The W-Si High Precision Preshower Detector of the FASER Experiment at the LHC

Daiki Hayakawa[1,*] , on behalf of the FASER collaboration

[1]Department of Physics, Chiba University, 1-33 Yayoi-cho Inage-ku, 263-8522 Chiba, Japan

Abstract. FASER is searching for light, weakly-interacting particles at the Large Hadron Collider. The first search for Axion-like particles (ALPs) decaying to a photon pair using data collected in 2022 and 2023 was performed and successfully excluded regions not previously ruled out. To further reduce neutrino background, a new preshower detector will be installed by the end of 2024. The detector is based on a monolithic active pixel sensor in 130 nm SiGe BiCMOS, which will allow resolving the photon pairs interacting in the preshower detector. The final ASICs have been produced in May 2024 and are currently being validated.

1 Introduction

The ForwArd Search ExpeRiment (FASER) [1] is an experiment at the Large Hadron Collider (LHC) designed to search for light, weakly-interacting particles. Positioned at 480 m downstream from the ATLAS interaction point (IP1) on the beam collision axis, the FASER detector studies long-lived particles (LLPs), which are often highly boosted and travel several hundred meters before decaying. Most Standard Model (SM) particles either get absorbed by approximately a hundred meters of rock in front of the FASER detector or are deflected by the LHC magnets before reaching the FASER detector, making it an ideal location for LLP searches.

Candidates for LLPs include new particles in a hidden sector, weakly interacting with the SM. The beyond-the-SM (BSM) scenario could explain dark matter (DM), which highly motivates search for the new particles. In addition to BSM particle searches, FASER also studies SM particles generated in the forward direction, such as neutrinos and muons.

Figure 1 shows a sketch of the FASER detector. On the detector upstream side, the right side in the sketch, there is a neutrino detection part (FASERν). FASERν consists of a front scintillator veto system, an emulsion detector with 1-ton tungsten target, and the interface tracker (IFT) for muon charge separation. On the downstream side, the left side in the sketch, there is a detector part to search for new particles. The part is composed of the scintillator veto station, the decay volume, the timing scintillator station, the FASER tracking spectrometer, the preshower scintillator system and the electromagnetic (EM) calorimeter system. The detector includes three 0.57 T dipole magnets, one surrounding the decay volume and the other two embedded in the tracking spectrometer.

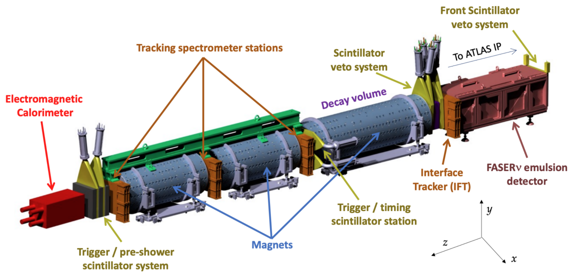

Figure 1. A sketch of the FASER detector, showing the different sub-detector system. The detector coordinate is also shown [2].

A search for dark photons, decaying into electron-positron pairs, was performed using data collected in 2022 [3]. A search for Axion-like particles (ALPs), decaying into photon pairs, was reported [4]. For the first time, neutrinos from colliders were directly observed using the electronic component of FASER in 2022 data [5]. Electron neutrinos were also directly detected for the first time using a nuclear emulsion detector, FASERν [6]. The cross-section for both electron and muon neutrinos were also measured in the unexplored TeV range with FASERν [7].

2 Search for ALPs with the FASER detector

ALPs is a general term for pseudoscalar particles, including axions. Here, we consider a scenario where ALPs interact with $SU(2)_L$ gauge bosons and, after electroweak symmetry breaking, interact with photons and weak gauge bosons. The Lagrangian $\mathcal{L}$ is expressed as

$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{aWW} a W^{a,\mu\nu} \tilde{W}^a_{\mu\nu} \,, \tag{1}$$

*e-mail: daiki.hayakawa@chiba-u.jp

where m_a and a represent the mass and field of the ALP, respectively, g_{aWW} is the coupling constant between the ALP and weak gauge bosons, and $W^{\mu\nu}$ represents the $SU(2)_L$ field strength.

Using data collected in 2022 and 2023 (57.7 fb^{-1}), FASER searched for ALPs decaying into two photons. Since ALPs have no electric charge, they leave no signal in the veto stations and the tracking detectors. High-energy photon pairs emitted from ALP decays interact in the preshower and are observed as EM showers in the calorimeter. Due to the collimated pair of photons, they cannot be resolved by the FASER detector. Events observed as a single EM shower with the energy of at least 1.5 TeV in the calorimeter are required. The signal region was defined to require the energy deposited in the second layer of the preshower scintillator exceeded 10 MIPs, and more than 4.5 times larger than the energy deposited in the first layer.

The primary background events are charged current interactions of neutrinos in the preshower calorimeter. Neutrino background events were estimated using Monte Carlo simulations (MC) and checked with the data, confirming the consistency of the MC estimates. Other background considerations included inefficiencies in the veto detectors, muons, neutral hadrons, cosmic rays, and beam background arriving at the FASER detector, all of which were estimated to be negligible. The most significant systematic uncertainties were the flux uncertainties of forward hadrons production, followed by uncertainties in the energy scale calibration of the calorimeter. The neutrino background events in the signal region are summarized in Table 1. One event was observed in the signal region after unblinding, and an exclusion limit was set as shown in Figure 2, successfully excluding regions not previously ruled out.

Table 1. Summary of the MC estimate of the neutrino background in the signal region. Uncertainties on the flux, as well as experimental uncertainties, are also given. The MC events are normalised to 57.7 fb^{-1}, and MC statistical uncertainties are given [4].

	> 1.5 TeV signal region
Light	$0.23^{+0.01}_{-0.11}$ (flux) $\pm$ 0.11 (exp.) $\pm$ 0.04 (stat.)
Charm	$0.19^{+0.32}_{-0.09}$ (flux) $\pm$ 0.06 (exp.) $\pm$ 0.03 (stat.)
Total	**0.42 ± 0.38 (90.6%)**

3 Preshower upgrade

LHC will complete Run 3 in 2025 and continue Run 4, as part of High Luminosity LHC, after Long Shutdown 3. The continuation of running FASER in Run 4 has been approved by the CERN Research Board, which will increase the dataset in the future analysis. However, given that neutrinos are the main background and considering the uncertainties of the neutrino flux in the forward direction, background will be dominant for the future analysis. By the end of 2024, the preshower detector will be replaced by a new high X-Y granularity preshower detector. The

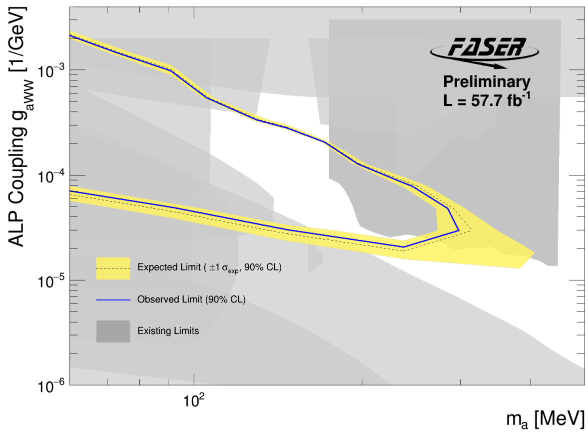

Figure 2. Interpretation of the signal region yield as ALP exclusion limits with the assumption of 0.42 neutrino background events. Systematic and statistical uncertainties described in Table 1 are included [4].

detector consists of six detector planes based on monolithic pixel sensors [8] interleaved with tungsten plates. This upgrade will allow resolving a pair of photons, previously observed as a single electromagnetic shower. It will enhance the experiment's sensitivity to the di-photon final state and significantly reduce the neutrino background. The expected sensitivity with the capability of the di-photon separation was studied, as shown in Figure 3. The new detector will also improve search for dark photons, that decay into electron-positron pairs, or other similar final states.

Figure 4 shows the sketch of the new preshower detector. The first two tungsten plates are 6 mm thick, and the last four plates are 2 mm thick. Each detector plane is

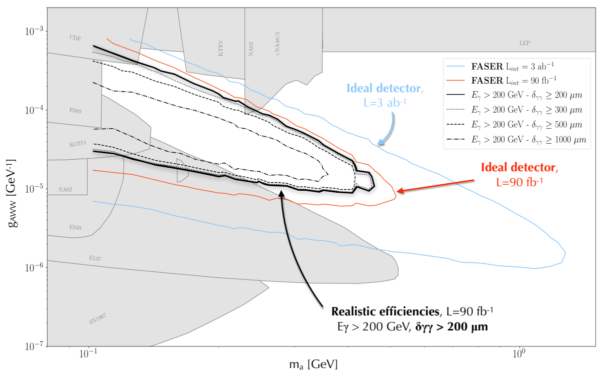

Figure 3. Sensitivity reach of the FASER W-Si preshower in the ALP parameter space. The blue and red lines show the reach for an ideal detector with 100% photon-pair reconstruction efficiency for the Run 3 (90 fb^{-1}) and HL-LHC (3 ab^{-1}) expected integrated luminosities for 14 TeV collision energy. The black lines show the sensitivity reach for 90 fb^{-1} of data including simulated efficiencies for photon-pairs with $E_\gamma > 200$ GeV and various values of the diphoton separation δ_γ. The grey-shaded regions represents the parameter space currently excluded by the other experiments [8].

composed of 12 modules mounted on a 20×20 cm^2 aluminum plate. Each module consists of 6 monolithic silicon pixel ASICs, with 208×128 pixels.

The detector simulation was implemented with the Allpix^2 software framework [9]. EM showers in the preshower detector initiated by two high energy photons were simulated for the optimization of the preshower layout and the study of the shower reconstruction algorithm. Figure 5 shows a simulation example of pixel charge deposit distribution in the third layer for two 1 TeV photons separated by 500 µm. Thanks to the high granularity and large dynamic range of the sensor, the new preshower resolves the cores of the two EM showers at distances as small as 200 µm. Energy measurements of the calorimeter system are also studied with the same software framework. Figure 6 shows the energy resolution as a function of beam energy. For energies above 100 GeV, which is our primary area of interest, FASER maintains good energy resolution with the preshower correction.

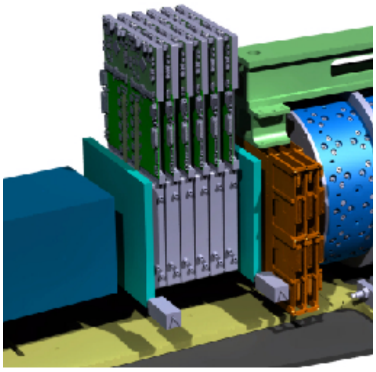

Figure 4. A sketch of the new preshower detector.

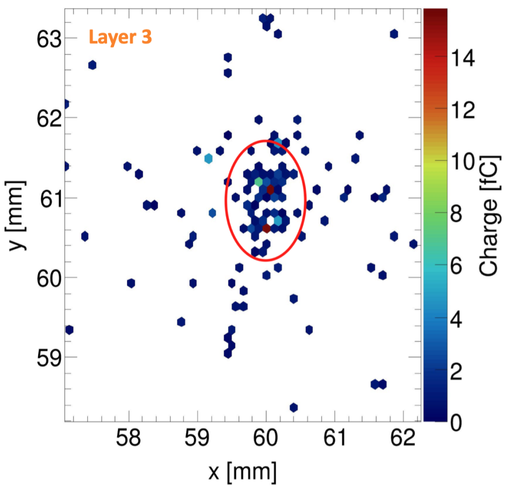

Figure 5. Charge distribution in the third layer of the detector from two electromagnetic showers initiated by 1 TeV photons with 500 µm separation.

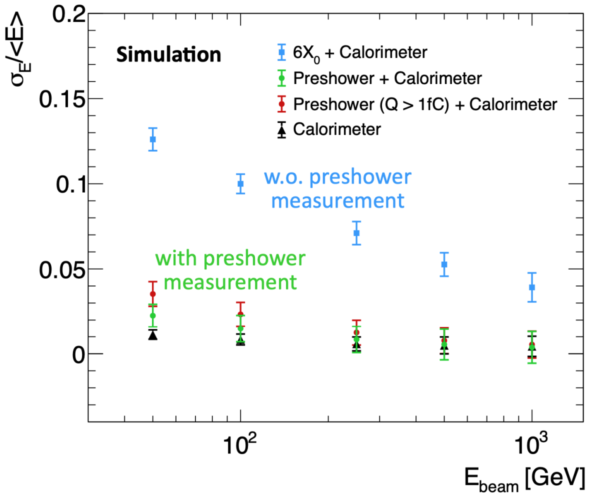

Figure 6. Energy resolution as a function of beam energy. The preshower detector does not degrade the performance of the energy measurement of the calorimeter with preshower correction for the energy above 100 GeV.

4 The SiGe monolithic ASIC

The monolithic active pixel sensor (MAPS) for the new preshower detector is produced in 130 nm Silicon-Germanium (SiGe) BiCMOS technology (SG13G2 by IHP Microelectronics). The SiGe heterojunction bipolar transistors (HBT), combined with CMOS transistors on the same die, provides fast signal amplification with low noise, enabling excellent time resolution. As shown in Figure 7, the pixels have hexagonal shape (65 µm side) to suppress high electric field on the edges, and the interpixel pitch is ~100 µm. The resistivity of the substrate is $220\,\Omega \cdot$ cm and its thickness is 130 µm including the epitaxial layer and the substrate. A negative bias voltage is applied to the back side, and the pixel capacitance is 80 fF. The main specifications of the sensor are a large charge dynamic range from 0.5 fC to 65 fC, a maximum readout time of 200 µs, a power consumption less than 150 mW/cm^2 and a time resolution better than 300 ps.

Prototypes from a pre-production run were received in June 2022. Tests of the pre-production ASICs show that

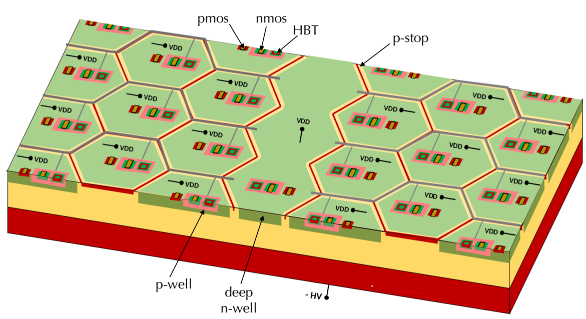

Figure 7. A sketch of the SiGe BiCMOS chip for the new FASER preshower [8].

all the main blocks, the front-end, flash ADC, pulsing circuit and readout logic, are functional. A large mismatch of Time Over Threshold (TOT) response of the front-end amplifier among the pixels was observed. The source of the mismatch was identified and it is corrected in the final design of the ASIC [10].

The final ASICs were fabricated and post-processed wafers were received in May 2024 (Figure 8). The ASICs are tested at a probe station for quality assurance. Module assembly is being performed with dedicated support tools in parallel with the quality assurance of the ASICs. Tests of the detector planes and the assembled detector will be performed in EHN1 at CERN using stray muons and cosmic rays.

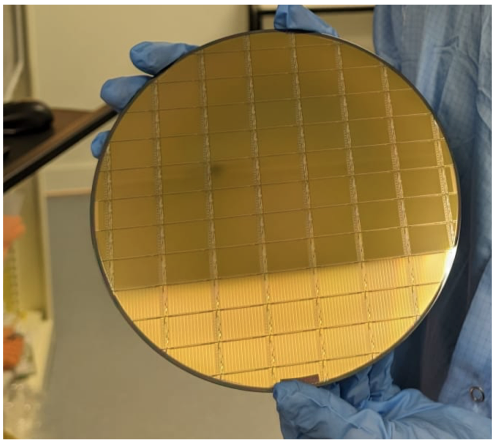

Figure 8. A post-processed wafer received in May 2024.

5 Summary

FASER searched for axion-like particles (ALPs) using data collected in 2022 and 2023. The dominant backgroud source was neutrinos interacting at the preshower detector of FASER. One event was observed in the signal region, with a background expectation of 0.42 ± 0.38. FASER successfully excluded an unprobed region in the ALP mass and coupling phase space. A W-Si high precision preshower detector is being developed to reduce the neutrino background. It allows resolving two high energy photons, coming from the decay of an ALP produced in the decay volume of the detector. The new preshower detector is based on a monolithic pixel ASIC developed in 130 nm SiGe BiCMOS technology. The pre-production ASICs are intensively examined and final ASICs were received in May 2024. The preshower detector will be tested on the surface and installed by the end of 2024. The detector will collect data during part of LHC Run 3 and High-Luminosity LHC.

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