PROCEEDINGS OF SCIENCE

The MUonE detector at CERN

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The MUonE experiment at CERN has been proposed as a novel approach to address the muon *g-2* anomaly puzzle through precise measurement of the differential cross section of elastic scattering $\mu e \to \mu e$. This measurement can be achieved using an intense 160 GeV SPS muon beam directed onto atomic electrons in a light target. In recent years, the project has advanced through tests of increasing complexity. The first performance results will be presented from the analysis of the 2023 test run, which used a minimal prototype setup and recorded events in triggerless mode during one week of data taking. The Phase-1 pilot run is scheduled for 2025 and will involve a four-week run with a reduced setup, including three tracking stations, an electromagnetic calorimeter, and new subdetectors: a spectrometer to measure the incoming muon momentum event by event, scintillator planes to probe the dependence on muon arrival time, and a muon filter to identify the scattered muons. All subdetectors will be operated by a newly developed DAQ system, featuring real-time processing and online selection based on FPGA technology at a frequency of 40 MHz. The status of the Phase-1 pilot run and future plans will be presented.

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1. Introduction

The persistent tension between the experimental measurement of the muon magnetic anomaly $a_\mu = (g-2)/2$ and the data-driven Standard Model (SM) prediction may indicate the presence of new physics. The MUonE experiment aims to provide a direct and independent determination of the hadronic contribution to the running of the electromagnetic coupling $\alpha(t)$ by exploiting elastic μe scattering in the spacelike region [1]. This measurement enables evaluation of the hadronic vacuum polarization (HVP) term entering a_μ without relying on e^+e^- annihilation data.

The final MUonE setup will consist of forty tracking stations, each with a thin low-Z target, followed by an electromagnetic calorimeter (ECAL) and a muon filter. The Phase-1 pilot run in 2025 used a reduced configuration to demonstrate the complete detection and data acquisition chain under realistic CERN SPS beam conditions.

2. Experimental Concept

Muons with a momentum of 160 GeV/c from the SPS M2 beamline scatter elastically off atomic electrons in thin Be or C targets (figure 1). The experiment measures the scattering angles of both the outgoing muon and electron. Kinematically, the muon angle is always less than 5 mrad. Measuring the shape of the differential cross-section allows extraction of $\Delta\alpha(t)$ and, consequently, the leading-order hadronic contribution a_μ^{HLO}.

Control of systematics is crucial and requires precise alignment, mechanical stability better than 10 µm, uniform tracking efficiency, control of multiple scattering, and accurate knowledge of the beam momentum to within a few MeV.

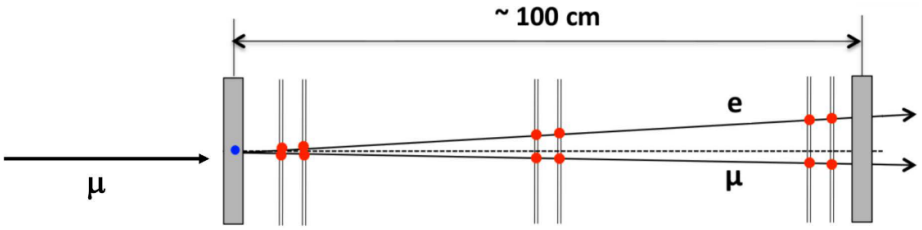


Figure 1: Schematic concept of one tracking station in the MUonE experiment: a high-energy muon beam scatters off atomic electrons in a thin target.

3. Phase-1 Detector Setup (2025)

The 2025 Phase-1 configuration (figure 2), installed on the CERN SPS M2 beamline, includes:

- Three silicon tracking stations with two carbon targets;
- A $PbWO_4$ electromagnetic calorimeter (ECAL);
- A muon filter downstream of the ECAL;
- A beam momentum spectrometer (BMS) upstream of the trackers;

- Timing scintillators for time-of-arrival correlation.

This setup reproduces, on a reduced scale, all the main elements of the final detector design.

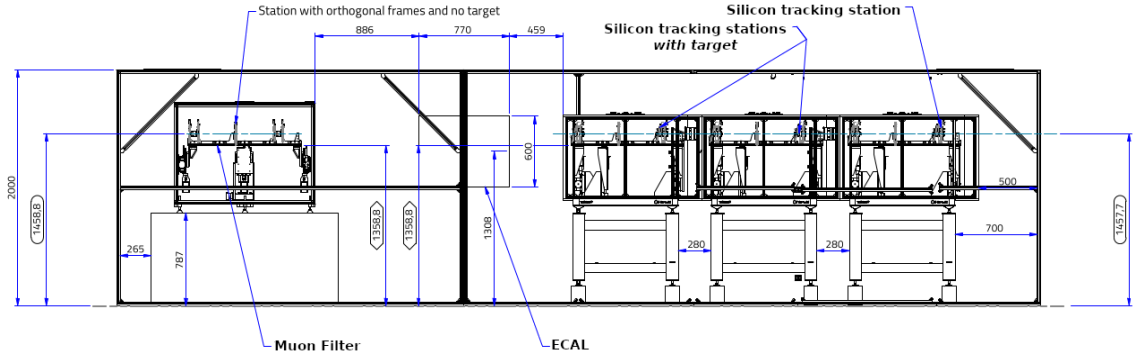


Figure 2: Mechanical layout of the MUonE Phase-1 setup installed on the CERN SPS M2 beamline. This setup is enclosed in an insulating tent. It includes three tracking stations, each equipped with CMS 2S modules (see text), an electromagnetic calorimeter, and a downstream muon filter station. The drawing shows the relative positions and overall dimensions of the apparatus in millimeters.

3.1 Tracking System and Alignment

Each tracking station consists of six "2S" silicon modules from the Phase-2 upgrade of the CMS experiment [2], arranged as two (X, Y) planes tilted by 233 mrad and one (U, V) plane rotated by 45°, as shown in the schematic in figure 3. The intrinsic resolution of the 2S modules is approximately 26 µm, which is improved by the tilt through charge sharing, achieving about 12 µm single-hit resolution.

Modules are mounted on an Invar support frame, called the "gondola", with integrated water cooling to maintain thermal stability. The gondolas are enclosed in a light-tight, humidity-controlled box and can be remotely aligned using stepper motors.

The 2025 alignment was performed in two steps:

1. A laser survey and 3D scan provided the initial module positions with approximately 100 µm precision.

2. A software alignment based on a χ^2 minimization procedure using clean single-muon tracks.

After alignment, the residuals between track and hit positions are centered within 0.05 µm, as shown in figure 4, demonstrating the excellent mechanical stability of the tracking system.

A Holographic Alignment Monitor (HAM) [4], based on digital holographic interferometry at 532 nm, measures relative plane displacements with approximately 0.25 µm sensitivity. Figure 5 shows part of a gondola with the 2S module illuminated by the laser of the HAM system. A future upgrade with IR lasers will enable continuous monitoring without interfering with the silicon sensors.

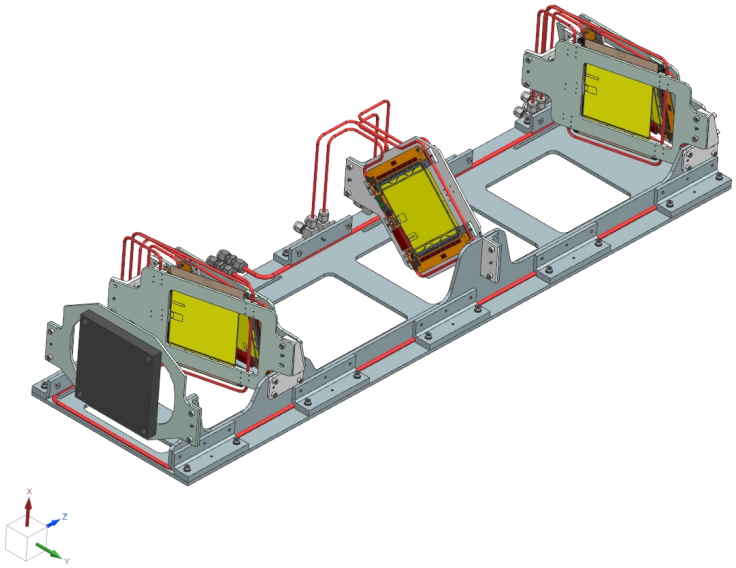


Figure 3: Schematic of a MUonE tracking station using CMS 2S modules (in yellow) arranged in an XY–UV–XY geometry (see text). The target is shown in black.

3.2 Electromagnetic Calorimeter

The ECAL consists of 25 $PbWO_4$ crystals (2.85×2.85×23 cm^3) on loan from the CMS ECAL. Each crystal is read out by a 10×10 mm^2 avalanche photodiode (APD) coupled to MGPA ASIC preamplifiers. The ECAL provides independent e/μ identification and measures electron energy from 1 to 150 GeV, enabling direct kinematic reconstruction and background rejection.

During the 2025 run, synchronized operation with the tracker was achieved, and the correlation between the reconstructed electron impact point and the calorimeter shower barycenter showed an RMS difference of 3.7–3.9 mm, consistent with design expectations.

3.3 Muon Filter and Scintillating-Fiber Prototype

The Muon Filter (MF) plays a key role in identifying scattered muons after the electromagnetic calorimeter (ECAL). Electrons are completely stopped in the ECAL, while muons continue through. By detecting these downstream tracks and correlating them with tracker information upstream of the ECAL, the MF enables effective muon identification and background rejection.

The 2025 Phase-1 configuration includes a Muon Filter station composed of four 2S tracking planes arranged in two X–Y pairs. Each 2S plane covers the full beam cross section and provides spatial resolution compatible with the upstream tracker. The system is fully integrated into the readout and synchronized with the 40 MHz DAQ clock. During the 2025 pilot run, the MF station operated stably and recorded data concurrently with all other subdetectors. Dedicated analysis is underway to quantify the muon detection efficiency and optimize its role in the event reconstruction chain.

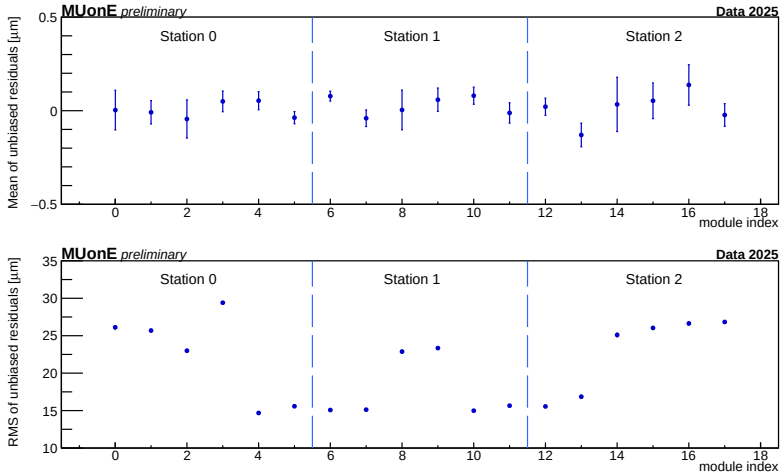


Figure 4: Summary plot showing the mean (top) and standard deviation (bottom) of the unbiased residuals for all 18 modules in the three tracking stations. The vertical blue lines highlight the different stations. A clear difference between tilted and non-tilted modules is visible. The standard deviation for the first and last pairs of modules is larger than for the other tilted modules, because the error on the track extrapolation is greater for those detectors under test.

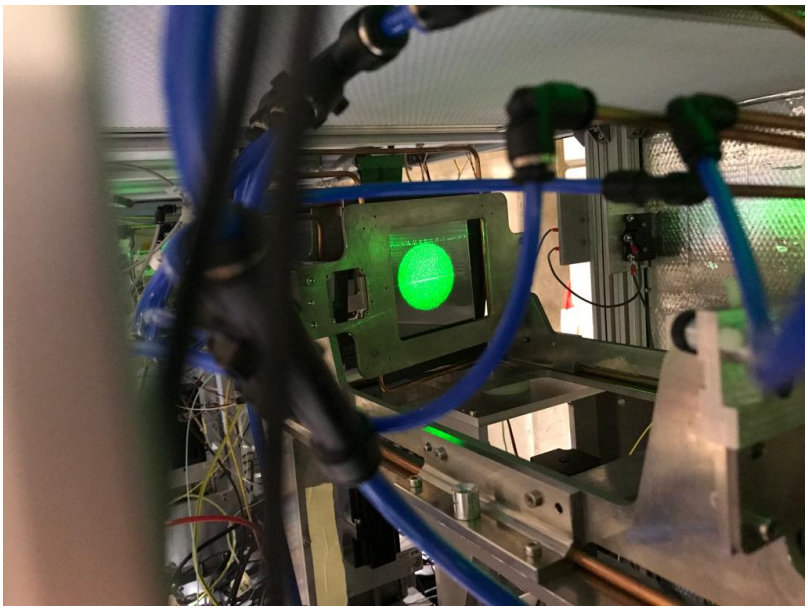


Figure 5: Detail of the MUonE tracking station: CMS 2S module illuminated by the HAM laser system.

In parallel, an R&D program is underway to develop an upgraded muon filter based on plastic scintillating fibers (SciFi). The goal is to design a compact, modular detector capable of covering large transverse areas with fine granularity, simple mechanics, and compatibility with the 40 MHz readout architecture. The SciFi prototype uses 0.5 mm diameter double-clad Kuraray SCSF-78 fibers arranged in double, staggered layers to eliminate dead zones. Individual bundles of four fibers are optically coupled to a single-channel silicon photomultiplier (SiPM) (Hamamatsu

S13360-1350). Custom front-end readout electronics are currently in development.

3.4 Beam Momentum Spectrometer

The BMS is based on two tracking telescopes installed before and after the M2 bending magnets, with a total bending power of 16 T·m (30 mrad at 160 GeV). It provides event-by-event momentum measurements with an expected precision better than 0.5%. The BMS will use the same 2S technology and DAQ infrastructure as the tracker.

4. Data Acquisition and Online Selection

The MUonE Phase-1 DAQ operates at 40 MHz and is based on the Serenity Z1 board equipped with two KU15P FPGAs [5]. All subdetectors (BMS, 2S tracker modules, ECAL, timing scintillators, and MuonID) are read out continuously through lpGBT (Low Power GigaBit Transceiver) links.

A first level of real-time selection is implemented directly in the firmware. For each station, the FPGA evaluates simple topological conditions based on the occupancy and stub pattern of the 2S modules, selecting events according to the hit pattern through the three tracking stations, as shown in figure 6(a). This serves as MUonE's effective online trigger, as in figure 6(b), reducing the data volume transferred downstream while preserving high efficiency for elastic scattering events. Selected fragments are sent via high-speed links to the second FPGA, where event building is performed using a common bunch-crossing identifier. Completed events are transmitted to the DAQ PCs through a set of 10 Gb/s Ethernet links with load balancing. A future upgrade will include real-time track finding as a second-level online selection.

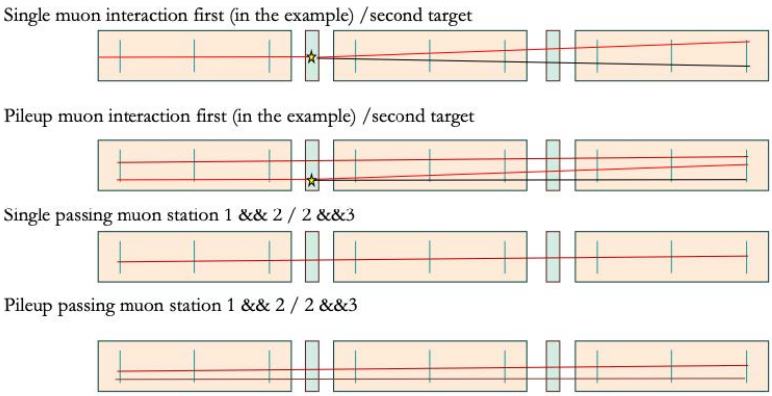
Accurate synchronization of the entire system is achieved through a combination of fast command alignment, DLL tuning in the 2S modules, and adjustable buffer delays on Serenity, ensuring deterministic timing across all stations at 40 MHz. During the 2025 run, the system reached stable operation, with firmware updates progressively improving synchronization, data integrity, and monitoring.

5. Results from the 2025 Phase-1 Run

The 2025 Phase-1 run marked the first integrated operation of the MUonE detector. Approximately four weeks of stable data taking were achieved as the main user of the M2 beamline.

Key results include:

- Excellent mechanical and thermal stability of the tracker, with residuals below 0.05 μm after alignment;
- Verified synchronization between the tracker, ECAL, Muon Filter and BMS systems;
- Reconstructed beam profile consistent between ECAL and tracker data;
- Successful operation of the FPGA-based DAQ at 40 MHz, validating data flow;
- First combined reconstruction of μe scattering events using all detector subsystems.



(a) Online trigger selection is implemented in the FPGA firmware based on the hit pattern in the three tracking stations. In the schematic, the muon beam direction is from left to right; the red line represents the muon track, while the black line represents the scattered electron. The larger orange blocks represent the stations, and the green blocks are the targets, with the hit marked by a star.

(b) Screenshot of the Grafana page showing an example of the different online trigger rates. The maximum trigger rate (single/double passing muons) is on the order of 1 MHz with a beam intensity of ≈ 40 MHz.

Figure 6: Effective online trigger selection logic and a screenshot from Grafana during data taking, showing the rates for the different cases.

6. Outlook

The 2025 Phase-1 run marks a major milestone toward the full MUonE experiment. Analysis of these data will enable the first measurement of the leptonic and, with less precision, hadronic running of $\alpha(t)$, as well as an evaluation of systematic uncertainties.

Future activities will focus on several experimental aspects, depending on the results of the 2025 data analysis, with special attention to:

- Optimization of FPGA-based online filtering;
- R&D and further improvement of the detectors (e.g., the IR-laser HAM, SciFi Muon Filter);
- Preparation of a proposal for the full 40-station detector for operation after the LHC Long Shutdown 3 (expected $\sim$ 2029).

Acknowledgments

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