# FASER-2: detector design and performance

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#### Abstract

FASER-2 is a proposed upgrade to the FASER experiment, and could be hosted in the proposed Forward Physics Facility (FPF) located 620m to the west of the ATLAS interaction point, in the far-forward region of the LHC collisions. The experiment is designed to have sensitivity to long-lived particles (LLPs) produced by rare meson decays that are candidates for light dark matter. The proposed upgrade involves a significantly enlarged volume compared to FASER, resulting in an increase in reach for various BSM signals of several orders of magnitude and allows sensitivity to models that were previously out of reach, such as Dark Higgs and Heavy Neutral Leptons. This document will present different possible designs and technologies for the FASER-2 detector and compare their perfomances for momentum resolution, physics reach and geometrical acceptance to optimise the FASER-2 detector both in cost and physics performance.

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# 1 Introduction

Since the discovery of the Higgs boson, much research has focused on searching for physics beyond the Standard Model to explain phenomena such as the nature of dark matter. Large detectors at the LHC are well instrumented at large angles relative to the beamline but have a blind spot for particles produced approximetely parallel to the beamline, making the previously unexplored far-forward direction an attractive option for new physics searches. Experiments in this far-forward direction may detect long-lived particles (LLP) [1] characteristic of very weakly interacting particles produced by rare meson decay that are possible candidate for light dark matter. As proof of principle the FASER [2], ForwArd Search ExpeRiment, detector has been proposed and installed to study collisions at 480 m from the ATLAS interaction point and has been taking data during Run-3 of the LHC.

The Forward Physics Facility (FPF) [3] [4] is a proposal to construct a dedicated 65 m long cavern facility to house a suite of far-forward experiments during the High-Luminosity LHC era approximately 620 m west of the ATLAS Interaction Point. The location of the FPF provides a low background environment thanks to the shield of concrete and rock which is crucial for weakly interacting particles and rare processes to be observed. The FPF is expected to host a suite of complementary detectors.

- 1. FASER2 is a magnetic tracking spectrometer created to search for light and weaklyinteracting particles, such as new force carriers, sterile neutrinos, axion-like particles, and particles from the dark sector.
- 2. FASER $\nu 2$  is an on-axis emulsion detector with a pseudorapidity range of  $\eta > 8.4$ . It will detect neutrinos at TeV energies with exceptional spatial resolution and is expected to capture thousands of tau neutrinos, which are among the least understood known particles.
- 3. FORMOSA is a detector crafted from scintillating bars and boasts world-leading sensitivity to millicharged particles over a wide range of masses.
- 4. FLArE is a liquid argon fine-grained time projection chamber with a scale of 10 tons, aimed at detecting neutrinos and searching for light dark matter. It offers high kinematic resolution and a broad dynamic range.

FASER-2 [4] is a proposed experiment for the FPF featuring a volume approximately 800 times greater than that of FASER. It increases the angular acceptance of long-lived products from neutral pions and B-meson and improves sensitivity for larger LLP masses that results in an improvement in the reach by a factor of four orders of magnitude. LLPs are predicted to be produced in rare decays of heavy mesons, and their charged decay products efficiently detected by the magnetic spectrometer and tracker that is FASER-2. The ability to reconstruct the mass of these decay products will also be invaluable in the observation of a signal. The dark photon and dark Higgs models serve as benchmarks for LLPs in FASER-2 detector design studies.

In addition, the FASER2 magnet and tracking stations will act as a spectrometer for the FPF neutrino detectors, FLArE and FASER $\nu$ 2. The neutrino physics programme of the FPF is one of its major strengths, where it will study neutrino interactions at TeV energy, with sensitivity to parton density functions PDFs, forward hadron production and BSM physics in the neutrino sector. The main requirements on this spectrometer is the accurate measurement of muon (and possibly electron) momentum and charge. This note documents the performance of various possible designs to explore the performance of various options in terms of detector technologies and cost for a set of benchmark performance metrics. These metrics will include muon momentum, charge and mass resolution, and the efficiency to separate charged particles.

# 2 Physics motivation and benchmarks

The following section outlines in more detail some of the physics goals of the FASER2 and it's contribution to the wider FPF physics programme and the design requirements these imply.

### 2.1 Long-lived particle search

For many BSM models the sensitivity is directly related to the size of the decay volume. This strongly motivates the case for an enlarged detector, FASER2, which was already explored in the FASER Letter of Intent [5], Technical Proposal [6], and Physics Reach [1] documents.

In previous studies the nominal FASER2 design is comprised of a decay volume 5m in length and 2m in diameter. This results in an angular acceptance of neutral pions that increases from 0.6% in FASER to 10% in FASER2. The larger decay volume also improves sensitivity to larger LLP masses and longer LLP lifetimes. The combined effect of all these factors is an improvement in reach of 4 orders of magnitude for some models as shown in Figure 1 (left) from [1]. In addition, there is a significant improvement in sensitivities to LLPs produced in decays of heavy mesons, due to the additional acceptance to B-meson production, as shown in Figure 1 (right)



Figure 1: Sensitivity plots for the Dark Photon (left) and the Dark Higgs (right) for the FASER-2 baseline design compared with other proposed detector such as Mathusla [7]

The larger size and sensivity to higher mass ranges offers the potential to have sensitivity in additional production and decay modes as shown in Figure 2.



Figure 2: Sensitivity plots for the Dark Photon (left) and the Dark Higgs (right) splitting the sensitivity by production mode (top) and decay mode (middle). The bottom row shows the branching fractions for each model as a function of the dark sector particles mass.

### 2.2 Inelastic DM

There are also well-motivated DM scenarios featuring a rich dark sector structure that can be probed only at the FPF. This is nicely illustrated in Fig. 3, which shows the expected sensitivity of FASER2 to two realisations of inelastic DM (iDM). This model contains an excited dark sector state that decays into a somewhat lighter DM particle plus a visible final state. The left panel considers a relatively heavy iDM scenario with masses in the tens of GeV range [8]. Such states are beyond the kinematic threshold of beam dump experiments, but the high energies available at the LHC imply significant production rates, and the sensitivity of the FPF to highly-displaced decays allows it to uniquely explore new regions of parameter space beyond the reach of the existing large LHC detectors. The right panel considers a case with a very small mass splitting between the excited state and the DM. Due to the large particle energies in the forward direction of the LHC, sufficiently energetic signals can be observed the FPF, while a corresponding signal at beam dump experiments would be below the threshold of detectability. In both scenarios FASER2 will be able to decisively test a broad swath of parameter space where DM is produced in the early universe through thermal freeze-out.



Figure 3: Inelastic dark matter searches at the FPF. The discovery potential of FASER2 and other experiments for inelastic DM. Left: For heavy inelastic DM, the high energy of the LHC allows FASER2 to probe masses up to tens of GeV [8]. Right: For light inelastic DM with very small mass splittings, the large LHC energy boosts the signal to observable energies [9]. In both scenarios, the reach of FASER2 extends beyond all other experiments, including direct and indirect DM searches, LHC experiments, and beam dump experiments, such as SHiP. The cosmologically-favored parameter space corresponding to the thermal relic target shown as solid black lines.

# 2.3 Quirks

Quirks (Q) are new particles that are charged under both the SM and an additional strongly-interacting gauge force. After they are produced at a collider,  $Q\overline{Q}$  pairs then travel together down the beamline, bound together by a hidden color string. Discovery prospects for quirks are shown in the right panel of Fig. 4. For hidden confinement scales  $\Lambda \gtrsim 100$  eV, current bounds do not exclude quirk masses of even 100 GeV., FASER2 should probe masses up to 1 TeV, a range motivated by neutral naturalness solutions to the gauge hierarchy problem [10]. Such heavy quirks cannot be produced in fixed-target experiments and demonstrate another unique search capability of forward detectors at the LHC.



Figure 4: The discovery reach of FASER and FASER2 for color-neutral quirks [10]. In both panels, we also show existing bounds (gray shaded regions) and projected sensitivities of other experiments (dashed contours)

# 2.4 FASER-2 spectrometer for neutrino physics

Several of the neutrino measurements at the FPF rely on measuring the energy spectrum of the neutrinos and separating neutrinos and anti-neutrinos, this imposes a need to measure precisely the momentum and charge of muons produced in the neutrino interactions. Projections for the FPF sensitivity to neutrino energy spectrum measurements including statistical and systematic uncertainties are estimated in Ref. [11] and shown in Figure 5.



Figure 5: Statistical and systematic uncertainties on neutrino cross section measurements (from Ref. [11].

# 2.5 Goal and requirement for the detector

Physics process	Models	Detector requirement	
Search	Dark Photon $e^+e^-, \mu^+\mu^-$ , hadrons	<ul><li>Tracker resolution</li><li>Muon detector</li></ul>	
	Dark Higgs $e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-$ hadrons	<ul><li>Magnet strength</li><li>Momentum resolution</li><li>Good vertex resolution</li><li>PID</li></ul>	
	ALPs Decay: $\gamma\gamma$	<ul><li>Photon ID and separation</li><li>Calorimeter resolution</li></ul>	
	Inelastic DM	<ul> <li>Low energy γ reconstruction</li> <li>Calorimeter resolution</li> </ul>	
	Quirks	• Timing resolution	
Neutrino physics	$ u_e,  u_\mu,  u_ au$	<ul><li>Detector acceptance</li><li>Good charge identification</li><li>Momentum resolution</li></ul>	

Table 1: Table of benchmark physics processes used to optimise FASER-2 detector performances

# 3 FASER-2 detector concept

The FASER2 design requirements that must be defined with highest priority are the needs of the spectrometer, both in terms of the magnetic field strength and the tracker resolution. In the following sections there will be analysis of different spectrometer designs to see the impact on

#### 3.1 Baseline design: Samurai-like magnet

The baseline option involves a superconducting dipole magnet modelled after the SAMURAI spectrometer [12]. This magnet features a large rectangular aperture measuring  $3 \text{ m} \times 1 \text{ m}$  and spans 4 m along the line of sight. A 1T magnetic field has been proposed, resulting in an integrated field of 4Tm. The design utilizes two horizontal, circular superconducting coils to maintain a uniform magnetic field across the pole gap. A substantial return yoke is included around the coils to enhance field uniformity and minimize stray fields. However, the magnetic field strength significantly diminishes at a distance greater than 1 m from the magnet's center. Drawing from the SAMURAI instance, studies are underway on the technical feasibility of various window sizes (such as  $1.5 \text{ m} \times 2 \text{ m}$  and  $1.7 \text{ m} \times 1.7 \text{ m}$ ) and field strengths (like 2 Tm).



Figure 6: FASER-2 detector Geant4 simulation. From left to right, it comprises a veto system, a large cuboid decay volume, followed by a spectrometer composed of a large 1T magnet [12] with 3 tracking stations based on LHCb's SciFi detector [13] each upstream and dowstream, electromagentic and hadronic dual-readout calorimeters [14], an iron wall, and a muon detector.

## 3.2 Alternative design: Industrial magnet

An alternative magnet option has been suggested to decrease both the design cost and procurement time of the reference setup by using a off-the-shell option. Notably, TOSHIBA manufactures wide-aperture dipole magnets meant for producing Silicon singlecrystals [15]. Magnetic fields are often utilized in drawing out growing mono-crystalline wafers to enhance crystallization uniformity. The alternative idea involves repurposing these crystal-pulling magnets as the FASER2 spectrometer. These cylindrical superconducting magnets come in various diameters based on the Si wafer size. The largest available off-the-shelf option has a diameter of 1.6 m, with the possibility of further increase upon request. This setup proposes using three or more magnets with a 1.6 m and length of 1.25 m, each rotated by 90° to align with incoming particles.



Figure 7: FASER-2 alternative design from Geant4 simulation. The magnet technology is expected to be based on modules of Toshiba Silicon Crystal pulling magnets [15]. Each module has a diameter of 1.6m and magnetic field strength 0.7 Tm. Options between 2 (1.25 Tm) and 4 modules (2.5 Tm) are under study

# 3.3 FASER-2 designs scenarios

Scenarios	Tracker	Magnet	Aperture Dimension	Field Integral	Cost
Baseline	SciFi tracker	Samurai-style	Rectangular: 3m x 1m	4 Tm	
Samurai reduced	SciFi tracker	Samurai-style	Rectangular: 3m x 1m	2 Tm	
			Rectangular: 2.6m x 1m	2 Tm	
			Rectangular: 2m x 1.5m	2 Tm	
				1.25  Tm (2  modules)	
Industrial style	SciFi trackers	Silicon crystal pulling	Circular: 1.6m (2m) $\Phi$ X 1.25m	1.9  Tm (3  modules)	
				2.5  Tm (4  modules)	
Better tracking	SciFi + Pixel Mighty tracker	Samurai-style	Rectangular: 3m x 1m	4 Tm	
Gaseous tracker	Gaseous tracker (MM, GEM)	Samurai-style	Rectangular: 3m x 1m	4 Tm	

Table 2: FASER-2 scenarios considered driven by the magnet SAMURAI-style magnet and Industrial silicon crystal pulling magnet. Different field strength are under study. Alternative for the SciFi tracker technology are also under studies: addition to the first layers of SciFi trackers some modules Mighty pixel [16], Gaseous trackers candidates are also considered

# 4 Simulation tools

Different simulation tools have been utilised for the studies in this note. The FORE-SEE [17] tool is used for the simulation and generation of event data for LLP production from forward hadrons. The Geant4 [18] simulation framework is used for the propagation of particles through a magnetic field in the LLP decay product separation studies. The ACTS [19] tool is used for track reconstruction studies.

## 4.1 FORESEE

FORward Experiment SEnsitivity Estimator [17], or FORESEE, is used to obtain the expected sensitivity reach for BSM models in various far-forward experiments. The package allows one to perform quick but accurate simulations for selected popular BSM simplified models. This can be done for user-defined experimental geometries and basic cuts applied to the visible signal. The package also provides a set of useful numerical data, including e.g. the far-forward spectra of light mesons, that can easily be accessed and employed in separate studies estimating the new physics sensitivity reach in other BSM scenarios. We illustrate below the capabilities of FORESEE for the popular dark photon and dark Higgs boson models, as well as for the model with a hadrophilic dark scalar with the dominant couplings to the up quarks.

# 4.2 Geant4 simulation

Simple detector geometry with sensitive detectors and magnetic fields are implemented in Geant4 [20] for various design option of FASER2. It has been implemented with the FASER2 Geant4 package https://github.com/joshmcfayden/FASER2\_G4/tree/main

# 4.3 ACTS simulation

## 4.3.1 ACTS: A Common Tracking Software

ACTS (A Common Tracking Software) [19] is a modern, experiment-independent toolkit specifically designed for charged particle track reconstruction in high-energy physics experiments. Implemented in contemporary C++, it offers the flexibility of being experiment-independent, meaning that it can be used by different experiments to implement their own track reconstruction algorithms. The goal of ACTS is to provide a common framework for the reconstruction of tracks.

The ACTS (A Common Tracking Software) toolkit facilitates a comprehensive reconstruction process that spans from simulation to track reconstruction. This process is divided into distinct phases, namely, event generation, event simulation, digitization, track finding and fitting, and vertex reconstruction.

## 4.3.2 FASER-2 implementation of ACTS

The integration of the ACTS (A Common Tracking Software) toolkit for FASER2 followed a series of structured steps that represented as a diagram in Fig.8:

- 1. FASER2 Geometry in ACTS: A preliminary effort to convert the Geant4 description of the detector (shown in Fig.[18]), into an ACTS-compatible surface-based geometry was unsuccessful due to inherent bias in the software toward transverse production of particle in cylindrical geometrical configurations. To overcome this challenge, FASER2 geometry was directly incorporated as ACTS geometry. The tracking stations were modeled as rectangular surfaces with homogeneous materials that corresponded to the density and radiation length of the SciFi tracker material. The detector resolution of 100 μm was incorporated into the digitization process that ultimately smears the hits.
- 2. Magnetic Field: For this simulation, the magnetic field within the  $3 \times 4 \times 1$  m bore with a dimension similar to the SAMURAI detector is approximated as constant. This magnetic field inside a restricted volume was integrated into the ACTS toolkit during this project to match FASER2's magnetic field requirements.
- 3. LLP Event generator: HepMC files were created with the FORESEE package, containing information on long-lived particle (LLP) decays into charged leptons and hadrons, served as the event generator for the ACTS simulation process. These files

were converted for compatibility with ACTS' simulation algorithm. A straightforward event generator for electrons and muons with FASER2-specific kinematics was also used to calibrate the detector design, providing BSM model-independent results.

4. Track reconstruction issue and solution: Despite accounting for all necessary input parameters, the track reconstruction process encountered issues. This is primarily due to the application of the Kalman Filter algorithm in the forward direction, where polar angles  $\theta$  close to 0 lead to numerical uncertainties with respect to ACTS' track parameters. This numerical instability arises from the fact that small  $\theta$  values render the azimuthal angle  $\phi$  ambiguous, resulting in a singularity for the derivatives.

The pragmatic solution employed was to rotate the global coordinate system, positioning the beamline along the X-axis instead of the Z-axis. This 90 rotation around the Y axis such that  $Z \rightarrow X$ , was applied to the FASER2 geometry, magnetic field, and event generator kinematics. This rectifies the issue as the value of  $\theta$  no longer leads to a singularity and the modified detector orientation aligns more closely with collider detectors such as ATLAS which is a favored scenario for ACTS track reconstruction algorithm. However, it is important to note that this rotation is required solely for the reconstruction process and maintains internal consistency. For the remainder of this discourse, references to geometry and axes will be made as though no rotation has been implemented.



Figure 8: Implementation process of FASER-2 with the ACTS toolkit

Summary of hypothesis used in the simulation:

- Constant magnetic field
- No background in the simulation
- Tracking station simulated as homogeneous materials with accurate X0 and digitized resolution
- Track finding algorithm use truth finding information

# 5 LLP sensitivity

## 5.1 Decay volume

We start with sensitivity studies based solely on the acceptance of LLP decay products in the decay volume of FASER2. This determines the number of signal events expected as a function of mass and coupling assuming a 100% efficient detector.

The dependence of sensitivity on the size and shape of the decay volume has first been explored in a general way. Figure 9 shows the affect on the sensitivity to Dark Photon and Dark Higgs models of different decay volumes compared to the very first FASER2 design. As expected we observe that the number of events reaching the FASER2 decay volume depends broadly on the mass of the LLP which defines the cross section, and the coupling which determines the lifetime and therefore the likelihood of a decay in the Decay Volume.



Figure 9: Sensitivity of the Dark Photon (left) and the Dark Higgs (right) models to various FASER2 decay volume shapes and sizes (described in the text). The compared designs are: in green a cylindrical decay volume of 10m in length and diameters of 1.5 and 2.0 m; in orange a rectangular aperture with width of 2.0 m and height of 0.5 and 1.0m; in purple a rectangular aperture with width of 3.0 m and height of 0.5 and 1.0 m; and in blue a rectangular aperture with width of 4.0 m and height of 0.5 and 1.0 m

The sensitivity is studied for a more refined specific set of detector layouts based on those described in Table 2. The results are shown in Figure 10 for the originally proposed FASER2 dectector (red), and configurations assuming the SAMURAI magnet (green) and Industrial Silicon magnets (blue).



Figure 10: Sensitivity of the Dark Photon (left) and the Dark Higgs (right) models to the latest FASER2 design scenarios.

## 5.2 LLP decay product separation

The golden signature of a LLP in FASER2 is the appearance of the decay products of that particle in the decay volume. Different models have different branching fractions, but as can be seen in Figure 2(bottom) the for large ranges of phase space of the Dark Photon and Dark Higgs models the decay is to a pair of oppositely charged particles. Therefore, a crucial detector signature for the appearance of a LLP is two tracks with opposite charge that can be separated with sufficient detector resolution.

To study the separation of these charged particles at different points in the detector the FASER2\_GenSim tool is used to take HepMC events from FORESEE that contain four-vectors of the LLP decay products and propagate them through a magnetic field and detect their position at various transverse planes along the beam (z)axis, corresponding to tracker stations. Then the positions are used to calculate the separation of these decay products at the different tracking stations. This allows to understand what tracker resolution is required to resolve the two tracks and what the dependence of a given resolution on the efficiency to separate the two tracks is as a function of the Dark Photon and Dark Higgs parameter space.

Figure 11 shows these particle separations for three tracking stations at different z-axis positions across a range of Dark Photon mass and coupling values.



Figure 11: Dark Photon decay product (electron-positron) separations for different mass and coupling points Each figure shows Station 1, 2, 3, 4, 5 which correspond to z-axis positions of X, Y and Z respectively. Station 1 (positioned at 10m in z-axis) is representative of the first tracking station at the beginning of the upstream tracker, Station 2 (positioned at 11m in z-axis) is the last tracking station just before the magnet, Station 3 (positioned at 15.5m in z-axis) is placed just after the magnet, Station 4 (positioned at 19.5m in z-axis) is representative of the first tracking station in the downstream tracker and Station 5 (positioned at 20.5m in z-axis) is representative of the last tracking station and/or the front of the calorimeter..

Once the particle separations are in hand one can apply cuts requiring the separation to be above a given separation value, simulating the requirement of two resolved particle hits of a tracker of that resolution, and then determine the efficiency of that separation requirement. Figure 12 shows the efficiency for separation requirements of 0.01, 0.05, 0.1, 1, 10 and 100 mm across the Dark Photon mass and coupling plane.



Figure 12: Dark Photon decay product efficiencies for different separation requirements at the first tracking station.

Given the extracted efficiency values for a given particle separation cut across the mass-coupling plane it's then possible to apply those efficiencies to the expected number of LLP decays in the Decay Volume already estimated by FORESEE to see the effect on the expected sensitivity. This is shown in Figure 13 for the Dark Photon parameter space, for Station 1 (left) and Station 3 (right) for the separation requirements described above.



Figure 13: Dark Photon sensitivity for different decay product separation requirements for the 1st tracking station (left) and final, fifth tracking station (right).

# 6 Neutrino acceptance

## 6.1 Muon acceptance from FLArE into FASER-2: Geant4

Study made by Matteo Vicenzi and Wenjie Wu from BNL FLArE collaboration (more details)

### 6.1.1 FPF options

Geant4 simulation of the FPF cavern and the detectors. Many options for the placement of the FPF detectors are under study with the goal of reducing the distance between FASER-2 and FLArE to improve the muon acceptance



Figure 14: Simulation of the different configurations for the FPF detectors resulting in reduced distances between FLArE and FASER-2:

Options 0 (baseline): 36 m, Option 1: 30m, Option 2: 20m, Option 2 squeezed: 17m

#### 6.1.2 Muon acceptance

The acceptance to muons from neutrino interactions for different sizes and shapes of FASER2 are studied using a sample of muons from FLUKA. Investigation of muon acceptance originating from FLArE reaching FASER-2 in the context of the dual magnet option (SAMURAI, Industrial Crystal Pulling) involves a Geant4 simulation. This simulation tracks the journey of muons resulting from 100 000  $\nu_{\mu}$  charged current interactions within the FLArE fiducial volume measuring 1m x 1m x 7m.

Fig. 15 provides an overview of muon acceptance, depicting it against the distance separating the magnet(s) from FLArE. Different markers signify various magnet choices, with individual plotting for each magnet in the crystal-pulling strategy. This can also be seen as representing varying magnet count requirements, as mentioned earlier. The color coding indicates various configurations: reference (blue), option 1a/1b (orange), and option 2 (green).



Figure 15: Muon acceptance into the FASER2 magnet(s) as a function of the distance between the magnet(s) and the center of FLARE 14. The colors represent different configurations: reference (blue), option 1a/1b (orange), option 2 (green). The different markers indicate the different magnet options.

Considering acceptance, both the  $2 \text{ m} \times 1.5 \text{ m}$  SAMURAI-like magnet and the crystalpulling method yield similar outcomes. Consequently, the anticipated acceptance range lies between 45% - 55%, contingent on the ultimate magnet configuration.

# 7 Tracking performance

The ability to accurately measure the position and momentum of a particle is essential when assessing the performance of track reconstruction. The following section will compare the performance in momentum resolution and on the invariant mass reconstruction of Long-Lived particles of different detector geometries

# 7.1 Trackers design

### 7.1.1 Tracker resolution

To obtain the required tracking performance, FASER2 aims to use a detector technology similar to the SciFi tracker with a resolution of 100  $\mu$ m. Discussions are on-going to choose the number of tracking layers needed between 6 and 12 layers.



Figure 16: Momentum resolution plots to compare the track reconstruction performance of trackers with detector resolution from 1  $\mu$ m to 250  $\mu$ m (left), and the performance of a FASER2 layout with 6 trackers compared to 12 (right)

Figure [16] displays the momentum resolution for individual tracker planes resolutions of 250  $\mu$ m, 100  $\mu$ m, and 10  $\mu$ m. Though the simulated tracker with resolution of 10  $\mu$ m slightly outperforms the others, all resolutions under study maintain momentum resolution below 5% across the momentum spectrum, which gives ample tracking performance. This indicates that the examination of trackers with marginally reduced resolution without substantial performance degradation which might be more cost effective. Nevertheless, the choice of tracker spatial resolution also considers the need for separating charged particles before they enter the magnetic field, which will be discussed in Section 5.2. The performance of the tracker with a resolution of 1  $\mu$ m shows that to obtain significant improvements, particularly at high momentum, necessitate a detector resolution below 10  $\mu$ m, with that very high resolution, detector are likely to be prohibitively expensive .

The second figure in Fig. [16] a direct comparison of the momentum resolutions of 6 and 12 tracking station configurations. Although the 12 station layout slightly outperforms the 6 station setup due to increased trajectory measurements, it also significantly increases costs. Given the current state of the tracking simulation, a 12 station configuration may not present a cost-effective option. However, it is important to remember that these simulations use truth information to track findings and an increase in the number of tracking stations could increase the accuracy of the track finding algorithm when more realistic seeding is performed.

#### 7.1.2 Tracker material budget

The plot in Fig.[17] explores the invariant mass resolution under three different material budgets characterized by the fraction of the radiation length  $(X_0)$  per modules. As the material budget increases, two key changes are apparent: the invariant mass resolution mean shifts and a broadening of the peak. As the material budget increases, two key changes are apparent: the invariant mass resolution mean shifts and a broadening of the peak. These changes can be attributed to two principal material effects: energy loss and multiple scattering. With more material present the particle is more likely to lose energy resulting in a shift of the invariant mass but also deviate more from the initial trajectory due to more scattering which would lead to a more diffuse distribution.



Figure 17: Effect of different radiation length X0 per layers of tracker on the momentum resolution (left) and the invariant mass for the Dark Higgs models (right).

## 7.2 Magnet design comparison

Being FASER2's costliest and largest component for track reconstruction. The design of the magnet requires careful optimization, particularly regarding its magnetic field strength and shape, as it is important both for physics sensitivity and the overall optimization of the FPF experiments.

#### 7.2.1 Samurai style magnet

The option of reference for FASER2's spectrometer is a superconducting dipole magnet inspired by the SAMURAI magnet [12]. As a baseline a 1 T field is being proposed, for an integrated field of 4 Tm. An alternative option with a lower integrated field of 2 Tm is also being studied.



Figure 18: Comparison between the different FASER-2 scenarios: baseline Samurai like magnet 4 Tm [Fig.6] and reduced Samurai-like magnet 2 Tm [Table.2]. Invariante mass Dark Higgs models (left) and momentum plot resolution (right)

The plots in Fig. [18] compare both momentum resolution and the mass resolution of the SAMURAI style magnet with two different values of integrated field strength: a reduced 2 Tm and the baseline 4 Tm. While the stronger 4 Tm field improves momentum resolution by a factor of two at low momentum, the 2 Tm field option still offers ample performance for FASER2's physics research across the momentum range.

#### 7.2.2 Industrial Silicon Crystal pulling magnets

The Crystall Puller has been described in section 3.2, we studied and compared the momentum resolution and mass resolution for the different sets of Crystal pulling magnet modules and compares to the Samurai style magnet in fig. 19



Figure 19: Comparison between the different FASER-2 scenarios: baseline Samurai like magnet [Fig.6] and Industrial Silicon Crystal pulling magnet [Fig.7] for 2 (1.25 Tm), 3 (1.9 Tm), 4 (2.5 Tm) modules. Invariant mass Dark Higgs models (left) and momentum plot resolution (right)

We can infer that, although there is a decrease in momentum reconstruction capabilities and reduced mass resolution, the Crystall puller magnet, consisting of at least three modules, still provides sufficient performance to be regarded as a feasible choice.

### 7.3 Vertex resolution

In our simulation, the vertex positions of the LLP are uniformly distributed within the FASER2 cuboid  $1 \times 3 \times 10$  m decay volume. The ability to precisely point back the vertex of the particle to this decay volume reduces the risk of misidentification of decay products from other event of misattributing decay products to other events. This accuracy is also useful to distinguish charged particle coming from LLP decay, from those originating neutrino decays in the upstream experiments of the FPF or the muon background. The vertex position resolution plot in Fig.[20] shows a pronounced peak centered around a near perfect reconstruction of the vertex position and with a standard deviation of 3.5 cm, showing that the vertex position can be reconstructed with a precision within a few cm.



Figure 20: Distribution of the error on the reconstructed vertex position (cm), determined for 120 000 events Dark Higgs  $\rightarrow \mu^+\mu^-$  m= 0.81 GeV simulated in FORESEE. The vertex of LLP is within cuboid decay volume  $1 \times 3 \times 10$  m.

### 7.4 LLP models and masses

In figure 21 we show the momentum resolution we observe that the momentum resolution performances are very similar across the momentum range for both LLP models (dark Higgs and dark photon) as well as two different decay channel for LLP (e and  $\mu$ ). This result means that the choice of the LLP model and the decay channel does not have significant impact on the track reconstruction performance. The equivalent performance for the electron and muon channels can be credited to the tracker's low material budget, given that electrons are more likely to interact with the material. Thus, for the following studies the model use for simulation is the dark Higgs decays into muons.



Figure 21: Momentum resolution plots to compare the track reconstruction performance of FASER-2 comparing Dark Higgs and Dark Photon LLP model (left), compare the Dark higgs at differences masses values (right)

# 8 Alignment studies

### 8.1 Effect of misalignment on track reconstruction

The alignment of the trackers is expected to have a major impact on the tracking performance. In order to study the effect of the misalignment of the trackers. In these studies, an initially aligned geometry of the tracking stations is intentionally misaligned. This process is achieved by introducing a translation to each tracking station in the implementation of the FASER2 geometry described in this section. The translations follows a Gaussian distribution centered around zero, with standard deviations representing different misalignment values.

Due to the inherently random nature of the misalignment process, it inevitably influences track reconstruction results. To mitigate this randomness, a statistical averaging approach was employed. This method involved performing 15 iterations of the track fitting process for each misalignment value, thus producing results that are not significantly affected by random variations.



Figure 22: Plots with aligned detector and misaligned detector for different values of misalignment (0.25 mm, 0.75 mm, 1.0 mm) to explore effect of misalignment on the mass resolution (left) and on the momentum resolution (right)

Notably, the mechanical precision of the tracker placement for the SciFi detector, according to experts, is estimated to be around 250 µm. This suggests that the degree of misalignment encountered in practice is likely to remain within acceptable. Moreover, the presence of a muon background can be used to conduct a track-based alignment.

## 8.2 Track-Based Alignment

An investigation into track-based alignment for the FASER-2 detector has been conducted using ACTS and a similar geometry to Figure 6, with a uniform 1 T vertical magnetic field and 6 total tracking planes instead of 12. We keep the first and final three tracking planes, and move the magnet to 0.5 m from the third tracking plane with the ACTS implementation otherwise following the process outlined in Figure ??. The muon background data comes from a FLUKA simulation of the muon flux during the HL-LHC era at the FPF cavity entrance. The simulations predict the muon flux to be  $0.6 \text{ Hz/cm}^2$  on the line of sight from the ATLAS detector but can be significantly higher at locations around 1 m from the line of sight. The input data consists of 2.6 million events though only about 150,000 are expected to propagate through the entire detector.

For all detector geometries, misalignments are defined relative to the centre of the first tracking plane, which is used as a reference plane to remove the global degrees of freedom. Axes used in this description are the generic axes not ACTS axes, detector axis is Z, horizontal axis is Y and vertical axis is X.

#### 8.2.1 Misalignment Reconstruction Algorithm

We aim to reconstruct the misalignment of the tracking planes by finding the transformation parameters that best map the measured hit positions to the predicted hit positions.

The predicted hit positions come from simulating the propagation of the muon through an aligned detector using the fitted momentum parameters and first tracking plane hit position given by ACTS. We implement this in Python, neglecting material effects, and assume a straight path followed by a helical path through the magnetic field and finally a straight path. This process could be achieved using ACTS for a more accurate simulation, but was more computationally intensive and did not provide significant reconstruction benefit (predicted hit positions for an aligned detector had error -0.35  $\pm$  242  $\mu$ m using Python, and 0.11  $\pm$  242  $\mu$ m using ACTS).

The transformation of the measured hit positions is given by Equation 1 and returns the aligned coordinates; where the particle would have hit an aligned tracking plane given the measured hit position and inputted misalignment parameters. We compare  $x_{al}$ ,  $y_{al}$ , to  $x_{pred}$ ,  $y_{pred}$  for various transformation parameters, minimising the absolute difference between the two sets of values to find the misalignment parameters.

$$\begin{pmatrix} x_{al} + z_{al} \times \frac{p_x}{p_z} \\ y_{al} + z_{al} \times \frac{p_y}{p_z} \\ z_{al} \end{pmatrix} = \begin{pmatrix} \delta_x \\ \delta_y \\ \delta_z \end{pmatrix} + \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_x & -\sin \theta_x \\ 0 & \sin \theta_x & \cos \theta_x \end{pmatrix} \begin{pmatrix} \cos \theta_y & 0 & \sin \theta_y \\ 0 & 1 & 0 \\ -\sin \theta_y & 0 & \cos \theta_y \end{pmatrix} \begin{pmatrix} \cos \theta_z & -\sin \theta_z & 0 \\ \sin \theta_z & \cos \theta_z & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_{hit} \\ y_{hit} \\ 0 \end{pmatrix}$$
(1)

For fitting the parameters we use the sum of the absolute differences as we wanted a lower sensitivity to outliers. We bound the fitted parameters to within 5 times the standard deviation of the estimated misalignment. The X and Y rotations are each fitted twice, with inverted starting parameters, to avoid a local minimum since the difference between positive and negative rotations is small. An equal number of positive and negative muons were also used in the reconstruction.

Muons with momentum less than 10 GeV tended to have poor predicted hit position resolution due to the error on the momentum causing large changes in the calculated position after the magnetic field.

Figure 23 shows that using only high momentum muons produces the best results for translations along the Y axis. We repeated the test for all parameters and found Y axis translations and rotations and X axis rotations were significantly improved by the higher momentum cut so chose to use the 1.5 TeV momentum cut for fitting. For all other parameters we use the 10 GeV cut.



Figure 23: Standard deviation of Y axis translations as a function of ACTS iteration number (150,000 propagated muons per iteration) for different momentum cuts used in the reconstruction.

We found that 15 iterations of the fitting process were sufficient to reduce misalignment to acceptable levels in all cases, with one iteration consisting of simulating the incident muon background, generating predicted hit positions, fitting the misalignment parameters, and applying the results.

#### 8.2.2 Track-Based Alignment Performance

All results are shown for 15 different simulated detectors, each with tracking plane misalignment parameters drawn from normal distributions with parameters specified in the relevant section. These detectors are fitted using 15 iterations of the ACTS fitting process and all of the available input data (150,000 propagated muons per iteration). Taking  $\sigma = 250 \ \mu m$  in X and Y axis translation, these are reconstructed well (Figure 24) with the maximum misalignment being approximately 10  $\mu m$  after 15 iterations in all cases.



Figure 24: Translation reconstruction value (left) and standard deviation (right) against ACTS iteration number (150,000 propagated muons per iteration). Each line in the left figure represents a single tracking plane.

Z axis translations were poorly reconstructed, with predicted misalignments often diverging. Assuming a translation of 250  $\mu$ m along the Z axis, the difference in measured hit position would be approximately 1  $\mu$ m given  $\frac{p_x}{p_z}$ ,  $\frac{p_y}{p_z} \sim 10^{-3}$  implying a very limited effect on the momentum resolution so this is not a major concern.

For rotations we expect a reasonable worst case to be a 5 mm misalignment at the furthest point. We take the standard deviation of the rotation misalignment to be half of that angle, for X axis rotations this is  $\sigma = 1.67$  mrad, and for the Y and Z axes  $\sigma = 5$  mrad. These are simulated individually at first in Figure 25.



Figure 25: Rotation angle reconstruction against ACTS iteration number (150,000 propagated muons per iteration) for rotation about each principal axis. Each line represents a single tracking plane.

Oscillatory behaviour in the reconstruction of the X and Y axis rotation angles is present only in the tracking planes after the magnetic field and is likely due to the small effect of these rotations on the muon hit positions. For a 5 mrad rotation around the Y axis, the distance between the predicted and aligned hit positions in the worst-case is 14.0  $\mu$ m, while a 2 mrad rotation around the X axis gives distance 10.0  $\mu$ m. The equivalent number for a 5 mrad Z axis rotation is 7.91 mm. While Z axis rotations are well reconstructed, there is a group of planes remaining at 0.043 mrad misalignment. These are exclusively the second tracking plane, and result in an average 47.9  $\mu$ m misalignment in these tracking planes. This would be worth investigating in the future.

To simulate aligning a real detector, we take  $\sigma = 250 \ \mu m$  for all translations,  $\sigma = 5 \ mrad$  for Y and Z axis rotations, and  $\sigma = 1.67 \ mrad$  for X axis rotations. We fit the parameters for Z axis rotations, X axis translations, and Y axis translations only as the other transformations have much smaller effects on the measured hit position so tend to cause instability with no significant alignment benefits when included in the fitting.



Figure 26: Reconstruction of misalignment parameters against ACTS iteration number (150,000 propagated muons per iteration), lines on these graphs indicate individual tracking planes.



Figure 27: Left graph shows mean total misalignment across all tracking planes to first order in rotation angle against ACTS iteration number (150,000 propagated muons per iteration). Right graph shows evolution of the momentum resolution at different truth momentum levels across ACTS iterations.

The imperfect momentum resolution is due to the intrinsic position uncertainty of 100  $\mu$ m present in the SciFi trackers; simulating a 1  $\mu$ m position uncertainty increases the average momentum resolution to 0.60% and to 0.43% for the aligned detector. Hence, we do not see much improvement in momentum resolution from further alignment below  $\approx$  50  $\mu$ m as the tracking plane position uncertainty dominates.

All significant misalignments are corrected using this track-based alignment method, with current alignment precision  $\sim 10 \ \mu m$  obtainable. This, combined with the strong performance in increasing momentum resolution, indicates track-based alignment would be a viable tool for the FASER-2 detector.

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