Development of tracking software and detector design studies for the proposed FASER2 experiment at the Large Hadron Collider

Olivier Salin

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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 report will present the development of a tracking software for the FASER-2 experiment using the A Common Tracking Software (ACTS) toolkit to aid in track reconstruction, accurate mass and pointing reconstruction of charged particles. The developed tracking software will be used to compare various FASER-2 layouts and tracker technologies, thereby contributing to the design studies of the FASER-2 experiment.

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Contents

Abbreviations

FASER: ForwArd Search ExpeRiment

LHC: Large Hadron Collider

BSM: Beyond Standard Model

LLP: Long-Lived Particle

ACTS: A Common Tracking Softaware

X_0**:** Radiation Length

1 Introduction

Since the discovery of the Higgs boson [1], 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) [2] 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 [3], 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) [4] [5] 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 existing upgraded detectors such as FASER2, FASERnu2, and Advanced SND, as well as new experiments such as FORMOSA, which seeks to identify millicharged particles and related signals, and FLArE, a noble liquid TPC that might detect neutrinos and look for light dark matter produced by the LHC.

FASER-2 [5] is a new experiment proposed for the FPF with a significantly enlarged volume compared to FASER, which 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 by rare decays of heavy mesons, and their charged decay products would be efficiently detected by the magnetic spectrometer and tracker that is FASER-2. The proposed dark photon and dark Higgs models serve as benchmarks for LLPs in FASER-2 studies. An earlier design, consisting of three large cylindrical magnets with tracking station between each, was replaced with a single rectangular magnet design after discussion with magnet manufactures, a change which significantly reduces the magnet cost. Despite this change, the new design has comparable sensitivity to LLPs. Further studies are required to investigate the detector's performance capabilities. These studies include track reconstruction for LLP mass and pointing reconstruction.

The reconstruction of the trajectories of charged particles, called track reconstruction, is the process of recovering the properties of a charged particle tracks using the signals produced by the interactions of these particles with the detector material, the sensitive trackers. The magnetic field plays a crucial role in the tracking process: by measuring the curvature of a particle's trajectory in the magnetic field, detectors can determine the momentum of the particle.

Particle physics experiments often rely on tracking software that can depend strongly on the specific design of the detector but share common features on some algorithms. This is why A Common Tracking Software (ACTS) [6] was developed as an experiment-independent toolkit in modern C++ and Python for charged particle track reconstruction in high-energy physics experiments. The ACTS project offers high-level track reconstruction modules that can be utilized in any tracking detector. Several experiments, such as the ATLAS, ALICE experiment [7] or LDMX [8], are implementing ACTS.

The aim of this project is to develop a reliable tracking software for FASER-2 using the ACTS toolkit to facilitate accurate mass and pointing reconstruction of the detector. This tracking software will then be utilised to compare possible FASER-2 layouts and tracker technologies to contribute to the design studies of FASER-2.

2 Forward Physics: Physics and experiments

2.1 Forward physics motivation

Proton-Proton collisions at the LHC produce many light and weakly-coupled particles approximately parallel to the beamline, in the forward direction. This region of kinematic space is currently missed by conventional collider detector at the LHC.

Neutrinos and antineutrinos of all three flavors (electron, muon, and tau) are produced in intense, strongly collimated, and TeV-scale beams in the forward direction through the decays of pions, kaons, and charmed hadrons at the LHC. The study of the fluxes of TeV neutrinos in the forward direction and of their interaction with matter can impact our understanding of the Standard Model by sheding light on forward hadron production and both perturbative and non-perturbative QCD while being complementary to other neutrino experiments such IceCube.

The forward region of the LHC is a promising place to search for new particles because of the large rate of meson production in this region. These mesons can decay into exotic particles that are not described by the Standard Model, such as light, weakly interacting particles with long lifetimes. These long-lived particles (LLPs) are of interest in many models because they could be responsible for some of the most significant outstanding questions in particle physics, such as the nature of dark matter, the electroweak hierarchy problem, the matter-antimatter asymmetry, the origin of neutrino masses, inflation, and the strong CP problem [2].

A numerical package called FORESEE [9] (FORward Experiment SEnsitivity Estimator) has been developed to simulate BSM searches and models for various far-forward experiments. The package takes into account the production rates, lifetimes, and decay channels of long-lived particles, as well as the detector's acceptance and efficiency, to study the sensitivity of forward detectors to long-lived particles models. FORESEE creates HepMC [10] files of LLP decays with information on the position of the vertex, the type and momentum of the decayed particles, which can be used for simulation.

2.2 FASER

The ForwArd Search ExpeRiment or FASER [3] is a small experiment that was installed in 2021 and started taking data in 2022 in Run 3. The detector is designed to search for light and very weakly-interacting new particles produced in the LHC collisions and neutrinos of all flavours produced at the LHC with the FASERν sub-detector.

As shown in Fig.1, the detector is positioned on the beam collision axis line-of-sight (LOS) 480 m from the ATLAS interaction point 1 (IP1). Almost all standard model particles produced will either be bent away by the LHC magnets or stopped in the 100 m of rock, thus backgrounds are highly suppressed. FASER is therefore well suited to search for light and weakly-interacting particles in a very low background environment.

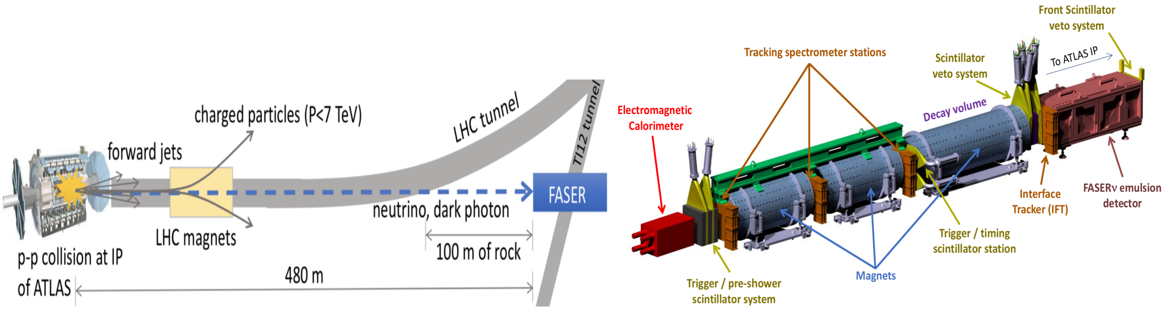

Figure 1: Left: The FASER experiment, located 480 m downstream of the ATLAS interaction point. The detector is located along the beam collision axis line-of-sight. Right: sketch of the FASER detector, showing the different detector systems

The FASER detector layout description is shown in Fig.[1]. The main FASER detector components are contained within the 1.5 m long detector decay volume and so immersed in a 0.57 T dipole magnetic field. They comprise the tracking spectrometer, the scintillator system and the electromagnetic calorimeter. The active transverse area of the detector is contrained by the magnet aperture, which is a circle of 10 cm radius. They are preceded by FASERν [11], a tungsten/emulsion detector which is dedicated to neutrino measurements.

The FASER experiment's first year of operation in 2022, collected data corresponding to an integrated luminosity of 37 fb^{-1}, yieled outstanding results and demonstrated the promise of forward direction experiments. The FASER collaboration reported the first direct observation of neutrino interactions at a particle collider experiment [12], 153 neutrinos candidates were observed with a significance of 16 standard deviations above the background-only hypothesis. Furthermore preliminary studies of long-lived particles also set new constraints on the parameter space of the LLP model dark photons [13].

2.3 Forward Physics Facility

The Forward Physics Facility (FPF) [4] [5] is a proposal to build a new subterranean cavern roughly 617–682 m west of the ATLAS IP to house a range of far-forward experiments during the High-Luminosity LHC (HL-LHC) era. This location is shielded from the ATLAS interaction point (IP) by over 200 m of concrete and rock, providing an ideal location to search for rare processes and very weakly interacting particles. The residual background of the FPF experiments will primarily consist of muons, with a predicted flux of 0.6 Hz/cm^2 around the line-of-sight (LOS) as calculated by a detailled simulation.

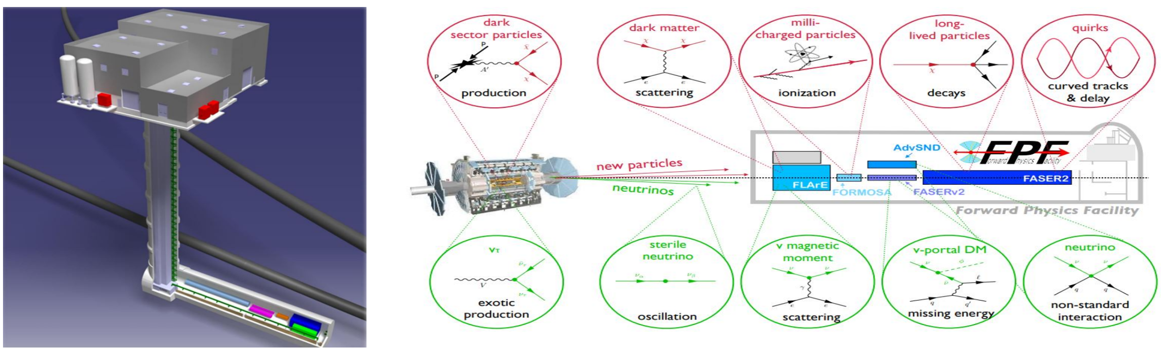

Figure 2: Left: Forward Physics Facility cavern 65 m long and 9 m wide, and shaft 88 m deep. Right: Experiments inside the FPF cavern and their physics goal.

The facility comprises a dedicated access shaft 88 m deep, connected to a cavern that is 65 m long, about 9 m wide and high, and centered on the LOS. A 3D simulation of the cavern is shown in Fig.[2]. The dimensions of the cavern were defined based on the requirements of the proposed FPF experiments. Civil engineering studies on vibration have shown that construction work on the facility will cause no major disruption to the HL-LHC operation. The expected timeline is for the FPF to be built during Long Shutdown 3 from 2026-28, the support services and experiments and proposed to be installed starting in 2029, and the experiments to begin taking data in 2032, not long after the beginning of Run 4 of the HL-LHC.

The proposed experiments inside the facility and their physics goals are illustrated in Fig.[2]. Several experiments are dedicated to neutrino measurements, which are expected to detect more than 10^6 neutrino interactions at a TeV scale. They are:

- FASERν2: Operating as an on-axis emulsion detector, anticipated to detect TeV neutrinos with fine spatial resolution. It is expected to detect 10^4 ν_τ, eventually testing lepton-fragment universality in neutrino scattering.
- Advanced SND: This off-axis electronic detector study neutrinos resulting from charm decays and will provide comprehensive observations of neutrino interactions across all neutrino flavors.
- FLArE: a 10-ton-scale noble-liquid fine-grained time projection chamber that will detect neutrinos and search for light dark matter with high kinematic resolution and wide dynamic range.

Other experiments are designed to search for new long-lived particles:

- FORMOSA: Comprised of scintillating bars, boasting world-leading sensitivity to millicharged particles across a wide range of masses.
- FASER2: Magnetic tracking spectrometer designed for the detection of light and weakly interacting particles. It will also used as a muon spectrometer to differentiate between neutrino and antineutrino charged current for neutrino detectors. The FASER2 detector will be described in section 3.

3 FASER2 experiment

3.1 FASER2 geometry

FASER2 is a new experiment building on the success of the FASER experiment, with a much larger volume by a factor around 600 which results in significant increased the statistics and reach in BSM signals such as long-lived particles.

The design of FASER2 is depicted in Fig.[3] using a Geant4 [14] simulation, created during this project using the python library pyg4ometry [15]. This library has been used to generate Geant4 geometry saved in Geometry Description Markup Language (GDML) file format.

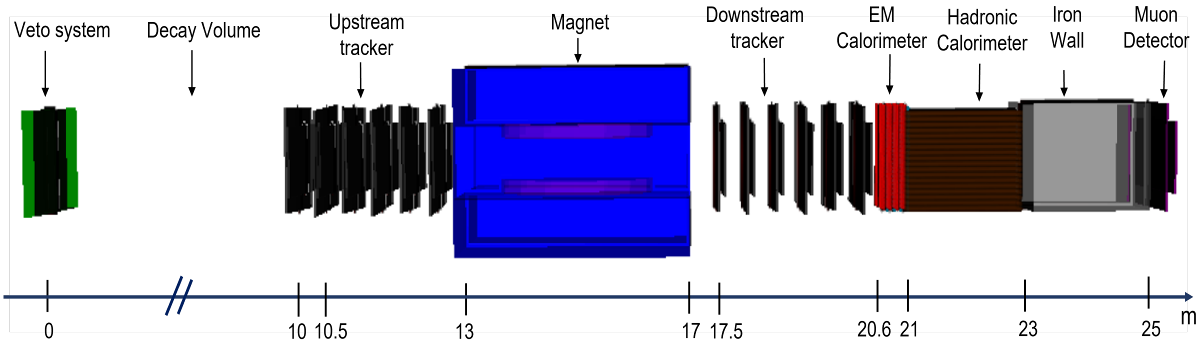

Figure 3: FASER2 detector design. From left to right, it comprises a veto system, a large cuboid decay volume, followed by a spectrometer composed of a large magnet with 6 tracking stations each upstream and dowstream, electromagentic and hadronic calorimeters, an iron wall, and a muon detector for particle identification and precise muon reconstruction.

This simulation describes the position, shapes and material of the current FASER2 detector. It was implemented recognising that the design is still being optimised, making it easily adaptable to any modifications in the existing design. Moreover, this simulation is compatibile with simulation software like Geant4. Additionally, this simulation of FASER2 has provided visual representation of the detector's current design in the Forward Physics Facility (FPF) documentation.

3.2 Detector Technologies

The proposed design of FASER2 incorporates a range of expected detector components based on already existing technologies:

- **Magnet**: Superconducting magnet technology required to maintain a 1T field strength across a large aperture based on the SAMURAI experiment magnet [16]. The simulated magnet has a rectangular aperture of 1 m in height and 3 m in width and 4 m long. The integrated magnetic field is therefore 4 Tm.

- **Trackers**: The tracking detectors envisaged employ a silicon photomultiplier and scintillating fiber tracker technology, based on LHCb's SciFi detector [17]. This technology gives spatial resolution around 100 µm and material budget around 1% of radiation length (X0) per tracking module. Each tracking station is composed of a vertical and horizontal modules to cover both dimension of space.
  The exact number of tracking stations is under evaluation, aiming for an optimal balance between cost and performance. The proposed number of stations ranges between 6 and 12.

- **Calorimeter**: Dual-readout calorimetry technology [18], is proposed with spatial resolution at $\sim$ 1-10 mm separation to distinguish and separate particles. Electromagnetic and hadronic components perform particle identification and distinguish electrons and pions for example.

- **Iron Wall and Muon detector**: A mass of iron is placed after the calorimeter, thick enough to absorb hadrons, followed by a muon detector made of SciFi planes.

This is important to have the ability to identify separately muons from electrons or hadrons which will help with signal charaterisation, interface with neutrino experiments,and perform background suppression.

- **Veto system** A scintillator-based is proposed to reject background muons.

3.3 FASER2 physics goals

The BSM physics goal of FASER2 is the search for any Long-Lived Particles (LLP) that would be produced at the ATLAS IP, move along the beam collision axis, and decay visibly within the detector. The benchmark process is:

$$\text{pp} \to \text{LLP} + \text{X}, \quad \text{LLP travels} \sim 620 \text{ m}, \quad \text{LLP} \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-, K^+K^-, ...$$

Two benchmark models of the LLP search for FASER2 are the dark photon [19] and dark Higgs [20] models, new particles with spin-1 and spin-0, respectively, that couple to SM particles through renormalizable couplings.

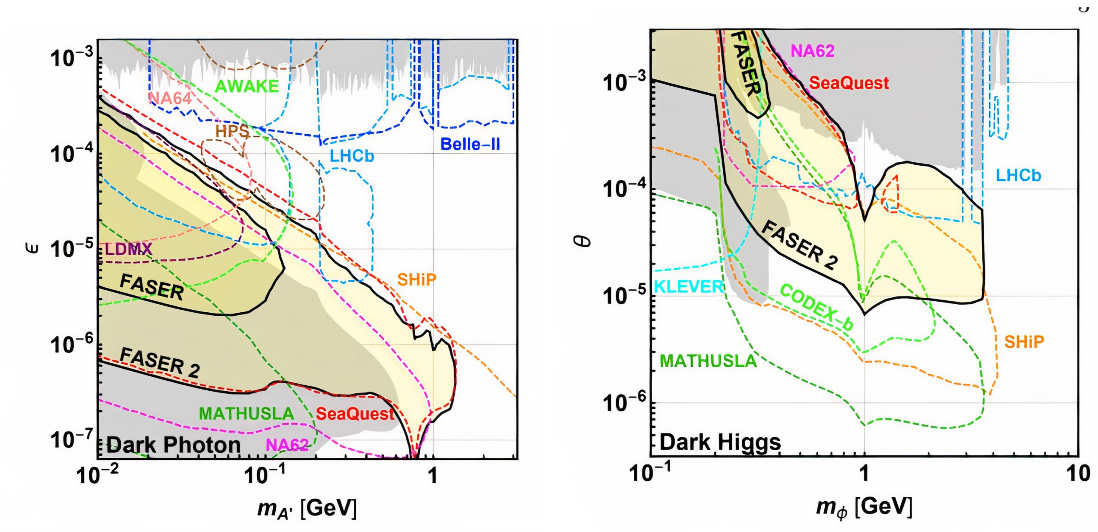

Figure 4: Sensitivities for the dark photon (left) and dark Higgs (right) in the new particle (mass, coupling) plane. The gray-shaded regions are excluded by current bounds, and the projected future sensitivities of other experiments are shown as colored contours some of the projected experiments make demanding and as yet unproven requirements on background rejection. From [5]

The sensitivity plots (Figure 4) for the dark photon and dark Higgs for the FASER, FASER2 detector, and for other proposed experiments focused on LLP such as MATHUSLA [21] were obtained by using the FORESEE tool. For both LLP models, the sensitivity for FASER2 configuration is significantly greater than for FASER both in mass range and in exploring weaker couplings values.

The neutrino programme at the FPF will require on the detection of muons resulting from neutrino intersections. Precise measurements of momentum and reliable charge identification of these muons will allow for the differentiation between muon neutrinos (ν_μ) and anti-muon neutrinos (ν_μ^-). The FASER2 spectrometer will play an indispensable role in these measurements, for both the FASERν2 and FLArE experiments.

For both the LLP searches and the neutrino programme, a detailed understanding of momentum, mass, and vertex measurements with the FASER2 detector is crucial. Therefore, a thorough tracking simulation is essential for conducting effective detector design studies.

4 Tracking software for FASER2

4.1 Tracking in a Nutshell

Tracking in particle physics experiments is the process of reconstructing the trajectory or path of electrically charged particles from a set of measurements caused by the interaction with some form of sensitive detector known as a tracker. When a magnetic field is present in the entire or part of the tracker, the Lorentz force law predicts that a charged particle will move along a curved path. The radius of the curved path is inversely proportional to the particle's momentum, which allows the measurement of the momentum of the particle.

The precision of this tracking process depends on a multitude of factors. These include, but are not limited to, the spatial resolution capabilities of the trackers, the intensity of the magnetic field, and the effect of the material of the trackers on the particles. One such effect is energy loss, which can occur through ionization or radiation when particles interact with the tracker material. Another effect, multiple scattering, can subtly alter the particles' trajectories from their original path.

Various algorithm are used in experimental particle physics for track finding and track reconstruction such as the Kalman filter, which motivated the creation of A Common Tracking Software (ACTS) an experiment independent toolkit which provides among other features those algorithms for track reconstruction

4.2 A Common Tracking Software description

ACTS (A Common Tracking Software) [6] 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 track reconstruction.

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.

Geometry and material modeling are integral components of ACTS. The software's geometric model is primarily constructed on a surface-based description, and stores information about the sensitive surfaces significant for track reconstruction. The requisite specifications for the tracking geometry are determined by the demands of each individual experiment.

ACTS also contains a material implementation feature that offers a mode to detail the material properties of tracking devices, which includes aspects like density, radiation length, and nuclear interaction length. It can also map material from an intricate full-detector geometry onto the simplified surface-based ACTS geometry. Furthermore, it incorporates algorithms capable of accounting for the interactions of the charged particle with the material of the detector components in its trajectory.

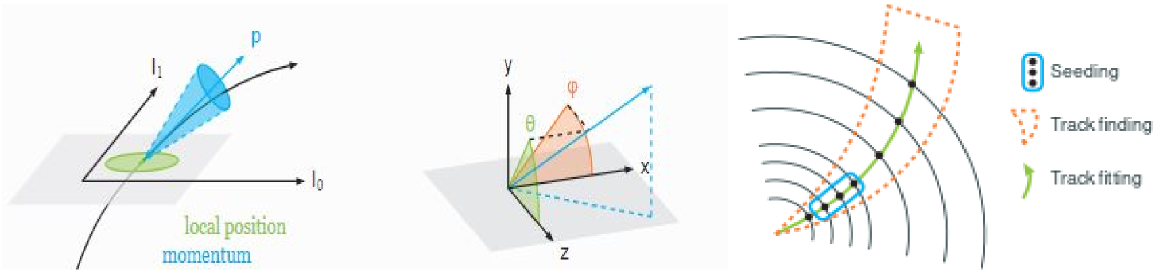

Figure 5: Illustration of the parametrization of a particle track $(l_1, l_2, \phi, \theta, \frac{q}{p}, t)$ with respect to a surface and illustration of the track reconstruction process (right).

The simulation aspect comprises an event generator for initiating particle events, and an event simulation for propagating the particles through the detector system. This process concludes with a digitization phase, wherein the detector's resolution is applied to the simulated hits on the sensor surface. This simulation phase is followed by the reconstruction process, which encompasses track finding and fitting algorithms, as well as a vertex reconstruction algorithm

The track parameters in ACTS, defined in Fig.[5], used for track reconstruction, are six-dimensional $(l_1, l_2, \phi, \theta, \frac{q}{p}, t)$. These parameters include two local surface positional dimensions (l_1, l_2), azimuthal (ϕ) and polar (θ) angles, the ratio of particle's charge to its momentum $(\frac{q}{p})$ characterizing the curvature of tracks, and the time parameter (t). The track reconstruction operation can be broken down into the following steps illustrated in Fig.[5] :

1. **Track Finding**: The procedure commences with the initial estimate of track parameters. These can be obtained either via truth information from event generator or through experiment-specific seeding (or track fitting) algorithms.

2. **Track Fitting**: The Kalman Filter algorithm is then employed for the track fitting. This algorithm is recursive and is utilized for the progressive estimation of a system's state. The algorithm iteratively refines the track parameters based on the hits registered in the tracking detectors, eventually furnishing the optimal estimate of the track parameters. Other algorithms such as χ^2 fitting can also be used.

The essential inputs required for the successful implementation of ACTS for FASER2 include the detector geometry, material specifications, resolution, and magnetic field parameters. Although ACTS is designed to be experiment independent, its original coding and parametrization bear a strong leaning towards cylindrical and collider detectors. Given FASER2's design, which features a rectangular shape detector placed in the forward direction, several modifications and adaptations were necessary to ensure the implementation of the ACTS toolkit.

4.3 Implementation of FASER2 for ACTS

The integration of the ACTS (A Common Tracking Software) toolkit for FASER2 followed a series of structured steps:

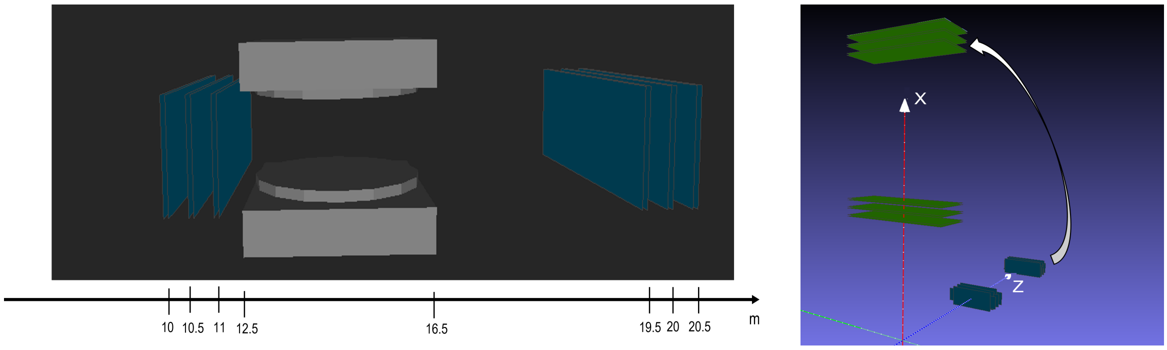

Figure 6: Left: Visualisation of the FASER2 geometry implemented in ACTS, with 3 tracking stations each upstream and dowstream of a large rectangular magnet with a 1T magnetic field. Right: Global rotation of the FASER2 geometry such that Z $\rightarrow$ X. This rotation was needed to fix fitting error in the forward direction.

1. **FASER2 Geometry in ACTS**: A preliminary effort to convert the Geant4 description of the detector (shown in Fig.[3]), into an ACTS-compatible, surface-based geometry was unsuccessful due to inherent bias in the software towards cylindrical geometrical configurations. To overcome this challenge, the FASER2 geometry was directly incorporated as ACTS geometry as depicted in Fig.[6]. The implemented geometry consists of a total of six tracking stations, rather than the twelve detailed in Fig.[3]. This modification aims to evaluate the performance with a more cost-effective design for the FASER2 experiment. The tracking stations were modeled as rectangular surfaces with homogeneous materials, matching 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 magnet is approximated as being constant. A constant 1T magnetic field within a confined cuboid volume defined in Fig.[6] was integrated into the ACTS toolkit during this project to match FASER2's magnetic field requirements.

3. **LLP Event generator**: HepMC files from the FORESEE package, containing information about 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 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 θ close to 0 lead to numerical uncertainties with respect to ACTS' track parameters. This numerical instability stems from the fact that small θ values render the azimuthal ϕ angle 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 θ 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.

Several approximations were made during the FASER2 implementation for ACTS:

- Each tracker layer was represented as a rectangular surface with homogeneous materials, rather than as strip detectors composed of SciFiber modules. This approach simplified the implementation process and is a reasonable approximation given that the detector's active area constitutes more than 99% of the total surface.
- The magnetic field was assumed to be constant throughout the simulation, neglecting potential fringe-field effects that might be present in an actual field map, with the expectation that these would have a subdominant impact on the reconstruction.
- During the FASER2 reconstruction, the track finding process used truth information, as opposed to a dedicated space point formation and seeding algorithm, which could not be implemented within the project's timeline. This approximation is justified by the extremely low background in the FPF facility but remains to be tested.

This successful implementation of ACTS for FASER2 creates the opportunity to perform track reconstruction. The first step presented in the next section will be to study the quality and robustness of the track fitting algorithm and results.

5 Performance of the track reconstruction

5.1 Evaluation of tack fitting quality

Evaluating track reconstruction quality is key in developing reliable FASER2 tracking software. We use two key metrics for this evaluation: track efficiency and the χ^2 distribution of track fitting. These are presented in Fig.[7] for 100,000 simulated long-lived particle (LLP) decay events into muons.

- Track efficiency, representing the ratio of successfully reconstructed tracks to total simulated tracks, is maintained above 98% for particles with momentum values up to 5 TeV, as shown in Fig.[7]. This high efficiency rate signifies accurate track reconstruction across a broad momentum range with minimal information loss. For particles with momentum above 5 TeV, efficiency decreases due to fewer events in this range and the challenges in distinguishing two separate tracks that are less deflected in the magnetic field.
- The χ^2 distribution is a quantitative indicator of the accuracy of fitted tracks versus simulated tracks. As Fig.[7] demonstrates, the χ^2 distribution of the FASER2 track fitting, using 12 degrees of freedom, aligns well with the theoretical distribution. This agreement indicates the high quality of the fit and implies the absence of significant systematic bias from the tracking software.

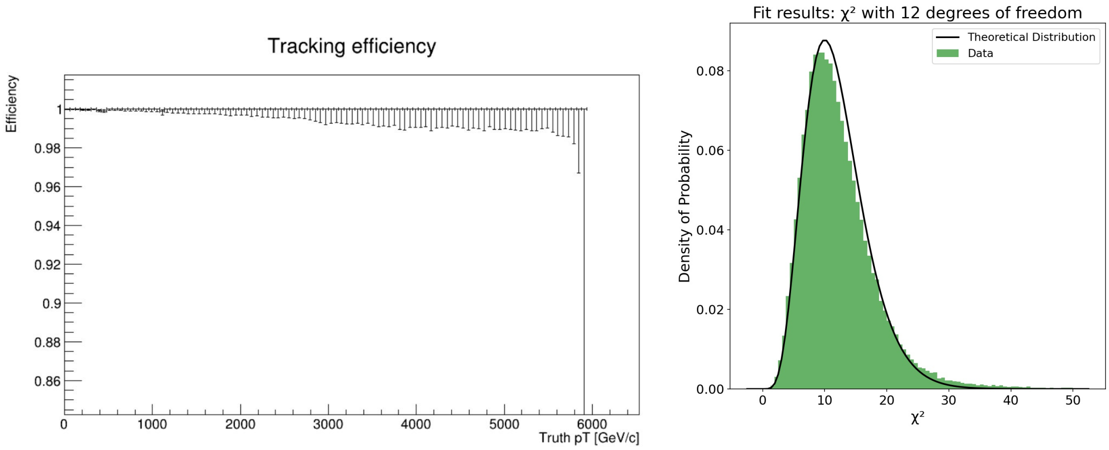

Figure 7: Track efficiency plots in function of the truth momentum (left) and χ^2 distribution of the Kalman fitting of the reconstructed data superposed by the theoretical distribution of the χ^2 with 12 degrees of freedom

The high track efficiency and alignment of the χ^2 distribution with its theoretical counterpart confirm the robustness and precision of the tracking software. However, it should be noted that these results were obtained from a truth-based track finding algorithm and did not include background simulation. For further enhancements to the FASER2 tracking software may provide more realistic values for those metrics.

5.2 Track reconstruction performance

The ability to accurately measure the position and momentum of a particle is essential when assessing the performance of track reconstruction, hence why the position and momentum resolution are important metrics. For the following plots in Fig[8] 50 000 muons were generated for each relevant momentum value in the plot within FASER2's kinematic range using muon generator incorporated in ACTS.

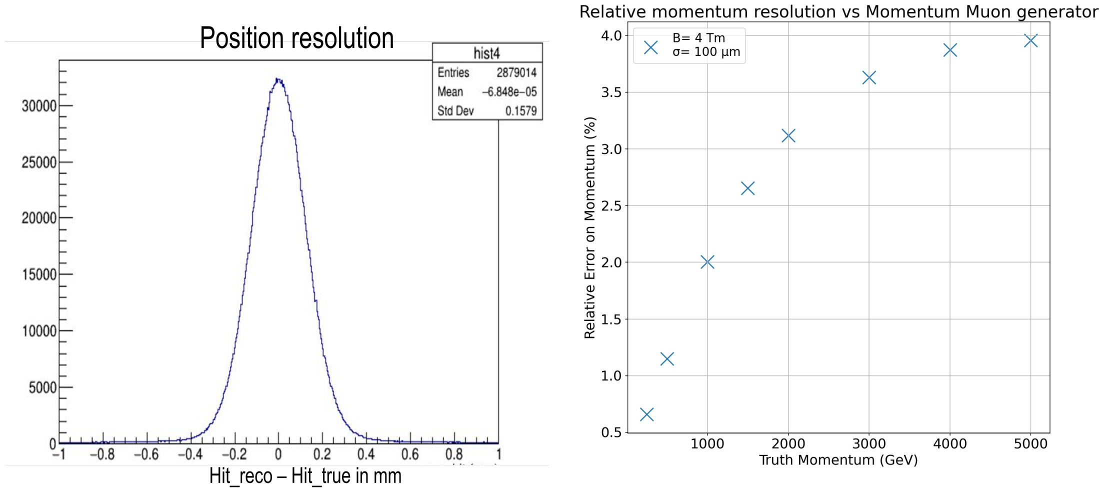

Figure 8: Left: Position resolution of each hits after the effect of the detector resolution modeled by a gaussian of $\sigma = 100$ um. Right: Plot of the momentum resolution $\sigma(\frac{p_{\rm reco}-p_{\rm truth}}{p_{\rm truth}})$ with the nominal FASER2 geometry described in Section.3.1

Position resolution refers to the disparity between the reconstructed and true positions of a charged particle's hit in the tracker. As illustrated in Fig.[8], the position resolution appears to follow a Gaussian distribution, nearly centred at zero, with a standard deviation close to 150 μm. This results is consistent with our tracking algorithm, which applies a Gaussian smearing to the particle's position, centered at zero with a standard deviation equivalent to the detector's resolution ($\sigma = 100$ μm). This verifies that the FASER2 trackers' hit resolution behaves as expected. The slight deviation from the exact 100 μm standard deviation for the position resolution may be due to multiple scattering from material interactions with the tracker.

Fig.[8] also presents the relative momentum resolution plotted against the particle momentum, which ranges from 250 GeV to 5 TeV. Here, the relative momentum resolution is defined as the standard deviation of the distribution of the fraction $\frac{p_{\rm reco}-p_{\rm truth}}{p_{\rm truth}}$, where $p_{\rm reco}$ and $p_{\rm truth}$ represent the reconstructed and true momenta, respectively. The resulting plot shows the relative momentum resolution ranging from 0.5% for lower momenta up to 4% for the highest momenta. This increase is due to the less curved tracks for high momentum particles.

The relative error on momentum remains less than 5%, indicating very good momentum measurement performance from the tracking for the FASER2 nominal detector concept. Precise momentum measurements are vital for accurately estimating the mass of LLP particles and for the neutrino program at the FPF. Several factors, including the strength of the integrated magnetic field and the number and spatial resolution of tracking layers, influence this measurement. Therefore, this metric will be important during the detector design study to evaluate the influence of changes these factors on the FASER2 detector's performance.

5.3 Mass and vertex resolution

The search for Long-Lived Particles (LLP) in FASER2 relies heavily on the detector ability to reconstruct the LLP's invariant mass from its decay products and accurately reconstruct the position of the decay point of the LLP, also known as the vertex. One of the goals of the development of the tracking software is to evaluate the performance of FASER2 for both mass and vertex resolution.

The invariant mass of the LLP that decays into charged particles 1 and 2 is defined, in units with c=1 as:

$$m_{\mathrm{LLP}} = \sqrt{(E_1 + E_2)^2 - ||\vec{p}_1 + \vec{p}_2||^2} \quad \text{with } E^2 = p^2 + m^2 \tag{1}$$

The distribution of the invariant mass and relative error on the decay vertex position can be observed in Fig.[9], for the track and vertex reconstruction of 120 000 simulated events of the LLP model Dark Higgs $\rightarrow \mu^+\mu^-$ from FORESEE. Those plots shows very good precision for both metrics.

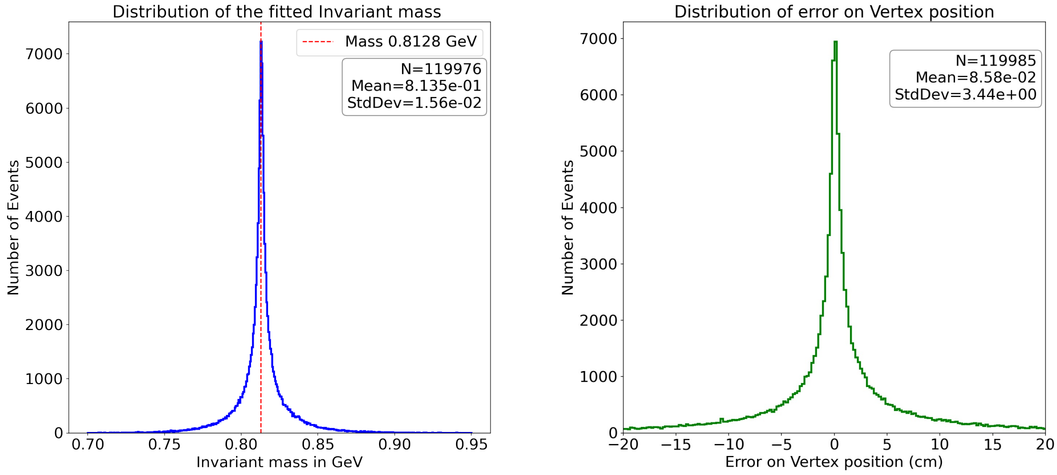

Figure 9: As determined for 120 000 events of Long-Lived Particle decays with benchmarkmodel Dark Higgs $\rightarrow \mu^+\mu^-$ m= 0.81 GeV simulated in the BSM event generator FORESEE Left: Dark Higgs invariant mass resolution plots. Right: Distribution of the error on the reconstructed vertex position. The vertex of LLP is expected to be in cuboid decay volume $1 \times 3 \times 10$ m.

The mass resolution plot reveals a sharp peak at the expected LLP invariant mass of 0.81 GeV. The width of this distribution does not extend beyond 0.75 and 0.85 GeV, marking a relative error of order 5%. This mass resolution aligns with the momentum measurement results from the previous section. High-resolution invariant mass measurement is crucial for enhancing our sensitivity to LLP signals against the standard model background. Additionally, it facilitates an accurate determination of LLP properties.

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.[9] 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.

5.4 Impact on resolution of the material effect and LLP models

A study of the impact of the material effects and the choice of the LLP models and decay channel on the tracking performance helps one understand the tracking simulation and resolution plots.

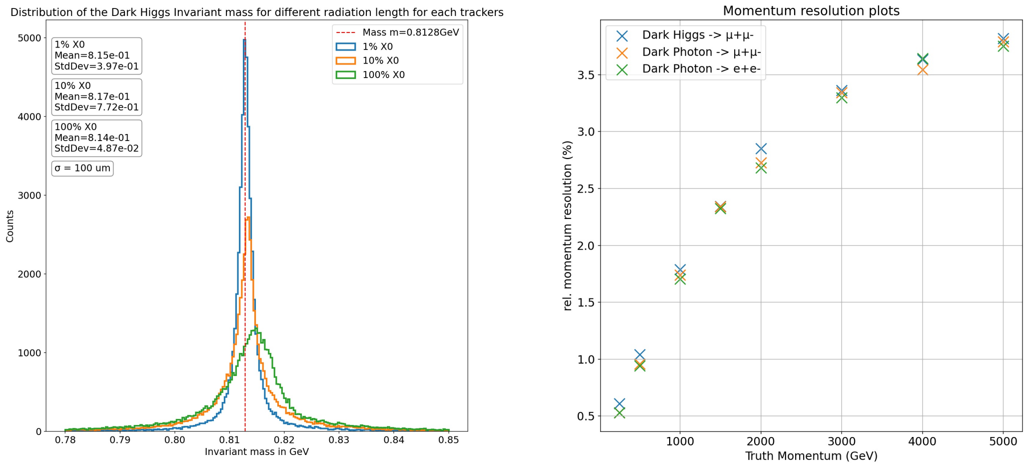

Figure 10: Left: Invariant mass plot for trackers with the SciFi tracker expected 1% X_0 (radiation length) to artificially high 100% X_0 material budget to explore the impact of the material effect on track reconstruction. Right: Momentum resolution for different model of LLP and decay mode, dark Higgs$\rightarrow \mu^+\mu^-$ and dark photon $\rightarrow \mu^+\mu^-$, e^+e^-

5.4.1 Material Effect

The plot in Fig.[10] explores the invariant mass resolution under three different material budgets characterized by the fraction of the radiation length (X_0) per modules. The radiation length is the average length into the material an electron travels before losing most of its energy. 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 scatering which would lead to a more diffuse distribution. This result demonstrates that the choice of the SciFi detector as a tracker for FASER2 with low material budget (1% X_0) helps to get better performance.

5.4.2 LLP models and decay channel

In figure 10 we show the momentum resolution using the LLP generator FORESEE. The plot reveals 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 μ). 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.

Overall, the tracking simulation shows very good performance for both mass and pointing ability for the FASER2 detector. Those promising resilts gives motivation to explore different, more cost-effective FASER2 layouts that continue to deliver good performance in these key metrics.

6 FASER2 detector design studies

6.1 Tracker design based on tracking performance

The spatial resolution and number of tracking station are the parameters that have the most impact on the tracking performance. FASER2 aims to use a SciFi detector with a resolution of 100 μm and 6-12 tracking layers, with an anticipated cost between 4 to 6 MCHF (million Swiss francs).

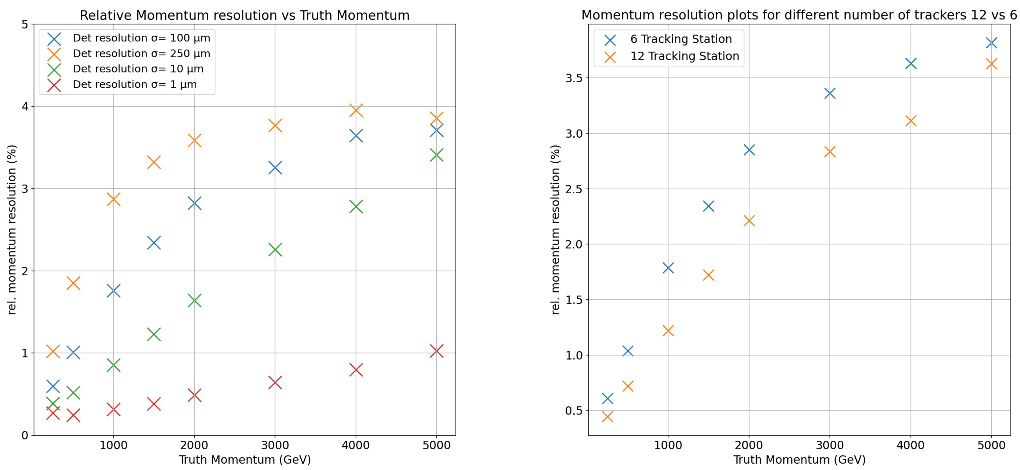

Figure 11: Momentum resolution plots to compare the track reconstruction performance of trackers with detector resolution from 1 μm to 100 μm (left), and the performance of a FASER2 layout with 6 trackers compared to 12 (right)

Figure [11] displays the momentum resolution for tracker resolutions of 250 μm, 100 μm, and 10 μm. Though the simulated tracker with resolution of 10 μm slightly outperforms the others, all resolutions under study maintain momentum resolution below 5% across the momentum spectrum, which gives great 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, that will be discussed in section 6.3. The performance of the tracker with a resolution of 1 μm shows that to obtain significant improvements, particularly at high momentum, necessitate a detector resolution below 10 μm. However, this level of precision, equivalent to a near-perfect detector, would demand unrealistic cost increases.

The second plot in Fig.[11] compares the momentum resolutions of 6 and 12 tracking station configurations. While the 12 station layout (Fig.[3]) slightly outperforms the 6 station setup (Fig.[6]) due to increased trajectory measurement, it also escalates costs significantly, raising the overall tracking station expense from 4 to 6 MCHF.

Given the current state of the tracking simulation, a 12 station configuration may not present a cost-effective option. Nonetheless, it is important to remember that these simulations use truth information to track findings, and an increased number of tracking stations could boost track-finding algorithm accuracy when more realistic seeding is performed.

6.2 Magnet studies

Being FASER2's costliest (10-15 MCHF) and most influential component for track reconstruction, the magnet requires careful optimization, particularly regarding its magnetic field strength and shape.

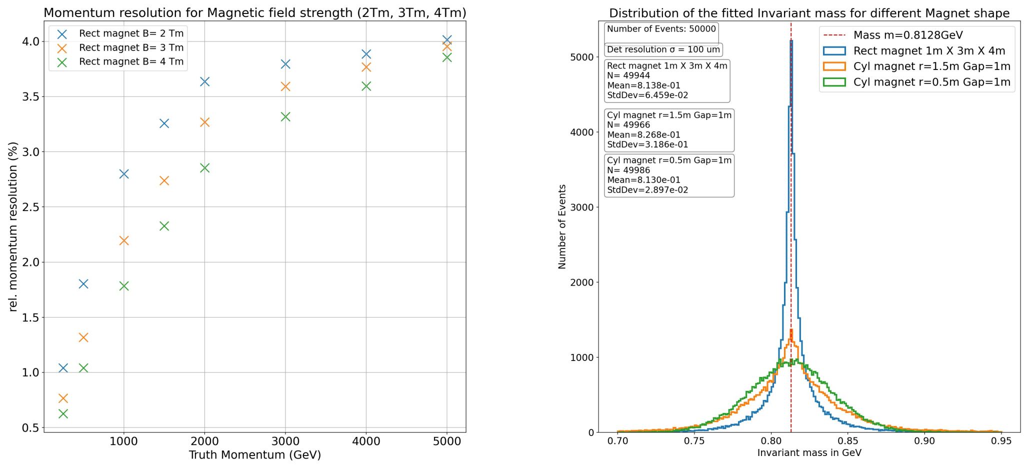

Figure 12: Left: Momentum resolution for different values of magnetic field integrated (2 Tm, 3 Tm, 4 Tm). Right: Invariant mass distribution for different magnet shapes (rectangular, cylindrical)

Figure [12] compares the momentum resolution of different integrated magnetic fields from 2 Tm to 4 Tm. While the stronger 4 Tm field improves momentum resolution by a factor of two at low momentum, the 2 Tm field still offers ample performance for FASER2's physics research and reduces the magnet cost substantially. However, we also need to consider how a reduced magnetic field impacts particle separation, in the next section 6.3, before settling on the 2 Tm field.

The magnet's shape also invites discussion. In our simulations, we modelled the magnetic field as constant within a cuboid volume. However, consultations with magnet manufacturers indicate that a cylindrical coil (with the magnetic field confined within a 0.5 m to 1.5 m radius cylinder) could be more feasible and cost-effective. This design change would alter the integrated magnetic field value, maximizing it at the center and reducing it at the edges. High-momentum particles, requiring a stronger magnetic field, are expected to converge at the center, supporting this design choice. Figure [12] compares the invariant mass distribution for rectangular and cylindrical shapes. A noticeable decrease in resolution for the cylindrical shape magnet is evident, particularly due to peak broadening. Nevertheless, a 1.5 m radius cylindrical magnet still delivers satisfactory resolution.

6.3 Charged particles separation

The separation of charged particles is an important factor when considering options for the trackers minimum resolution and minimum magnetic field strength, as mentioned in previous sections. Figure [13] depicts the separation of particles as a histogram, showing distances between two charged particles resulting from an LLP decay. Each plot also contains a colored box indicating the fraction of events where separation surpasses required values. Figure[13] compares particle separation in the first and last tracking stations (6), located before and after the magnetic field.

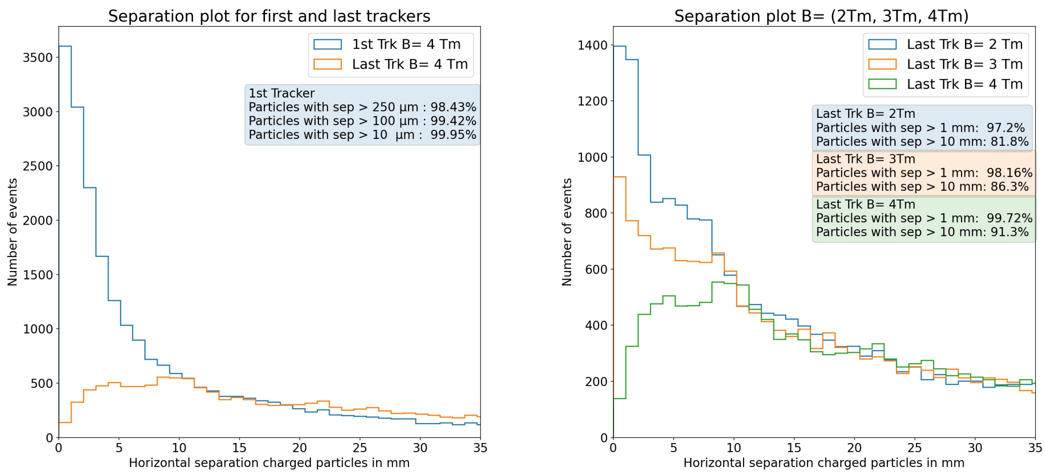

Figure 13: Charged particles separation plots for the first and last tracking station (left) and for different magnetic field strength (right)

The initial tracker's minimum separation must exceed its spatial resolution to get at least two tracks, which justifies a minimum separation requirement in the first tracking station using the tracker resolution from section 6.1. From these results, the SciFi tracker with 100 μm resolution appears to be the most cost-effective choice while retaining the majority of events (99.42%). Nonetheless, a 250 μm resolution tracker may also be a viable option considering its momentum resolution performance and the ability to distinguish two particle tracks.

The last tracker's particle separation provides insight into the charged particles' interaction with the FASER2 calorimeter, which has a spatial resolution between 1-10 mm. Figure [13] reveals that if the calorimeter's spatial resolution is closer to 1 mm, a 2 Tm magnetic field strength would allow a high fraction (97%) of particles to be separated by the calorimeter. However, if the spatial resolution nears 10 mm to achieve high fraction of particles with enough separation ($> 90\%$), opting for a 4 Tm magnetic field strength, despite its higher cost, might be the preferred choice.

6.4 Alignment Tracking Studies

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.

To implement this study, the aligned geometry was used during the ACTS simulation process, while the misaligned geometry was incorporated during the reconstruction phase. This was done to conserve computational resources, as the simulation process needed to be executed only once.

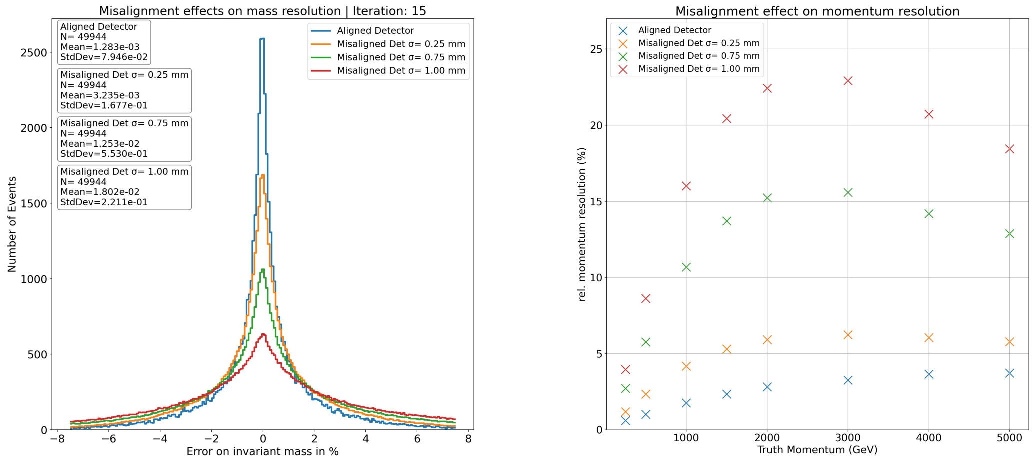

Figure 14: Plots with aligned detector and misaligned detector for different values of misalignment (0.25 mm, 0.75 mm, 1.0 mm) to explore effect of misalignment on the mass resolution (left) and on the momentum resolution (right)

The plots depicted in Fig.[14] focus on the effect of misalignment in translation ranging from 250 µm to 1 mm on the invariant mass resolution and the momentum resolution for a LLP decays into muons simulated by FORESEE. The results reveal that misalignment starts to significantly impact both mass and momentum measurements when the misalignment surpasses 250 µm.

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.

7 Conclusion and perspective

The promising new results of the FASER experiment is a proof of concept of the physics potential of the proposed Forward Physics Facility and the FASER2 experiments. In this report we have explored the simulation effort for FASER2, first with a GEANT4 description of the FASER2 conceptual design then through the process of development of a tracking software for FASER2 using the ACTS (A Common Tracking Software) toolkit.

Our study of the evaluation of the track reconstruction demonstrated very good performance and showed the great potential of FASER2 for precise mass and vertex reconstruction. Additionally, we were able assess and compare the performance of various FASER-2 layouts for the search of Long-Lived Particle. Theses insights have influenced our FASER-2 detector design studies, leading to potential modifications to the tracker and magnet design that could significantly reduce the cost of the detector without compromising performance.

Even though substantial progress has been made, there is room for further improvement and refinement of the FASER2 tracking software. Improvement could include the implementation of a dedicated track finding algorithm, the incorporation of a magnetic field map or a more realistic description of the tracker detector. In-depth study of the background and the synergies of FASER2 with the neutrino experiments at the FPF are also interesting aspect to explore.

Throughout the course of this project, I had the privilege of presenting my work at the international conference LHCP Belgrade 2023, in a poster session and play a key role in the FPF collaboration during two in-person meetings at CERN.

Figure 15: Left: Group photo of the FPF collaboration at CERN for the FPF6 collaboration meeting 7-9 June 2023. Right: Photo taken at the poster presentation at the international conference LHCP 2023 Belgrade.

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