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Solar neutrino constraints on $U(1)'$ models via elastic neutrino-electron scattering

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Outline

Introduction

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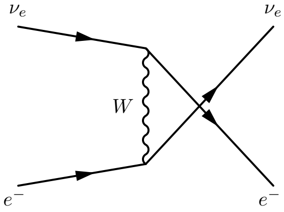
- Elastic neutrino-electron scattering is a precisely known pure leptonic process in which neutrinos scatter off an electron ('t Hooft, 1971).
- The solar neutrino is one of the most intense natural neutrino sources on Earth.
- Solar neutrinos can induce elastic neutrino-electron scattering in dark matter (DM) direct detection (DD) experiments (Cẽrdeno *et al.*, 2016).
- It produces detectable event rates at current facilities of DM-DD, which is one of the irreducible backgrounds.

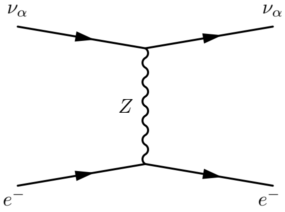
- It is feasible to view the SM as an effective theory and that new physics effects are suppressed at low energies.
- In many extensions beyond the SM (BSM), low-mass particles appearing from hidden sectors are widely proposed to incorporate this presumption.
- Correspondingly, we investigate new physics effects of the light mediator models: $U(1)'$ anomaly-free gauge symmetries (Mohapatra & Marshak, 1980; Ge *et al.*, 1991).
- We focus particularly on leptophilic Z' models.
- We derive robust limits using electronic recoil data from PandaX-4T (Zeng *et al.*, 2025) and XENONnT (Aprile *et al.*, 2022).

Theoretical Background

EνES in the Standard Model

- 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 neutrino scatters off an electron by the exchange of a charged boson (ν_e only) or a neutral boson (ν_e, ν_μ, ν_τ).





- The differential cross section can be written as

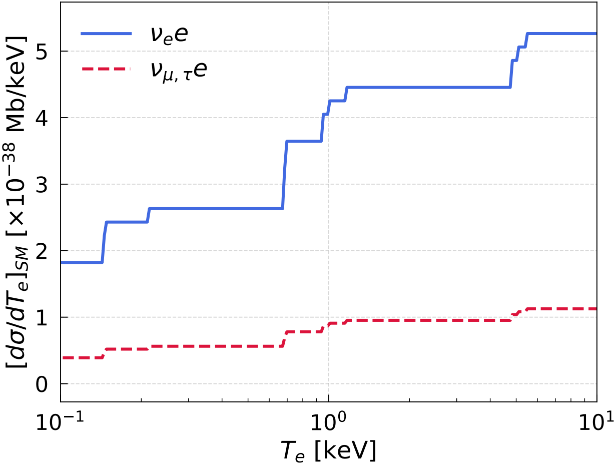
$$\left[\frac{d\sigma_{\nu_\alpha e}}{dT_e}\right]_{\rm SM} = (T_e)\frac{G_F^2 m_e}{2\pi}\left[(g_V + g_A)^2 + (g_V - g_A)^2\left(1 - \frac{T_e}{E_\nu}\right)^2 - (g_V^2 - g_A^2)\frac{m_e T_e}{E_\nu^2}\right], \quad (1)$$

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

- Multiplied by the number of ionizable effective electron charges (Chen *et al.*, 2017):

$$Z_{\rm eff}(T_e) = \sum_\alpha n_\alpha \theta(T_e - B_\alpha), \quad (3)$$

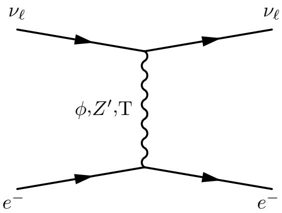
n_α : no. electrons; B_α : binding energy in the atomic shell α.



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

The anomaly-free $U(1)'$ models

- New physics effects can be examined on EνES in the presence of light mediators that couple to SM leptons.
- We consider the $U(1)'$ extensions of the SM with $U(1)_{L_e-L_\mu}$, $U(1)_{L_e-L_\tau}$, and $U(1)_{L_\mu-L_\tau}$ (He *et al.*, 1991; Gninenko & Gorbunov, 2021); Coloma *et al.*, 2022.
- The light mediator models are constructed to include only a few new particles and interactions and can be considered as a limit of a more general BSM scenario.



- The general Lagrangian for an additional vector mediator is

$$\mathcal{L}_{Z'} \supset Z'_\mu \left[Q^{e}_{Z'} g^{e}_{Z'} \bar{e}\gamma^\mu e + Q^{\nu_\ell}_{Z'} g^{\nu_\ell}_{Z'} \bar{\nu}_{\ell L}\gamma^\mu \nu_{\ell L} \right], \tag{4}$$

  where the vector coupling constants $g^{e}_{Z'}$ and $g^{\nu_\ell}_{Z'}$ are for electron and neutrino, respectively.
- The individual vector charges of electrons and neutrinos are denoted by $Q^{e}_{Z'}$ and $Q^{\nu_\ell}_{Z'}$.
- We apply these charges for a generalized form of anomaly-free UV-complete models including only the SM particles plus right-handed neutrinos (Allanach *et al.*, 2019).

- The Z' contribution to EνES process:

$$g_V \longrightarrow g_V + \frac{Q^e_{Z'} g^e_{Z'} Q^{\nu_\ell}_{Z'} g^{\nu_\ell}_{Z'}}{2\sqrt{2} G_F (m^2_{Z'} + 2 m_e T_e)} \tag{5}$$

into Eq.(1). It is valid for $L_e - L_\mu$.

- Meanwhile, there is no direct coupling to electrons at tree-level for $L_\mu - L_\tau$; the effect appears at the loop-level. In this case (Altmannshofer *et al.*, 2019):

$$g_V \longrightarrow g_V - \frac{\sqrt{2}\alpha_{\text{em}} g^e_{Z'} g^{\nu_\ell}_{Z'} (\delta_{\ell\mu} - \delta_{\ell\tau})}{\pi G_F (m^2_{Z'} + 2 m_e T_e)} \epsilon_{\tau\mu}(|\vec{q}|), \tag{6}$$

with

$$\epsilon_{\tau\mu}(|\vec{q}|) = \int_0^1 x(1-x) \ln\left(\frac{m^2_\tau + x(1-x)|\vec{q}|^2}{m^2_\mu + x(1-x)|\vec{q}|^2}\right) \approx \frac{1}{6} \ln\left(\frac{m^2_\tau}{m^2_\mu}\right). \tag{7}$$

- The couplings for new physics contributions are weighted by vector charges.:

Model	$Q_{Z'}^{e/\nu_e}$	$Q_{Z'}^{\mu/\nu_\mu}$	$Q_{Z'}^{\tau/\nu_\tau}$
$L_e - L_\mu$	1	-1	0
$L_e - L_\tau$	1	0	-1
$L_\mu - L_\tau$	0	1	-1

Neutrino Survival Probability

- Neutrinos undergo oscillations during their propagation from the Sun to Earth.
- Solar neutrinos reach a detector as a mixture of ν_e, ν_μ, and ν_τ.
- The cross-section hence needs to be weighted with the relevant survival probabilities:

$$\left[\frac{d\sigma}{dT_e}\right]_X^{\nu e} = P_{ee}\left[\frac{d\sigma_{\nu_e}}{dT_e}\right]_X + \sum_{f=\mu,\tau} P_{ef}\left[\frac{d\sigma_{\nu_f}}{dT_e}\right]_X, \tag{8}$$

with $P_{e\mu} = (1 - P_{ee})\cos^2\vartheta_{23}$ and $P_{e\tau} = (1 - P_{ee})\sin^2\vartheta_{23}$.

- The P_{ee} denotes the survival probability of ν_e which satisfies (Maltoni & Smirnov, 2016):

$$P_{ee} = \cos^2(\vartheta_{13})\cos^2(\vartheta_{13}^m)\left(\frac{1}{2} + \frac{1}{2}\cos(2\vartheta_{12}^m)\cos(2\vartheta_{12})\right) + \sin^2(\vartheta_{13})\sin^2(\vartheta_{13}^m). \quad (9)$$

- We consider the day-night asymmetry due to the Earth matter effect in the calculation of these probabilities.
- We take the normal-ordering neutrino oscillation parameters from the latest 3-ν oscillation of NuFit-5.3, without the Super-Kamiokande atmospheric data (Esteban *et al.*, 2020).

Analysis Details

Event Rate

- The differential event rate:

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

- The minimum energy:

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

- The predicted event numbers of EνES :

$$R_X^k = \varepsilon N_t \int_{T_e^k}^{T_e^{k+1}} dT_e\, \mathcal{A}(T_e) \int_0^{T_e^{\prime\,\max}} dT'_e\, \mathcal{R}(T_e, T'_e) \times \sum_{i=pp,{}^7\mathrm{Be}} \left[\frac{dR}{dT'_e}\right]^i_X, \tag{12}$$

χ^2-minimization

- The χ^2-function :

$$\chi^2(\mathcal{S}) = \min_{(\alpha_i,\beta_i)}\left[\sum_{k=1}^{30}\left(\frac{R^k_{\mathrm{exp}}(\mathcal{S};\alpha,\beta) - R^k_{obs}}{\sigma^k}\right)^2 + \sum_i\left(\frac{\alpha_i}{\sigma_{\alpha_i}}\right)^2 + \sum_i\left(\frac{\beta_i}{\sigma_{\beta_i}}\right)^2\right], \quad (13)$$

- The expected : R^k_{SM} plus R^k_{BSM} $(\phi, Z', \cdots)$ and other background component R_{Bkg} L

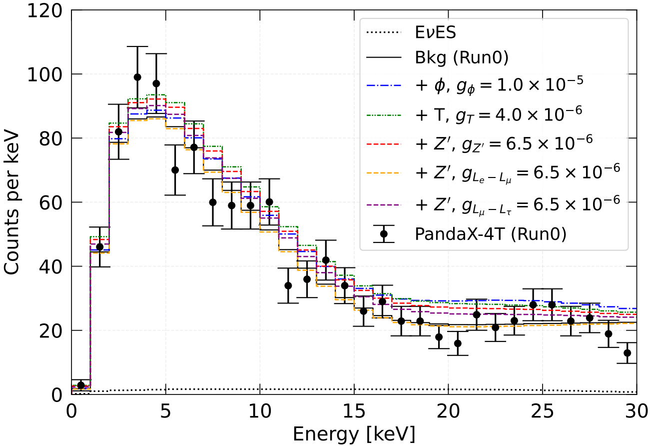
$$R^k_{\mathrm{exp}}(\mathcal{S};\alpha,\beta) = (1+\alpha)(R^k_{\mathrm{SM}} + R^k_{\mathrm{BSM}}(\mathcal{S})) + (1+\beta)R^k_{\mathrm{Bkg}} \quad (14)$$

- Nuisance parameters: α (neutrino flux) and β (background component).
- Uncertainties: σ_α (neutrino flux) and σ_β (background component).
- The experimental data: PandaX-4T, Run0 and Run1 (Zeng *et al.*, 2025).
    - additional: XENONnT SR0 (Aprile *et al.*, 2022)
- Neutrino flux:
    - Bahcall's energy spectrum (Bahcall *et al.*, 2005)
    - B16-GS98 Standard Solar Model (Vinyoles *et al.*, 2017).

Results and Discussion

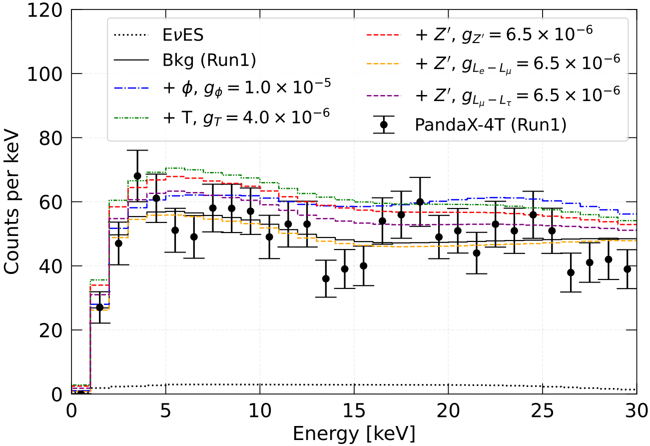
Predicted event rates

- We obtain the total neutrino-electron event rates with a good agreement with the results of the considered PandaX-4T.
- Run0 : 41.65 events.

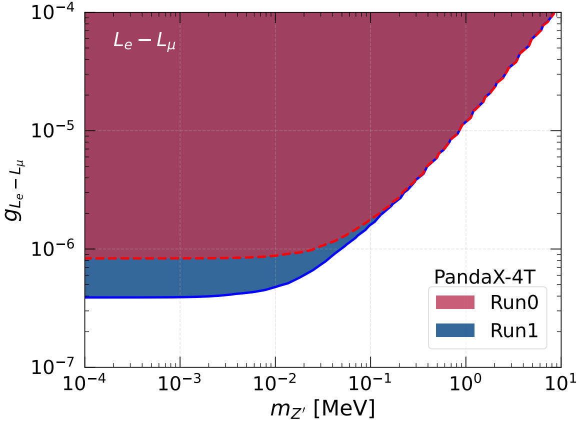


Predicted event rates

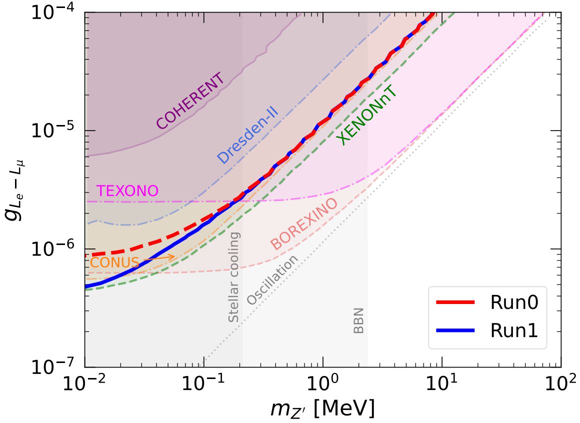
- Run1: 74.68 events.



Exclusion region at 90% of $L_e - L_\mu$

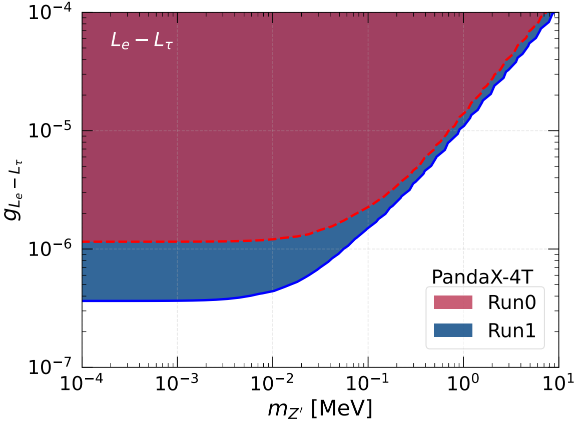


- Run0: $\lesssim 8.2 \times 10^{-7}$, Run1: $\lesssim 3.9 \times 10^{-7}$.

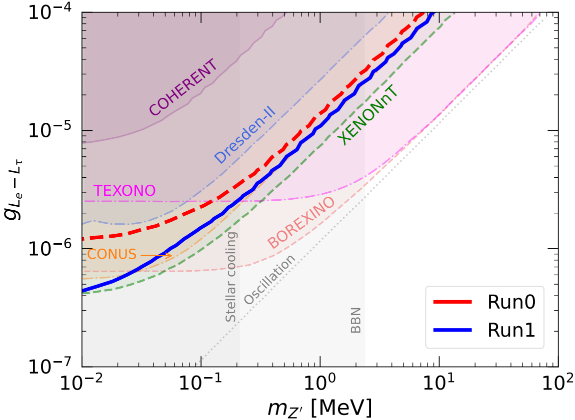


- Comparison with previous limits.

Exclusion region at 90% of $L_e - L_\tau$

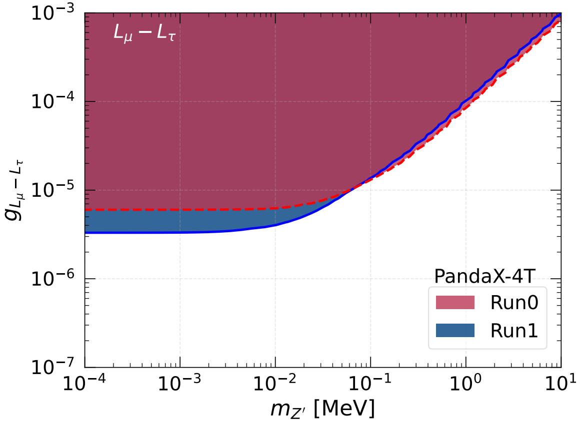


- Run0: $\lesssim 1.2 \times 10^{-6}$, Run1: $\lesssim 3.7 \times 10^{-7}$.

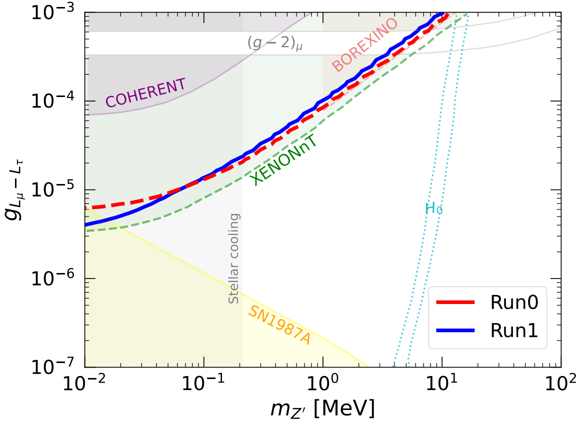


- Comparison with previous limits.

Exclusion region at 90% of $L_\mu - L_\tau$



- Run0: $\lesssim 6.0 \times 10^{-6}$, Run1: $\lesssim 3.3 \times 10^{-6}$.



- Comparison with previous limits.

Summary

Summary

- We have investigated effects of flavor-dependent light mediators from $U(1)'$ models through EνES at DD-DM experiments.
- We used recent datasets from PandaX-4T Run0 and Run1.
- The deviations are clearly seen in the low-scale energy, indicating the need for enhancing detector sensitivity in this region.
- From our results, the derived limits from the Run1 data is a few times more sensitive than the Run0 data, and show improvement over most of the existing limits.
- Our results hopefully would complement the activities of hunting new physics signatures.

Thank You for Your Attention!