Neutrino / Dark Particle Detectors for the HL-LHC Forward Beam

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Abstract

The FASER experiment will open new opportunities for both neutrino studies at TeV energies and weakly-interacting particle searches by exploiting the large production rates available in the forward direction of p-p collisions at the LHC. For an experiment placed into this neutrino beam during the HL-LHC era with 3 ab^{-1} *of data, one expects* $\mathcal{O}(10^5)$ *neutrino interactions per ton, including all three neutrino flavors. Furthermore, sensitive tests of dark sector particle models could be performed at the same time. In this letter, we discuss the optimal detector designs to exploit this unique neutrino beam at the HL-LHC.*

Introduction - Although no LHC neutrino has been detected so far, collisions at the LHC produce an intense neutrino beam in the far-forward direction. This neutrino beam is both strongly collimated, with an effective width of $\mathcal{O}(10)$ cm, and highly energetic, with energies peaking around 1 TeV. During the upcoming Run 3 of the LHC, the FASERν detector [1, 2], which is located about 480 m downstream from ATLAS and aligned with the beam collision axis, will take advantage of this neutrino beam to detect and study LHC neutrinos for the first time. The expected number of neutrino interactions is $\mathcal{O}(10^4)$/ton/150 fb^{-1}, while even larger events rates of $\mathcal{O}(10^5)$/ton/3 ab^{-1} are available at the HL-LHC.

The physics motivations for LHC neutrino measurements have been discussed in a variety of frontier groups and are discussed in separate LOIs [3, 4]. This includes the proposal of a Forward Physics Facility (FPF), which is a dedicated experimental hall in the forward location of the LHC's collision point. The FPF would provide an environment for experiments to study properties of LHC neutrinos [1, 5–8] and to perform searches for new physics [9], extending the physics potential of the HL-LHC. In particular, it would provide the opportunity to host different detector technologies for neutrino studies. We invite the community to explore these opportunities for neutrino measurements with state-of-the-art detectors.

Environment and Detector Requirements - Below we give an overview of the environment at the FPF location and discuss the resulting requirements for neutrino detectors.

Detector size and mass: Since the beam is collimated and the muon background increases as a function of distance from the beam axis (see Figure 14 in [1]), a detector with a small transverse dimension and long lateral length may be preferable. The interaction rate would be $\sim 10^4$ ν_e, 10^5 ν_μ, and 10^2 ν_τ events/ton at the HL-LHC within a 12.5 cm radius around the beam collision axis. To achieve sizable statistics for ν_τ, a multi-ton to multi-10-ton detector would be needed. If the detector can accommodate a high background rate, it would be able to study particles from heavy particle decays (D, B, W, Z) by enlarging the transverse dimensions.

Neutrino vertex reconstruction: Neutrinos with TeV energies interact via deep inelastic scattering, creating ~ 10 charged particles and some γ-rays in a small angular space ($\lesssim 50$ mrad) at the neutrino interaction vertex [1], which will be followed by electromagnetic showers and hadronic showers. A high spatial resolution would be needed to reconstruct individual trajectories.

Event classification: The signal processes of interest include charged-current neutrino interactions, $\nu_\ell N \to \ell N'$ for $\ell = e, \mu, \tau$, neutrino-induced heavy quark production, $\nu_\ell N \to \ell D N'$ or $\ell B N'$, as well as light dark matter scattering, $\chi e \to \chi e$. The topologies of these channels in the detector are shown in Fig. 1. To study these channels, the neutrino detector should have sensitivities to different lepton and quark flavors.

Light dark matter scattering: The signal topology of this channel is a single electron starting in the volume without any other hadronic activities at the interaction point. A leading background is the high-energy γ-rays produced by high-energy muons the upstream of the detector. Such a background can be controlled by actively tagging the parental muon.

Energy resolution: Higher is better. The reconstructed energy is one of the most discriminating parameters to separate the neutral hadron background (low energy) from neutrino events. Also, it is important for many other physics analyses (cross sections, oscillations). In FASERν, $\sim 30\%$ relative resolution is expected, which is considered reasonable for these studies.

Background event rate: With the default configuration in Run 3, a muon background rate of about 1 muon/sec/cm^2 is expected. These high-energy muons are also the source of high-energy γ-rays and neutral hadrons, which could be a physical background for neutrino detection.

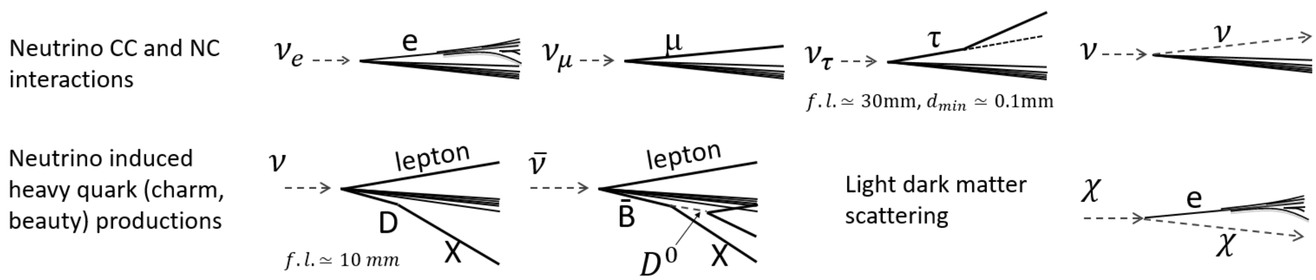


Figure 1. Topologies of channels of interest.

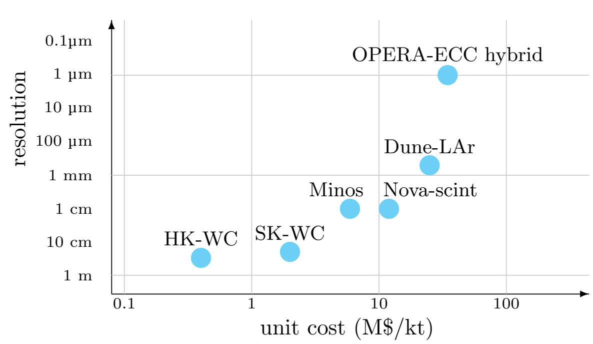
Detectors Technologies - Several detector technologies could be suitable for LHC neutrino measurements.

Emulsion Detectors: Neutrino detectors using photographic emulsion films are well-known to be sensitive to ν_e, ν_μ, and ν_τ (DONuT [10], OPERA [11], and also charm (CHORUS [12], OPERA [13], DsTau/NA65 [14]) and beauty particles (E653 [15]). In FASERν during Run 3, an emulsion-based detector will be employed [1]. Using an interface to a magnetized electronic detector, lepton charge identification can be realized, so that ν and $\bar{\nu}$ are measured separately. A drawback is the lack of timing information in emulsion detector, leading to pile up of events (mainly due to muon, $\sim 10^7$ tracks/cm^2/150 fb^{-1}). Frequent replacement of emulsion films would be needed to operate an emulsion detector at the HL-LHC. A reduction of muon background is desirable. This is feasible by installing a sweeping magnet upstream of the detector hall. Emulsion film R&D to achieve higher resolution, high sensitivity, long-term stability, and mass production are to be carried out. The optimization of detector structure and the development of efficient event reconstruction algorithms are also to be established.

Liquid Argon Detectors: A high resolution LAr TPC could be an alternative. It can provide decent spatial resolution and work as the vertex detector, electromagnetic/hadron calorimeter and muon ID. However, to fully identify τ and heavy flavor production, the spatial resolution should be significantly improved with respect to the conventional LAr TPCs. The minimum distance between the neutrino vertex point and τ's daughter line will be $\sim c\tau = 87\ \mu$m. The sum of the resolutions of vertex definition and daughter trajectory definition should be better than this value. To achieve such a high resolution, both the suppression of charge diffusion (shorter drift length, higher drift voltage) and high segmentation readout (e.g., pixel readout [16, 17] with 100 μm segmentation) are to be realized. The sensitivity of LAr detectors to light dark matter scattering would be higher than emulsion detectors, because the parent muons of background γ-rays can be tagged in the same detector volume.

Others: *Gas TPCs* could have good resolution and less hadronic backgrounds to τ identification. However, the expected event rate is suppressed by factor of 1000 compared to solid or liquid targets. *Scintillator or strip/fiber detectors* may not have sufficient resolution to resolve the vertex structure or identify quark and lepton flavors. However, they might be an interesting possibility if one targets inclusive neutrino interactions or di-muon events (like NuTeV [18]).

Scalability - Considering a large scale experiment with a ~kilo-ton mass in view of the FCC, the cost performance becomes relevant. The figure on the right shows the cost-resolution plot from the large experiments. The cost performance of emulsion based detectors (OPERA-ECC) with respect to the resolution is good. The emulsion technique is suitable for building a purpose-specific detector, such as one for beam experiments.



Conclusions - The HL-LHC can provide a unique opportunity for neutrino research at the highest human-made energies. We propose both to explore the physics potential and to develop the optimal detector technologies for collider neutrino experiments at the LHC and future colliders, and we look forward to many great ideas from the energy frontier community.

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