# Snowmass2021 - Letter of Interest

# *Tau Neutrino Physics*

**NF Topical Groups:** (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
□ (NF4) Neutrinos from natural sources
□ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
□ (NF7) Applications
■ (TF11) Theory of neutrino physics
□ (NF9) Artificial neutrino sources
□ (NF10) Neutrino detectors
□ (Other) *[Please specify frontier/topical group(s)]*


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**Abstract:**
Tau neutrinos remain the least well-understood particles of the Standard Model. Their direct identification was only 20 years ago, and the community has already learned a significant amount regarding their interactions since then. With upcoming experimental results (IceCube DeepCore, IceCube Upgrade, and DUNE), the community will gain an even deeper understanding of tau neutrinos. These precise measurements will allow us to perform studies regarding neutrino oscillations, both within the three-massive-neutrinos paradigm and, potentially, beyond. Going beyond the planned experimental program, new sources and/or detectors will be required, but doing so can significantly improve our knowledge of tau neutrinos.

In 1998, Super-Kamiokande observed a depletion of muon neutrino ($\nu_\mu$) charged-current (CC) interactions for neutrinos produced in the atmosphere traveling up through the Earth compared to those traveling down[1], which they interpreted as evidence for $\nu_\mu$ oscillating into $\nu_\tau$. This implies that neutrinos have mass, which was one of the first indications of physics beyond the Standard Model. Since then, neutrino oscillations have been confirmed in $\nu_e$ produced by the Sun[2], in $\bar{\nu}_e$ produced by nuclear reactors[3;4], and in $\nu_\mu$ and $\bar{\nu}_\mu$ produced by accelerators[5;6]. Experiments at a short distance from nuclear reactors have demonstrated that the mixing between $\nu_e$ and $\nu_\mu$ is relatively large[7–9], and recent results from T2K and NOvA suggest that CP may be maximally violated in the leptonic sector[10;11]. Virtually all oscillation experiments have been consistent with the three-flavor paradigm, which posits that there are three neutrino weak-interaction flavor-eigenstates ($\nu_e$, $\nu_\mu$, and $\nu_\tau$) and three neutrino mass-eigenstates ($\nu_1$, $\nu_2$, and $\nu_3$) which are related through a unitary $3 \times 3$ mixing matrix[12–14], and that flavors oscillate with frequencies which depend on $\Delta m^2_{ji} \equiv m^2_j - m^2_i$, the neutrino energy, and the distance traveled.

Despite increasing understanding of neutrino oscillations from $\nu_e$ and $\nu_\mu$, there is less direct experimental knowledge of $\nu_\tau$ than any other Standard Model particle. The $\nu_\tau$ was not directly observed until 2000 by the DONuT experiment which collected nine $\nu_\tau$ events[15;16]. The OPERA experiment was designed with high resolution emulsion technology to discover $\nu_\tau$ appearance in a $\nu_\mu$ beam[17], succeeding in discovering $\nu_\tau$ appearance in 2015[18]; however, the baseline and energy of the experiment was unfavorable, and thus, only ten $\nu_\tau$ candidates were observed[19]. The Super-Kamiokande experiment has recently developed a method to statistically separate a sample of $\nu_\tau$ events in atmospheric neutrinos to exclude the no-$\nu_\tau$ appearance hypothesis at a 4.6$\sigma$ significance level, and measured the normalization of the $\nu_\tau$ sample relative to expectations to be $1.47 \pm 0.32$[20;21]. The IceCube experiment performed a similar analysis using data from the DeepCore detector component. Using CC events only, they were able to exclude the no-$\nu_\tau$ appearance hypothesis at the 2.0$\sigma$ level and measure the $\nu_\tau$ normalization to be $0.57^{+0.36}_{-0.30}$[22]. In both cases, the limitations of Cherenkov detectors prevented the experiments from improving the purity of their samples beyond 5%.

Our knowledge of the $\nu_\tau$ cross-section is inferred from measurements of $\nu_\mu$ assuming lepton universality, such that any cross-section differences are only due to the large mass of the $\tau$ lepton. However, recent data from Belle, BaBar, and LHCb, as combined by the Heavy Flavor Averaging Group, shows that $\mathcal{B}(B \to D\tau\nu_\tau)/\mathcal{B}(B \to Dl\nu_l)$ and $\mathcal{B}(B \to D^*\tau\nu_\tau)/\mathcal{B}(B \to D^*l\nu_l)$ differ from Standard Model predictions by 3.9$\sigma$[23], assuming lepton universality. Similarly, almost all knowledge of $\nu_\tau$ mixing-matrix elements comes from assuming unitarity of the mixing matrix. Without assuming unitarity, $|U_{\tau 3}|$ is only known to only 60%[24;25].

Over the next two decades, several currently available and developing sources will allow for direct measurement of $\nu_\tau$. Soon, it is expected that IceCube will be able to use DeepCore data to constrain the normalization of the $\nu_\tau$ sample at the $10\%$ level[26]. Future data from the IceCube upgrade will allow this measurement to be effectively systematically limited. The upcoming DsTau/NA65 experiment[27] (based at CERN) will directly study tau neutrino production using a measurement of $D_s \to \tau X$ decays following high-energy proton-nucleus interactions. DsTau aims to provide an independent $\nu_\tau$ flux prediction for future neutrino beams with accuracy under 10% which will reduce the systematic uncertainty of the $\nu_\tau$ CC cross section measurement. FASER$\nu$ will also have capability in measuring this high-energy cross section[28]. In the Deep Underground Neutrino Experiment (DUNE), significant oscillation of the $\nu_\mu$ beam into $\nu_\tau$ can allow for a precise measurement of the appearance oscillation probability at long baselines and $\mathcal{O}(5\text{ GeV})$ energy[29;30]. Additionally, DUNE's atmospheric neutrino sample will contain a large number of $\nu_\tau$ events; albeit the identification of the $\tau$ track is unattainable in DUNE, $\nu_\tau$ events can be identified via statistically inference by analyzing the event kinematics[31;32]. Importantly, performing such studies in an environment like DUNE requires new techniques to reduce the other neutrino-related backgrounds from the intense beam[33].

If a sufficiently high statistics sample can be generated with adequate background rejection and a deep understanding of $\nu_\tau A$ final state topologies, either directly or through oscillations, detailed studies of the differential $\nu_\tau$-CC cross section could be possible. This could potentially answer questions which cannot be answered using $\nu_e$-CC and $\nu_\mu$-CC interactions. For example, most formulations of the quasielastic pseudoscalar form factor are calculated in the $Q^2 = 0$ limit. Due to the high kinematic threshold for $\nu_\tau$-CC events, most events at threshold will be quasielastic with a large $Q^2$. Similarly, the form factors $F_4$ and $F_5$ are suppressed when the mass of the charged lepton is small compared to the neutrino energy, so they are negligible except in $\nu_\tau$-CC interactions[34].

With these upcoming measurements, one will have the ability to better understand oscillations involving $\nu_\tau$ in the standard three-massive-neutrinos paradigm and beyond. If only three neutrinos exist, then the oscillations involving $\nu_\tau$ can be determined perfectly by measuring only oscillations involving $\nu_e$ and $\nu_\mu$. Precision understanding of $\nu_\tau$ can serve as a (relatively weak) cross check of this determination[29;30]. Additionally, in beyond-the-Standard-Model scenarios of neutrino oscillations, $\nu_\tau$ measurements can provide unique information beyond that inferred from $\nu_\mu$ and $\nu_e$ oscillations.

To be a valid description of a physical process, neutrino-mixing must be unitary. However, many new physics models predict heavy fermionic gauge singlets, and these states can mix with the familiar neutrino flavors. The mixing of these states is described by an expanded mixing matrix of size $n \times n$ which must be unitary, but the $3 \times 3$ sub-matrix describing the mixing of the known states would not be. If these extra states are near the GUT scale, they can explain the lightness of the known neutrinos via the seesaw mechanism[35;36]. However, since no known symmetry protects the masses of the extra states, there is no theoretical reason to prefer any mass scale. For very low mass scales, the extra states could be the sterile neutrinos potentially observed at LSND and MiniBooNE. At higher masses, above the kaon mass, the extra states are kinematically inaccessible at neutrino oscillation experiments and can be integrated out.

The effect on oscillations between the known flavors when the heavy states are kinematically inaccessible can be described through a non-unitary modification of the mixing matrix[37;38]. The effect of apparent non-unitary mixing produces zero-baseline flavor change (effectively a normalization shift at short baselines), and a modification to the matter potential for propagating neutrinos[29]. For GUT-scale sterile states, non-unitarity is highly constrained by rare decays like $\mu \to e\gamma$, but at lower energy scales, these constraints are no longer valid[24]. Therefore, searching for non-unitary neutrino mixing provides a way to extend the search for sterile neutrinos to mass scales typically believed to be inaccessible for neutrino oscillation experiments, and one in which $\nu_\tau$ appearance can make great strides toward.

Beyond the non-unitarity hypothesis, measuring $\nu_\mu \to \nu_\tau$ oscillations in a beam- or atmospheric neutrino context can allow for improved limits (or discovery potential) in searches for sterile neutrinos[29;30], non-standard neutrino interactions[29;30], and neutrino decays[39]. Beyond these, one could learn even more with a clean, well-understood, $\nu_\tau$-enriched source: measurements of $\nu_\tau$ disappearance, like those performed for $\nu_\mu$ disappearance currently, would provide exciting complementary information to the broader neutrino program. While no such source is currently planned, it it nevertheless useful for the community to consider what can be learned from such experiments.

While there exist obvious challenges in the regime of measuring and identifying $\nu_\tau$ interactions in a neutrino oscillation experiment, the benefits are plenty. Given that new physics is required to explain non-zero neutrino masses, the community should exploit upcoming and future experiments in as many ways as possible to learn about neutrinos, especially those of the $\nu_\tau$ variety. It is quite possible that $\nu_\tau$ are a unique entry point to uncovering new physics which may be difficult to elucidate in any other way.

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