LETTER OF INTENT

FASER
FORWARD SEARCH EXPERIMENT AT THE LHC

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Executive Summary

FASER is a proposed small and inexpensive experiment designed to search for light, weakly-interacting particles at the LHC. Such particles are dominantly produced along the beam collision axis and may be long-lived, traveling hundreds of meters before decaying. To exploit both of these properties, FASER is to be located along the beam collision axis, 480 m downstream from the ATLAS interaction point, in the unused service tunnel TI18. We propose that FASER be installed in TI18 in Long Shutdown 2 in time to collect data from 2021-23 during Run 3 of the 14 TeV LHC. FASER will detect new particles that decay within a cylindrical volume with radius $R = 10$ cm and length $L = 1.5$ m. With these small dimensions, FASER will complement the LHC’s existing physics program, extending its discovery potential to a host of new particles, including dark photons, axion-like particles, and other CP-odd scalars. A FLUKA simulation and analytical estimates have confirmed that numerous potential backgrounds are highly suppressed at the FASER location, and the first in situ measurements are currently underway. We describe FASER’s location and discovery potential, its target signals and backgrounds, the detector’s layout and components, and the experiment’s preliminary cost estimate, funding, and timeline.

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I. INTRODUCTION

For decades, the leading examples of new physics targets at particle colliders were particles with TeV-scale masses and $\mathcal{O}(1)$ couplings to the standard model (SM). More recently, however, there is a growing and complementary interest in new particles that are much lighter and more weakly coupled [1]. Among their many motivations, such particles may yield dark matter with the correct thermal relic density and resolve outstanding discrepancies between theory and low-energy experiments [2–4]. Perhaps most importantly, new particles that are light and weakly coupled can be discovered by relatively inexpensive, small, and fast experiments with potentially revolutionary implications for particle physics and cosmology.

If new particles are light and very weakly coupled, the focus at the LHC on particle searches at high transverse momentum ($p_T$) may be completely misguided. In contrast to TeV-scale particles, which are produced more or less isotropically, light particles with masses in the MeV to GeV range are dominantly produced at low $p_T \sim 100$ MeV − GeV. In addition, because the new particles are extremely weakly coupled, very large SM event rates are required to discover the rare new physics events. These rates are available, not at high $p_T$, but at low $p_T$: at the 13 TeV LHC, the total inelastic $pp$ scattering cross section is $\sigma_{\text{inel}}(13 \text{ TeV}) \approx 75 \text{ mb}$ [5, 6], with most of it in the very forward direction. In upcoming runs at 14 TeV, where the inelastic cross section is very similar, we expect

$$N_{\text{inel}} \approx 1.1 \times 10^{16} \left(2.2 \times 10^{17}\right)$$

inelastic $pp$ scattering events for an integrated luminosity of 150 fb$^{-1}$ at LHC Run 3 (3 ab$^{-1}$ at the HL-LHC). Even extremely weakly-coupled new particles may therefore be produced in sufficient numbers in the very forward region. Given their weak coupling to the SM, such particles are typically long-lived and travel a macroscopic distance before decaying back into SM particles. Moreover, such particles may be highly collimated. For example, new particles that are produced in pion or $B$ meson decays are typically produced within angles of $\theta \sim \Lambda_{\text{QCD}}/E$ or $m_B/E$ of the beam collision axis, where $E$ is the energy of the particle. For $E \sim \text{TeV}$, this implies that even $\sim 500$ m downstream, such particles have only spread out $\sim 10$ cm − 1 m in the transverse plane. A small and inexpensive detector placed in the very forward region may therefore be capable of extremely sensitive searches.

FASER [7], the ForwArd Search ExpeRiment, is specifically designed to take advantage of this opportunity. An ideal location exists in TI18$^1$, an existing and unused side tunnel that is 480 m downstream from the ATLAS interaction point (IP). We propose that FASER be installed along the beam collision axis in TI18 in Long Shutdown 2 (LS2) from 2019-20 in time to collect data in Run 3 from 2021-23. With an active volume of only 0.16 m$^3$, FASER will complement the LHC’s existing physics program, with remarkable sensitivity to dark photons, axion-like particles, and other proposed particles. In the following sections, we discuss FASER’s location and discovery potential, the detector’s layout and components, backgrounds, and the experiment’s preliminary cost estimate, funding, and timeline.

$^1$ Note added: Since this document was prepared, additional measurements made by the CERN survey team during LHC Technical Stop 2 in September 2018 have shown that tunnel TI12 on the other side of LHC interaction point IP1 will more easily accommodate the detector with the dimensions presented here. TI12 is the same distance from IP1 as TI18 and the expected signal and backgrounds are very similar. FASER is now expected to be located in TI12.
FIG. 1. Location of FASER. Top panel: A schematic drawing of the LHC and the very forward infrastructure downstream from the ATLAS IP, with FASER located 480 m from the IP, after the LHC tunnel starts to curve. Bottom panels, left to right: the view toward the ATLAS IP, with the main LHC tunnel on the left and tunnel TI18 on the right; the beam collision axis marked on the floor of TI18 by the CERN survey team; the location of the beam collision axis in TI18; and a map showing the intersection of the beam collision axis and TI18 from above.

II. DETECTOR LOCATION

As shown in Fig. 1, an ideal location for FASER is along the beam collision axis, 480 meters downstream from the ATLAS IP in service tunnel TI18. This tunnel was formerly used to connect the SPS to the LEP tunnel, but it is currently empty and unused. Light, weakly-interacting particles produced at the ATLAS IP will travel along the beam collision axis through matter without interacting, and then can decay in TI18.

In this location, then, FASER harnesses the enormous, previously “wasted,” cross section for very forward physics to search for light, weakly-coupled new particles. This location also benefits from the fact that, when long-lived particles (LLPs) are produced at the unprecedented center-of-mass energies of the LHC, their large boosts result in decays that are far beyond the main LHC infrastructure in regions where backgrounds are highly suppressed.

In more detail, as shown in the bottom panels of Fig. 1, the beam collision axis emerges from the floor of TI18 for a distance of roughly 3.8 m before intersecting the side wall. The beam collision axis has been located to within a mm by the CERN survey team, but at any given time, its precise location depends on the beam crossing angle at ATLAS. For example, the current beam crossing half angle of 150 µrad in the upward direction raises the beam collision axis by 7 cm in TI18 relative to what is shown in Fig. 1. Prior to installing FASER, we propose that the floor in TI18 be lowered by 50 cm to allow a longer detector to be placed along the beam collision axis. This will not disrupt essential services, and no other excavation is required. Detailed studies are ongoing to assess exactly how long the detector can be for the different beam crossing angles currently envisioned for Run 3, but preliminary estimates suggest a length of 5 m will be possible.

III. NEW PHYSICS DISCOVERY POTENTIAL

The potential for discovering new LLPs has been studied for a plethora of new physics models [7–14], both for FASER and for a possible larger follow-up experiment, FASER 2,
which would run in the HL-LHC era. To illustrate this discovery potential, here we present
results for three examples of light, weakly-interacting new particles: dark photons [7], axion-
like particles (ALPs) [13], and CP-odd scalars that couple dominantly to SM fermions.

**Dark photons:** A massive dark photon arises when a hidden sector contains a broken
$U(1)$ gauge symmetry. The hidden sector’s gauge boson can then mix with the SM photon via
kinetic mixing and obtain a small coupling to the SM electromagnetic current proportional
to the kinetic mixing parameter $\epsilon$, leading to the Lagrangian terms

$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e_j^\mu EM A'_\mu ,$$

where $\epsilon$ is naturally small if the mixing is loop-induced. Dark photons are primarily produced
in the decay of light mesons or via dark bremsstrahlung and are therefore very collimated
around the beam collision axis. They can decay into all kinematically-allowed charged
particles. In the parameter space probed at FASER, they decay via $A' \rightarrow e^+ e^-$, and most
of the signal is confined to within 10 cm of the beam collision axis [7].

**Axion-like particles (ALPs):** ALPs are pseudoscalar SM-singlets that appear as
pseudo-Nambu-Goldstone bosons in theories with broken global symmetries. We consider a
low-energy effective theory in which an ALP couples only to photons through the dimension-5
interaction, leading to the Lagrangian terms

$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F^\mu\nu \tilde{F}_{\mu\nu} .$$

ALPs reaching FASER are predominantly produced through the Primakoff process by high
energy photons colliding with the TA(X)N [13]. The initial photons are highly collimated
along the beam axis, leading to similarly collimated signal when ALPs decay via $a \rightarrow \gamma\gamma$.

**CP-odd scalars:** For our last example, we consider light pseudoscalars that couple
dominantly to SM fermions. Such particles could be ALPs or part of an extended Higgs
sector. Following the model presented in Ref. [15], we require the fermion couplings to be
proportional to Yukawa couplings, leading to the Lagrangian terms

$$\mathcal{L} \supset -\frac{1}{2} m_A^2 A^2 - i \sum_f g_{Aff} y_f A f \gamma^5 f .$$

These LLPs are mainly produced in the heavy quark decay $b \rightarrow s A$, leading to a larger
spread around the beam collision axis. At FASER, the leading signal is from $A \rightarrow \mu^+ \mu^-$.  

Figure 2 shows FASER’s sensitivity reach for each of these three models. These results are
for a cylindrical decay volume of radius $R = 10$ cm and length $L = 1.5$ m at the 14 TeV LHC
with 150 fb$^{-1}$. They are $N = 3$ signal event contours and so assume 100% signal efficiency
and negligible background (see Secs. V and VII). We see that even with such a small active
decay volume, FASER can probe significant new regions of parameter space in a variety of
models. These results use the EPOS-LHC [23] Monte Carlo generator, which is tuned to
the recently available forward scattering data from the LHC [24], to simulate forward light
meson production and FONLL [25] with CTEQ 6.6 to simulate heavy meson production. For
comparison, we also show the projected reach of other proposed experiments. For the CP-
odd scalar model, results for the proposed LHC experiments MATHUSLA [26] and CODEX-
b [27] can be expected to be complementary and probe lower couplings than FASER. We
also show the reach of FASER 2, a possible larger detector with a decay volume of radius
FIG. 2. Projected sensitivity reaches for FASER at the 14 TeV LHC Run 3 with 150 fb$^{-1}$ for dark photons (left), axion-like particles (center), and CP-odd scalars (right). The gray-shaded regions are excluded by current bounds. For comparison we also show the sensitivities of FASER 2, a possible upgraded detector running in the HL-LHC era (see text), and other current and proposed experiments: NA62 assumes $3.9 \times 10^{17}$ protons on target (POT) while running in a beam dump mode that is being considered for LHC Run 3 [16]; SeaQuest assumes $1.44 \times 10^{18}$ POT, which could be obtained in two years of parasitic data taking and requires additionally the installation of a calorimeter [12, 17]; the proposed beam dump experiment SHiP assumes $2 \times 10^{20}$ POT collected in 5 years of operation [16, 18]; Belle-II and LHCb assume the full expected integrated luminosity of 50 ab$^{-1}$ [19] and 300 fb$^{-1}$ [20, 21], respectively; and HPS assumes 4 weeks of data at JLab at each of several different beam energies [1, 22].

$R = 1$ m and length $L = 5$ m collecting data at the 14 TeV HL-LHC with 3 ab$^{-1}$. Such an upgrade would extend FASER’s reach significantly, particularly towards larger masses.

The general features of the sensitivity curves can be understood as follows: for relatively large $\epsilon$, the sensitivity is reduced because the LLPs tend to decay before they reach FASER. The reach is extremely sensitive to $\epsilon$, and changing other parameters, for example, requiring 10 signal events instead of 3, or including a 50% signal efficiency factor, leads to almost imperceptible changes in the sensitivity reach contours. In contrast, for relatively small $\epsilon$ and large LLP masses, the reach is limited by the LLP production cross section, and larger datasets can extend the reach in parameter space significantly.

The regions of parameter space probed by FASER are of interest for both particle physics and cosmology. For example, if a dark photon couples to a dark matter particle with mass $\sim m_{A'}$, the dark matter can have the correct thermal relic density if $m_{A'} \sim \epsilon m_{\text{weak}}$, where $m_{\text{weak}} \sim 1$ TeV. For $m_{A'} \sim 10 - 100$ MeV, one obtains $\epsilon \sim 10^{-5} - 10^{-4}$, which is a region of parameter space that will be probed by FASER.

Finally, we note that FASER’s physics potential is not restricted to the models mentioned above. Other particles probed by FASER and FASER 2 include dark Higgs bosons [8], flavor-specific scalar mediators [9], heavy neutral leptons [10, 11], $R$-parity violating neutralinos [11], $U(1)_{B-L}$ gauge bosons [12], and inelastic dark matter [14].
IV. DETECTOR OVERVIEW

A. Signal and Background: General Characteristics

FASER will search for LLPs that are produced at or close to the IP, move along the beam collision axis, and decay visibly within FASER. The characteristic event is

\[ pp \rightarrow LLP + X, \quad LLP \text{ travels } \sim 480 \text{ m}, \quad LLP \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \gamma\gamma, \ldots \quad (5) \]

LLPs that travel in the very forward direction and decay in FASER typically have very high energies \( \sim \) TeV. The target signal at FASER is therefore striking: two oppositely charged tracks or two photons with \( \sim \) TeV energies that emanate from a common vertex inside the detector and have a combined momentum that points back through 90 m of rock to the IP.

When the LLPs decay, because they are light and highly boosted, their decay products are very collimated. For example, for an LLP with mass \( m = 100 \text{ MeV} \) and energy \( E = 1 \text{ TeV} \), the typical opening angle of the decay products is \( \theta \sim m/E \sim 100 \mu \text{rad} \) implying a separation of only \( \sim 100 \mu \text{m} \) after traveling 1 m. To use these striking kinematic features to distinguish signal from background, a measurement of the two individual decay products is highly desirable.

For charged tracks, a magnetic field of 0.5 T, achievable with permanent magnets, is able to both split the tracks sufficiently and allow for a track momentum measurement, as discussed in Sec. V A. Tracking layers, surrounded by a magnet to separate highly collimated tracks, and supplemented by a calorimeter to distinguish electrons from muons and provide additional energy measurements, will be the key components of FASER.

For the di-photon signal, distinguishing the two photons requires a calorimeter with exquisite spatial resolution. For this purpose, a pre-shower detector to convert and spatially resolve the photons is under consideration. As discussed in Sec. VII, however, the expected background of single, \( \sim \) TeV photons is very low, and so even if di-photon events are mis-reconstructed as single showers, they may be indicative of new physics.

The natural (rock) and LHC infrastructure (magnets and absorbers) shielding eliminates most potential backgrounds. Muons and neutrinos are the only known particles that can transport TeV energies through 90 m of rock between the IP and FASER. The dominant source of background is radiative processes associated with muons from the IP, which is identified by the presence of a high-energy muon traversing the full detector. This is suppressed by using a charged particle veto layer at the front of the detector. Additional backgrounds from neutrino interactions within the detector are small and generally have different kinematics.

B. Detector Layout

The detector design is driven by the following considerations:

- the detector should be highly sensitive to the signals discussed above and allow multiple background estimates from the data;
- the active area of the detector should lie close to the floor so that it can intersect the beam collision axis for all possible beam crossing angles;
FIG. 3. Layout of the proposed FASER detector. LLPs enter from the left. The detector components include scintillators (gray), dipole magnets (red), tracking stations (blue), a pre-shower detector (light purple), and a calorimeter (dark purple).

- the detector should be inexpensive and robust, using well-established technologies and, where possible, existing detector components;
- the required services (power, cooling, gas, etc.) should be minimized, since access to the detector will not be possible when the LHC is running; and
- the detector components are limited by the need to transport them through the LHC tunnel and over the LHC dipoles at the entrance to TI18.

The layout of the proposed FASER detector is illustrated in Fig. 3. At the entrance to the detector, a double layer of scintillators is used to veto charged particles coming through the cavern wall from the IP, primarily high-energy muons. In between the layers is a 20-radiation-lengths-thick layer of lead for converting any photons produced in the wall into electromagnetic showers that can be efficiently vetoed by the scintillators.

The veto layer is followed by a 1.5 m long, 0.5 T permanent dipole magnet with a 10 cm aperture radius. This is the decay volume for LLPs decaying into a pair of charged particles, with the magnet providing a horizontal kick to separate the decay products to a detectable distance. The decay volume is not foreseen to be under vacuum.

After the decay volume is a spectrometer consisting of two 1 m long, 0.5 T dipole magnets with three tracking stations, each composed of layers of precision silicon strip detectors, located at either end and in between the magnets. The magnet covering the decay volume, and those in the spectrometer, will have their fields aligned to give the maximum separation for charged particles in the bending plane. Scintillator planes for triggering and precision time measurements are located at the entrance and exit of the spectrometer. The primary purpose of the spectrometer is to observe the characteristic signal of two oppositely charged particles pointing back towards the IP, measure their momenta, and sweep out low-momentum charged particles before they reach the final layer of the spectrometer.

The final component is the electromagnetic calorimeter. This will identify high-energy electrons and photons and measure the total electromagnetic energy. As the primary signals are two close-by electrons or photons, these cannot be resolved by the main calorimeter. It is therefore under consideration to place a high-granularity pre-shower detector between the last tracking layer and the main calorimeter. This could be constructed from a layer of tungsten and one or two layers of silicon strip detectors.
V. DETECTOR REQUIREMENTS, OPTIMIZATION AND PERFORMANCE

The detector is designed to identify the two high-momentum, oppositely-charged particles from LLP decay and reject backgrounds that are topologically or kinematically inconsistent with the expected signal.

FASER’s very high energy threshold for analysis is a powerful background rejection tool. Conservatively requiring $A'$ decay products above 100 GeV introduces negligible loss of physics sensitivity, and virtually eliminates non-instrumental SM backgrounds. To identify the signal with single-event sensitivity, the detector must be able to:

- efficiently tag charged particles entering from the IP direction with energies $> 100$ GeV,
- locate and distinguish exactly two oppositely-charged, nearly collinear primary particles (both with energies above 100 GeV) consistent with an origin inside the detector decay volume and the expected direction, and
- confirm the expected high-energy, electromagnetic character of the signal by robust, independent means.

A. Tracker

The tracker’s performance is constrained by limited space, services, and budget, as well as the high energy of the signal. The minimum requirement is the ability to distinguish two tightly collimated high-momentum charged tracks. If additional primary tracks are present, the tracker functions as a topological veto. A magnetic field is applied to the decay volume, even though no measurements are made there, to increase the spatial separation of tracks before they reach the first tracker plane.

Figure 4 shows the expected track separation in the forward (planes 1 and 2) and central (planes 3, 4, 5, and 6) tracking stations for $m_{A'} = 100$ MeV. There is no significant dependence on the dark photon mass. The dotted vertical line corresponds to an expected one/two-track separation threshold of 300 $\mu$m. For $E_{A'} > 2$ TeV, the oppositely-charged tracks are typically separated by less than this distance at the first tracking station, but the majority are sufficiently separated by the second for all energies.

Although the dark photon search does not rely on reconstructing the decaying particle’s mass, measurement of charged track momenta is a second important goal. Using ATLAS SCT modules as a point of reference (see Sec. VI C), the hit occupancy in FASER is nearly zero and the tracks are nearly straight. If the track separation is sufficient to produce distinct strip clusters, track finding and fitting will present no technical challenges, but the combination of modest magnetic field and high momentum limits the achievable resolution.

Karimaki [28] has calculated the expected performance of a magnetic spectrometer under extremely general assumptions. Momentum resolution scales linearly with coordinate resolution and field strength, but quadratically with the length of the detector. The dependence on the number of measurements and where they are made is more complicated, but also calculable.

Figure 5 shows FASER’s idealized momentum resolution for different energies and numbers of sensor planes, assuming perfect alignment. The momentum resolution naturally degrades as the curvature of the track ($\rho$) decreases. The track stiffness ($K \equiv 1/\rho$) can be measured with roughly Gaussian errors. As $K$ becomes consistent (within errors) with zero, the sign of the track’s charge becomes indeterminate and only a lower limit on the
FIG. 4. Left: Separation of charged tracks from decay of a dark photon ($m_{A'} = 100$ MeV) at three energies. The solid (dashed) histograms are the expected separation in the forward (central) tracking stations, as defined in the text. Right: Separation of photons from the decay of an ALP ($m_a = 100$ MeV) at the end of the tracking system. In both panels, the decays are averaged over longitudinal position, and the vertical line at 300 $\mu$m represents a conservative estimate of the separation required to create isolated clusters in a silicon strip detector.

FIG. 5. Estimated fractional momentum resolution ($\sigma/p$) as a function of the number of tracker planes for six different momenta, assuming the nominal coordinate resolution, tracker length, and magnetic field, and the theoretically optimal arrangement. FASER’s choice of eight tracker planes represents a reasonable trade-off between performance, cost, and complexity.

momentum is possible. For FASER, this estimated resolution limit is 1.5 TeV at 5$\sigma$ and 2.5 TeV at 3$\sigma$. This implies that when a track is too straight to measure its curvature accurately, we will be able to set a fairly high bound on its minimum momentum. At low energies, FASER should have excellent (few percent) momentum resolution to reject tracks below the 100 GeV analysis threshold.

B. Calorimeter

FASER’s dark photon decay signal consists of extremely high-energy electrons, while the dominant event rate is extremely high-energy (entering) muons. To demonstrate compelling
evidence of new physics, it will be important to independently establish the presence of hundreds of GeV of electromagnetic energy. Extremely precise energy resolution is not essential, but containment of TeV-energy showers requires a depth of at least 25 radiation lengths. The LHCb ECAL modules (see Sec. VI D) are a robust and economical design that would be well-suited to most of our needs. Increased leakage at FASER energies would likely degrade the nominal energy resolution ($\sigma_E/E \approx 10\% \sqrt{E} \oplus 1\%$) only slightly.

For ALPs predominantly coupled to two photons, the signature is two, highly collimated photons; typical separations are shown in the right panel of Fig. 4. This search would therefore benefit from a pre-shower detector of 1–2 radiation lengths depth, with the finest possible granularity, to convert and spatially resolve the photons. The possibility of adapting the silicon strip modules used in the tracker for this purpose is under study.

C. Geant4 Simulation

A GEANT4-based [29] simulation has been developed to model the integration of detector components and their response to the signal. All sensitive elements of the detector (trigger/veto, tracker, pre-shower detector, and calorimeter) are represented. A simplified (uniform dipole) magnetic field model is used, pending a full calculation based on the magnet design. Dark photon decays are generated with the correct kinematics, assuming uniform solid-angle and $\log p_{A'}$ distributions (which can be re-weighted in subsequent analysis). A clustering algorithm has been developed and tested to validate analytic estimates of the two-track separation efficiency. Track-finding and reconstruction algorithms using the ATLAS-derived ACTS framework [30] are under development.

D. Signal Efficiency

The expected tracker resolution and magnetic field will make it possible to realize FASER’s excellent discovery potential for new physics after applying experimental selections. In the following, we illustrate this by an analytical estimate of the signal efficiency to detect a dark photon decaying to two charged particles within FASER’s decay volume. With the proposed detector we would not be able to measure the mass or the decay position of the LLP, due to the very large energies and small opening angle of the decay particles. However, to select the signal, we require that the reconstructed particles be consistent with originating from a common decay point in the decay volume. This requirement should be 100% efficient for signal events.

In addition, we require the dark photon decay products to (1) be completely enclosed in the tracker within a radius $R = 10$ cm, and (2) be separated by more than $\delta = 0.3$ mm in the bending plane at the tracking stations. We consider two possible selection criteria: a loose requirement, in which we require the tracks to be separated sufficiently in the second and third stations only, and a tight requirement, in which we require the tracks to be separated in all three tracking stations. The signal efficiency as a function of dark photon energy and vertex position is shown in the left panel of Fig. 6. We can see that high-energy events decaying at the far end of the decay volume have a reduced signal efficiency, which is further reduced for the tight selection. There is also a slight loss of efficiency for low-energy ($< 500$ GeV) events, where the decay products can be swept outside the detector by the magnetic field. Despite these effects, the signal efficiency has only a limited impact on the
FIG. 6. Left: Signal efficiency for the loose selection criterion as a function of dark photon energy and the decay’s longitudinal position, averaged over the transverse position, for the dark photon benchmark point $m_{A'} = 100$ MeV and $\epsilon = 10^{-5}$. Center: FASER dark photon reach without signal efficiencies (dotted), with loose selection cuts (dashed), and tight selection cuts (solid). The “all” and “loose” curves are almost indistinguishable. Right: Energy spectrum of dark photon decay products in FASER for $m_{A'} = 100$ MeV and $\epsilon = 2 \times 10^{-5}$ (solid), $\epsilon = 10^{-5}$ (dashed) and $\epsilon = 0.7 \times 10^{-5}$ (dotted). We show the spectrum for all dark photons decaying in FASER (red), and those passing the loose (green) and tight (blue) selection cuts.

sensitivity reach, which is shown in the central panel of Fig. 6.

In the right panel of Fig. 6 we show the energy spectrum of dark photon decay products in FASER for $m_{A'} = 100$ MeV and three values of the kinetic mixing parameter $\epsilon = 2 \times 10^{-5}$, $1 \times 10^{-5}$, $0.7 \times 10^{-5}$. As can be seen, a softer spectrum is obtained for decreasing values of $\epsilon$. This is due to an increasing $A'$ lifetime, which results in a smaller boost factor for the $A'$s that can reach the detector before decaying. The colored lines show the expected spectra for all dark photons decaying in FASER (red), and those passing loose (green) and tight (blue) selection cuts. In particular the tight selection reduces the event rate at high energies, as the most energetic decay products cannot be separated enough before reaching the first tracking station. We can see that the tracks produced by a dark photon decay in FASER typically have energies of $\sim 1$ TeV and above.

A similar energy spectrum is also expected for photons produced by the decay of an ALP in FASER. A search for ALP decays into two photons can make use of the full volume of FASER in front of the calorimeter and requires a very good efficiency for separating two close-by showers. Importantly, as discussed in Sec. VII B, the expected background of high-energy photons in FASER is very low and such events will typically be associated with a collinear charged particle(s) that will be detected in the front veto and the tracker. As a result, even two-photon events from ALP decays that will be mis-reconstructed as a single shower in the calorimeter could already be indicative of new physics.

VI. DETECTOR COMPONENTS

A. Magnets

Three dipole magnets are needed to separate energetic pairs of charged particles and to perform momentum measurements. An electromagnet would provide the strongest field, but,
for the large aperture needed, is rather bulky compared to the available space and requires a significant amount of supporting infrastructure. Therefore a solution with permanent dipole magnets is preferred. The field strength of such magnets will have some dependence on the temperature, but given the high momentum of the signal particles, this is not expected to contribute significantly to experimental uncertainties.

An attractive solution is to use magnets based on a Halbach array [31] constructed from permanent magnet blocks with different magnetization directions as illustrated in Fig. 7. Such a magnet design with very similar requirements was prepared by the CERN magnet group for the N-Tof experimental area, and it is expected this could be adapted for all three magnets. Using SmCo for the magnet material, a dipole field of 0.52 T can be reached. With NdFeB the field could be as high as 0.6 T at the cost of a small increased temperature sensitivity and reduced radiation hardness, which is not expected to be a problem in the FASER location. As can be seen in the figure, such magnets are very compact compared to more traditional magnets. A one-meter-long magnet is expected to weigh about 1000 kg. As shown in Fig. 7, the fringe fields extend out minimally radially, but, due to the large aperture, will extend out between the magnets. A minimum distance of 200 mm between magnets will therefore be needed for safety reasons. These openings will be used for detector elements.
B. Scintillator Trigger and Veto Layers

Four identical scintillator layers are used to provide efficient veto and trigger signals for charged particles. The basic design of each layer is shown in Fig. 8 and consists of a 2 cm thick, 25 cm × 25 cm plastic scintillator connected through a light guide on each side to a PMT. The transverse size of the scintillator is larger than the magnet aperture to further ensure no charged particle can enter undetected, and the 2 cm thickness is chosen to provide a high detector efficiency for these. The dual PMTs on each layer provide redundancy and ensure a very high veto efficiency for the veto layers as well as improving the timing resolution. The target efficiency for minimum ionizing particles is 99.99% for each of the two veto stations with a timing resolution for the trigger chambers that is better than 1 ns. The time difference between the two trigger layers separated by 2.2 m will provide rejection of signals not originating from the IP, particularly beam background coming from behind the detector. By measuring the signal amplitude, each of the trigger layers will also provide some discrimination power for the number of charged particles traversing the scintillator.

C. Tracker

In the current design FASER will include 8 to 10 tracking layers: two layers in the first tracking station, four layers in the second station, two layers in the third station, and possibly two layers inside the calorimeter as a pre-shower. Each layer consists of two single-sided silicon strip detectors with dimensions 24 cm × 24 cm, corresponding to an area of 0.06 m², which is sufficient to cover the aperture of the magnets.

Possible candidates for the silicon strip detectors are spare modules of the SemiConductor Tracker (SCT) in the ATLAS experiment [32, 33]. The SCT has 4 cylindrical barrel layers and 18 planar endcap discs, covering 60 m². The SCT consists of 4088 independent modules which have two single-sided silicon strip detectors with a stereo angle of 40 mrad. Each side of the modules has 768 strips with a constant pitch of 80 µm. Figure 9 shows a barrel module with 6 on-detector ASICs per side, which are integrated into the module. These ASICs are the first stage of the detector readout, as well as setting the detector configuration. The modules for the barrel region are 6 cm × 12 cm, such that 8 modules would give 1 tracking layer in FASER. The SCT module design resolution is 17 µm × 580 µm, and the modules would be arranged in FASER such that the precision measurement is in the bending plane.

During the SCT assembly, more than 400 modules (238 modules for the barrel and 225 modules for the endcap) passing mechanical and electrical tests were kept as spare modules [34, 35]. The above design could be realized using 80 of these. The ATLAS SCT power supply and interlock system could also be used in FASER. A crate for the SCT power supply houses 6 HV cards and 12 LV cards, which provide power for 48 SCT modules [36]. For FASER, two SCT power supply crates would be sufficient. Given the expected low radiation levels in the TI18 tunnel, the SCT modules would be operated at room temperature using a water cooling system to cool the on-detector ASICs (5 W per module).

An attractive solution for the tracker readout would be to use the ATLAS SCT readout system [37]. It consists of Readout Driver (ROD) VME modules, each of which is connected to one Back-of-Crate card that connects optically to up to 48 modules, therefore 2 RODs would be needed for the full FASER system. The RODs are primarily responsible for module configuration, trigger propagation, and data formatting.
FIG. 9. A picture of the barrel module of the SCT of the ATLAS experiment.

FIG. 10. Design of the LHCb outer ECAL module [38]. For FASER, the PMT might be replaced with a more compact sensor that can operate in a magnetic field.

D. Calorimeter

The electromagnetic calorimeter provides strong identification of high-energy electrons and photons over muons and hadrons and allows to measure their energies. Since for most signal events the $e^+e^-$ or photon pair is separated by less than a few millimeters, it is not feasible to measure the individual particle energies, and the main calorimeter requirement is therefore to measure the total electromagnetic energy with good accuracy for multi-TeV deposits in a compact detector.

The planned calorimeter is a Shashlik-type calorimeter, as used in HERA-B and LHCb, for example, with interleaved scintillator and lead plates, and with wavelength shifting fibers penetrating the full calorimeter. The baseline is to use the same type of modules as the LHCb outer ECAL modules [38], shown in Fig. 10. With modules with transverse dimensions of 121.2 mm $\times$ 121.2 mm, the full FASER acceptance can be covered with just four modules. The calorimeter contains 66 layers of 2 mm lead and 4 mm plastic scintillator, for a total depth of 25 radiation lengths. The energy resolution for TeV deposits in such a calorimeter is expected to be around 1%, although this will be degraded at the highest energies as 25 radiation length will not fully contain all such showers.

To detect the presence of two electromagnetic showers separated by 300 $\mu$m $–$ 2 mm, particularly for di-photons which are not seen in the tracker, a pre-shower detector could be placed in front of the main calorimeter. This could be constructed from a layer of tungsten or
lead followed by two layers of silicon strip detectors with the strips in the two layers oriented orthogonal to each other. The thickness of the pre-shower detector is being optimized for efficiency and separation power.

E. Trigger and Readout System

The detector read out will be triggered on either a coincidence in time between the two trigger scintillator layers or on a minimum amount of energy deposited in the calorimeter. The latter should provide a very efficient, but low rate selection of events with energetic electrons and photons, while the scintillator coincidence provides a trigger for signal decays to a pair of charged particles as well as a large sample of muons from the IP for alignment and calibration.

The CAEN V1743 VME module is a candidate trigger and readout module for the scintillators and calorimeter PMTs. This module is a 16 channel, switched capacitor digitizer, which can record up to 1024 12-bit samples at 3.2 GS/s on internally generated triggers based on combinations of channels passing a discriminator threshold. Recording the full signal pulse at high precision allows for a very precise timing measurement as well as scrutinizing the details of all scintillator and calorimeter channels for non-physical anomalies in case of a possible signal. The trigger rate will be limited to less than 500 Hz to keep the dead time low. The trigger outputs will be combined in a programmable logic board, such as the CAEN V2495 module, with orbit and bunch clock signals from the LHC to align the trigger signals with IP1 collisions. The module will also generate a trigger signal for the tracker readout. No attempt will be made to combine data with the ATLAS experiment, and no signal will be exchanged between the two experiments.

The readout of the CAEN V1743 module and the tracker will be done optically to a PC located outside the LHC tunnel area. The PC will merge the two data streams and carry out additional signal processing and compression before recording to local and offline storage for data analysis. The raw output data is expected to be about 40kB/event, but compressible to less than 4kB/event, i.e. less than 2MB/s.

F. Support Services

The best access to the TI18 tunnel is to enter the LHC at Point 1 (where the ATLAS experiment is situated) and to follow the LHC tunnel for 480 m. To enter TI18, one must then cross over the LHC machine. Informal discussions with the CERN transport, civil engineering, and cryogenic teams suggest that it should be possible to transport detector components of up to about 1000 kg to the location and carry them over the LHC into TI18.

Discussions with CERN civil engineering experts suggest that excavating up to 50 cm down in the tunnel floor should be possible in LS2. This is needed to have enough room for a 5 m long detector to lie along the beam collision axis of the IP1 collisions.

Investigations are ongoing to find the best location to install the detector services, including a chiller for the cooling of the detector electronics, power supplies, and the readout electronics.
VII. BACKGROUNDS

FASER’s signal is multiple coincident, collimated particles of very high energy ($E \geq 100$ GeV). Muons and neutrinos are the only SM particles that can transport such energy through hundreds of meters of material between the IP and FASER. The CERN Sources, Targets, and Interactions (STI) group have computed muon fluxes at the FASER location using a FLUKA simulation. These muon fluxes, in turn, allow estimation of the rate and energy spectrum of muon-associated radiative processes near the detector. FASER-specific neutrino flux simulations will be completed in one to two months; in the interim, previous calculations of LHC neutrino fluxes are used to estimate neutrino-induced backgrounds.

To complement and validate calculated background estimates, an emulsion detector and a battery-operated radiation monitor (BatMon) began collecting data at the FASER site in June 2018. These will provide the first in situ measurements.

A. FLUKA Simulation

Recently a study from the CERN STI group [39] using the FLUKA simulation program [40, 41] was completed to assess backgrounds and the radiation level in the FASER location. The study uses a detailed geometry of the LHC and T18 tunnels and includes the effects of the LHC infrastructure (magnetic fields, absorbers), the rock between the IP and FASER, and realistic machine optics. Backgrounds from three sources were considered:

- Particles produced at the IP coming directly into the FASER detector.
- Showers initiated by protons hitting the beam pipe close to the FASER location (in the dispersion suppressor region of the LHC). These originate from off-momentum (and therefore off-orbit) protons following diffractive processes at the ATLAS IP.
- Beam-gas interactions in beam-2 (the beam passing FASER in the direction of the ATLAS IP), which can lead to particles entering FASER without passing through any rock.

The results show that muons are the only high-energy ($> 100$ GeV) particles entering FASER from the IP, with an expected rate of 70 Hz (for the expected Run 3 conditions with a peak luminosity of $\approx 2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$). The study shows that no high-energy particles are expected to enter FASER from proton showers in the dispersion suppressor or from beam-gas interactions.

The radiation level expected at the FASER location is very low due to the dispersion function in the LHC cell closest to FASER (cell 12). Simulations and measurements show that the radiation level in neighboring cells (50 m upstream and downstream from FASER) are orders of magnitude larger, as can be seen in Fig. 11. FLUKA predicts that the radiation level at the FASER location from proton showers in the dispersion suppressor is less than $4 \times 10^{-3}$ Gy per year or equivalently less than $4 \times 10^7$ 1 MeV neutron equivalent fluence per year. Beam-gas interactions are not expected to contribute due to the excellent vacuum in the LHC beam pipe. Such radiation levels are not expected to be problematic for the detector components, electronics, or services to be used in FASER.
B. Muon-associated Radiative Processes

TeV-energy muons will produce photons and electromagnetic and hadronic showers in the rock surrounding FASER. Kinematics ensures that the scattered muon and any secondary above FASER’s 100 GeV analysis threshold will be separated by an angle of a few mrad or less. Thus, tagging the presence of an entering muon is sufficient to differentiate these events from signal. The rates are nevertheless interesting, since they set the scale of muon rejection required and illuminate the composition of FASER’s raw data.

Production of secondaries with energies above 100 GeV is very rare, so numerical integration is an efficient alternative to Monte Carlo. These processes are well understood, and their properties accurately parameterized [42, 43]. Rates and spectra are calculated from the FLUKA-predicted muon spectrum, assuming an exposure of 150 fb$^{-1}$, and summarized in Table I. Bremsstrahlung is the dominant radiative process, but most photons convert in the rock before reaching FASER. An estimated 41,000 photons with energies above 100 GeV will enter FASER unconverted; of these, roughly 7400 will convert in detector material before reaching the calorimeter. The muon-induced photon spectrum is sharply peaked toward lower energies (see Fig. 12), and all will be accompanied by the parent muon.

Bremsstrahlung conversions and direct $e^+e^-$ pair production will lead to muons accompanied by electromagnetic showers, and photo-nuclear interactions will produce muons ac-

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected Number of Events</th>
</tr>
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<tbody>
<tr>
<td>$\mu$</td>
<td>540M</td>
</tr>
<tr>
<td>$\mu + \gamma_{\text{brem}}$</td>
<td>41K</td>
</tr>
<tr>
<td>$\mu + (\gamma_{\text{brem}} \rightarrow e^+e^-)$</td>
<td>[7.4K]</td>
</tr>
<tr>
<td>$\mu + \text{EM shower}$</td>
<td>22K</td>
</tr>
<tr>
<td>$\mu + \text{hadronic shower}$</td>
<td>21K</td>
</tr>
</tbody>
</table>

TABLE I. Expected number of events for muons and muon-induced processes that enter FASER from the direction of the IP with energy $\geq$ 100 GeV in Run 3 with integrated luminosity 150 fb$^{-1}$. One muon event occurs for every 170K bunch crossings. The bracketed process is the subset of all $\mu + \gamma_{\text{brem}}$ events in which the photon pair converts in FASER before reaching the calorimeter.
FIG. 12. The calculated flux spectrum of muon-induced photons from bremsstrahlung entering FASER unconverted in an exposure of 150 fb$^{-1}$. All will be accompanied by the parent muon.

comppanied by hadronic showers. In these cases, the probability for any single particle (other than the muon) to reach FASER with 100 GeV or more is very small; the calculated rates are instead based on the looser requirement that the total shower energy reaching FASER (attenuated by the number of radiation or hadronic interaction lengths from the interaction, as appropriate) is over 100 GeV. The calculation predicts that roughly $8 \times 10^4$ muons entering FASER (one in 7000) will be accompanied by additional, visible, electromagnetic or hadronic energy above 100 GeV. We see that, with two layers of scintillator at the front of the detector, each vetoing entering charged particles with an efficiency of 99.99%, the backgrounds in Table I will all be reduced to negligible levels.

A last muon-induced background is one in which a muon first radiates a high energy photon in the rock before the detector and then decays. We expect $\mathcal{O}(0.01)$ events of this kind in Run 3.

C. Neutrino-induced Backgrounds

For the large pseudorapidities characteristic of FASER with a 10 cm radius, the dominant source of neutrinos is in-flight $\pi^\pm$ decays; heavier mesons play a less important role [44]. A good estimate of the high-energy neutrino flux can therefore be obtained from the forward pion spectrum, which can be convoluted with the neutrino interaction cross section to estimate the number of neutrino-induced charged current (CC) events in the detector. The result is that, requiring neutrino energies above 100 GeV (1 TeV), one expects $\sim 10$ ($\sim 0.1$) CC neutrino events per kg of detector material for 150 fb$^{-1}$ integrated luminosity [7]. Considering the small mass of the first tracking station (roughly 500 g) and the air in the decay volume (60 g), we therefore expect at most a few $\sim 100$ GeV CC events, and far fewer with TeV energies, where most of the signal is. In addition, these neutrino events typically produce only one high-energy charged track, since the momentum transfer to the nucleus is form-factor suppressed, resulting in the other scattering products typically having much lower energy. For the same reason, neutral current (NC) interactions will typically only lead to low-energy events. One therefore expects neutrino-induced backgrounds to be negligible.
D. \textit{In situ} Measurements

An emulsion detector was prepared and installed at the FASER location on 21 June 2018, during Technical Stop 1 (TS1). The purpose is to validate the FLUKA background estimation results. Furthermore, this measurement may pave the way for using emulsion detectors for LLP searches. Emulsion detectors are made of micro-crystals with a diameter of about 200 nm, which leads to a position resolution of 50 nm and an angular resolution of 0.35 mrad with a 200 $\mu$m-thick base [45]. The high resolution of emulsion detectors, as well as their energy-loss ($dE/dx$) measurement capability, allows them to separate $e^+e^-$ pair signals from single electron background. In addition, low-energy components can be rejected by their multiple Coulomb scattering inside the detector materials.

The installed detector structure is shown in the left panel of Fig. 13. It comprises two sections. Upstream is a tracking section made of 10 emulsion films interleaved with 10-mm-thick Styrofoam, designed to detect two almost-parallel tracks. Each emulsion film comprises two emulsion layers (65 $\mu$m thick) that are poured onto both sides of a 200 $\mu$m-thick plastic base. The downstream section builds a sampling calorimeter, the so-called Emulsion Cloud Chamber (ECC), which has a repeated structure of emulsion films interleaved with 1-mm-thick or 5-mm-thick lead plates for the electromagnetic shower energy measurement. The total radiation length in the ECC is $12X_0$. The emulsion films are vacuum-packed with a light-tight bag and enclosed in an acrylic box as shown in the right panel of Fig. 13. A single module, consisting of 31 emulsion films, is 173 mm wide, 124 mm high, and 210 mm thick. Additionally, two removable emulsion detectors have been placed on the front and back faces of the acrylic box to provide the possibility of a prompt check of the track density shortly after TS1.

The energies of electromagnetic showers will be determined by counting the number of shower tracks in each emulsion film within a circle of radius 100 $\mu$m centered on the shower axis [46]. An energy resolution of 10.6% at 200 GeV has been found in simulations and validated by experimental data. If high-energy showers are detected in the downstream ECC section, they will be followed up to the upstream tracking section. Parallel electron tracks separated by 1 $\mu$m can be identified and possible decay points can be estimated.

Concerning the measurement in TS1, the additional two emulsion detectors outside the box will first be removed and analyzed before TS2. The measured track density in these layers will then inform the decision of when to remove the rest of the emulsion detector. The
data readout of the emulsion films will be performed with scanning microscopes [47, 48]. The emulsion readout and reconstruction chain allows one to work with a track density of up to $10^6$ particles/cm$^2$. The track density and high-energy electromagnetic components will be measured and compared to the background prediction from the FLUKA simulations.

To validate the FLUKA simulation results on the radiation level at the FASER location, a BatMon, commonly used in the LHC, was installed in situ in TS1. This will be read out in TS2 to measure the accumulated dose during this period.

VIII. COST, FUNDING, AND TIMELINE

An essential feature of FASER is its ability to do world-leading physics at a very affordable cost, thanks to the size and location of the experiment. FASER’s active volume is just 0.16 m$^3$, and the entire experiment fits in a box with dimensions 1 m $\times$ 1 m $\times$ 5 m. In addition, FASER’s location in TI18 is exceptionally quiet, so detector components do not need to be radiation hard, and background radiation for electronics is not a great concern.

The most costly components of the detector are the tracker, calorimeter, and magnets. To meet the experiment’s cost and schedule goals, we are actively exploring the possibility of using available spare silicon strip and calorimeter hardware from the larger LHC experiments. As noted above, roughly 200 spare ATLAS barrel SCT modules exist; FASER would require about 80 of those. We hope to present a formal proposal and request to the SCT Institutional Board at their September 2018 meeting. For the calorimeter, the LHCb ECAL project leader has advised us that the experiment has sufficient spares to consider a similar request from FASER. While it is important to emphasize that no commitments have been made, initial discussions are encouraging.

If spare modules are available for the tracker and calorimeter, the largest remaining construction expense are the magnets. The CERN magnet group estimates that the magnets will cost 350 kCHF and require one year to construct. Combined with the smaller costs of the scintillators, PMTs, trigger/readout electronics, support services, and personnel costs such as graduate student support and collaboration travel, we estimate that FASER’s total cost is 1–1.5 MCHF. A respected private research foundation has expressed interest in funding FASER at this level, and FASER will be presented as a top priority by the foundation’s Program Officer for Science to its Board in late September 2018. A preliminary decision is expected then, with funding starting as early as January 2019 if CERN approves the experiment. We also intend to seek funding from national funding agencies and other sources to support additional operations costs, as well as a possible future upgrade to FASER 2.

The current FASER collaboration is growing and will attract even greater interest once our proposals for approval and funding are successful. If, as hoped, we are able to use spare silicon strip and/or calorimeter hardware from existing LHC experiments, we are hopeful that interested experts from the associated institutions will choose to join us. Also, after FASER obtains funding, we will be able to offer graduate students a unique opportunity to take part in all aspects of an LHC experiment.

FASER will be installed in TI18 over LS2 in time to take data during Run 3. To place FASER on the beam collision axis, the floor of TI18 must be lowered by 50 cm; this is possible without disrupting essential services and is expected to be sufficient for any beam crossing angle planned for Run 3. With this aggressive, but feasible, schedule, FASER will have world-leading sensitivity to a broad array of LLPs, including dark photons, ALPs, and other CP-odd scalars.
If FASER is successful, a larger version, FASER 2, with a fiducial decay volume 1 m in radius and 5 m in length, could be installed over LS3 and take data during the HL-LHC era. FASER 2 would require extending TI18 or widening UJ18, but would greatly extend FASER’s sensitivity to more massive dark photons and probe currently uncharted territory for many other models, including dark Higgs bosons and heavy neutral leptons [7–14].

IX. SUMMARY

FASER will extend the LHC’s physics program by searching for light, weakly coupled new particles with the potential to discover physics beyond the SM and shed light on dark matter. If installed in LS2 and collecting data in Run 3, FASER will have unprecedented sensitivity to dark photons, other light gauge bosons, and axion-like particles with masses in the 10 MeV to GeV range. A larger detector, FASER 2, running in the HL-LHC era, will extend this sensitivity to larger masses and will probe currently unconstrained parameter space for all renormalizable portals (dark photons, dark Higgs bosons, and heavy neutral leptons), ALPs with photon, fermion, or gluon couplings, and many other new particles.

FASER will be placed in TI18, an existing and unused tunnel 480 m from the ATLAS IP. To maximally intersect the beam collision axis, the floor should be lowered by 50 cm, but no other excavation is required. FASER will run concurrently with the LHC, requiring no beam modifications and interacting with the existing experiments only in requesting luminosity information from ATLAS and bunch crossing timing information from the LHC.

At present, it appears possible that the cost of design, construction, and installation, as well as some personnel costs, for FASER will be 1–1.5 MCHF. A private foundation has expressed interest in funding FASER at this level, with a preliminary approval decision in late September 2018 and funding beginning as early as January 2019, contingent upon CERN approval. We also intend to seek funding from national grant agencies and other sources to support additional operations costs and are actively working to increase the size of the collaboration.

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Appendix A: Developments related to FASER Design and Physics since the LOI was submitted to the LHCC

The following points were presented to the LHCC on 10 September 2018.

1: We have decided to drop the pre-sampler based on SCT modules from the baseline detector design, as we think this will not be able to reliably resolve very closely spaced high-energy photons, and will make the detector more complicated.

2: Following discussions with the CERN civil engineering and Survey teams, a mismatch of 20 cm in the vertical direction was found between the model of the TI18 tunnel region and measurements. This has now been resolved, but (unfortunately) will limit the detector length compared to what was presented in the LOI. We are still working on the best way to deal with this change, but one option would be to have the decay volume composed of a region with no magnetic field of 0.9 m, followed by region of 0.7 m with a magnetic field. The spectrometer would then be shortened to be made of two 0.7 m magnets. Initial studies with this design show only a small degradation in physics sensitivity compared to the LOI, although the spectrometer momentum resolution is a factor of two worse due to the shorter spectrometer. We are also investigating the possibility of using the TI12 tunnel for FASER rather than TI18. TI12 intersects the LHC the same distance away on the other side of IP1, and so crosses the line of sight in a similar way. In order to have a precise measurement of the line of sight in TI12 a laser scan, and survey measurement will be carried out in LHC Technical Stop 2 to see if this will allow a longer detector than in TI18.²

3: We have been looking at the interesting possibility of doing neutrino physics with FASER. There is a huge flux of high-energy muon neutrinos traversing FASER, and these can interact in the lead plate, which is part of the veto at the entrance to the detector. As can be seen in Fig. 14 (center), with 10 cm of lead we could expect ~1400 events with $E_\nu > 100$ GeV, ~600 events with $E_\nu > 500$ GeV, and ~240 events with $E_\nu > 1$ TeV in 150 fb$^{-1}$ of data. There are currently no measurements of the cross-section in the regime with $E_\nu > 400$ GeV (except at very high energy from IceCube), see the bottom plot in Fig. 14 (right). Given this, we may have an opportunity to measure the charged-current muon neutrino cross section at these unexplored energies.

In addition, it may also be possible to measure tau neutrino interactions at the FASER location using emulsion detectors, and this is being investigated. As an example we would expect two tau neutrino interactions (with $E_\nu > 100$ GeV) with a radius of 10 cm, and 10 cm thick lead plate (centered on the LOS) in 150 fb$^{-1}$ of data. If we were to instrument a much larger and deeper region around FASER with (for example) lead based emulsion detectors we could expect to have 100s of high energy tau neutrino interactions.

² Note added: Since this document was prepared, additional measurements made by the CERN survey team during LHC Technical Stop 2 in September 2018 have shown that tunnel TI12 on the other side of LHC interaction point IP1 will more easily accommodate the detector with the dimensions presented here. TI12 is the same distance from IP1 as TI18 and the expected signal and backgrounds are very similar. FASER is now expected to be located in TI12.
FIG. 14. Left: the expected number of muon neutrinos going through FASER in 150 fb$^{-1}$ of 14 TeV data, as a function of the neutrino energy, and broken down by the production mechanism; Center: the same, but for neutrinos interacting with a 10 cm thick lead plate in FASER; Right: existing measurements of the muon neutrino CC cross section as a function of neutrino energy. Figure adapted from Ref. [49].

4: We now have first results from in situ measurements of high-energy particles, and the radiation field in the FASER location. These broadly agree with the FLUKA expectations, and we will make more detailed measurements for the rest of the 2018 LHC run.

Appendix B: Replies to Questions from the LHCC

The following answers were presented to the LHCC on 10 September 2018 in response to questions from the LHCC reviewers.

1. Physics Studies

Question 1: Please provide more explicit comparisons against the reach of MATHUSLA, CODEX-b, and comment on synergy/complementarities.

FASER, MATHUSLA, and CODEX-b are complementary. Roughly speaking, FASERs strength is low-$p_T$ physics (e.g., long-lived particles produced in light particle decays, such as pion decays), while the strength of MATHUSLA and CODEX-b is high-$p_T$ physics (e.g., long-lived particles produced in Higgs boson decays). These detectors are also quite different in cost: FASERs estimated cost is $\sim$1.5M CHF and MATHUSLA appears to be in the several 10M CHF range; we are not aware of a CODEX-b cost estimate.

Fig. 15 shows some explicit comparisons, where the MATHUSLA and CODEX-b contours are taken from their submissions to the Physics Beyond Colliders (PBC) group. Fig. 15 (left) is the dark photon plot from the LOI, but now with the MATHUSLA reach included. MATHUSLA does not probe new parameter space. No reach was submitted by CODEX-b at the time of the last PBC meeting. One can also expect that FASER covers more parameter space for new particles produced in pion decays, such as $B - L$ gauge bosons and ALPs. The center plot of Fig. 15 shows the reach for dark Higgs bosons. These are dominantly produced in $B$ decays, and so have characteristic $p_T \sim m_B$. FASER is too
FIG. 15. Left/Center: Comparison of projected physics reach between experiments, including MATHUSLA (and for dark-Higgs also CODEX-b), for dark-photons (left), and dark-Higgs (center).

small to probe new parameter space. FASER 2 can probe significant regions of unconstrained parameter space, and this region is complementary to the coverage of CODEX-b and MATHUSLA.

There are other synergies between the detectors. For example, MATHUSLA is sensitive to the trilinear coupling $h\phi\phi$, where $h$ is the SM Higgs boson and $\phi$ is the dark Higgs bosons, by looking for $h$ production followed by decays $h \rightarrow \phi\phi$. FASER is also sensitive to this coupling through the process $B \rightarrow K\phi\phi$; see Fig. 15. For some parameters, the trilinear coupling $h\phi\phi$ could be probed through complementary processes by MATHUSLA and FASER.

Finally, FASER may be able to detect muon neutrinos through their charged-current interactions in FASER and constrain the muon neutrino CC cross section in the TeV-energy range, which is currently unconstrained. This relies on the extraordinary high-energy neutrino event rates at low $p_T$, which are not accessible at MATHUSLA and CODEX-b.

Question 2: For dark photons and axion-like particles, the exclusion limits of SeaQuest look very similar to those of FASER 2, surpassing FASER a lot. Are the two experiments complementary in the sense that an observation in both would shed further light on the observed particle? What are the prospects of SeaQuest being realised?

The SeaQuest plans have been described in Ref. [17]. Currently SeaQuest runs without an ECAL. For dark photons, it is therefore insensitive to $A' \rightarrow ee$, and the $A' \rightarrow \mu\mu$ channel is expected to suffer from significant backgrounds. The SeaQuest contours in the LOI assume that SeaQuest is upgraded to include an ECAL, which would make it sensitive to $A' \rightarrow ee$. The current plans are to submit a proposal for this ECAL upgrade in 2019, install the ECAL in 2021, and collect data from 2022 - 2024. This plan requires Fermilab to redirect some beam time from its neutrino program to SeaQuest.

Regarding complementarity, as noted above, given muon backgrounds, SeaQuest would be unable to see muon neutrino CC events and $A \rightarrow \mu\mu$. These can be detected at FASER and FASER 2. Also, given its low COM energy, SeaQuest is not highly sensitive.
to particles dominantly produced in $B$ decays, such as dark Higgs bosons. Such particles also escape FASER, but will be seen in FASER 2. This can be seen in Fig. 16.

**Question 3:** What appears here as a background (e.g., muons from the IP), can also be viewed as a physics signal, probing the most forward and most energetic particle production at the LHC. This is a domain of great interest (QCD tests and MC validation, cosmic ray shower modeling, etc), which could provide a guaranteed physics return independently of the exotic particles search programme. It would be interesting to see this discussed.

This is an interesting idea we would need to look at in more detail. We have been in contact with QCD and nuclear physics experts to discuss this possibility, but more discussions are needed. We would expect that such a measurement would require an excellent muon momentum resolution, which FASER might not be able to provide. The expected momentum resolution was discussed in the LOI (Fig. 5), assuming perfect detector alignment. However, at high momentum, the alignment quality will be the main limitation and will possibly deteriorate the momentum resolution. This may mean that FASER cannot say very much here for very high-momentum muons.

In addition the FLUKA expectation for the high-energy muons going through FASER includes components from muons produced directly at the IP, and those produced by secondary showers (e.g. in the TAN), which would complicate any interpretation. Further studies would be needed to understand what we could learn here.

Finally, as said at the beginning of this document, since the LOI we have been looking at the possibility of measuring the muon neutrino charged current interaction cross section in FASER (which is a similar guaranteed physics Standard Model measurement that we may be able to do). Initial studies suggest that we may be able to measure this cross section in the currently unexplored $0.5 - 1$ TeV energy regime.
2. Background Simulations

Question 4: Contrary to what stated in the text, EPOS-LHC is not really tuned to LHC forward data, rather to MB data. When compared to LHCf data, EPOS-LHC, like all other available MCs, shows important discrepancies, especially at the highest photon energies. It would be useful to see an assessment of the robustness of the predictions for backgrounds from the IP.

EPOS is used as the event generator when simulating signal processes. Early studies of the signal were done comparing EPOS with SIBYLL and QGSJET, which gave the same results within a factor of 2 (leading to almost imperceptible changes in the high-$\epsilon$ boundary of the projected reach curves for dark photons).

For the background studies the FLUKA team uses the DPMJet3 (dual parton model), internally using PhoJet, as the event generator [50, 51]. This is validated in two ways:

- It is benchmarked against LHC data—e.g., see Refs. [50, 51].
- It is benchmarked by comparing the full FLUKA results with beam loss measurements in the machine (which agree very well) (e.g., see Fig. 17).

The above validates things pretty well for diffractive processes (and therefore losses in
the dispersion suppressor relevant for the radiation expectation in FASER). For the high-energy charged particles entering FASER from the IP (either directly or from secondary showers) this is less well validated. However the FLUKA results have been, and are being, validated with in situ data measurements (from the emulsion detector) and so far agree quite well (within factor of $\sim 2$).

**Question 5:** As part of this, but also in relation to point 2 above, it would interesting to see the breakdown of the sources of muons reaching FASER from the IP ($\pi/K$ decays, heavy quark decays, $DY$, ...).

The FLUKA team has not got a detailed breakdown of the sources of muons entering FASER, but there is clear evidence that the dominant source ($>90\%$) is from light meson (pion) decay. If sufficiently important the FLUKA team could do a study to provide a more detailed breakdown.

It is worth noting that the meson decaying could come from the primary $pp$ interaction or from secondary showers (for example, high energy particles hitting the TAN and leading to high energy showers), at the moment they have no knowledge on the relative contribution of these two possibilities. Again this could be investigated further if relevant.

**Question 6:** What is the fraction of muons from the IP reaching FASER, as a function of muon momentum? The reason for the question is that, in the momentum regions where the fraction is large, the modeling of the propagation through the rock is probably not critical; while in $p$ regions where the fraction is small, the modeling systematics could significantly alter the yields.

Fig. 18 shows the relevant plots, produced by the CERN FLUKA team. Muons lose 55 – 60 GeV traversing the rock between the IP and FASER, and the fraction that reach FASER from IP1 is above 90% for initial momentum above 70 GeV.

**Question 7:** Related to the previous point: are particles from the IP with $p < 100$ GeV left out of the discussion simply because they do not make it to FASER? Or are they rejected by the trigger?
Particles with $p < 100$ GeV are left out for computing efficiency reasons in the FLUKA study. We have asked the FLUKA team to look at decreasing this energy threshold, and their first (rough) estimate is that the charged particle flux increases by a factor $\sim 2$ with a much lower threshold. (This is in rough agreement with the emulsion detector results, with large(ish) uncertainties.) They are currently working on a more complete study down to a muon energy threshold of 10 GeV (using a new biasing technique to improve the statistics).

The FASER trigger is not relevant here, but we expect there to be a momentum cut of $\sim 10–15$ GeV for charged particles going through the full detector due to the bending of the magnetic field (this is for the LOI detector, and would be reduced a bit for detectors with a shorter region in magnetic field).

**Question 8:** What is the role of $\nu \to \mu$ conversions in the rock ($\nu$s from the IP)? Can you clarify the issue of the main source of high-energy neutrinos from the IP? The text says that its dominated by light meson decays, and cites Ref. [44]. But Ref. [44] seems to conclude that the dominant source is actually heavy quarks ...

In the current FLUKA studies muons from neutrino interactions are not included in the results, as FLUKA propagates neutrinos without interaction (unless specially asked for).

A simple calculation of the expected rate of muons entering FASER which originate from neutrino interactions gives rates 0.0025 Hz/cm$^2$, 0.0022 Hz/cm$^2$, 0.00033 Hz/cm$^2$ for 10 GeV, 100 GeV and 1 TeV thresholds. Compared to the expected rate of muons of $\sim 70$ Hz (for $E > 100$ GeV), this is completely negligible.

As mentioned above we are looking at the possibility of measuring the muon neutrino cross section in an unexplored energy region with FASER. Our studies show that the dominant source of neutrinos is from pion decay, as you can see in the left panel of Fig. 14 (made using EPOS-LHC for the light meson flux and PYTHIA 8 for the neutrinos from heavy meson decay).

**Question 9:** Was the process of gamma conversion to di-muons considered? The process is rare, but non negligible for the multi-TeV photons produced in the forward, and the final state mimics the signal more closely than single muons.

Gamma conversions to di-muons are included in the FLUKA simulations. The contribution is very small (so small it can’t be quantified at the moment), but this can be looked at in more detail if considered very important.

However it is unclear to us that this is a relevant process. If the conversion to muons happens before the FASER detector, these events would be vetoed by the scintillator. Also, for a high-energy photon entering FASER, this would be converted to a charged particle shower in the lead plate, and then the event vetoed by the second veto scintillator. In addition, our studies suggest that any high-energy photon entering FASER will originate from muon bremsstrahlung and this would very likely be accompanied by the parent muon which would also veto the event.

The FLUKA team will look at the rate of high-energy photon fluence entering FASER, but again this will (mostly) be accompanied with a charged particle that can be used to reject the event.
Question 10: Please provide FLUKA plots for expected contributions to backgrounds at TI18 (usual rad-physics 2d plots overlaying the apparatus and the nearby tunnel). Present evidence that indeed the positioning proposed for FASER is optimal, in view of backgrounds induced by the LHC (beam-gas, halos, ...)

The current version of this plot that we have is shown in Fig. 19. The small bold black circle shows the FASER location (at 485 m from the IP). This circle is of diameter $\sim 1$ m compared to the FASER active volume which has diameter 20 cm. This is shown for particles with $E > 100$ GeV at the FASER location.

It is interesting to observe that the peak flux is not at the FASER location (on the line-of-sight) but shifted (oppositely for +/- muons) in the horizontal plane by $1 - 2$ m. The FLUKA study estimates that all other particle fluxes (except for neutrinos) at FASER are at least 3 orders of magnitude suppressed compared to muons. The FLUKA team are working on updating the above plots reducing the muon energy threshold from 100 GeV to 10 GeV, and also showing the flux distribution for neutrinos (also down to 10 GeV).

The detector positioning is not really optimized due to backgrounds, but to be able to collect the most signal. The distance from the IP is governed by the existing tunnel, but is actually quite optimal as it is close to where the LHC tunnel starts to bend away from the line-of-sight, and therefore has low backgrounds, but is on the collision axis line of
sight. With this location we are sensitive to an interesting region of un-excluded signal parameter space (the distance is particularly sensitive to the coupling/lifetime we are sensitive to).

**Question 11: Summarize current simulation status and expected improvements in the near term.**

The FLUKA simulation study for $p > 100$ GeV for charged particles is basically complete, it will be improved to get a more accurate momentum distribution of muons (as currently the biasing used for this was not optimal). Improvements in the pipeline for the next study are:

- Move to using the LHC layout rather than HL-LHC layout for the simulations. (The current studies are done with HL-LHC as they were originally for a FASER 2 type experiment feasibility study). This change is not expected to cause large differences (for example there are no differences in the dispersion suppressor between HL-LHC and LHC, so low levels of radiation at FASER will still be the case).
- Reduce the energy threshold down to 10 GeV for neutrinos and muons.
- Look at high-energy threshold photons spectrum (for photons entering FASER).
- Investigation of the breakdown of the sources of muons (primary vs shower, pions vs other mechanisms), if considered sufficiently important.
- An updated comparison of the radiation level (both high energy hadrons, and thermal neutrons) between data measurement (BatMon and an improved TimePix3 radiation detector to be installed in TS2) and FLUKA simulation with more data statistics ($\sim \times 10$ more luminosity compared to current comparison).

For the FASER detector simulation, we are continuing to implement the detector in GEANT4, and to write the digitization and reconstruction to be able to get final results from this. This will be needed for the detailed background estimates and signal efficiency numbers.

**Question 12: Are first results from the two additional emulsion detectors available? Please present at the September LHCC meeting an update of what has been learned from the backgrounds study, as well as plans for going forward.**

Figure 20 (right) shows the angle of tracks reconstructed in the emulsion detector in the $x$ and $y$ directions, from a first/preliminary analysis of $3 \text{ fb}^{-1}$ of 13 TeV data. This shows a clear peak of charged particles entering the detector with an angle compatible with the ATLAS IP (the peak population of tracks at close to $0, 0$ on the Figure). The observed number of charged particles corresponds to a flux of $1.7 \times 10^4 / \text{cm}^2$ without the detection efficiency correction (this correction is expected to be in the range $40 - 90\%$). This can be compared with the expected flux from the FLUKA simulations of $3 \times 10^4 / \text{cm}^2$ for particles with energy above 100 GeV, a rough FLUKA estimate suggests that this flux would double when including lower energy charged particles (which the emulsion detector would be sensitive to). Implying that the measurement agrees with the simulation within about a factor of two, and the two are likely consistent given the detection efficiency and uncertainty in the simulation.

An interesting feature in the emulsion detector data is a small secondary peak visible in Fig. 20 (right) at $(-0.75, 0)$, with $\sim 1\%$ of the total number of tracks. This corresponds
FIG. 20. Left: The geometry and coordinate definition of emulsion measurement. The $z$-axis was chosen to be almost the same as the line of sight. Right: The measured angular distribution in the emulsion detector. There are two clear angular peaks, corresponding to the tracks from the ATLAS IP and the LHC beamline at the bottom of the TI18 tunnel (Q 12).

to tracks entering the detector with an angle consistent with originating at the LHC beamline at the bottom of the TI18 tunnel (and therefore entering the detector without passing through any rock). The coordinate system and the tunnel geometry can be seen in Fig. 20 (left). The FLUKA simulations do not show such a population of tracks, but this only considered high energy particles ($E > 100$ GeV), whereas the emulsion is sensitive to particles with much lower energies. It is therefore likely these are low energy particles and will not be problematic for the experiment.

A more detailed analysis of the emulsion detector is ongoing, and should allow to also determine the rate of high energy electromagnetic objects. We also will get a better idea of the emulsion detector efficiency from this analysis, which would allow us to revise the above estimates.

The CERN radiation monitoring device (BatMon) installed close to the FASER location\(^3\) was read out after a period corresponding to $\sim 3$ fb\(^{-1}\) of 13 TeV collisions had been delivered to IP1. The readings showed the high energy hadron fluence was below the device sensitivity (corresponding to $10^6$ cm\(^{-2}\)) completely consistent with the expectation from the FLUKA simulation studies. For thermal neutrons the measured flux is $4 \times 10^6$ cm\(^{-2}\) to be compared with the simulation estimation of $6 \times 10^6$ cm\(^{-2}\) (where the simulation also includes non-thermal neutrons, but these are expected to add a small contribution). In general the measured radiation level seems consistent with the simulations, and is generally low, and dominated by beam-gas interactions in beam-2.

For future plans we intend to install two new emulsion boxes into the TI18 tunnel in TS2 (mid-September) which would be placed more directly on the LOS (the previous detectors were $\sim 20$ cm higher than the LOS) to give additional information. In addition we will install an emulsion detector in TI12 to measure the particle flux there. These emulsion

\(^3\) The BatMon is actually placed $\sim 2$m or more closer to the LHC machine than the FASER detector or electronics would be. Therefore the readings from this are actually a conservative estimate of the radiation that we would face for FASER.
detectors may also be able to detect a small number of muon neutrino interactions in the rest of the 2018 $pp$ run.

The BatMons will continue to accumulate radiation measurements until the end of the 2018 $pp$ run, and so will give better statistics on the expected radiation (they will be read out in TS2 and TS3). In addition we will install a new TimePix3 beam loss monitor in TI18 in TS2 which can give additional information (this allows to look at beam losses in this location as a function of time - e.g. to correlate with beam conditions etc...).

3. Detector Issues

Question 13: Since the ability to distinguish single photons from di-photons heavily depends on a pre-shower for the calorimeter, please provide more details on this and how it influences the physics reach.

Further studies have shown that it will be very difficult to be able to distinguish two very closely separated photon showers even with a pre-shower. We therefore think it is better to drop the SCT-based pre-shower from the detector design, which simplifies the setup, and reduces the detector length somewhat. We hope that an $a \rightarrow \gamma\gamma$ signal could still be detected by seeing an excess of events with very large EM energy and no tracks (a single photon signature) possibly in a background free way. More studies are needed to confirm this.

Question 14: Besides the discussed $2\gamma$, $2e$, and $2\mu$ also pion pairs are a possible signal. How well does the proposed detector layout do in terms of distinguishing the particle types? Could additional HCAL-like components improve that?

We do not think we will be able to identify pions reliably. Simulations of the pion response to the calorimeter would be needed to see in detail what signature we expect, but most probably this would be similar to a two-muon signal in the ECAL. Given the detector length constraints and the complexity/time-line we do not think adding a dedicated HCAL would make sense for FASER. For FASERs dark-photons signature we do not expect to be sensitive to $A'$ with masses that can decay to muons or pions (this is not true for other models or for FASER 2).

Question 15: It’s understood that the design of FASER is to a large extent influenced by available components. How much does this limit the physics reach? Would this be changed for FASER 2?

The main limitation for FASER is the size of the decay volume (both in length, and to gain sensitivity to other models, also in the transverse directions), which is limited by the civil engineering that can be done in LS2. The tracking detector position resolution does not play a large role in the sensitivity.

FASER 2 is much bigger and the required civil engineering and the magnet to cover the larger volume, will be considerably more expensive. We would need to cover the larger volume with tracking/calorimeters that can satisfy the experimental requirements. The timescale of FASER 2 means we have more time to design and construct the detector. Given the timescale we have concentrated most of our thinking about the detector design on FASER for the moment.
Question 16: At 500 Hz, the trigger rate can just barely cope with the expected muon rate. How robust is the trigger vs. current uncertainties in the actual background rate? Would the trigger hardware/strategy be adequate for a possibly programme of physics measurements using the muons from the IP (see point 2)?

Following the first results from the emulsion detector, we actually would expect \(\sim 150\) Hz of muons traversing FASER (this is in agreement with the FLUKA simulation expectation). (The 500 Hz number was a conservative guess of how the particles with \(E < 100\) GeV would contribute, whereas more recent FLUKA studies suggest the \(E < 100\) GeV component would only double the flux). In addition, if necessary we should be able to use the scintillator veto info in the trigger to pre-scale the set of muons going through the detector to a reasonable level (mostly for alignment purposes). However this could be problematic for neutrino physics and/or high energy forward muon physics. Finally using a different digitizer technology would allow us to run at higher rates without deadtime if needed (but we think this would not be necessary).

Question 17: FASER expects to get luminosity information from ATLAS, and timing signals from the accelerator. How/where will the timing signals be provided to FASER? Where will TDAQ live? What sort of access is required for readout electronics? Is the cost of these elements included in the cost estimates?

Timing signals from the LHC would come as to other experiments from the TTC system (possibly from the LHC beam instrumentation infrastructure). Luminosity from ATLAS could come over the DIP protocol (the luminosity signals shown on LHC page-1), although these signals are not needed in realtime, and could also come through the offline Massifiles. The current thought is that the DAQ would be housed in the TI18 tunnel close to the detector. First estimates suggest this will be OK from radiation point of view for off the shelf electronics.

To go to TI18 requires no beam in the LHC and a Radiation Protection survey (need \(\sim 2 - 3\) hours with no beam). FASER should not need to cause any LHC downtime (except for safety issues) - we should only parasitically use existing LHC accesses. The system should be made such that all electronics in the tunnel can be power-cycled/re-booted from the surface to allow the detector to run. We have included preliminary cost estimates of DAQ in the experiment costs.

4. General Issues

Question 18: Please present a notional schedule through LS2. Please include civil engineering work in TI18 in this schedule.

Our current schedule foresees the construction of the magnets, and the civil engineering work in TI18 being completed in 2019, as well as progress in the design, construction and stand-alone commissioning of the different detector components. 2020 would see commissioning of the detectors (and possibly a combined test-beam (without magnet)), and then installation of the detector, and in situ commissioning.

Question 19: Please map out in detail the schedule for activities for the balance of CY 2018.
The main goal of 2018 is to secure funding and approval and to build the collaboration to be able to construct/install and commission the detector in LS2, as well as finalizing the detector design details. We are progressing on a number of fronts, with many discussions ongoing to pin down the details of the detector design and to enlarge the collaboration. Specific items that we will work on in the remaining time in 2018 include: starting quality assurance for the spare SCT modules; finalizing the readout strategy for the SCT modules; and making improved in situ measurements (we plan to install further emulsion and radiation monitoring devices in LHC Technical Stop 2 in mid-September). We aim for a technical proposal to be submitted to the LHCC by early-November. The funding (if approved) would become available at the start of 2019.

**Question 20:** The cost is estimated to be $1 - 1.5M$ CHF. Please provide details for this estimate. Please include assumptions made about what will be provided by CERN, what will be provided by the Foundation, and what might come from other sources.

The first draft costing was presented to the LHCC in September, a more detailed costing will come for the Technical Proposal. The assumptions about what will be provided by CERN are as follows:

- Civil engineering to dig 50 cm from the TI18 tunnel in the FASER location
- The design and construction of the FASER magnets. Here we would pay for this from external sources, but the work would be done by the CERN warm magnet group. Informal discussion with that group suggest this could be done within one year, and cost $\sim 350k$ CHF (for the LOI design; it would be cheaper for designs with shorter magnets).
- Some items related to detector installation (e.g. transport of the components), and integration (power, readout etc.) will also require CERN effort, although this is expected to be relatively small.
- We may require some small input from the CERN EP-DT group for help purchasing / setting-up certain components (chiller, scintillator, PMTs)
- We expect the scintillator light-guides to be constructed at CERN (paid for by FASER), which is a small amount of work, already informally discussed with the relevant experts.

**Question 21:** Please provide details of expected time commitments by the proponents. What commitments of effort are there by the proponents to existing experiments. In particular, what are peoples commitments to Phase I and Phase II upgrades.

None of the current experimentalists in the collaboration have commitments for Phase I upgrades, and only one has a small (0.1 FTE) commitment to Phase II (ITk pixel readout). Some do have small commitments in ATLAS. Brian Petersen will be the LHC Programme Coordinator from 2019-2021, although the workload for this should be much reduced during LS2. Assuming LHCC/CERN approval and funding being granted, we would expect that all current members of the experiments would spend a significant part of their research time on FASER. We would also need to enlarge the collaboration and are actively working on that at the moment.

**Question 22:** Report on the status of discussions and commitments/agreements with ATLAS and LHCb regarding the spare hardware requests. Will transfer of these spares to
FIG. 21. Left: The geometry and coordinate definition of emulsion measurement. The $z$-axis was chosen to be almost the same as the line of sight. Right: The measured angular distribution in the emulsion detector. There are two clear angular peaks, corresponding to the tracks from the ATLAS IP and the LHC beamline at the bottom of the TI18 tunnel (Q 12).

**FASER be a loan; or will they require in-kind contributions; or will they be provided strings-free?**

Approval to use SCT modules will be discussed at the SCT institute board meeting in late September. Informal discussions with the SCT project leader are very positive and from these, it seems likely that this request will be granted. For the LHCb ECAL modules, discussions with the project leader were also very positive, and it seems likely that this request will be granted. From the discussions so far, we believe these will be provided with no strings attached.

**Question 23:** Please update the experiment diagram. Please identify on the diagram all components.

Figure 21 shows a version identifying the different components.

**Question 24:** Have facilities been identified on the surface for preparation of the detector? Is preassembly of the detector on the surface part of the plan?

We have not yet identified facilities on the surface for this. We need to demonstrate some level of LHCC pre-approval before beginning detailed discussion with CERN teams about
this. We would imagine pre-assembling the tracking stations and the calorimeter on the surface.

**Question 25:** Discussions have been held with many service organizations. These seem to have been 1:1 discussions with the proponents. Has there been a face-to-face sit-down with all relevant parties in the same room to hash out potential interferences, and come to general consensus on how the execution of FASER construction/installation could be supported?

There have been a few dedicated meetings with accelerator/technical experts as part of the physics beyond colliders accelerator track (including with civil engineering, survey, radiation monitoring, FLUKA team etc...). There have also been discussions in the TREX (tunnel region experiments LHC group) about FASER, which included the transport and integration teams.

Further discussions are certainly needed, but await pre-approval from LHCC. The LS2 planning committee would be the place for the final discussions with all relevant stakeholders represented.

**Question 26:** What is ATLAS reaction to FASER installations need for access to TI18 through the ATLAS experimental hall during LS2? Can ATLAS planned work program accommodate FASER installation?

We have not had formal discussion with ATLAS Technical Coordination (Ludovico Pontecorvo) about this. ATLAS management and TC have been informed about FASER and were sent the draft LOI and have given positive reactions. Access to FASER would use the LHC access point at IP1, rather than the access point used for ATLAS, so we believe there will not be a problem.

**Question 27:** It would be interesting to consider the options, opportunities, pros and cons, of a closer integration of FASER and ATLAS data (triggers, offline analysis, ...). The text says that this is not expected to happen: is it obvious that it is not worth considering the possibility?

Since the signal we look for in FASER is produced in the decay of SM particles (pions and other light mesons), which are copiously produced in each bunch crossing in IP1, we can’t see any reason why combining data with ATLAS would be useful.

**Question 28:** How much do your rate estimates (signal and background) depend on (nominal) LHC beam settings? For example, if the LHC would have to go to the 8b4e scheme again, would that make any difference for you?

Generally the beam settings wont make any practical difference to FASER. The signal and background rates will be proportional to instantaneous luminosity, but since the rates are generally low, they will not be influenced by changes in the bunch structure such as 8b4e versus 25 ns bunch trains. The only setting that we are really sensitive to is the crossing angle which shifts the line-of-sight in FASER by ~ 7 cm. The exact crossing angle that will be used in IP1 in Run-3 has not been decided upon yet. There are two options for the LHC optics in Run-3 so-called round beams (with equal $\beta^*$ in the horizontal and vertical planes), or flat-beams (with different $\beta^*$ in the two planes, allowing to reduce the luminosity loss from the crossing angle). For round beams the IP1 crossing plane will be vertical and the sign of the crossing angle will be changed every year (so the LOS will...
move by $\sim 14$ cm between years), whereas for flat beams the IP1 crossing angle would be horizontal and the sign will not change. The magnitude of the crossing angle would be similar in both cases, and the angle will be reduced during each physics fill, but this is a small effect and should not affect FASER. The current idea for FASER is to position the detector on the nominal LOS (assuming no crossing angle), and then live with the loss of signal acceptance due to the crossing angle, which is estimated to be about 25%, and has a very small impact on the expected physics sensitivity.


https://cds.cern.ch/record/1091485.

[37] **ATLAS** Collaboration, T. Vickey, “A read-out driver for silicon detectors in ATLAS,” in 


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