Status of MUonE

Liverpool, November 2024
U. Marconi, INFN Bologna

Content

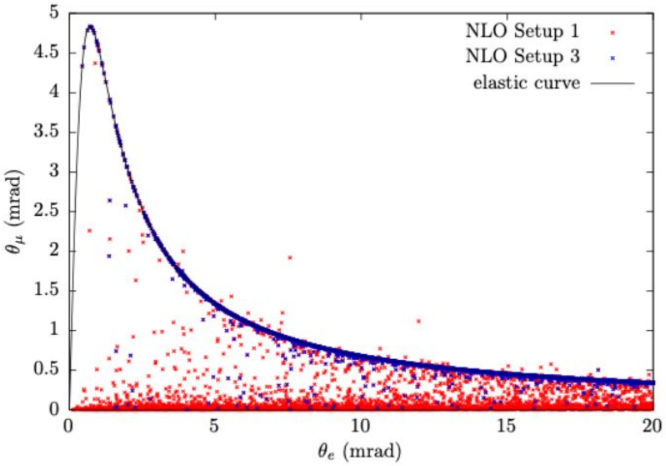
- The MUonE project
- We recently submitted to the CERN SPSC our proposal:
  Proposal for phase 1 of the MUonE experiment
  CERN-SPSC-2024-015 ; SPSC-P-370
- The proposal has been approved and we are now planning for the 2025 test run
- Key progress in 2023 and 2024 includes advancements in both the detector and DAQ systems.
- The current status of the analysis will be fully covered by Giovanni Abbiendi in his talk.

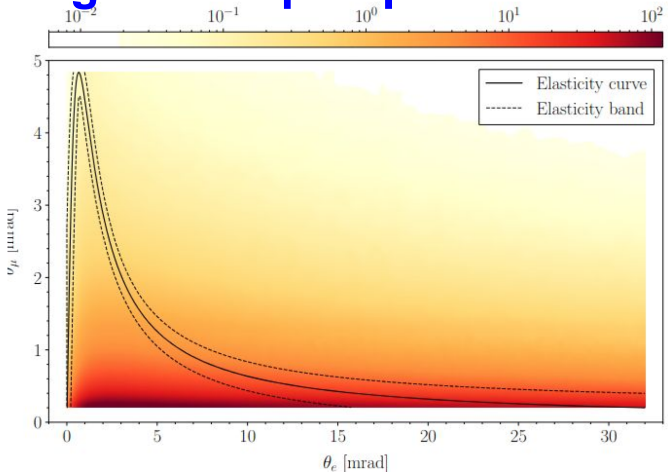
The MUonE Project

- In MUonE Phase 1, we aim to assess the feasibility of a precise measurement of the running of $\alpha(t)$ in muon-electron elastic collisions, allowing us to infer the hadronic contribution to the running.
- The method relies on detecting the angular distributions of electrons and muons from elastic scattering events.
- For 160 GeV muons colliding with electrons at rest, the scattering angles of interest are generally below 30 mrad.
- On a meter scale—the length of a tracking unit used in MUonE—this corresponds to an effective geometrical acceptance of approximately 10 cm x 10 cm.
- Our target muon intensity at M2 is of about 40 MHz.
- For this purpose, we can use an existing detector: the 2S microstrip detector developed by CMS for their planned upgrade.

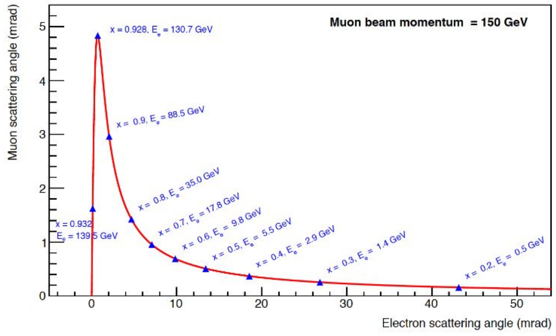
Signal and the main background

MESMER the event generator for signal and pair production





muon angle vs the electron angle for the elastic process



The MUonE modular tracking system

Thin targets are used to limit the effect of MS and is repeated many times to achieve the necessary luminosity

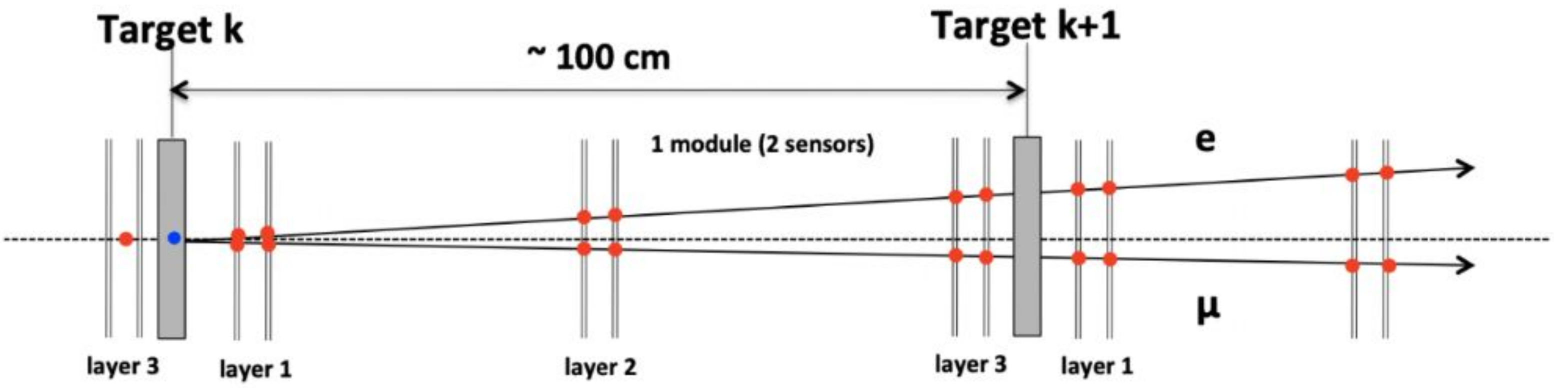


Figure 2.13: An overview of one station, composed by one target and six tracking modules. This is repeated 40 times in the final apparatus.

The tracking station

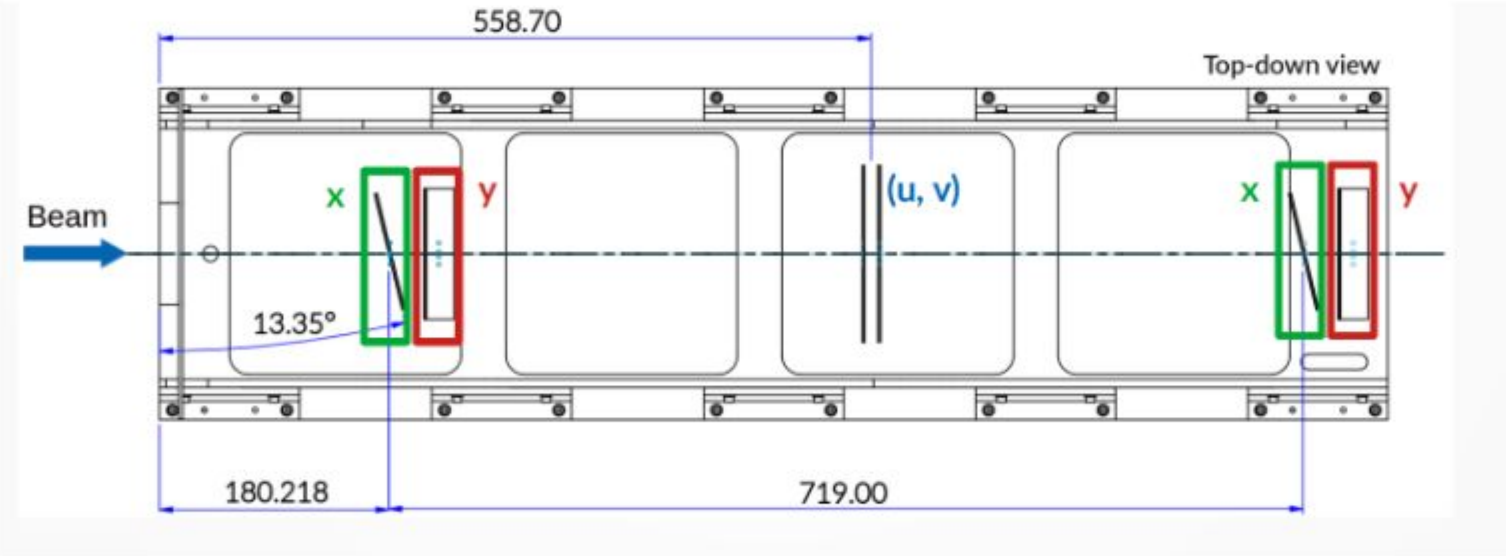


Fig. 6: An engineering drawing of a tracking station, showing how the x and y modules are tilted. The graphite target is on the left, with its upstream face at the edge of the diagram. The dimensions are mm.

The 2S modules (microstrip silicon detector)

- The 2S modules were designed to provide a fast trigger for CMS, enabling the selection of high-pT tracks for the Level-1 trigger. To achieve this, each module is equipped with two sensors mounted 1.8 mm or 4 mm apart. The displacement of hit positions between the two sensors, caused by the intense magnetic field, provides CMS with prompt information on pT.
- MUonE can use this trigger information produced at 40MHz, known as "stubs," to effectively detect tracks at 40 MHz.
- The 2S modules transmit data at 40 MHz via optical links to the Serenity readout boards, which CMS designed for their DAQ system and which support high data throughput.
- In 2023, MUonE borrowed 12 prototype modules from CMS to conduct an initial measurement of elastic collisions at high rates. We used these modules to equip two tracking stations, which are the basic detection units in our detector.

The 2S modules

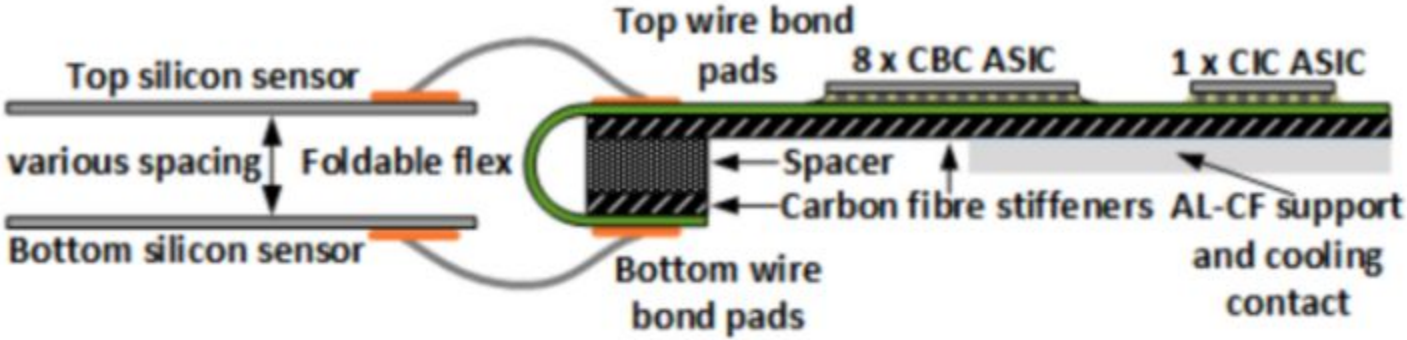
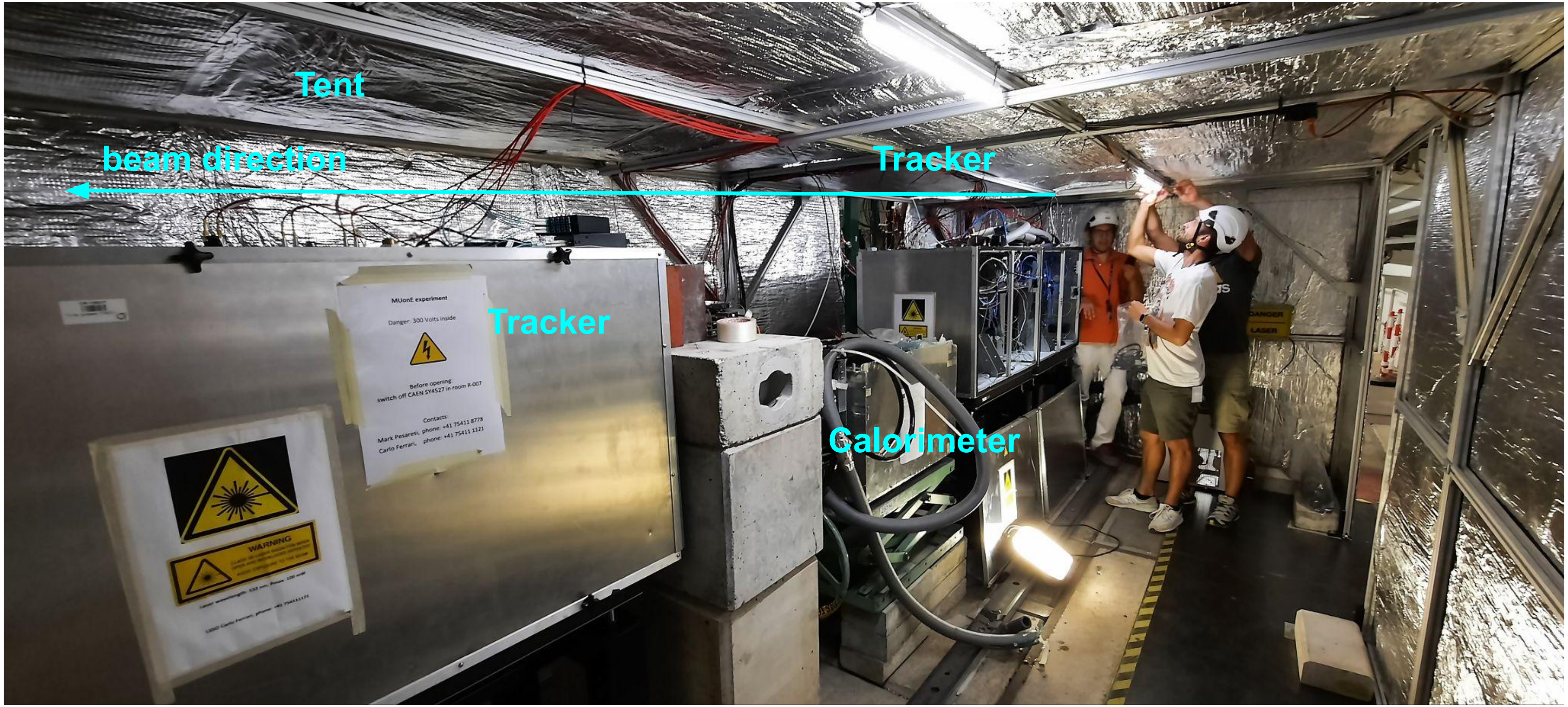
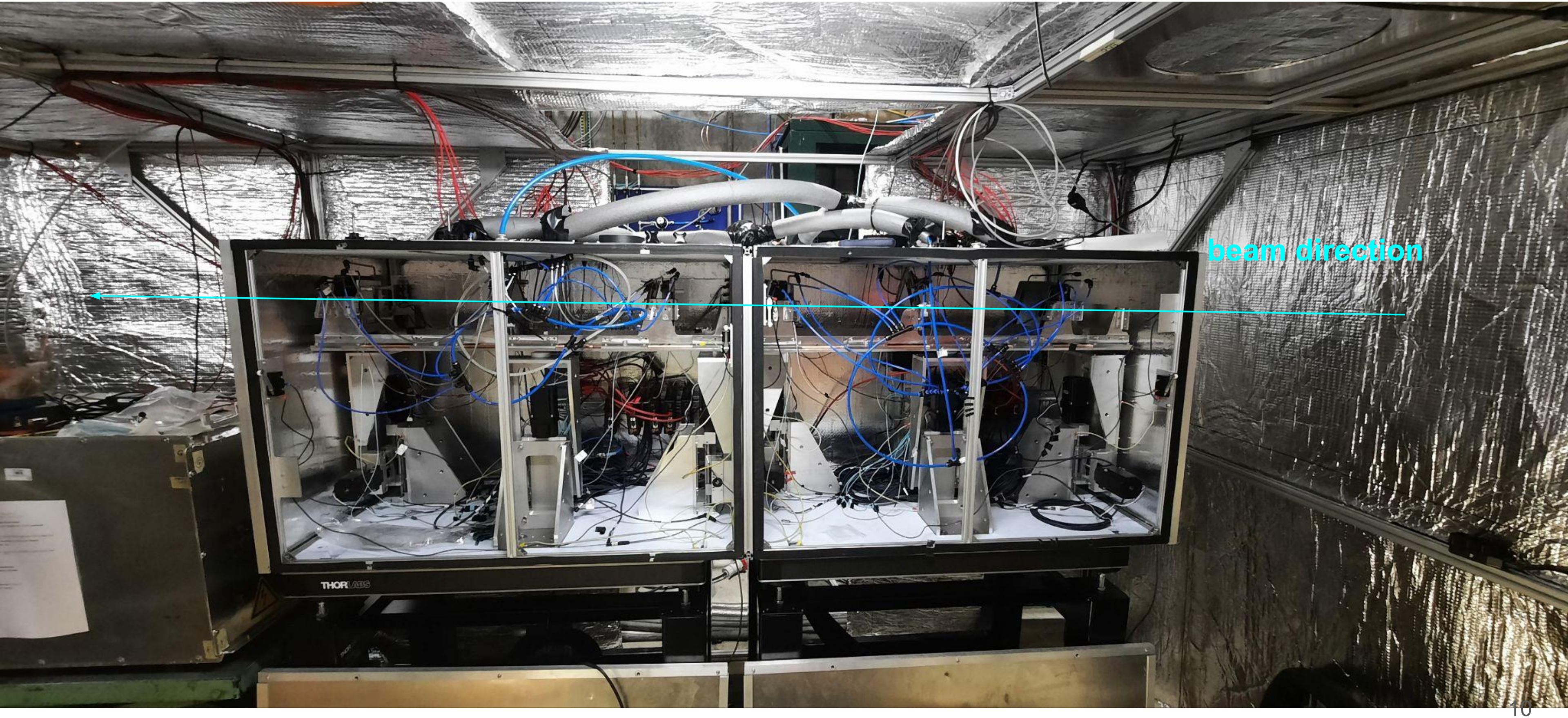


Fig. 7: A schematic showing how the 2S-module is assembled. The ASICs are bump-bonded to the flex-hybrid substrate. A service hybrid, not shown, provides DC power, and electro-optical interfaces.

Detector setup in the 2023 test run



The two tracking stations

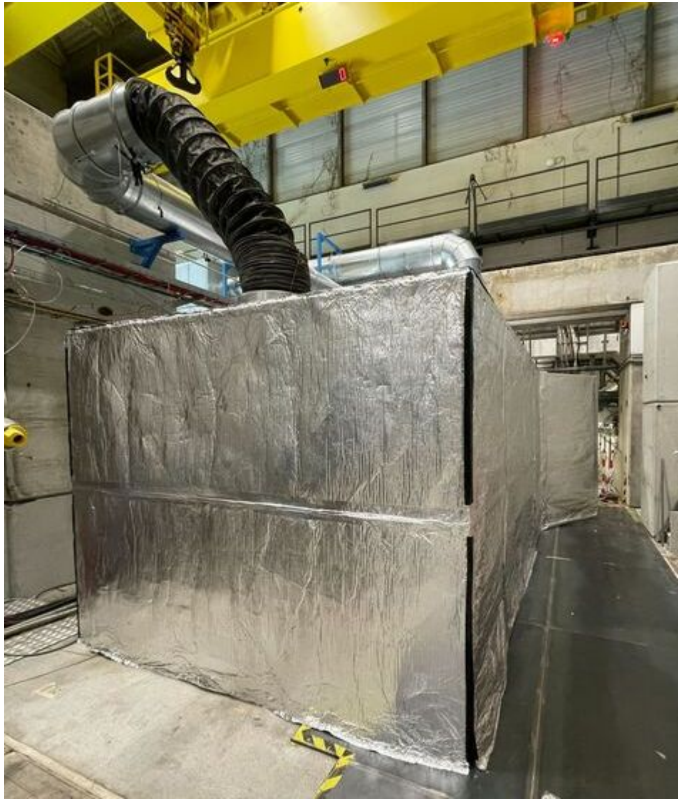


The tent for stable temperature and humidity

Air flux at 18C

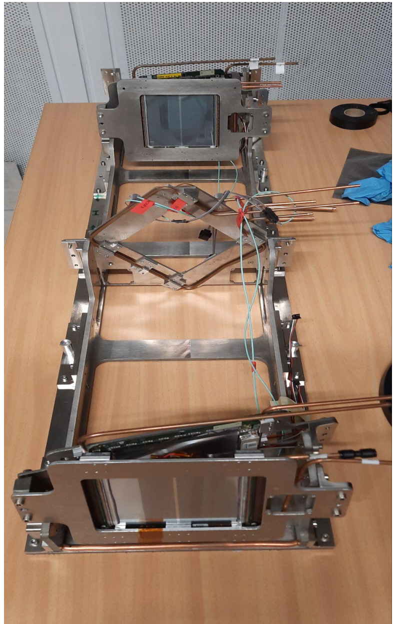
Front view

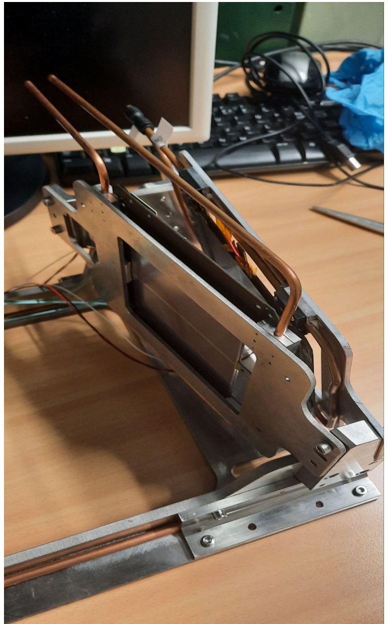
Rear view

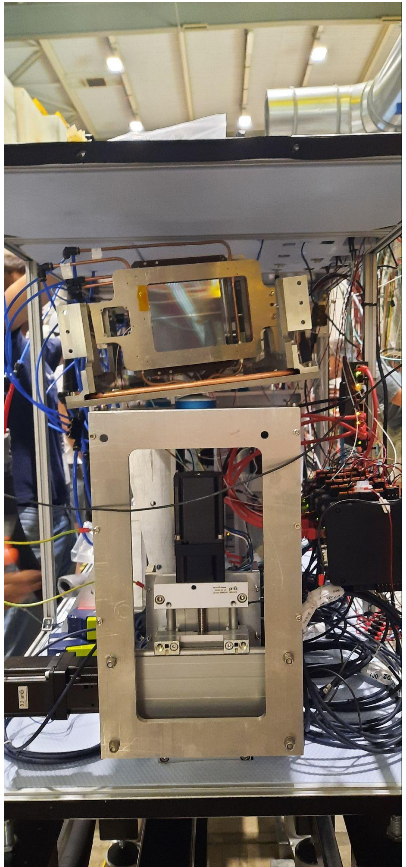


The tracking station:detection elementary unit

- A station hosts 6 modules
- X,Y modules are tilted to improve the spatial resolution. UV central modules are orthogonal to beam and are used to match 2D segments in 3D tracks



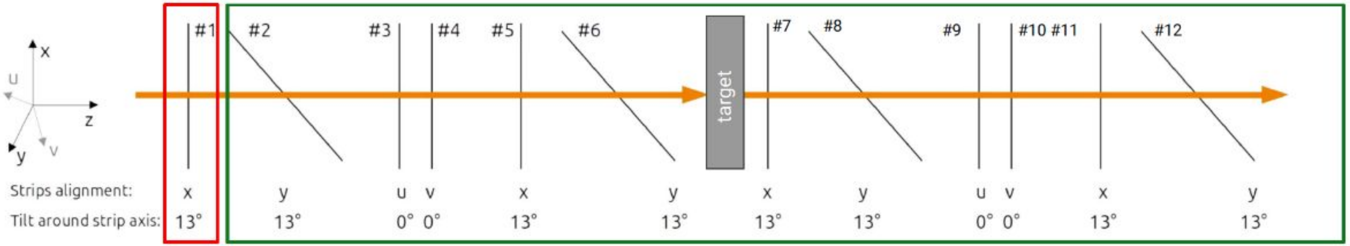




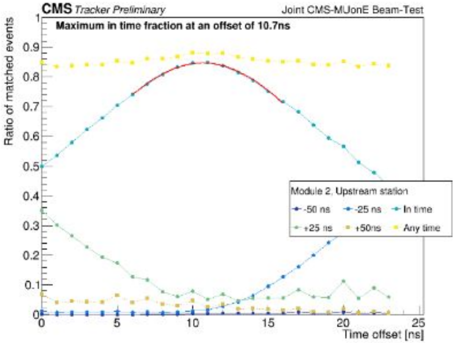
Main results of the 2023 test run

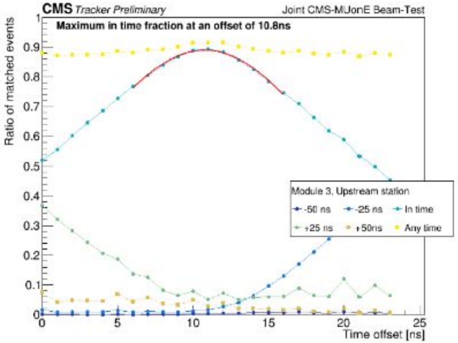
- Stubs have been recorded at 40 MHz
- Low intensity beam was used for commissioning
- High intensity beam used for measurements ($\sim 2\times10^8$ muons/spill)
- Carbon (graphite) target of 2cm e 3cm for data comparison
- Runs without targets for high precision alignment studies
- Long data taking lasting ~12 h
- 300 TB of raw data recorded:
  $\sim 1\text{x}10^8$ elastic collisions with the 3 cm target,
  $\sim 2\text{x}10^8$ elastic collisions with the 2 cm target.

Synchronisation of the modules



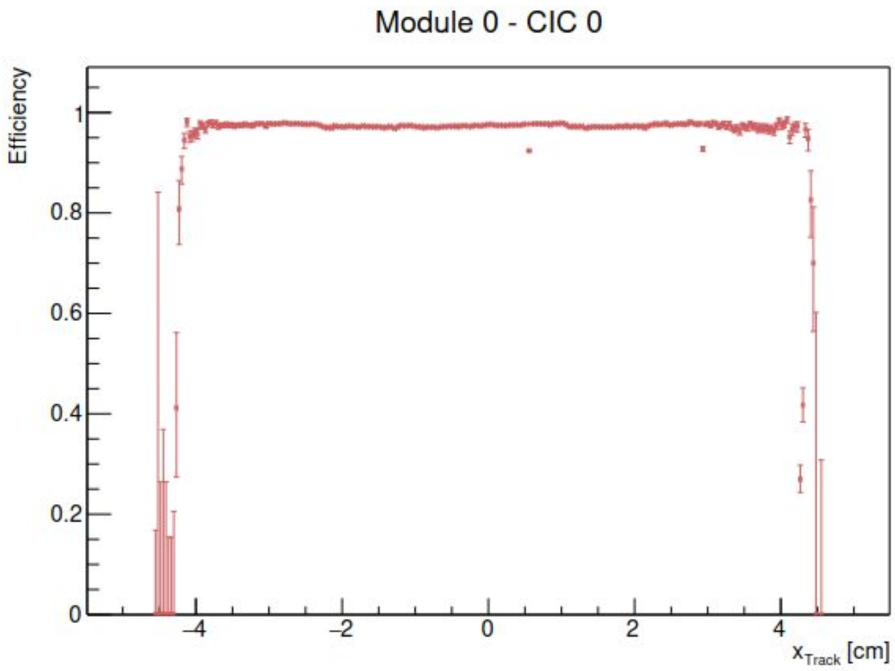
Computing fraction of events with a hit in module 1, if a hit ifs found in module X





→ **Gives us the relative timing of modules (here, 0.1ns between module 2 & 3)**

2S detection efficiency



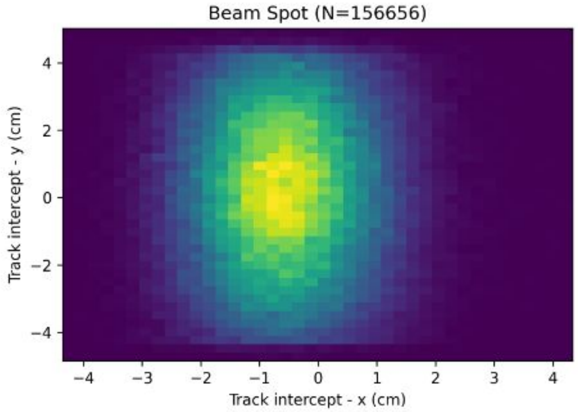
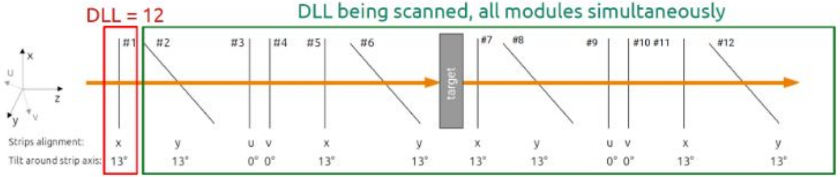


Figure 4.6: Example module efficiency as a function of the track position, obtained in one run with low intensity beam.

Asynchronous beam and detection efficiency

The detection efficiency depends on the muon arrival time relative to the system clock, meaning that not all muons can be utilized.

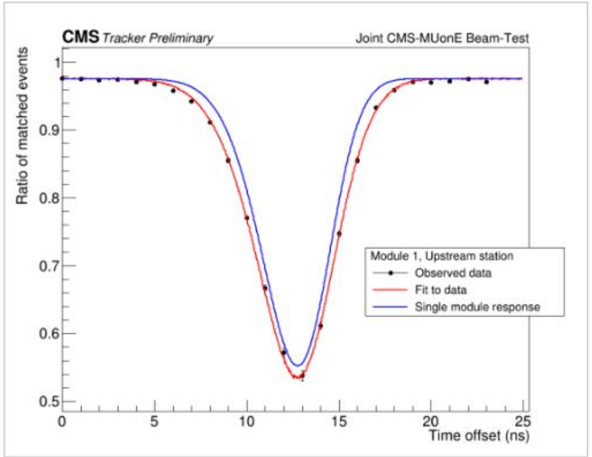
The DLL measurement



Selecting events with a single stub on module 2 & 3, and maximum 1 stub in all other

Requiring stubs in 2 & 3 to have $\Delta \mathrm{BX} = \pm 1$ → **Selecting clock edges**

Looking at fraction of events with a hit in module 1



Probability of observing a stub if two reference modules observe a stub in subsequent 25ns bins, as a function of delay between the device tested and the two reference modules. The data is fitted to a simulation assuming the in-time detection efficiency of all modules is modelled by two error functions, and is overlaid with the corresponding single module detection efficiency.

Martin Delcourt talk at BTTB12:

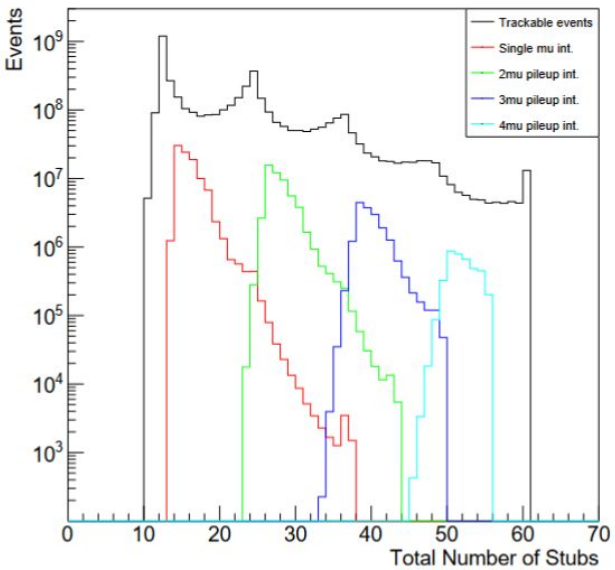
Commissioning and study of a CMS 2S module with 40MHz readout

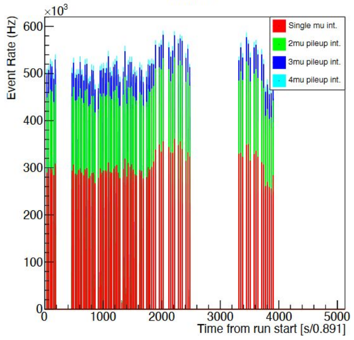
https://indico.cern.ch/event/1323113/contributions/5823586/

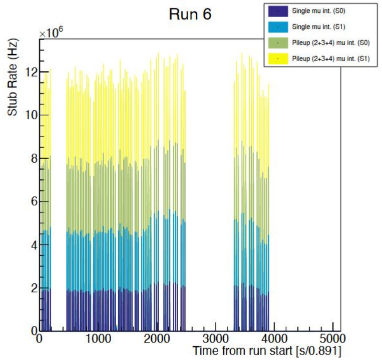
Online Filter (tested offline)

- Essential to keep the data flux to disk manageable.
- Studied on MC and real data offline
- Rejection power ~1:100
- Efficiency on reconstructable events 100%
- On a data set of ~12E+9 events the filter selected:
  85 M, as single muon interactions
  80 M, as interactions with overlapping muons
- Single muons corresponds to 50% of the sample

Filter event tag







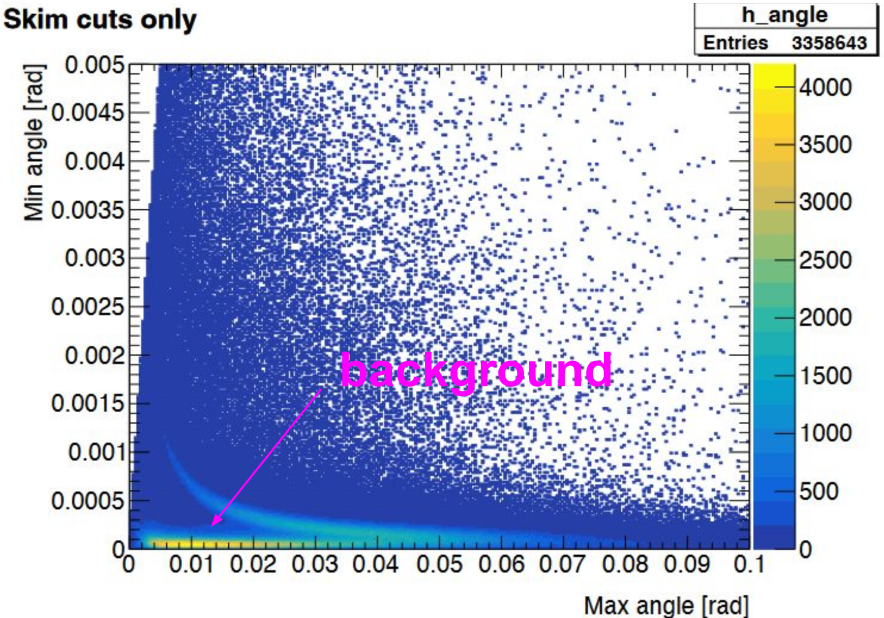
Events' 2D angular distribution

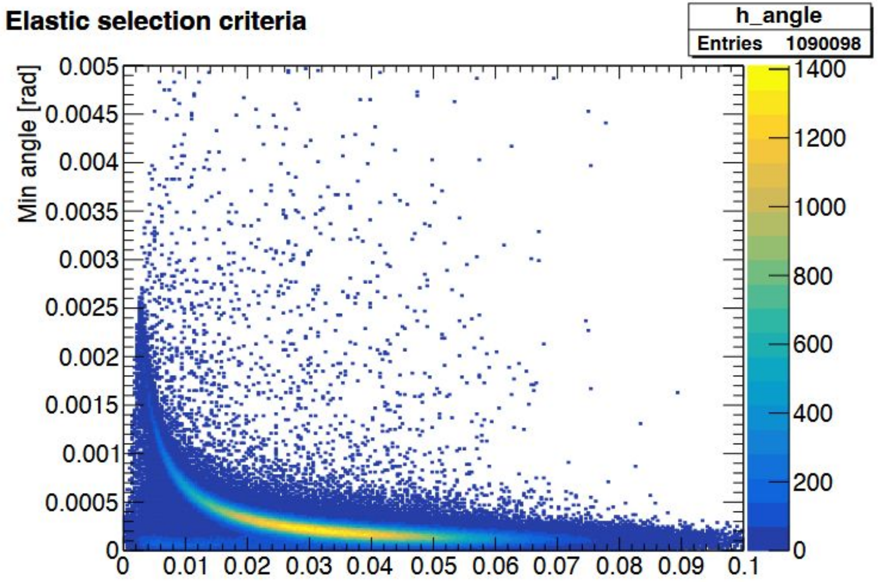
Event signature: 1 incoming track + 2 outgoing tracks

Track quality established relying on the stubs pattern

Acoplanarity cut, |zvertex − ztarget| ≤ target thickness

- The detector angular resolution depends on the modules stubs resolution and on the MS
- We minimized the MS using a tracker with only 3 points per view.



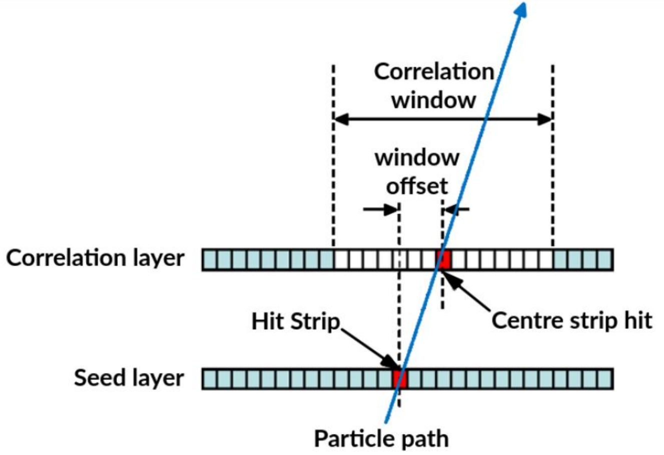


2S module stub resolution

- The module's readout electronics returns the position of the hit in the first sensor (seed sensor) and the bend, i.e. the displacement of the hit in the second sensor (confirmation sensor)
- The stub position can then be measured as:

$$x = x_s + 0.5 * \text{bend}$$

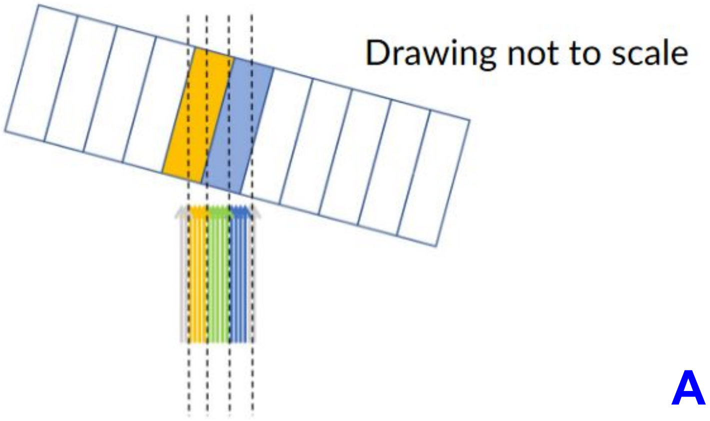
- The bend is defined with respect to the offset and must lay within the search window

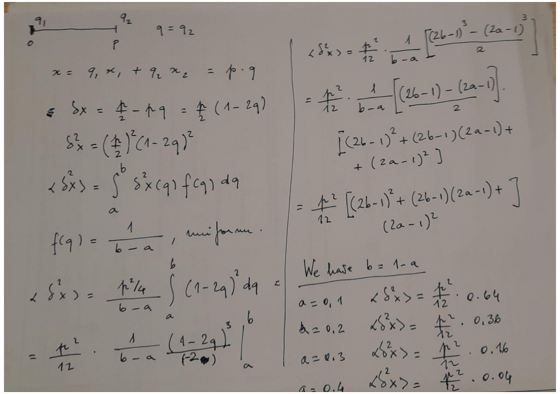


- To improve the intrinsic resolution we though to tilt the modules with respect to the beam axis along the strip direction such to improve x_s and to exploit the bend information.

Tilting the module to induce charge sharing

charge sharing between adjacent strips





The resolution of a stub made out of two strips is generally better than those of stubs made of a single strip, even though the digital readout

A simple estimate gives:

0.4 p/sqrt(12) < sigma < 0.6 p/sqrt(12)

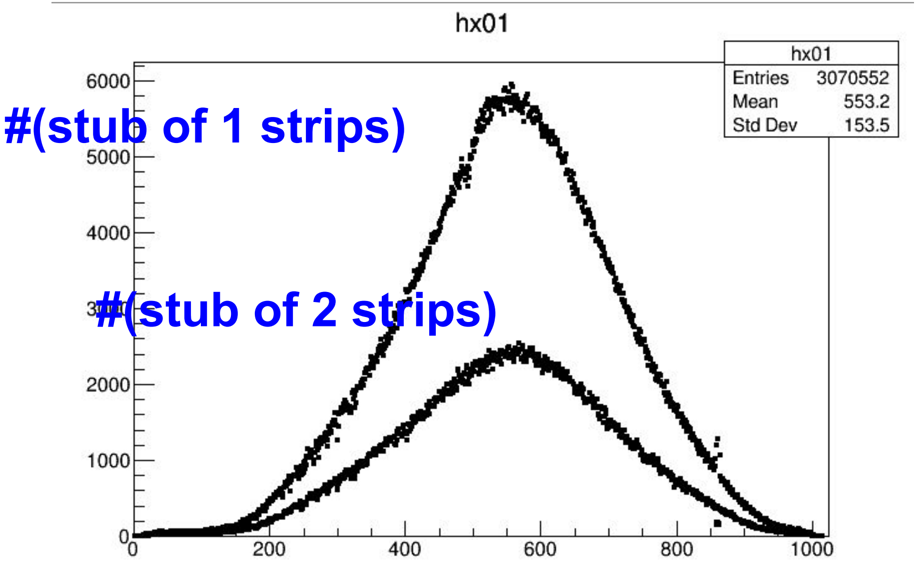
Detailed studies had been performed and are available at:

https://etd.adm.unipi.it/t/etd-02222023-185026/

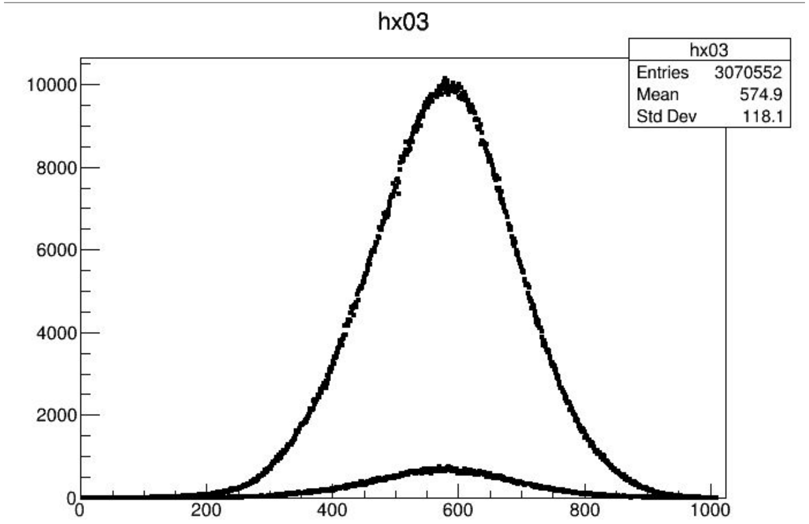
Measuring the so-called parity

parity = #(stub of 2 strips) / #(stub of 1 strip)

Tilted module



Orthogonal module

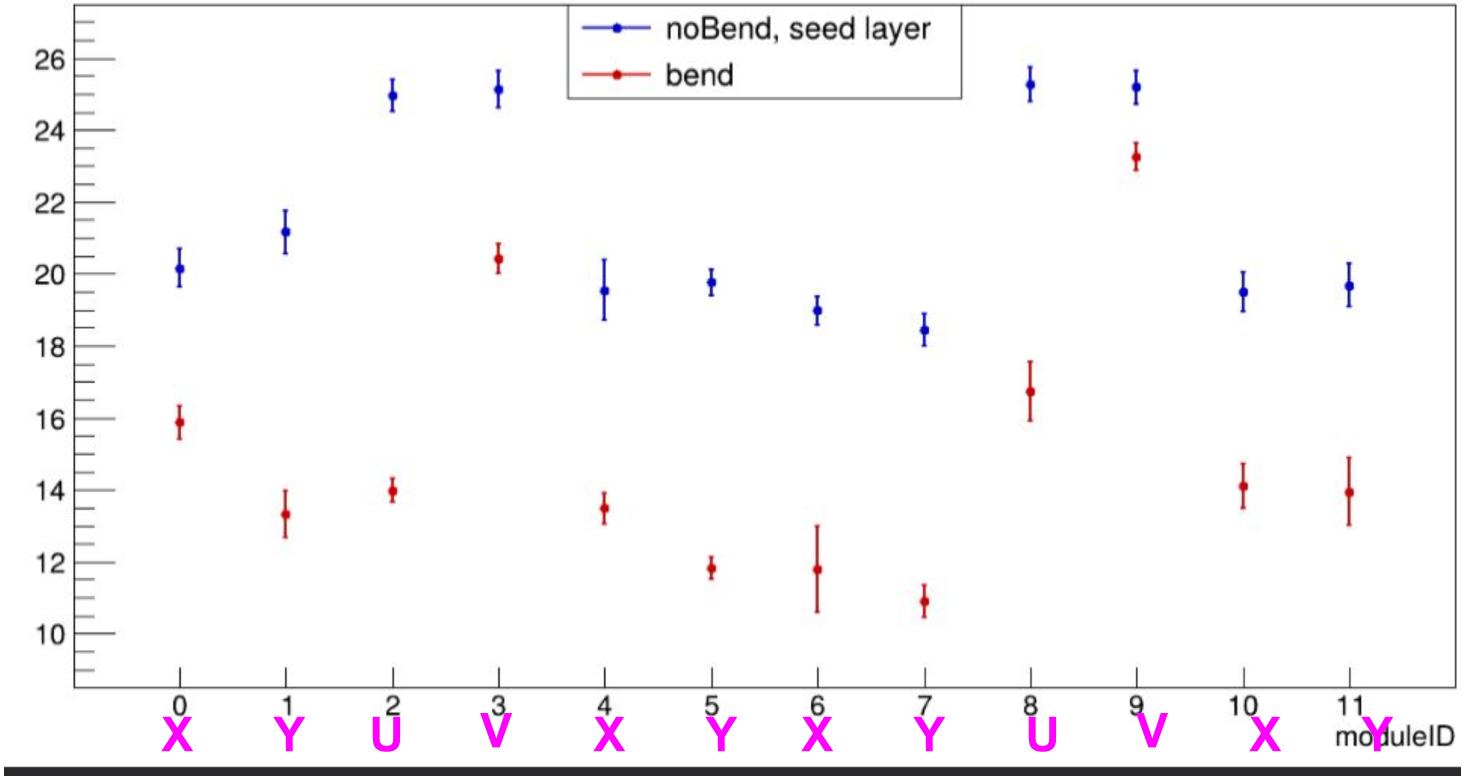


160 GeV single muon crossing the detector

Modules resolution

Riccardo Pilato

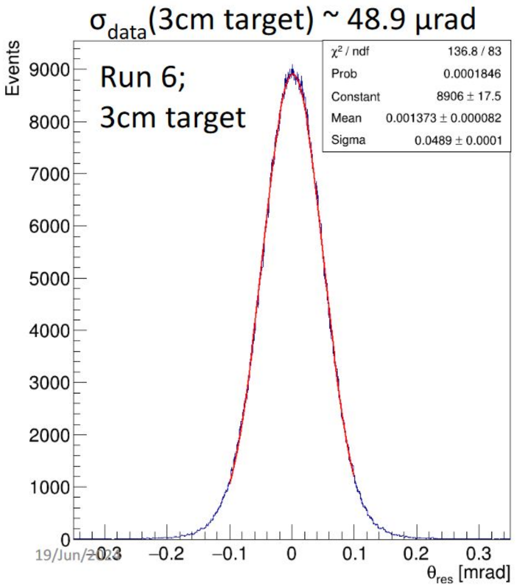
With improved tracking and detector geometry



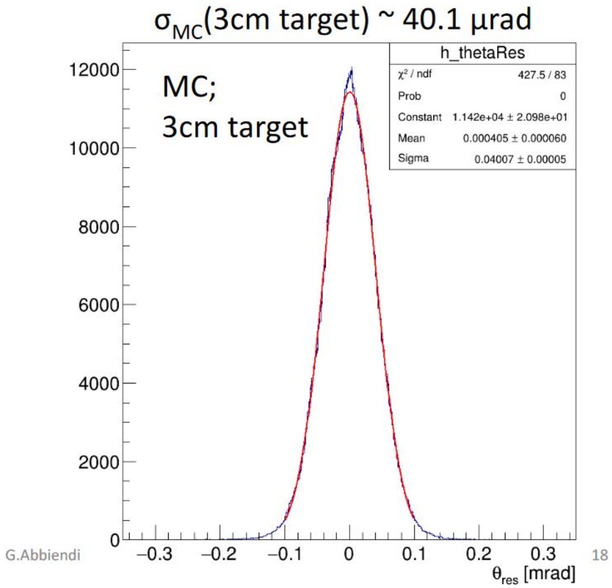
Angular resolution: still an open problem

160 GeV muons

Real data



Model



With the present reconstruction and alignment: hopefully it will improve with better alignment, imorved tracking and more accurate simulations

Tilting the modules has one drawback

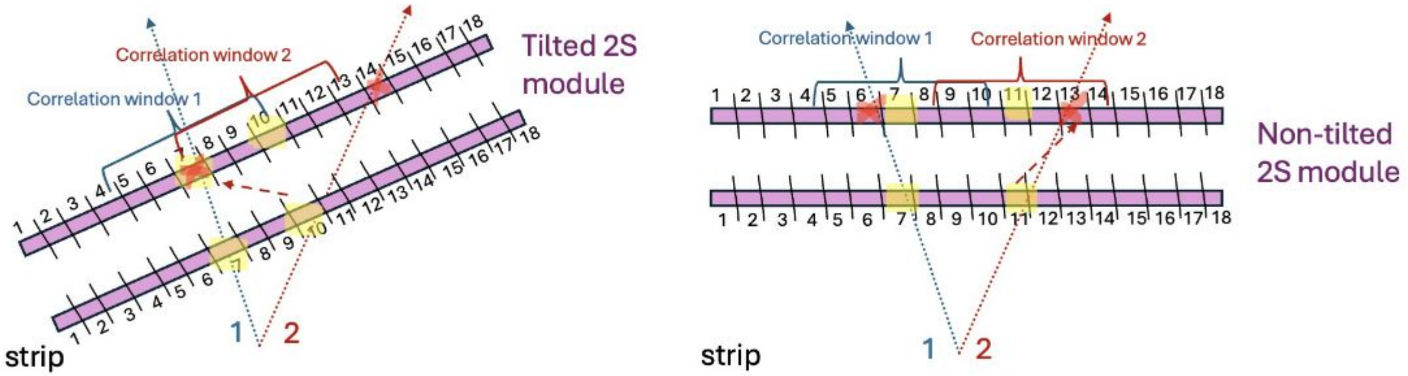
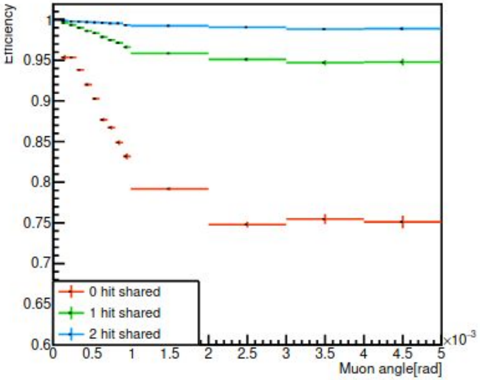
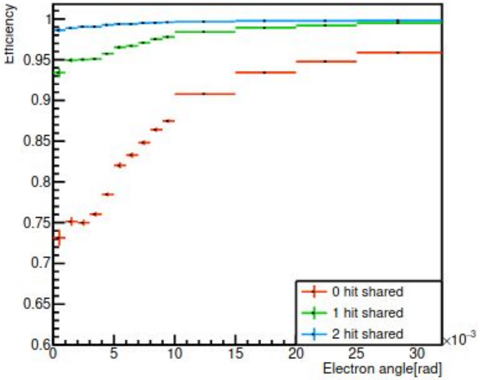


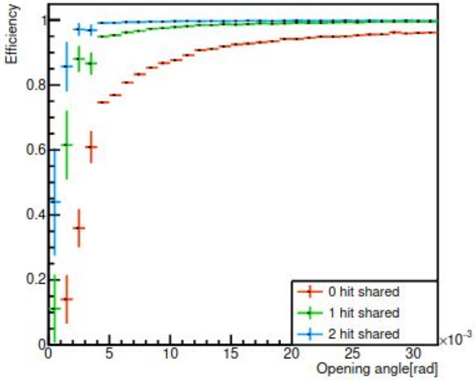
Figure 3.15: Sketch of scattering event in a tilted (left) and non-tilted (right) module, with the creation of seed and correlation cluster (respectively first and second layer). The yellow spot represents the strip fired in the seed layer and, as a consequence, the center of the correlation window (blue and red brackets) without offset, while the red cross is the fired strip in the correlation layer. The dashed red arrow represents the associated strips forming the stub of particle 2.

Pattern recognition

- The layout of the tracking station, with 6 modules, 3 per view XZ and YZ, is minimal, with almost no redundancy for an efficient pattern recognition.
- On MC data we proved to have a high and uniform event detection efficiency the reconstruction has to permit the elastic tracks candidates to share 2 hits. Problems with real data.







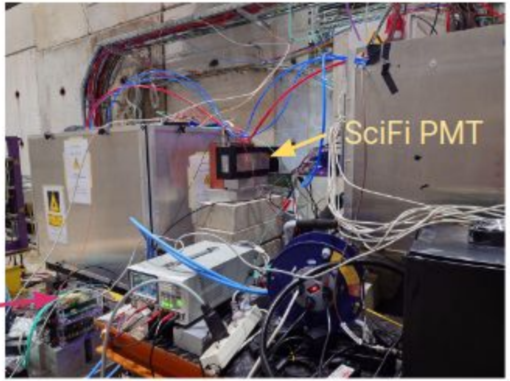
Test in 2024

- A new scalable DAQ system has been successfully developed and tested. This system will enable scaling up to the final experiment, where we will manage a much larger number of data streams through optical links.
- Online event building has been implemented to support the online event filter—a key feature of the DAQ system.
- However, some detector components remain untested, including the Beam Magnetic Spectrometer (BMS) and the muon-ID. Although ECAL data has been collected synchronously with the tracker, we still need a larger data sample collected via the 40 MHz Serenity readout channel.

Timing system: progress, status & outlook

- Completely new for 2024 →
  - Install fast timing reference as independent reference for efficiency
    - For in-depth studies of dynamic or asynchronous effects
  - scintillator + ~1 ns resolution TDC firmware running on FC7
  - PMT (SciFi) signal provides additional input - also 'digitised' into time
  - TDC FC7 endpoint is much like ECAL FC7 endpoint - both transmit data every BX (40MHz) to Serenity over lpGBT
  - data decoded on Serenity and **synchronised in time with Tracker** (small fixed delay) & **TDC information included in DAQ event packet**

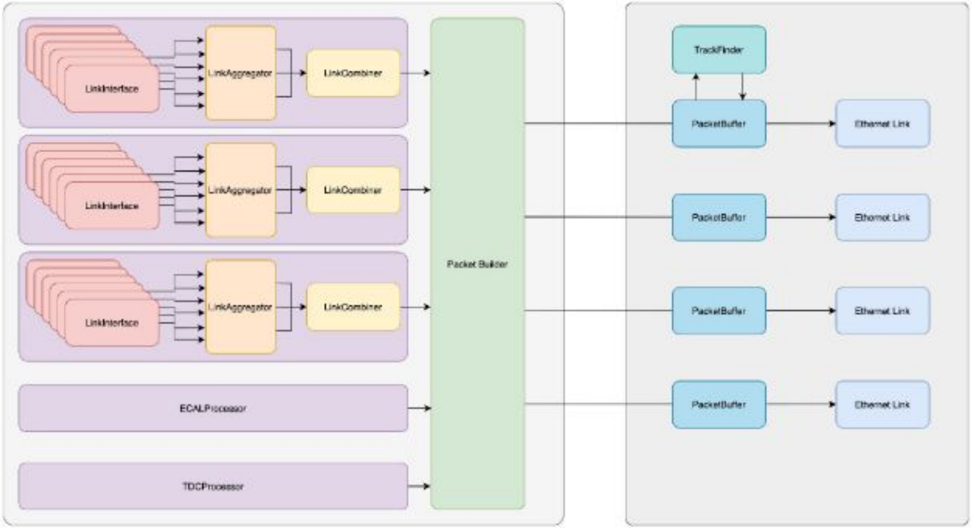
- Main activities during testbeam
  - integrated system with new DAQ requiring some time
  - aligned detectors with beam
  - synchronised scintillator and PMT with Tracker



DAQ: Move to Dual-FPGA Solution

- Adding a second FPGA decouples ethernet link from front end firmware
  - Each FPGA can be reprogramed independently
- Uses CSP link protocol to send data between the FPGAs at 25 Gb/s
  - First demonstration of this link protocol for the CMS tracker
- Reduces resource usage on first FPGA
- Extra resources on second FPGA allow for inclusion of online tracking into the mainline DAQ
- Migration to multi-FPGA/board design is an inevitable requirement as the experiment scales, this proved it is possible

Dual FPGA



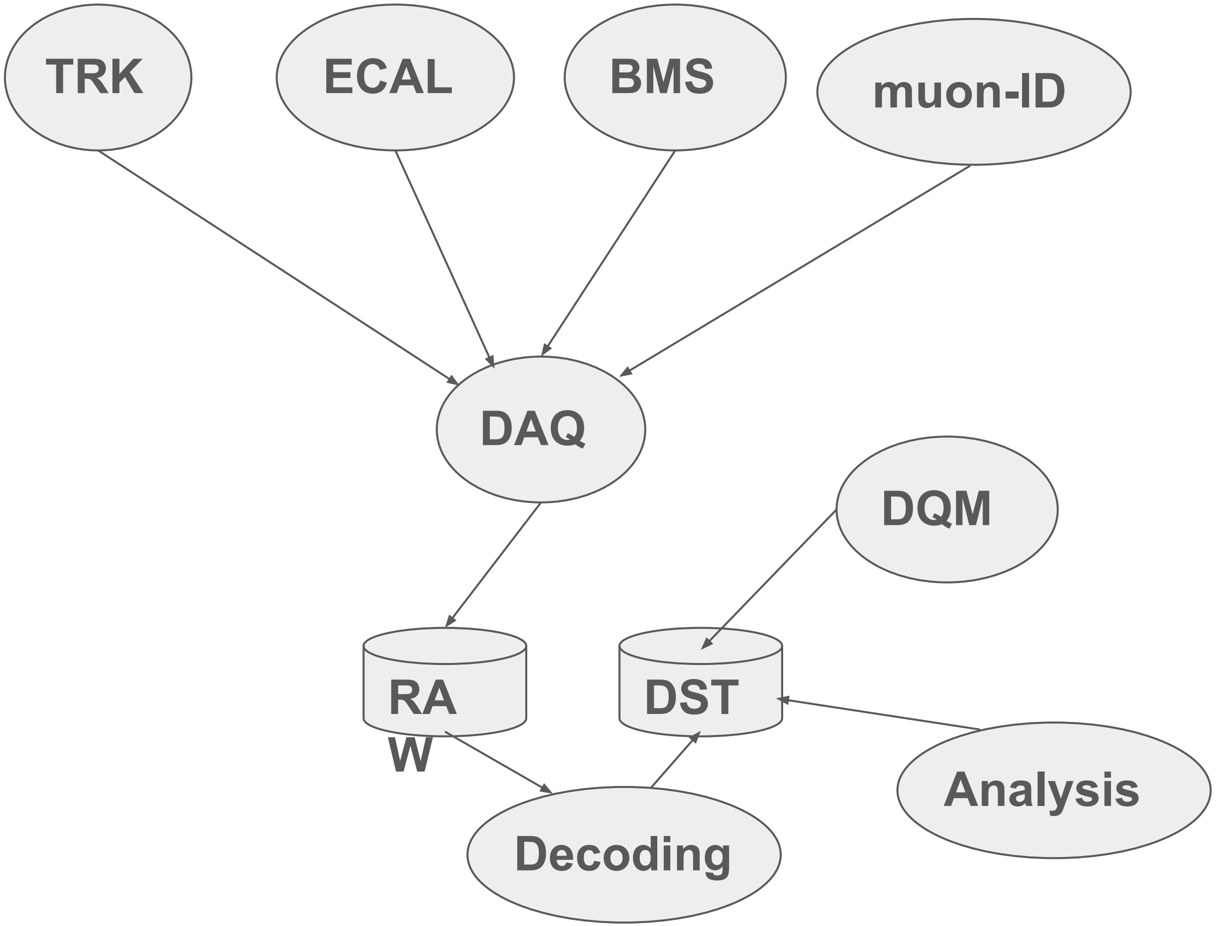
Not trivial!

Conclusive test run in 2025

- This will be an extended test run aimed at collecting a large data sample to achieve statistical sensitivity to the hadronic running correction to α (t).
- Key objectives include:
- Qualification of new 2S modules
- Integration of all additional detector components into the DAQ system
- Utilizing the PID capabilities provided by the ECAL and muon-ID
- Exploring ECAL’s potential for consistency checks
- Defining the optimal detector layout with the 2S modules

Main sub-systems

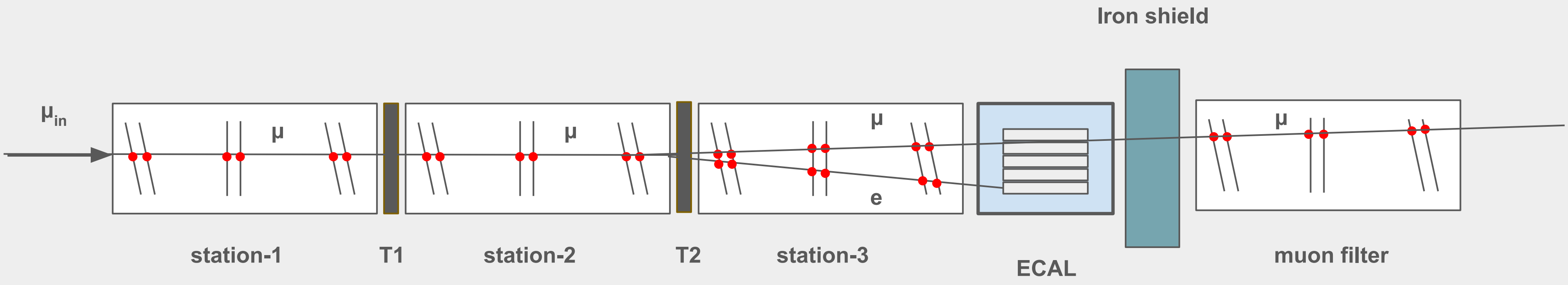
- TRK
- ECAL
- MUON-ID
- BMS
- DAQ
- DQM
- SOFTWARE/ANALYSIS



Conclusive test run in 2025

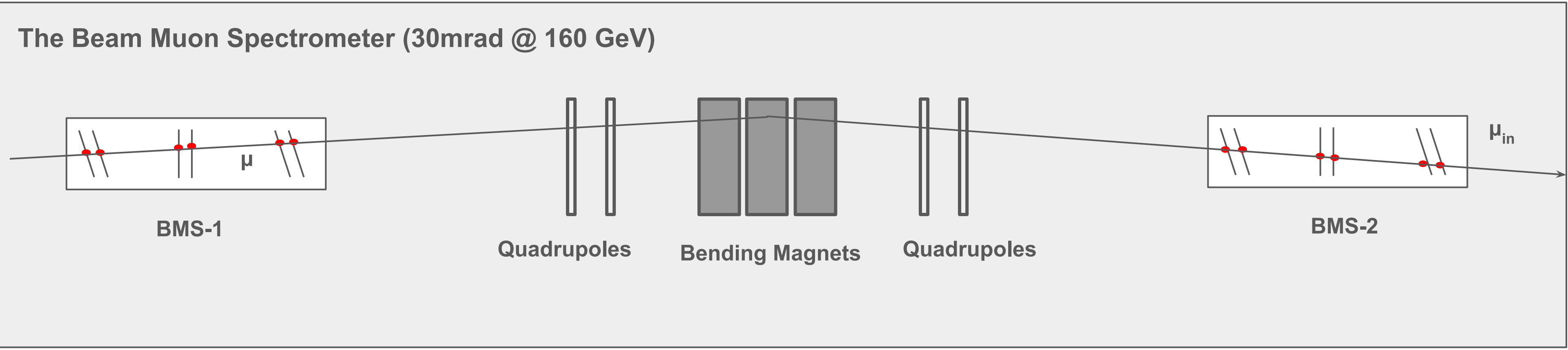
- ## The detector components

MUonE Detector. Controlled environment



Conclusive test run in 2025

The Beam Magnetic Spectrometer



Conclusions

- The 2S modules are performing as designed.
- The DAQ system has progressed to its final version.
- The detector layout is still under discussion.
- Significant recent progress has been made in the analysis, which will be presented by Giovanni Abbiendi.
- We are developing a new module for use in the full experiment. The concept and current status of the 1S module will be presented in this meeting.
- We are confident that we can achieve significant improvements in detector performance and data analysis as we prepare for the full experiment.