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The Forward Physics Facility at the High-Luminosity LHC

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. The proposed Forward Physics Facility (FPF), to be located several hundred meters from the ATLAS interaction point and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). In this report, we review the status of the civil engineering plans and the experiments to explore the diverse physics signals that can be uniquely probed in the forward region. FPF experiments will be sensitive to a broad range of BSM physics through searches for new particle scattering or decay signatures and deviations from SM expectations in high statistics analyses with TeV neutrinos in this low-background environment. High statistics neutrino detection will also provide valuable data for fundamental topics in perturbative and non-perturbative QCD and in weak interactions. Experiments at the FPF will enable synergies between forward particle production at the LHC and astroparticle physics to be exploited. We report here on these physics topics, on infrastructure, detector, and simulation studies, and on future directions to realize the FPF's physics potential.

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Executive Summary

The Facility The Forward Physics Facility (FPF) is a proposal to build 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 have holes along the beam line, and so miss the physics opportunities provided by the enormous flux of particles produced in the far-forward direction. The FPF will realize this physics potential. A preferred site for the FPF is along the beam collision axis, 617-682 m west of the ATLAS interaction point (IP); see Fig. 1. This location 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. FPF experiments will detect 10^6 neutrino interactions at the highest human-made energies ever recorded, expand our understanding of proton and nuclear structure and the strong interactions to new regimes, and carry out world-leading searches for a wide range of new phenomena, enhancing the LHC's physics program through to its conclusion in 2040.

Experiments The FPF is uniquely suited to exploit physics opportunities in the far-forward region, because it will house a diverse set of experiments, each optimized for particular physics goals. The envisioned experiments and their physics targets are shown in Fig. 2. 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. FASER 2 and Advanced SND, proposed emulsion and electronic detectors, respectively, will detect 10^6 neutrinos and anti-neutrinos at TeV energies, including 10^3 tau neutrinos, the least well-understood of all known particles. FLArE, a proposed 10-tonne-scale noble liquid detector, will detect neutrinos and also search for light dark matter. And FORMOSA, a detector composed of scintillating bars, will provide world-leading sensitivity to millicharged particles and other very weakly-interacting particles across a large range of masses.

Figure 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 to explore the many physics opportunities in the far-forward region.

Figure 2: The Forward Physics Facility will probe topics that span multiple frontiers, including new particles, neutrinos, dark matter, QCD, and astroparticle physics.

Physics Beyond the Standard Model The FPF will allow tests of a wide variety of theories of physics Beyond the Standard Model (BSM), explaining outstanding questions such as the hierarchy problem, neutrino masses, the nature of dark matter, inflation, and the matter-antimatter asymmetry of the universe. New particles and forces can be detected at the FPF in different ways. Many theories feature light, weakly-coupled particles that have lifetimes long enough to be produced at the ATLAS IP and subsequently decay within FPF detectors, like FASER2. Alternatively, DM particles may scatter inside a dense detector like Advanced SND, FASER2, or FLArE and produce visible signatures. Both electron and nuclear scattering are possible. Finally, some models have new states, for example, millicharged particles, which would leave non-standard energy deposits in detectors. Such particles could be observed at FORMOSA and possibly other detectors.

Searches for new heavy particles benefit from the unparalleled energies at the LHC, and the FPF will provide leading sensitivities if such states are preferentially produced in the forward direction, as in the case of quirks. Searches for light states may also be enhanced at the energy frontier, as they are produced with very high boosts, allowing probes of shorter lifetimes, or through rare B decays and similar processes that are much less common at other facilities. These capabilities result in unique projected sensitivities in many BSM models that surpass current, or even future expected, limits.

Quantum Chromodynamics The FPF has the promising potential to probe our understanding of the strong interactions as well as of 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 the very high-x regions of the colliding protons. The former regime is sensitive to novel QCD production mechanisms, such as BFKL effects and non-linear dynamics, as well as the gluon parton distribution function (PDF) down to x $10^{\ 7}$, well beyond the coverage of other experiments and providing key inputs for astroparticle physics. The latter regime provides information on open questions relating to the high-x PDFs, and in particular intrinsic charm. In addition, the FPF acts as a neutrino-induced deep-inelastic scattering (DIS) experiment with TeV-scale neutrino beams. The resulting measurements of neutrino DIS structure functions represent a valuable handle on the partonic structure of nucleons and nuclei, particularly their quark flavour separation, that is fully complementary to the charged-lepton DIS measurements expected at the upcoming Electron-Ion Collider (EIC).

Neutrino Physics The LHC produces high energy and intense fluxes of all flavors of neutrinos and anti-neutrinos in the forward region. Ten-tonne-scale experiments at the FPF are being designed to detect 10^5 $_e$, 10^6 , and 10^3 interactions with energies between several hundreds of GeV and a few TeV, an energy range that has not been directly probed for any neutrino flavor. In addition, by measuring the charge of the resulting muons in charged-current interactions, muon and tau neutrinos and anti-neutrinos will be distinguished. These neutrino event will significantly extend accelerator cross section measurements and provide the first opportunity for detailed studies of tau neutrinos and anti-neutrinos. They will also open up new avenues to discover or constrain BSM physics effects in neutrino production, propagation, and interactions, with important implications for QCD and astroparticle physics.

Astroparticle Physics The FPF provides opportunities for interdisciplinary studies at the intersection of high-energy particle physics and modern astroparticle physics. Cosmic rays enter the atmosphere with energies up to 10^{11} GeV and beyond, where they produce large cascades of high-energy particles. The development of these extensive air showers is driven by hadron-ion collisions under low momentum transfer in the non-perturbative regime of QCD. Measurements at the FPF will improve the modeling of high-energy hadronic interactions in the atmosphere, reduce the associated uncertainties of air shower measurements, and thereby help to understand the properties of cosmic rays, such as their energy and mass, which is crucial to discover their origin. Moreover, atmospheric muons and neutrinos produced in these extensive air showers in the far-forward region are the main background for searches of high-energy astrophysical neutrinos with large-scale neutrino telescopes. The FPF will help to understand the atmospheric neutrino flux and reduce the uncertainties for astrophysical neutrino searches in the context of multi-messenger astrophysics.

Timeline and Cost The FPF is well aligned with the 2020 European Strategy Update's first recommendation that \the full physics potential of the LHC and the HL-LHC...should be exploited." To fully exploit the far-forward physics opportunities, many of which will disappear for several decades if not explored at the FPF, the FPF should be available for as much of the HL-LHC era as possible. The FPF requires no modifications to the LHC, and all of the planned experiments are relatively small, inexpensive, and fast to construct. A very preliminary costing for the FPF has yielded estimates of 25 MCHF for the construction of the new shaft and cavern and 15 MCHF for all necessary services. To this must be added the cost of the individual experiments. A possible timeline is for the FPF to be built during Long Shutdown 3 from 2026-28, the support services and experiments to be installed starting in 2029, and the experiments to begin taking data not long after the beginning of Run 4. Such a timeline is guaranteed to produce exciting physics results through studies of very high energy neutrinos, QCD, and other SM topics, and will additionally enhance the LHC's potential for groundbreaking discoveries that will clarify the path forward for decades to come.

Contents

Chapter 1

Introduction

Particle colliders have been used for decades to discover the fundamental building blocks of the universe and study their properties. The high energy frontier is now at the Large Hadron Collider (LHC) at CERN, which began colliding protons with protons in 2010 and is expected to run until 2040. Soon after the LHC started, the Higgs boson was discovered [1, 2], but so far no other new fundamental particles have been found. At the same time, deep mysteries remain, including the origin of neutrino masses, the identity of dark matter, and many others. These problems provide overwhelming evidence that we are far from a complete understanding of the universe, and they strongly motivate new experiments that will deepen our understanding of the Standard Model (SM) and maximize our potential for discovering new physics in the years to come.

An important question is whether opportunities for groundbreaking discoveries are currently being missed at the LHC. History provides a cautionary tale. In 1971, the first proton-proton collider, the Intersecting Storage Rings (ISR), began operating at CERN. As recounted in numerous talks and articles celebrating the ISR's 50th anniversary last year [3, 4], when the ISR began operating, physicists believed that new discoveries would be made by observing particles emitted in the forward region, that is, roughly parallel to the beamline. Detectors therefore focused on this region. For this reason, the ISR missed the discovery of the charm quark, which was discovered at Brookhaven and SLAC in 1974 in what is now recognized as one of the most important breakthroughs in the history of physics.

Recently, it has been recognized that we may be missing opportunities at the LHC for a similar, but opposite, reason. Having absorbed the lessons of the 1970's, the current large detectors at the LHC are well instrumented at large angles relative to the beamline. Unfortunately, they have holes in the far-forward direction. Particles produced parallel to the beamline are therefore undetected, leading to the possibility that new discoveries may have simply escaped the LHC through these holes in the far-forward region.

In fact, it is now known that interesting physics opportunities have indeed been missed in the far-forward region. In May 2021, the FASER Collaboration announced the detection of neutrino candidates using an 11 kg pilot detector placed in the far-forward region for a month in 2018 [5]. These were the first neutrino candidates ever detected at a collider, and the highest energy neutrino candidates ever seen from a terrestrial source. To date, an entire program of neutrino physics has been missed at the LHC, and it is natural to wonder if even greater discoveries could be made with dedicated experiments placed in the far-forward region.

Motivated by such considerations, in the last 3 years, three new far-forward detectors have been approved and constructed at the LHC: FASER [6{9], FASER [5, 10, 11], and SND@LHC [12, 13]. Despite their small size (meter-scale) and inexpensive and rapid construction, these detectors will significantly extend the LHC's physics program when Run 3 begins in mid-2022. Exploiting the enormous fluxes of particles in the far-forward direction, and shielded from the ATLAS interaction point (IP) by 100 m of rock and concrete, FASER, FASERν, and SND@LHC will together detect $\sim 10{,}000$ TeV-energy neutrinos and search for signs of new particles, with important implications for models of new physics, dark sectors, QCD, neutrino physics, and astroparticle experiments.

FASER, FASERν, and SND@LHC are currently located in previously abandoned service tunnels constructed for the Large Electron-Positron Collider in the 1980's. These locations were never intended to house experiments and the necessary services, and they cannot accommodate larger detectors or additional experiments. At the same time, it has become abundantly clear that these detectors do not fully exploit the possibilities offered by the far-forward region.

The Forward Physics Facility (FPF) is a proposal to construct a dedicated facility to house a suite of far-forward experiments during the High-Luminosity LHC era. Studies of potential sites for the FPF have now converged on two preferred options. In the first, a purpose-built facility is excavated with a new shaft and new cavern providing 65 m of space along the beam collision axis or line of sight (LOS), 617-682 m west of the ATLAS interaction point (IP). An alternative option is to expand the current location of FASER and FASERν with alcoves to provide space along the LOS 480-521 m to the east of the ATLAS IP. Based on the expected costs, and a number of important benefits for the experiments, the new purpose-built facility is currently considered the baseline option for the FPF. Experiments currently planned for the FPF include upgraded versions of the existing detectors (FASER2, FASERν2, and Advanced SND), as well as new experiments, including FORMOSA, which will search for millicharged particles and related signals, and FLArE, a noble liquid TPC, which will detect neutrinos and also search for light dark matter produced by the LHC.

The FPF's special location makes its experiments uniquely sensitive to many SM and BSM phenomena, and its physics capabilities are complementary to those of other current and proposed experiments at the LHC. Besides the large LHC experiments probing high-p_T physics, these include a number of smaller detectors performing SM measurements in the forward region, including ALFA [14], AFP [15], CASTOR [16], CT-PPS [17], LHCf [18], and TOTEM [19]. These are located in or around the LHC beam pipe close to either the ATLAS or CMS IP, but, in contrast to the FPF, are not shielded from these IPs by hundreds of meters of concrete and rock. Such shielding is essential for searches for extremely rare phenomena, where the goal is to reduce backgrounds so that even a few events over the course of the entire HL-LHC era will be sufficient to claim a signal. The FPF is also complementary to the existing experiments MilliQan [20, 21] and MoEDAL [22], as well as proposed experiments, such as ANUBIS [23], CODEX-b [24, 25], and MATHUSLA [26–28], which also aim to search for long-lived particles and other new physics at the LHC, but, in contrast to FPF experiments, are located at large angles relative to the beamline. Last, there are also important synergies of FPF physics with experiments running or proposed at other facilities, including, for example, BSM searches at beam dump experiments, such as SHiP [29] at the SPS. Compared to fixed target experiments, FPF experiments have lower pp interaction rates, but higher center-of-mass energies. Of course, practically, the FPF also has the virtue of being completely parasitic, requiring no dedicated beam time and no modifications to the existing accelerator structures.

The FPF was first proposed in May 2020 and has been the subject of 4 dedicated meetings held in November 2020 [30], May 2021 [31], October 2021 [32], and February 2022 [33]. In parallel, the FPF activities have been strongly supported by CERN's Physics Beyond Colliders Study Group [34] and through the activities of numerous Snowmass 2021 working groups [35]. A brief Letter of Interest was submitted to Snowmass in August 2020 [36], and the status of the FPF was summarized by 80 authors in a 75-page document in October 2021 [37]. This current document contains a more comprehensive summary of the status of the FPF, including studies of the facility and its environment in Chapter 2, the proposed far-forward experiments in Chapter 3, and its unique potential to discover long-lived particles, detect DM and other scattering signatures, and study QCD, neutrinos physics, and astroparticle physics in Chapters 4, 5, 6, 7, and 8, respectively.

The FPF is well aligned with the 2020 European Strategy Update's first recommendation that \the full physics potential of the LHC and the HL-LHC...should be exploited" [38]. To realize this goal, the FPF and its experiments should be available for as much of the HL-LHC era as possible. A possible timeline is for the FPF to be built during Long Shutdown 3 from 2026-28, the support services and experiments to be installed starting in 2029, and the experiments to begin taking data not long after the beginning of Run 4. To realize this timeline, Conceptual Design Reports for the FPF and all experiments must be prepared in the near future, to be followed by Technical Design Reports, approvals, and funding. The timeline benefits from the fact that the purpose-built facility can be mostly constructed even while the LHC is running and requires no modifications to the LHC, while all of the planned experiments are small, fast, and inexpensive, relative to most collider detectors. Of course, the driving force is the FPF's potential to enrich the physics program of the LHC. If not constructed for the HL-LHC era, many of the FPF's physics opportunities will be lost for at least several decades. On the other hand, if prepared for the HL-LHC era, the FPF is guaranteed to produce exciting physics results through studies of neutrinos, QCD, and other SM topics, and it will enhance the LHC's potential for groundbreaking discoveries that will clarify the path forward for decades to come.

Chapter 2

The Facility

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The physics goals of the FPF require that it be located on the beam collision axis or line of sight (LOS) near an LHC interaction point (IP). The location should also be sufficiently shielded from the IP to provide a very low-background environment for studies of neutrinos and searches for other very weakly-interacting particles. In this Chapter, we present the results of studies to identify suitable locations for the FPF and to understand the particle fluxes and backgrounds at these locations.

The civil engineering (CE) studies have been based on the requirement that the FPF be approximately 500-600 m away from a high-luminosity LHC IP on the LOS. Following an initial study of the existing LHC infrastructure and geological conditions, several options were considered to accommodate the facility around both the ATLAS IP (IP1) and the CMS IP (IP5). The options considered included constructing a new facility, which could be built around the needs of the experiments, and widening or expanding the existing LHC infrastructure, with the potential benefit of minimizing the cost and the disruption to LHC operations and reducing the overall schedule of the required CE works. The many possibilities were then narrowed down to two preferred options: (1) a new purpose-built facility, approximately 617–682 m west of the ATLAS IP, and (2) alcoves extending the existing UJ12 cavern, which is 480–521 m east of the ATLAS IP. The locations of these two options are shown in Fig. 2.1. Based on the expected costs and a number of important benefits for the experiments, the new purpose-built facility is currently considered the baseline option for the FPF.

This Chapter is organized as follows. In Sec. 2.1 the purpose-built facility is described, including the experimental cavern, access shaft, safety gallery, and support buildings and infrastructure. The necessary services for this facility are discussed in Sec. 2.2. We then present the UJ12 alcoves option in Sec. 2.3. Preliminary estimates of the engineering costs for both options are given in Sec. 2.4, and the benefits of the purpose-built facility are summarized in Sec. 2.5.

We then describe the results of studies to evaluate the particle fluxes and backgrounds in the FPF. FLUKA simulation studies are described in Sec. 2.6, and the implications of these studies for radiation protection studies are discussed in Sec. 2.7. Complementary studies with the BDSIM and PROPOSAL simulation programs are described in Sec. 2.8 and Sec. 2.9, respectively. Finally, the

Figure 2.1: The locations of the two preferred FPF sites currently under consideration. In the baseline option, a new cavern and shaft are excavated to create a new purpose-built facility, providing a detector hall along the LOS roughly 617{682 m west of the ATLAS IP (IP1) in France. An alternative option is to build alcoves to extend the existing UJ12 cavern, which is located 480{521 m east of the ATLAS IP in Switzerland.

location and design of a sweeper magnet to reduce the dominant muon background are summarized in Sec. 2.10.

2.1 Purpose-Built Facility

Cvili engineering generally represents a significant portion of the effort for physics projects like the FPF. For this reason, CE studies are of critical importance to ensure a viable and cost-efficient conceptual design. This section provides an overview of FPF CE studies for the purpose-built facility, including key considerations and the current design being studied. As noted above, the purpose-built facility is now considered the baseline implementation of the FPF at CERN. The main advantage of having such a new facility is not being limited in size and length. In comparison to options extending the existing LHC infrastructure, the facility would be designed around the needs of the experiments.

Studies for the purpose-built facility benefit from many similar projects carried out at CERN. A recent example carried out from 2018-21 is the CE works at Point 1 for the HL-LHC (the so called UPR), which involved the digging of similar shaft and tunnel/cavern structures and the installation of the needed services. Studies, designs, and lessons learned during the UPR construction helped to make rapid progress in the conceptual design of the FPF purpose-built facility.

Figure 2.2: Situation plan of the purpose-built facility, located approximately 617-682 m to the west of IP1 on the French side of CERN land, 10 m away from the LHC tunnel. The SPS beamline is 30 m above the FPF cavern.

The proposed location begins approximately 617 m from IP1 on the French side of CERN land, 10 m away from the LHC tunnel, as shown in Fig. 2.1. A more detailed view is given in Fig. 2.2.

The major CE elements required to implement the FPF are:

- An 88 m-deep access shaft.
- A 65 m-long experimental cavern.
- A safety gallery connecting the FPF cavern to the LHC tunnel.
- Support buildings and infrastructure.

These are described in turn in the following subsections.

Vibrations during the digging of the shaft and cavern could have a detrimental effect on the performance of the LHC. A study is ongoing to understand what part of the FPF CE works could be carried out during LHC operations. Based on observations during the UPR works, it is expected that a significant part of the FPF works could be done during LHC running. Of course, the excavation of the safety gallery and the connection to the LHC tunnel will have to be done during an LHC shutdown.

2.1.1 Experimental Cavern

To meet the physics requirements, the experimental cavern is designed to be located on the LOS, beginning approximately 617 m from the ATLAS IP1 and 10 m away from the LHC tunnel. The cavern will be 65 m-long and 8.5 m-wide, leaving enough space around the experiments for easy access for transport and installation of the required services, as shown in Fig. 2.3. The floor level is set at 1.5 m under the LOS, with a 1.25% fall towards IP1, following the inclination of the LOS. The experiments are centralized on the LOS and are served by a crane system along the cavern, as shown in Fig. 2.4 and Fig. 2.5. For safety reasons, given the potential of cold gas leakage, a 1 m-deep trench is foreseen under the LAr detector (FLArE), as shown in Fig. 2.5.

Figure 2.3: General layout of the FPF experimental cavern. The colored boxes indicate the possible experiments (and their dimensions) that could be installed in this option, including FASER2 to search for long-lived particles, FASER 2 and AdvSND to study neutrinos and search for new particles, FORMOSA to search for mCPs, and FLArE to detect neutrinos and search for DM. The green box is a possible cooling unit for FLArE.

Figure 2.4: Section through the cavern with the proposed experiments and crane system.

Figure 2.5: Cross sections through the cavern. Section C-C shows the FASER2 detector, and section D-D shows the FLArE detector in blue, a possible cooling unit in green, and a 1 m-deep trench for safety in the case of cold gas leakage.

2.1.2 Access Shaft

The cavern is connected to the surface through an 88 m-deep and 9.1 m-diameter access shaft located on the top of the cavern. It will be equipped with a lift and staircase for access with enough space reserved for transport, as shown in the Fig. 2.6.

Figure 2.6: Shaft equipped with lift and staircase. The red area showing the space reserved for transport.

2.1.3 Safety Gallery

To comply with CERN's safety requirements and avoid any possible dead ends, a safety gallery will connect the experimental cavern to the LHC and serve as a secondary emergency exit, as shown in Fig. 2.7.

A key virtue of the dedicated facility is that access to the cavern will be possible during LHC operations. This would allow the installation of services and experiments, as well as maintenance and upgrades of experiments, to be possible at any time. A radioprotection (RP) study (discussed in detail in Sec. 2.7) has been carried out to assess the feasibility of this due to the radiation level in the cavern, which shows this is sensitive to the design of the safety gallery connecting the cavern to the LHC tunnel.

Based on the first RP study, the initial layout of the gallery has been modified to further reduce the dose levels in the cavern. As part of the modification, a third chicane wall was added, the thickness of the walls was increased from 40 cm to 80 cm, and a change was made in the location of the walls, as shown in Fig. 2.7 and Fig. 2.8. A new RP study will be made to verify the effectiveness of the above-mentioned modifications.

The safety gallery will only be used as an emergency escape route from the FPF cavern into the LHC tunnel, with an interlocked access door between the two. In the case that this door is opened, LHC operation will be automatically stopped for safety reasons.

Figure 2.7: Section through the LHC tunnel, safety gallery, and experimental cavern.

Figure 2.8: Plan view of the safety gallery.

2.1.4 Support Buildings and Infrastructure

Above ground, an access building and two auxiliary buildings are proposed to house the necessary infrastructure and utilities for the experiments, with their size being based on similar projects at CERN. The proposed layout of the buildings is shown in Figs. 2.9 and 2.10.

Figure 2.9: Proposed surface buildings for the facility (left shows the existing situation, right with the proposed surface buildings included).

The 33 m-long and 21 m-wide access building located over the shaft will provide access from the ground level to the experiments for both personnel and equipment. It is designed as a basic steel portal frame structure with an internal height of 15 m, however the walls on the south and southwest will be part-formed from a retaining wall to support the excavation. The hall will be

Figure 2.10: General layout of the proposed surface buildings.

Figure 2.11: 3D model of the proposed surface buildings.

equipped with a 25 t overhead crane to lower the experiments into the cavern.

The service buildings for the electrical, cooling, and ventilation infrastructure are also characterized as steel portal frame structures, similar to the access building. The cooling and ventilation building will be 20.5 m long, 21 m wide, and 13.5 m high, with the wall on the west side partformed from a retaining wall to support the excavation. The electrical building will be adjacent to the cooling and ventilation building and will be 20.5 m long, 12 m wide, and 5.5 m high. Both buildings will have a 1.2 m-deep false floor to allow the services to be distributed into the shaft. The proposed design of the surface buildings is shown in Fig. 2.11.

An access road will be provided, linking to the existing roads and infrastructure of the SM18 buildings at the northeast, as shown in Fig. 2.12. A requirement for a maximum gradient of 6% has been respected, in line with the requirements of CERN's transportation services.

The volume of earthworks arising from the project is significant, predominantly because of the existing site levels and ground conditions. The proposed location has been previously used as a spoil disposal area, and the ground levels vary between 453-457 m above sea level, 5-8 m above the existing infrastructures in the surrounding area. As a result, to reduce the volume of the excavated material as much as possible, and taking into consideration the ground condition, the finished ground level of the buildings is proposed to be at 450 m, as shown in Fig. 2.13.

2.2 Services

Given the early stage of the project and the lack of detailed designs and requirements for the proposed experiments in the FPF, further work is required for a detailed understanding of the needed services.

Based on similar underground facilities at CERN, it is clear that the purpose-built facility would need dedicated services, including electrical distribution, ventilation system, transport/handling infrastructure, communication infrastructure, access and alarm systems, and safety systems. This contrasts with the case of the UJ12 alcoves option, to be discussed in Sec. 2.3, where most of the needed services would be available from close by within the LHC infrastructure.

The details and costs for some of the needed infrastructure and services are fairly well known, whereas in other cases there are very large uncertainties, mostly stemming from the lack of detailed requirements. A very preliminary costing of the main services is summarized in Table 2.1[1]. For

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[1] Note that, for a large LAr TPC detector, an additional gas extraction system would be needed for safety reasons,

Figure 2.12: Section through the surface buildings showing the proposed excavated volume and existing site levels.

Item	Details	Approximate cost (MCHF)
Electrical Installation	2MVA electrical power	1.5
Ventillation	Based on HL-LHC underground installation	7.0
Access/Safety Systems	Access system Oxygen deficiency hazard Fire safety Evacuation	2.5
Transport/Handling Infrastructure	Shaft crane (25 t) Cavern crane (25 t) Lift	1.9
Total		12.9

Table 2.1: Breakdown of the main services and infrastructure for the dedicated FPF facility, with a very preliminary costing. This costing was done in mid-2021 and so, where applicable, reflects prices at that time.

the approximate overall costing of the facility to be presented in Sec. 2.4, a total of 15 MCHF for services has been assumed to also account for items not included in Table 2.1.

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and this has not been included in this costing.

Figure 2.13: Section through the surface buildings showing the proposed excavated volume and existing site levels. The section lines are shown in Fig. 2.12.

2.3 UJ12 Alcoves Option

An alternative to the purpose-built facility is the UJ12 alcoves option, in which the existing UJ12 cavern is expanded on one side with separate alcoves to accommodate the experiments and to provide the space needed around them. UJ12 is part of the LHC tunnel system and is 480-521 m west of the ATLAS IP1 at CERN's site in Switzerland, as shown in Fig. 2.1.

A significant drawback of the UJ12 option is the difficulty of accessing the work site. Transport to UJ12 along the LHC from ATLAS is limited to small equipment that is approximately 1 m wide, prohibiting using this route for an excavating machine for any works in UJ12. As an access point, it is therefore envisaged to use the existing 40 m-deep PGC3 shaft located on the top of the abandoned TI12 tunnel and then pass through the 536 m-long TI12 tunnel, which currently houses the FASER experiment, as shown in Fig. 2.14. The PGC3 shaft has an internal diameter of 3 m, as shown in Fig. 2.15, which imposes significant space constraints, and the works need to be designed around what can be achieved with only small equipment.

Figure 2.14: Access to the UJ12 cavern using the existing PGC3 shaft and passing through the 536 m-long TI12 tunnel.

Figure 2.15: Internal dimensions of the PGC3 shaft.

Following the conceptual design studies, the baseline layout includes three alcoves of 6.4 m width, but with different lengths of 2.9 m, 3.7 m, and 4.4 m, as shown in Figs. 2.16, 2.17, 2.18, and 2.19. It must be noted that the impact of the foreseen works on the existing wall of the cavern and the cavern itself has yet to be fully assessed. All the works must be carried out in a way that minimises the impact on the existing facility. It is assumed that all the existing

Figure 2.16: Proposed CE works for the UJ12 alcoves option.

services and equipment will be removed from the cavern prior to the works. This would include temporarily removing 4 LHC dipole magnets, a 60 m-long section of the QRL cryogenic line, and also electrical and ventilation equipment. Initial studies suggest that this would be possible during a Long Shutdown between LHC runs, but it would entail significant work for many CERN teams.

Figure 2.17: 3D model of the UJ12 alcoves option with possible experiments shown.

Figure 2.18: Plan view of the UJ12 alcoves option. The coloured boxes indicate the possible experiments (and their dimensions) that could be installed in the alcoves, including FASER2 to search for long-lived particles, FORMOSA to search for millicharged particles, and FASERν2 and AdvSND to detect neutrinos and search for DM.

Figure 2.19: Longitudinal section through the UJ12 cavern with alcoves and possible experiments.

2.4 Engineering Costs

The cost of construction of the FPF is difficult to estimate at such an early stage of the study. The variability of ground conditions, inflation, change of scope, and lack of detailed design means that developing a high level of confidence is not possible. For FPF costing purposes, a comparative costing was adopted, based on the presented layouts.

A very preliminary cost estimate suggests that the cost of the dedicated purpose-built facility, including 15 MCHF for the needed services, as discussed in Sec. 2.2, would be about 40 MCHF. The cost of the UJ12 alcoves option would be about 15 MCHF. The accuracy of the estimates is considered Class 4 – Study or Feasibility, with the actual cost possibly 15–30% lower or 20–50% higher [39]. Until the project requirements are further developed, it is suggested that a suitable band to adopt would be 20% lower to 40% higher for CE costs.

2.5 Choice of Baseline Facility

Given the preliminary costing of the two options studied, with only a factor of 2.7 difference in cost, there is a strong preference from the physics community to make the purpose-built facility the baseline FPF option. The main reasons for this are:

- Much more space for the experiments, allowing for them to be designed/optimized for physics reach rather than around the available space. This also allows for experiments to be placed somewhat off-axis,[2] as is motivated by some of the physics goals;
- Much better access for equipment to be transported into the experimental area, since there are strict size and weight limitations for transporting items to UJ12 in the LHC complex;
- A LAr TPC detector (FLArE) with a strong physics case, could be installed in the dedicated facility, but not the UJ12 alcoves option, given safety requirements;
- For the dedicated facility, it is expected that people can access the experiments during beam operations (pending the RP study detailed in Sec. 2.7), which allows improved flexibility in terms of scheduling of detector installation and maintenance;
- Beam backgrounds will be minimized for experiments in the dedicated facility, which may be important for experiments searching for rare and low-energy signatures (such as neutrino interactions or dark matter scattering);
- The dedicated facility's location would allow a factor of two larger lever arm for a sweeper magnet to deflect background muons away from the LOS, as discussed in Sec. 2.10.

2.6 FLUKA Studies of the FPF Environment and Backgrounds

The physics goals of the FPF require a low-background environment so that weakly-interacting particles and very rare processes may be observed. In addition, an important potential benefit of the purpose-built facility discussed above is that the radiation backgrounds in the cavern may be low enough to allow access to the FPF even during LHC operations.

For all of these aspects, it is important to have an accurate understanding of the particle fluxes and radiation environment in the FPF cavern. In this section, preliminary results from FLUKA are presented, with a particular focus on the fluxes of high-energy muons that are the dominant particle physics background for many FPF signals. FLUKA studies may also be used to determine

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[2] It is worth noting that as the detector is moved off-axis, a larger detector is needed to fully cover a given rapidity range. For example, a 1 m^2 detector centred 1 m away from the LOS, will cover only approximately 16% of the full solid angle corresponding to this rapidity range ($6.7 < |y| < 7.8$).

the low-energy radiation backgrounds, and their implications for radiation processes, access to the cavern, and safety will be discussed in the following Sec. 2.7.

2.6.1 Introduction to FLUKA

At particle colliders, it is essential to characterize the radiation field to cope with the multiple effects of the interaction of regular and accidental beam losses on machine and detector components. To quantify these effects starting from the relevant loss terms, multipurpose Monte Carlo codes are a critical tool, enabling the evaluation of macroscopic quantities through the microscopic description of particle transport and interactions in matter. This requires tracking through magnetic fields, as well as accounting for all applicable electromagnetic and nuclear processes over an extremely wide energy range. The code's reliability is verified through individual benchmarking of physics models against exclusive data. A profitable calculation requires modeling the machine and detector geometry, including material information, to a challenging degree of accuracy. This allows in turn for an inclusive validation against measurements from extended monitor systems (see below).

At CERN, FLUKA [40–42] is the reference tool to assess the machine protection aspects and the complementary radiation protection scope, as well as the machine-induced background to experiments. It is regularly and extensively used for the whole accelerator chain, from the beam dump design of low-energy injectors as Linac4, up to LHC collimation and the High Luminosity (HL) upgrade of the LHC. For future colliders, FLUKA also plays a crucial role, starting in the early stages of planning, for both accelerator and detector design and for both hadron and lepton machines. This means that simulations have to deal with protons up to some million TeV (the beam energy with a target at rest required to reach 100 TeV center-of-mass collisions) down to the lowest transport limit of 100 eV photons (for the study of lepton ring synchrotron radiation). Such a task calls for the continuous improvement of the different interaction models, having in mind that, despite the very high energy of beams of interest, several quantities, such as those related to radionuclide inventory, are extremely sensitive to the low-energy nuclear physics ingredients ruling the reaction fragment de-excitation.

Together with this physics-oriented effort, notable technical developments have made it possible to automatize the construction of consistent geometry models of several-hundred-meter accelerator portions [43, 44].

The operation of the LHC has provided the opportunity to probe the degree of reliability of simulations performed over the long course of the LHC design phase. In particular, the Beam Loss Monitor (BLM) system, consisting of a few thousand ionization chambers all along the 27 km beam line, provides on-line measurements of the energy released by the particle shower originated by beam particle interactions, and it triggers beam aborting if the detected values exceed pre-defined thresholds. Particle shower calculations make it possible to predict BLM signals for different loss scenarios, correlating them at the same time with the energy deposition levels in the most exposed or sensitive elements and the radiation levels, namely differential particle fluences, in areas of interest. Various representative examples of comparisons between BLM measurements and FLUKA predictions are presented in Ref. [45].

2.6.2 The FLUKA Model of the ATLAS Insertion

For the FPF, it is particularly important to understand the particle debris generated by colliding beams at the ATLAS IP during HL-LHC running. Given an inelastic cross section of about 80 mb (including diffractive events), the collision products carry almost 7 kW towards each side of IP1 at the ultimate instantaneous luminosity of 7.5×10^{34} cm^{-2} s^{-1} for 7 TeV proton operation. Only a

Figure 2.20: View of a portion of the FLUKA model of the HL-LHC. On the bottom left, one can see the ATLAS forward shielding surrounding the TAXS. The LHC tunnel extends to the west of the ATLAS IP up to the first DS cells (top right), with the violet wall shielding the RR alcove that sits at 250 m from the ATLAS IP.

limited fraction of this power ($< 5\%$) impacts the detector itself, while 80% of it is transported out of the experiment's cavern by high-energy, forward-angle particles travelling inside the beam vacuum chamber through the accelerator elements. These particles amount on average to 6 per single pp collision out of the 155 particles emerging on average from IP1 after neutral pion decay, and are mostly photons, charged pions, protons, and neutrons. The accelerator elements will be protected by a 1.8 m-long copper absorber, called the TAXS, located near the interface between the cavern and the LHC tunnel about 20 m from IP1, and featuring a 60 mm-diameter cylindrical aperture, considerably larger than the present one. The TAXS absorbs another 8%, while the following 60 m-long string composed of single-bore superconducting quadrupoles (the final focus triplet), corrector magnets and separation dipole (D1) take 22% (as part of the above 80%, which does not include the TAXS fraction, though). In fact, the majority of the energetic pions matching the TAXS aperture are then bent by the magnetic field onto the massive beam screen structure traversing the aforementioned string and embedding tungsten layers to protect the 150 mm-diameter aperture of the magnets.

A new version of the other main absorber (TAXN) will sit 45 m after the D1, incorporating the transition between one single central aperture and two separate symmetrical apertures of 88 mm-diameter and intercepting the LOS of neutral particles coming from IP1. Its effectiveness in protecting downstream elements will be slightly weakened by the adoption of horizontal beam crossing in IP1, since, in this case, the axis of the debris cone, instead of hitting exactly in-between the two TAXN twin apertures (as for vertical crossing), moves closer to the external aperture, as a function of the crossing angle. For the baseline half crossing angle of 250 rad, the ATLAS TAXN is expected to absorb 20% of the one-side debris power.

An 8 m-long superconducting twin bore recombination dipole will open to the matching section, taking 100 m of the experimental insertion up to the Dispersion Suppressor (DS). The matching

Figure 2.21: Positive (left) and negative (right) muon fluence rate distributions over a 16 m^2 square centered on the ATLAS LOS at 348.5 m from IP1. Values are normalized to the HL-LHC nominal luminosity of $5L_0 = 5 \times 10^{34}$ cm^{-2} s^{-1}. The black circle represents the superconducting magnet transverse section, indicating the accelerator line position at the end of half-cell 9.

section features four main superconducting quadrupole assemblies (numbered Q4 to Q7) and ends 270 m from IP1. Less than 10% of the one-side debris power, mostly carried by photons, neutrons, and protons, is absorbed in this machine segment, concentrated in the first (TCLPX4) of the three metallic horizontal collimators to be installed on the outgoing beam aperture to further shield the cold magnet coils. Most of the remaining debris power goes to the preceding tunnel walls.

The third TCL collimator, in front of Q6, can also provide an effective cleaning of the initial part of the DS, where the beam lines are bent by the LHC main dipoles and no layout modification is planned for the HL-LHC era. Nevertheless, beyond the TCL6 range, losses take place in the DS odd half-cells, according to the periodicity of the single turn dispersion, as already regularly observed. They consist of protons that underwent diffraction at IP1 and are affected by a magnetic rigidity deficit of the order of 1%, leading them to touch the beam screen of the outgoing beam chamber in the horizontal plane towards the center of the ring.

2.6.3 Radiation Characterization in the Dispersion Suppressor

The implementation in FLUKA of the ATLAS insertion model described above has enabled multiple studies, mainly oriented to HL-LHC design [46], but also serving other purposes, for instance, the evaluation of background and neutrino fluxes for SND@LHC [13]. We present here preliminary results for the calculation of the flux of high-energy muons reaching FPF along the ATLAS LOS, which originate in both primary IP1 collisions and downstream shower development.

Thanks to a dedicated optimization, featuring a suitable transport threshold adjustment and combined biasing techniques, including artificially increasing the decay probability of parent mesons and controlling statistical weight fluctuations, it was possible to produce a meaningful muon sample just upstream of the proposed sweeper magnet location, as shown in Fig. 2.21. For both positive and negative muons, the fluence is maximal on the accelerator line, a bit less than 1 m from the ATLAS LOS at $x = y = 0$. In contrast, a fluence minimum is found at the LOS for positive muons, while negative muons display a concentration on the horizontal plane ($y = 0$) on the external side

Figure 2.22: Positive (green) and negative (violet) muon fluence spectra averaged over a 16 m^2 square centered on the ATLAS LOS at 348.5 m from IP1. Values are normalized to one pp inelastic collision; the ultimate HL-LHC luminosity of 7.5×10^{34} cm^{-2} s^{-1} corresponds to 6×10^{9} inelastic pp collisions per second.

of the ring, compatible with the bending action of the DS dipole field. The positive and negative muon energy spectra, averaged over the square of Fig. 2.21, are reported in Fig. 2.22, indicating that positive muons are predominant above 1 TeV.

The muon samples shown constitute the source term for a second step simulation implementing the sweeper magnet (see Sec. 2.10) and the further propagation of muons to the FPF through the rock. The goal of this second step will be to quantify the muon background, as well as the related dose equivalent contribution (see Sec. 2.7).

2.6.4 Validation of FLUKA Estimates

In preparation for the FASER experiment, *in situ* measurements were made during 2018 LHC running in the TI12 and TI18 tunnels in the LHC, 480 m from IP1 and along or close to the LOS. Measurements were made using emulsion-based detectors, which can be used to determine the number of charged particles that traverse the detector while it is installed and very accurately measure the track angles. There is, however, no knowledge of the time the particles cross the detector. In addition to this, measurements were made with a TimePix3 beam loss monitor (BLM), which is able to measure the rate of charged particles with excellent time resolution, but, given a lack of calibration, could not give an absolute rate. The measurements are discussed in detail in the FASER Technical Proposal [10]. The measurements were used to validate the FLUKA estimate of the muon flux for the 2018 LHC running conditions on the LOS.

The emulsion detector observed a clear peak of charged particles entering the detector with an angle consistent with the direction from IP1. The number of particles observed in this angular peak was $(1.2 - 1.9) \times 10^4$ fb cm^{-2}, when normalised by the luminosity that the detector was exposed to. This can be compared to the estimate from FLUKA of 2.0×10^4 fb cm^{-2} with an uncertainty of $\mathcal{O}(50\%)$. The FLUKA simulation result is consistent with the measurement within the expected uncertainties from FLUKA. The measurements with the BLM showed that the observed rate is correlated with the instantaneous luminosity in IP1 during an LHC fill, with the rate falling off during the fill as the luminosity decreases. Again, this is consistent with the FLUKA expectation that the background muon rate is originating from collision debris. With two circulating beams that were not colliding, the measured rate was very close to zero. The agreement between the FLUKA simulations and in situ measurements for the 2018 setup of the LHC gives confidence that FLUKA estimates for the HL-LHC will describe the background with reasonable accuracy. To further validate the simulations of the muon backgrounds in this region, when Run 3 begins in 2022, the FASER Collaboration plans to make further measurements using small emulsion detectors placed at various distances from the LOS.

2.7 Radiation Protection Studies

2.7.1 Radiation Protection at CERN

The CERN Radiation Protection (RP) rules are provided in the so-called “Safety Code F” [47, 48]. The objective of Safety Code F is to define the rules for the protection of personnel, the population, and the environment from ionising radiation produced at CERN. Safety Code F is based on and updated to the most advanced standards of European and other relevant international legislations, including the legislation of CERN host states France and Switzerland.

With regard to the design of new facilities, different RP aspects must be taken into account at the design level, including shielding requirements, radiation levels during operation (prompt) and technical stops (residual), area classification, radiation monitoring, and the activation for future disposal of radioactive wastes. Among these, area classification and dose limits are discussed here. These aspects are particularly relevant, as they determine whether access to the new experimental cavern will be possible during LHC beam operation.

Areas inside CERN's perimeter are classified as a function of the effective dose a person would receive during his stay in the area under normal working conditions and routine operation. The potential external, as well as internal, exposures must be taken into account when assessing the effective dose researchers may receive when working in the area considered. The exposure limitation in terms of effective dose is ensured by limiting correspondingly the operational quantity ambient dose equivalent rate $\dot{H}^*(10)$ for exposure from external radiation, and the action levels of specific airborne radioactive material (airborne radioactivity) and specific surface contamination at the corresponding workplaces for exposure from incorporated radionuclides. In addition, exposure of people working on the CERN site, the public, and the environment must remain below the dose limits under normal, as well as abnormal, conditions of operation. Table 2.2 shows the limits for area classification of Non-designated and Supervised Radiation Areas at CERN. These limits are relevant for the experimental FPF cavern, which will be discussed in the following.

2.7.2 Radiation Protection FLUKA Simulations

The RP-FLUKA simulations aim to determine the prompt radiation levels in the new purpose-built FPF cavern and in the shaft for different scenarios (normal/abnormal LHC operation); verify the

Area	Annual dose limit (year) [mSv]	Ambient dose equivalent rate (low-occupancy) [Sv/h]
Non-designated	1	2.5
Supervised	6	15

Table 2.2: The effective dose limits for area classification at CERN for Non-Designated and Supervised Radiation Areas. Dose limits for Controlled Radiation Area not reported since not relevant for this study. FPF is considered a low-occupancy area, i.e. $<$ 20% working time.

accessibility of the experimental cavern during LHC and SPS operation; and check the effectiveness of the chicane in the safety tunnel.

The FLUKA model of the LHC tunnel (Fig. 2.20) presented in Sec. 2.6 has been modified to include a detailed model of the new experimental cavern. This model contains 500 m of LHC beam line elements (from 250 m to 750 m to the west of IP1) and the experimental cavern and its access shaft, based on technical drawings provided by CERN CE. The safety tunnel connecting the LHC tunnel to FPF includes a chicane made of 2 40 cm concrete walls, representing the baseline layout at the time of computation. Simulations were conducted with and without the chicane walls to verify its effectiveness.

Several source terms were considered to simulate the operational and accidental scenarios relevant for the RP calculations:

- Beam-gas interactions: this source term is relevant for normal LHC operation, as it originates from inelastic interactions of the 7 TeV proton beam with residual gas within the beam pipes.
- Direct muon component from IP1: this source term is also relevant for normal LHC operation, and originates from muons directly streaming from ATLAS's pp collisions and from the particle showers produced in the Long Straight Section (LSS) by the collision debris.
- Loss of the LHC beam: this source is relevant only for abnormal LHC operation (accidental scenario). It considers the loss of the full 7 TeV proton beam on the MB.B15R1, the superconductive dipole placed in front of the safety tunnel connection to the LHC tunnel.
- Loss of the SPS beam: this source term is relevant for the access of the FPF shaft, due to the vicinity of the two infrastructures, and it considers the loss of the 450 GeV proton beam in the SPS tunnel.

In all LHC simulations, Beam 1, the clockwise beam traveling from the ATLAS IP toward the FPF, was simulated. In addition, the HL-LHC beam intensity was simulated using a scaling/normalization factor to consider 2748 bunches and 2:3 10^{11} proton per bunch. With regard to beam-gas interactions, a conservative residual gas-density of 1:0 10^{15} H_2 m ^{3} was used. As reported in Ref. [49], this value ensures a 100 hour beam lifetime. Recent studies conducted at CERN [50] indirectly determined lower residual gas densities during Run 2 operations (2:25 0:25 10^{13} H_2 m ^{3}), with higher values registered at the beginning of the physic run.

Finally, the prompt ambient dose equivalent was scored in the LHC tunnel, the safety tunnel, and the new experimental cavern by using a Cartesian XYZ mesh.

2.7.3 Radiation Protection Aspects and Constraints

Figs. 2.23 and 2.24 show the prompt ambient dose equivalent rates, in Sv/h, during normal LHC operation. The particle shower due to beam-gas interactions streams through the safety tunnel into the FPF cavern, but the presence of the chicane lowers the H (10) at the FPF entrance.

Figure 2.23: Prompt ambient dose equivalent rate during LHC operation (beam-gas interaction { HL-LHC beam conditions). Panels a/c (left) are with the chicane and panels b/d (right) are without the chicane. Panels a/b (top) and c/d (bottom) are generated at different distances from the IP1 (z-coordinates) to show the connection of the safety tunnel with the FPF and the LHC tunnel, respectively.

Figure 2.24: Prompt ambient dose equivalent rate during LHC operation (beam-gas interaction { HL-LHC beam conditions). Panels a/c (left) are with the chicane and panels b/d (right) are without the chicane. Panels a/b (top) and c/d (bottom) are generated at different heights (y-coordinates) to show the connection of the safety tunnel with the FPF and the LHC tunnel, respectively.

Figs. 2.25 and 2.26 show the prompt ambient dose equivalent in mSv if the full LHC 7 TeV proton beam is accidentally lost on MB.B15R1, the superconductive dipole placed in front of the safety tunnel connection to the LHC tunnel. Similar to the normal operation case, the particle shower generated during this undesired event streams through the safety tunnel and could be potentially harmful for people standing at the entrance of the FPF cavern.

A quantitative assessment of the radiation levels along the safety tunnel, for LHC normal and

Figure 2.25: Prompt ambient dose equivalent when the full beam is lost on the MB.B15R1 dipole (accidental scenario – HL-LHC beam conditions). Panels a/c (left) are with the chicane and panels b/d (right) are without the chicane. Panels a/b (top) and c/d (bottom) are generated at different distances from the IP1 (z-coordinates) to show the connection of the safety tunnel with the FPF and the LHC tunnel, respectively.

Figure 2.26: Prompt ambient dose equivalent when the full beam is lost on the MB.B15R1 dipole (accidental scenario – HL-LHC beam conditions). Panels a/c (left) are with the chicane and panels b/d (right) are without the chicane. Panels a/b (top) and c/d (bottom) are generated at different heights (y-coordinates) to show the connection of the safety tunnel with the FPF and the LHC tunnel, respectively.

abnormal operation, is provided through the 1D profile shown in Figs. 2.27 and 2.28. Fig. 2.27 shows the $H^*(10)$ considering different residual gas densities in the LHC beam screen: independently from the shielding configuration (with or without the chicane), even considering a conservative residual gas density of 1.0×10^{15} H_2 m^{-3}, the $H^*(10)$ remains below the limit for Non-Designated Radiation Areas. On the other hand, the results shown for the accidental scenario in Fig. 2.28 show that the

Figure 2.27: Prompt ambient dose equivalent rate profile in the safety tunnel during LHC operation (beam-gas interaction – HL-LHC beam conditions). Different residual gas densities have been considered to take into account the machine conditioning, and results are presented both with and without the chicane. The footprint (width) of the FPF has been highlighted with a gray box.

Figure 2.28: Prompt ambient dose equivalent profile in the safety tunnel when the full beam is lost on the MB.B15R1 dipole (accidental scenario – HL-LHC beam conditions). Different residual gas densities have been considered to take into account the machine conditioning, and results are presented both with and without the chicane. The footprint (width) of the FPF has been highlighted with a gray box.

cumulative H (10) exceeds the annual dose limit for classified personnel (20 mSv), even including the positive effect of the chicane.

With regard to the other source terms to be considered, the loss of the full 450 GeV proton beam in the SPS tunnel, which is most relevant for the FPF shaft, produces a negligible dose, since the distance between the shaft and the SPS tunnel is > 35 m. The direct muon contribution coming from IP1/LSS1 to the prompt ambient dose equivalent rate needs to be further investigated and simulations are currently ongoing.

The verification of the accessibility of the experimental cavern during LHC operation requires the evaluation of different scenarios/source terms, considering both normal and abnormal operation. At present, the limiting scenario is the possible loss of the full LHC beam on the MB.B15R1 dipole: possible mitigation actions such as adding a turn in the safety tunnel, adding another wall (\triple chicane") and thickening the chicane walls, might be evaluated and integrated into the CE model. However, the missing direct muon contribution might have an impact on the accessibility of the FPF cavern during operation, which needs to be addressed.

2.8 BDSIM Studies of the FPF Environment and Backgrounds

2.8.1 Introduction

For any particle physics experiment in proximity to an accelerator, an understanding of the background sources, their origin, the particle types, and their spectra is crucial at both the design stage as well as during operation. To predict and understand these backgrounds requires the use of Monte Carlo techniques, as the particle fluence close to an accelerator originates from many different and indirect sources. For the FPF specifically, we focus on the region of the LHC close to IP1, where the ATLAS experiment is located. This entails predicting the particle flux due to:

1. pp collisions at IP1 (and potentially also Pb-Pb and Pb-p)
2. Inelastic proton interactions with residual vacuum gas in the LHC arcs
3. Other beam losses in the arcs due to other-IP physics debris, collimation losses, and other beam losses

The first is expected to be the dominant contribution, as the FPF is on the LOS of the IP where the collisions occur, and they will produce high-energy, penetrating particles, such as muons and neutrinos. The second and third sources are from a significantly different direction, but are expected to be small contributions, since the distance of between 10 m and 16 m from the FPF inside wall to the LHC tunnel is expected to be sufficient to absorb the majority of background particles from these sources.

To simulate the particle fluence, a 3D radiation transport model is required, along with the transport and description of many subatomic particles. Both electromagnetic and hadronic interactions with the material of the accelerator, the tunnel, and the surrounding rock must also be simulated, as well as the deflection of charged particles by the many unique magnetic fields of the accelerator magnets.

In contrast to conventional transverse-orientated detectors, the far-forward location of the FPF requires simulation of the accelerator complex including its varied conditions throughout operation. The magnet strengths (the optics) are varied throughout each fill and generally throughout the operation (the Run) for various purposes. The crossing-angle of the colliding beams as well as the beam size (and therefore divergence angle) are varied to maintain, or level, the luminosity at the collision point to best serve the experiments. Throughout the Run, the optics may generally be improved upon depending on the machine performance, machine protection, the upstream injector-chain performance, and collimation performance.

BDSIM [51] is a Monte Carlo tool based on Geant4 [52–54], ROOT [55], and CLHEP that creates Geant4 models of accelerators from an optical description (one concerned with the magnetic strengths), such as MADX [56], used as the magnetic description of the LHC. It includes a library of geometries for many accelerator components in many styles including those of the LHC. It also includes parameterised magnetic fields for all of the conventional accelerator magnets, as well as the ability to load and interpolate field maps. Crucially, being based on Geant4, it allows the production and tracking of all subatomic particles provided by Geant4, as well as the extensive physics processes for them. Geant4 is a particle physics library commonly used in detector simulation and underpins the Monte Carlo for countless experiments in particle physics as well as being used in the space and medical physics domains. It is regularly updated with the latest developments from the field. Similar codes also used for this purpose include FLUKA [41, 42], described above in Sec. 2.6, and MARS [57, 58].

Although BDSIM provides a library of approximate and scalable geometries suitable for most applications, it is required in many cases to provide a more accurate geometry for a specific installation, where relevant. In this case, BDSIM provides the ability to load GDML format geometry, which is the geometry persistence format of Geant4 based on XML. The Python library pyg4ometry [59] is used to create, convert, and composite geometry. This allows detailed descriptions in other formats, such as the IR1 tunnel complex at CERN described in FLUKA geometry format, to be converted and incorporated into the model.

An important feature of BDSIM is the ability to filter and store select trajectories of particles in a linked data structure in ROOT format. Therefore, a BDSIM model allows not only fluences to be estimated, but also may be used to provide insight into the origin of background sources and their production mechanisms.

As an input, event generator output in HepMC [60] format can be used for each event. BDSIM is also usable as a C++ class to simulate individual events for a given model. Therefore, it can be integrated into an analysis framework if required, or used to generate a static Monte Carlo sample. The output of BDSIM is a ROOT-format file that is standard in high-energy physics, and either ROOT itself or the included tools with BDSIM can be used to perform a large scalable analysis, including skimming. BDSIM has been used for studying accelerator beam losses in a variety of machines; the models described here were originally developed for LHC collimation studies [59, 61].

2.8.2 BDSIM Model of the LHC IP1

A model of the LHC accelerator from IP1 towards the FPF was created using BDSIM. This model was originally developed for the FASER experiment [62] at both the pilot detector location ("C-side" of IP1 at the TI18 LOS location) and the FASER experiment location ("A-side" of IP1 at the TI12 LOS location). Several data sources are used to prepare the BDSIM input automatically using its associated pybdsim Python library. These include:

1. A MADX "Twiss Table" file providing an optical description of the magnets
2. A detailed aperture model from the LHC Collimation Group (BE-ABP-NDC)
3. Corresponding collimator settings for the optical configuration
4. Tunnel geometry converted from FLUKA format
5. Tunnel geometry from BDSIM and pyg4ometry
6. Select geometry pieces for various components (e.g., TAN, JSCA(A,B) shielding).

Figure 2.29: Comparison of LHC (top) and HL-LHC (bottom) machine layouts from IP1 at $S = 0$ m along the direction of Beam 1 (outgoing). Dipoles are shown in blue, quadrupoles in red, sextupoles in yellow, and collimators in black.

Items (1) and (3) are expected to vary throughout the Run and the model can be easily adjusted to reflect these through automated preparation. The model was originally created for LHC Run 2 (2015-18) and Run 3 (2022-25). However, for the FPF, during HL-LHC [46], a new model is required as the accelerator layout will have changed. There are several key differences from the LHC-era machine, namely:

- New TAXS absorber replaces the TAS absorber with increased aperture
- New TAXN absorber replaces the TAN absorber
- The `D1' separation dipole is now superconducting
- New collimators for incoming and outgoing beams in the layout

The TAXS absorber (currently TAS in the LHC) is a cylindrical copper absorber approximately 19 m from the IP. The TAXN (currently TAN in the LHC) is an absorber between the two separation dipoles to protect the machine from predominantly neutral physics debris. The layout and geometry in the BDSIM model has been updated according to the optics configuration HL-LHC V1.5.

A 3D view of the complete BDSIM model is shown in Fig. 2.30. The proposed FPF cavern is not simulated, as a particle flux on its entrance is desired in this study and will have no effect on that result. In the future, the geometry for the cavern will be added.

2.8.3 Simulation Procedure

To generate a Monte Carlo sample, the CRMC [63] event generator tool is used to generate the $\sqrt{s}$ = 14 TeV pp collisions. CRMC provides several underlying generators including EPOS-LHC [64], QGSJet [65], and Sibyll [66]. For this study, Sibyll was used. CRMC writes a HepMC format file that is subsequently loaded by BDSIM BDSIM is set to simulate only loaded particles in the forward direction of the model and with a pseudorapidity 2:3 for simulation efficiency. A minimum kinetic energy cut of 10 GeV was used. Geant4 V10.7.p03 was used with reference physics list FTFP_BERT (a complete physics list including electromagnetic, decay, and hadronic processes). HL-LHC V1.5 MADX optics were used with a primary proton beam energy of 7 TeV. The crossing angle was 250 rad. An aperture model was used from the BE-ABP-NDC collimation group.

Cross section biasing is used to reduce the computational time required to estimate muon fluxes by increasing the cross section of several particles' decay processes. Given the small forward area at a great distance, this biasing scheme is required to estimate the relevant quantities in a reasonable

Figure 2.30: Visualisation of the BDSIM model of the HL-LHC from ATLAS IP1 along the Beam 1 direction to the TI18 tunnel and the FPF. The geometry above Y = 1 m has been removed for the visualisation. A green line shows the LOS from the IP (top left), through the accelerator (blue and red magnets), the cryogenic coolant line (grey tube beside it), a sweeper magnet (small grey box), and a partial view of the ascending ramp of the TI18 tunnel (lower right).

amount of time on an available computer farm. The numerical biasing factors used per particle are shown in Table 2.3.

Passive and invisible planes, called \samplers" in BDSIM, were placed at several positions in the model to record muons and neutrinos only, as it is foreseen that these are the most relevant Standard Model particles at the FPF for this study. These samplers record the kinematic variables of particles in a 2D plane at a given position with a given square size. Samplers were placed at 3 locations in the LOS of IP1, as shown in Fig. 2.31. These were at distances 370 m, 475 m, and 617 m, which correspond to just into the tunnel after the accelerator starts to bend; the opening into the TI18 tunnel; and in front of the FPF. The data from the samplers can be analysed individually or together, as well as be re-launched into the model or another for further study.

Particle	Factor in Vacuum & Air	Factor in Material
	50	10^4
K	50	10^3

Table 2.3: Numerical scaling factors applied to the Geant4 Decay physics process for charged pions and charged kaons. Two factors were generally applied, firstly for inside the beam pipe vacuum and any air, and secondly for other material.

Figure 2.31: Visualisation of the BDSIM model of the HL-LHC from IP1 at ATLAS (left) along the Beam 1 direction (to the right) in plan view with the geometry above $Y = 1$ m removed. Three sample planes are shown, all centred on the LOS from IP1. At $Z = 370$ m (green), a plane is placed in front of the potential sweeper magnet location as the tunnel starts to bend. At $Z = 475$ m (yellow), a plane is located in the TI18 tunnel as it connects to the main LHC tunnel; this was the location of the FASER pilot detector and the current location of SND@LHC. Finally, a plane at $Z = 617$ m (pink) is placed before the entrance to the proposed FPF cavern. The Z dimension has been compressed by a factor of 10.

Figure 2.32: A 2D view of the proposed SmCo sweeper magnet with an overlaid magnetic field map. The full width is 20 cm, and the outer layer (red) is iron.

The model preparation was validated by tracking 10,000 primary protons from the IP to the end of the model, analysing the beam size, mean offset, and calculated optical Twiss functions from the tracks recorded in samplers after every magnet. The tracking showed excellent agreement with the MADX model.

For this study, a proposed sweeper magnet was included. It was 20×20 cm in area, with a peak field of 1.4 T, and placed in the LOS ($X; Y = 0; 0$ m) at $Z = 370$ m. The field was orientated vertically, with the return flux in an iron layer 10 cm wide. The core of the magnet was samarium cobalt. A cross section of it with overlaid magnetic field map is shown in Fig. 2.32. The field map is based on previous permanent magnet designs and was provided by the SY-STI-BMI group at CERN. The geometry was created in GDML using pyg4ometry.

A Monte Carlo sample of 100M pp events was generated using the Royal Holloway computing cluster. This sample includes the trajectories of (exclusively) muons and neutrinos that reach the

Figure 2.33: The 2D muon distribution at $Z = 370$ m from IP1 in front of the proposed sweeper magnet location. Outlines of the LHC magnets (left tube) cold-mass, the cryogenic coolant line (right tube), and the tunnel are shown in black. The proposed sweeper magnet is shown as a square outline also in black. The data is scaled to the nominal HL-LHC luminosity of 5 10^{34} cm ^{2} s ^{1}.

2 2 m sample plane at the entrance to the FPF. Additionally, the select parent track trajectories linking each particle back to the primary vertex are stored. This will enable a detailed analysis of origins and production mechanisms in the future.

2.8.4 Muon and Neutrino Fluxes

The BDSIM studies provide results for the distribution of muons along the LOS at several distances from the ATLAS IP. The results can be displayed using the coordinate system shown in Fig. 2.31. Firstly, the 2D distribution of muons at $Z = 370$ m (the green line in Fig. 2.31) is shown in Fig. 2.33, with a magnified view in Fig. 2.34. As the primary proton energy is 7 TeV, very high-energy, and therefore penetrating, muons can be produced. A subset of the muons shown in Fig. 2.33 is displayed in Fig. 2.35, where only muons with $E_k > 1$ TeV are shown. These are less frequent but are more likely to reach the FPF through the accelerator complex and the surrounding rock.

The 2D muon distribution in front of the entrance to the FPF, $Z = 617$ m from IP1 (the pink line in Fig. 2.31), is shown in Fig. 2.36. The spectrum of the muons and neutrinos at the FPF entrance plane is shown in Fig. 2.37. It should be noted that the production of is not implemented in the version of Geant4 used (10.7.p03), but the recently released Geant4 V11.0 can produce them through positron annihilation. Here, we also expect only electron and muon neutrinos to be present in the simulation. The high end of the kinetic energy spectra is still statistically limited, but is expected to continue downwards.

The predicted muon fluxes based on averaging the 2 m 2 m sample plane at the FPF location are given in Table 2.4. These are integrated across all kinetic energies in the simulation (E_k 10 GeV).

Using the trajectory information stored in ROOT-format BDSIM output files, we can visualise the origin of muons that reach the FPF 2 m 2 m sample plane. The origins are shown in Fig. 2.38 as a function of the global Cartesian coordinate Z. The distribution shows that the majority of muons originate from before the accelerator begins to curve at approximately 350 m, and there appears to be significant structure. Many of the peaks (e.g., from $Z = 100$ m to $Z = 250$ m) are explained by the TAXN (the absorber at the 2-beam separation point), as well as by subsequent collimators that

Figure 2.34: The 2D muon distribution at Z = 370 m, viewed more closely than in Fig. 2.33 and showing the muon flux at the location of a sweeper magnet. The data is scaled to the nominal HL-LHC luminosity of 5 10^{34} cm ^{2} s ^{1}.

Figure 2.35: The 2D muon distribution at Z = 370 m, as in Fig. 2.33, but only for muons with E_k > 1 TeV. The data is scaled to the nominal HL-LHC luminosity of 5 10^{34} cm ^{2} s ^{1}.

Scenario	(Hz/cm ^{2})		$^{+}$ (Hz/cm ^{2})	
With sweeper	0:4937	0:0145	0:2827	0:0139
No sweeper	0:5342	0:0163	0:2881	0:0139

Table 2.4: Predicted muon fluxes at the entrance to the FPF at Z = 617 m from IP1 along the LOS, based on the nominal HL-LHC luminosity of 5 10^{34} cm ^{2} s ^{1}. The rate is calculated from a sample area of 2 m 2 m across all kinetic energies from the minimum simulated kinetic energy of 10 GeV.

Figure 2.36: 2D Muon distribution at $Z = 617$ m from IP1 in front of the proposed dedicated FPF location. The data is scaled to the nominal HL-LHC luminosity of 5×10^{34} cm^{-2} s^{-1}.

Figure 2.37: Muon (left) and neutrino (right) spectra at the FPF location at $Z = 617$ m integrated across an area of 2 m × 2 m and scaled to the nominal HL-LHC luminosity of 5×10^{34} cm^{-2} s^{-1}.

are designed to protect the machine from the high-power forward physics debris. Secondary particles can in turn produce muons that may reach the FPF from these locations. The two broad peaks are initially believed to be from the increasing dispersion (transverse position-energy correlation) in the accelerator as we enter the arcs. The increased dispersion causes greater transverse excursions for off-energy particles resulting in their loss and interaction with the accelerator, eventually producing muons. These results provide an initial insight into where muons originate from and how they can be be mitigated with the choice of sweeper magnet location.

2.8.5 Outlook

The model presented is a first step in modelling the FPF muon backgrounds and further improvements are required. Firstly, a simplified geometry based on the aperture can be exported for a RIVET module suitable for testing new and existing generators and their models. This method

Figure 2.38: The origin of muons reaching the $2\,\text{m} \times 2\,\text{m}$ sample plane at the $Z = 617\,\text{m}$ FPF location. This figure shows where such muons were created as a function of the global Cartesian Z coordinate, that is, the distance from IP1. The results are scaled to the nominal HL-LHC luminosity of $5 \times 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$.

and tool is described in Ref. [67]. Such a technique allows rapid iteration to test key quantities and responses of potential experiments to different physics models. The Monte Carlo sample here required $\sim$80000 cpu-hours to be generated, despite the decay cross section biasing. Whilst the simulation data provided is highly useful in understanding backgrounds, the approach using RIVET by Ref. [67] using a simplified geometry from this model will allow many more variations to be studied.

Secondly, the geometry can be improved further to include the collimator vacuum tanks and cooling apparatus. The BDSIM-provided LHC magnet geometries will also be improved. The magnetic fields used in the yokes of the magnets are parameterised multipole fields according to the Biot–Savart law. However, more accurate field maps will be used in the future. Additional systematic errors can be investigated, including the varied proton beam optical parameters (e.g., the crossing angle) and the effect of the rock density uncertainty.

Here, only the contribution from collisions at IP1 is presented. The contribution from the inelastic interaction of protons with residual gas in the vacuum can be simulated, as can any physics debris from other IPs that can cause proton losses, albeit at a low rate, throughout the whole accelerator.

The model presented and BDSIM in general present a method that can be used as part of a physics analyses and Monte Carlo chain to predict quantities at the FPF, as well as estimate the impact of design choices including a sweeper magnet.

2.9 The PROPOSAL Framework For Simulating Particles Fluxes

In addition to the FLUKA and BDSIM frameworks discussed in Sec. 2.6 and Sec. 2.8, respectively, the simulation framework PROPOSAL may be used to estimate particle fluxes at the FPF. PROPOSAL provides 3D Monte Carlo simulations of high-energy leptons and photons [68]. It is used in several experiments, for example, in the simulation chain of the IceCube Neutrino observatory, to propagate muons and taus [69]. However, its design is focused on flexibility, so that the framework can be used for a wide range of applications.

One key advantage of PROPOSAL is that the framework provides the options to find an optimal tradeoff between simulation precision and simulation performance for each individual use case. This is realized by introducing a combination of energy cuts: an absolute energy cut e_{cut}, as well as a relative energy cut v_{cut}. Energy losses above these energy cuts are treated by sampling each interaction individually, while all energy losses below these energy cuts are treated continuously. Furthermore, the settings for the energy cuts can be varied for the different parts of the simulation environment. This is especially useful for setups where specific areas may have to be simulated with a higher focus on precision, while other areas can be simulated with a focus on performance to save computing time.

To precisely simulate the energy loss processes of muons, an accurate knowledge of the underlying cross sections is necessary. For this purpose, PROPOSAL provides the possibility to choose from a set of different theoretical models, including up-to-date parametrizations of muon energy losses. The effects of these modern parametrizations, in comparison to commonly used parametrizations in other simulation tools, can be of the order of up to two percent, depending on the energy range [70]. Especially for muon propagation over long distances, these differences may have an observable impact on the simulation results. Furthermore, the flexible structure of PROPOSAL allows for a straightforward implementation of additional parametrizations into the framework, for example, including BSM physics, if necessary.

To simulate the effects of magnetic fields on charged particles, which is relevant to estimate the effects of sweeper magnets on the muon background in the FPF, magnetic field deflection may be implemented directly in PROPOSAL in the future. As an alternative, PROPOSAL can be used together with the particle cascade simulation tool CORSIKA 8 [71]. In this case, the magnetic field deflection would be provided by CORSIKA 8, while the physics of muon interactions are provided by PROPOSAL via an existing interface.

2.10 Sweeper Magnet

For many of the physics goals of the FPF, reducing the rate of background particles traversing the FPF experiments would be very beneficial. For example, for emulsion-based neutrino detectors such as FASER 2, reducing the rate of background charged particles would allow the emulsion films to be exchanged less often, significantly reducing the cost. For a LAr-based neutrino/dark matter detector, reducing the background rate will allow improved physics sensitivity, and may allow one to loosen some of the requirements, resulting in a cheaper and simpler detector. In this section, we discuss the use of a sweeper magnet, to be installed on the LOS significantly in front of the FPF, to reduce the background rate from muons, is discussed. The effectiveness and feasibility of such a sweeper magnet are under study, and this section gives a snapshot of the current studies.

2.10.1 Sweeper Magnet Location

Early feasibility studies carried out for the FASER experiment showed that we expect a significant rate of high-energy muons travelling along the LOS; see Sec. 2.6.4 and Ref. [10]. The rate on the LOS is reduced due to the LHC magnets, particularly the separation/re-combination dipoles, D1 and D2. FLUKA simulations and *in situ* measurements show that the direction of the muons is consistent with following the LOS from the IP, which means that a sweeper magnet should be placed on the LOS in between the IP and the FPF. The LOS is inside the LHC beam pipe for the long straight section of the LHC machine, and then inside the LHC magnet cryostat volume for

Figure 2.39: Plan view of the LHC complex between the ATLAS IP and the proposed FPF location. The LOS is shown as a red line, and the region where it has left the LHC magnet cryostats, but remains in the LHC tunnel, is highlighted in the zoomed in region. (Taken from the CERN GIS portal.)

the first part of the arc. However, after about 350m from the IP, the LOS leaves the cryostat and remains in the LHC tunnel for about a further 50m. This is the location where a sweeper magnet could be installed, and it is shown in Fig. 2.39.

A preliminary integration study, using the 3D model of the LHC machine in this region, was carried out. This suggested that there would be space for a 7 m-long magnet, of transverse size 20 cm diameter, to be placed on the LOS. This magnet would be about 200 m from the FPF, providing a significant lever arm for the deflected muons to move away from the LOS before they get to the FPF. Fig. 2.40 shows the plan view and side view of the magnet compared to the existing LHC infrastructure from this integration study. The magnet is very close to the QRL cryogenic line, which is a delicate piece of equipment in the LHC tunnel. The study does not take into account the support of the magnet, or the handling equipment needed to install and remove it from this location.

Following this study, a laser scan was carried out in this area of the LHC tunnel to validate the 3D integration model used in the integration study. Unfortunately, this revealed a number of components that were not included in the original 3D model used. These components significantly reduce the available space for the sweeper magnet, assuming no modifications to the infrastructure are made. In this case the magnet length would be limited to about 2 m, as shown in Fig. 2.41. We are currently investigating if some of the infrastructure in this area of the LHC could be minimally modified, to allow the 7 m magnet to be installed there.

2.10.2 Conceptual Magnet Design

The location of the sweeper magnet in the LHC arc has significant radiation when the LHC is operating. It is therefore difficult to reliably operate a power converter in this region, which suggests

Figure 2.40: Plan view (top) and side view (bottom) from the initial integration study to place a 7 m-long, 20 cm-diameter sweeper magnet on the LOS. The magnet is shown as a red cylinder. (The location shown is where the LOS leaves the beampipe to the west of ATLAS, but the symmetric location to the east of ATLAS and in the direction of the FPF is expected to be essentially identical.)

that a permanent magnet could be a desirable solution for the sweeper magnet. A conceptual design for a possible permanent sweeper magnet is shown in Fig. 2.42. The magnet is made up of a central block of permanent magnetic material (e.g., NdFeb or SmCo) of 10 cm by 10 cm transverse dimensions, surrounded by an outer ring of construction steel (making up a 20 cm by 20 cm transverse size magnet). The magnetic field distribution for this configuration is shown

Figure 2.41: Integration study of the FPF sweeper magnet, using the LHC geometry updated after a laser scan in the relevant LHC area. The top panel shows the plan view, with the clash between the infrastructure, particularly the cryogenic warm return line (WRL), and the proposed sweeper magnet envelope highlighted in yellow. The bottom panel shows the view from in front of the sweeper magnet. (The location shown is where the LOS leaves the beampipe to the west of ATLAS, but the symmetric location to the east of ATLAS and in the direction of the FPF is expected to be essentially identical.)

in Fig. 2.43 with a central field of 1.1 T for a SmCo magnet or 1.4 T for a NdFeb magnet.[3] The radial stray magnetic field is negligible at the level of < 0.002 T at 10 cm from the magnet, which is not expected to be problematic for the LHC beam or any equipment in the LHC tunnel. Assuming a field integral of 7 Tm for the sweeper magnet, this would sweep a 100 GeV (500 GeV) muon 4.2 m (0.8 m) from the LOS at the FPF (200 m away). However, it still needs to be studied with simulation if the magnet would also sweep muons into the LOS, and if so what the overall reduction

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[3] There is a risk that the magnet could become de-magnitized by radiation for the NdFeB magnetic material. This will need to be studied further before deciding on what material to use.