The MUonE detector at CERN

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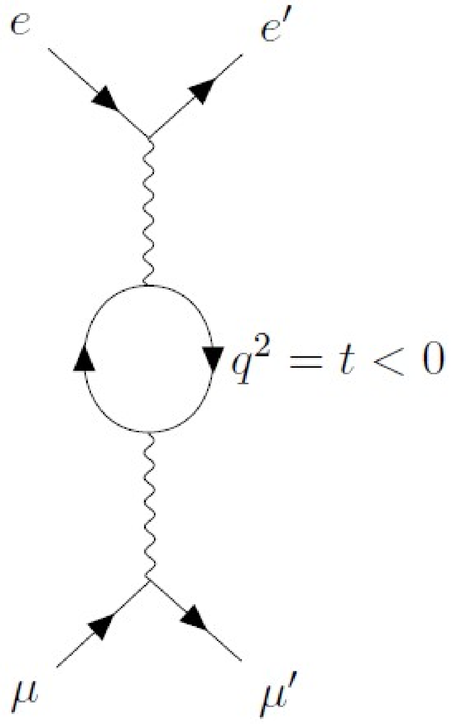
Istituto Nazionale di Fisica Nucleare

MUonE

- Experiment proposed at CERN
- Phase I ongoing on M2 beamline, 2025 run
- Direct indipendent determination of the hadronic contribution to the g-2 anomaly
- Measure of the angular distribution from μ-e scattering
- Aims to a precision of ~0.5%
  - ~3 years of data taking (integrated luminosity ~1.5x10^4 pb^{-1})

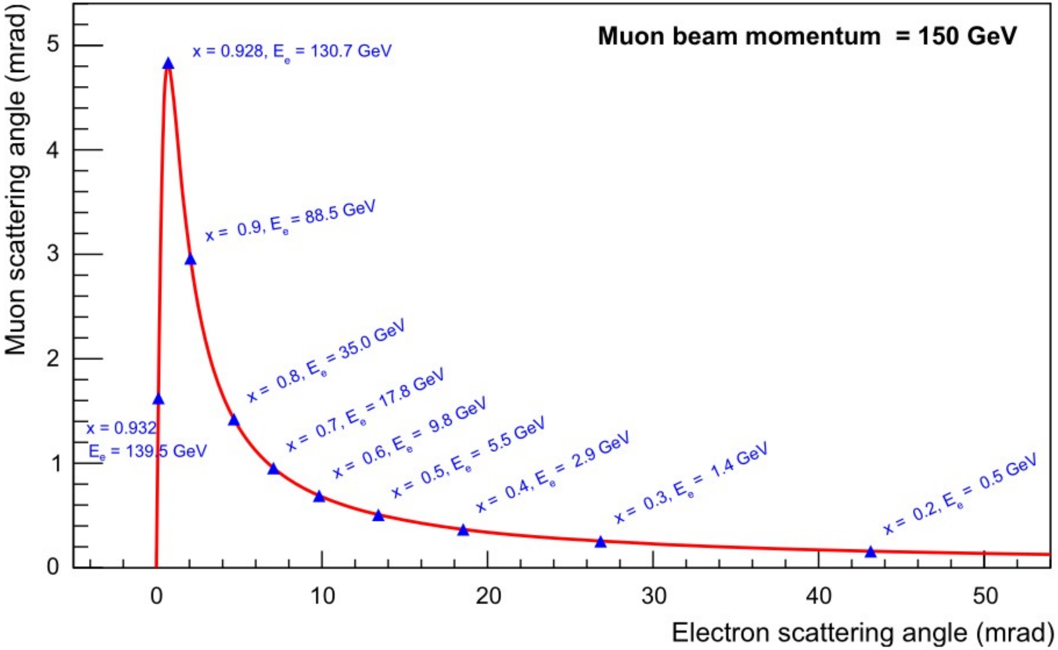


MUonE experiment

- Elastic curve (leading order)
- Scattering angles of the leptons:

  $0 < \theta_\mu < 5\ mrad$

  $0 < \theta_e \lesssim 32\ mrad$

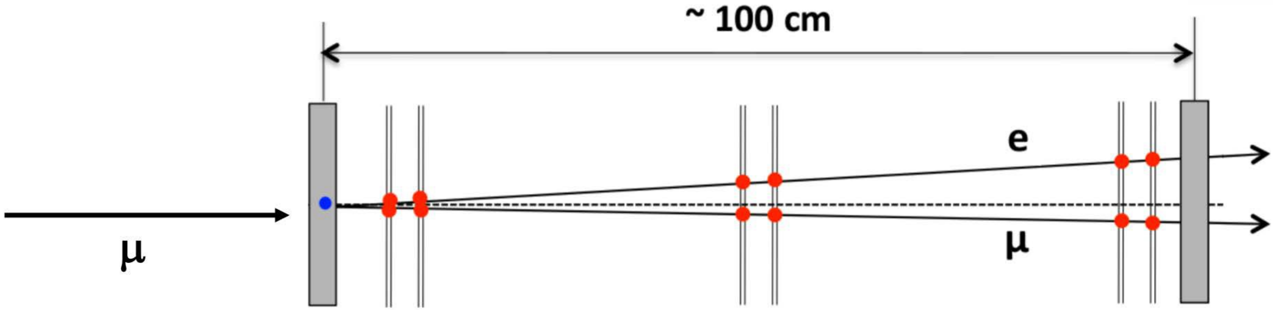


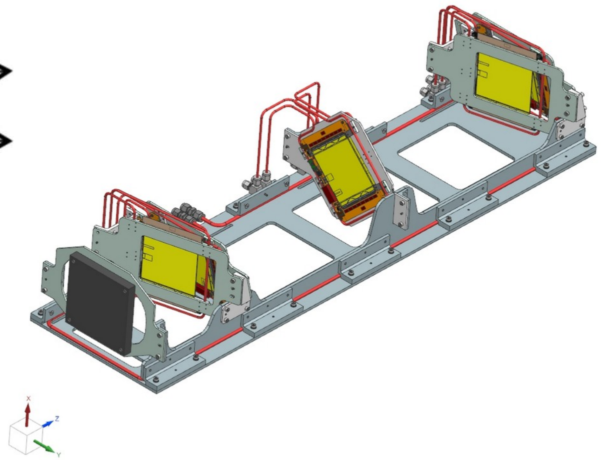
Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

Considerations and requirements

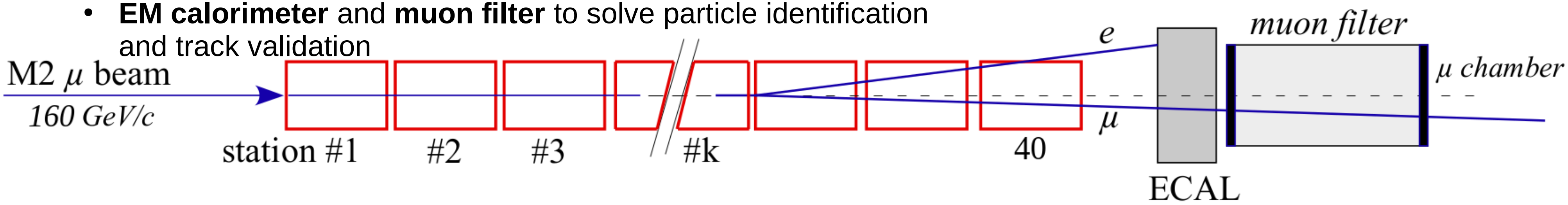
- In order to control the systematic errors:
  - Extreme precision in the alignment and detector stability
  - Uniform efficiency in the all the range of angles
  - Background discrimination, e.g. pair production events, by direct measure and simulations
  - Precise measure of the beam energy (few MeV)
  - Angular resolution
  - Study of the Multiple Scattering effects

MUonE: Setup

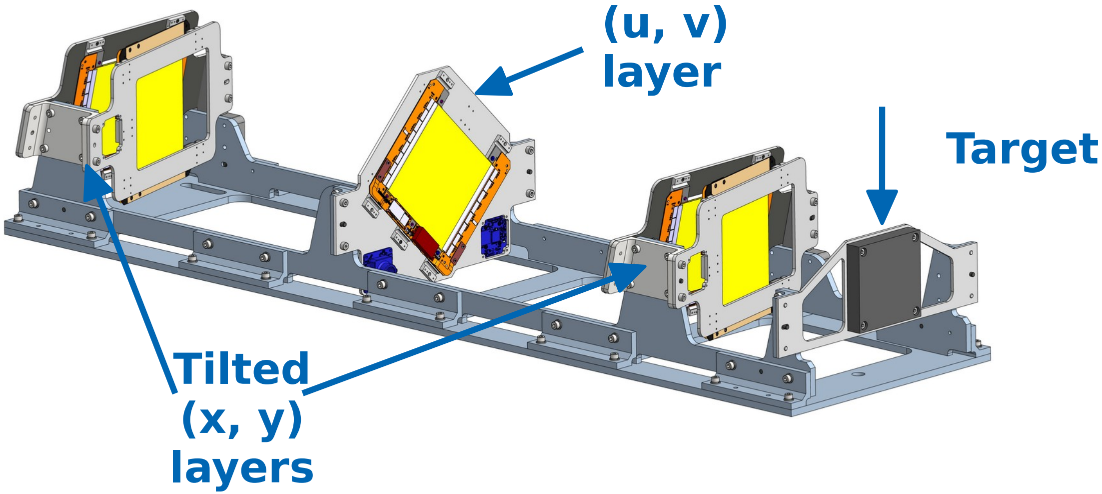


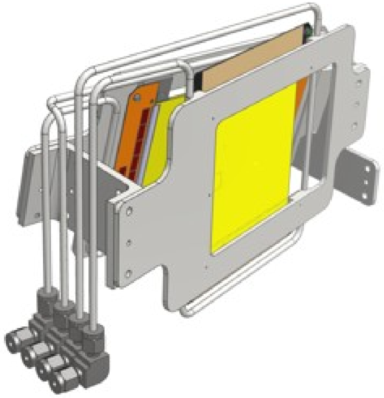


- Tracking station made by 6 planes of **silicon microstrip sensors** (**CMS 2S Modules**)
- **Modules arranged in perpedicularly oriented pairs** (**X** and **Y coordinates**)
- Middle pair rotated by 45° to resolve ambiguity (**U** and **V**)
- **Be** or **C** 1.5-2 cm target
- Final version: **40 tracking stations**
- **EM calorimeter** and **muon filter** to solve particle identification and track validation



Tracking Station

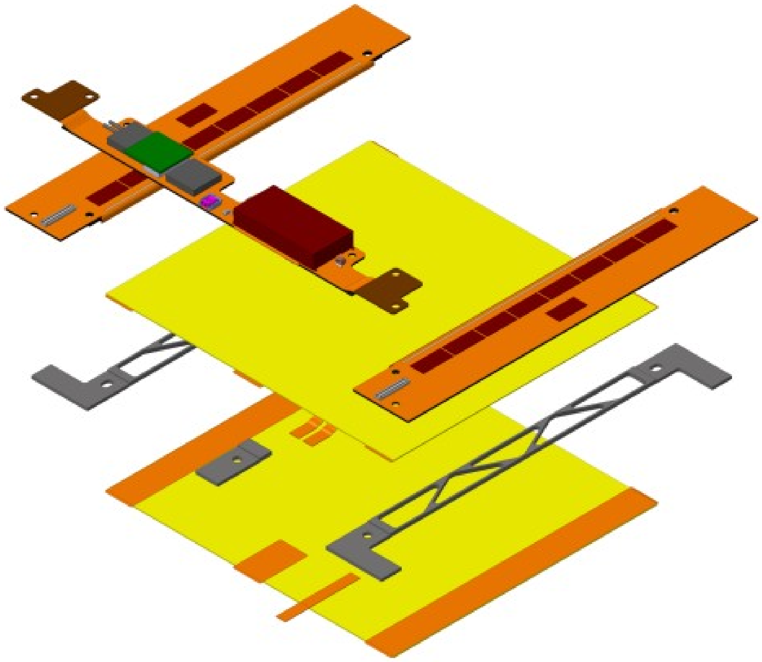




- (x, y) layers tilted by 233 mrad: improved hit resolution
- Modular layout: each station is an indipendent detector

2S modules

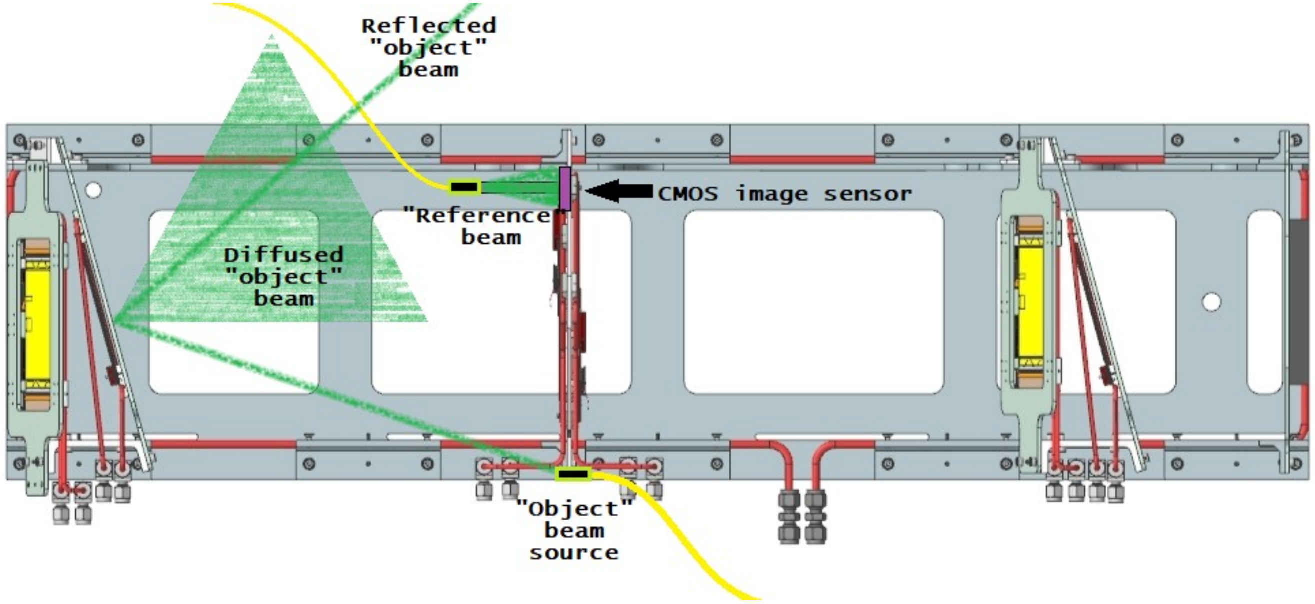
- Silicon strip sensors developed for the CMS-Phase2 upgrade.
- Two close-by strip sensors reading the same coordinate and read-out by the same electronics.
- 40 MHz readout rate
- Active area ~90x90 mm^2
- Digital readout, 90 µm
  - Resolution ~26 µm

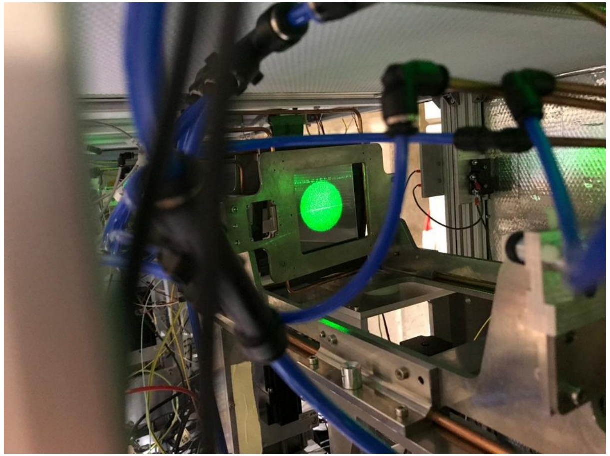


https://cds.cern.ch/record/2272264/files/CMS-TDR-014.pdf

Holographic Alignment Monitor

- Monitoring system of the relative displacement between tracking planes
- Relative position of the sensors within a station must be stable < 10 μm
- Developed using custom digital holographic interferometric methods
- Sensibility ~0.25 micron (half wavelength) – 532 nm fiber-coupled laser



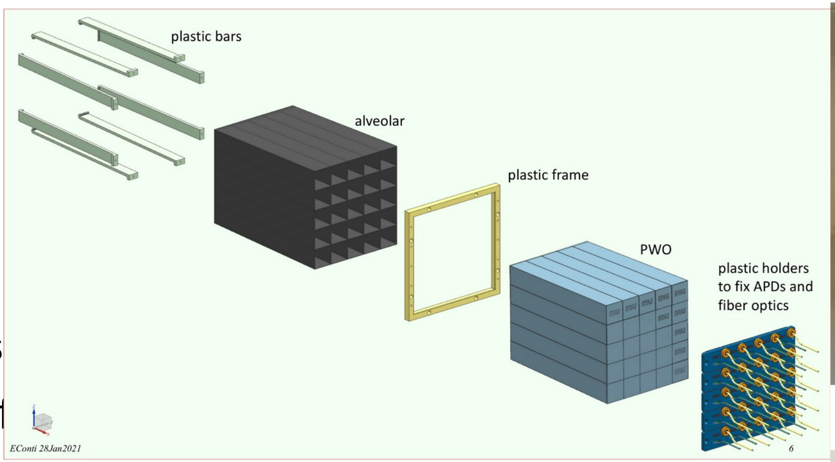


Holographic Alignment Monitor

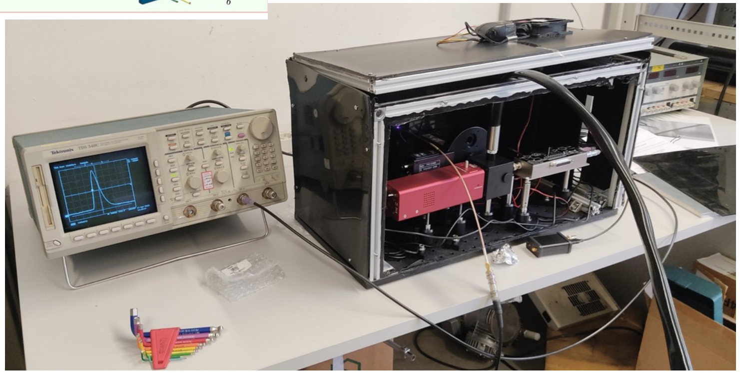
- Current setup limitation:
  - It is not possible to constantly take data since the 2S modules are sensitive to visible light
- Use of IR laser (~>1500 nm) where the silicon sensors are not sensitive
- An IR laser setup would make possible to monitor the stability more precisely without gaps

Electromagnetic Calorimeter

- 25 lead tungstate crystals, $PbWO_4$ used in the CMS ECAL:
  - Area: 2.85×2.85 cm^2
  - Length: 23 cm (~25 X_0)
- APDs coupled to the crystals
- Measure electron energies of 1-150 GeV
- Useful also for an indipendent direct measure of the hadronic running $\Delta\alpha_{had}$.



Fiber-coupled laser calibration system →

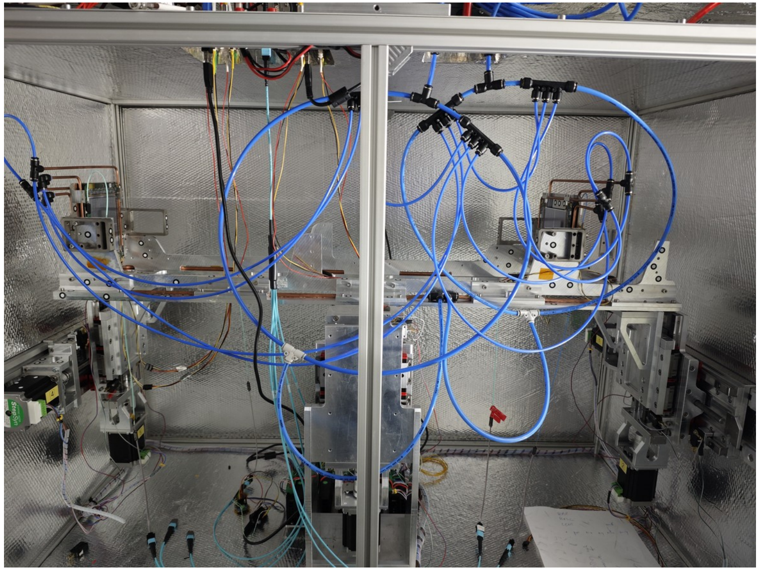


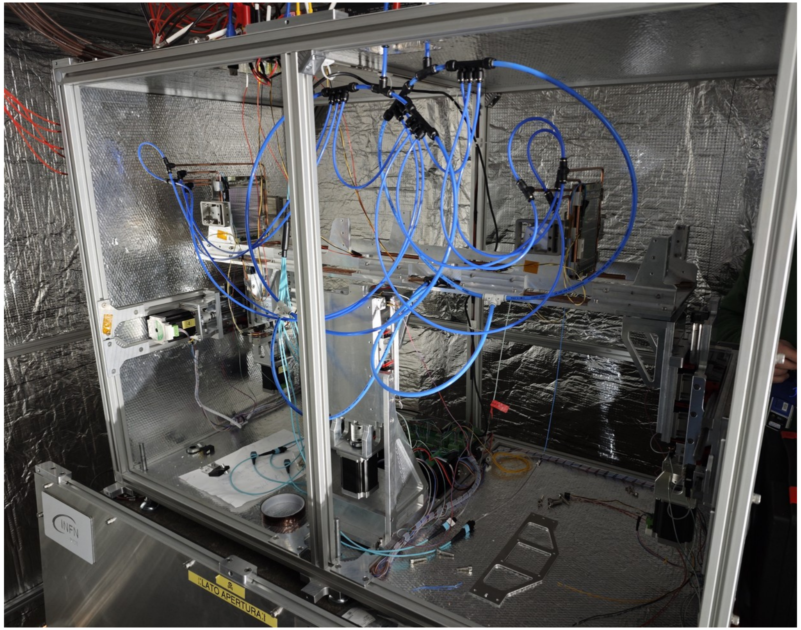
Muon Filter

- General idea:
  - track muons after the ECAL, where electrons have been absorbed
  - improve PID by connecting with tracks before the ECAL
- Requires the coverage of the beam cross-sectional area after the ECAL
- Precise study of the Multiple Scattering effects
- Four 2S modules (2 pairs of X-Y) in the current version of the 2025 detector
- 2S Modules or Scintillating Fibers (R&D) for the final detector

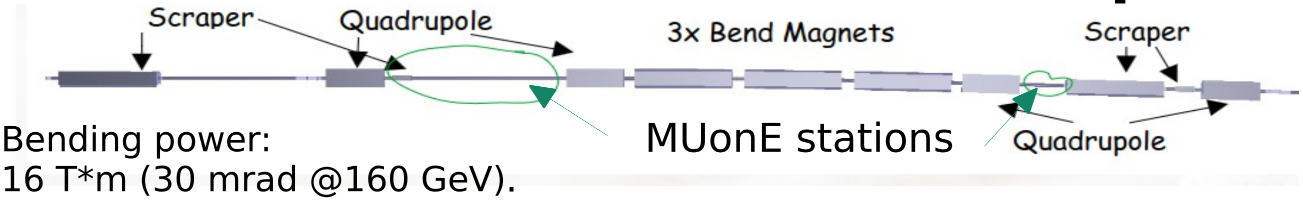
Muon Filter 2025

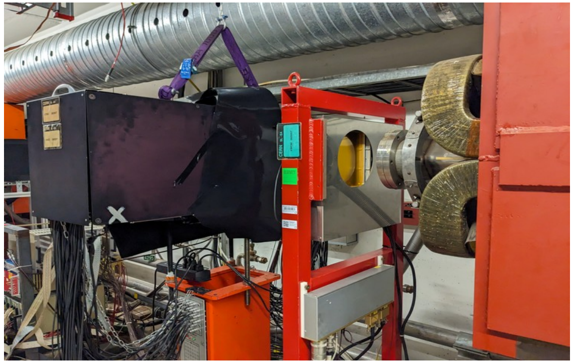
- Use of the CMS 2S modules
- 2 X-Y non-tilted planes



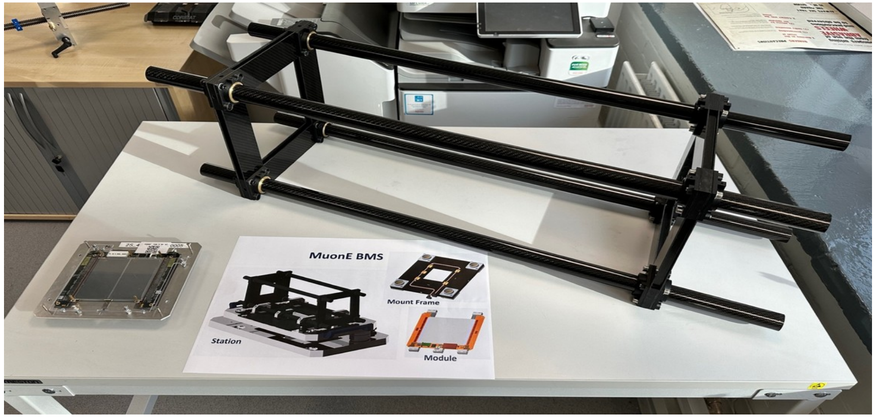


Beam Momentum Spectrometer



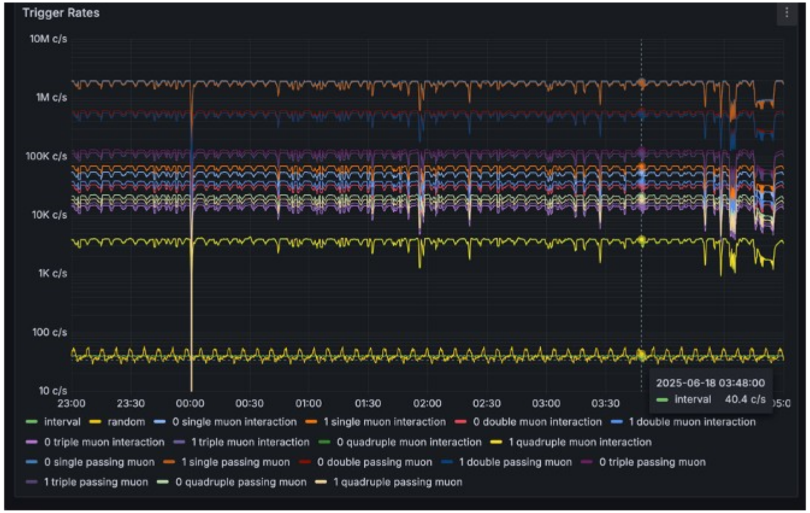


- Bending power:
  16 T*m (30 mrad @160 GeV).
- Determine the muon momentum event by event.
- Goal: < 0.5% momentum resolution.
- In 2025, limited by the precise knowledge of the magnetic field.



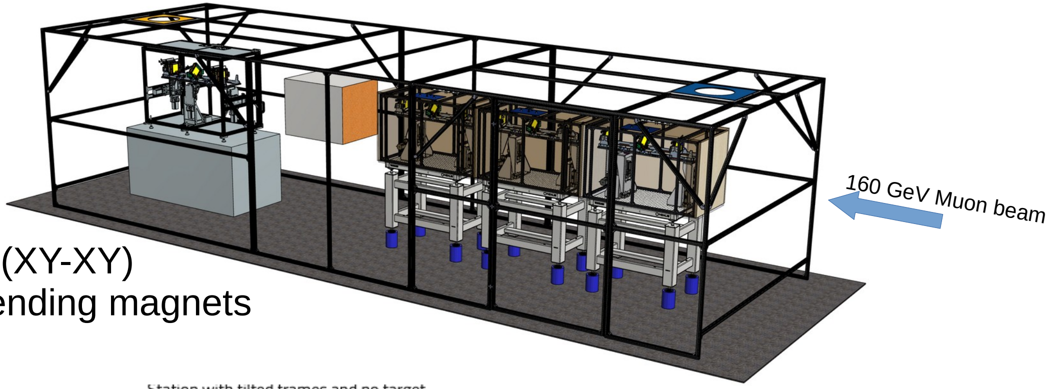
MUonE DAQ

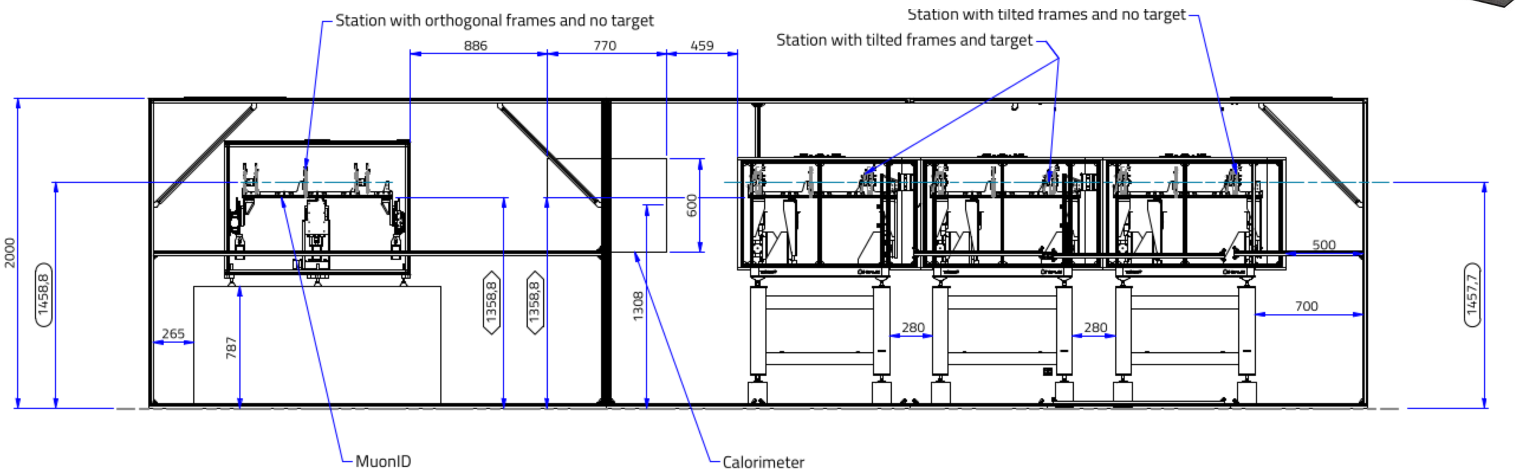
- FPGA-based readout, triggerless architecture at 40 MHz clock cycles
  - MUonE DAQ uses the Serenity processing card for CMS Phase-II upgrade
- DAQ firmware split over 2 FPGAs:
  - Stage 1: manages interface with on detector electronics, event selection using tracker information
    - Event selection using tracker module occupancy used and demonstrated to be effective
  - Stage 2: event building, ethernet interface
    - General-purpose AXI-stream event builder collates fragments from each sub detector into a coherent packet
- Online decoding provides analysis-ready NTuples in real time, highly scalable. Built upon kubernetes to provide fault tolerance



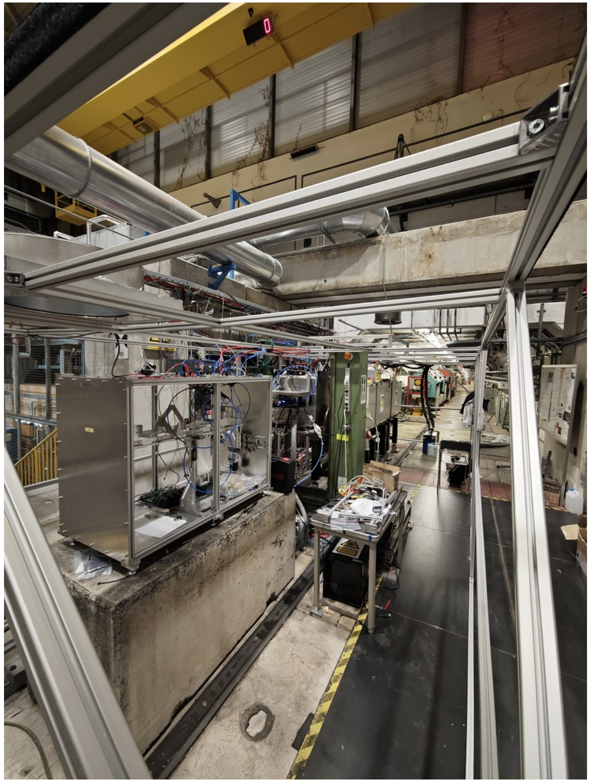
MUonE Phase I Apparatus 2025

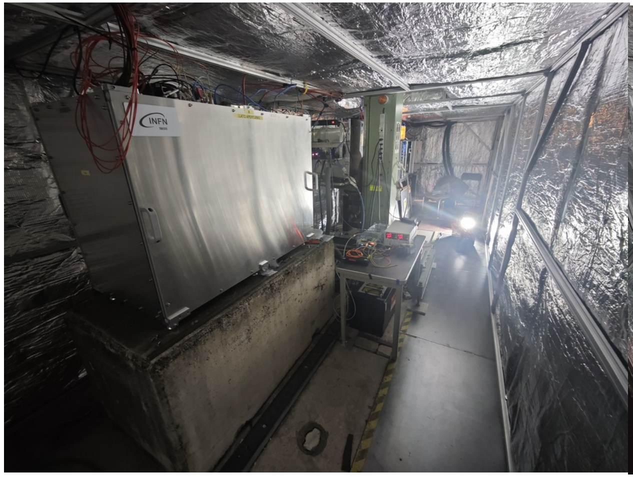
- Mini MUonE experimental setup:
  - 1st station without target
  - 2nd and 3rd stations with 2 cm C target
  - ECAL
  - MuonID station with 4 tracking planes (XY-XY)
  - Upstream: 2 BMS stations between bending magnets



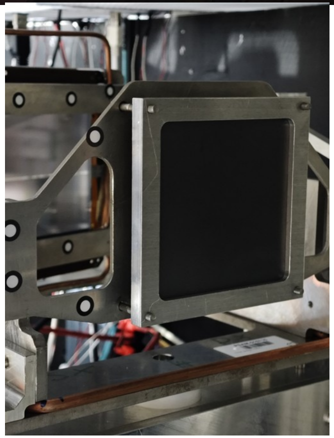


MUonE Phase I Apparatus 2025





MUonE detectors during installation and after (inside the tent)



Tracker Alignment

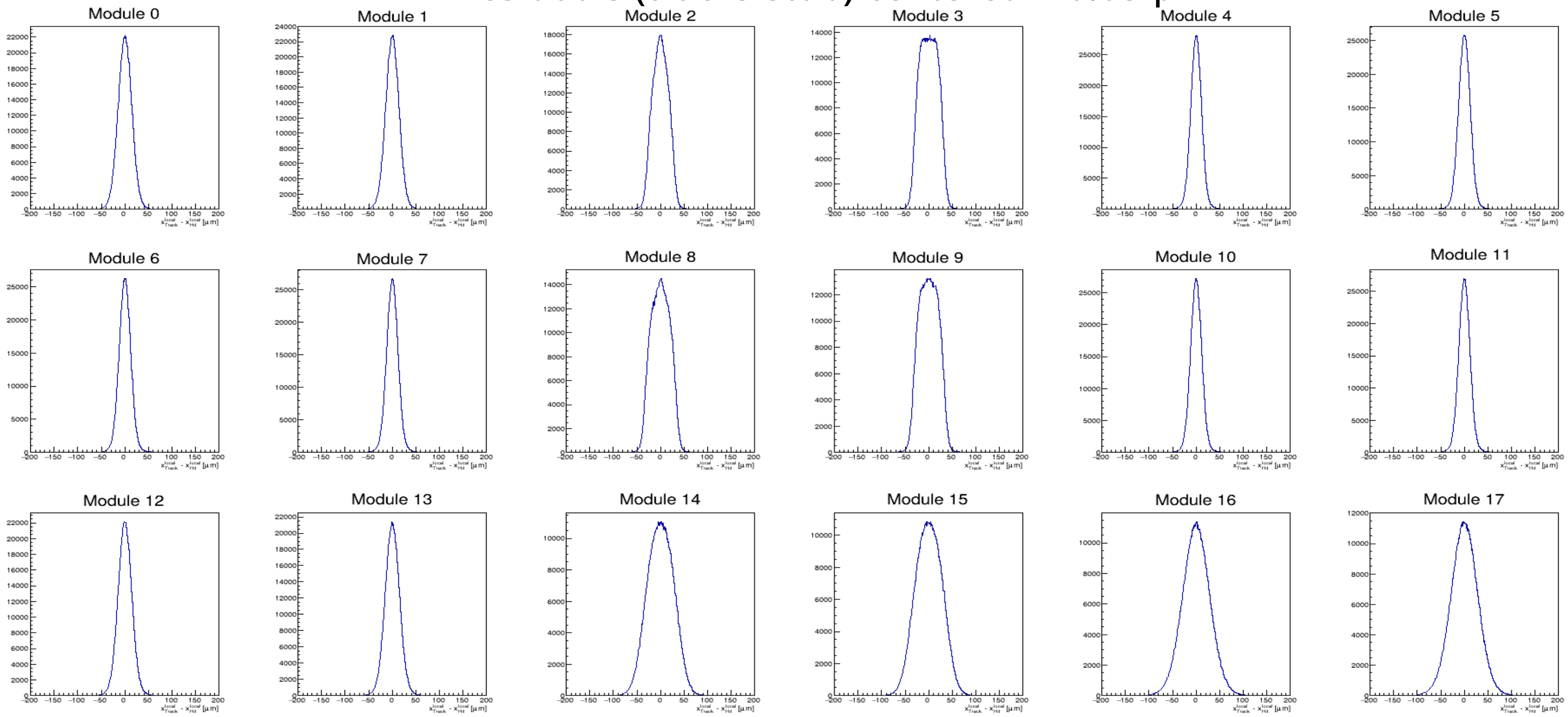
- Hardware, using stepper motors:
  1) Center each 2S module to the beam < 500 μm
  2) Align the longitudinal axis of each station to the beam axis < 0.5 mrad
  3) Align the 3 stations one relative to the other < 200 μm

- Software: local χ^2 minimization on a sample of clean single passing muon events (1 stub/module = 18 stub/event).

- 3D scanning + laser survey to determine the position + orientation of each module with ~100 μm precision. Result of these surveys will be used as starting point of the software alignment.

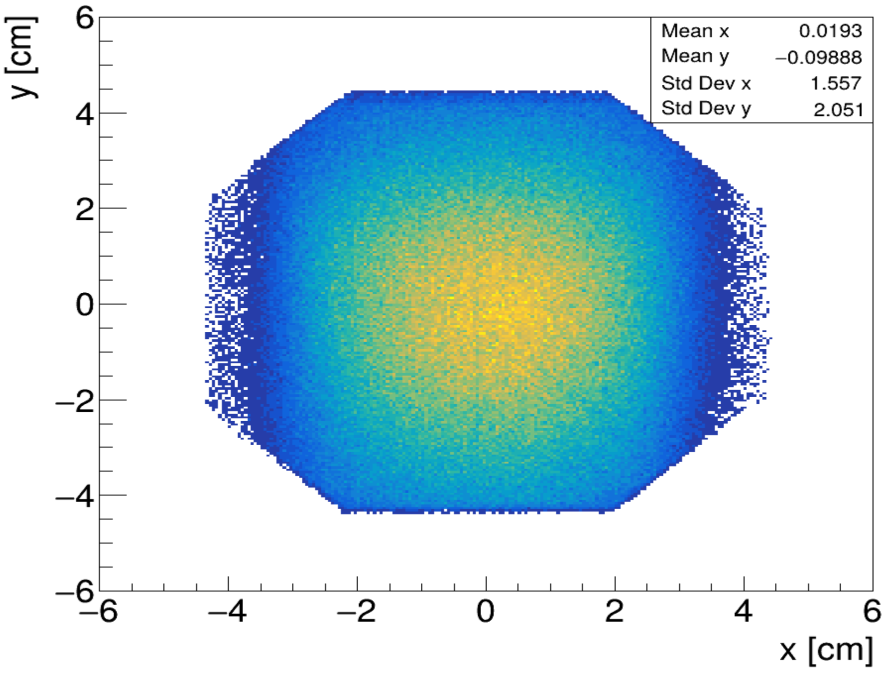
Tracker Software Alignment

Residuals (tracks-stub) centered < 0.05 µm

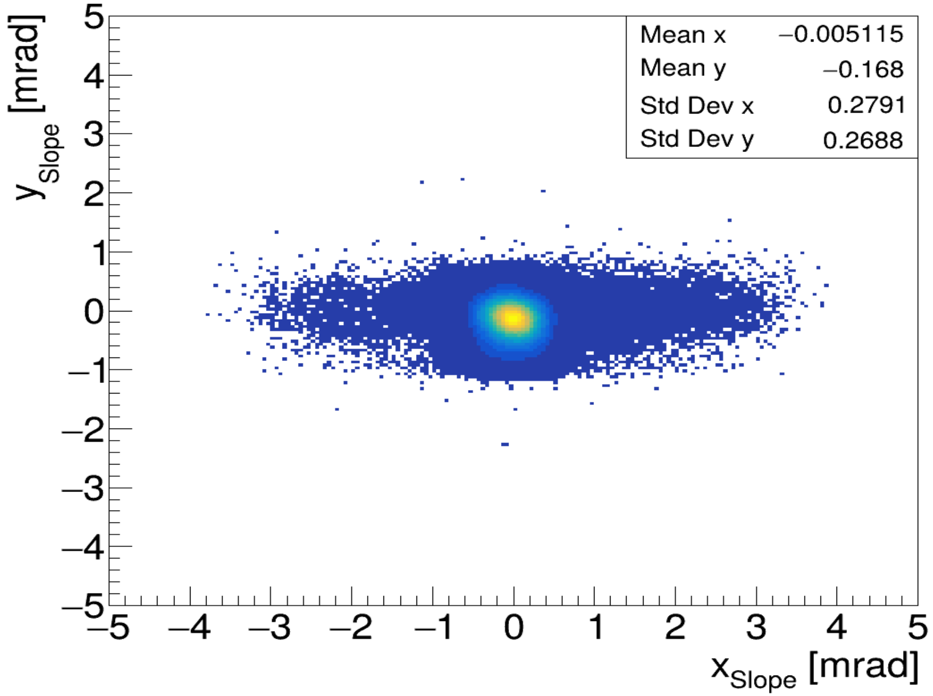


Beam Characteristics

Beam spot @ 1st target



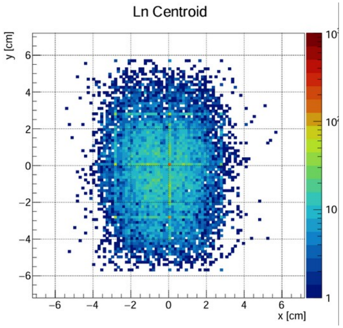
Beam direction



Sync test between ECAL and Tracker with High Intensity beam

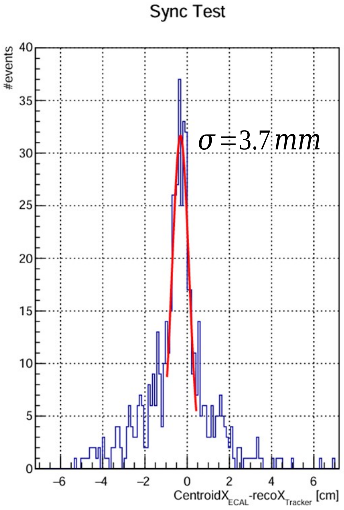
Electrons scattered off a target using the **trackers** and the **ECAL**

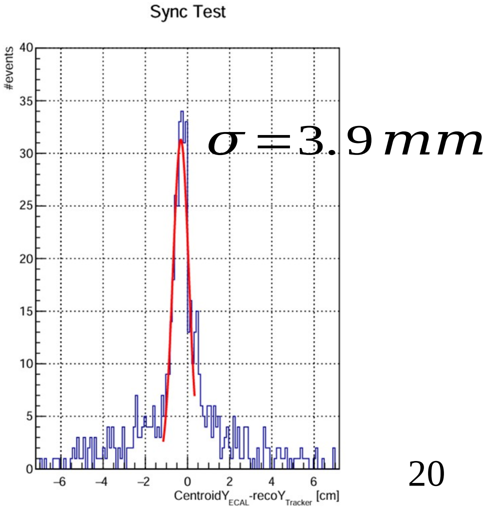
- **Precise timing and alignment** between these systems is essential for reconstructing particle events correctly — especially under challenging high-rate (pile-up) conditions.
- Event selection criteria for the test:
    - Events with energy > 20 GeV
    - High-quality tracking information
- **Excellent agreement** between the position measured by the ECAL and the one predicted by the tracker.
- **Beam profile** extracted directly from calorimeter data, confirming the expected beam shape during the high-intensity muon run.



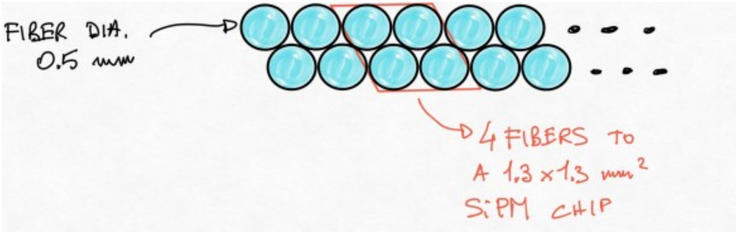
Beam Profile (from ECAL):Reconstructed using energy clusters from scattered electrons

Spatial Agreement between Tracker and ECAL:
The difference in reconstructed particle position is within ~4 mm in both X and Y directions

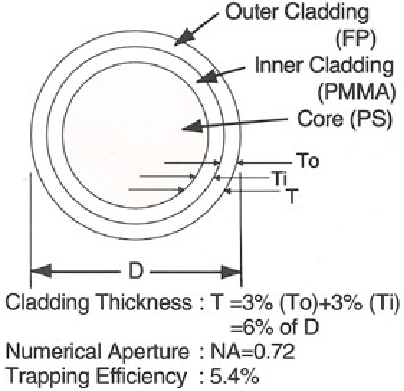




SciFi Muon Filter

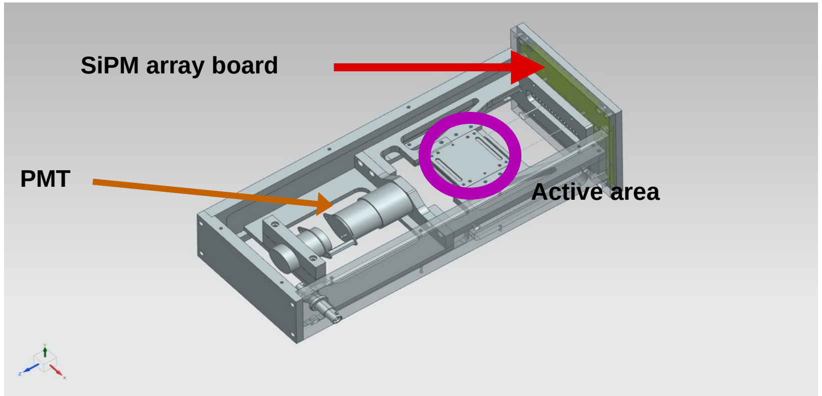


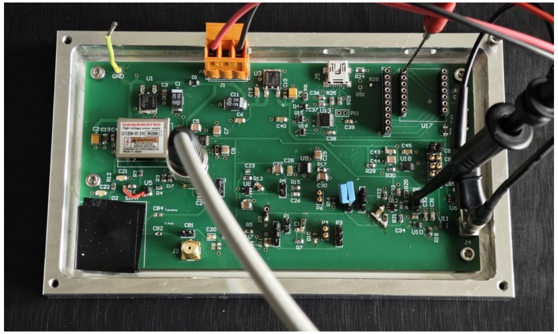
- Polystyrene (PS) round fibers, multi cladding (6% of the thickness)
- 88% of mechanical effficiency for single layer SciFi array
- Used double and shifted layers array – 4 fibers coupled to 1 SiPM
- Pitch 1.25 mm – resolution ~360 μm



SciFi Muon Filter Prototype

- 0.5mm dia. plastic scintillating fibers (Kuraray SCSF-78)
- SiPMs 1.3x1.3 mm^2 (Hamamatsu S13360-1350)
- PMT (Hamamatsu R1924A)
- Easy to cover large beam cross sections – easily scalable
- “Simple” mechanics
- Custom Front-End electronics in development





Conclusions

- The MUonE Phase I is ongoing with reduced setup – MiniMUonE
- 3 more weeks of data taking as main users of the M2 beamline
- Next step:
  - Analysis of the data taken during 2025
  - R&D activities to improve the experimental apparatus
    - e.g. SciFi Muon Filter, IR HAM, mechanics of the tracking stations..
- Full Setup ready after the Long Shutdown 3 (~2029)
- More info about the MUonE experiment with some preliminary results will be given in Eugenia Spedicato’s talk “*Tackling the muon g-2 anomaly with the MUonE experiment at CERN*”