I. DETECTORS FOR THE FORWARD PHYSICS FACILITY AT THE LHC

The Forward Physics Facility (FPF) will be a new underground cavern at the Large Hadron Collider (LHC) to host a suite of far-forward experiments during the High-Luminosity LHC era. The existing large LHC detectors do not cover particles beyond pseudorapidity range of $|\eta| \leq 4.5$ [1], and so they miss the physics opportunities provided by the enormous flux of particles produced in the far-forward direction. The FPF will realize this physics potential. In the following we will briefly summarize the physics considerations for FPF detectors, the technical challenges, and novel approaches to these detectors.

A. Physics Requirements

The FPF will need a diverse set of experiments, each optimized for particular physics goals. Details of the physics reach can be obtained in [2, 3].

FASER2, a magnetic spectrometer and tracker, will search for light and weakly-interacting states, including long-lived particles, new force carriers, axion-like particles, light neutralinos, and dark sector particles. FASER2 will increase sensitivity by many orders of magnitude beyond the FASER experiment [4] by increasing the acceptance and the length of the magnetic spectrometer. FASERν2 and Advanced SND are proposed emulsion and electronic neutrino detectors, respectively. They are both in the several ton scale. FLArE is a proposed 10-tonne-scale noble liquid detector. These detectors will detect neutrinos and also search for light dark matter. They will each detect $\sim 10^6$ neutrinos and anti-neutrinos at energies ranging from 100 GeV to few TeV. Each is expected to detect $\sim 10^3$ tau neutrinos also at very

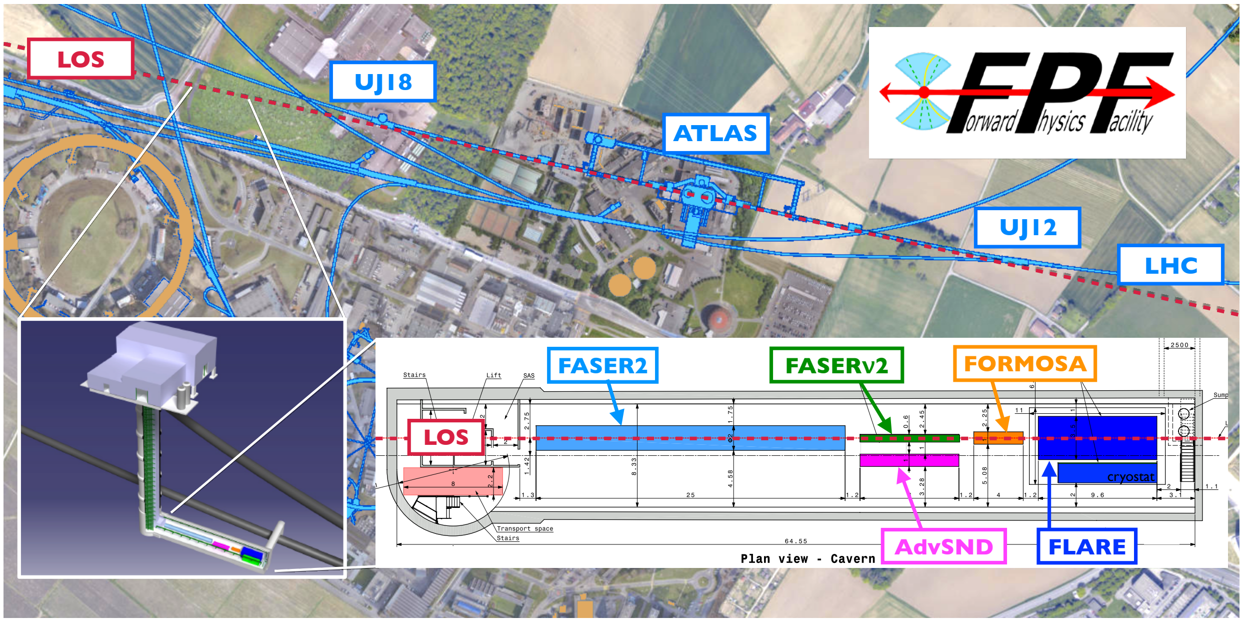

FIG. 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments along the line of sight (LOS) to explore the many physics opportunities in the far-forward region.

high energies. Laboratory experiments have not detected neutrinos in this high energy range in the past. The detection, reconstruction, energy measurement, and particle identification present unique challenges to existing instrumentation. Detection of tau particles either by explicit identification of decays near the vertex (in emulsion) or by kinematics (in electronic detectors) in a high energy charged current tau neutrino interaction particularly presents unique challenges. Collecting a large sample of well identified tau neutrino interactions is a unique capability of the FPF. This capability will be fully utilized by multiple detectors with very different technical approaches. Lastly, it is of great interest that these same detectors have low thresholds ($<$ few hundred MeV) for detection of light dark matter scattering.

Finally, the FORMOSA detector is composed of scintillating bars. These bars are arranged to measure charge deposition from straight-through millicharged particles and other very weakly-interacting particles across a large range of masses.

B. Technical Considerations

The most important technical issue is finding a location along the line of sight (LOS) at an appropriate distance and with features that include access, safety, and the ability to have a large space to house multiple detectors and their infrastructure. During 2021-2022, in a series of workshops [5] informed by the CERN civil engineering team and accelerator advisory body, the location 617-682 m west of the ATLAS interaction point (IP) has been selected. This location is about ~ 80 m deep and shielded from the ATLAS IP by over 200 m of concrete and rock, providing an ideal location to search for rare processes and very weakly-interacting particles. A dedicated shaft will provide access to the underground hall, and the construction of both the facility and detectors can be substantially decoupled from HL-LHC construction and activities; this will make planning, scheduling, as well as safety aspects easier for the FPF.

Despite the shielding from the IP due to LHC magnets, concrete and rock, there is a substantial flux of high energy μ^-/μ^+ particles directly from the IP as well as produced in the various LHC accelerator structures. Studies are progressing to reduce this flux to < 1 Hz/cm^2 during the HL-LHC running (with nominal luminosity of $\sim 5 \times 10^{34}$/cm^2/sec) using sweeping magnets with momentum kick of ~ 7 Tesla-meter in a location ~ 350 m from the IP. Given the many uncertainties including the maximum luminosity in the planned long running of the HL-LHC (until 2040) detectors at the FPF should be designed to operate with an expected high energy muon flux in the range of ~ 1 Hz/cm^2. For comparison, the neutrino event rate will be approximately 50 charged current events per day per ton of detector with 45 ν_μ CC, 5 ν_e CC, and $\sim$0.2 ν_τ CC.

C. Experimental Technologies

The proposed experiments vary in their technological readiness. While they are conceptually similar to previous efforts, many of them require scaling up of hardware and software technologies to a new level. And some will require focused R&D efforts to tackle specific issues. Two such efforts will be the ability to trigger the detectors in the presence of considerable muon backgrounds, and the ability to track and reconstruct neutrino vertices with high multiplicities due to the very high energies of the events.

FASER2: The experiment proposes a large superconducting spectrometer magnet of 2 to 3 meter diameter and decay volume length of 10-20 meters. The very high energies of expected tracks from decays of long lived particles implies that for reasonably large magnetic fields (1 T), the spectrometer will require charged particle resolution exceeding $\sim$1 mm in large area tracking detectors. The detector will also need to include a fine grained EM calorimeter and a muon identification system. A sophisticated trigger system to select LLP decays in the spectrometer volume in the presence of background muons will be needed.

FASERnu2: This will be a ×10 scaled up version of the current FASERnu (1.2 ton) detector composed of emulsion and tungsten stacks. A pilot run of this technology has already yielded 6 candidate neutrino events from the LHC [6]. The scaled up version for the FPF presents two issues that need to be solved. The HL-LHC presents much high muon rate for this kind of detector which has no trigger capability; the emulsion detectors need to be changed regularly because of the muon radiation. The increased size and frequency of replacement will mean over two orders of magnitude greater production and handling of emulsion films with correspondingly larger analysis effort for FASERnu2. The experience from FASERnu, however, will prove to be extremely valuable to automate much of this process.

Electronic Neutrino Detectors:

Advanced-SND is conceived to be an electronic fine grained detector with a magnetic muon spectrometer. The neutrino target is nominally expected to be a few tons. The technology is still under development with several choices including a detector with silicon tracking detectors sandwiched with passive neutrino target material. Such a silicon readout will require further development.

FLArE will be a noble liquid tracking time projection chamber with a hadronic calorimeter to capture particles escaping from the downstream end, as well as a muon tagger. The default fill is considered to be liquid argon, although liquid krypton is also under consideration. The nominal size of the detector is approximately 2m wide, 2m high, and 7m long for the TPC and an additional few meters for the hadronic calorimeter and muon tagging system. The key technical challenges for the detector are the installation of the cryostat and cryogenic systems, the TPC design to obtain the highest spatial resolution for tracks near the vertex, and the scintillation photon system to trigger on neutrino and dark matter events with sufficiently low threshold. This detector benefits enormously from the last decade of R&D investment into DUNE[7] technologies, however the needed tracking resolution and trigger capability is unique for FLArE and will require dedicated R&D.

FORMOSA: The technologies for FORMOSA are standard with scintillation counters and readout of photo-multiplier pulses, however care has be exercised in limiting backgrounds from muons and instrumental effects. Much will be learned from a prototype experiment, expected to be built and run during the upcoming Run-3 of the LHC.

All detectors will require intelligent flexible trigger systems that can capture interesting events and associate them across detector systems. Requirements for such triggers to cooperate across detector systems as well as with the collider detector at the IP are in consideration.

---

[1] G. Aad *et al.* (ATLAS), JINST **3**, S08003 (2008).

Technology	FASER2	FASERnu2	Adv-SND	FLArE	FORMOSA
Large aperture SC magnet	x				
High resolution tracking	x		x	x	
Large scale emulsion		x			
Silicon tracking			x		
High purity noble liquids				x	
Low noise cold electronics				x	
Scintillation				x	x
Optical materials				x	x
Cold SiPM				x	
Picosec synchronization			x	x	x
Intelligent Trigger	x		x	x	x

TABLE I: Enabling technologies for the detectors and systems of the far forward physics facility.

[2] L. A. Anchordoqui *et al.*, (2021), arXiv:2109.10905 [hep-ph].

[3] J. L. Feng *et al.*, (2022), arXiv:2203.05090 [hep-ex].

[4] A. Ariga *et al.* (FASER), (2018), arXiv:1812.09139 [physics.ins-det].

[5] "Forward physics facility workshops," https://indico.cern.ch/category/13966/.

[6] H. Abreu *et al.* (FASER), Phys. Rev. D **104**, L091101 (2021), arXiv:2105.06197 [hep-ex].

[7] B. Abi *et al.* (DUNE), (2018), arXiv:1807.10334 [physics.ins-det].