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Snowmass 2021 Letter of Interest

Forward Physics Facility

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Abstract

A rich physics program remains unexplored in the far-forward region at the LHC. The Forward Physics Facility (FPF) is a proposal to enlarge an existing cavern in the far-forward region of ATLAS to house a suite of experiments with groundbreaking new capabilities for neutrinos, long-lived particle searches, milli-charged particle searches, QCD, dark matter, dark sectors, and cosmic rays. The FPF will be located 500 m from the ATLAS interaction point. It is shielded from the ATLAS interaction point by 100 m of concrete and rock, creating an extremely low-background environment, ideal for many standard model studies and new physics searches. In this Letter of Interest, we describe the FPF's location and general features, its physics potential in the HL-LHC era, and topics for further study.

Thematic Areas

- (EF05) QCD and Strong Interactions: Precision QCD
- (EF06) QCD and Strong Interactions: Hadronic Structure and Forward QCD
- (EF09) BSM: More General Explorations
- (EF10) BSM: Dark Matter at Colliders
- (NF03) BSM
- (NF06) Neutrino Interaction Cross Sections
- (NF10) Neutrino Detectors
- (RF06) Dark Sector Studies at High Intensities
- (CF07) Cosmic Probes of Fundamental Physics
- (AF05) Accelerators for PBC and Rare Processes
- (UF01) Underground Facilities for Neutrinos
- (UF02) Underground Facilities for Cosmic Frontier

Introduction In planning for the coming decades in particle physics, it is critically important to maximize the physics potential of the High-Luminosity LHC (HL-LHC). For decades, the focus at the energy frontier has been on high-p_T physics and the production of heavy particles through processes with fb to nb cross sections. The total pp interaction cross section at the LHC is 75 mb [1, 2], however, and most of the events, and most of the highest-energy particles created, are in the far-forward region at low p_T. These low-p_T events escape down the beampipe of the LHC's large detectors, and it is important to understand now if interesting physics opportunities are currently being missed in this "wasted" cross section.

In recent years, it has become clear that this is in fact the case, and there is a rich physics program that is largely unexplored in the far-forward region at the LHC. In this Letter of Interest, we consider the possibility of creating a Forward Physics Facility (FPF) to house a diverse set of experiments dedicated to carrying out this program in the HL-LHC era.

Location and General Features The FPF can be created by enlarging the existing cavern UJ12, which is approximately 500 m from the ATLAS IP. The beam collision axis passes just beyond UJ12's southern wall (see Fig. 1). By extending UJ12 to encompass the beam collision axis with a 2 m buffer, all experiments so far envisioned for the FPF can be accommodated. Cavern UJ18 is a nearly identical alternative location on the opposite side of ATLAS.

The FPF's location is shielded from the ATLAS IP by 100 m of concrete and rock. Beam and other backgrounds have been simulated with FLUKA [3–5], and these results have been validated with data taken by pilot detectors in 2018 [6, 7]. These results confirm that backgrounds at this location are exceptionally low, providing an ideal environment for the detection of neutrinos and other feebly-interacting particles.

Currently a number of experiments, including MilliQan [8, 9], FASER [6, 7, 10], CODEX-b [11, 12], FASERν [13, 14], SND [15], and MAPP [16], are being constructed in or proposed for underground locations around the LHC. These are highly constrained by tunnels and infrastructure that were never intended to house experiments, and the necessary surveying and support services have been assembled piecemeal. Several of these experiments could find a home at the FPF, which would provide a unifying infrastructure, with sufficient space for both planned detectors and future experiments emerging from new ideas.

Long-Lived Particles New long-lived particles (LLPs) are motivated by the existence of a dark sector and searches for them are of great interest [17–19]. The FPF will be an excellent home for experiments searching for LLPs with masses in the MeV to several GeV range. At the HL-LHC, all mesons will be produced in large numbers, and their decays can produce a large flux of energetic forward-going LLPs. The discovery potential for LLPs at the FPF is well-documented. Building on the FASER experiment, currently under construction for Run 3, an upgraded FASER 2 detector is currently planned for the HL-LHC [20]. With a radius of 1 m and a length of 5 m, FASER 2 is too big for the existing tunnel, but could be easily accommodated in the FPF. Such a detector has the potential to discover dark photons and other light gauge bosons [10, 21–26], dark Higgs bosons and other light scalars [27–30], heavy neutral leptons [31–33],

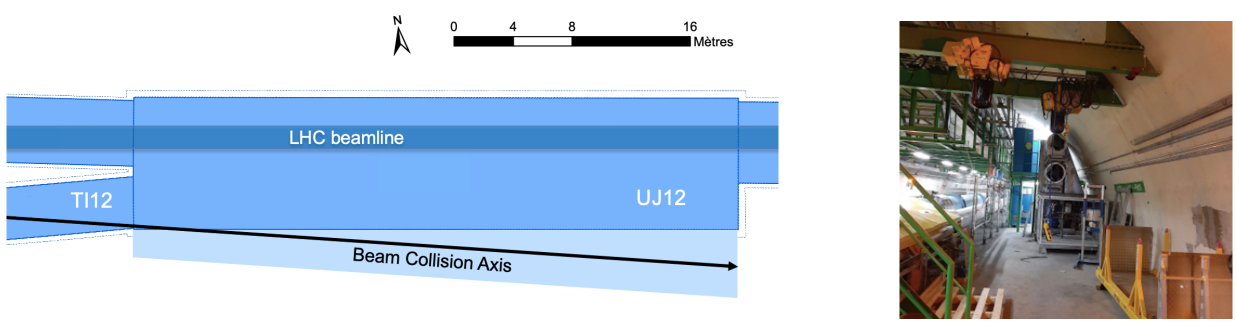

Figure 1. **Left**: The existing cavern UJ12 and side tunnel TI12 (blue), the LHC beamline (dark blue), and the extension of UJ12 around the beam collision axis (light blue) needed to create the Forward Physics Facility. [Credits: CERN GIS, Liam Dougherty.] **Right**: View of UJ12 from TI12. The LHC beamline is on the left, and the beam collision axis passes along the wall on the right, roughly 90 cm above the cavern floor. [Credit: Jamie Boyd.]

axion-like particles [34, 35], and many other models [36–44].

Milli-Charged Particles The MilliQan [8] demonstrator experiment, located in a tunnel near CMS, has already established world-leading sensitivity to milli-charged particles [9]. The possibility of placing a MilliQan-type detector at the FPF location is currently under study [45]. Preliminary results indicate that the enormous meson fluxes, leading to large milli-charged particle fluxes, at the FPF imply significantly improved sensitivities to milli-charged particles, including the prospect of detecting particles with charges around 10^{-4} to 10^{-2} e for masses between 10 MeV and 100 GeV [46].

Dark Matter Detection LLPs may decay to dark matter particles, which may be detected in a far-forward detector. The search for dark-matter scattering has been studied for the off-axis SND emulsion detector [15], and preliminary studies are underway for on-axis locations [47, 48]. Provided backgrounds, for example, from neutrino scattering, can be brought under control, experiments at the FPF may be able to probe significant new regions of parameter space, including those with the right thermal relic density.

High-Energy Neutrinos Although no collider neutrino has ever been detected, the LHC provides an intense, strongly collimated beam of highly energetic neutrinos of all three flavors in the far-forward region around the beam collision axis. The prospects for neutrino detection in the far-forward region have been studied for the emulsion detectors FASERν [13, 14] and SND [15], and the prospects for a larger detector, FASERν 2, which could be housed at the FPF, have also been considered [49, 50]. With the expected luminosity of the HL-LHC and ~ 10 tons of emulsion, FASERν 2 will detect 10^5 ν_e, 10^6 ν_μ and 10^3 ν_τ with TeV energies, constraining neutrino cross sections at the highest human-made energies ever recorded in a way complementary to IceCube [51, 52], starting an era of precision tau-neutrino physics, and providing a novel probe of many other neutrino properties and neutrino-related models of new physics [53–56].

QCD and Forward Hadron Production Although existing LHC detectors have great coverage of the central region, the production of particles in the far-forward direction is poorly constrained. In this regime, the measurement of the neutrino flux and spectrum will provide constraints on QCD that are complementary to those provided by other facilities, such as the EIC [57] and LHeC [58]. This will help validate and improve the underlying hadronic interaction models [59–61] and multi-purpose event generators [62–64], help constrain the gluon PDF at $x \sim 1$, test intrinsic charm at large x [65, 66], test the DGLAP formalism in the low x region ($x \sim 10^{-7}$) for $Q^2 \sim$ few GeV^2, and quantify potential effects due to the transition to other factorization and evolution formalisms, eventually incorporating gluon saturation [67]. In addition, DIS neutrino interactions will constrain PDFs, particularly the strange quark's through $\nu s \to \ell c$ [68, 69]. Measurements for a variety of nuclear targets, ranging from light to heavy nuclei, will also constrain nuclear PDFs [70–72] and may help resolve tension in existing DIS data [73].

Cosmic Rays and Cosmic Neutrinos The understanding of forward particle production plays an important role in astroparticle physics [74–77]. Measurements of forward muons and muon neutrinos may provide useful information to understand the observed excess of muons in cosmic-ray air showers [78–81]. In addition, constraints on forward charm production using LHC neutrinos [53, 82] would be a key input for both the current and upcoming generations of large-scale neutrino telescopes, as they will reduce some of the important uncertainties affecting prompt atmospheric neutrino fluxes. Although this process is most certainly the dominant background for searches for high-energy astrophysical neutrinos above 100 TeV, current analyses of IceCube data have not been able to disentangle the prompt neutrino flux from other flux components [83], and present state-of-the-art theory predictions have large uncertainties [84].

Summary The Forward Physics Facility will provide a unifying infrastructure for far-forward experiments at the HL-LHC. Relative to the cost of the HL-LHC, the FPF and its experiments require a modest additional investment. At the same time, these experiments will be unique probes of standard model physics, will significantly extend the LHC's discovery potential, and are well aligned with the European Strategy Update's recommendations for a diverse experimental program [85]. Additional studies of the FPF's physics potential, the optimal mix of experiments for the FPF, the civil engineering required to construct the FPF, and similar facilities at other future colliders are all important topics for further study.

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