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Extending the sensitivity of heavy sterile neutrino searches with solar experiments

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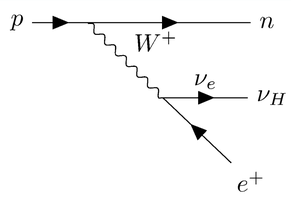
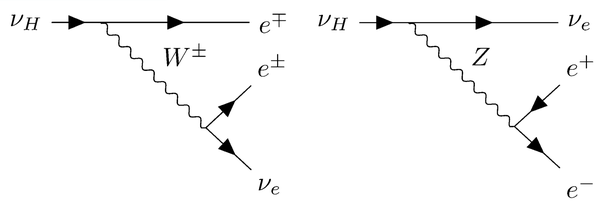
Introduction

- To explain the non-zero mass of neutrinos, one convenient way is to add right-handed neutrinos to SM, which can bring neutrino masses in various ways such as Dirac or Majorana mechanism.
- As a result of these theories, searches for heavy sterile neutrino ν_H from eV to TeV mass range have been performed with many experiments. In this research we discuss methods to further extend the sensitivity in the **MeV** mass range with solar neutrino detectors.

ν_H Production and Decay



Production of MeV ν_H by mixing, p comes from ^{8}B decay



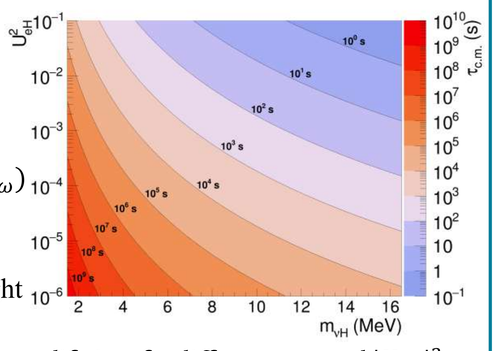
Decay of MeV ν_H, $\nu_H \to e^+e^-\nu_e$

ν_H Lifetime

The decay width of $\nu_H \to e^+e^-\nu_e$ is:

$$\Gamma_{e^+e^-\nu_e} \approx \frac{G_F^2}{192\pi^3} m_{\nu_H}^5 |U_{eH}|^2 \cdot \frac{1}{4}(1 - 4\sin^2\theta_\omega + 8\sin^2\theta_\omega)$$

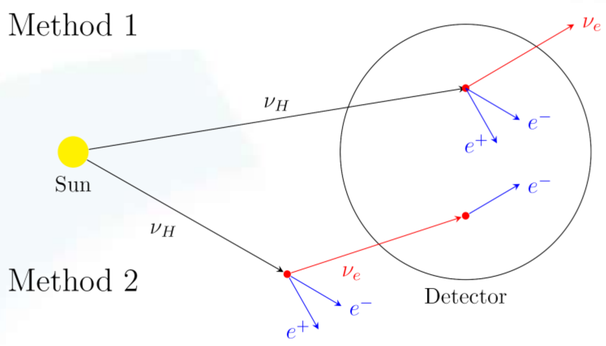
- Lifetime of ν_H decrease rapidly with m_{ν_H} and $|U_{eH}|^2$ increasing according to the formula, validated by the right plot.



ν_H lifetime for different m_{ν_H} and $|U_{eH}|^2$

According to the ν_H decay position determined by lifetime, we have two methods to search for them:

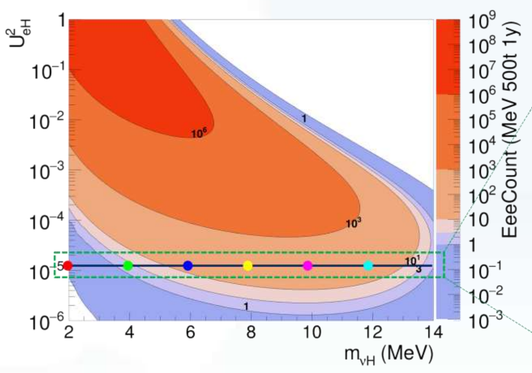
- Method 1: If the lifetime of ν_H is intermediate and a sufficient number reach and **decay inside the detector, search for e^+e^- signal**.
- Method 2: If the lifetime of ν_H is short, such that the vast majority **decay before reaching the detector, search for ν_e signal**.



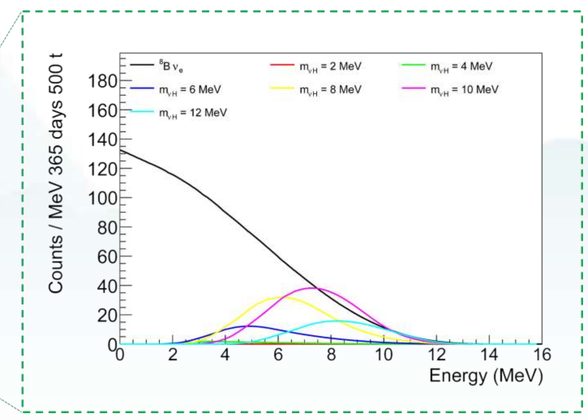
Two methods to detect ν_H

Method 1: search for ν_H by e^+e^- signal

- For ν_H decay inside detector, the left figure below shows that we can expect to observe a handful of $\nu_H \to e^+e^-\nu_e$ events for most regions where $|U_{eH}|^2 > 10^{-6}$ and 2 MeV $< m_{\nu_H} <$ 14 MeV.
- One specifical energy spectrum of e^+e^- from ν_H decay is also given.
  - Distinct spectral peaks emerge at the tail of the background spectrum for most ν_H masses, suggesting that precise energy measurements can enable excellent signal-background discrimination by fitting.



The event rate (per year) of e^+e^- from ν_H decay in a 500-ton detector on the earth, for different m_{ν_H} and $|U_{eH}|^2$



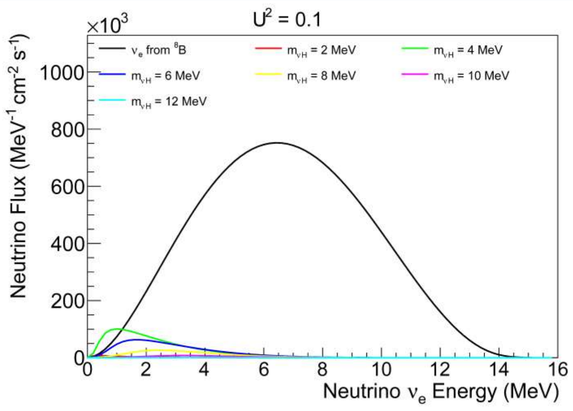
The energy spectrum of e^+e^- from ν_H decay specifically with different m_{ν_H} and fixing $|U_{eH}|^2 = 10^{-5}$

Method 2: search for ν_H by ν_e signal

We focus on two variables to differentiate ν_e from ν_H decay and solar neutrino background: the ν_e energy and direction, which yield markedly distinct distributions for signal versus background events.

ν_e Energy

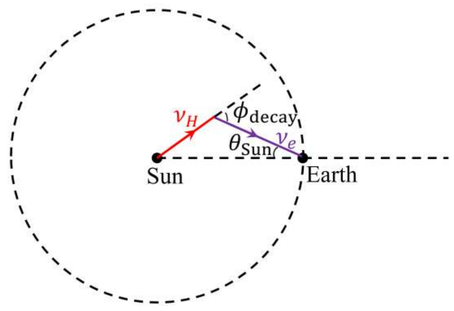
- ν_e signal of the figure is much softer than the background, peaking below 5 MeV.
- Distinguishing these signals is challenging since the electron energy from the elastic scattering of ^{8}B also peaks at low energies, as the previous plot.



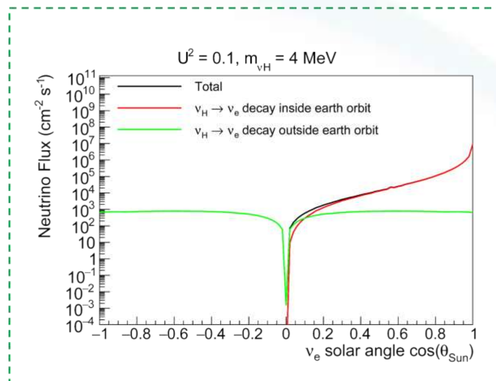
The energy spectrum of ν_e from ν_H decay outside detector for different m_{ν_H} and fixing $|U_{eH}|^2 = 0.1$

ν_e Direction

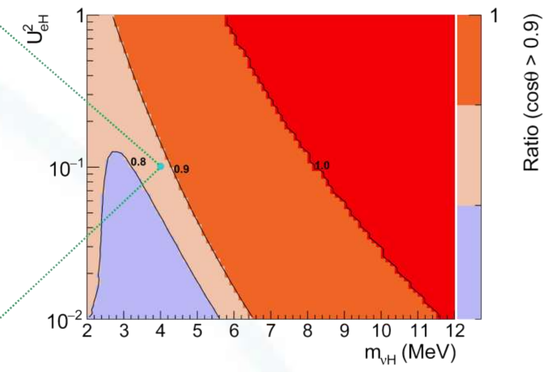
- For signal ν_e, there is a small but significant tail with large solar angles that can exceed typical angular resolution limits (around 25°, cosine around 0.9) of standard detectors.
- Right figure below shows that for $|U_{eH}|^2 > 10^{-2}$, there is a large region with at least 10% of ν_e events with $\cos\theta_{\text{Sun}} < 0.9$, allowing them to be distinguished from background neutrinos.



ν_e emission angle ϕ_{decay} and ν_e solar angle θ_{Sun}

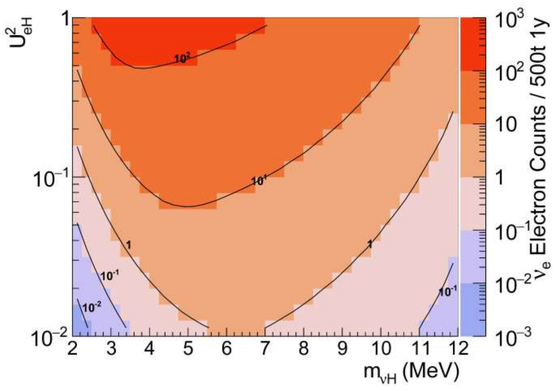


Distribution of the solar angle for signal ν_e for $m_{\nu_H} = 4$ MeV and $|U_{eH}|^2 = 0.1$



The ratio of ν_e with $\cos\theta_{\text{Sun}} > 0.9$ for different m_{ν_H} and $|U_{eH}|^2$

- Considering the ν_e-electron scattering, we estimate the expected event count rate as the right figure.
- In most of the phase space where $|U_{eH}|^2 > 10^{-2}$, we expect to observe at least a few ν_H events by detecting ν_e from its decay. Much of this phase space **cannot be explored by searching for e^+e^- signals** due to the short lifetime of ν_H.



Event rate of ν_e-electron elastic scattering with a 500-ton detector for ν_e signal from ν_H decay

Conclusions

- We presents two methods based on MeV ν_H's decay: one focuses on detecting e^+e^- signals from ν_H decays with an intermediate lifetime, while the other aims to find ν_e from short-lived ν_H decays.
- The estimated signal and background event yields indicate the **complementary** sensitivity of both methods. Key variables to distinguish the ν_H signal from solar neutrino events are proposed with their distributions. By combining both methods, it is expected to be sensitive in most of the phase space where $|U_{eH}|^2 > 10^{-6}$ and 2 MeV $< m_{\nu_H} <$ 14 MeV for a 500-ton detector over one year.

References

1. **Zhu, Y.; Fu, H.; Luo, W.; Chen, S.; Yang, L.; Zhang, Z. Extending the Sensitivity of Heavy Sterile Neutrino Searches with Solar Neutrino Experiments. arXiv.2507.01675.**