Faculty of Physics
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The MUonE detector at CERN

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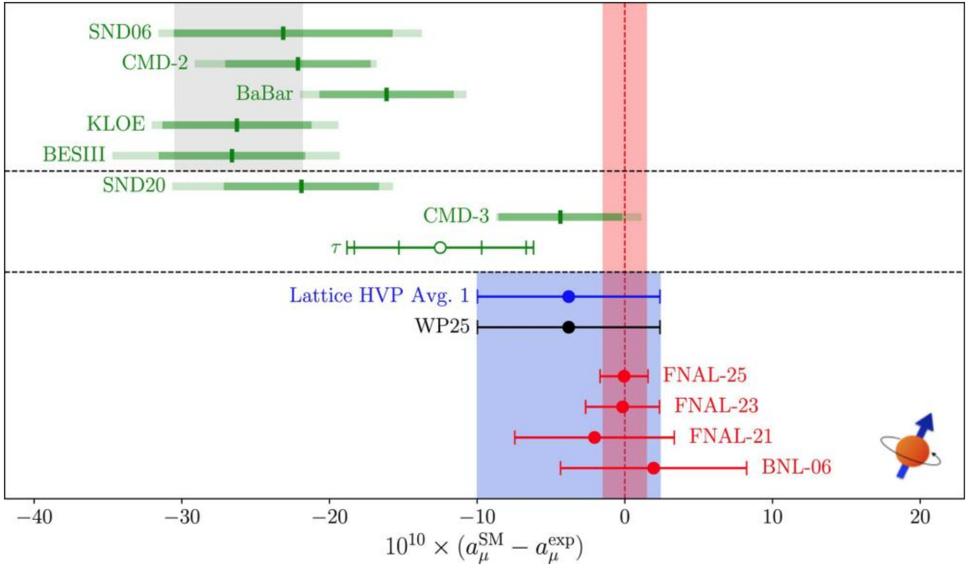
On behalf of the MUonE Collaboration

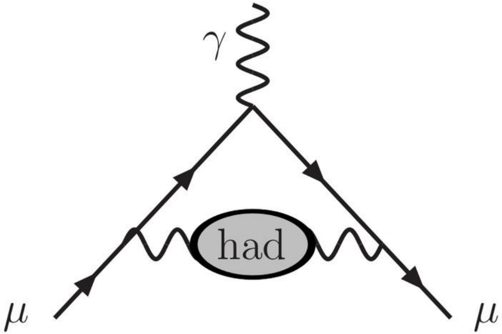
14th Beam Telescopes and Test Beams Workshop, Mainz, Germany.

Istituto Nazionale di Fisica Nucleare

Muon g-2: current status



https://www.sciencedirect.com/science/article/pii/S0370157325002157



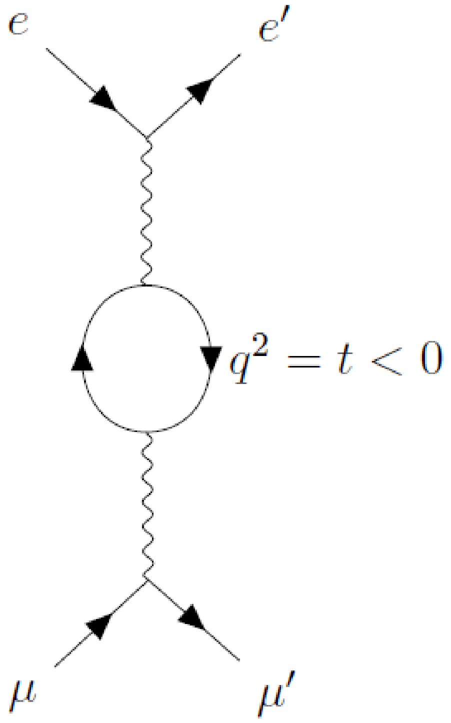
Main source of uncertainty of the theoretical prediction

Tensions in the evaluation of $a_\mu^{HVP,LO}$ using lattice QCD (WP2025)or e^+e^- hadronic cross sections

A clarification of the theoretical prediction is needed

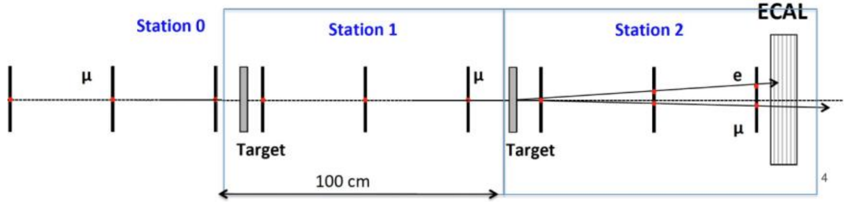
MUonE

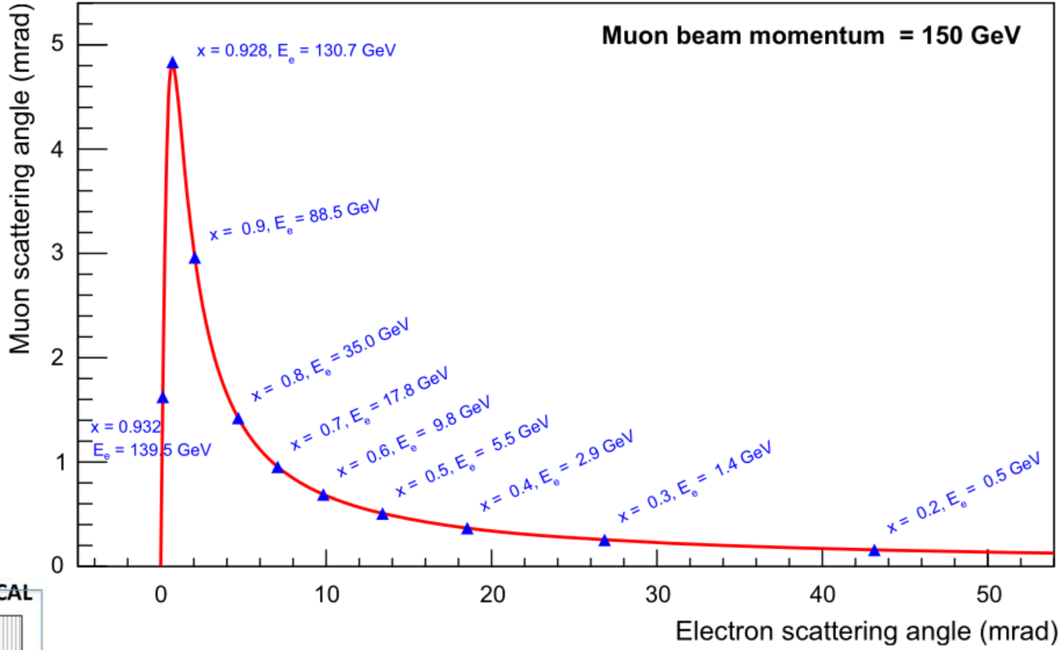
- Experiment proposed at CERN
- Phase-1 pilot run carried out on M2 beamline, summer 2025
    - ~160 GeV muon beam scattered on fixed target
- Direct independent determination of the hadronic contribution to the muon g−2 anomaly
- Measurement of the angular distribution from μ–e elastic scattering
- Aims at a precision of ~0.5%
    - ~3 years of data taking (integrated luminosity ~1.5×10^4 pb^{-1})



MUonE experiment

- Elastic curve (leading order)
- Scattering angles of the leptons:
  - $0 < \theta_\mu < 5$ mrad
  - $0 < \theta_e \lesssim 32$ mrad





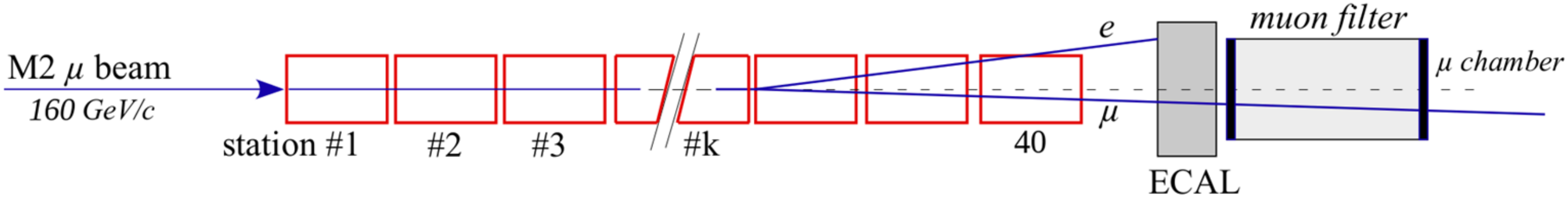
Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

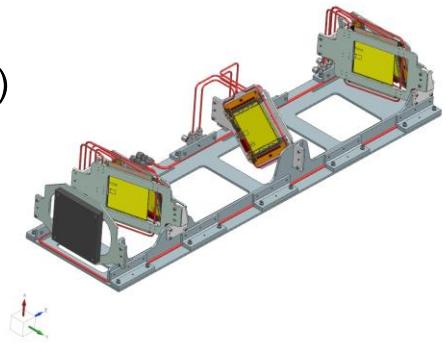
Considerations and requirements

In order to control the systematic errors:

- Extreme precision in the alignment and detector stability
- Uniform efficiency over the full range of angles
- Background discrimination, e.g. pair production events, by direct measurement and simulations
- Precise measurement of the beam energy (few MeV)
- Angular resolution
- Study of Multiple Scattering effects

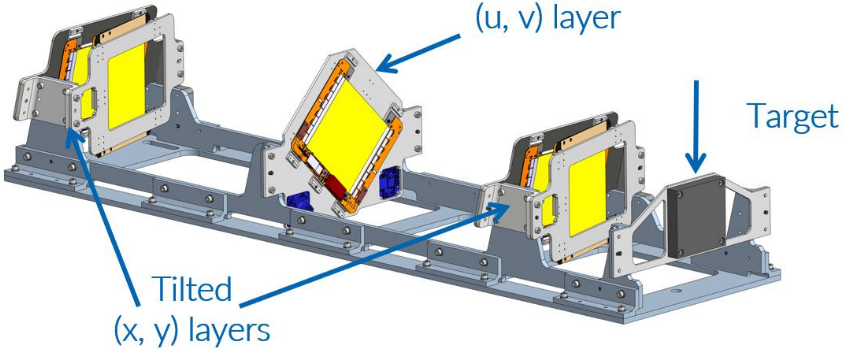
MUonE: Setup

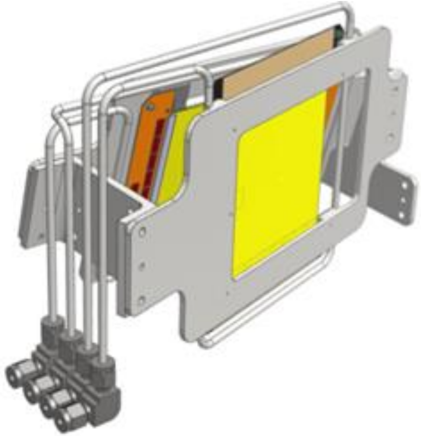




- Tracking station: 6 planes of silicon microstrip sensors (CMS 2S Modules)
- Modules arranged in perpendicularly oriented pairs (X and Y coordinates)
- Middle pair rotated by 45° to resolve ambiguity (U and V)
- Be or C 1.5–2 cm target
- Final version: 40 tracking stations
- EM calorimeter and muon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

Tracking Station

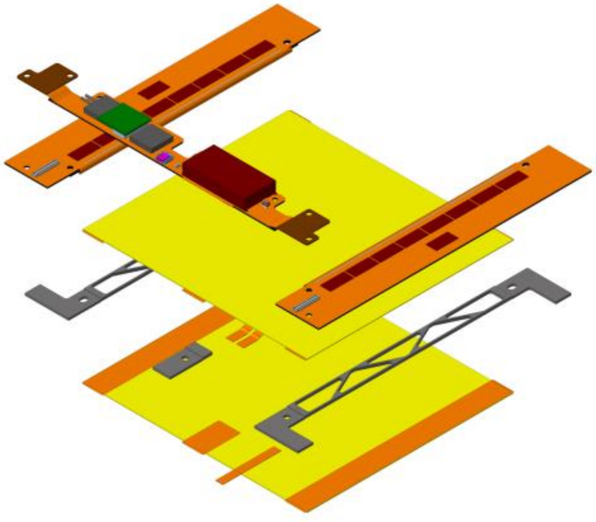




- (x, y) layers tilted by 233 mrad: improved hit resolution, charge sharing increased
- Modular layout: each station is an independent detector
- Frames made from Invar (iron/nickel alloy): CTE ~1.2 ppm/K, stability < 10 μm
- Stepper motors for alignment; laser holographic system monitors stability

2S Modules

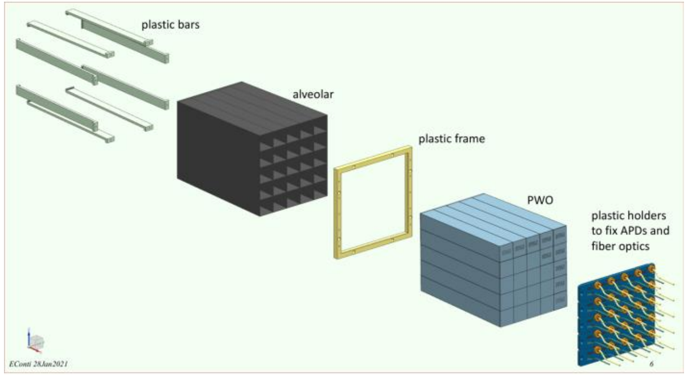
- Silicon strip sensors developed for CMS Phase-2 (HL-LHC) Outer Tracker - CMS-TDR-014.pdf
- Two close-by strip sensors reading the same coordinate, read out by CBC3.1 ASICs
- Correlations between sensors → "stubs" read out at 40 MHz
- Active area ~10×10 cm²; 90 μm strip pitch, 4064 channels per module
- Binary readout → resolution ~26 μm
- All MUonE tracking systems (TK, BMS, μFilter) use the same technology



CMS Tracker TDR

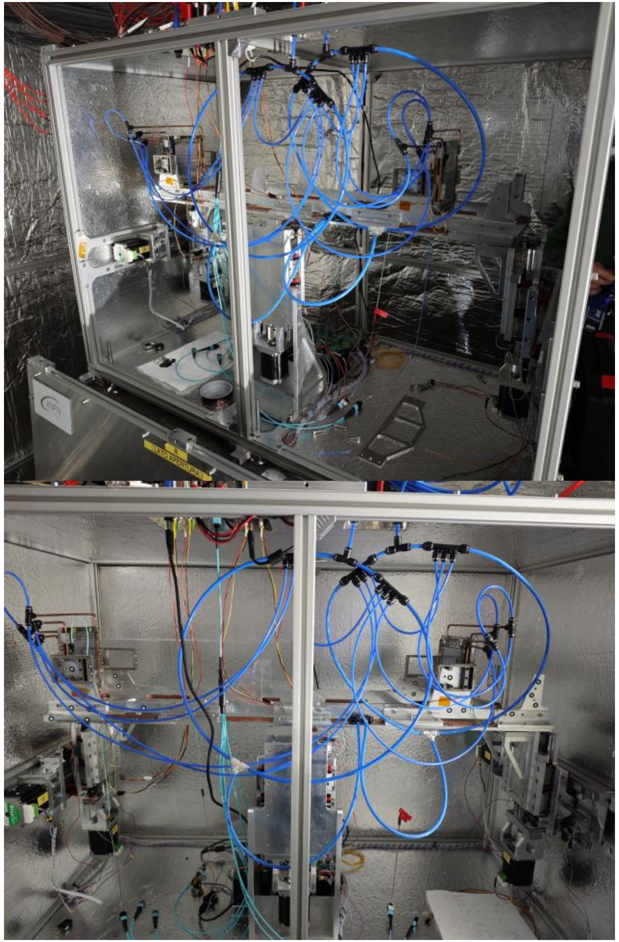
Electromagnetic Calorimeter

- Prototype used in MUonE Phase-1 2025
- 25 lead tungstate crystals ($PbWO_4$) from CMS ECAL endcap
    - Area: 2.85 × 2.85 cm²; Length: 22 cm (~25 X_0)
- APDs coupled to the crystals; MGPA preamplifier ASICs + 16-bit ADCs
- Transmission to DAQ via FC7 at full 40 MHz rate
- Covers ~14 × 14 cm²
- Independent measurement of electron energies (1–150 GeV)
- Compare energy against track angle to filter radiative background
- Also useful for an independent direct measurement of Δα_had

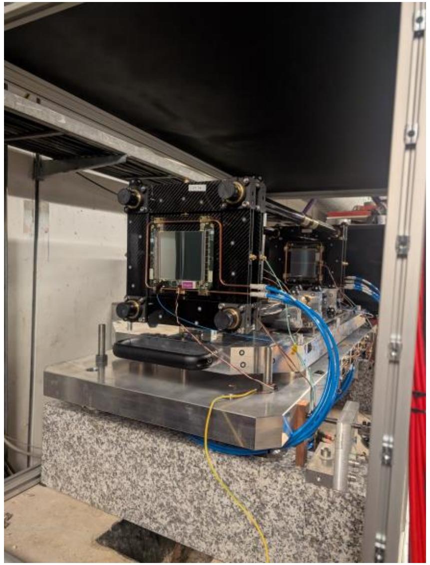


Muon Filter

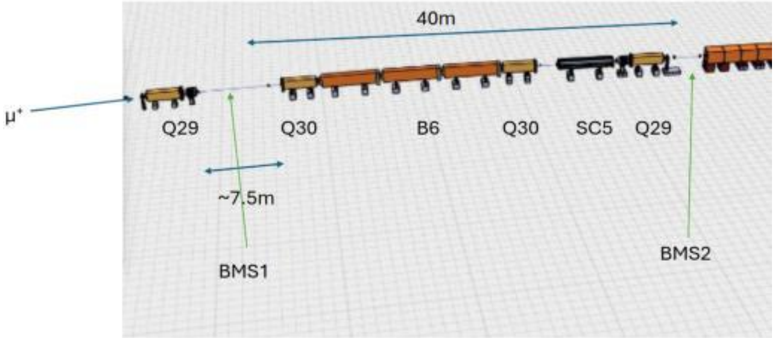
- Track muons after the ECAL, where electrons have been absorbed
- Improve PID by connecting tracks before and after the ECAL
- Both ECAL and μFilter help disambiguate muon vs electron in the region θ < 5 mrad
- μ identification also filters beam contamination (e.g. pions, pile-up muons)
- Study of Multiple Scattering effects on muon track tagging
- Phase-1 (2025): four 2S modules (2 X-Y non-tilted planes)
- Final detector: 2S Modules or Scintillating Fibers (R&D ongoing)



Beam Momentum Spectrometer



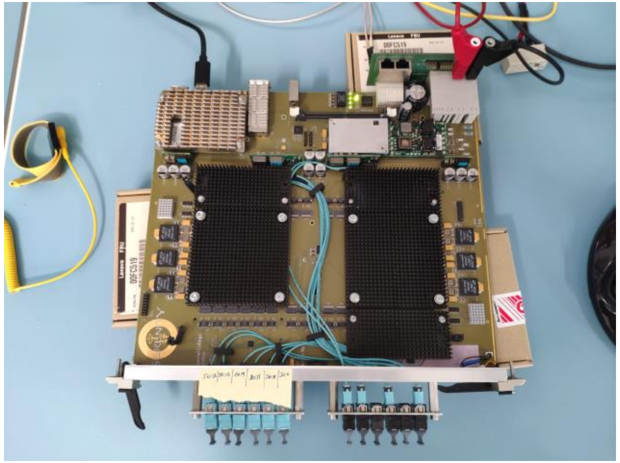
- Improves measurement of incoming beam momentum event by event
  - M2 beamline σ(p)/p: 3.75% → aim to measure better than 0.5%
- Replaces previous scintillator-based COMPASS BMS
- Two locations (before/after M2 16 T·m bending magnets, ~30 m apart)
  - 4 2S modules at each location (2 X-Y pairs, non-tilted)
- Modular mechanical design using carbon-fibre composite
  - Sliding CF plate for fine-tuning to few μm, CTE stability
  - Prototypes an alternative station design for Phase 2
- First integrated in August 2025 – preliminary analysis underway

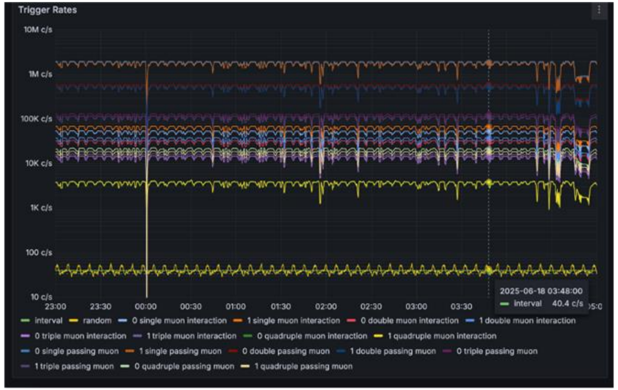


MUonE DAQ

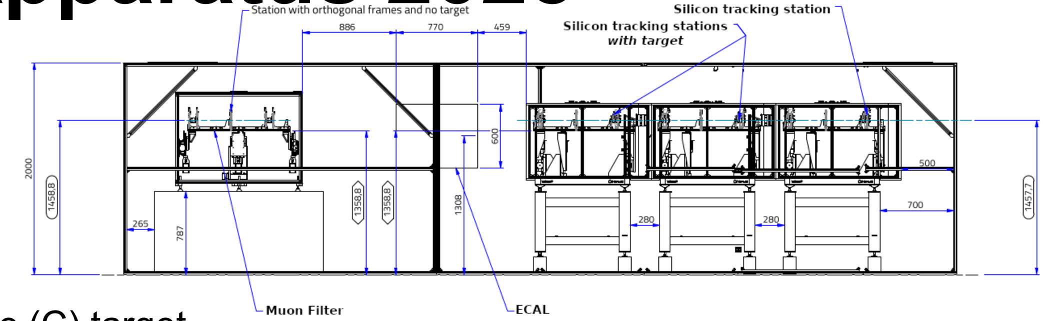
https://serenity.web.cern.ch/serenity/

- FPGA-based readout, triggerless architecture at 40 MHz clock cycles
  - Serenity ATCA platform (CMS Phase-2): Z1 with 2× KU15P FPGAs; new S1 with VU13P - https://serenity.web.cern.ch/serenity/
- DAQ firmware split over 2 FPGAs:
  - FPGA 1: decoding, per-station aggregation, event selection using module occupancy topologies at 40 MHz
  - FPGA 2: AXI-Stream event building, collecting fragments from all subdetectors, ethernet interface
- Online event selection: 40 MHz → ~500 kHz averaged (1.5 MHz in-spill), >99% efficiency
  - First successful demonstration for the entire 2025 run
- Online decoding provides analysis-ready NTuples in real time (Kubernetes-based, fault tolerant)



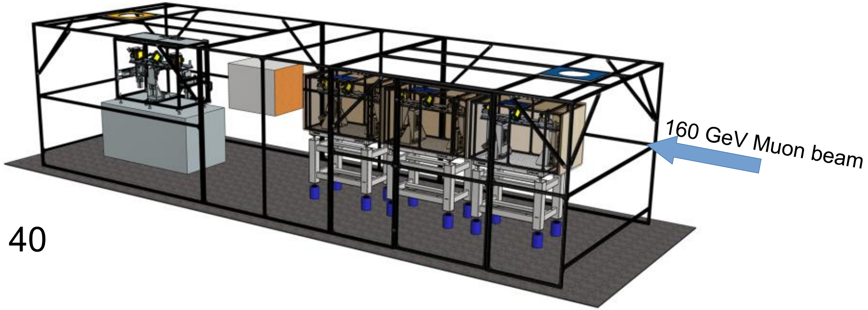


MUonE Phase-1 Apparatus 2025



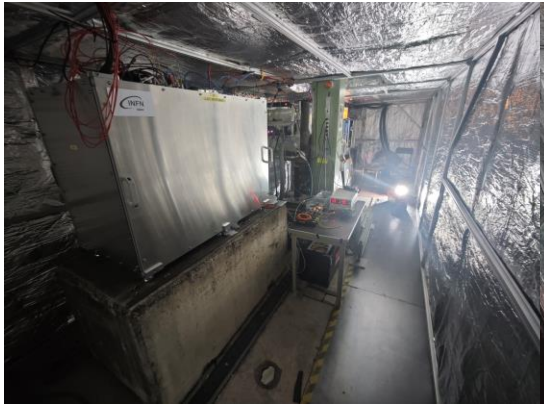
Mini MUonE experimental setup:

- 1st station without target
- 2nd and 3rd stations with 2 cm graphite (C) target
- ECAL
- MuonID station with 4 tracking planes (XY-XY)
- Timing detector (scintillator tiles + PMTs)
- Upstream: 2 BMS stations between bending magnets

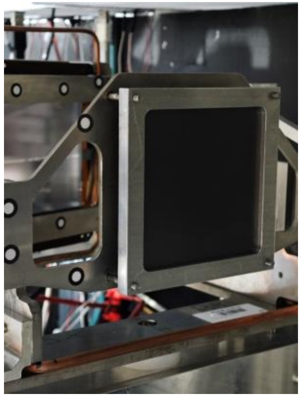


- All detector systems integrated into unified DAQ at 40 MHz
- Two months of data taking (May–August 2025)
- Proof-of-principle Δα_lep measurement; aiming at ~20% Δα_had

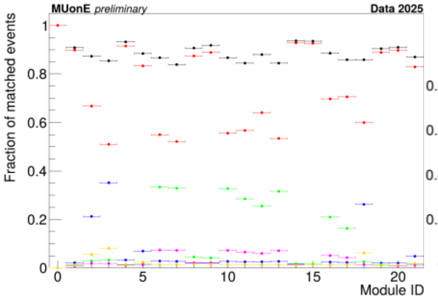
MUonE Phase-1 Apparatus 2025

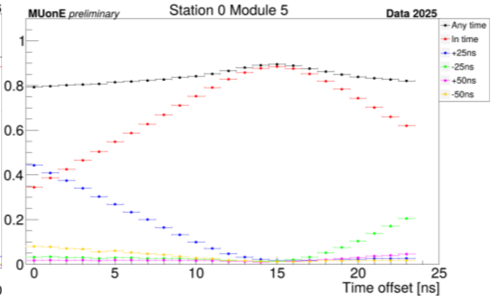


MUonE detectors during
installation and after (inside the tent)

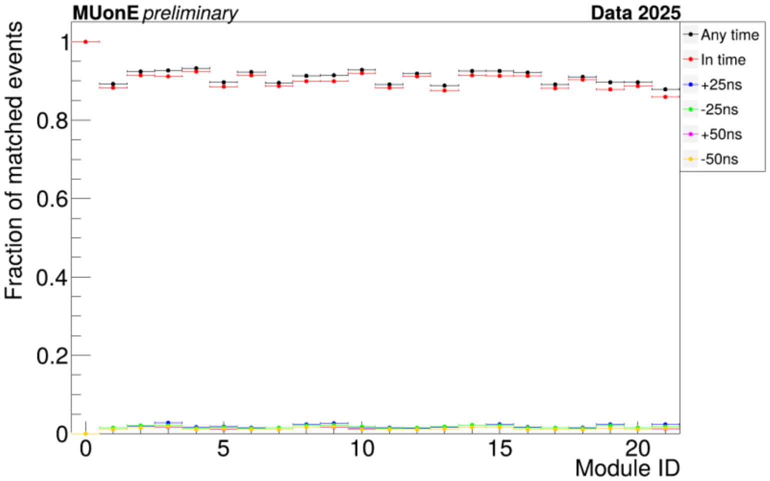


Phase-1: Detector Commissioning

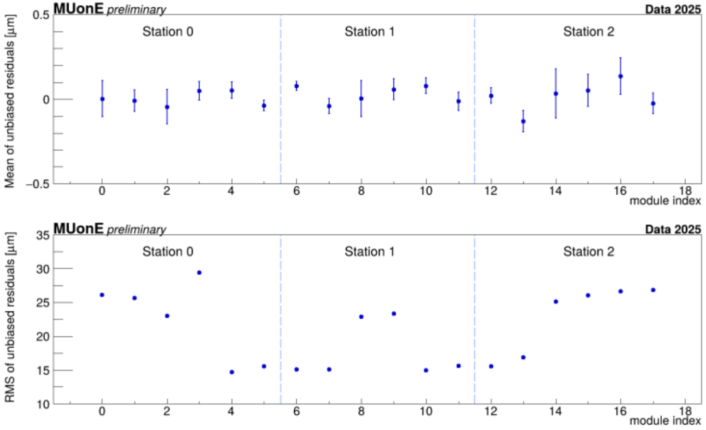




- Multiple detectors distributed over ~80 m
  - System synchronisation to ~1 ns is a key challenge
  - Muons are asynchronous w.r.t. sampling clock
- Coarse delay scan: align all modules to within 25 ns
  - Using a reference module, find delay that maximises correlations
- Fine delay scans at CBC: align each module to < 1 ns
  - On-chip DLL scan of sampling clock offset
- Same technique for ECAL, using tracker as a reference
- System successfully synchronised for the entire 2025 run



Tracker Alignment

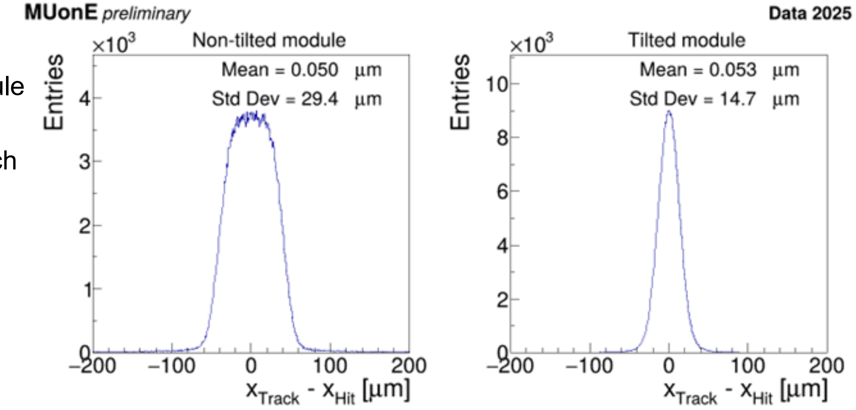


Hardware, using stepper motors:

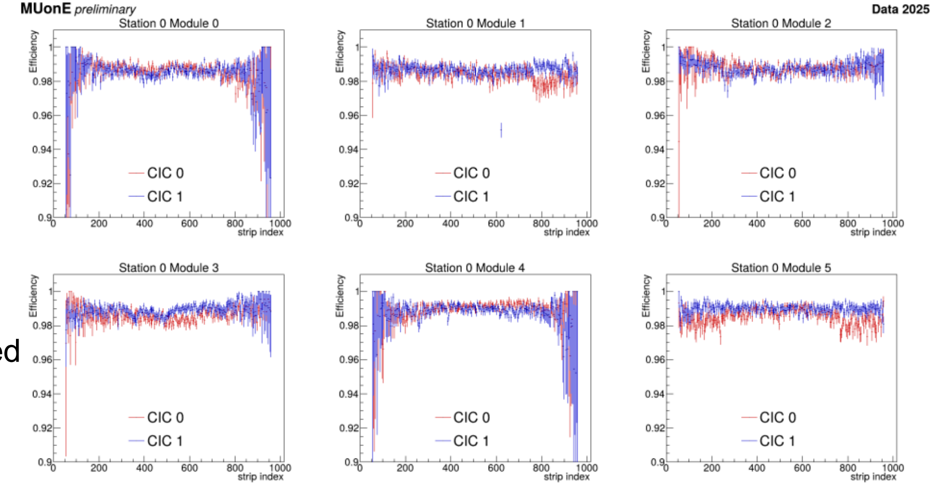
- 1) Centre each 2S module to the beam < 500 µm
- 2) Align the longitudinal axis of each station to the beam axis < 0.5 mrad
- 3) Align the 3 stations relative to each other < 200 µm

Software:

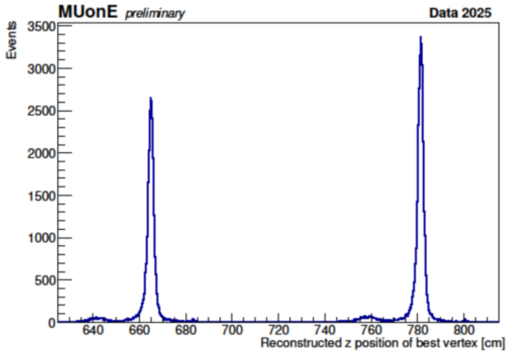
- Local χ² minimisation on clean single passing muon events (1 stub/module = 18 stubs/event)
- 3D scanner photogrammetry + laser survey: position + orientation of each module with ~100 µm precision
- Survey results used as starting point for software alignment
- Residuals (track – stub) centred < 0.05 µm



Phase-1: Tracking Performance



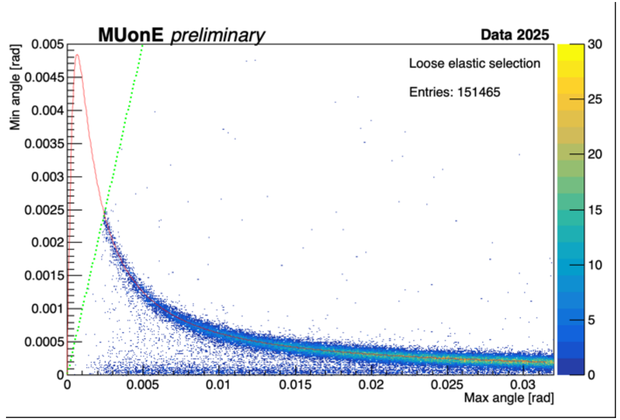
- Excellent tracking performance demonstrated
  - Efficiency typically 98–99% per module in Tracker
  - Efficiency independent of beam intensity
- Good effective hit resolution (preliminary from unbiased residuals):
  - Tilted XY modules: σ ≈ 11-12 μm
  - Non-tilted UV modules: σ ≈ 22-23 μm
  - Recall binary hit resolution: 90 μm/√12 ≈ 26 μm
- Vertex reconstruction:
  - Vertex identified using incoming track + two outgoing tracks
  - Targets clearly visible; σ_z(vertex) ~ 8 mm

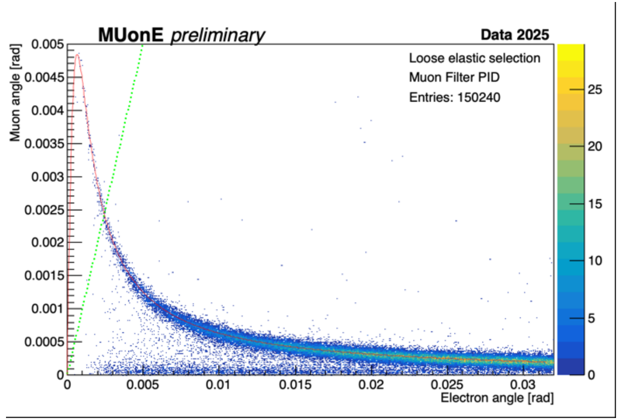


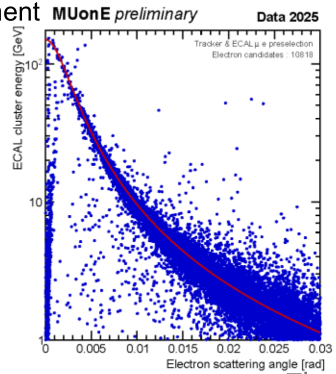
Phase-1: Detector Performance

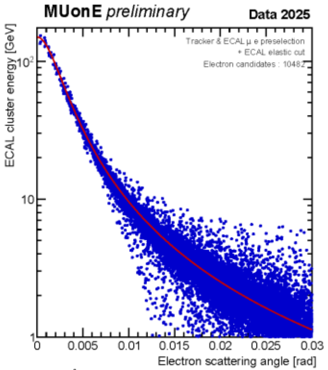
Very first results highlighting potential of PID:

- Elastic curves show correlation of outgoing μ/e track angles
  - Loose cuts (vertex, acoplanarity) to identify elastic events
- μFilter helps correctly identify muon vs electron in ambiguity region
- ECAL cluster energy compared against electron scattering angle
  - Track + ECAL centroid matching + elastic kinematics compatibility
  - Removes background – much potential for further PID improvement





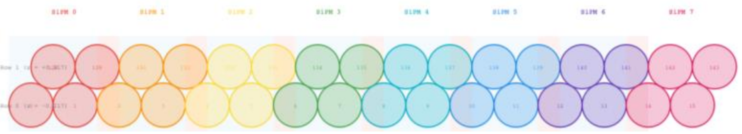


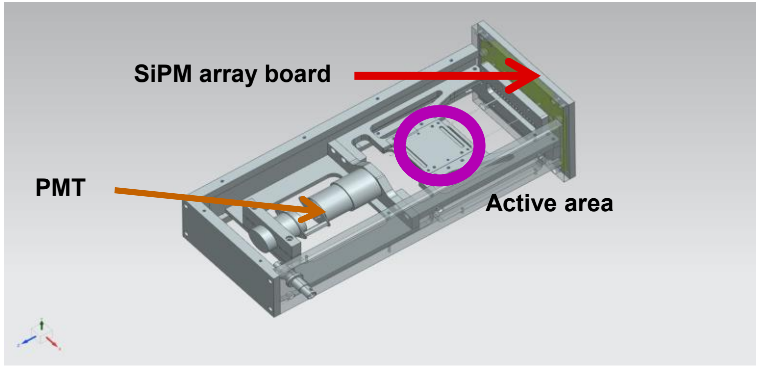


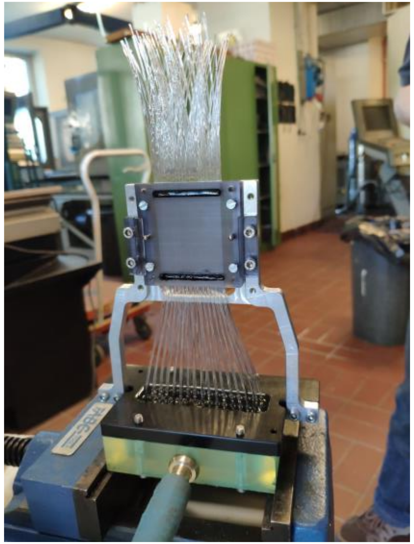
Conclusions

- Successful MUonE Phase-1 run demonstrated all detector technologies and their operation
  - Over 5×10^{11} pre-selected events to disk (~500 TB on EOS)
  - Expect confirmation of Δα_lep and ~20% measurement of Δα_had
- Online event selection at full 40 MHz for the entire run
  - State-of-the-art FPGA-based processing; stable operation throughout
- Excellent tracking performance: >98% hit efficiency, synchronisation within 1 ns
- Phase 2 goal (after LS3, ~2030): 40 tracking stations
  - → 1.5×10^{4} pb^{-1} integrated luminosity (3 years)
  - → < 0.5% on $a_{\mu}^{(HVP, LO)}$
- R&D activities ongoing: SciFi Muon Filter, IR HAM, ECAL, mechanics improvements
- 2026: analysis-focused year; EHN1 test beam requested for ECAL characterization and SciFi R&D

SciFi Muon Filter (R&D)



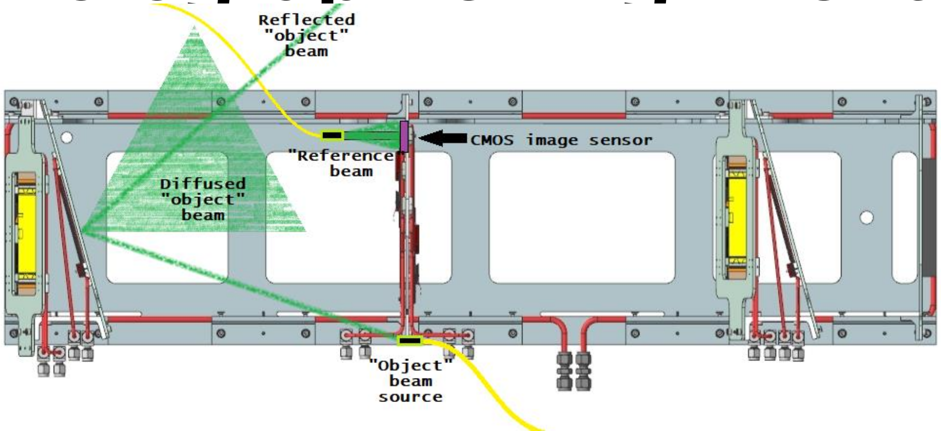


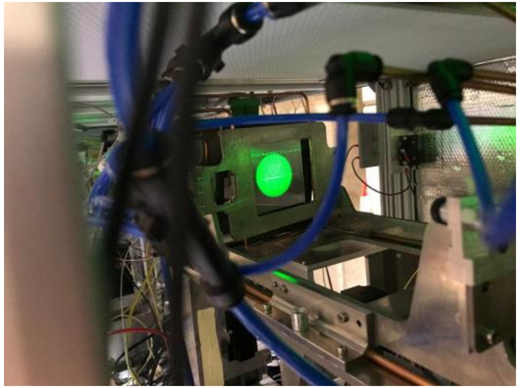


- Prototype for the Muon Filter upgrade (final detector)
- 0.5 mm dia. plastic scintillating fibers (Kuraray SCSF-78MJ)
  - Polystyrene core, double cladding (6% of thickness)
- Double and shifted layer array: 4 fibers coupled to 1 SiPM
  - SiPMs 1.3×1.3 mm² (Hamamatsu S13360-1350)
  - PMT (Hamamatsu R1924A) for triggering
- Pitch 1.25 mm – resolution ~360 μm
- Easy to cover large beam cross sections – easily scalable
- Custom front-end electronics (LIROC2 ASIC) in development

BACKUP

Holographic Alignment Monitor

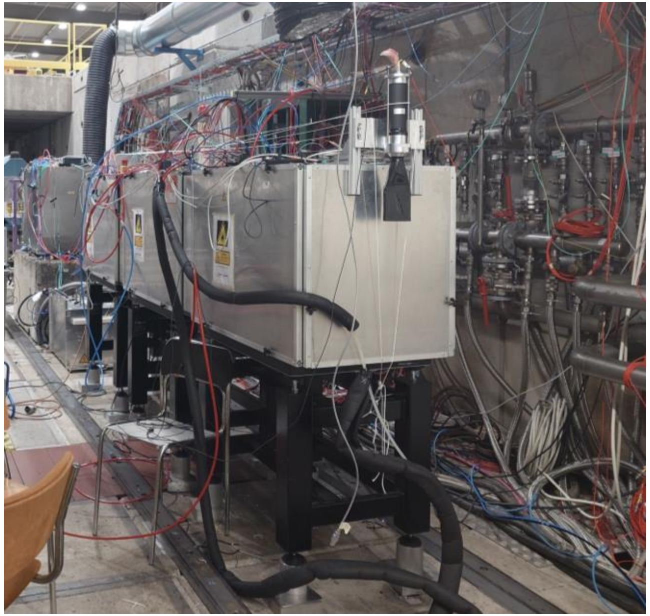




- Monitors relative displacement between tracking planes within a station
- Relative position of the sensors must be stable < 10 μm
- Developed using custom digital holographic interferometric methods
- Sensitivity ~0.25 μm (half wavelength) – 532 nm fiber-coupled laser
- Current limitation: 2S modules are sensitive to visible light → cannot monitor continuously during beam
- Improvement: use IR laser (>1500 nm) where the silicon sensors are blind
  - HAM-IR would enable continuous monitoring without gaps during datataking

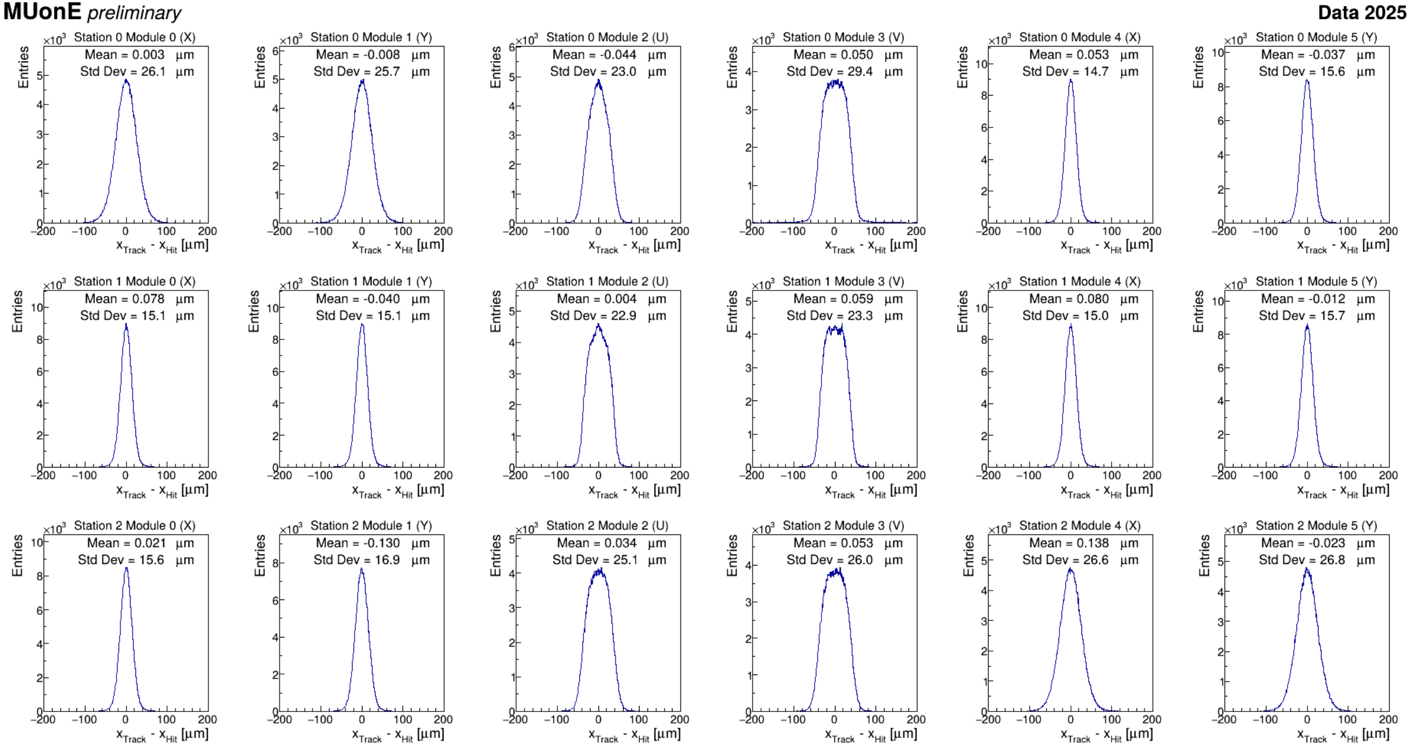
Timing Reference

- Two 10×10 cm² plastic scintillator tiles with Hamamatsu H6410 PMTs
- Provides a global timing reference for incoming/outgoing particles
- M2 beam muons are asynchronous w.r.t. the 40 MHz sampling clock
  - Loss of efficiency when particles arrive near clock edges
- FC7 + FMC digitises signals with 0.89 ns precision
  - 28-bit TDC + ToT implemented in firmware
  - Full information transmitted to DAQ via in-FPGA 'emulated lpGBT' at 5 Gb/s



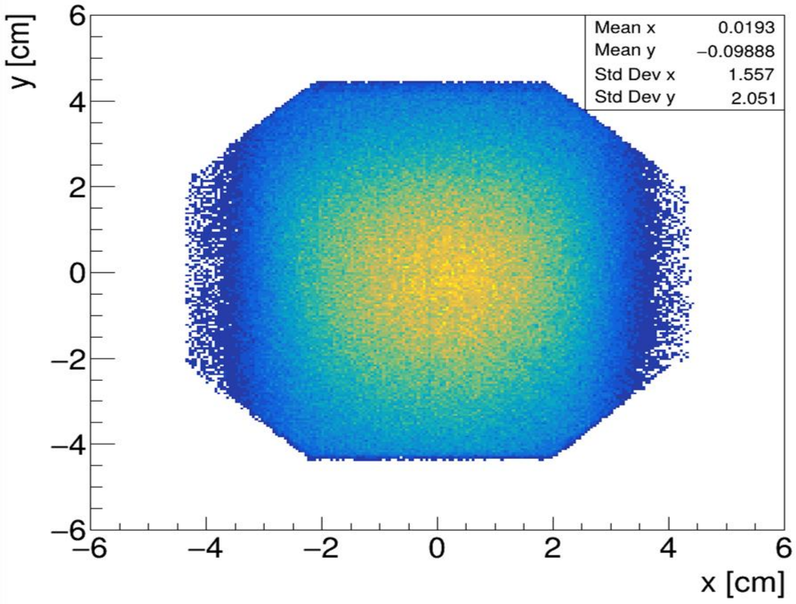
Tracker Software Alignment

Residuals (track – stub) centred ~ 0.05 µm



Beam Characteristics

Beam spot @ 1st target



Beam direction