MUonE

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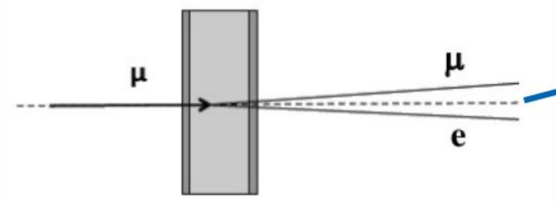
- **The MUonE project**
- **Status of the detector, software and analysis tools**
  - 2S modules
  - Tracking system
  - Data acquisition
  - Electromagnetic calorimeter
  - Software
  - Analysis
- **Plans**

The hadronic contribution space-like

Extraction of $\Delta\alpha_{had}(t)$ from the shape of the $\mu e \to \mu e$ differential cross section

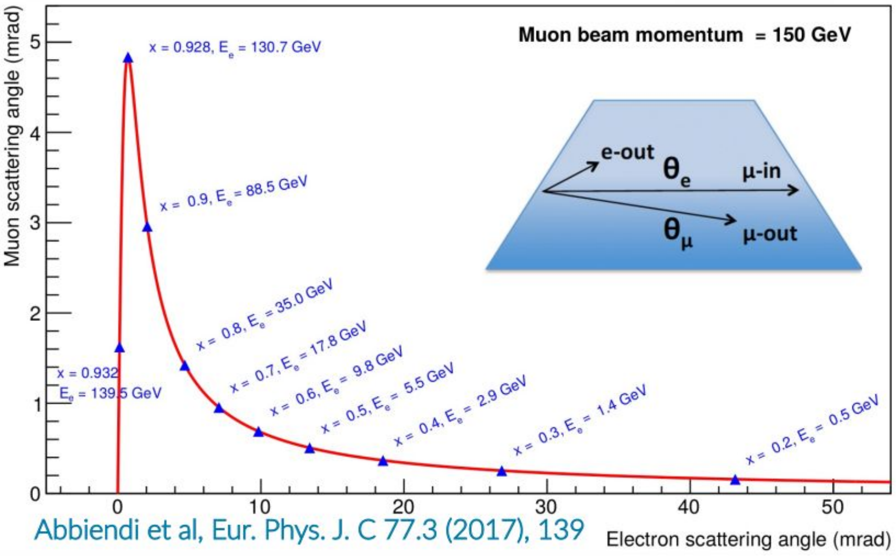


$$\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$

From theoretical calculation

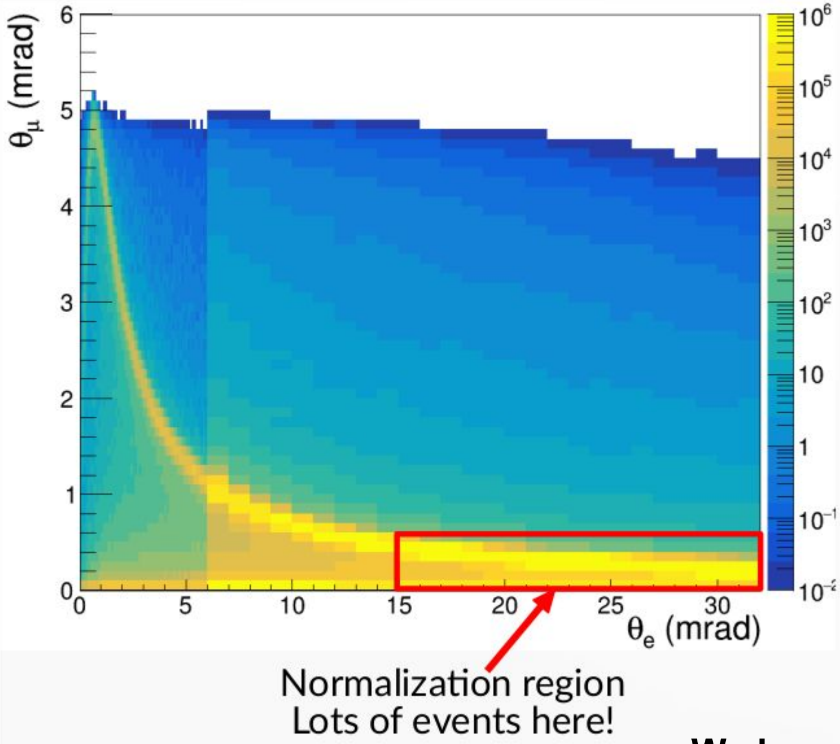
To be measured

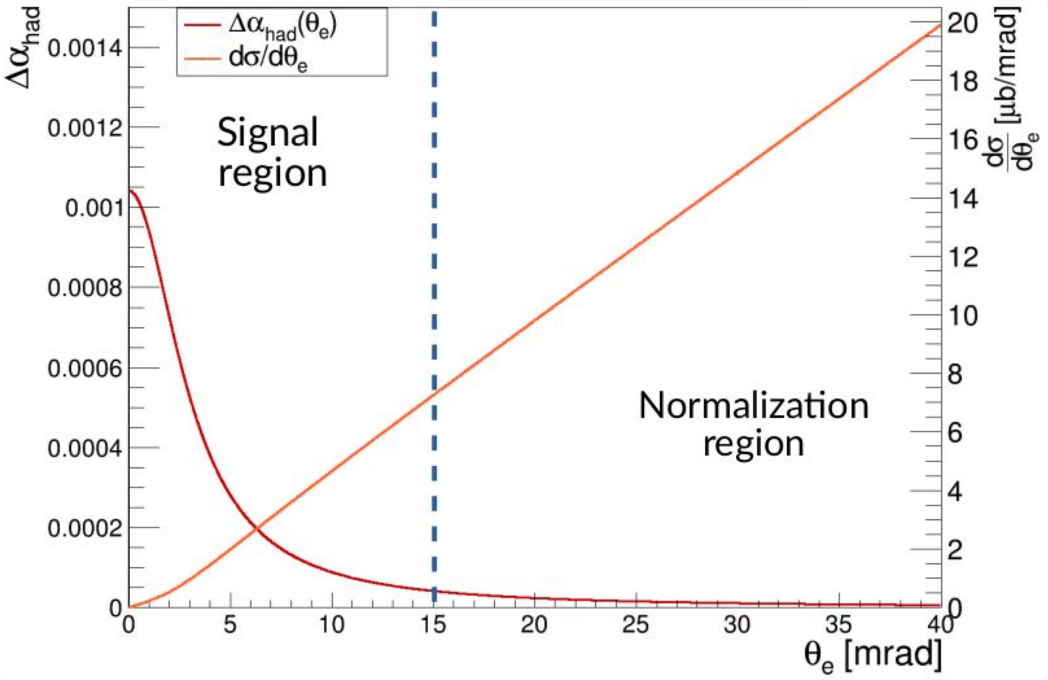
- A beam of 160 GeV muons allows to get the whole a_μ^{HVP} (88% directly measured + 12% extrapolated).
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



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

The 2D observable angular distribution





We have to reproduce this pattern by means of a template fit

Parameterization of the hadronic running

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

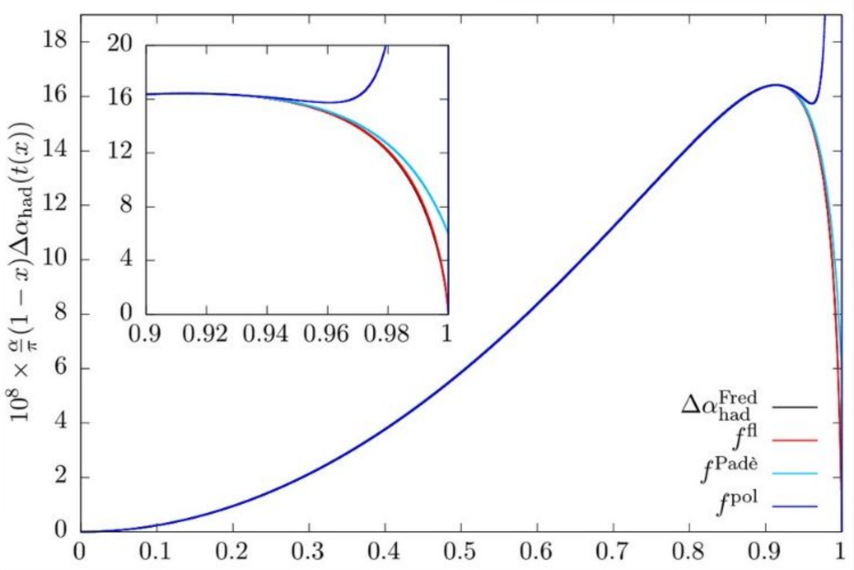
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters:
K, M

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

Dominant behaviour in the MUonE kinematic region:

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



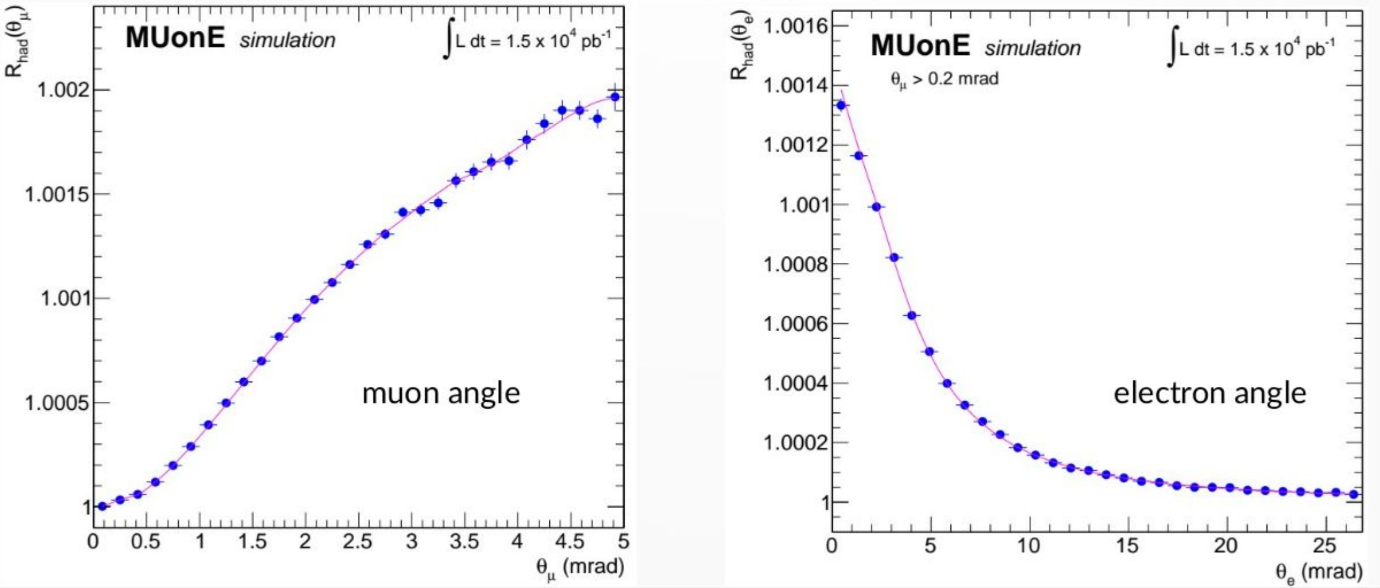
Template fit statistical precision

Extraction of $\Delta\alpha_{had}(t)$ through a template fit to the 2D (θ_e, θ_μ) distribution

Results from simulation: $a_\mu^{HVP} = (688.8 \pm 2.4) \times 10^{-10}$

Input value (FJ): $a_\mu^{HVP} = 688.6 \times 10^{-10}$

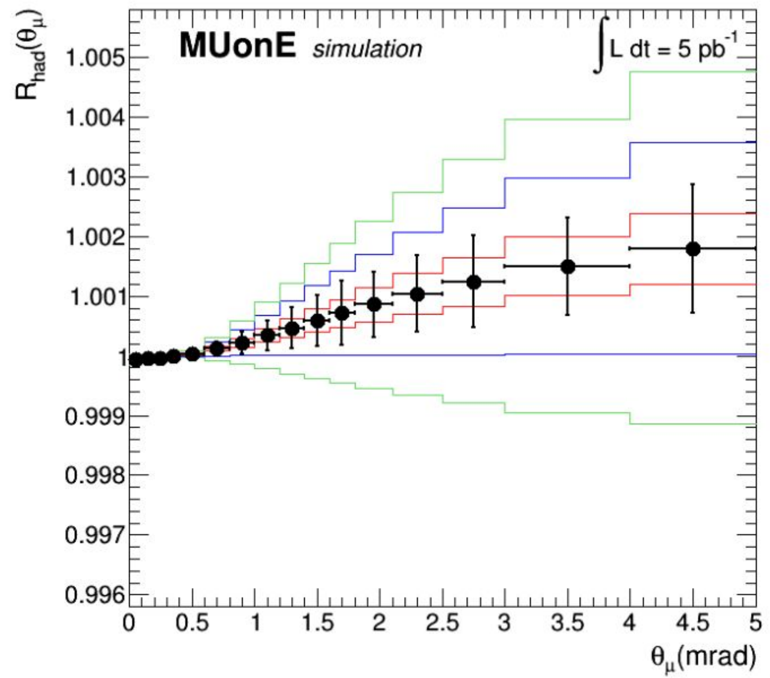
$$R_{had} = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had} = 0)}$$



Expected sensitivity 1 week of data taking

Expected luminosity for the Test Run: $L_{TR} = 5\ pb^{-1}$ ⟷ $\sim 10^9$ events with $E_e > 1$ GeV ($\theta_e < 32$ mrad)

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



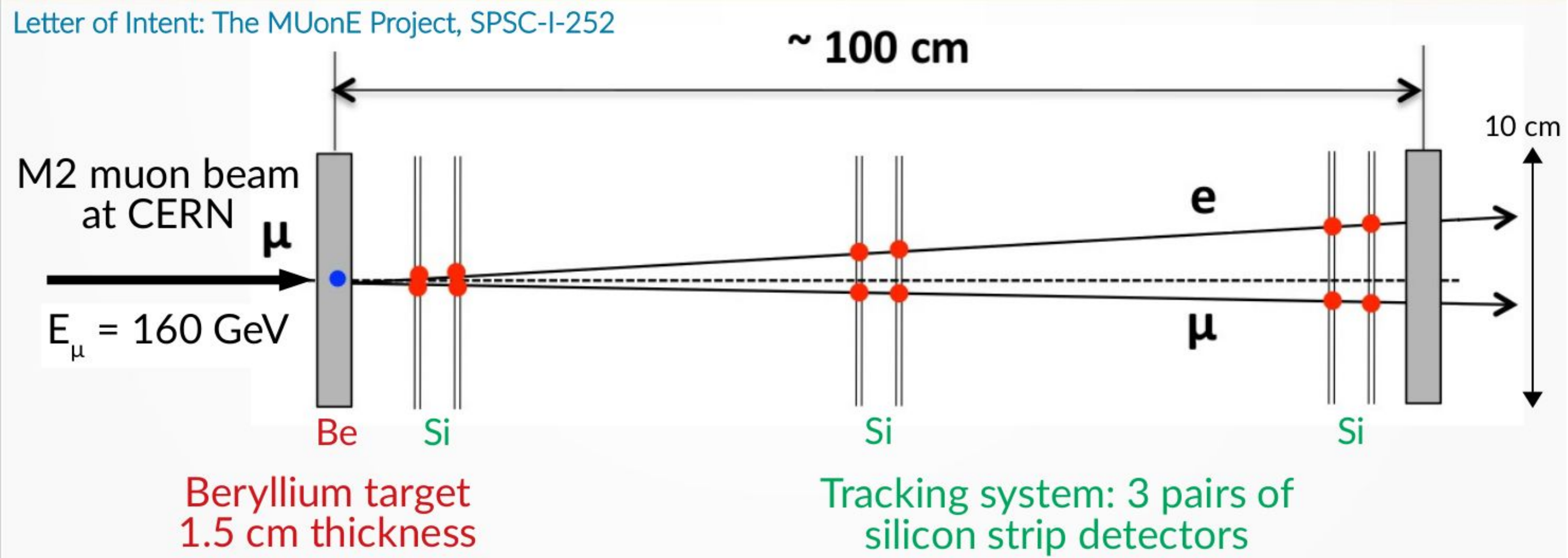
Low sensitivity to the hadronic running ($\Delta\alpha_{had}(t) < 10^{-3}$)

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

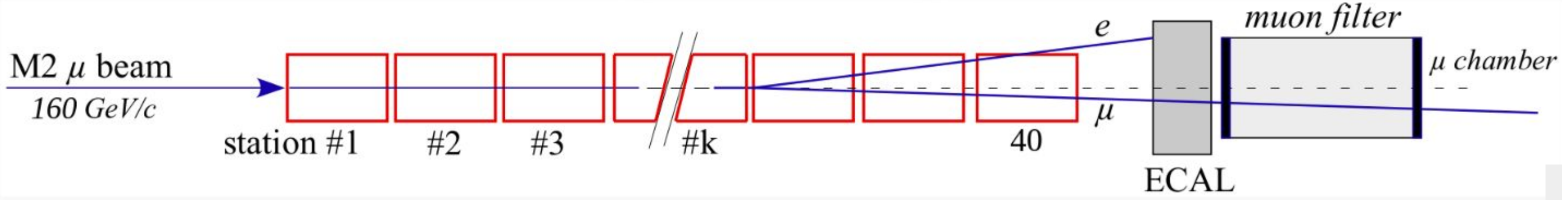
$K = 0.136 \pm 0.026$
(20% stat error)

We will be sensitive to the leptonic running ($\Delta\alpha_{lep}(t) < 10^{-2}$)

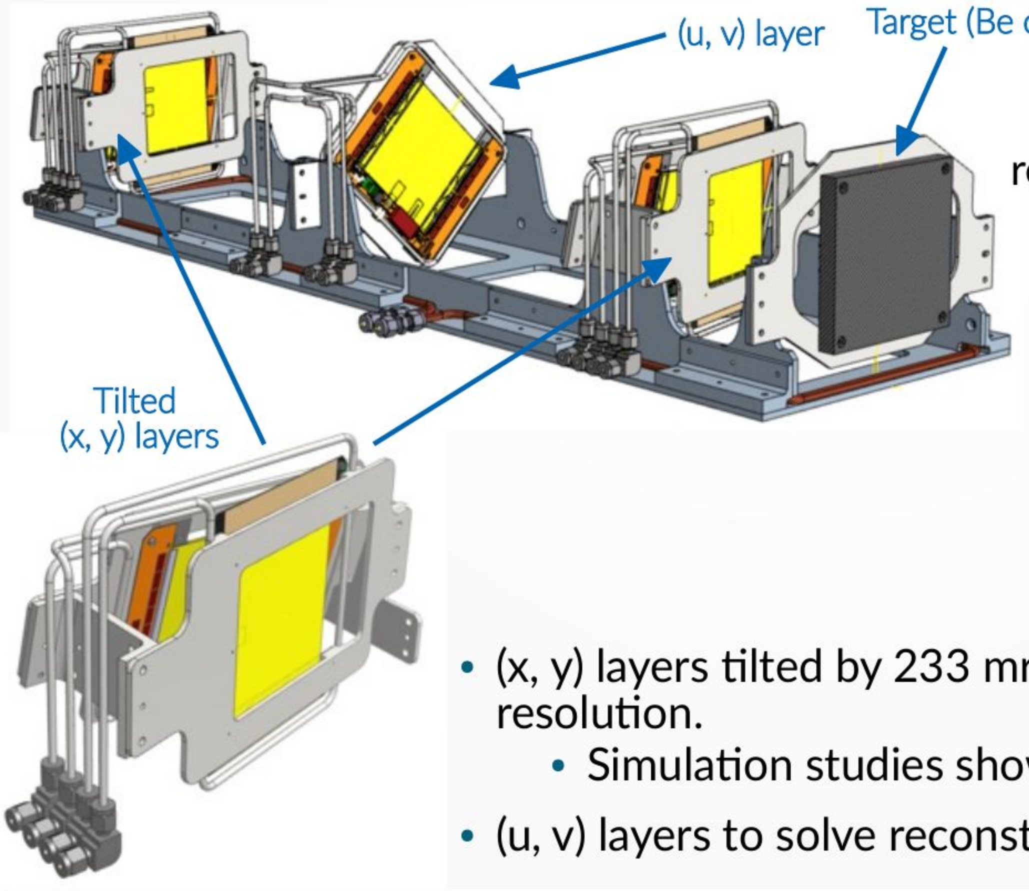
The detector



A spectro



A tracking station



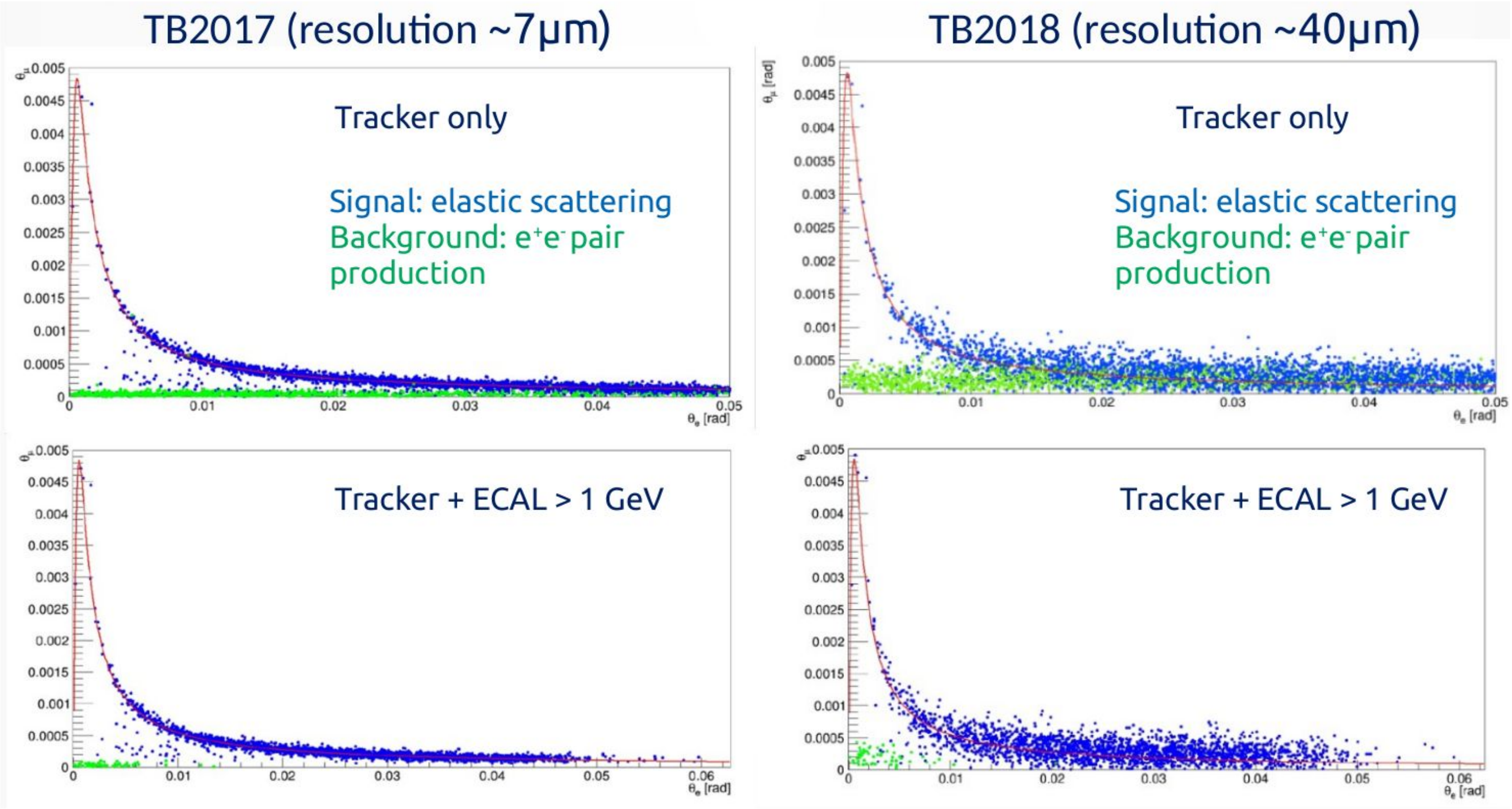
Stringent request:
relative position within a station must be stable at 10 μm.

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

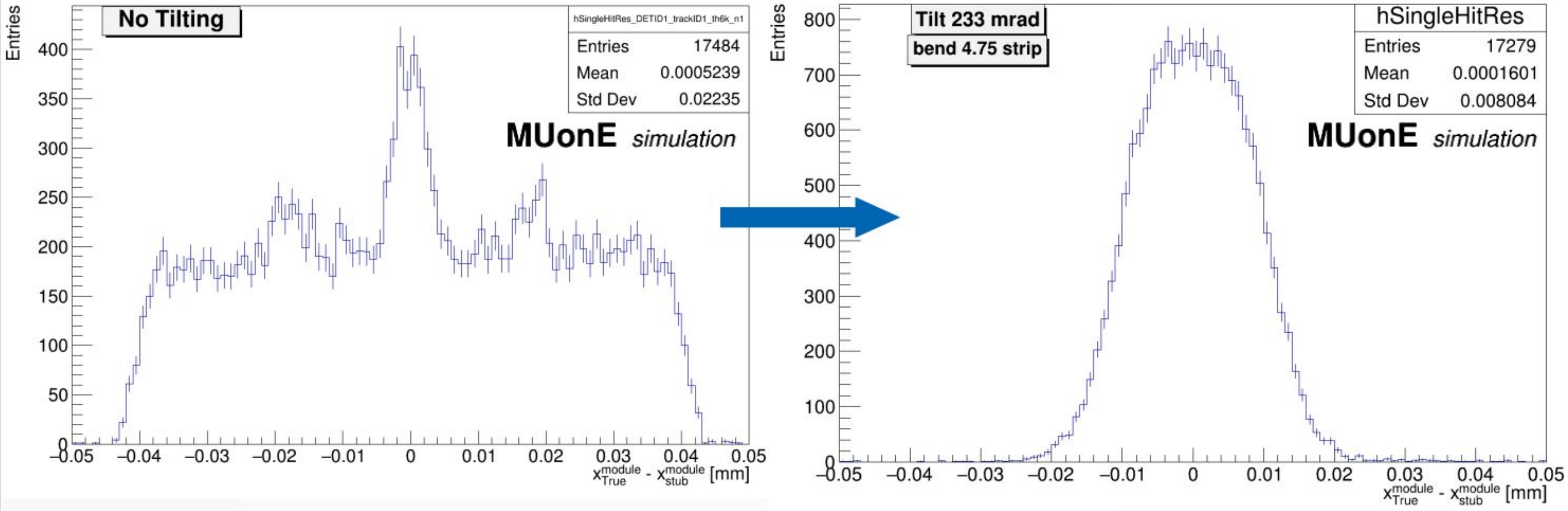
Laser holographic system to monitor stability.

- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
    - Simulation studies show a resolution of ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

Role of the detector resolution



Resolution: charge sharing by tilting of the modules



Improvement due to:

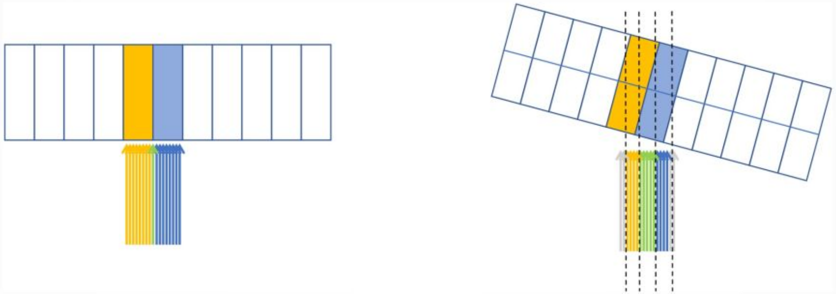
- charge sharing between adjacent strips
- effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

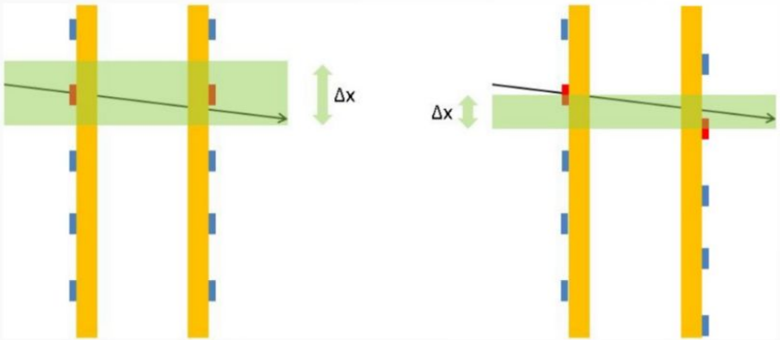
Final resolution

22 μm → 8-11 μm

Resolution: charge sharing by tilting of the modules

1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips



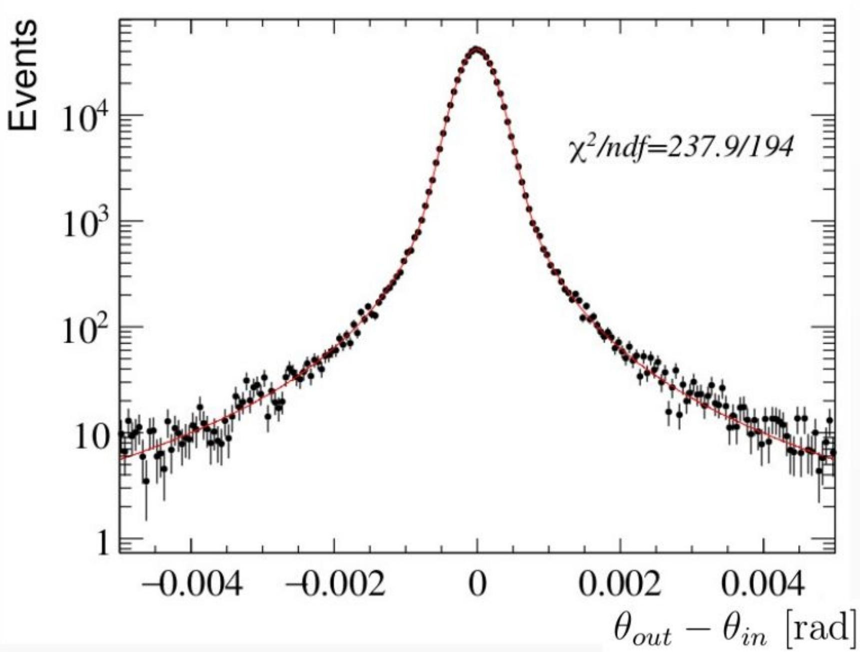


2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

40

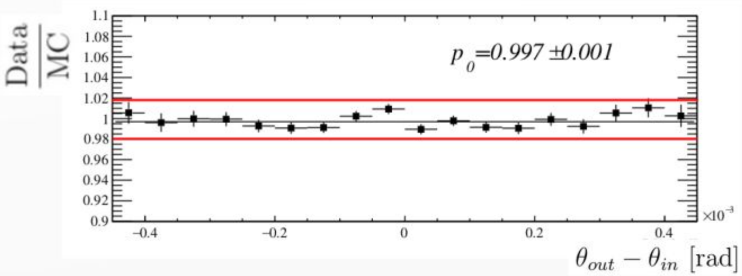
Multiple Scattering studies in 2017

$$f_e(\delta\theta_e^x) = N\left[(1-a)\frac{1}{\sqrt{2\pi}\sigma_G}e^{-\frac{(\delta\theta_e^x-\mu)^2}{2\sigma_G^2}} + a\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma_T\Gamma(\frac{\nu}{2})}\left(1+\frac{(\delta\theta_e^x-\mu)^2}{\nu\sigma_T^2}\right)^{-\frac{\nu+1}{2}}\right]$$



$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

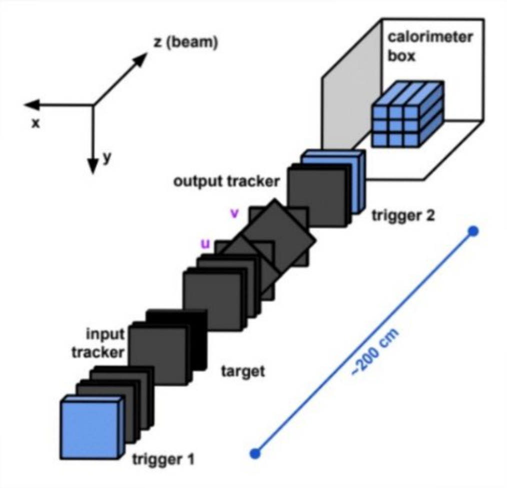
Results show a ~1% agreement between data and MC for the Gaussian core



Elastic events in the Test Beam of 2018

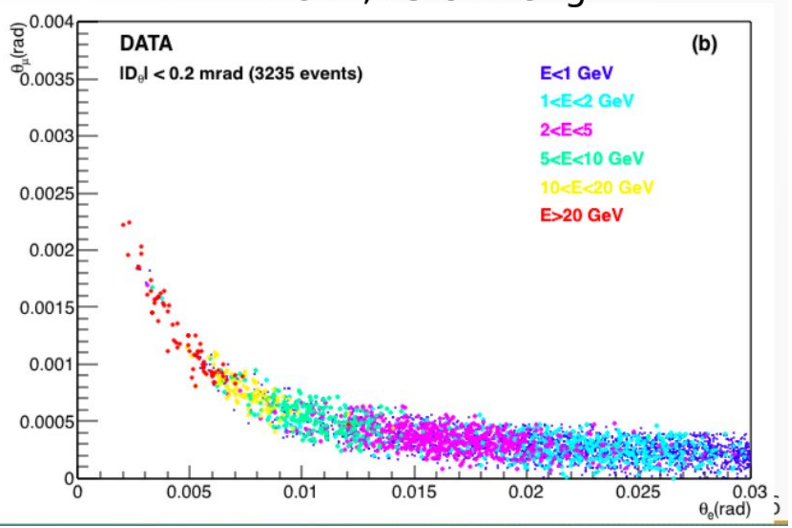
Test Beam 2018

Abbiendi et al, JINST 16 (2021) P06005



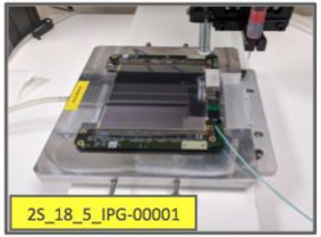
First evidence of elastic scattering.

- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. $2.1\times2.1\,\mathrm{cm}^2$, 23 cm length



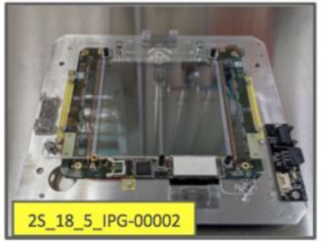
Status of the CMS 2S modules

- Four 2S modules assembled in Perugia.
- First 2 built in 2021 and successfully tested in the first MUonE-CMS combined test performed in November 2021
- The second pair of modules built in 2022 show problems:
    - **Module-3**: is presently unusable, because of electronics problems appeared after the assembling.
      It has to be returned to Perugia to try fixing the issue.
      The same problem has been observed in the Bruxelles laboratory.
    - **Modules-4**: half the module is effectively working.
      It’s a well known problem due to a faulty CIC. A fix exists and it’s relatively easy to apply.
- A fifth module could be built, but again there is an issue with the electronics.



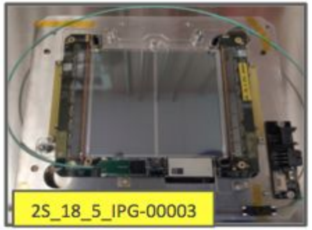
Rotation	135 [μrad]
Shift ⊥	13 [μm]
Shift //	-4 [μm]

Built on September 2021



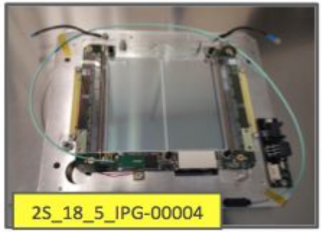
Rotation	120 [μrad]
Shift ⊥	22 [μm]
Shift //	-10 [μm]

Built on October 2021



Rotation	[μrad]
Shift ⊥	39 [μm]
Shift //	4 [μm]

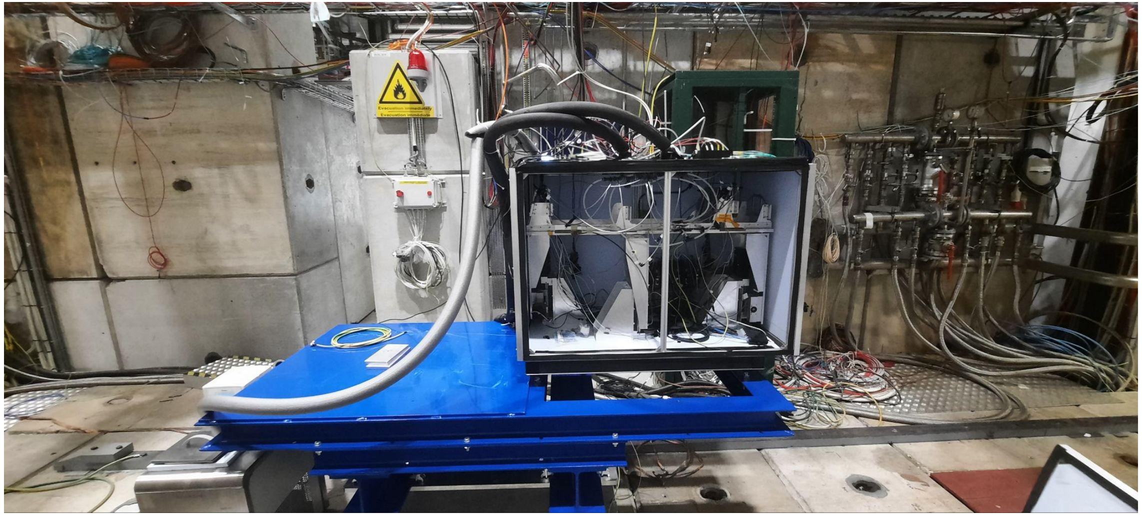
Built on March 2022



Rotation	45 [μrad]
Shift ⊥	6 [μm]
Shift //	-15 [μm]

Built on April 2022

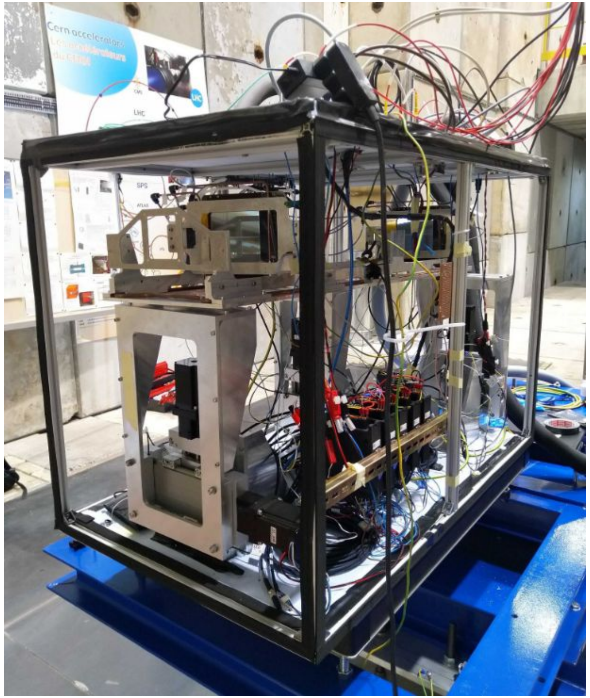
Tracker beam test setup in M2



- We managed to keep running in M2 for testing and debugging the 2S modules available
- Station placed on rails to allow easy movement in and out of the M2 beam

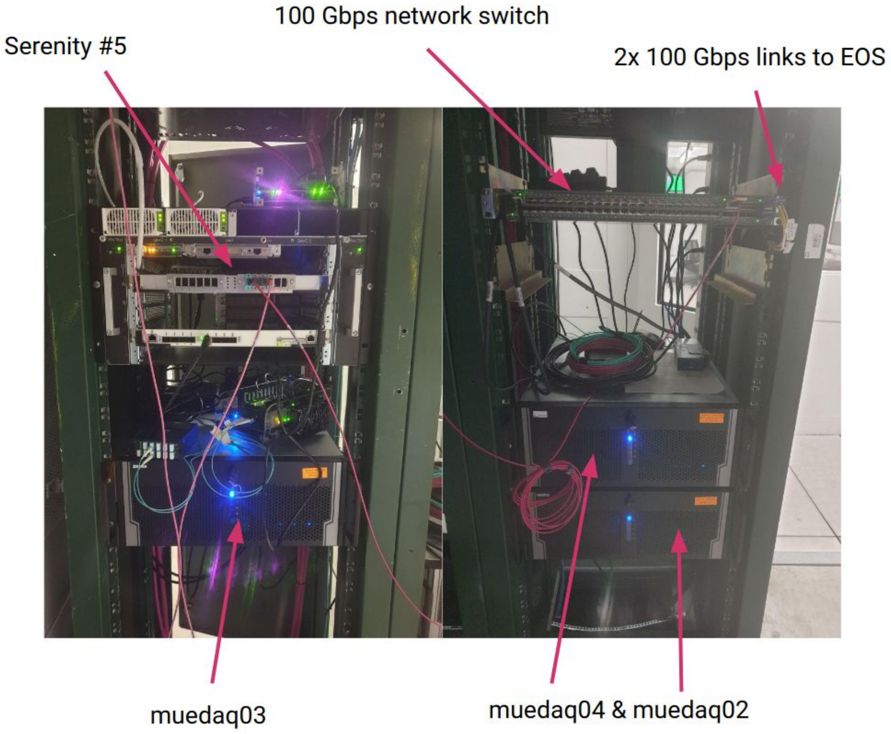
Tracker beam test setup in M2

- 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

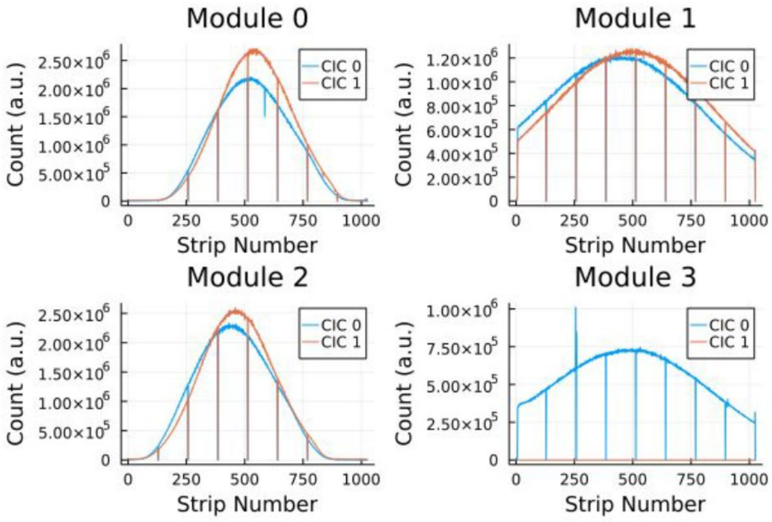
- Stubs are sent to the **Serenity** via optical links
- Packets of stubs are decoded in the **FPGA** of the Serenity card, and stubs collated by Bx
- Packets of stubs are formed and sent to **DAQ PCs,** over **10 Gbps Ethernet** link using the UDP protocol
- Packets are decoded in PCs and written successively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

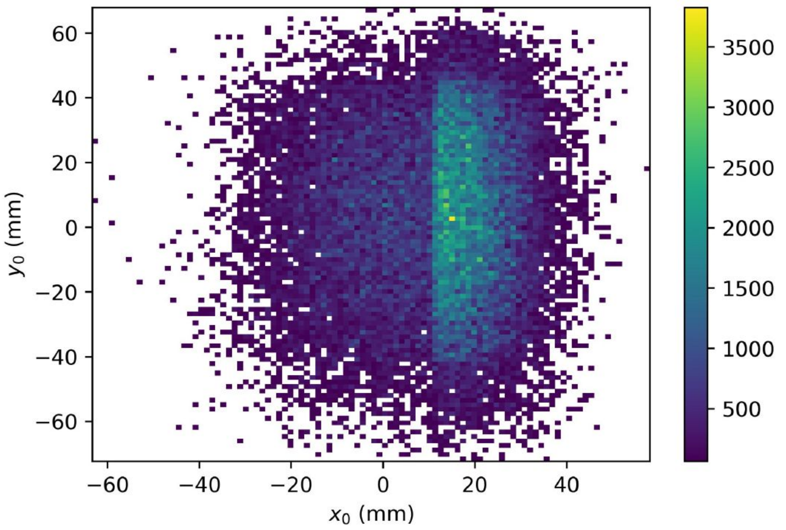


Back End Development

- **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

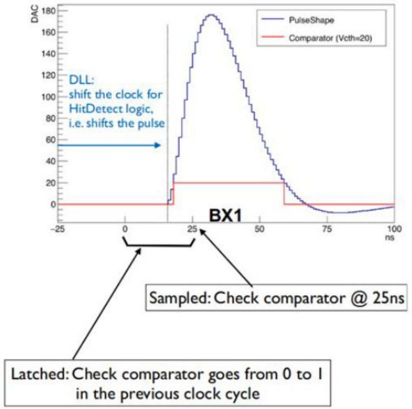


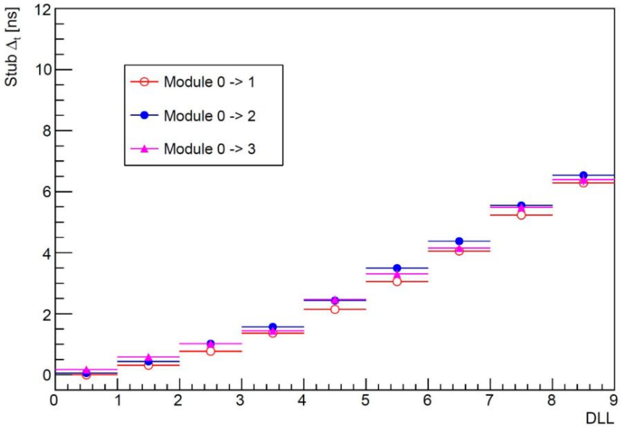


Module furthest downstream has faulty CIC:
can only read stubs from half of module

Preliminary results. 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

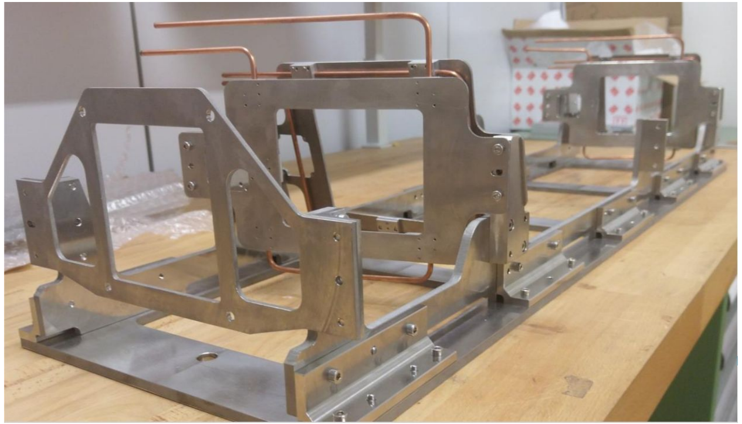


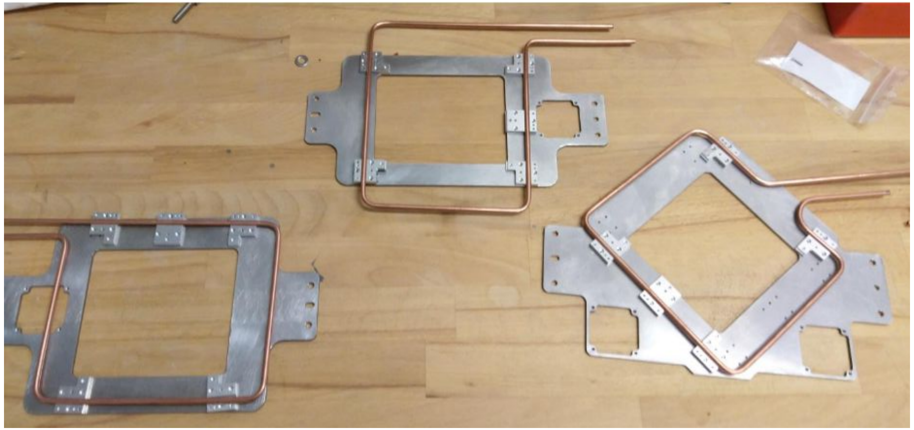


The procedure can correct for offsets in the modules to maximise detetction efficiency to **0.5 ns**

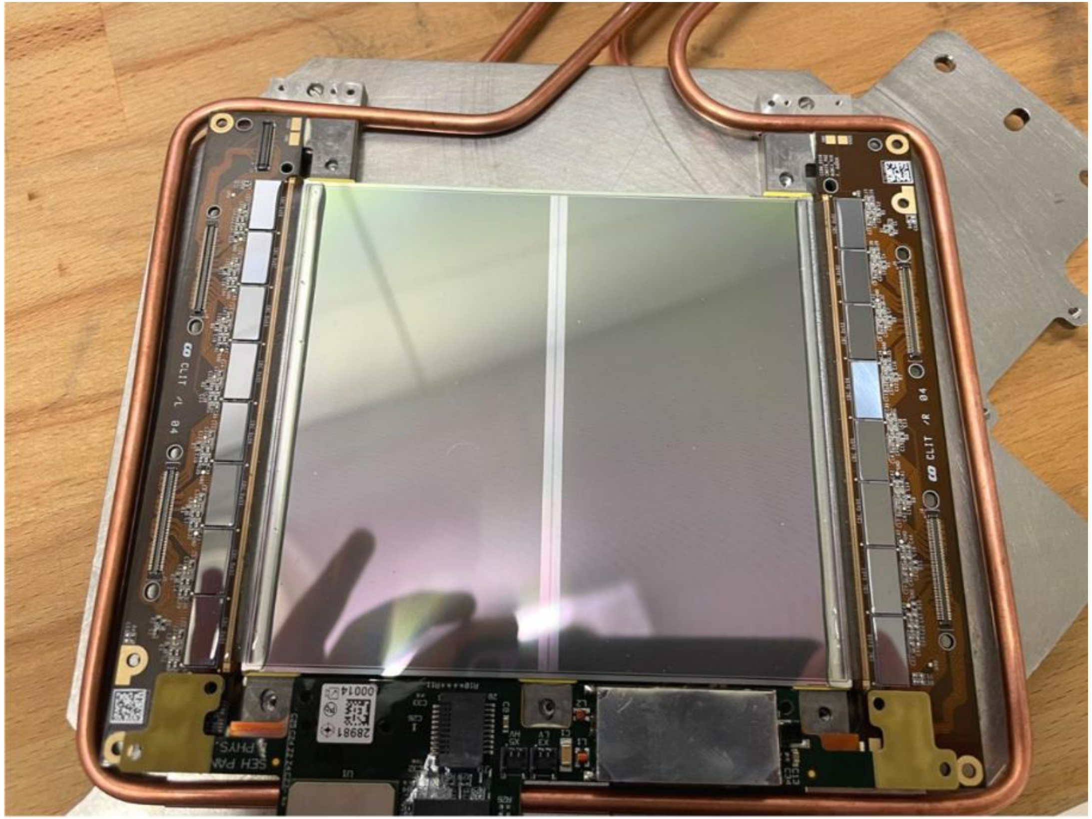
Support in INVAR (low CTE material)

- Two supports of three have been built
- They will be delivered to CERN on September 15th
- The third support has to be completed.
  The INVAR bar has been ordered





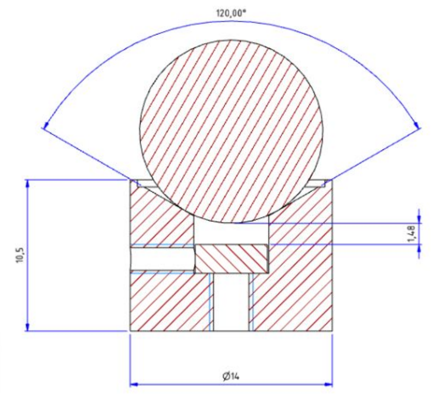
Modules, frames and cooling pipes

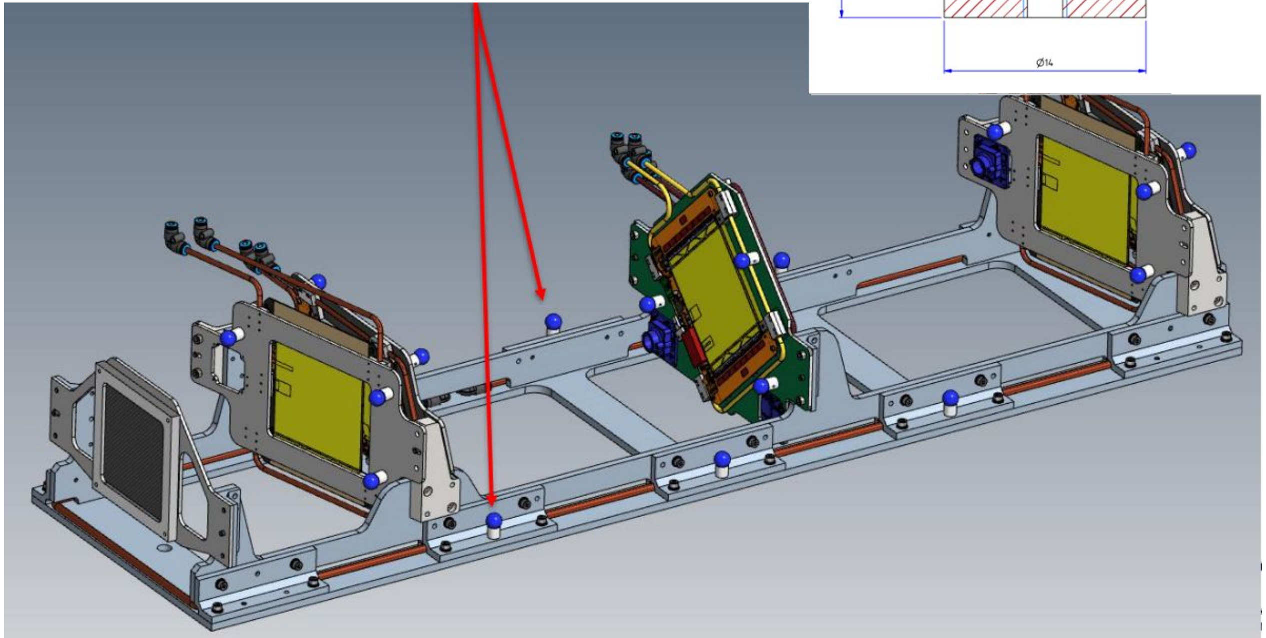


A good match

Mechanical Survey

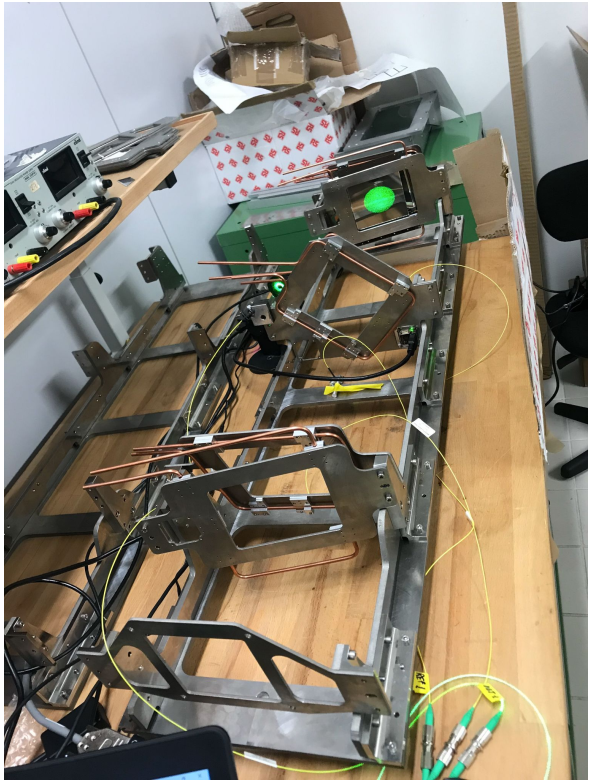
- Fiducial markers ordered (2 spheres, 1/2 inch)
- Design of the aluminum holders for spheres done
- To set the alignment initial conditions

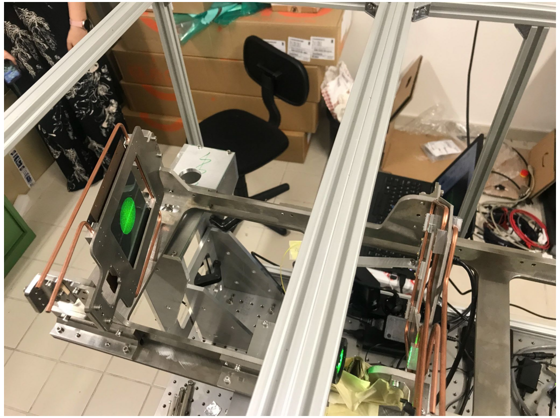


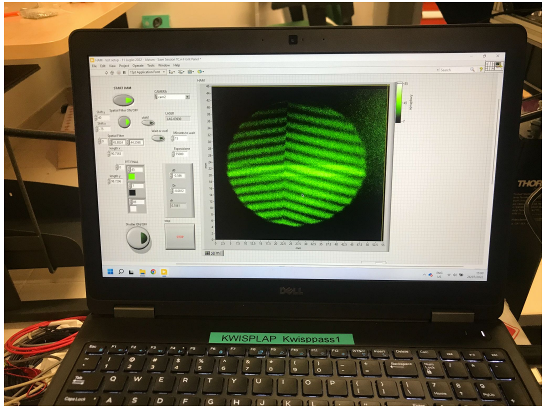


The holographic system

- **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

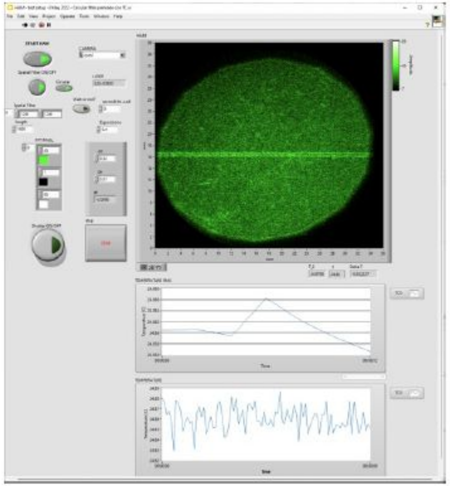


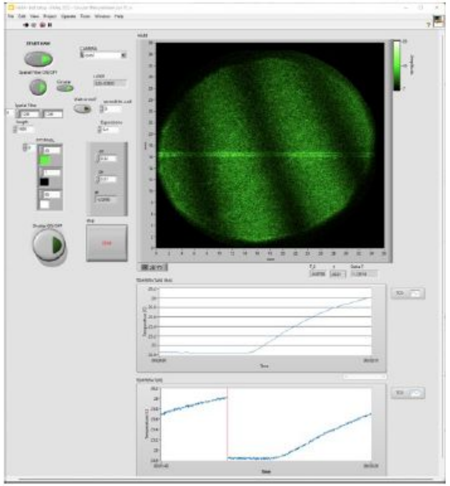


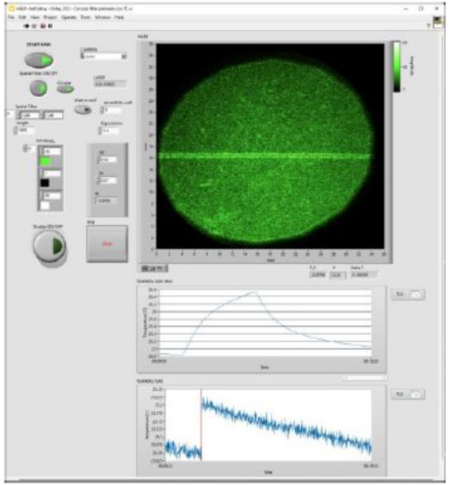


The holographic system (cont.)

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

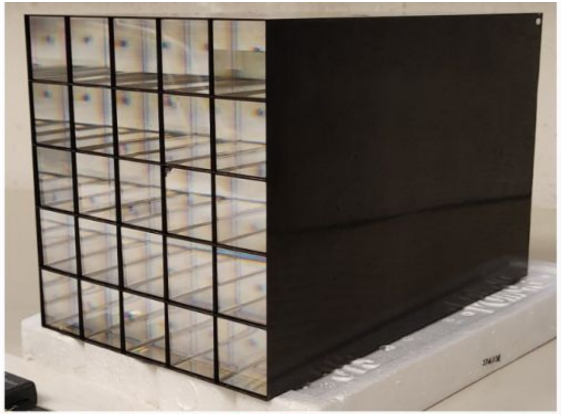
Steady power on

Power off

Estimated relative displacement between planes 1.5 µm

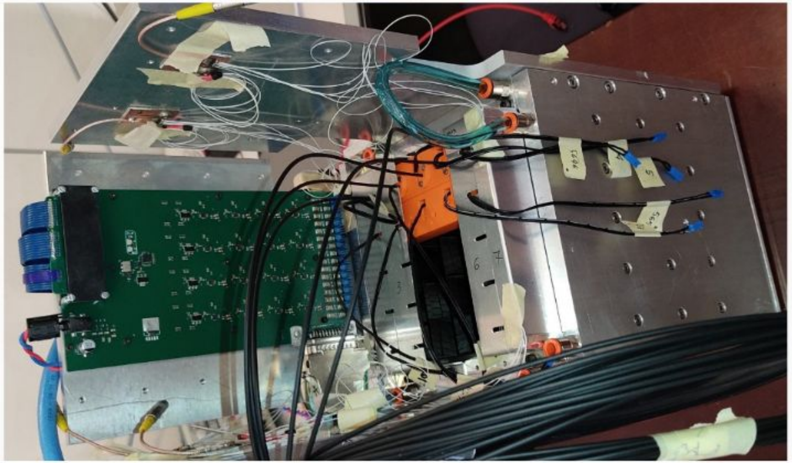
ECAL

- 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.



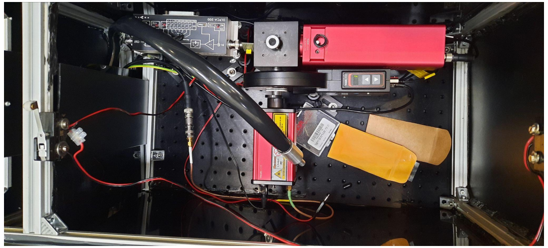
Beam Test: 20-27 July 2022,
CERN East Area.

- 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.

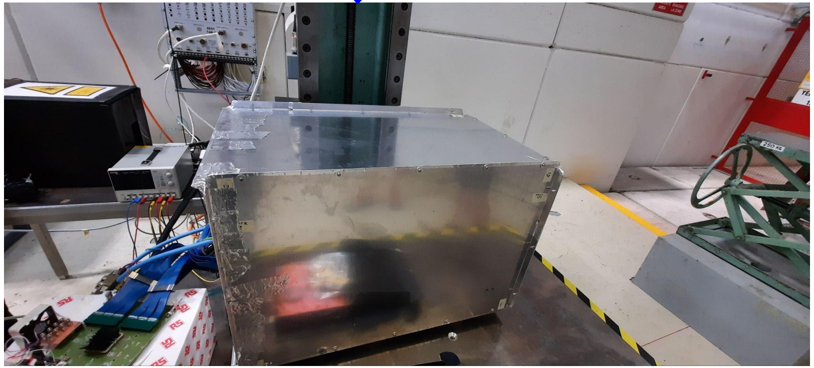


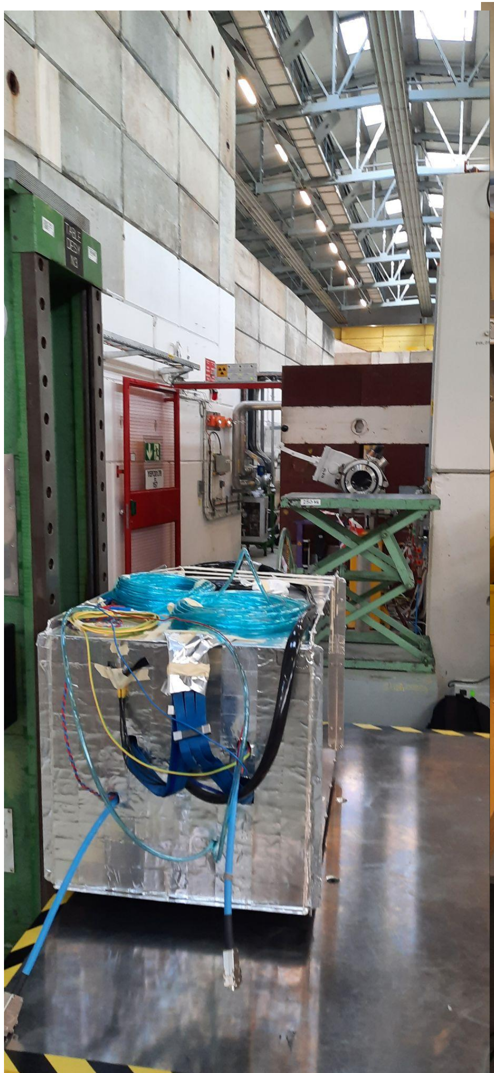
ECAL tests in CERN’sT9

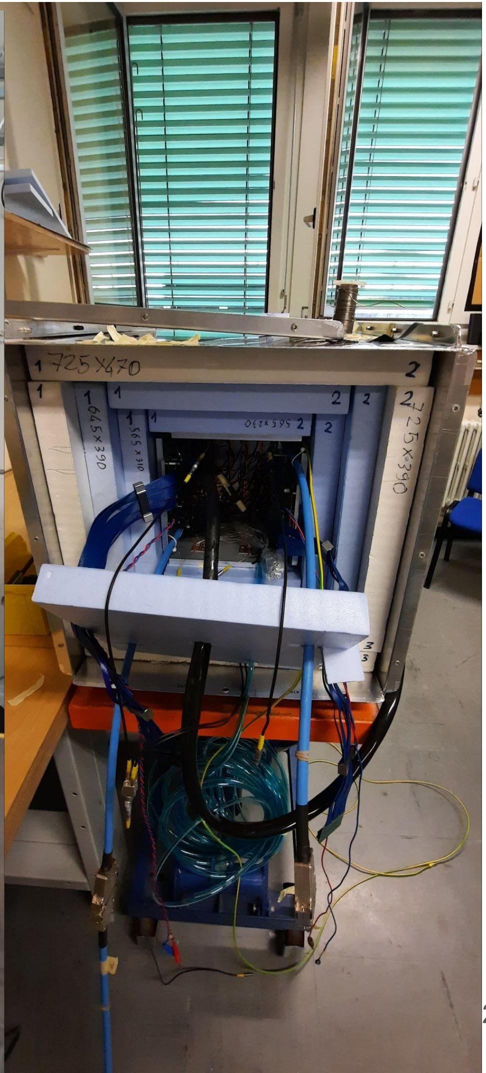
- ECAL assembled and tested at the end of July in the CERN T9 electron beam line



Laser pulses

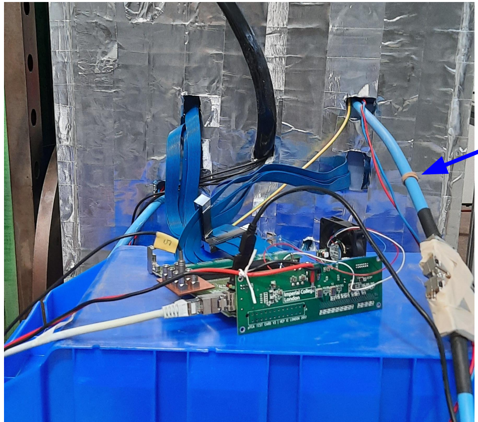






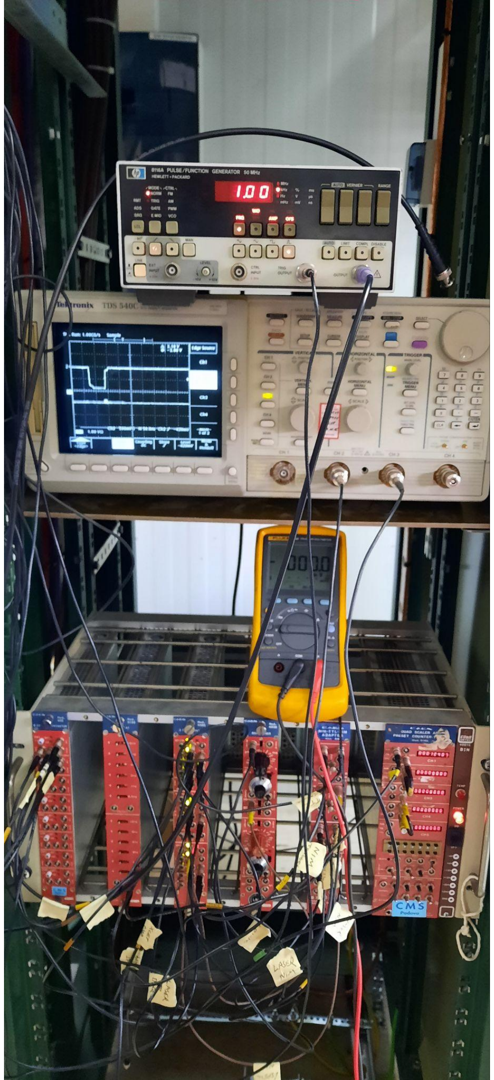
ECAL test setup and DAQ

- 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 crucial for settings and monitoring the stability of the channels



The readout

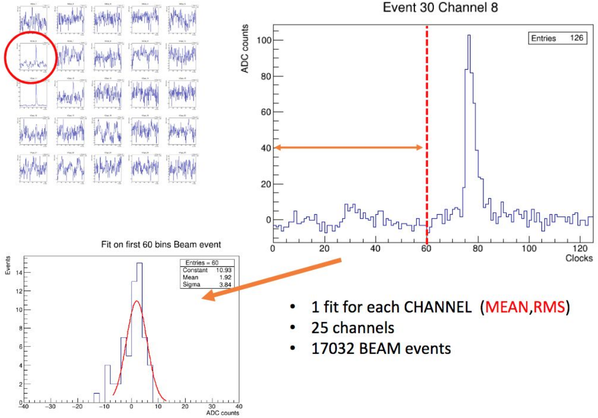
External trigger
Beam scintillators and
Cherenkov counters



ECAL test setup: main achievements

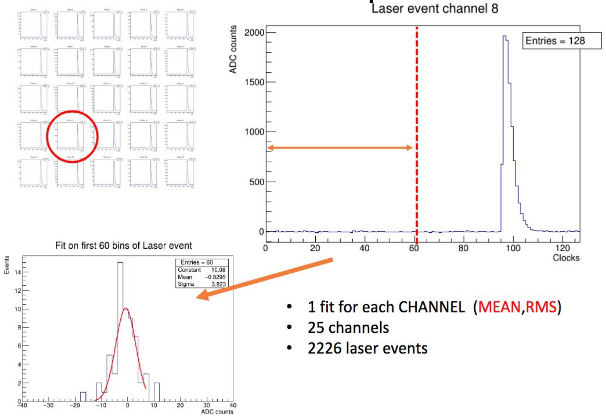
- The **light yields** have to be improved: the APD-PbWO4 optical coupling has to match.
- **Electronic noise** has to be reduced: the analysis of the main sources is ongoing.
- Cooling of the ADPs was not entirely satisfactory
- The monitoring system of the APD temperature has to be improved/replaced
- Laser stability is monitored by a dedicated Photodiode, whose output signals has to be registered for reference checks

4 GeV electrons



- 1 fit for each CHANNEL (MEAN,RMS)
- 25 channels
- 17032 BEAM events

Laser pulses



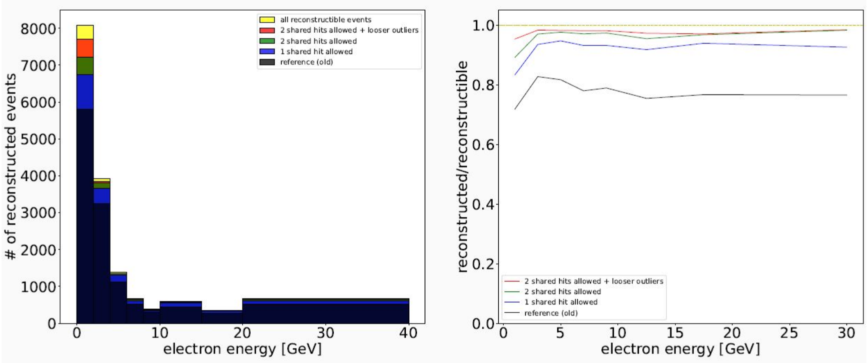
- 1 fit for each CHANNEL (MEAN,RMS)
- 25 channels
- 2226 laser events

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.

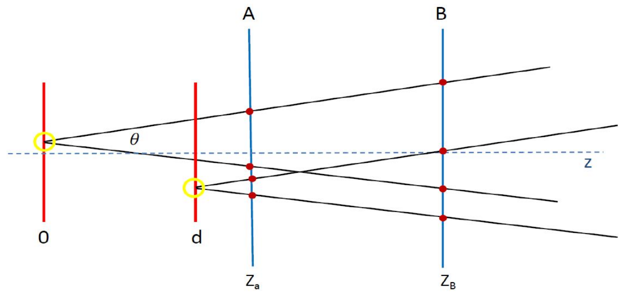
$$\chi^2_{\mathrm{global}} = \sum_i \chi_i^2, \qquad \frac{\mathrm{d}\chi^2}{\mathrm{d}\boldsymbol{\alpha}} = 0, \qquad \boldsymbol{\rho} \equiv \boldsymbol{\rho}(\boldsymbol{\pi}(\boldsymbol{\alpha}), \boldsymbol{\alpha})$$

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.)

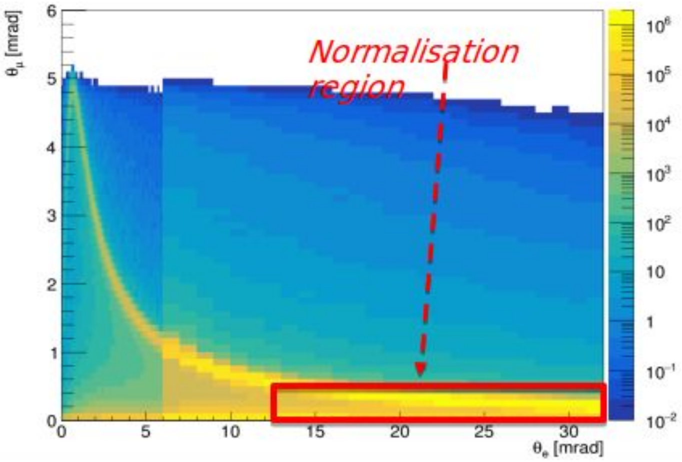
- Design and construction of the targets system by the CERN accelerator group



- 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

Analysis

- For a detailed description of the **analysis strategy** see:
  G.Abbiendi, Phys. Scr. 97 (2022) 054007 [arXiv: 2201.13177]
- **Template fit** of the 2D distribution using the **CMS Combine tool**:
  Fit with systematic effects included as nuisance parameters, and extracted along with the signal parameters.

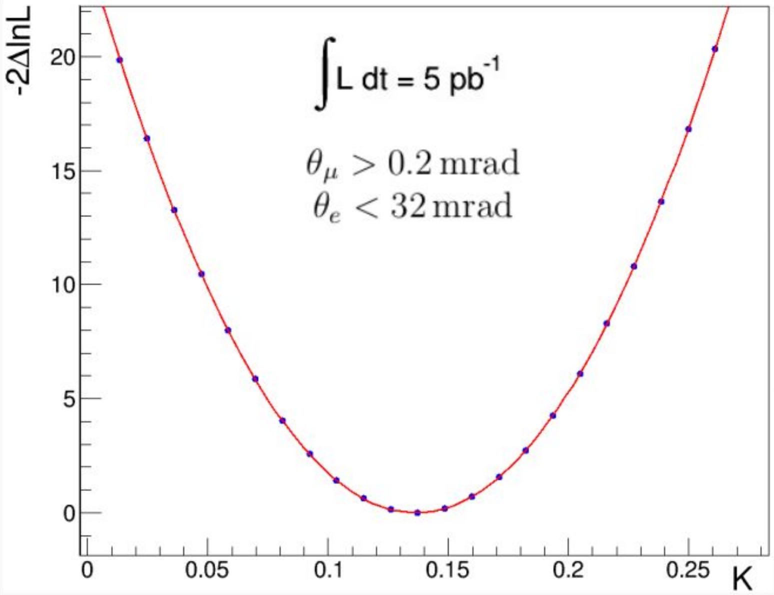


Use **normalization region** to calibrate the larger systematic effects: beam energy, angular intrinsic resolution.
MESMER MC + fast detector simulation to generate template distributions.
Combine analysis tool to perform the combined likelihood fit to the signal and systematics.

Analysis (cont.)

Pseudo-data sample:

- $E_{beam} \rightarrow + 6$ MeV
- $\sigma_{Intr} \rightarrow + 5\%$
- $\sigma_{MS} \rightarrow + 0.5\%$



K : signal parameter

μ_{Ebeam} : nuisance parameter for beam energy

μ_{Intr} : nuisance parameter for intrinsic resolution

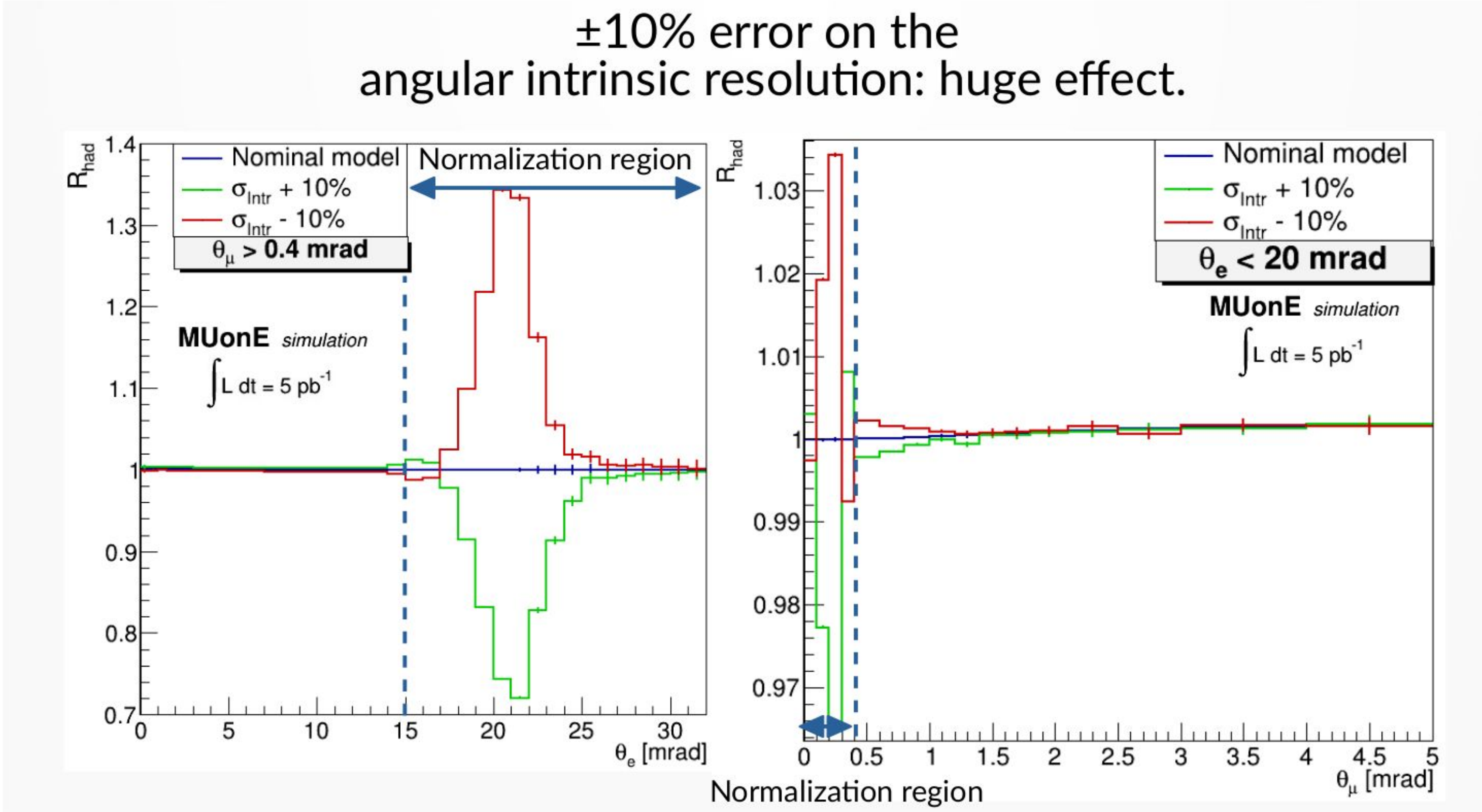
μ_{MS} : nuisance parameter for multiple scattering

Selection cuts	Fit results
$\theta_\mu > 0.2$ mrad $\theta_e < 32$ mrad	$K = 0.135 \pm 0.026$ $\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV $\mu_{Intr} = (4.99 \pm 0.02)\%$ $\mu_{MS} = (0.51 \pm 0.03)\%$

Systematic effects identified with good precision.
No degradation on the signal parameter.

Work in progress to optimize the procedure.

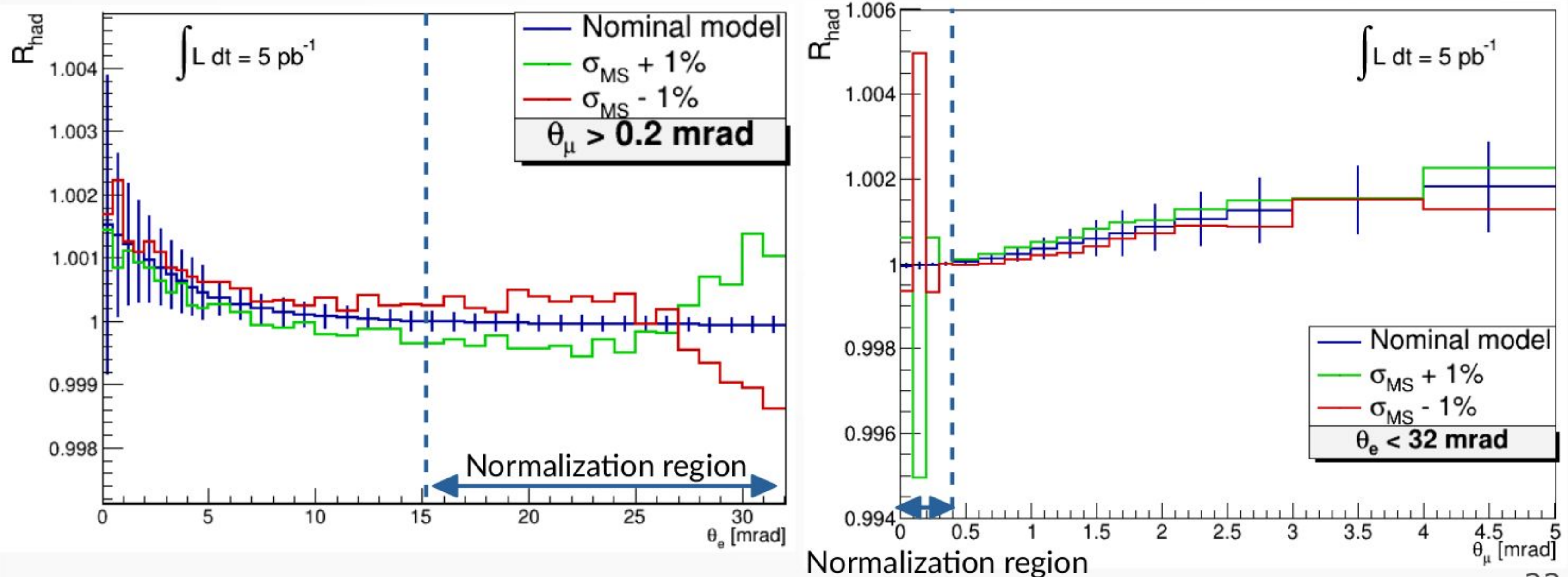
Analysis (cont.): systematic on the angular resolution



Analysis (cont.): systematic on the MSC

Expected precision on the multiple scattering model: ± 1%

G. Abbiendi et al JINST (2020) 15 P01017



Analysis (cont.)

github.com/cm-cc/mesmer

- **MESMER MC generator**
  - **NLO** QED corrections, 1 extra virtual or real photon
  - **NNLO** QED corrections, up to 2 extra photons
  - Include also $\mu + e \to \mu + e + l^+ + l^-$ and NNLO virtual leptonic corrections
  - $\mu + e \to \mu + e + \pi^0$

- **Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini, Muon-electron scattering at NLO, JHEP 02 (2019), 15**
- **Carloni Calame, Chiesa, Hasan, Montagna, Nicrosini, Piccinini, Towards muon-electron scattering at NNLO, JHEP 11 (2020), 028**
- **Budassi, Carloni Calame, Chiesa, Del Pio, Hasan, Montagna, Nicrosini, Piccinini, NNLO virtual and real leptonic corrections to muon-electron scattering, JHEP 11 (2021)**
- **Budassi, Carloni Calame, Del Pio, Piccinini, Single π0 production in μe scattering at MUonE, Phys.Lett.B 829 (2022) 137138**

Plans

- Prove the feasibility of the proposed MUonE method in 2023
- Detect elastic scattering at 40 MHz
  - Reconstruction efficiency
  - Background studies
- Study the alignment in test beams to then measure the beam energy
- Integrate ECAL and correlate its response to the tracker
- Write the experimental proposal
- Move to the experiment with 10 stations to get a first measurement before the LS3

Backup slides

Likelihood fit results with 4 nuisance parameters

Input Signal parameter: K = 0.136
Input Nuisances: $\nu = 1$; $\mu_{Ebeam} = 6$ MeV; $\mu_{intr} = 5\%$; $\mu_{MS} = 0.5\%$

Selection cuts	Fit results		
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 32\,\mathrm{mrad}$	$K = 0.135 \pm 0.026$ $\nu = 0.990 \pm 0.003$	$\mu_{MS} = (0.51 \pm 0.03)\%$ $\mu_{Intr} = (4.99 \pm 0.02)\%$	$\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV
$\theta_\mu > 0.4\,\mathrm{mrad}$ $\theta_e < 32\mathrm{mrad}$	$K = 0.134 \pm 0.031$ $\nu = 0.996 \pm 0.007$	$\mu_{MS} = (0.50 \pm 0.04)\%$ $\mu_{Intr} = (5.00 \pm 0.03)\%$	$\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 20\,\mathrm{mrad}$	$K = 0.134 \pm 0.030$ $\nu = 1.007 \pm 0.008$	$\mu_{MS} = (0.51 \pm 0.04)\%$ $\mu_{Intr} = (4.99 \pm 0.03)\%$	$\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV
$\theta_\mu > 0.4\,\mathrm{mrad}$ $\theta_e < 20\,\mathrm{mrad}$	$K = 0.134 \pm 0.031$ $\nu = 0.995 \pm 0.007$	$\mu_{MS} = (0.50 \pm 0.04)\%$ $\mu_{Intr} = (5.00 \pm 0.03)\%$	$\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV
$\theta_{L,R} \in [0.2, 32]$ mrad	$K = 0.135 \pm 0.028$ $\nu = 0.990 \pm 0.003$	$\mu_{MS} = (0.48 \pm 0.03)\%$ $\mu_{Intr} = (5.01 \pm 0.02)\%$	$\mu_{E_{Beam}} = (6.1 \pm 0.5)$ MeV
$\theta_{L,R} \in [0.4, 20]$ mrad	$K = 0.135 \pm 0.033$ $\nu = 0.994 \pm 0.007$	$\mu_{MS} = (0.44 \pm 0.04)\%$ $\mu_{Intr} = (5.04 \pm 0.04)\%$	$\mu_{E_{Beam}} = (6.3 \pm 0.6)$ MeV

Output Fit Results are in excellent agreement with the input values for all the selections, both with and without PID

Precision

40 stations (60 cm Be) + 3 years of data taking (~4x10^7 s) (I_μ ~ 10^7 μ^+/s) ~4x10^{12} events with E_e > 1 GeV = ~0.3% statistical accuracy on a_μ^{HVP}

Competitive with the latest theoretical predictions.

Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm at the peak of the integrand function (low θ_e, large θ_μ)

Main systematic effects:

- Longitudinal alignment (~10 μm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)
- Angular intrinsic resolution (few %)