Neutrino Floor modification in Leptophilic $U(1)$ models

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Based on
"Neutrino Floor in Leptophilic $U(1)$ Models: Modification in $U(1)_{L_\mu - L_\tau}$" (ArXiv:2006.05981)

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Outline

Introduction and motivation

- With increasing sensitivity and exposure, direct detection experiments are reaching the parameter space where it will become increasingly difficult to differentiate between DM events to that of neutrino scattering events.
- Any BSM interaction which enhances ν interaction strength with electrons and or nucleons can further enhance neutrino background hence neutrino floor.
- This enhanced background can lead to detection of false positive dark matter(DM) scattering events.

Model I

For leptophilic U(1) models, namely $U(1)_{L_\mu - L_e}$, $U(1)_{L_e - L_\tau}$ and $U(1)_{L_\mu - L_\tau}$ beyond the standard model terms are given by.

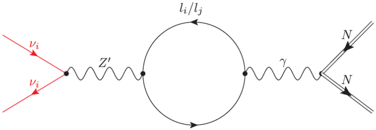
$$\begin{aligned} L_{new} = \quad & -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} + \sum_l \bar{l} \gamma^\mu \left(-g_{i-j} \, Y'_l \, Z'_\mu \right) l \\ & + \left(D_\mu S\right)^\dagger \left(D^\mu S\right) + \mu_S^2 S^\dagger S + \lambda_S \left(S^\dagger S\right)^2 + \lambda_{SH} \left(S^\dagger S\right) H^\dagger H \end{aligned}$$

- Z' boson couples with leptons l through $\mathrm{Y}'_l = L_i - Lj$ for respective $\mathrm{U}(1)_{i-j}$ model, highlighted by the interaction term,

$$L_i - L_f = -g_{i-j} (\bar{l}_i \gamma^\mu l_i - \bar{l}_j \gamma^\mu l_j + \bar{\nu}_i \gamma^\mu L \nu_i - \bar{\nu}_j \gamma^\mu L \nu_j) Z'_\mu$$

Model II

- Dominant feynman diagram for neutrino-nucleon interaction



- Mixing between Z' and γ is given by

$$\delta_{ij}^{\mu\nu} = \frac{1}{(2\pi^2)}[-q^\mu q^\nu + g^{\mu\nu} l^2] \int_0^1 dx \,(\log \frac{x(x-1)q^2 + m_{l_i}^2}{x(x-1)q^2 + m_{l_j}^2}) x(1-x)$$

Model III

Taking into account the effects of the mixing, the total neutrino-nucleus differential scattering cross-section in $U(1)_{i-j}$ can be written as

$$\begin{aligned}\frac{d\sigma_{i-j}}{dE_r} &= G_f^2 \frac{m_N}{4\pi} Q_{\nu N}^2 \left(1 - \frac{E_r m_N}{2{E_\nu}^2}\right) F^2(E_r) - \frac{m_N\, G_f\, Q_{\nu N i-j} Q_{\nu N} \left(1 - \frac{E_r m_N}{2{E_\nu}^2}\right) F^2(E_r)}{\sqrt{2}\pi\,(2E_r m_N + {m_{Z'}}^2)} \\ &+ \frac{m_N\, Q_{\nu N i-j}^2 \left(1 - \frac{E_r m_N}{2{E_\nu}^2}\right) F^2(E_r)}{2\pi\,(2E_r m_N + {m_{Z'}}^2)^2},\end{aligned}$$

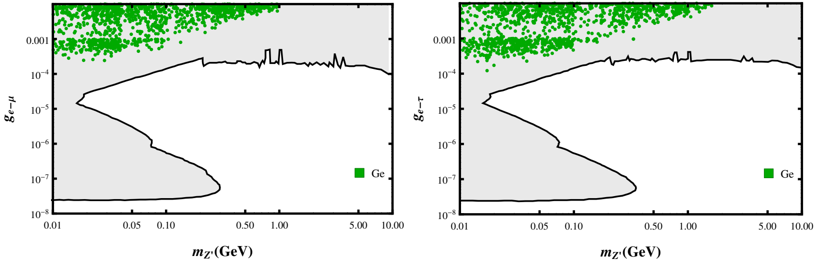
- Here G_F is the Fermi constant
- $Q_{\nu N} = N - (1 - 4\sin^2\theta_w)Z$ is effective weak hyper-charge in the SM for the target nucleus with N neutrons and Z protons
- $F(E_r)$ is the Helm form factor that exhibits the loss of coherence above recoil energies of $\approx$ 10 KeV.
- $Q_{\nu N i-j} = g_{i-j}^2 \frac{2\,\alpha_{EM}}{\pi} \delta_{ij} Z$

Constraints I

To discern the beyond standard model effect of these models, we define a ratio,

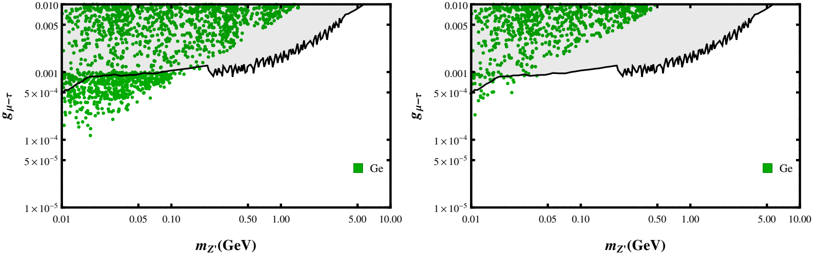
$$\frac{\sigma_{i-j}}{\sigma_{SM}} = \frac{\int_0^{E_r^{max}} \frac{d\sigma_{i-j}}{dE_r} dE_r}{\int_0^{E_r^{max}} \frac{d\sigma_{SM}}{dE_r} dE_r} \tag{1}$$

- We plot scatter points of $\frac{\sigma_{i-j}}{\sigma_{SM}}$(green points) against constraints combined (grey shaded) from COHERENT, TEXONO, Borexino, etc; ref JHEP, 07:094, 2018,
- Incident ν_e energies range from 0.1 to 100 MeV
- Left (right) panel show coupling g_{i-j} v/s $m_{Z'}$ for $U(1)_{e-\mu}$ ($U(1)_{e-\tau}$) for $\frac{\sigma_{e-\mu}}{\sigma_{SM}} \geq 1.05$



Constraints II

- Left(right) panel show scattering points for $\text{U}(1)_{\mu-\tau}$ for $\frac{\sigma_{\mu-\tau}}{\sigma_{SM}} \geq 1.05$ ($\frac{\sigma_{\mu-\tau}}{\sigma_{SM}} \geq 1.5$)
- For $\text{U}(1)_{\mu-\tau}$, incident ν_μ is considered.



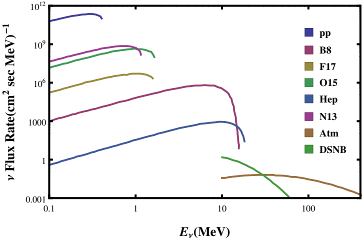
- For $\text{U}(1)_{e-\mu}$ and $\text{U}(1)_{e-\tau}$ case not even 5% enhancement in the scattering cross-section was seen, whereas for $\text{U}(1)_{\mu-\tau}$ enhancement of 50% can be seen in allowed parameter space.

Neutrino Flux I

- Solar neutrinos: neutrinos are produced in Sun as a by-product of fusion reactions. Depending upon the reaction involved, νs are emitted in different layer of Sun core.
  - PP νs: Highest flux of neutrinos are produced through $p + p \to D + e^+ + \nu_e$. PP νs production extends upto 30% of solar radius.
  - Hep νs : Hep νs are produced through $He^3 + p \to He^4 + e^+\nu_e$.
  - B8νs : The flux is generated through $B^8 \to Be^8 + e^+ + \nu_e$. the production layer extends upto 15% of solar neutrinos.
  - $O15, F17, N13$: Heavier elements also contribute to the solar neutrino flux through, $N^{13} \to C^{13} + e^+ + \nu_e$, $O^{15} \to N^{15} + e^+ + \nu_e$ and $F^{17} \to O^{17} + e^+ + \nu_e$ and production extends upto 4-5 % of solar radius.

Neutrino Flux II

- Atmospheric νs: Atmospheric neutrinos are produce due to collision of cosmic particle with Earth's atmosphere. These collision produce pions which decay to muon and electron neutrinos. The contribution is very small as compared to solar neutrinos but extends upto higher incident neutrino energies.
- DSNB: Diffuse supernova neutrino background is generated from supernova explosion of stars through out the universe. The contribution to negligible as compared to solar neutrinos



Neutrino nucleus interaction rate I

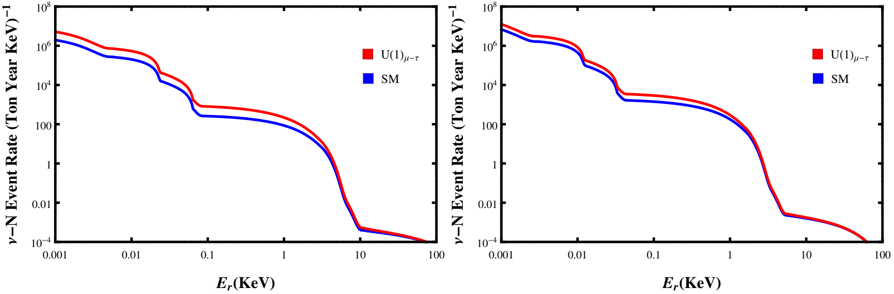
- Number of ν-nucleus scattering events per recoil energy generated for a detector of given mass and for time which experiment is given by the equation,

$$\frac{dR_{\nu-N}}{dE_r} = \frac{\epsilon}{m_N} \int_{E_\nu^{min}} \frac{d\phi_\nu}{dE_\nu}\bigg|_{\nu_\alpha} P(\nu_\alpha \to \nu_\beta, E_\nu) \frac{d\sigma_n(E_\nu, E_r, \nu_\beta)}{dE_r} dE_\nu \quad (2)$$

  - ϵ is the exposure of the experiment measured in units of mass × time.
  - E_ν^{min} is minimum incident neutrino energy required to produce a detectable recoil for a material nucleus of mass m_N with energy E_r, which in the limit of $m_N >> E_\nu$ can be written as, $E_\nu^{\min} = \sqrt{\frac{m_N E_r}{2}}$.
  - $\frac{d\sigma_n(E_\nu, E_r, \nu_\beta)}{dE_r}$ is β flavor dependent neutrino-nucleus differential scattering cross-section and $\frac{d\phi_\nu}{dE_\nu}\Big|_{\nu_\alpha}$ is the incoming neutrino flux of flavor α.

Neutrino nucleus interaction rate II

- Event rate for neutrino-nucleus scattering with change of recoil energy. Blue line is the event rate for SM whereas red line is for $U(1)_{\mu-\tau}$.
- Every point on the contours is computed by solving the intgeral in event rate equation.
- Benchmark points: Z' mass 19 MeV and coupling $g_{\mu-\tau} = 8 \times 10^{-4}$.
- Enhancement by factors of 2.8 and 1.8 for the cases of Germanium(left panel) and Xenon(right panel) respectively, at nuclear recoil energies around 0.01



Neutrino floor I

- Neutrino floor is defined as minimum value of DM-nucleon scattering cross-section(σ^0) above which can be certain that events are generated by χ-nucleon scattering as compared to ν background scattering.
- Neutrino floor can be established by constructing a contour such that for each DM mass , the ratio of 2.3 DM scattering events to one neutrino background is maintained.
- Construction of neutrino floor
  - First we evaluate the exposure (mass times time) required to produce one neutrino scattering event for a given E_{th} by setting $\int_{E_{th}}^{E_r^{max}} \frac{dR_{\nu-N}}{dE_r} dE_r = 1$

$$\epsilon_{n_\nu} = \frac{n_\nu}{1}\left(\int_{E_{th}}^{E_{max}} \frac{1}{m_N}\int_{E_\nu^{min}} \frac{d\phi_\nu}{dE_\nu}\bigg|_{\nu_\alpha} P(\nu_\alpha \to \nu_\beta, E_\nu)\frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r} dE_\nu\right)^{-1}$$

where $n_\nu = 1$ can be set for one neutrino-nucleus scattering event.

Neutrino floor II

- Next, for the same exposure and threshold energy, we integrate DM event rate equation ($\int_{E_{th}}^{E_{DM}^{max}} \frac{dR_{\nu-N}}{dE_r} dE_r = 2.3$) and solve for σ^0
- This can be recapitulated in form of the master equation,

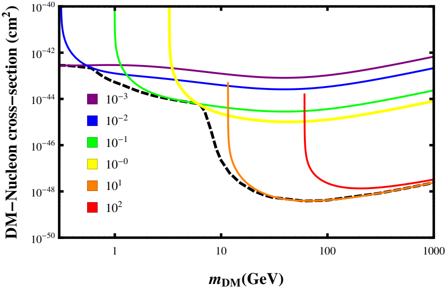
$$\sigma_n^0 = \frac{2.3}{1}\left(\int_{E_{th}}^{E_{max}} \frac{1}{m_N}\int_{E_\nu^{min}} \frac{d\phi_\nu}{dE_\nu}\bigg|_{\nu_\alpha} P(\nu_\alpha \to \nu_\beta, E_\nu)\frac{d\sigma(E_\nu, E_r, \nu_\beta)}{dE_r} dE_\nu\right) \times \left(\frac{\rho_{DM} A^2}{2 m_{DM}\mu_n^2}\int_{E_{th}}^{E_{DM}^{max}} F^2(E_r)\int_{v_{min}} \frac{f(v)}{v} d^3v\right)^{-1} \quad (3)$$

Here E_{DM}^{max} is the maximum recoil energy of DM with mass m_{DM} can produce in a given nuclei. It is written as,
$2\, m_{DM}\left(\frac{m_N m_{DM}}{(m_N+m_{DM})}\right) v_{esc}^2$.

- Using the expression , a number of curves for σ_n^0 (DM-nucleon scattering cross-section) as a function of DM mass are generated with varying threshold energy in logarithmic steps from 0.001 keV to 100 keV.
- Then the lowest cross-section among different E$_{th}$ plots are taken for each DM mass to draw a line in the DM-nucleon cross-section σ_n^0 versus m_{DM} plane.

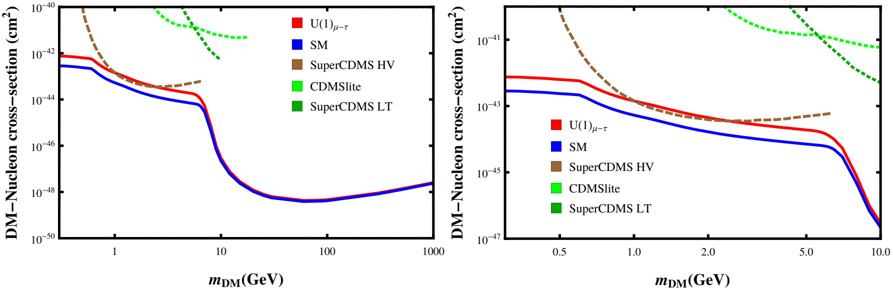
Neutrino floor III

- Neutrino floor (Black dashed line) constructed by taking lower limit of σ_n^0 with varying threshold in logarithmic steps from 0.001 to 100 keV with exposure to attain one neutrino scattering event each.
- Colored σ_n^0 contours for threshold energies 10^{-3}, 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2} keV show how neutrino floor is spanned.



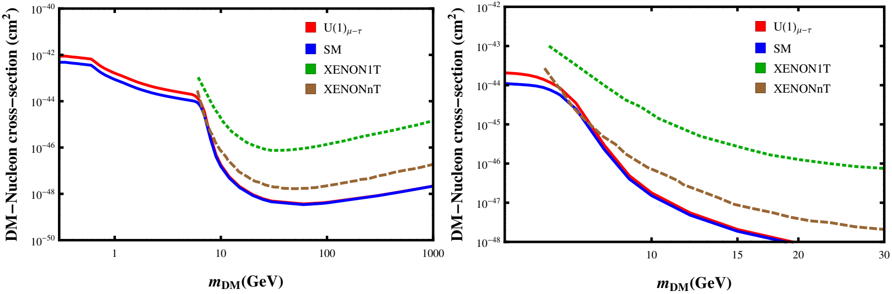
Neutrino floor IV

- Using the same method we compute the modification in neutrino floor due to $U(1)_{L_\mu - L_\tau}$ below
- Benchmark chosen: Z' mass 19 MeV and coupling $g_{\mu-\tau} = 0.0008$.



- Enhancement by a factor of 2.8 is seen for Germanium at dark matter mass $\leq$ 10 GeV

Neutrino floor V



- Enhancement by a factor of 1.8 is een for Xenon at dark matter mass ≤ 10 GeV

Conclusion

- We observed negligible enhancement in CEνNS for $U(1)_{L_\mu-L_e}$, $U(1)_{L_e-L_\tau}$ models, whereas greater than 50% enhancement was seen for $U(1)_{L_e\mu-L_\tau}$
- For the benchmark points Z' mass 19 MeV and coupling $g_{\mu-\tau} = 0.0008$, we observed an enhancement in neutrino-nucleus rate amplification by factors of 2.8 and 1.8 for the cases of Germanium and Xenon respectively, at nuclear recoil energies around 0.01 keV.
- The enhancement seen in event rate is translated by a factor of 2.8 and 1.82 in the neutrino floor respectively for Germanium and Xenon based experiments, in the lighter DM region with $m_{DM} < 10$ GeV.
- Future dark matter direct detection experiments like XENONnT and SuperCDMS HV will soon become sensitive to neutrino floor.

Thank You