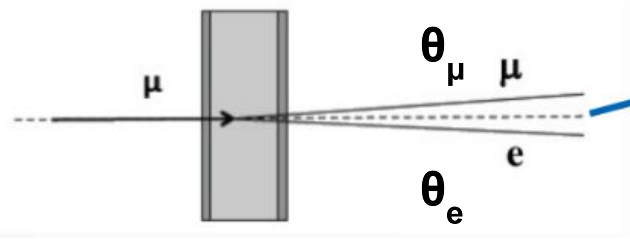
Status of MUonE

U. Marconi
Liverpool, 2022 November 8th

A novel method to measure $\Delta\alpha_{had}(t)$

- **160 GeV** muons hitting **electrons at rest** in a target of low Z material.
  A high intensity muon beam, the **M2** muon beam, exists in CERN.
- **The collisions result in a boosted kinematics** with scattering angles
  θ_μ < 5 mrad, θ_e < 30 mrad (E_e > 1 GeV)
  Angles measured with respect to the incoming muon direction.
- The **shape** of the differential cross section as a function of $t = q^2$ ($q^2 < 0$)
  depends on the hadron running $\Delta\alpha_{had}(t)$

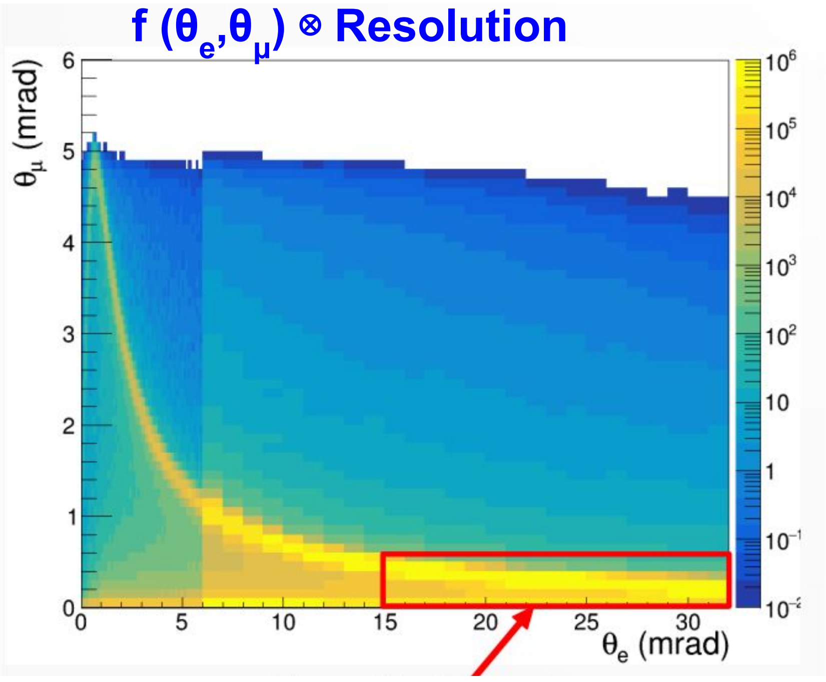


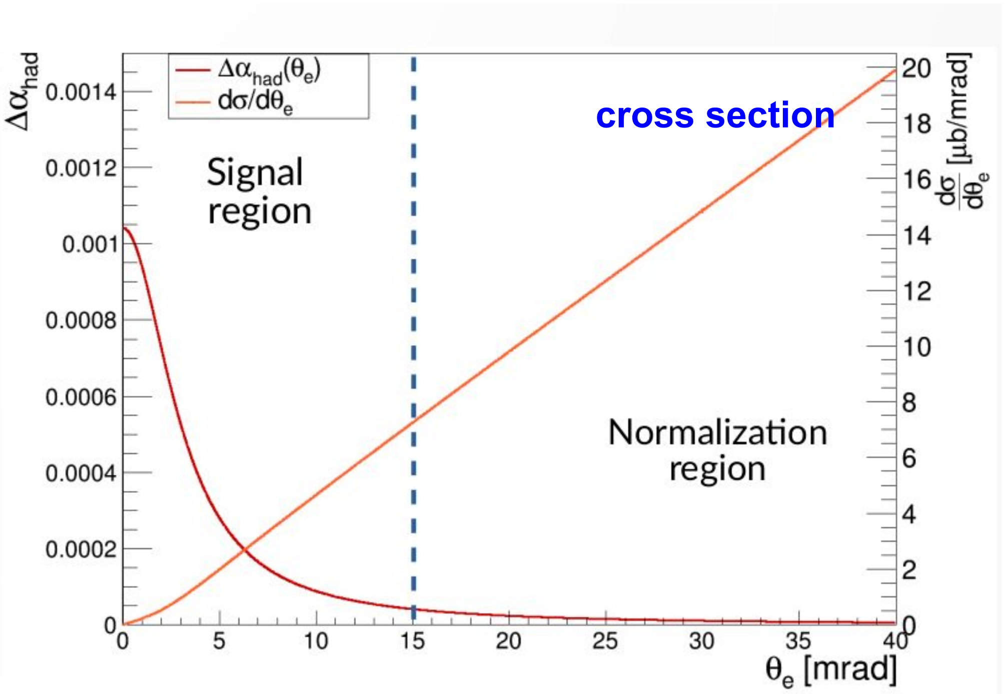
$$\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

From theoretical calculation

To be measured

The 2D angular distribution and the cross section





No effect here: the normalization region

Parameterization of the hadronic running

Inspired from the 1 loop QED contribution of lepton pairs and top quark at $t < 0$

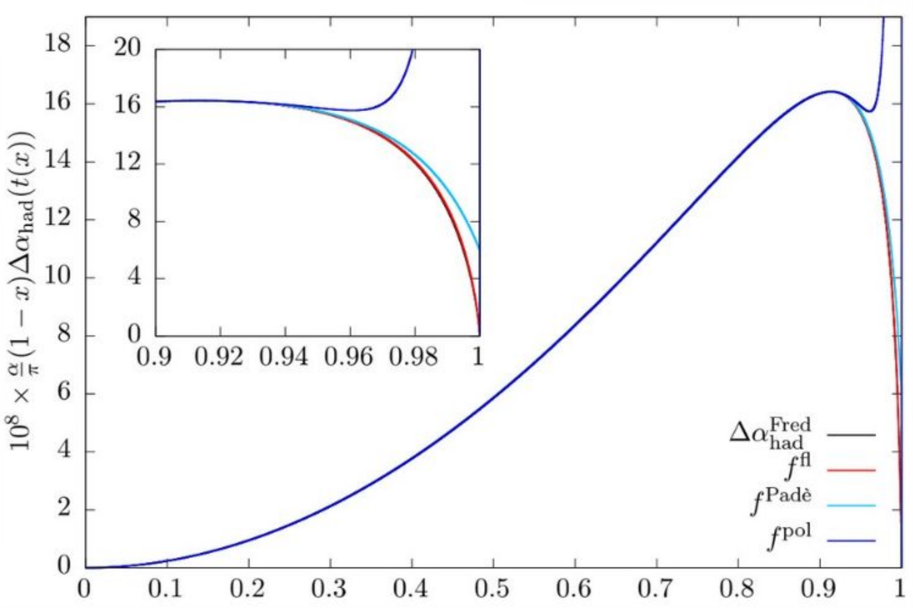
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

Allows to calculate the full value of a_μ^{HVP}

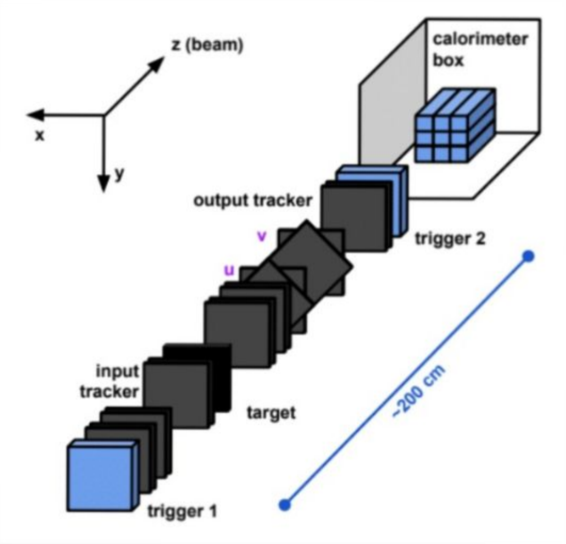
Dominant behaviour in the MUonE kinematic region:

$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$



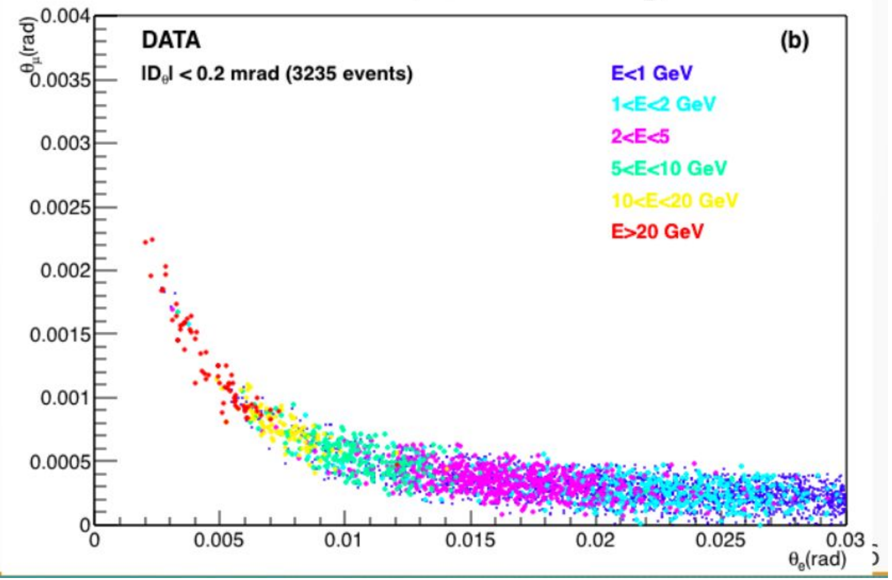
Elastic events in the Test Beam of 2018

Abbiendi et al, JINST 16 (2021) P06005

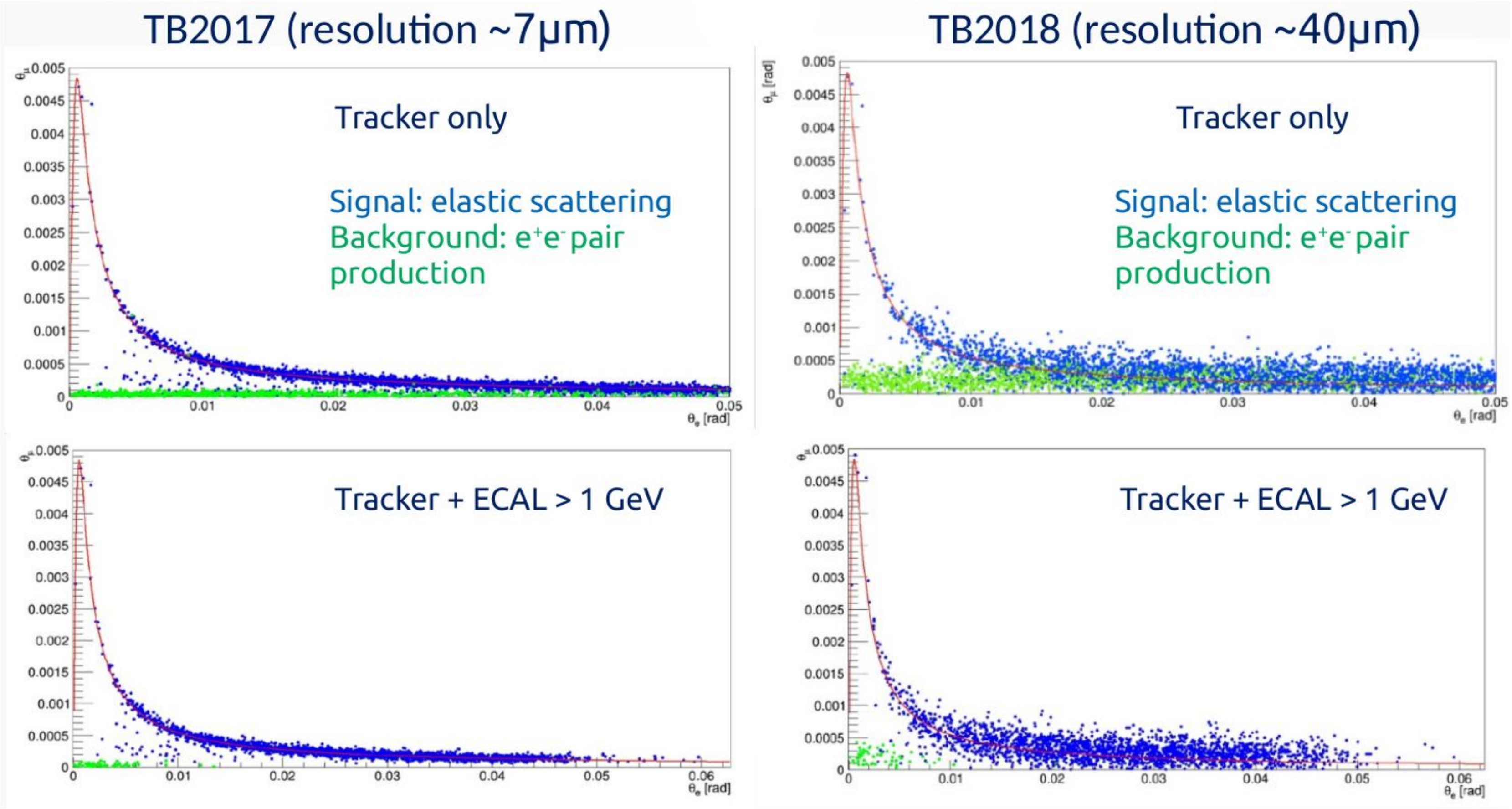


- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. 2.1x2.1cm^2, 23 cm length

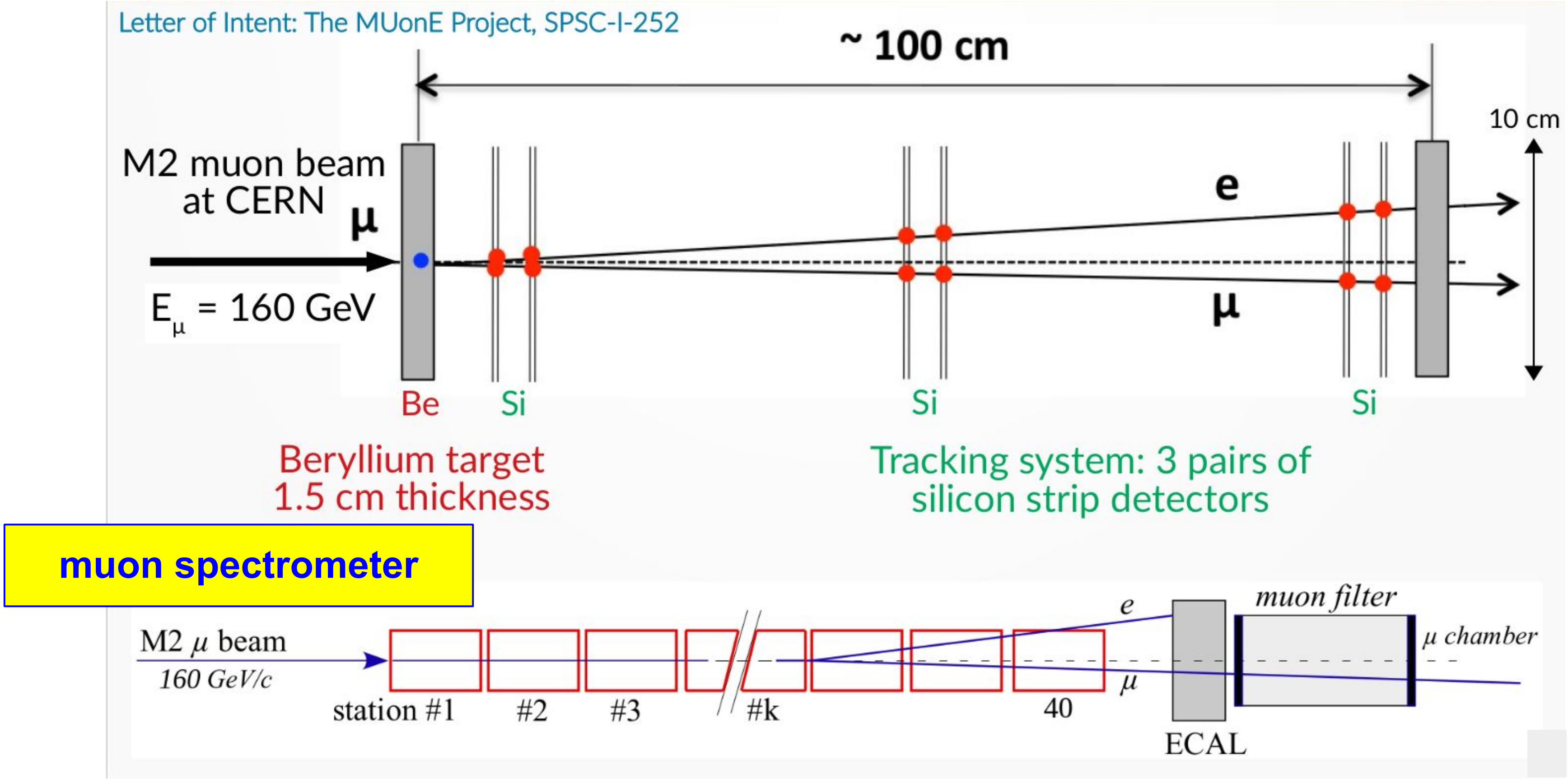
First evidence of elastic scattering.



The detector resolution



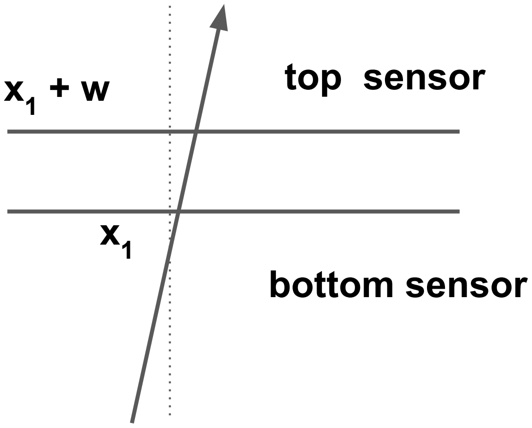
The detector



2S modules

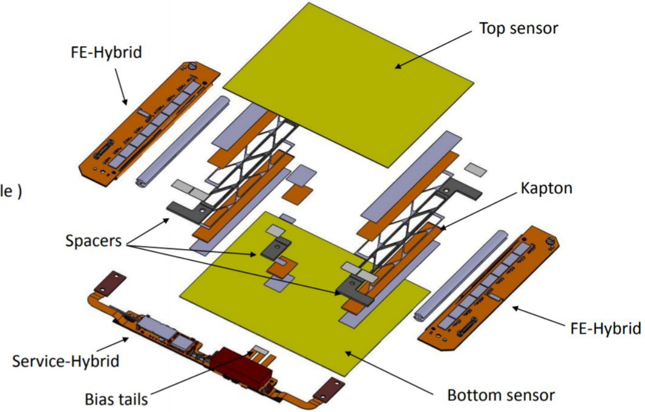
Digital readout at 40 MHz
Expected resolution 22 μm

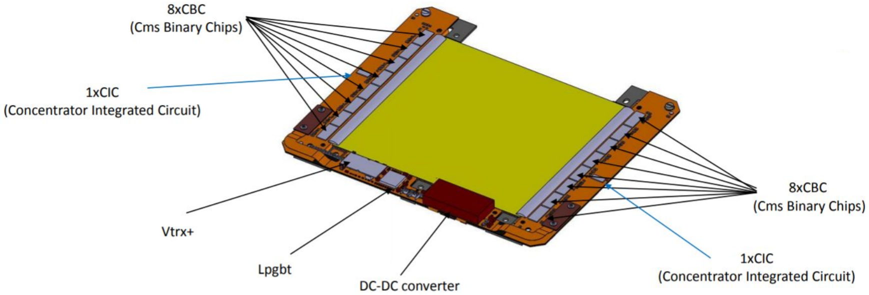
We use stubs i.e. trigger primitives for the CMS L1 trigger



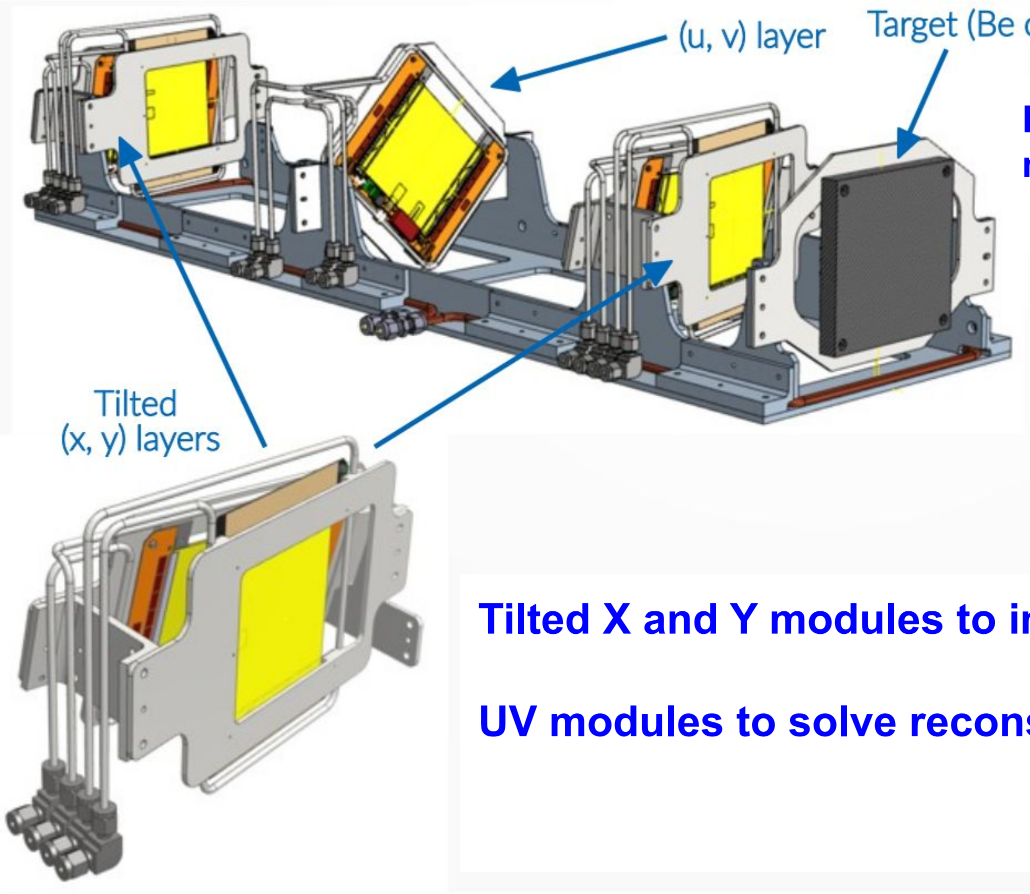
Components to be assembled:

- **Strip sensors** (2)
- **Kapton isolators** (4 long, 2 short)
- **Backplane bias tails** (1 double, 1 single)
- **Al-CF bridges** (2 main, 1 stump)
- **Front-end Hybrid** (1 Left, 1 right)
- **Service Hybrid + VTRX+** (1)





The tracking station



Positions of the modules must be stable within 10 μm

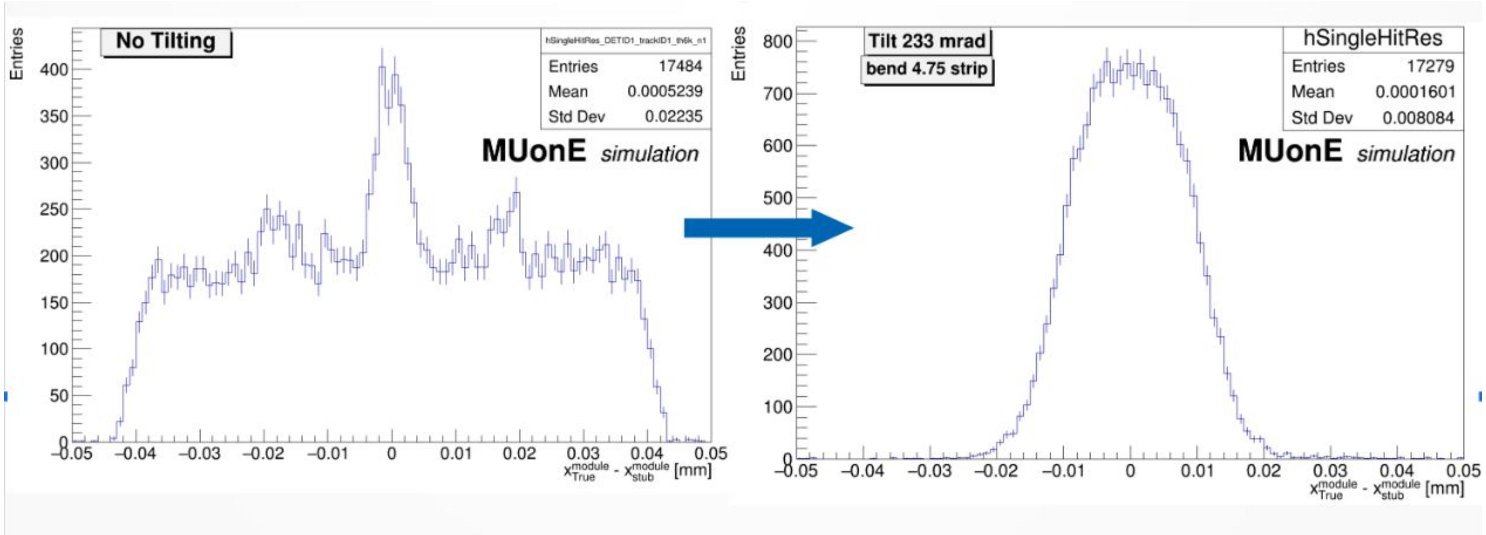
Low CTE material:
INVAR (CTE ~ 1.2×10^{-6} K^{-1})

Laser holographic system to monitor stability.

Tilted X and Y modules to improve the resolution

UV modules to solve reconstruction ambiguities

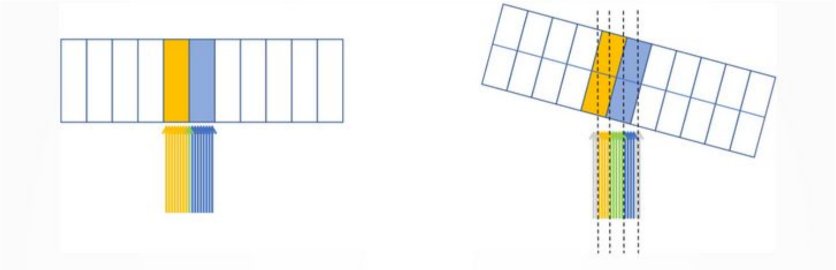
To improve the spatial resolution



By tilting the module we do expect to improve the resolution:

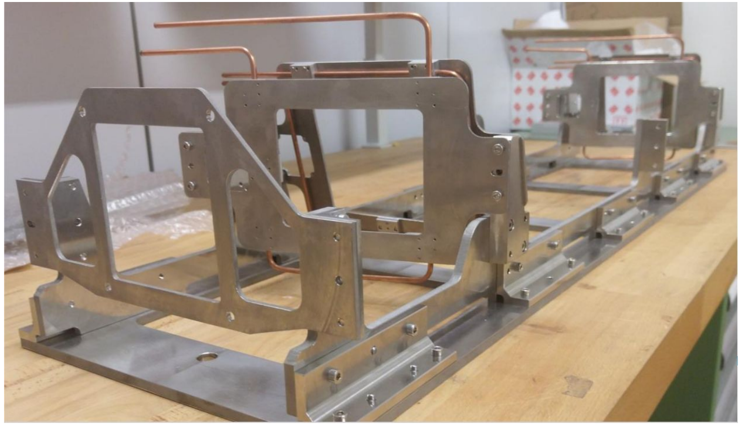
22 μm →10 μm

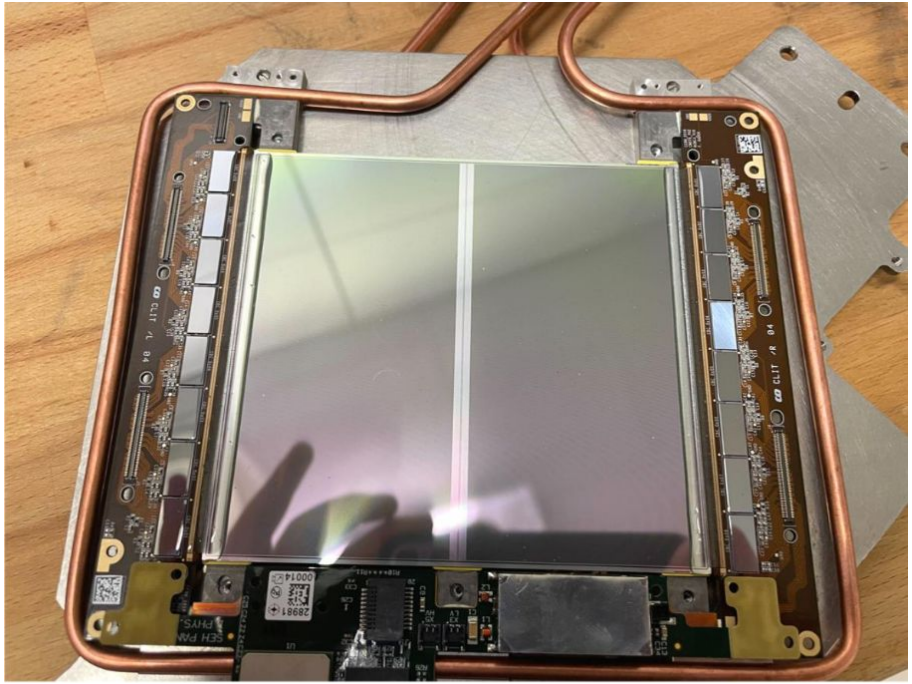
The tilting angle is **14 degrees**



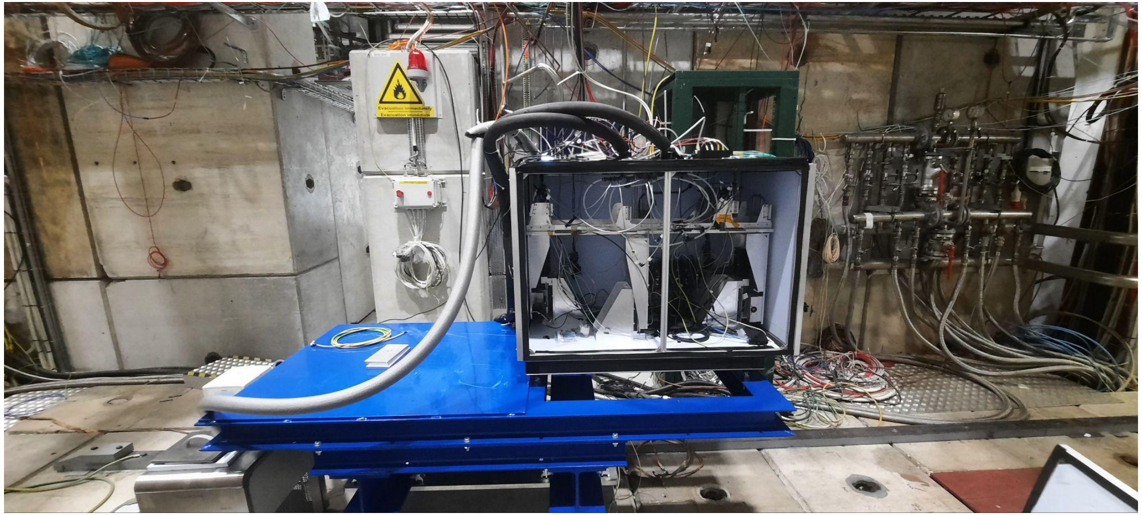
2S module on its frame

The support structure in INVAR





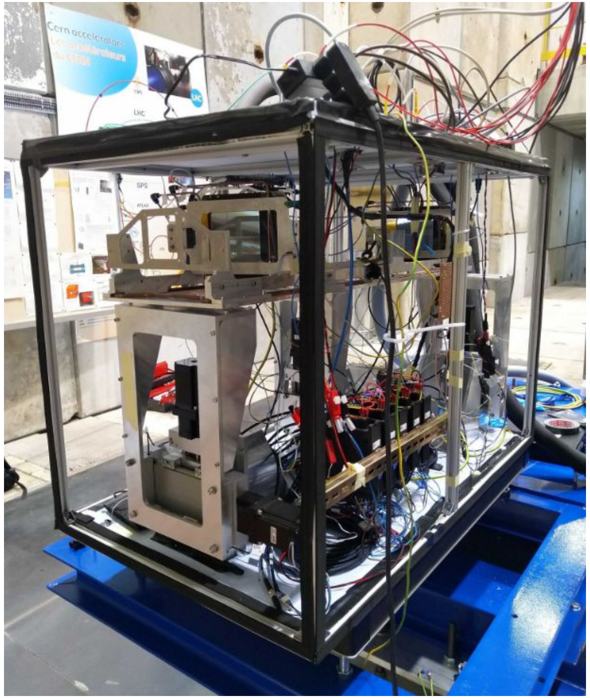
Tracker beam test setup



- We managed to keep running for debugging the DAQ and testing the 2S modules available
- The station placed on rails to allow easy movements in and out the M2 beam

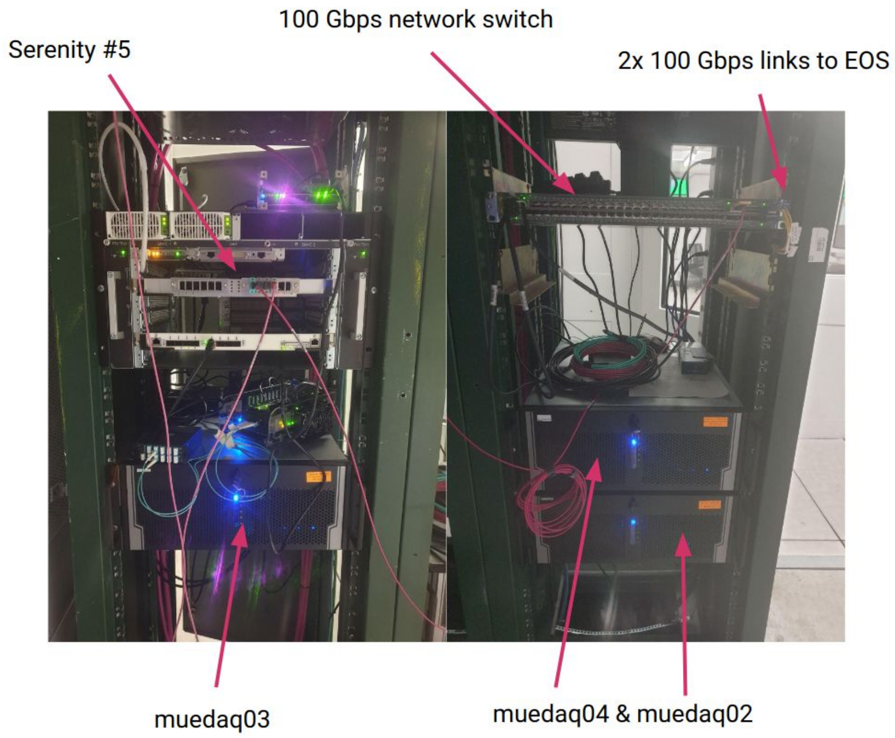
Tracker beam test setup in M2

- 4 of 6 2S modules installed into the station
- X and Y modules at front and back mounted
- U, V modules in centre are missing
- 40 MHz readout to Serenity DAQ card, then 10 Gbps Ethernet link to PC
- Data saved locally and on EOS
- Still possible to take data using the beam halo 1kHz vs 10 MHz counting rate



The DAQ Back End Architecture

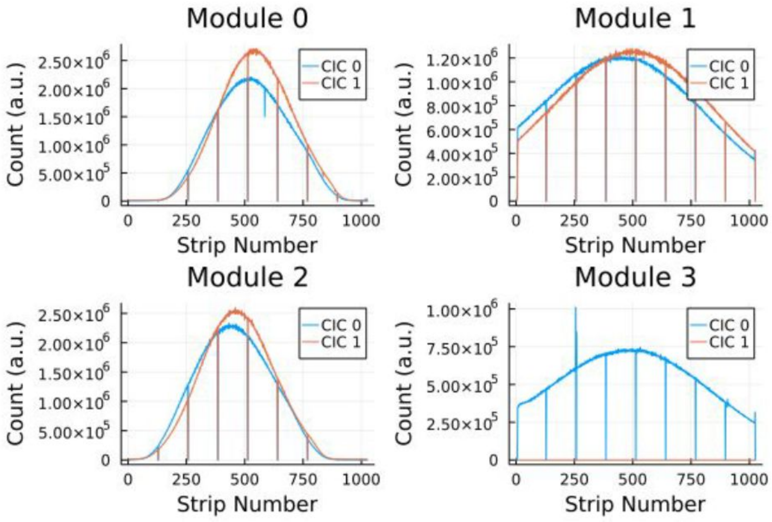
- Stubs are sent to the **Serenity** via optical links
- Packets of stubs are decoded in the **FPGA** of the Serenity card, and stubs collated by Bx
- Packets of stubs are formed and sent to **DAQ PCs**, over **10 Gbps Ethernet** link using the UDP protocol
- Packets are decoded in PCs and written successively to RAMdisk, NVME then HDD
- At the end of run data is transferred out to **EOS** for skimming and analysis

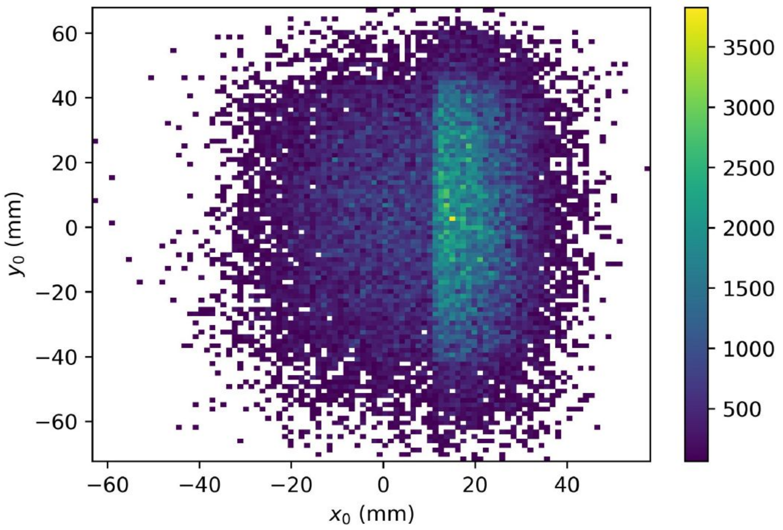


Back End Development

- **Firmware on Serenity** is largely unchanged from the November 2021 beam test
- **DAQ has been proven to be reliable:** ran for multiple days without errors
- **100 Gbps link to EOS installed**
- Data taking runs can now be controlled from **Grafana dashboard**
- Integration of in-depth health monitoring underway
- **“Express data stream”** from DAQ PC of sampled data is used for online DQM
- Significant effort has been made to improve **software**
  - Offline decoding software built upon common API framework to extract stubs and packet data from the binary files
  - Software extension to API to add additional fields (global coordinates, decoded bend) and saved to ROOT files for analysis

Preliminary results. Beam profile and beam spot

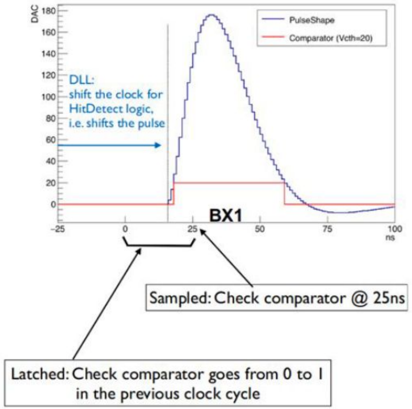


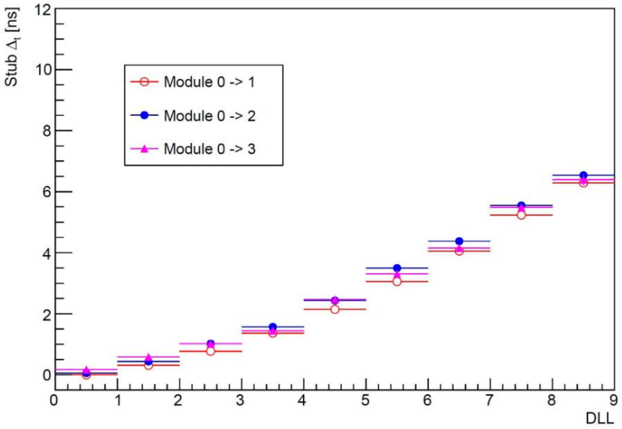


Module furthest downstream has faulty CIC:
can only read stubs from half of module

Synchronization studies

- Need to ensure the sampling point for each module is in sync for any given muon
- **Asynchronous beam**: no absolute timing reference
- Method: for a pair of modules take time difference in BX between captured stubs in each module: the first module is taken as reference, next modules checked in comparison. Check delta as function of DLL settings and plot the mean at each setting

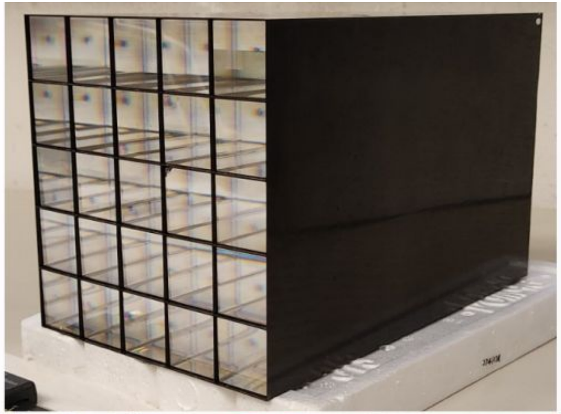




The procedure can correct for offsets in the modules to maximise detetction efficiency to **0.5 ns**

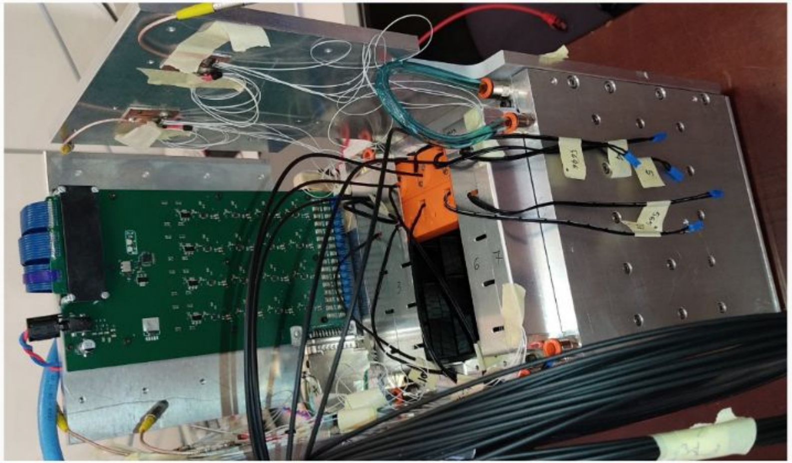
ECAL

- 5x5 $PbWO_4$ crystals:
  - area: 2.85×2.85 cm^2 , length: 22cm (~25 X_0).
- Total area: ~14×14 cm^2.
- Readout: APD sensors.



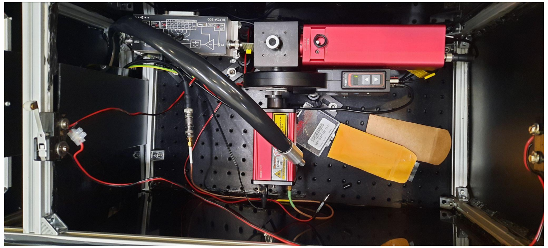
Beam Test: 20-27 July 2022,
CERN East Area.

- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter being installed downstream of the tracking station at the M2 beam line.

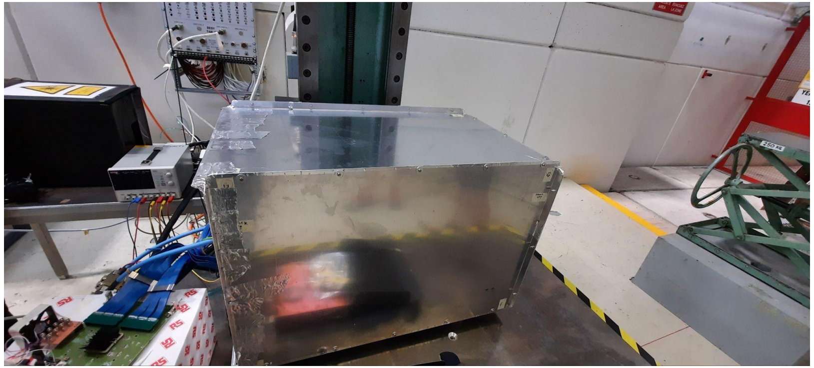


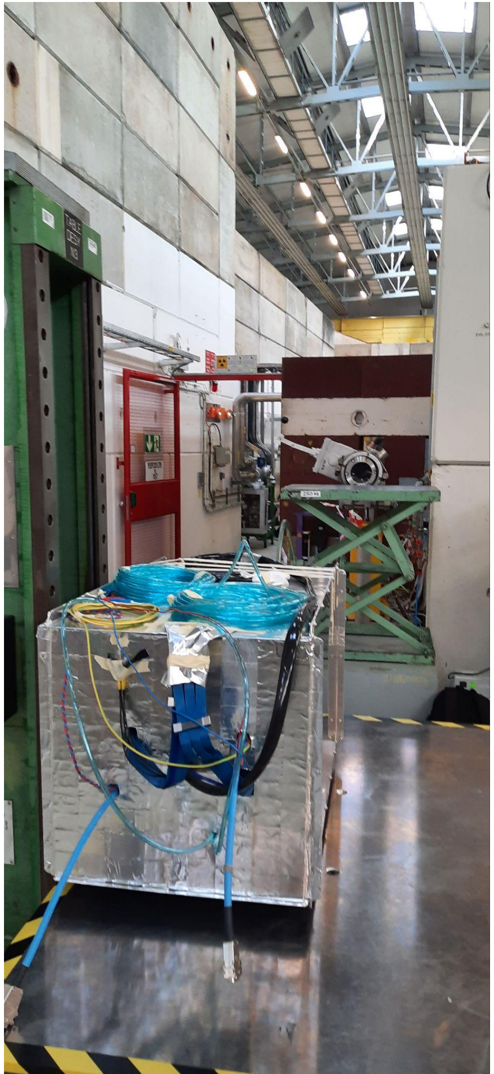
ECAL tests in CERN’sT9

ECAL assembled and tested at the end of July this year in the CERN T9 electron beam line



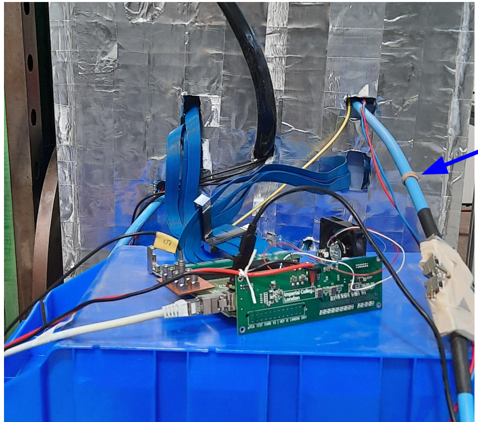
Laser pulses





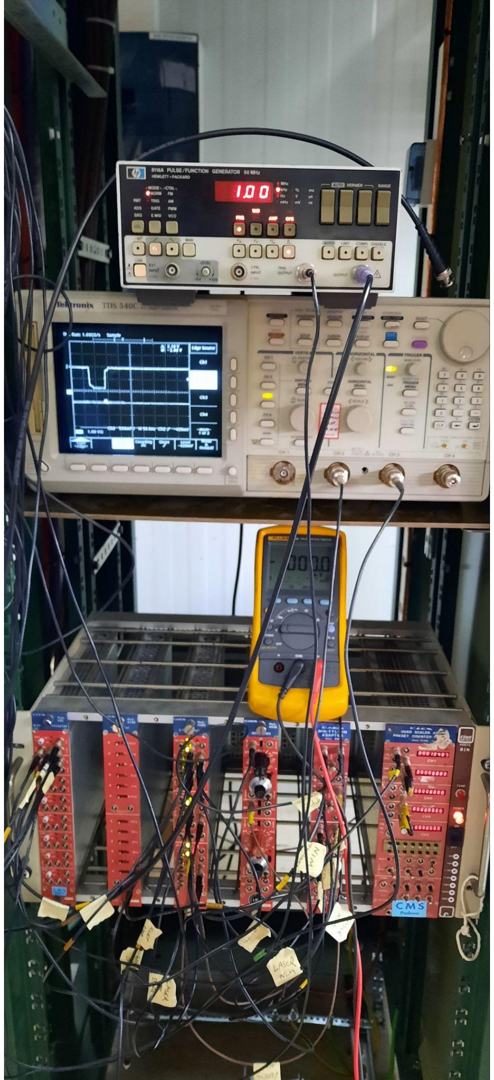
ECAL test setup and DAQ

- The **FC7 FEBs** are used to read out the digitizers and to transmit data to the PC through a 10 Gbps Ethernet link.
- Self **trigger** modes, relying of the ECAL’s cells energy content and external trigger successfully exploited.
- Counting rate capability **~1.5 kHz**
- The laser system confirmed to be important for settings and monitoring the stability of the channels



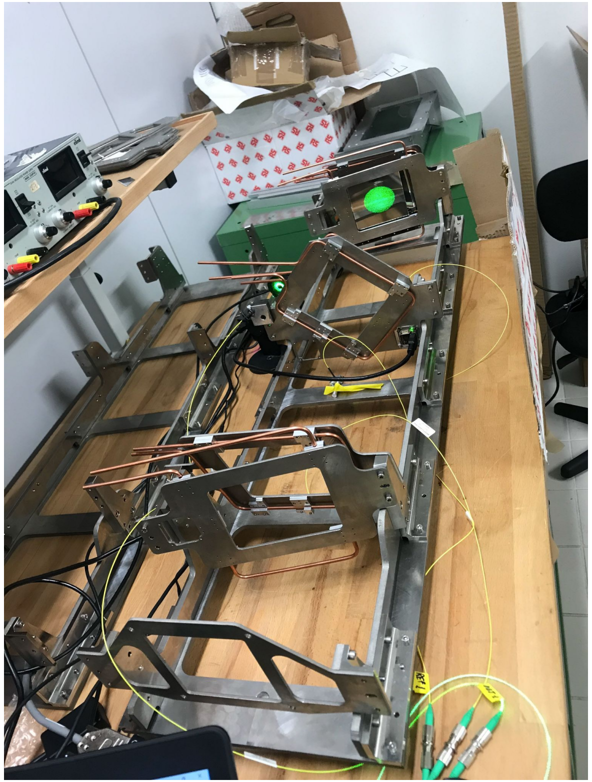
The readout

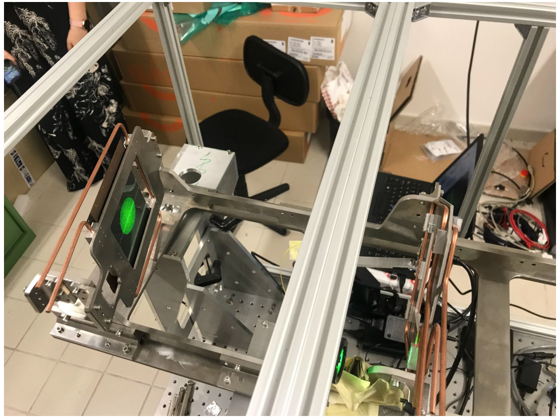
External trigger
Beam scintillators and
Cherenkov counters

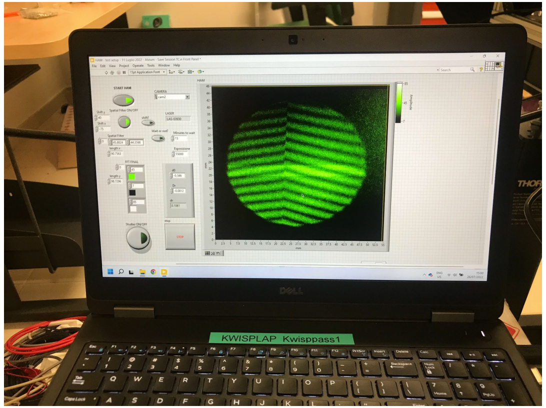


The holographic system

- **Laser interferometry** of rays going through different paths
- It allows monitoring the position of two sensors with respect to a reference one with **resolution of ~0.25 µm**
- To be used during alignment and data taking
- The system is ready to monitor one station
  Extensible to a second station easily

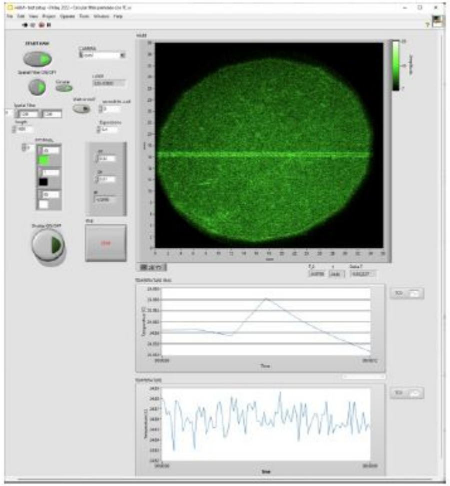




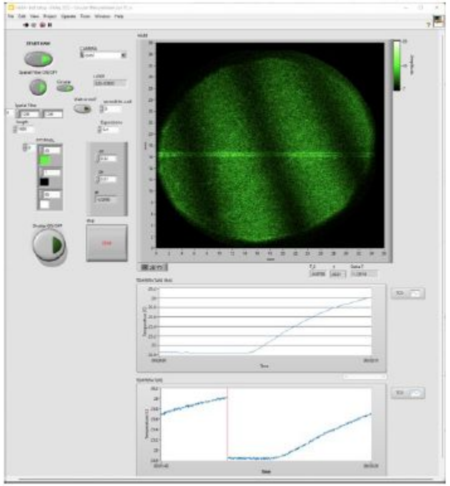


The holographic system (cont.)

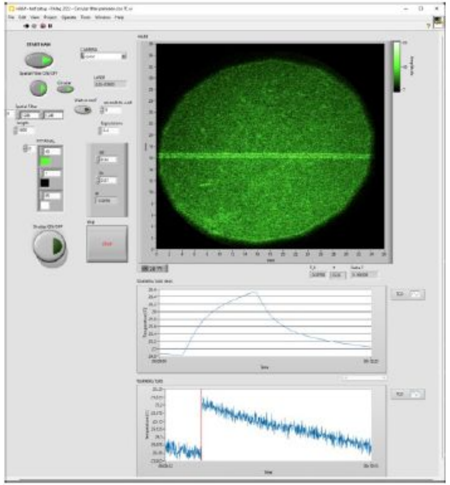
Thermal load corresponding to a power of 2W applied to the mechanical structure of the Aluminium prototype. Module’s consumption ~5 W: cooling system foreseen.



Initial state



Steady power on



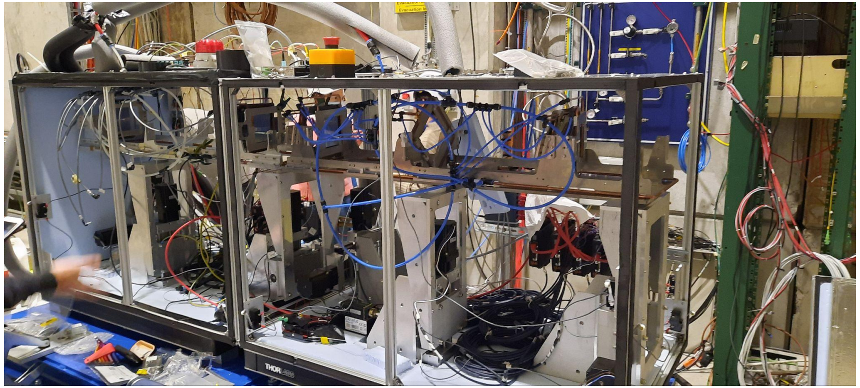
Power off

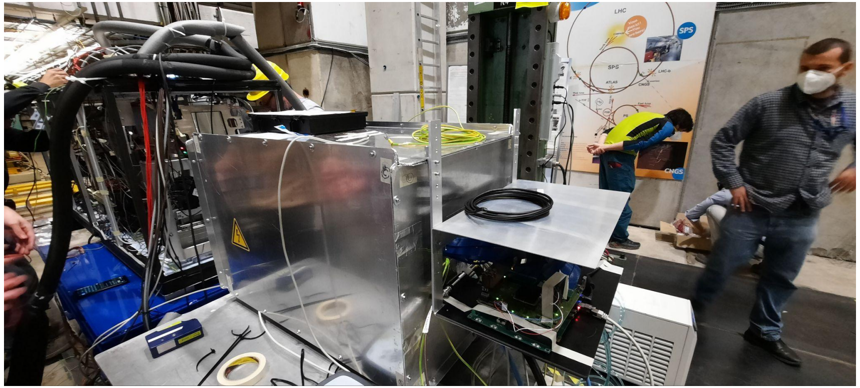
Estimated relative displacement between planes 1.5 μm

Test with a full station and calorimeter

- Fully equipped tracking station and the calorimeter
- One week of test in M2 as main users performed the last October

  High intensity muon beam, up to $2{\times}10^8$ muon/spill



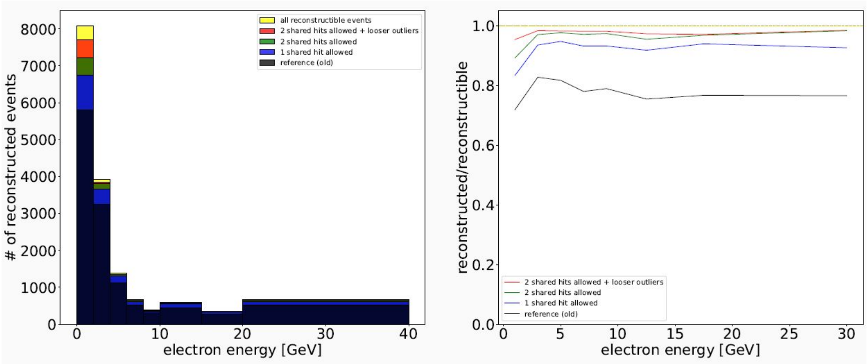


Software

- **FairMUonE**:
  FairRoot based software, for generation, simulation, digitization and reconstruction
- **Event generation**:
  NLO Mesmer generator for μ - e scattering
  Accurate beam profile description
- **Simulation:**
  Geant4 v10.7.1 implemented in FairRoot
  Detailed geometry description implemented, scalable to any number of stations
  Common geometry files (.yaml files) for simulation/digitization/reconstruction
- **Digitization:**
  Digitization for tracking stations ready
  Realistic electronic noise and channel cross-talk added
  Calorimeter digitization is ongoing

Software (cont.)

- **Track reconstruction**:
  Kalman filter for tracking implemented
  Tracking efficiency studies ongoing:
  Allowing shared hits improves
  track reconstruction efficiency
  dramatically in the whole energy range



- **Vertex reconstruction**:
  Kinematic fit constraining three tracks to meet in the middle of a given target
  Adaptive vertex fitter developed for the alignment

Detector alignment

- Initial conditions set by means of the mechanical survey: **$\Delta z \sim 50 - 100\ \mu m$**
- Software alignment shall reach the ultimate precision
- Alignment parameters will be determined by minimizing the **global χ^2**
  MUonE is perfectly suited for the global χ^2 approach because of the linearity.

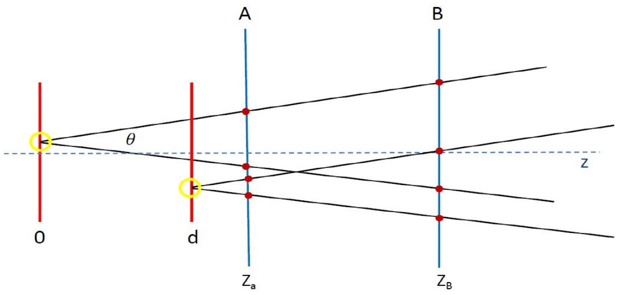
$$\chi^2_{\mathrm{global}} = \sum_i \chi_i^2, \qquad \frac{\mathrm{d}\chi^2}{\mathrm{d}\boldsymbol{\alpha}} = 0, \qquad \boldsymbol{\rho} \equiv \boldsymbol{\rho}(\boldsymbol{\pi}(\boldsymbol{\alpha}), \boldsymbol{\alpha})$$

Residuals **ρ** depend on the alignment parameters **α** as well as track parameters **π**

- The required precision for the alignment is **$\Delta z \sim 10\ \mu m$**
- **How to get the longitudinal scale to such a precision?**
  Use thin targets located to a known distance and reconstruct vertices from these targets to gauge the scale

Detector alignment (cont.)

- Design and construction of the targets system by the CERN accelerator group



- Use pion beams to enhance the multiplicity of tracks from the vertices in the thin targets
- Use the adaptive vertex fitter to determine the vertices positions
- Use the global alignment method to get the alignment parameters

Plans

- Prove the feasibility of the proposed MUonE method within the 2023
  Dedicated test beam with easy access
  Final test in M2 with two or three stations
- Writing the experimental proposal.
  We have to start now
- The experiment shall start with ~10 stations to get a first measurement before the LS3.
  The full experiment to reach the ultimate sub percent precision will take place after the LS3

Collaboration

- Imperial College London
- Liverpool University
- Virginia University
- North Western University
- Regis University
- Krakow INP
- Budker Institute
- Bologna INFN
- Perugia INFN
- Pisa INFN
- Padova INFN
- Trieste INFN