Sensitivity to Secret Neutrino Interaction at Tau Neutrino Experiments

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PPC 2023 : XVI International Conference on Interactions between Particle Physics and Cosmology Jun 12 – 16, 2023, IBS

P. Bakhti and M. Rajaee, S. Shin, “Sensitivity to Secret Neutrino Interaction at Tau Neutrino Experiments ”, work in progress.

Overview

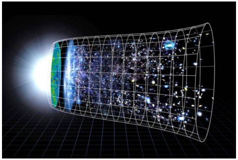
1. Secret Neutrino Interaction
2. Details of the experiments
3. Constraints and results
4. Conclusion

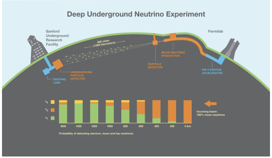
Secret Interaction of Neutrinos

"secret neutrino interactions" (SNI) indicates new physics that couples neutrinos. Several models with a new mediator (vector, scalar, etc...) have been studied for a large range of the new mediator mass.

- SNI in the active sector
- SNI in the sterile sector
- SNI in the active+sterile sector

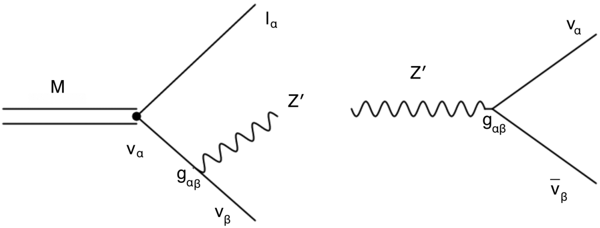
Secret neutrino interactions can be constrained from Astrophysics, Cosmology and Lab experiments.





Secret Interaction of Neutrinos and Current Constraints

- One of the primary motivations for SNI is to solve dark matter small-scale problems (B. Ahlgren, et al, 2013 and X. Chu, et al, 2015)
- SNI was proposed to solve several neutrino oscillation anomalies (Asaadi, et al, 2017, Smirnov, et al, 2021, Dentler, et al, 2019, Abdallah, et al, 2022, Dutta, et al, 2021, etc...)
- SNI have been proposed to generate tiny neutrino masses (K. Choi and A. Santamaria, 1991, Acker, et al, 1992)
- In the regions were neutrino number density is very high, the neutrino self-interactions becomes important; Thus, it is crucial to study SNI in core-collapse supernovae (Akita, et al, 2022)



Secret Neutrino Interaction (SNI) with the new vector boson Z'

$$\sum_{\alpha,\beta} g_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta \tag{1}$$

This interaction can lead to a new decay mode of meson decay to lepton, neutrino, and Z', which is followed by a subsequent Z' decay.

Constraints on SNI

Meson decay experiments can be used to constrain SNI

- Standard two-body decay of mesons $M \to \nu l$ is suppressed by m_l^2/m_M^2.
- For light Z' the three-body decay $M \to \nu l Z'$ from longitudinal polarization of Z' receives an enhancement of $m_M^2/m_{Z'}^2$
- A significant enhancement to the meson decay rate is expected.

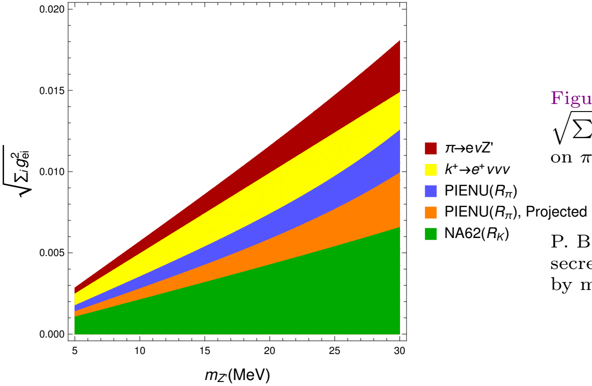


Figure: The 90% C.L. constraints on $\sqrt{\sum_i g_{ei}^2}$ versus $m_{Z'}$ from constraints on $\pi \longrightarrow e\nu Z'$.

P. Bakhti and Y. Farzan "Constraining secret gauge interactions of neutrinos by meson decays", 1702.04187

The total decay rate of the meson $\Gamma(M \longrightarrow e\nu_\alpha Z')$

$$\Gamma(M \longrightarrow e\nu_\alpha Z') = \frac{g_{e\alpha}^2 G_F^2 V_{qq'}^2 f_M^2}{6144\pi^3 m_M^3 m_{Z'}^2}\left(m_M^8 + 72 m_M^4 m_{Z'}^4 - 64 m_M^2 m_{Z'}^6 \right.$$
$$\left. + 24\left(3 m_M^4 m_{Z'}^4 + 4 m_M^2 m_{Z'}^6\right)\log\left(\frac{m_{Z'}}{m_M}\right) - 9 m_{Z'}^8\right) \quad (2)$$

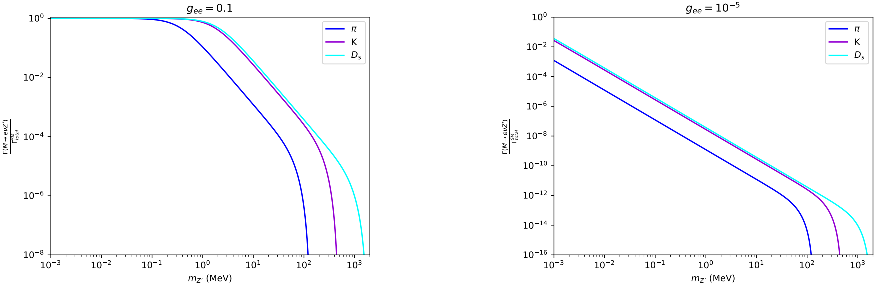


Figure: The branching ratio of the meson three-body decay to electron, anti-neutrino, and new gauge boson as a function of $m_{Z'}$ for different mesons, namely π, K, and D_s. $g_{ee} = 0.1$ (Left) and $g_{ee} = 10^{-5}$ (right).

Constraints on SNI

Decay of Z' to neutrino pairs can warm up the neutrino background during and right after the BBN era. The effect can be described by the contribution to the effective extra relativistic degrees of freedom $\Delta N_{\rm eff}$.

Observational constraints from BBN on secret neutrino interaction and its impact on the light element abundance have been studied for both the massive scalar and vector boson cases (Huang, et al, 2017, Phys. Rev. D 97, 075009).

- while meson decay experiments are sensitive to the *sum* of the coupling strength squares involving charged leptons produced in the decay of charged mesons $\sum_{\alpha\in\{e,\mu,\tau\}}|g_{e\alpha}|^2$ and $\sum_{\alpha\in\{e,\mu,\tau\}}|g_{\mu\alpha}|^2$ (by identifying the produced charged lepton), neutrino detectors can detect produced neutrinos and are sensitive to the couplings $g_{e\alpha}$, $g_{\mu\alpha}$ and $g_{\tau\alpha}$.
- The potential of DUNE near detector and FASERν to constrain the new interaction is studied P.Bakhti et al, 2018, Bahraminasr, et al, 2020.

Viable UV complete model?

$$\sum_{\alpha,\beta} g_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta.$$

$$a_e L_e + a_\mu L_\mu + a_\tau L_\tau + bB$$

- Famous combinations which have been extensively studied in the literature are $B - L = B - L_e - L_\mu - L_\tau$, $L_\mu - L_\tau$, $L_e - L_\tau$ and $L_\mu - L_e$.
- Aalong with neutrinos, the corresponding charged leptons also couple to Z'. There are strong bounds on the coupling of the electron to Z' from various observations across a wide range of Z' masses.

One possible UV model

Introduce a Dirac fermion Ψ charged under the new $U(1)$ and mixes with ν_α.

	$U(1)'$	$U(1)$	$SU(2)_L$	$SU(3)$
Ψ	1	0	1	1

$$g_\Psi Z'_\mu \bar{\Psi}\gamma^\mu \Psi$$

- Since Ψ mixes with active neutrinos, the active neutrinos of flavor ν_α will be a linear combination of mass eigenstates ν_i:
-
$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i \qquad (3)$$

  in which ν_4 is the heavier state that gives the main contribution to Ψ; *i.e.*, $U_{\Psi 4} \simeq 1$, $U_{\alpha 4}|_{\alpha=e,\mu,\tau} \ll 1$.

Integrating out the heavy fourth state, the light active neutrinos receive a coupling of the form $g_{\beta\alpha} Z'_{\mu\nu} \bar{\nu}_\beta \gamma^\mu \nu_\alpha$ in which $g_{\beta\alpha} \approx g_\Psi U_{\alpha 4} U^*_{\beta 4}$.

Y. Farzan and J. Heeck, (2016) Y. Farzan and M. Tortola (2018)

To mix Ψ with ν_α

	$U(1)'$	$U(1)$	$SU(2)_L$	$SU(3)$
Ψ	1	0	1	1
N	0	0	1	1
S	1	0	1	1

- Introducing a new sterile Dirac particle, denoted by N, which is neutral under $U(1)' \times SU(2)_L \times U(1)_Y$.
- Together with a scalar S that breaks the $U(1)'$ symmetry.
- the new Lagrangian terms can be expressed as follows: $m_\Psi \bar{\Psi}\Psi + m_N \bar{N} N + Y_\alpha \bar{N}_R H^T c L_\alpha + \lambda_L S \bar{\Psi}_R N_L$.
- By considering $Y_\alpha \langle H \rangle, \lambda_L \langle S \rangle, m_\Psi \ll m_N$, we can integrate out the heavy particle N, resulting in the mixing matrix element $U_{\alpha 4} = \frac{Y_\alpha \langle H \rangle \lambda_L \langle S \rangle}{m_N m_\Psi}$. [Y. Farzan, J. Heek, 2017]

As a result, three-body decays such as $\pi^+(\text{or } K^+) \to l_\alpha^+ \nu_\beta Z'$ can take place with a rate proportional to $|g_{\alpha\beta}|^2$

in this class of models at tree level only neutrinos couple to so they are free from the bounds on the coupling of the corresponding charged leptons to Z'

Can data from neutrino detector of the FLArE100, SND@LHC, FASERν2 and the proposed SHiP experiment as well as atmospheric data of DUNE experiment be used to extract information on the coupling of neutrinos to Z'?

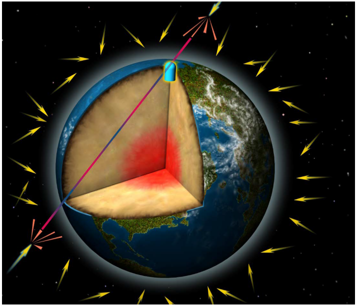
Detector		number of events		
Detector name	mass	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
FASERν2	20 tonnes	7.5×10^4	4×10^5	1.7×10^3
FLArE100	100 tonnes	2.5×10^4	1.38×10^5	1.3×10^4
AdvSND	5 tonnes	3.1×10^4	1.2×10^5	12.5×0^3
SHiP	10 tonnes	3.4×10^4	2.35×10^5	1.2×10^4

Table: Estimated number of background events per year.

We use the tau neutrino flux measurement to constrain the coupling of neutrinos with the new light gauge boson. These experiments are able to detect relatively high amount of τ neutrino number of event which is intriguing for constraining $g_{e\tau}$ and $g_{\mu\tau}$.

- In FLArE100, FASERν2, SND@LHC, and SHiP experiments, heavier mesons (charmed mesons) are produced at the interaction point, due to their high energy, enables the exploration of the relevant region of parameter space for higher masses of Z'.
- These detectors are capable of collecting a large number of events for tau neutrinos, which further opens up the possibility of using the tau neutrino flux measurement to constrain the coupling of neutrinos with the new gauge boson.

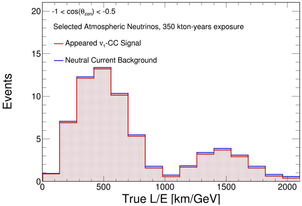
- Atmospheric neutrino experiments covering a wide range of L/E and benefiting from large flux can provide a promising tool to search for ν_τ as well as BSM.



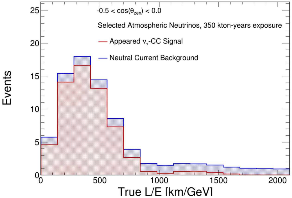
- Up going atmospheric neutrinos travel through a larger baseline can effectively oscillate into τ neutrinos.
- Down going atmospheric neutrinos travel a distance shorter than the oscillation length we expect to observe no τ neutrino event from above.

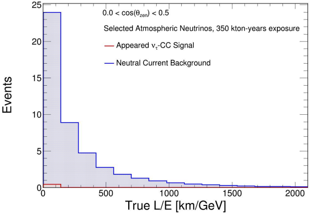
DUNE atmospheric neutrino data provide an interesting framework to study BSM due to the precise angular resolution in particular for the tau neutrinos.

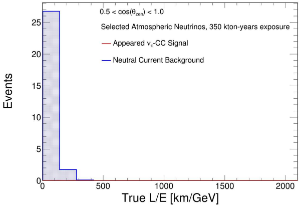
True Atmospheric Spectra



Clear 1st and 2nd oscillation maxima in true L/E







29 September 2021 NuTau 2021 - Adam Aurisano 12

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Constraints

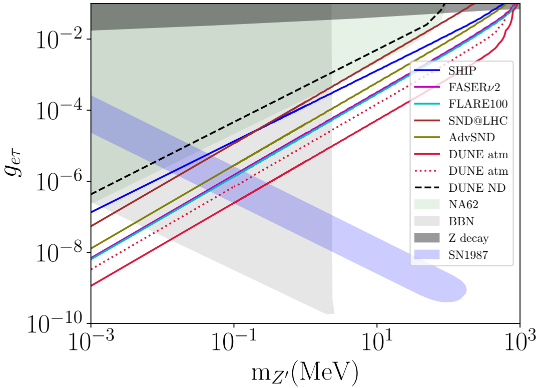
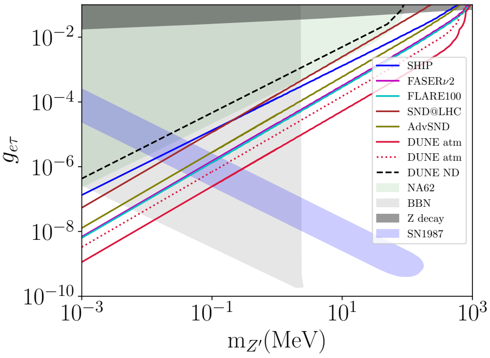


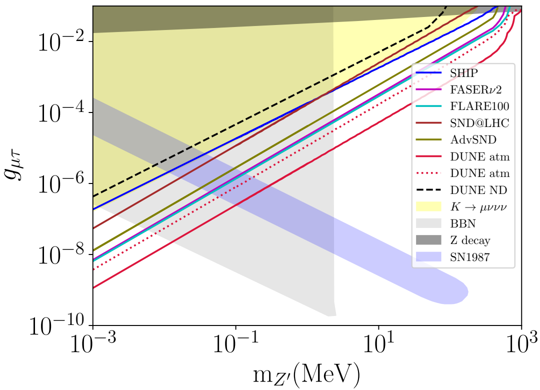
Figure: The upper bound on $g_{e\tau}$ vs. $m_{Z'}$ at 90% C.L.. The gray region shows the BBN constraint [Huang, et al, 2017]. The dark gray and light green regions show the current constraint from Z decay and NA62, respectively [Laha, et al, 2013, NA62, 2012]. The light blue region indicates the constraint from core collapse supernova [Akita, et al, 2022].

Constraints

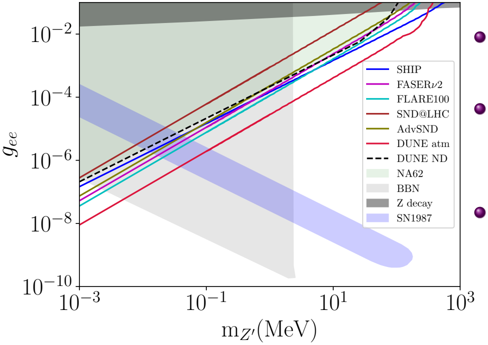


- Atmospheric data is the most sensitive probe to set bound on $g_{e\tau}$ even by including the neutral current background.
- FLARE100 (cyan curve) and FASERν2 (purple curve) can set comparable and the most stringent constraints on $g_{e\tau}$ among future beam experiments. This is due to their capability of detecting a large number of tau neutrino events.

The upper bound on $g_{\mu\tau}$ vs. $m_{Z'}$ at 90% C.L..



The upper bound on g_{ee} vs. $m_{Z'}$ at 90% C.L.



- Atmospheric data of DUNE can set the most stringent bound.
- For $M_{Z'} <$ few keV, FLARE100 can improve the current constraint.
- For $M_{Z'} > 400$ MeV, SHiP sets the most stringent bound due to its higher sensitivity to neutrinos originating from heavy meson decays, such as D_s.

Conclusion

- The upcoming beam and atmospheric tau neutrino experiments offer a promising avenue to explore the hidden interactions between neutrinos, mediated by a new light gauge boson, Z', with coupling $g_{\alpha\beta}$.
- DUNE atmospheric data has excellent detection capabilities for tau neutrinos, in setting the most stringent constraint on $g_{\alpha\beta}$ with the potential to improve the current constraint by up to two orders of magnitude.
- FLArE100 and FASERν2as well as Advanced SND have the potential to significantly enhance the current bounds on $g_{e\tau}$ and $g_{\mu\tau}$, while also slightly improving the constraints on g_{ee} and $g_{e\mu}$.

THANK YOU VERY MUCH