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QCD AT A FORWARD PHYSICS FACILITY AT THE HIGH-LUMINOSITY LHC*

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The Forward Physics Facility (FPF) is a proposal to build a new underground in the far-forward region of ATLAS to house a suite of experiments with groundbreaking new capabilities for many Standard Model studies and new physics searches. 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. This will help validate and improve the underlying hadronic interaction models and multi-purpose event generators, and constrain the gluon PDF in the low-x region.

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1. Introduction

The Forward Physics Facility (FPF) [1, 2] is a proposed addition to the Large Hadron Collider (LHC) that aims to study high-energy particle interactions in the far-forward region, that is currently not covered by the existing LHC experiments. This area is located along the beam collision axis, 617–682 m west of the ATLAS interaction point (IP) (see figure 1). The FPF will be built in an underground cavern and will consist of a suite of different experiments, each optimized for specific physics goals.

The proposed location for the FPF is 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. The FPF experiments will enable the detection of millions of neutrino interactions at the highest energies ever recorded, expand our understanding of proton and nuclear structure, and carry out searches for a wide range of new phenomena. The envisioned experiments include FASER2, FASERν2, AdvancedSND, FLArE, and FORMOSA.

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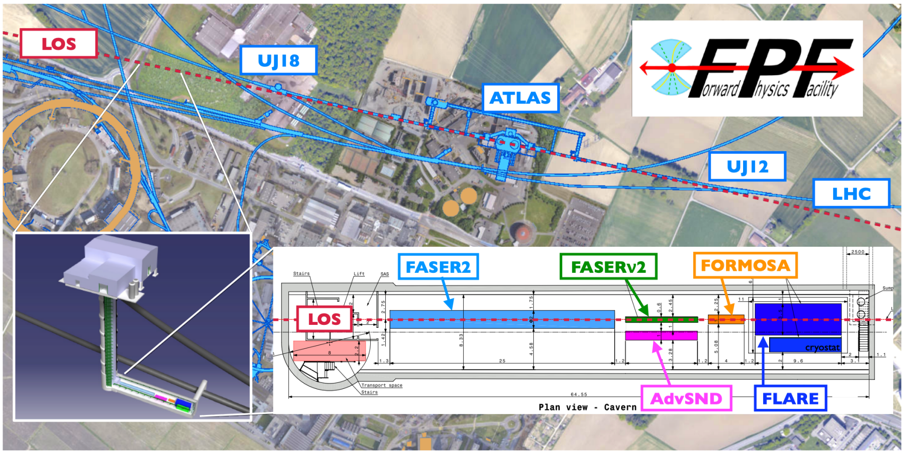

Fig. 1. The proposed cavern to host the Forward Physics Facility during High-Lumi LHC. The FPF will host different experiments to explore the many physics opportunities in the far-forward region [2].

The FPF has the potential to probe our understanding of strong interactions, and proton and nuclear structure. It will be sensitive to the very forward production of light hadrons and charmed mesons, providing access to both the very low-x and very high-x regions of colliding protons. The FPF will also act as a neutrino-induced deep-inelastic scattering experiment with TeV-scale neutrino beams, providing valuable information on the partonic structure of nucleons and nuclei. These measurements will be complementary to those expected at the upcoming Electron–Ion Collider (EIC).

2. The facility

The location of the FPF needs to be on the beam collision axis or line of sight (LOS) near an LHC interaction point (IP), and also be sufficiently shielded from the IP to provide a low-background environment for studies of neutrinos and searches for other very weakly-interacting particles. Civil engineering studies have been conducted to identify suitable locations for the FPF and to understand the particle fluxes and backgrounds at these locations. The studies have focused on a location that is approximately 500–600 m away from a high-luminosity LHC IP on the LOS. Two options have been considered: building a new purpose-built facility, approximately 617–682 m west of the ATLAS IP, and expanding the existing UJ12 cavern, 480–521 m east of the ATLAS IP. The new purpose-built facility (see figure 2) is currently considered the baseline option, as it offers many benefits for experiments, including not being limited in size and length, and being designed around the needs of the experiments. Civil engineering represents a significant portion of the effort for physics projects like the FPF, making it crucial to ensure a viable and cost-efficient conceptual design. The proposed location includes an 88 m-deep access shaft, a 65 m-long experimental cavern, and support buildings and infrastructure.

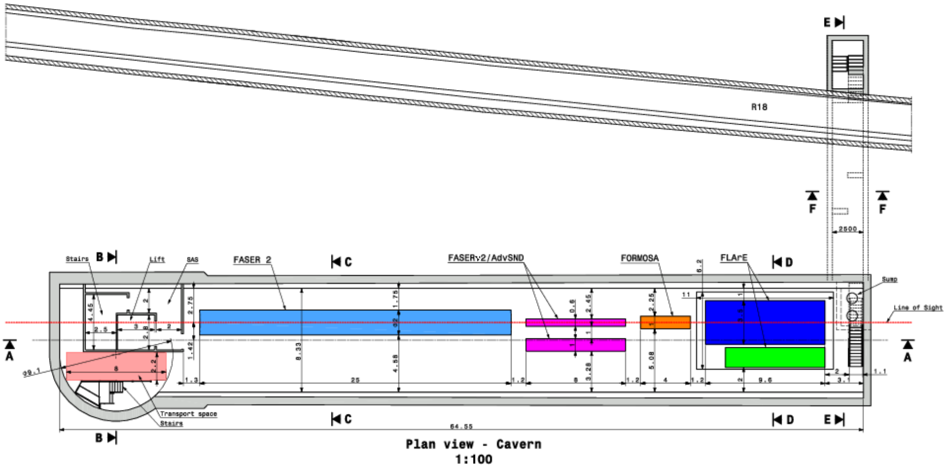

Fig. 2. General layout of the FPF experimental cavern. The colored boxes indicate the possible experiments that could be installed in this option [2].

3. The experiments

The FPF will host ten-tonne-scale experiments aimed at detecting neutrino interactions with energy ranging from hundreds of GeV to a few TeV, an energy level never directly explored before for any neutrino type. Furthermore, by determining the charge of resulting muons in charged-current interactions, it will be possible to differentiate between muon and tau neutrinos and anti-neutrinos. These neutrino events will greatly enhance accelerator cross-section measurements and offer the first chance to study tau neutrinos and anti-neutrinos in detail. Additionally, they offer new opportunities to find or limit BSM effects in neutrino production, propagation, and interactions, with important implications for QCD and astroparticle physics.

3.1. FASERν2

The FASERν [3] neutrino detector is part of the FASER [4] experiment designed to detect collider neutrinos and study their properties at TeV energies. FASERν started data taking in 2022 with a 1.1-tonne tungsten target, aiming at measuring $\sim 10^3$ flavor-tagged charged-current neutrino interactions. Its successor, the FASERν2 [2] detector will be able to perform precision tau neutrino measurements and heavy-flavor physics studies in the HL-LHC era, testing lepton universality and new physics.

The FASERν2 detector (see figure 3 (a)) is composed of 3300 emulsion layers and tungsten plates. Its target is a tungsten mass of 20 tonnes with a volume of 40 cm × 40 cm × 6.6 m. The detector will include a veto and interface detectors for global analysis and muon charge measurement. The veto system is scintillator-based and the interface detectors could use SiPM and scintillating fiber tracker technology. The total length of the detector, including emulsion films and interface detectors, is approximately 8 m and the detector will be located in a cooling system.

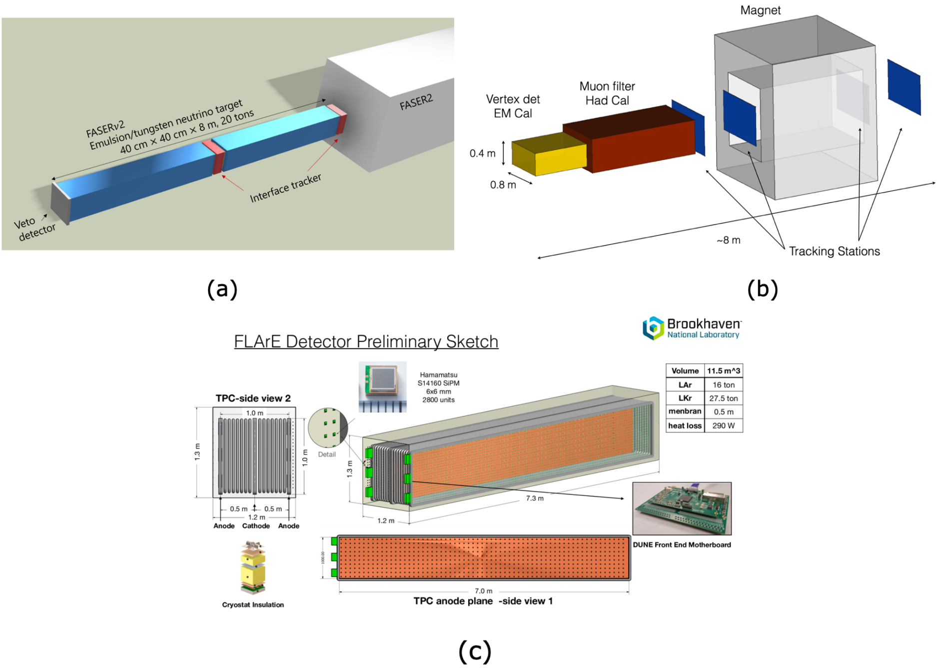

Fig. 3. Schematic layout of the FASERν2 (a), AdvancedSND (b), and FLArE (c) detectors [2].

3.2. AdvancedSND

The AdvancedSND [2] project aims to extend the physics capabilities of the SND@LHC experiment [5] by adding two detectors: AdvancedSND-FAR (in the region of $7.2 < \eta < 8.4$) and AdvancedSND-NEAR (in the region of $4 < \eta < 5$). These detectors are planned to operate during HL-LHC and beyond. AdvancedSND-FAR will be placed in the FPF, while NEAR will be more upstream due to its higher average angle. The goal of the project is to perform QCD measurements in an unexplored pseudo-rapidity range, measure neutrino cross sections in the TeV energy range and test lepton flavor universality with neutrino interactions.

Both detectors will have three main components: a target region for vertex reconstruction and electromagnetic energy measurement, a hadronic calorimeter, and a muon identification system. The target will consist of sensitive layers interleaved with tungsten plates, with a total mass of around 5 tons. The Collaboration is exploring the use of electronic trackers in the target region. The hadronic calorimeter and the muon identification system will be about 10 λ in length, with a magnetic field strength of about 1 T over 2 m length. A schematic view of the detector is shown in figure 3 (b).

3.3. FLArE

The FLArE experiment aims to use a liquid argon time projection chamber (LArTPC), that is well suited for neutrino detection and light dark-matter searches as it can perform particle identification and measure track angle and kinetic energy. The goal is to detect and measure TeV-scale neutrino events, including tau neutrinos generated at HL-LHC and to identify energetic, isolated, forward-going electrons for dark-matter events. The LArTPC provides high spatial and kinematic resolution, but requires R&D for trigger and event reconstruction.

The FLArE detector is $\sim$ 7 m-long and has a 10-ton fiducial mass, as shown in figure 3 (c). The detector will measure millions of neutrino interactions and requires a scintillation system, trigger, and selection to retain high efficiency while maintaining low trigger rates. A downstream hadronic calorimeter and a muon range detector may be required to contain particles escaping from the TPC for energetic neutrino events. The addition of magnetic field for momentum measurement is also under study.

4. QCD physics program

FPF will perform QCD studies on forward particle production in proton–proton collisions and neutrino deep-inelastic scattering on the target detector, as schematically shown in figure 4. The focus is on the forward production of particles such as light hadrons and charmed mesons at the ATLAS interaction point in proton–proton collisions. The kinematics of these processes reveals information about the low-x region of colliding protons and novel QCD production mechanisms, such as BFKL or non-linear dynamics.

The particles then decay into neutrinos that travel until they reach the FPF detectors, making the FPF effectively a neutrino-induced deep-inelastic scattering experiment with TeV-scale neutrino beams. Measurements of the resulting DIS structure functions offer a valuable understanding of the partonic structure of nucleons and nuclei, specifically for quark flavor separation.

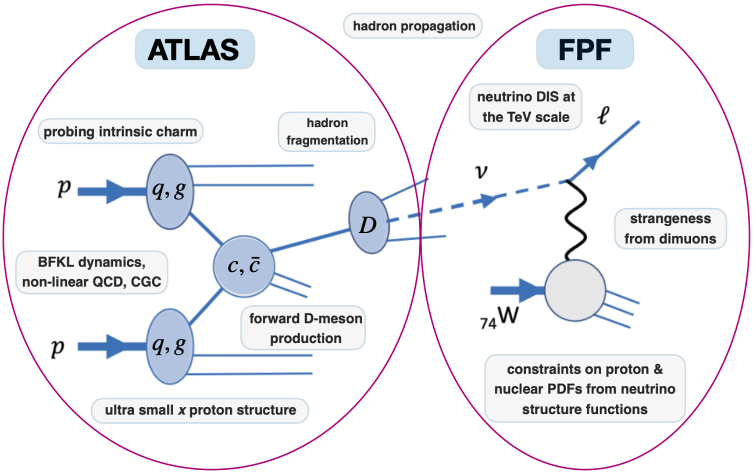

Fig. 4. Schematic representation of a typical QCD process (D-meson production in this case) taking place at the FPF [2].

Figure 5 illustrates the kinematic reach of proton–proton collisions that will be attainable with the FPF. The figure displays the coverage in the (x, Q) plane for D-meson production in proton–proton collisions at the LHC with $\sqrt{s} = 14$ TeV, followed by decay into neutrinos within the FPF acceptance. The figure also shows the approximate coverage of other experiments providing inputs for proton global PDF analyses, as well as future facilities such as the Electron–Ion Collider (EIC) [6] and the Forward Calorimeter (FOCAL) [7] upgrade of the ALICE experiment.

The availability of FPF measurements would extend LHC measurements in the low-x region by almost two orders of magnitude at low-Q, reaching x of 10^{-7}, depending on the FPF detector's specific acceptance. This extreme, largely uncharted kinematic range offers numerous opportunities for QCD studies such as mapping the gluon at low-x, uncovering non-standard QCD phenomena like BFKL dynamics, and testing Monte Carlo models for forward hadron production. This enhanced understanding of low-x QCD and nucleon structure also improves predictions for key astroparticle physics processes such as ultra-high energy (UHE) neutrino–nucleus and cosmic ray interaction cross-sections. Additionally, the forward production of light hadrons such as pions and kaons will also contribute to the overall neutrino yield at the FPF, probing a similar kinematic region as reported in figure 5.

FPF's ability to study low-x QCD dynamics in proton–proton collisions will become crucial for the future proton–proton collider such as the Future Circular Collider at 100 TeV [8–11]. Such extreme energies make low-x dynamics even more important in standard electroweak processes and in

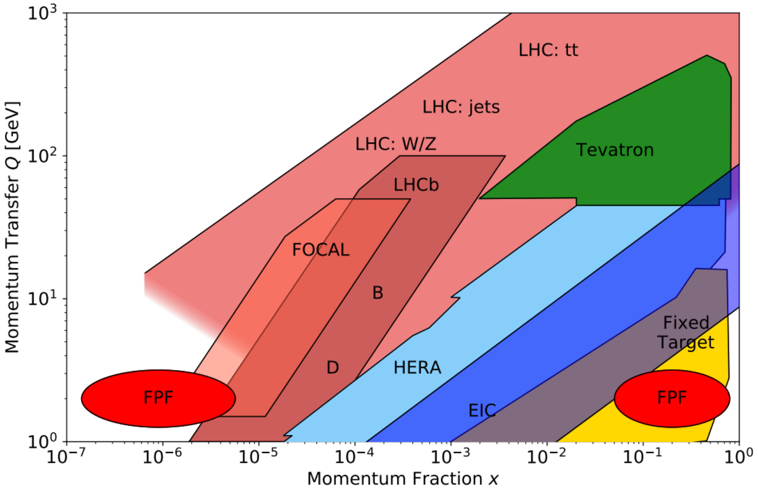

Fig. 5. The schematic kinematic coverage in the (x, Q) plane for D-meson production in proton–proton collisions at the LHC followed by their decay into neutrinos falling within the FPF acceptance [2].

calculating the Higgs production cross section. The low-x QCD mapping provided by FPF measurements will play a crucial role in connecting the physics program at the HL-LHC with the higher-energy proton–proton collider that will follow.

Figure 5 shows that the FPF will have sensitivity also to high-x kinematics, which is of interest due to the FPF's ability to detect intrinsic charm component in protons [12]. The FPF measurements will provide information on the intrinsic charm content of protons and could enhance the expected flux of prompt neutrinos from charm meson decays in cosmic ray collisions. These prompt neutrinos are a significant background source for astrophysical neutrinos in detectors such as IceCube and KM3NET.

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