FASERν 2: A Forward Neutrino Experiment at the HL LHC

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Abstract

Building on the FASERν experiment, currently under construction at the LHC, a far forward emulsion detector operating at the HL LHC could detect of the order of 10^5 ν_e, 10^6 ν_μ, and 10^3 ν_τ at TeV energies. The design of such a detector and its physics potential are described.

Introduction The LHC is the highest energy particle collider built so far, and it is therefore also the source of the most energetic neutrinos created in a controlled laboratory environment. The highest energy neutrinos are produced in an intense and highly collimated beam in the far forward region, and the possibility of detecting these has been discussed for decades [1–5]. This goal is currently being realized by the construction of FASERν [6, 7], an experiment located in the far forward region, 480 m from the ATLAS interaction point. With 150 fb^{-1} at Run 3, FASERν will detect roughly 10^3 ν_e, 10^4 ν_μ, and 10 ν_τ at TeV energies, along with a similar number of anti-neutrinos. XSEN [8] and SND@LHC [9] are complementary efforts that have been proposed for a similar location on the opposite side of ATLAS. These experiments extend the LHC's physics program in a new direction, opening a new window to study neutrino interactions at the highest human-made energies ever recorded.

In this LOI, we propose that a detector with roughly ten times the mass of FASERν be constructed to take data starting in 2026-27 at the HL LHC. With 3 ab^{-1} of luminosity, such a detector would collect roughly 10^5 ν_e, 10^6 ν_μ, and 10^3 ν_τ at TeV energies, opening up many new opportunities.

Experimental Facility and Detector The FASERν detector is composed of layers of tungsten plates and emulsion layers. The total target mass is 1.3 tonnes. This design makes use of thoroughly tested experimental technologies combining electronic and emulsion detectors.

For the HL LHC era, a ~ 10 tonne emulsion detector would be able to carry out precision tau neutrino and heavy flavor physics studies. A high resolution liquid argon TPC could also be an attractive alternative. These vertex detectors should be followed by a magnetic muon spectrometer for muon charge identification. Both detectors are relatively slow detectors, and so the high muon background in the LHC tunnel might be an experimental limitation. The possibility of sweeping away such muons, for example, with a magnetic field placed upstream of the detector, is currently being explored. Given 20 times the luminosity and 10 times the target mass of FASERν, one can expect a 200-fold increase in neutrino event rate, providing extraordinary opportunities for neutrino studies. Such opportunities will not be available elsewhere for at least 20 years until the operation of a next generation hadron collider, such as the FCC-hh, and they motivate the creation of a Forward Physics Facility dedicated to housing a suite of far forward experiments at the LHC.

Physics Potential There are several physics questions that could be addressed by a forward neutrino experiment at the HL LHC. The expected forward neutrino flux estimates as well as a fast detector simulation will be prepared by the FASER Collaboration and provided upon request.

Neutrino Cross Sections at TeV Energies: Neutrino interaction cross sections have been measured by beam dump experiments at low energies $E_\nu < 350$ GeV [10], as well as by IceCube at high energies, $E_\nu > 6.3$ TeV, for muon neutrinos [11]. The first cross section measurements at TeV energies will be performed by the FASERν detector. This will be further improved in the HL LHC phase with significantly larger event statistics for all three neutrino flavors and by using experimental expertise gathered during Run 3 of the LHC. Additionally, due to the large event rate available at the HL LHC, a forward neutrino experiment could also be sensitive to neutrino-electron scattering, neutrino tridents [12], and neutrino Non-Standard Interactions [13].

Tau Neutrino Physics: The tau neutrino is the least studied known particle, as only a few handful of interactions have been directly observed. Using the LHC's forward tau neutrino beam, FASERν will be able to observe about 20 v_τ CC interactions during Run 3 of the LHC, while thousands of such events could be detected with a forward neutrino experiment at the HL LHC. This would start an era of precision tau neutrino physics, allowing one to (i) measure the tau neutrino cross section over a wide range of energies, (ii) test lepton universality in neutrino interactions, (iii) detect heavy flavor-associated tau neutrino interactions $\nu_\tau c \to \tau b$ as a complementary probe of the persisting B-decay anomalies, $b \to c\tau\nu_\tau$, (iv) set constraints on the tau neutrino's magnetic moment [14], and (v) use the probe of tau neutrino flux measurements as a laboratory for additional new physics production modes [15].

Event Shapes and Kinematics: Given the high spatial resolution of emulsion detectors, forward neutrino detectors will be able to resolve the shapes of high energy neutrino, hadron and muon interaction events, measuring, for example, their track multiplicity, the momentum distributions of charged particles, and the neutrino inelasticity. These event shapes will provide valuable input to tune MC tools used to simulate high-energy neutrino events, such as Genie [16], and can also be sensitive probes of new physics and nuclear effects [17, 18].

Charm Associated Neutrino Interactions and PDF Measurements: In addition to the inclusive CC cross section, forward neutrino detectors can study specific exclusive neutrino interaction processes. Important examples are charm-associated neutrino interactions $\nu s \to \ell c$, which can be directly identified in the emulsion detector by the presence of the secondary charm decay vertex. This process has previously been used to probe the strangeness content of the nucleon [19, 20], and measurements at a forward LHC neutrino detector will further constrain the strange quark PDF in a wider range in x. Additionally, it could be possible to perform these measurements for a variety of nuclear targets, ranging from light to heavy nuclei, to provide ideal input for nuclear PDFs [21–23] and to resolve tension between existing neutral and charged current DIS data [24].

Forward Particle Production: Although the existing LHC detectors have great coverage of the central region, the production of particles in the very forward direction along the beam pipe is only poorly constrained. In this regime, the measurement of the neutrino flux and spectrum will provide complementary constraints on forward particle production. This will help to validate and improve the underlying hadronic interaction models describing light meson production, which play an important role in cosmic ray physics [25]. In addition, forward neutrino measurements provide a unique opportunity to directly constrain forward charm production [26]. This is a key input for the current and upcoming generation of large-scale neutrino telescopes, as it constrains the prompt atmospheric neutrino flux, which is one of the main backgrounds for searches for high-energy astrophysical neutrinos [27]. Such measurements will also allow one to probe the gluon PDF [28] and intrinsic charm [29].

Sterile Neutrino Oscillations: Since no observable neutrino oscillations at LHC neutrino experiments are expected in the standard model, any oscillation signal would be evidence of a new neutrino mass difference Δm^2. Forward neutrino experiments could therefore act as short baseline experiments and constrain models of sterile neutrinos [6, 26].

Further BSM Prospects: Similar to neutrinos, the LHC could also produce an energetic and highly collimated beam of light dark matter particles which could interact, leading to distinctive signatures in the emulsion detector [9]. The search for unstable forward-going LLPs in a future FASER 2 experiment at the HL LHC could be extended towards shorter lifetimes, thanks to the secondary production of new species in the dense material of a neutrino detector [30]. Additionally, given a large number of high-energy muons going through the detector, it could also effectively act as a high-energy muon beam dump facility, with the potential for further new physics searches.

Conclusions High energy neutrino measurements at the HL LHC will provide a unique opportunity to explore TeV-scale neutrino physics with the precision required to test the most elusive parts of the standard model, as well as to look for related signs of new physics. Such an experimental program will certainly benefit from the experience of running FASERν during LHC Run 3, as well as from the expertise of the broader collider and neutrino physics community. In addition, it will provide important input for future colliders, where a far forward neutrino detector, included early in the planning, could also greatly extend the physics program. We have briefly presented the main aims of the proposed project and look forward to further discussions that may be triggered by this summary.

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