Secret neutrino interaction at rare meson decay and neutrino experiments

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The 4th Workshop on New Physics Opportunities at Neutrino Facilities (NPN 2024)

3-5 June, 2024

Reference

- P. Bakhti, M. Rajaee and S. Shin, "Uncovering secret neutrino interactions at tau neutrino experiments," Phys. Rev. D **109** (2024) no.9, 095043 [arXiv:2311.14945 [hep-ph]].
- M. Bahraminasr, P. Bakhti and M. Rajaee, "Sensitivities to secret neutrino interaction at FASERν," J. Phys. G **48** (2021) no.9, 095001, [arXiv:2003.09985 [hep-ph]].
- P. Bakhti, Y. Farzan and M. Rajaee,"Secret interactions of neutrinos with light gauge boson at the DUNE near detector," Phys. Rev. D **99** (2019) no.5, 055019, [arXiv:1810.04441 [hep-ph]].
- P. Bakhti and Y. Farzan, "Constraining secret gauge interactions of neutrinos by meson decays," Phys. Rev. D **95** (2017) no.9, 095008, arXiv:1702.04187 [hep-ph].

Overview

Secret Neutrino Interactions

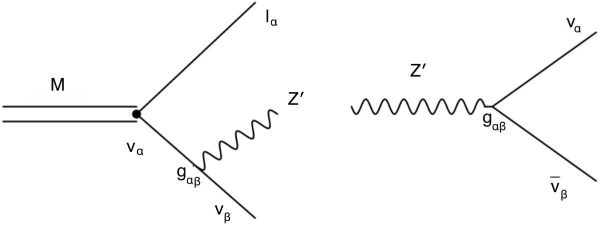
"Secret Neutrino Interactions" (SNI) indicates new physics that couples neutrinos. Several models with new mediator (vector, scalar, pseudo-scalar boson) have been studied for a large range of the new mediator mass.

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

The presence of secret neutrino interactions can be constrained through astrophysics, cosmology, and laboratory experiments.

Motivations for Secret Neutrino Interactions

- One of the primary motivations for studying Secret Neutrino Interactions (SNI) is their potential to address small-scale problems related to dark matter (B. Ahlgren et al., 2013; X. Chu et al., 2015).
- SNI have been proposed as a solution to various neutrino oscillation anomalies (Asaadi et al., 2017; Smirnov et al., 2021; Dentler et al., 2019; Abdallah et al., 2022; Dutta et al., 2021, etc.).
- The existence of SNI has also been suggested as a mechanism for generating tiny neutrino masses (K. Choi and A. Santamaria, 1991; Acker et al., 1992).
- In regions with high neutrino number density, such as core-collapse supernovae, the neutrino self-interactions become significant, highlighting the importance of studying SNI in these scenarios (Akita et al., 2022).



The Secret Neutrino Interaction (SNI) involving the new vector boson Z' is described by the following interaction term:

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

Here, $g_{\alpha\beta}$ represents the coupling between the new light boson Z' and neutrinos of flavor α and β. This interaction can lead to a new decay mode of meson decay to lepton, neutrino, and Z', followed by a subsequent Z' decay.

Leptonic Meson Decay

- The decay width is given by:

$$\Gamma(M \longrightarrow l_\alpha \nu_\alpha) = \frac{G_F^2 f_M^2 V_{qq'}^2}{4\pi m_M^3} m_l^2 (m_M^2 - m_l^2)^2 \quad (2)$$

- The ratio of the decay widths for leptonic decays can be expressed as:

$$R_M = \frac{\Gamma(M \longrightarrow e\nu_e)}{\Gamma(M \longrightarrow \mu\nu_\mu)} = (\frac{m_e}{m_\mu})^2 (\frac{m_M^2 - m_e^2}{m_M^2 - m_\mu^2})^2 \quad (3)$$

- In the case of pion and kaon

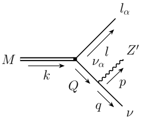
$$R_\pi = \frac{\Gamma(\pi \longrightarrow e\nu_e)}{\Gamma(\pi \longrightarrow \mu\nu_\mu)} = (1.2352 \pm 0.0002) \times 10^{-4} \quad (4)$$

$$R_K = \frac{\Gamma(K \longrightarrow e\nu_e)}{\Gamma(K \longrightarrow \mu\nu_\mu)} = (2.477 \pm 0.0001) \times 10^{-5} \quad (5)$$

A New Meson Decay Mode

- The decay amplitude for the new meson decay mode is given by:

$$\mathcal{M} = g_{\alpha i} G_F f_M V_{qq'} k_\mu \varepsilon_\alpha(p) \bar{u}(l) \gamma^\mu P_L \frac{\not{Q}}{Q^2} \gamma^\alpha P_L v(q),$$



Neglecting the lepton mass in the case of the electron, we have:

$$\sum_{spins} |\mathcal{M}|^2 = (\sum_i g_{\alpha i}^2) G_F^2 f_M^2 V_{qq'}^2 \Big(m_M^2 + m_{Z'}^2 - 2 m_M E_{Z'} + \frac{(m_M^2 - m_{Z'}^2 - 2 m_M E_l)(m_M^2 - m_{Z'}^2 - 2 m_M E_\nu)}{m_{Z'}^2} \Big) \quad (6)$$

The decay rate for the process $M \to l_\alpha \nu Z'$ is given by:

$$\Gamma(M \longrightarrow l_\alpha \nu Z') = \frac{1}{64\pi^3 m_M} \int_{E_l^{min}}^{E_l^{max}} \int_{E_\nu^{min}}^{E_\nu^{max}} dE_l dE_\nu \sum_{spins} |\mathcal{M}|^2. \quad (7)$$

A new meson decay mode

- For meson decay to electrons, the effect of the electron mass is negligible ($O(10^{-5})$). However, when considering meson decay to muons, the lepton mass introduces a 5% correction.
- The total decay rate of the meson ($\Gamma(M \longrightarrow e\nu_\alpha Z')$) is given by:

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

$$\left. +24 \left(3 m_M^4 m_{Z'}^4 + 4 m_M^2 m_{Z'}^6 \right) \log \left(\frac{m_{Z'}}{m_M} \right) - 9 m_{Z'}^8 \right) \qquad (8)$$

- The total decay rate of $Z' \longrightarrow \nu_\alpha \bar{\nu}_\beta$ is equal to:

$$\Gamma(Z' \longrightarrow \nu_\alpha \bar{\nu} \beta) = \frac{g_{\alpha\beta}^2 m_{Z'}}{24\pi}. \qquad (9)$$

A New Meson Decay Mode

- The condition for Z' decay before reaching the detectors is $\Gamma L/\gamma \gg 1$.
- The total spectrum of the (anti)neutrino produced from both pion and Z' decay is given by:

$$\left(\frac{dN_\nu}{dE_\nu}\right)_{\text{r.o.M}} = \left(\frac{dN_\nu}{dE_\nu}\right)_{\text{r.o.M}}^{\text{Z' decay}} + \frac{N_0(1-e^{-\Gamma L/\gamma})}{\Gamma(M \longrightarrow e\nu Z')}\frac{d\Gamma(M \longrightarrow e\nu Z')}{dE_\nu}, \tag{10}$$

  where N_0 is the total number of neutrinos produced from meson decay. It is equal to zero in the case of $\bar{\nu}_e$ and non-zero in the case of ν_e in M^+ decay mode.
- In the laboratory frame, the total neutrino spectrum is given by:

$$\left(\frac{dN_\nu}{dE_\nu}\right)_{\text{lab}} = \left(\frac{dN_\nu}{dE_{\text{r.o.}\pi}}\right)_{\text{r.o.}\pi}\frac{\partial E_{\text{r.o.}\pi}}{\partial E_{\text{lab}}}. \tag{11}$$

NA62

- Located in the North Area of the SPS accelerator at CERN
- Dedicated to studying rare decays of charged kaons
- Kaons decay in flight with an energy of 74 ± 1.4 GeV
- Kinematic identification: $M^2_{\text{miss}}(l) = (P_K - P_l)^2$
- NA62 criteria:

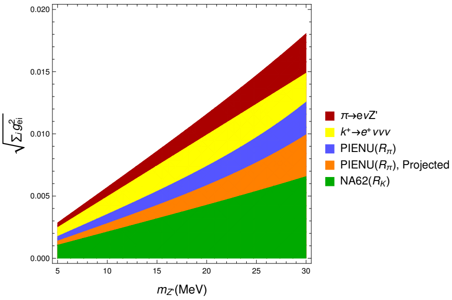
$$-M_1^2 < M^2_{\text{miss}}(l) < M_2^2,\ \ M_1^2 \approx 0.013 \text{ to } 0.016,\ \ M_2^2 \approx 0.010 \text{ to } 0.013$$

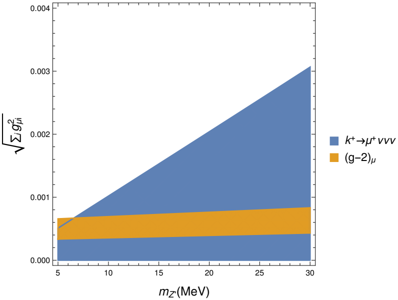
- Approximately 150,000 reconstructed $K^\pm \to e^\pm \nu_e$ events
- Reconstructed lepton momentum is in the range of 13 to 65 GeV
- $R_K = (2.488 \pm 0.010) \times 10^{-5}$

PIENU and Other constraints

- Decay of a pion at rest to either a muon or a positron and a neutrino
- $\pi^+ \to e^+\nu$, with $E_{e^+} = 69.8$ MeV
- $\pi^+ \to \mu^+\nu$, followed by $\mu^+ \to e^+\nu$, with $E_{e^+} = 0.5$ to 52.8 MeV
- Energy cut applied at 52 MeV
- $R_\pi = (1.2344 \pm 0.0023, (\mathrm{stat}) \pm 0.0019, (\mathrm{syst})) \times 10^{-4}$
- In the near future, statistical uncertainty to reduce by a factor of 3
- E949 at Brookhaven National Laboratory, USA, established an upper limit for $Br(K^+ \to \mu^+\nu\nu\nu)$: $< 2.4 \times 10^{-6}$ at 90% confidence level (C.L.) (arXiv:1606.09054 [hep-ex])
- Old TRIUMF (Phys. Rev. D **37** (1988) 1131):
  $R = \frac{\Gamma(\pi \to e\nu Z')}{\Gamma(\pi \to \mu\nu)} < 4 \times 10^{-6}$
- Nucl. Phys. B **149** (1979) 365: $Br(K^+ \to e^+\nu\nu\nu) < 6 \times 10^{-5}$ at 90
- KLOE, TREK, Measurements of R_K in the 1970s

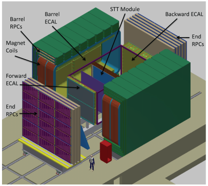
Constraining the coupling from meson decay to electron and muon

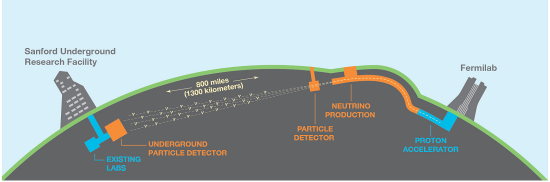




DUNE Near Detector

- While meson decay experiments primarily probe the coupling strengths involving charged leptons ($\sum_{\alpha\in e,\mu,\tau} |g_{e\alpha}|^2$ and $\sum_{\alpha\in e,\mu,\tau} |g_{\mu\alpha}|^2$) by identifying the produced charged leptons, neutrino detectors offer the ability to detect produced neutrinos and are sensitive to the couplings $g_{e\alpha}$, $g_{\mu\alpha}$, and $g_{\tau\alpha}$.



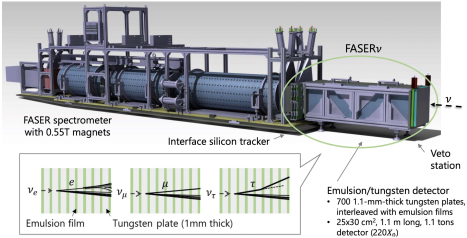


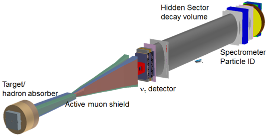
https://sciencesprings.files.wordpress.com/2019/10/fnal-dune-near-detector.png, https://www.dunescience.org/

- Measurement of neutrino flux and Cross-section and exploration of physics beyond the Standard Model

FASERν

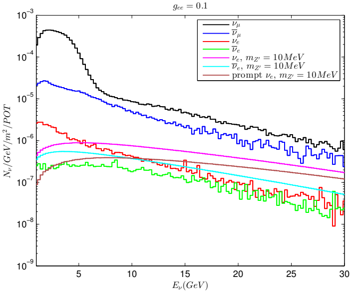
- First-time detection of collider neutrinos
- Located 480 m from the ATLAS interaction point
- Utilizes an emulsion detector technology, specifically designed to detect tau neutrinos and exploration of physics beyond the SM
- Future detectors, FASERν2 and FLARE, AdvSND planned for high luminosity LHC

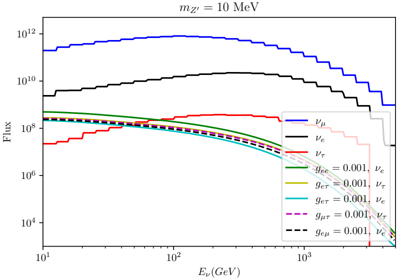




C. Betancourt, Neutrinos at LHC with FASER and SND@LHC

Neutrino spectrum at DUNE ND and FASERν





- The measurement of tau neutrino flux in these experiments provides a valuable tool for constraining the coupling of neutrinos with the new light gauge boson. These experiments can detect a significant number of τ neutrino events, which is crucial for constraining $g_{e\tau}$ and $g_{\mu\tau}$.
- In FASERν, FLArE100, FASERν2, SND@LHC, AdvSND, and SHiP experiments, heavier mesons (such as charmed mesons) are produced at the interaction point, thanks to their high energy. This enables the exploration of the relevant parameter space for higher masses of Z'. Furthermore, these detectors can collect a large number of tau neutrino events, allowing for the utilization of tau neutrino flux measurements to constrain the coupling of neutrinos with the new gauge boson.
- The proposed FLArE, a liquid argon time projection chamber (LArTPC) located at FPF, as well as FASERν2, are designed to detect hundreds of thousands of neutrino interactions, including tau neutrinos, and to search for dark matter.

Detector		number of events		
Detector name	mass	$\nu_e + \bar{\nu}_e$	$\nu_\mu + \bar{\nu}_\mu$	$\nu_\tau + \bar{\nu}_\tau$
FASERν	1.1 tonnes	1296	20439	21
SND@LHC	800 kg	250	1000	20
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	12.5×10^3
SHiP	10 tonnes	3.4×10^4	2.35×10^5	1.2×10^4

Table: Details of the experiments.

Atmospheric neutrino flux

- Cosmic rays, primarily consisting of protons and helium nuclei, collide with molecules in the Earth's atmosphere, leading to the production of various particles.
- Interactions include $p + atm \to \pi^{\pm}, \pi^0, K^{\pm}, K^0_{S,L}$.
- Atmospheric neutrinos are generated through the decays of these particles.
- Decay chains involve $\pi^{\pm}, K^{\pm} \to \mu^{\pm}\nu_{\mu}(\bar{\nu}_{\mu})$ and $\mu^{\pm} \to e^{\pm}\nu_e(\bar{\nu}_e)\nu_{\mu}(\bar{\nu}_{\mu})$.
- These neutrinos, known as conventional neutrinos, originate from long-lived mesons.
- Neutrinos arising from short-lived mesons like D mesons are referred to as prompt neutrinos.
- The contribution of ν_{τ} flux is considered negligible.

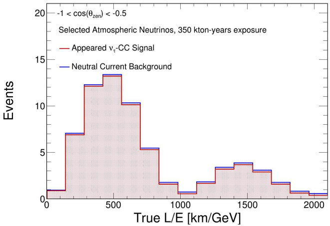
Atmospheric neutrino flux

- At low energies ($E \sim 1$ GeV), the ratio of muon neutrinos (ν_μ) and electron neutrinos (ν_e) is approximately $\frac{\phi_{\nu_\mu}+\phi_{\bar{\nu}_\mu}}{\phi\nu_e+\phi_{\bar{\nu}_e}} \simeq 2$.
- At higher energies, a larger fraction of muons reach the ground before decaying. Consequently, the ratio of muon neutrinos to electron neutrinos increases as the neutrino energy becomes larger and the electron neutrino flux becomes smaller.
- Cosmic rays are isotropic and originate from outside the solar system.
- Below 100 MeV, the cosmic ray flux is dominated by solar winds.
- Solar winds decelerate galactic cosmic rays with energies below approximately 10 GeV.
- Simple calculations for predicting the atmospheric neutrino flux on Earth often employ one-dimensional tracking, assuming all secondaries follow the direction of the parent cosmic ray and neglecting the bending effect of primary/secondary particles by the geomagnetic field.

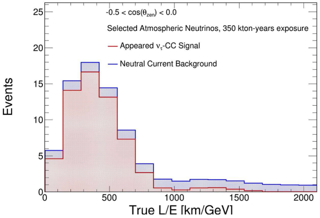
Atmospheric neutrino flux

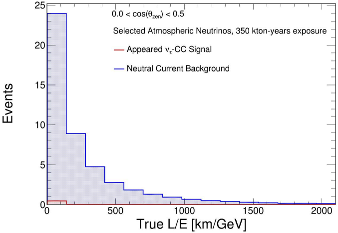
- The geomagnetic field significantly modifies the horizontal flux of atmospheric neutrinos at low energies below 10 GeV.
- The spectrum of atmospheric neutrinos peaks at around 1 GeV and exhibits a power-law behavior at higher energies, similar to the spectrum of primary cosmic rays and the resulting secondary particles.
- Below 1 GeV, the flux of all neutrino species sharply decreases due to the influence of the geomagnetic field on primary cosmic rays.
- At energies above TeV, secondary pions and kaons reach the Earth's surface before decaying, thus they do not contribute to the production of neutrinos.

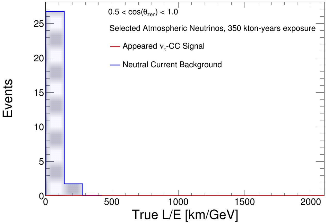
Atmospheric tau neutrino at DUNE



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

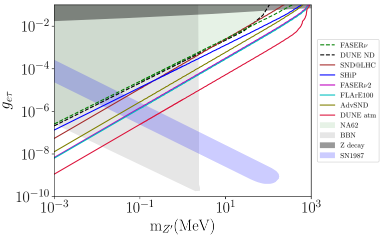






Adam Aurisano for the DUNE, Workshop on Tau Neutrinos 2021

Constraints



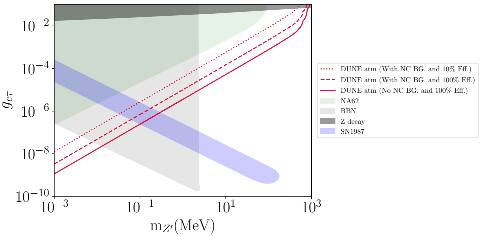
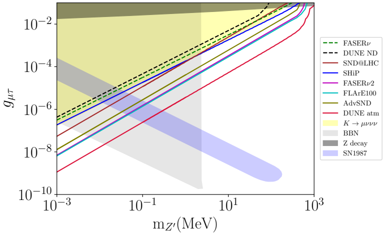
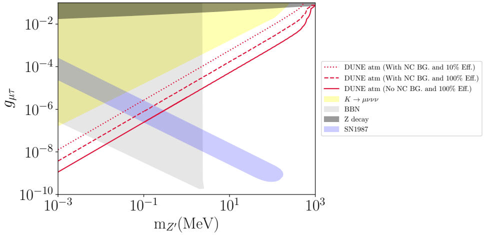


Figure: The upper bound on $g_{e(\mu)\tau}$ vs. $m_{Z'}$ at 90% C.L.. The gray region shows the BBN constraint [Huang, et al, 2017]. The dark gray and light green regions shows the current constraint from Z decay and NA62, respectively [Laha, et al, 2013 ,NA62, 2012]. The light blue region indicates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

Constraints





- Atmospheric data is the most sensitive probe to set bound on $g_{e\tau}$ and $g_{\mu\tau}$ 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.

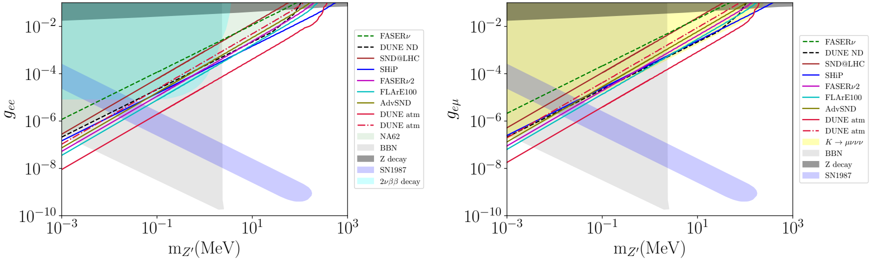


Figure: The upper bound on $g_{ee(\mu)}$ vs. $m_{Z'}$ at 90% C.L..

- Atmospheric data of DUNE can set the most stringent bound.
- For $M_{Z'} <$ few keV, FLARE100 can improve the current constraint.
- $M_{Z'} > 400$ 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 provide an exciting opportunity to investigate the hidden interactions between neutrinos mediated by a new light gauge boson, Z', with coupling g_α.
- DUNE's atmospheric data offers excellent detection capabilities for tau neutrinos, allowing for the most stringent constraints on $g_{\alpha\tau}$ in the mass range of 1 $\mathrm{MeV} < M_{Z'} < 500$ MeV, as well as for $M_{Z'} < \mathrm{few\ keV}$. These constraints have the potential to improve the current limits by up to two orders of magnitude.
- FLArE100 and FASERν2 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 for your attention.