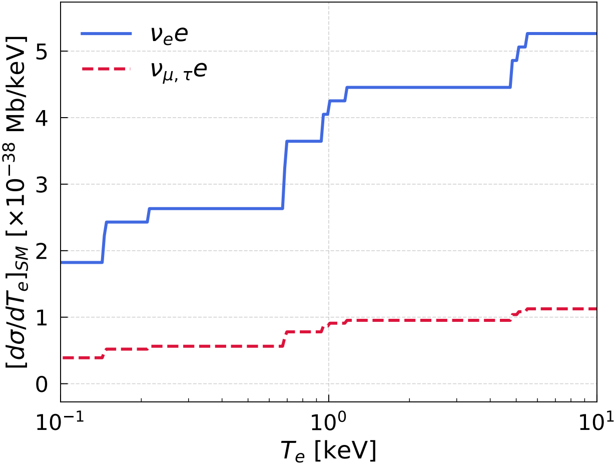


- The differential cross section can be written as

$$\left[\frac{d\sigma_{\nu_\alpha e}}{dT_e}\right]_{\rm SM} = Z_{\rm eff}(T_e)\frac{G_F^2 m_e}{2\pi}\left[(g_V+g_A)^2 + (g_V-g_A)^2\left(1-\frac{T_e}{E_\nu}\right)^2 - (g_V^2-g_A^2)\frac{m_e T_e}{E_\nu^2}\right], \tag{1}$$

$$g_V = -\frac{1}{2} + 2s_W^2 + \delta_{\alpha e}, \quad g_A = -\frac{1}{2} + \delta_{\alpha e}, \tag{2}$$

- The number of effective electron charges that can be ionized: $Z_{\rm eff}(T_e)$.



- The effective electron charge effects on the EνES cross-section for the case of xenon target.

Charged Higgs

Brief review

- The HTM is based on the same symmetry group $SU(2)_L \times U(1)_Y$ as in the SM (Arhib *et al.*, 2011), with additional triplet field $\Delta \sim (1, 3, 1)$.

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix} \tag{3}$$

- The gauge invariant Yukawa Lagrangian:

$$\mathcal{L}_{\mathrm{Yukawa}} = -f_{ij} L_i^T C i\sigma_2 \Delta L_j + \mathrm{h.c.}, \tag{4}$$

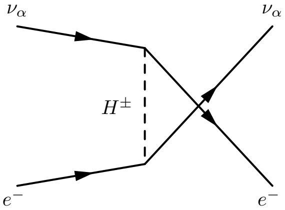
- It contains all the Yukawa sectors of the SM plus one extra term that leads after spontaneous symmetry breaking to (Majorana) mass terms for the neutrinos, without requiring right-handed neutrino states.

- The Higgs triplet interaction term at tree-level:

$$\mathcal{L} = -f_{ij}\nu_{iL}^T C\Delta^0 \nu_{jL} + \sqrt{2} f_{ij}\nu_{iL}^T C\Delta^+{}_{jL} + f_{ij} l_{iL}^T C\Delta^{++}{}_{jL} + \text{h.c.}. \quad (5)$$

  with $\nu^c(p) = C\bar{\nu}^T$ or $\bar{\nu}^c = \nu^T C$.
- In this work, the contribution of a singly charged boson from the HTM is investigated on neutrino-electron scatterings using solar neutrinos.
- We note that the model has been widely studied: mediator of DM (Greljo *et al.*, 2013), $e^- e^+$ annihilation (Aali *et al.*, 2022), multi-lepton anomalies at ATLAS (Ashanujjaman *et al.*, 2024).

Contribution to EνES



- The amplitude can be written as

$$-i\mathcal{M}_\Delta = [-if_{\alpha e}\sqrt{2}\bar{e}^c P_L \nu_\alpha]\left[\frac{-i}{q^2 - m_{H^\pm}^2}\right][-i\sqrt{2}f_{e\alpha}^*\bar{\nu}_\alpha^c P_L e], \quad (6)$$

- For massive $m_{H^\pm}$, and applying Fierz identity we obtain

$$\mathcal{M}_\Delta = \frac{f_{\alpha e}^2}{m_{H^\pm}^2}[\bar{e}\gamma^\mu P_L e][\bar{\nu}_\alpha \gamma_\mu P_L \nu_\alpha], \quad (7)$$

- It is in analogy with the SM form.
- Therefore, the contribution of the charged Higgs can be obtained by substituting to the SM results :

$$g_{V_\Delta} = g_V - \frac{f_\alpha^2}{m_{H^\pm}^2}\frac{1}{2\sqrt{2}G_F} \tag{8}$$

$$g_{A_\Delta} = g_A - \frac{f_\alpha^2}{m_{H^\pm}^2}\frac{1}{2\sqrt{2}G_F} \tag{9}$$

- Using solar neutrinos, we can evaluate the coupling constant $f_{ee}, f_{e\mu}, f_{e\tau}$.

Analysis Details

Event Rate

- The differential event rate:

$$\frac{dR}{dT_e} = \sum_{i=pp,{}^7\mathrm{Be}} \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \frac{d\Phi^i_{\nu_\ell}(E_\nu)}{dE_\nu} \frac{d\sigma(E_\nu, T_e)}{dT_e}, \qquad (10)$$

- The minimum energy:

$$E_\nu^{\min} = \frac{T_e}{2}\left(1 + \sqrt{1 + \frac{2m_e}{T_e}}\right). \qquad (11)$$

- Solar neutrinos arrive at the detector as a mixture of ν_e, ν_μ, and ν_τ:

$$\Phi^i_{\nu_e} = \Phi^{i\odot}_{\nu_e} P_{ee}, \qquad \Phi^i_{\nu_\mu} = \Phi^{i\odot}_{\nu_e}(1 - P_{ee})\cos^2\vartheta_{23},$$
$$\Phi^i_{\nu_\tau} = \Phi^{i\odot}_{\nu_e}(1 - P_{ee})\sin^2\vartheta_{23}. \qquad (12)$$

- P_{ee} is the survival probability of ν_e (Maltoni and Smirnov, 2016)

$$P_{ee} = \frac{1}{2} c_{13}^2 c_{13}^{m\,2} \left(1 + \cos 2\vartheta_{12} \cos 2\vartheta_{12}^m\right) + {s_{13}}^2 s_{13}^{m\,2}, \qquad (13)$$

- We consider the normal-ordering neutrino os- cillation parameter is taken from the latest 3-ν oscillation of NuFit-5.3, without the Super-Kamiokande atmospheric data (Esteban *et al.*, 2020).

χ^2-minimization

- We consider the following χ^2-function

$$\chi^2 = \min_{(\alpha_i,\beta_i)} \left[\sum_{j=1}^{30} \left(\frac{R^j_{\text{obs}} - R^j_{\text{exp}}}{\sigma^j} \right)^2 + \sum_i \left(\frac{\alpha_i}{\sigma_{\alpha_i}} \right)^2 + \sum_i \left(\frac{\beta_i}{\sigma_{\beta_i}} \right)^2 \right] \tag{14}$$

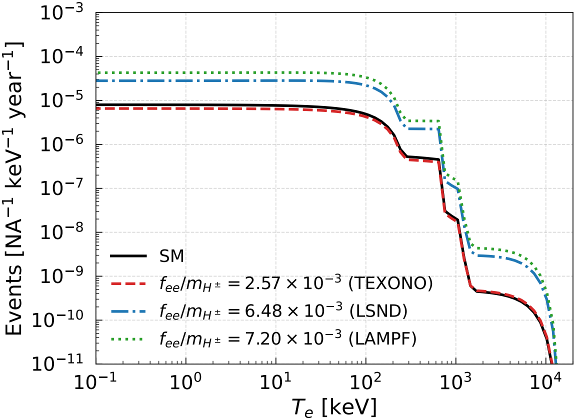
- The number of expected events:

$$R^j_{\text{exp}} = N_T \int_{T_e^j}^{T_e^{j+1}} dT_e \mathcal{A}(T_e) \int_0^{T_e'^{max}} dT_e' \, \mathcal{R}(T_e, T_e') \frac{dR}{dT_e}. \tag{15}$$

- The experimental data: XENONnT (Aprile *et al.*, 2022) and PandaX-4T (Zhang *et al.*, 2022).
- The nuisance parameters α and β account for the uncertainty on the neutrino flux and background normalization.
- The factor σ_α denotes the solar neutrino flux uncertainty and σ_β the background uncertainty.
- Solar neutrino flux from the B16-GS98 (Vinyoles *et al.*, 2017) and Bahcall's energy spectrum (Bahcall *et al.*, 2005) are taken into account.

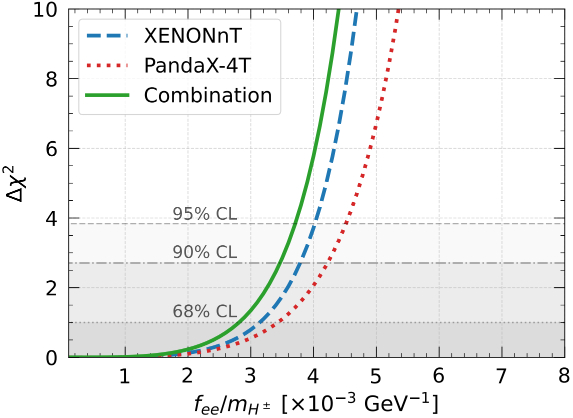
Results and Discussion

Expected event rates



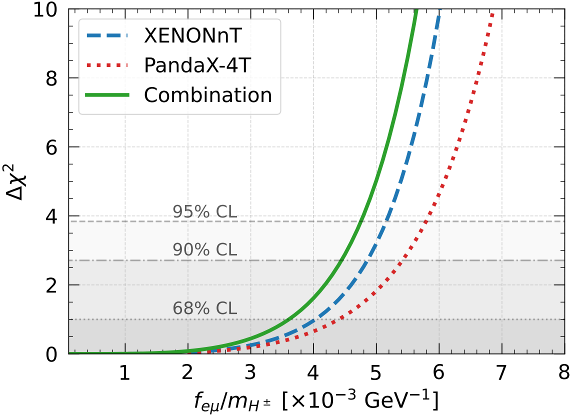
Expected contributions from previous values from TEXONO and LSND (Sevda *et al.*, 2017), and from LAMPF (Perez *et al.*, 1996).

$\Delta\chi^2$ profiles for $f_{ee}/m_{H^\pm}$



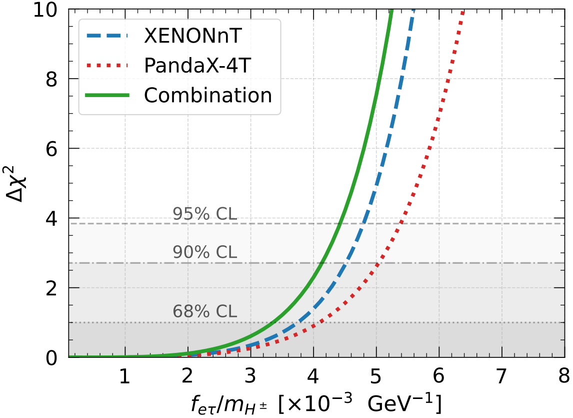
- At 90 % C.L., PandaX-4T: $\lesssim 4.22 \times 10^{-3}$ GeV^{-1}, XENONnT: $\lesssim 3.79 \times 10^{-3}$ GeV^{-1}, Combination: $\lesssim 3.46 \times 10^{-3}$ GeV^{-1}.

$\Delta\chi^2$ profiles for $f_{e\mu}/m_{H^\pm}$



- At 90 % C.L., PandaX-4T: $\lesssim 5.42 \times 10^{-3}$ GeV^{-1}, XENONnT: $\lesssim 4.86 \times 10^{-3}$ GeV^{-1}, Combination: $\lesssim 5.42 \times 10^{-3}$ GeV^{-1}.

$\Delta\chi^2$ profiles for $f_{e\tau}/m_{H^\pm}$



- At 90 % C.L., PandaX-4T: $\lesssim 5.04 \times 10^{-3}$ GeV^{-1}, XENONnT: $\lesssim 4.52 \times 10^{-3}$ GeV^{-1}, Combination: $\lesssim 4.13 \times 10^{-3}$ GeV^{-1}.

Collider constraints

- The LEP experiments exclude charged Higgs bosons lighter than approximately 80 GeV (PDG).
- From LHC searches of $H^{\pm} \to \ell^{\pm}\nu$ place stronger bound on m_{H^+} in the range of $300 - 500$ GeV.
- Assuming $m_{H^+} = 80$ GeV we have

$$f_{ee} < 0.297, \qquad f_{e\mu} < 0.380, \qquad f_{e\tau} < 0.354. \tag{16}$$

Summary

Summary

- We have studied the singly charged Higgs boson of the HTM contribution to neutrino-electron interactions induced by solar neutrinos.
- The HTM is a simple extension of the SM that can explain the smallness of neutrino masses without requiring right-handed neutrinos.
- The singly charged Higgs is relevant for EνES process.
- We have derived limits on f_{ee}/m_{H^+}, $f_{e\mu}/m_{H^+}$, $f_{e\tau}/m_{H^+}$ using data from XENONnT and PandaX-4T.
- The currently developed DM-DD facilities could be used as a testing ground to search for the charged boson of the HTM and also other scenarios of BSM in general.

Thank You for Your Attention!