

Status of MUonE

G. Cantatore
Università and INFN - Trieste

Outline

- **Why muon $g-2$?**
- **The MUonE project**
 - overview
 - 2025 MUonE test run
 - lessons learned and outlook
- **Conclusions**

2025 MUonE collaboration

Experimental Groups

Cornell University

IFJ PAN Kraków

Imperial College London

INFN Bologna

INFN Padova

INFN Perugia

INFN Pisa

INFN Trieste

J. Gutenberg Universität Mainz

Liverpool University

Northwestern University

Regis University

University of Rijeka

University of Virginia

Theory Groups

ETH Zürich

Paul Scherrer Institute

Università di Padova

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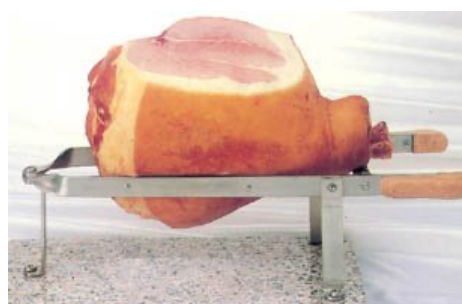
Università di Padova

Università di Pavia

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You are welcome to join!

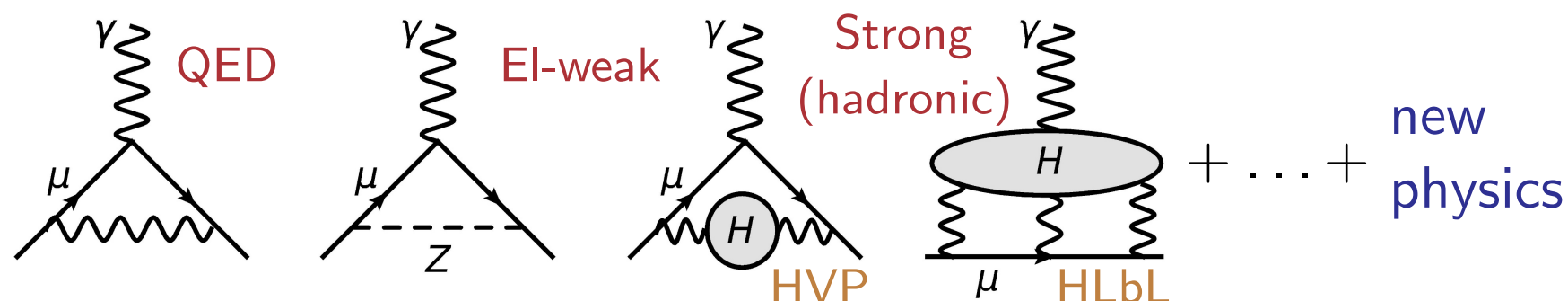
New collaborators will gain full access to specialties from Trieste



Why muon $g-2$

- Quantum fluctuations are responsible for the anomalous magnetic moments of leptons
- Magnetic anomaly $a_{lep} = (g_{lep} - 2)/2$
- The muon anomaly, a_μ , is more sensitive to loops with massive particles, due to $m_\mu > m_e$
- a_μ is an excellent probe of SM & BSM physics... if it exists!

Leading order processes contributing to a_μ :

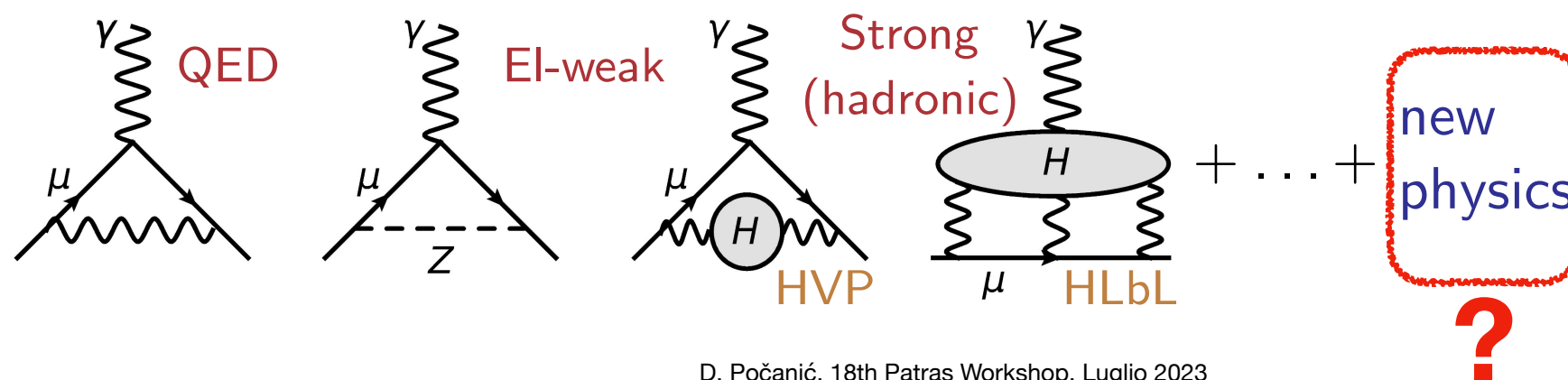


D. Počanić, 18th Patras Workshop, Luglio 2023

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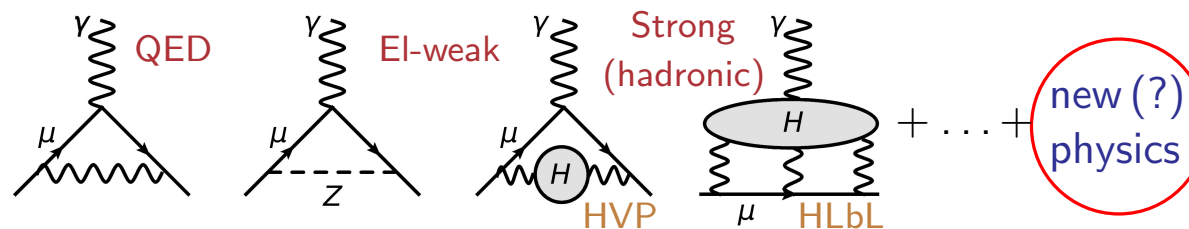
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Why muon g-2



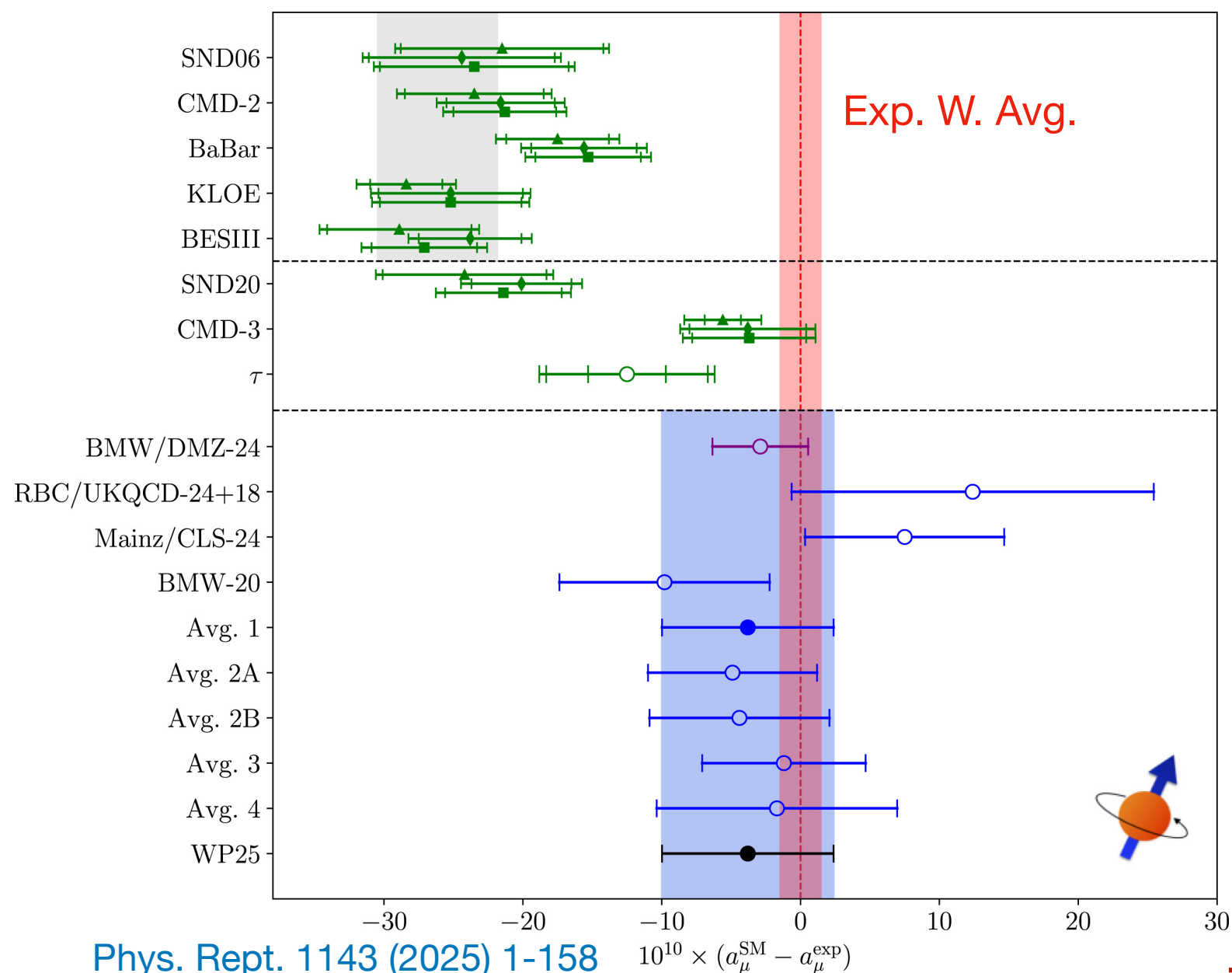
$$a_{\mu}^{had} = a^{HLO} + a^{HNLO} + a^{HLbL} + h.o.$$

- **Leading order processes contributing to a_{μ}**

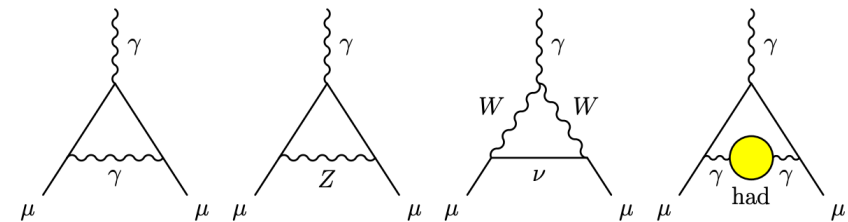
- QED
- HVP = hadronic vacuum polarization
- HLbL = hadronic light by light scattering

- EW

- a_{μ} SM calculations, 2025 status from the g-2 Theory Initiative white paper

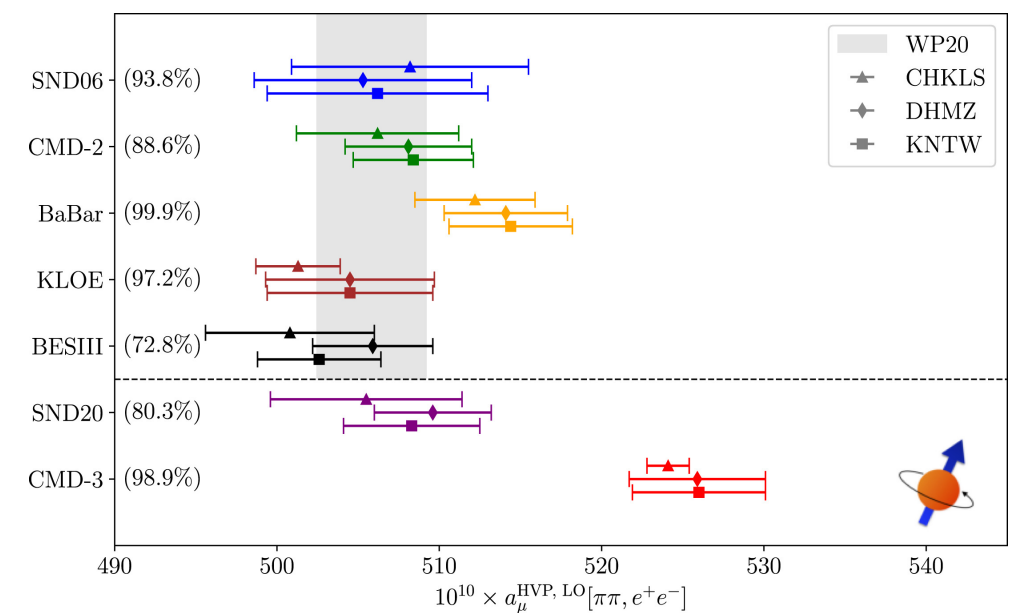
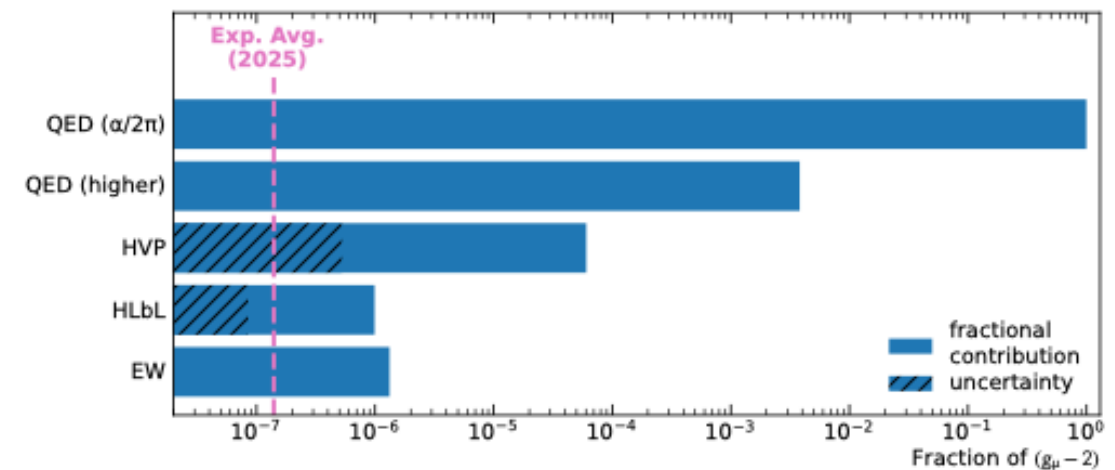


SM contributions to the muon anomaly

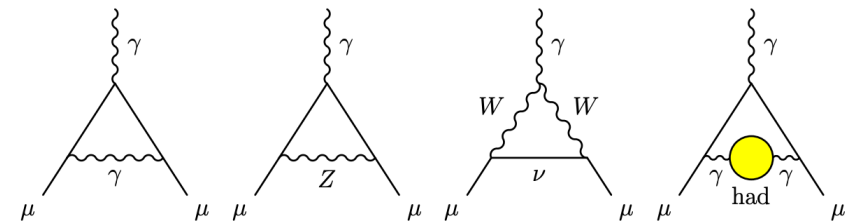


$$a_{\mu}^{had} = a_{\mu}^{HLO} + a_{\mu}^{HNLO} + a_{\mu}^{HLbL}$$

- Hadronic effects dominate the theoretical uncertainty on a_{μ}
- Lattice QCD seems to have tackled this problem
- But...
 - discrepancy between the data-driven calculation and the lattice approach
 - unexplained tension between the bulk of experimental e^+e^- measurements and the *outlier* represented by the CMD-3 results
- MUonE aims at an **independent** direct measurement of a_{μ}^{HLO}

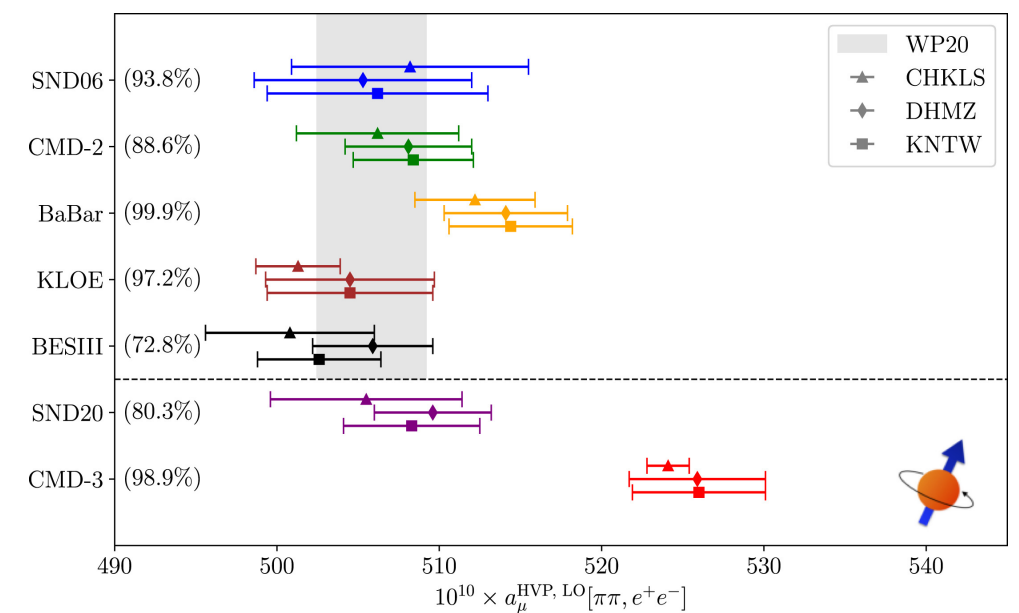
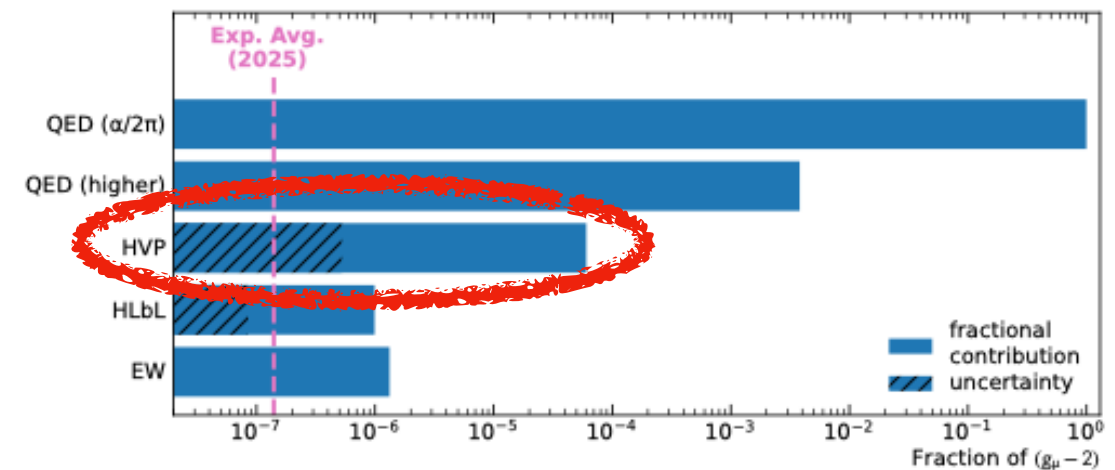


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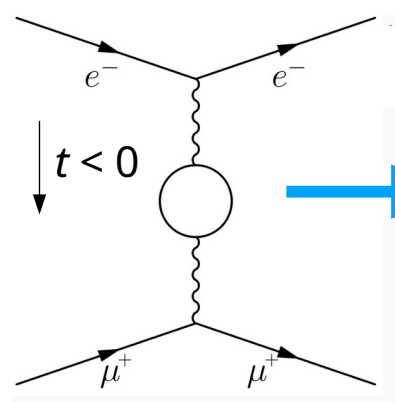
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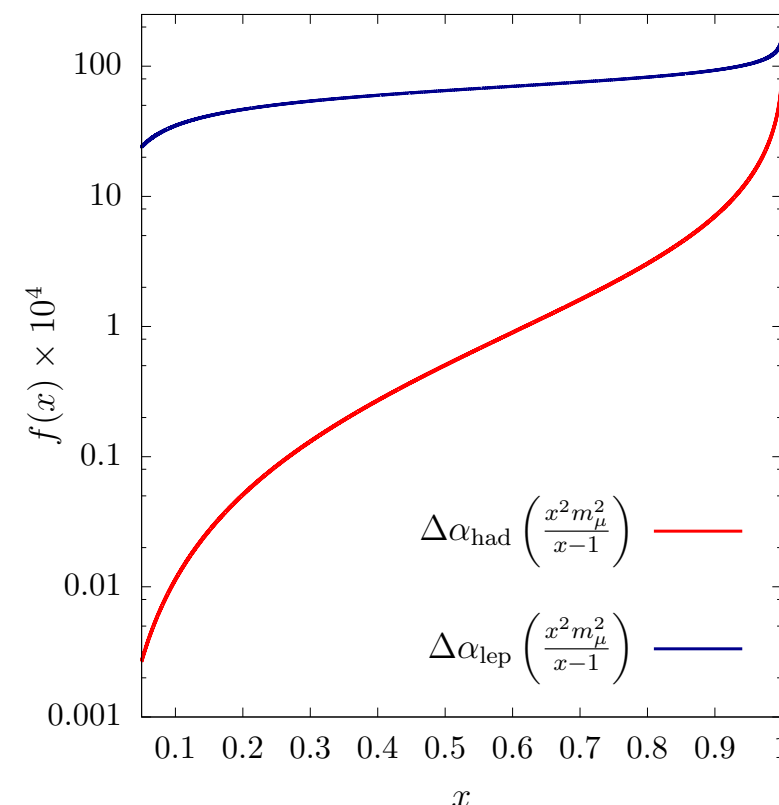
The MUnE method - I

- In the novel MUnE approach, a_μ^{HLO} is evaluated from a space-like integral, where $t = q^2$ is the squared momentum transfer and $\Delta\alpha_{had}(t)$ is the hadronic part of the “running” with t of the fine structure constant



$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)] \quad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

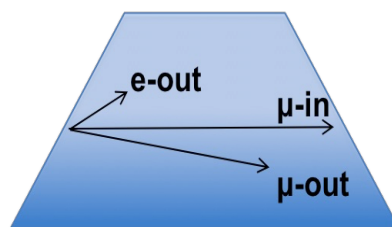
- Key advantage: $\Delta\alpha_{had}(t)$ is a smooth function free of resonances



The MUonE method - II

- $\Delta\alpha_{had}(t)$ can be extracted from the shape of the $\mu - e$ elastic scattering differential cross-section by comparing data with a MC

- $\theta_e, \theta_\mu \rightarrow x \rightarrow t$

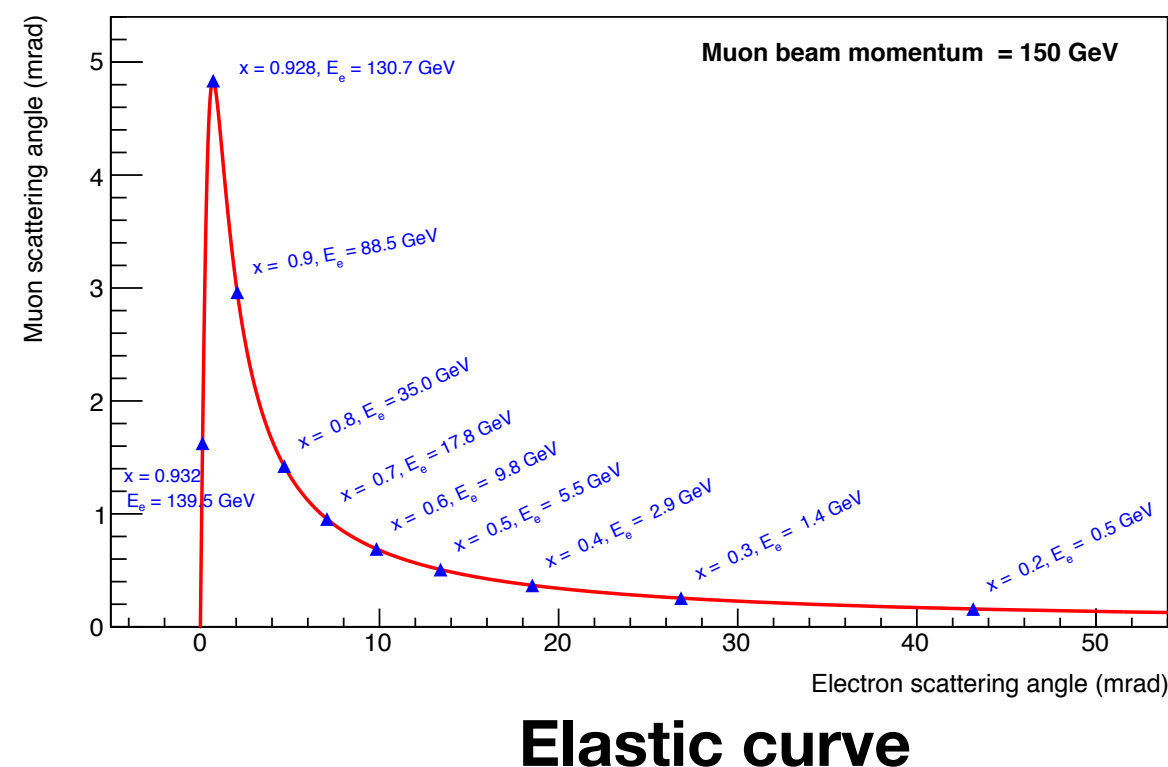


- the elastic curve also rejects main background $\mu N \rightarrow \mu N e^+ e^-$

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

From MC

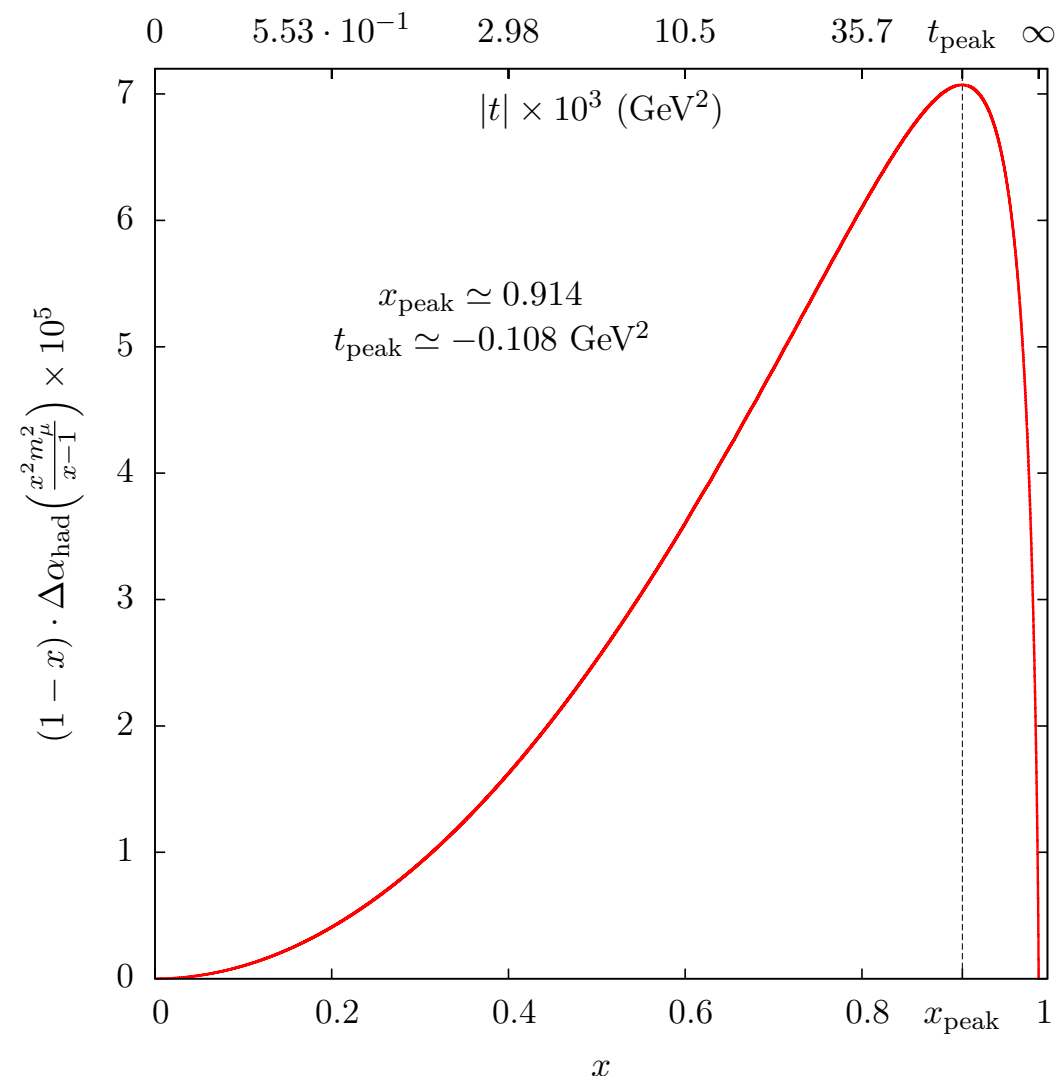
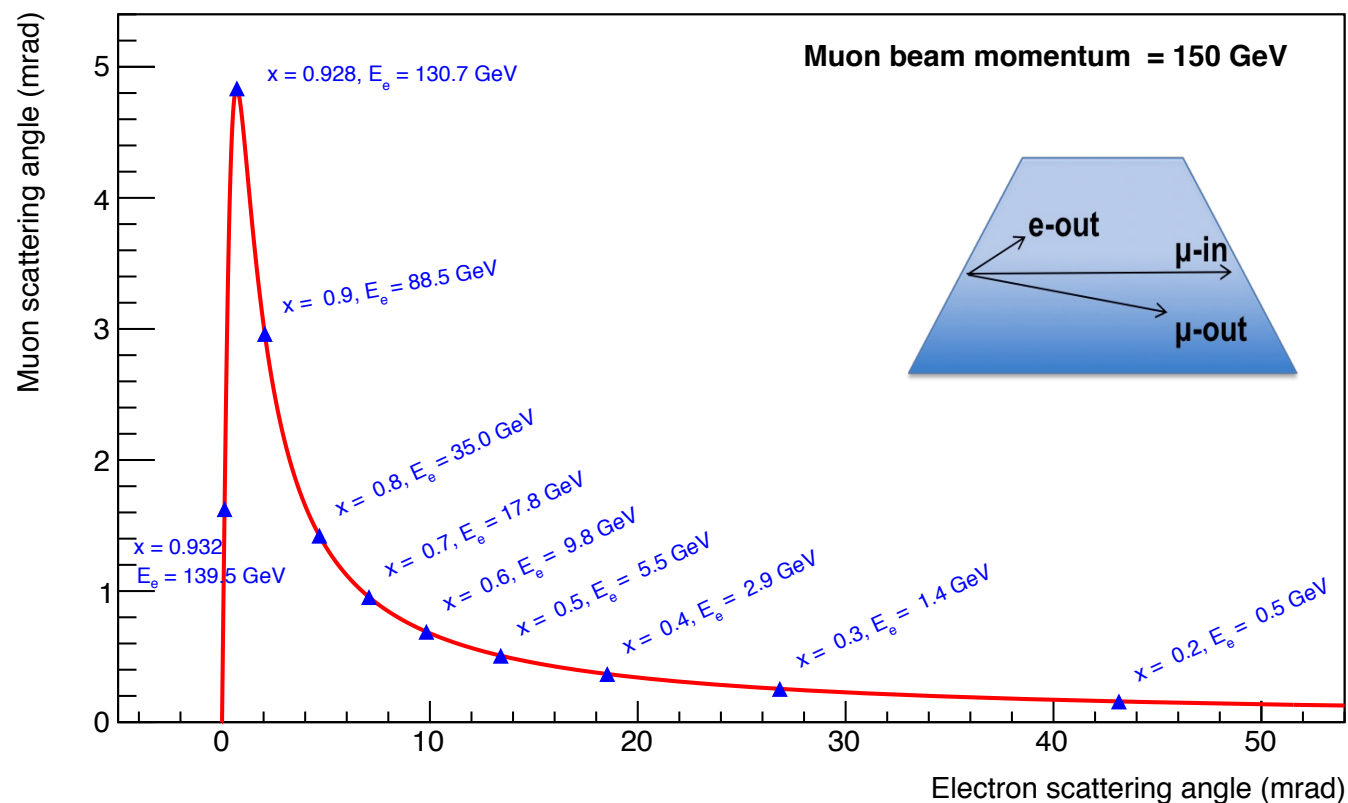
$$\frac{d\sigma_{\text{elastic}}}{dt} \xleftrightarrow{\text{Simple kinematics relations } (t \leftrightarrow \theta_l)} \frac{d\sigma_{\text{elastic}}}{d\theta}$$



The MUonE method III

- Start from the experimental observables θ_μ and θ_e
- Build the elastic curve and extract the x variable
- Construct the integrand function from the elastic curve $\Rightarrow$ direct access to >80% of the integral, the remaining part is interpolated
- Evaluate a_μ^{HLO}

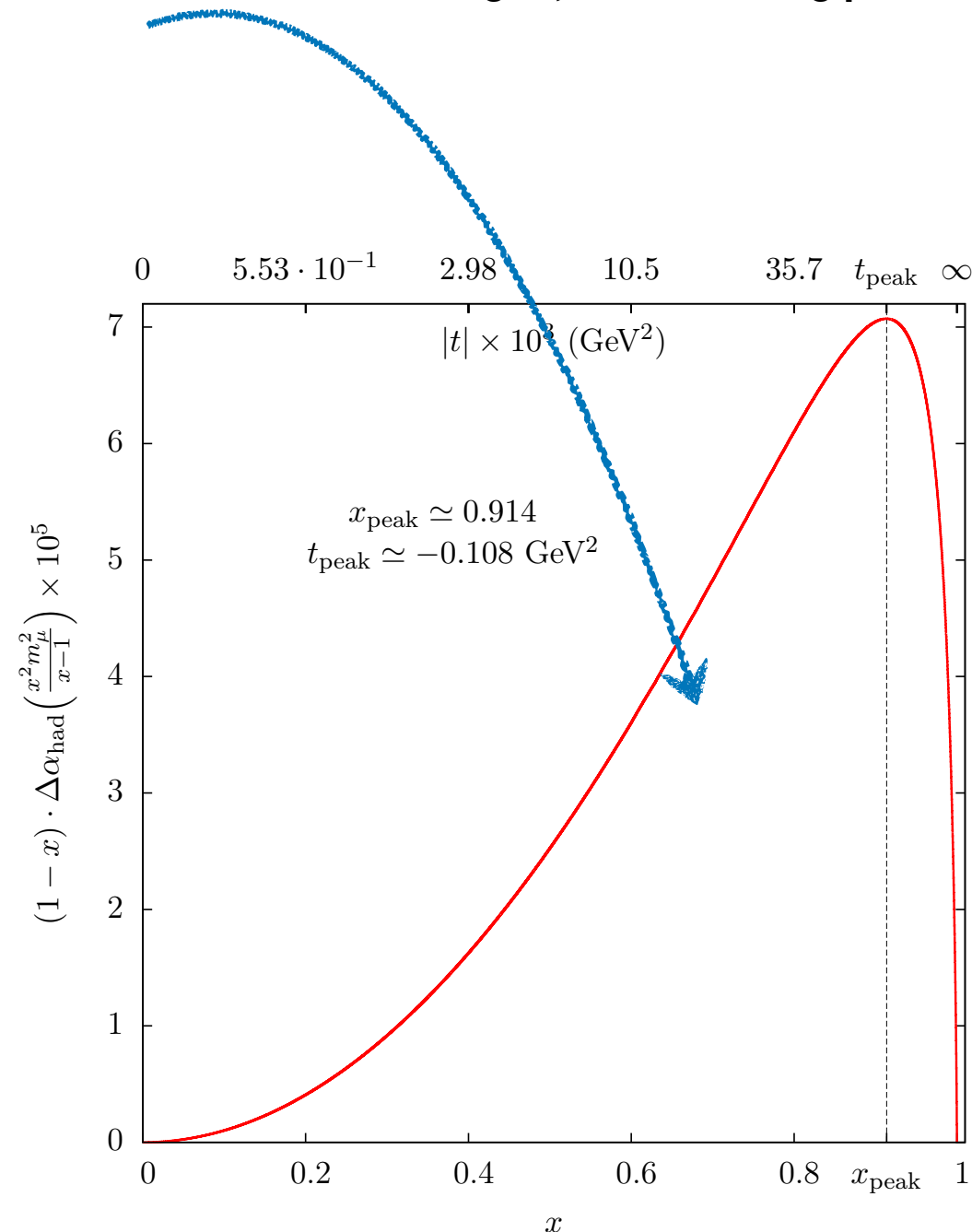
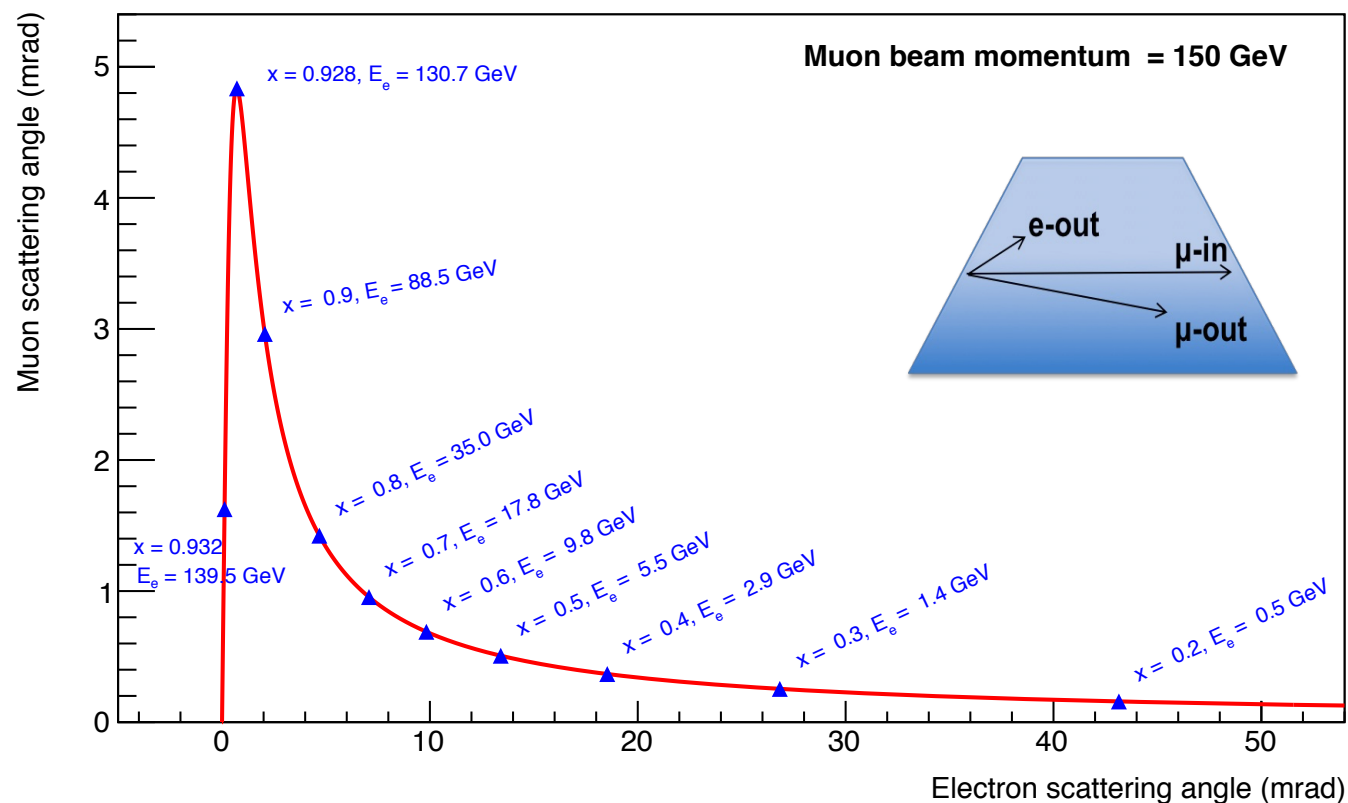
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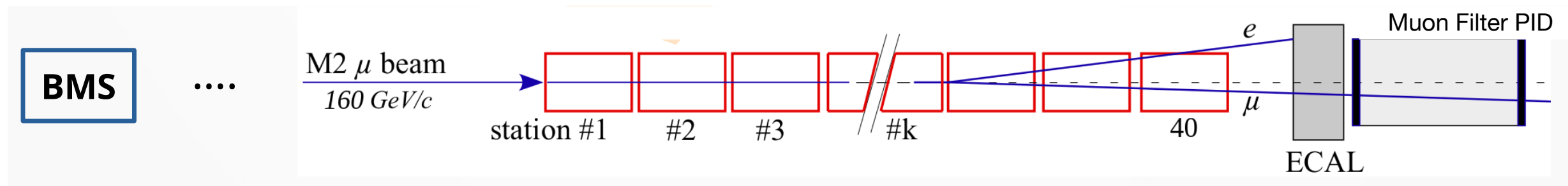
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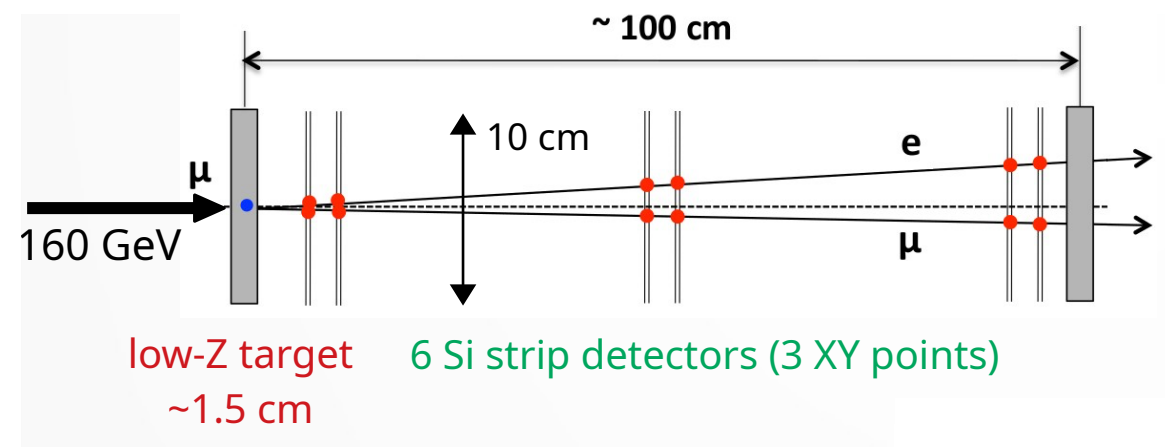
MUonE apparatus

- String of tracking stations, each with a thin low-Z target (Be or C)
 - “re-use” through-going muons
 - modular construction, up to 40 stations



Figures from R. Pilato, FCCP workshop, Anacapri, Italy 2025

- Beam Momentum Spectrometer
- ECAL - PID and e^- energy
- Muon Filter PID - small angle muon track ID

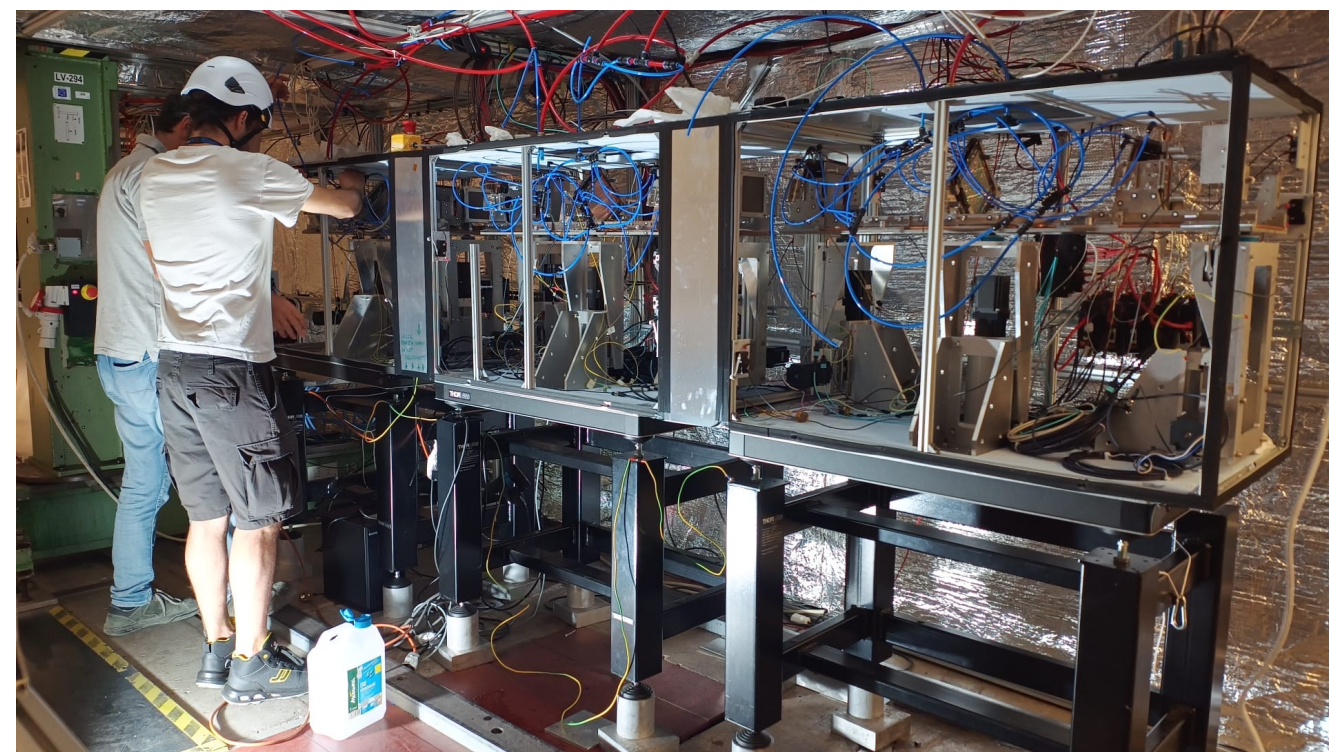
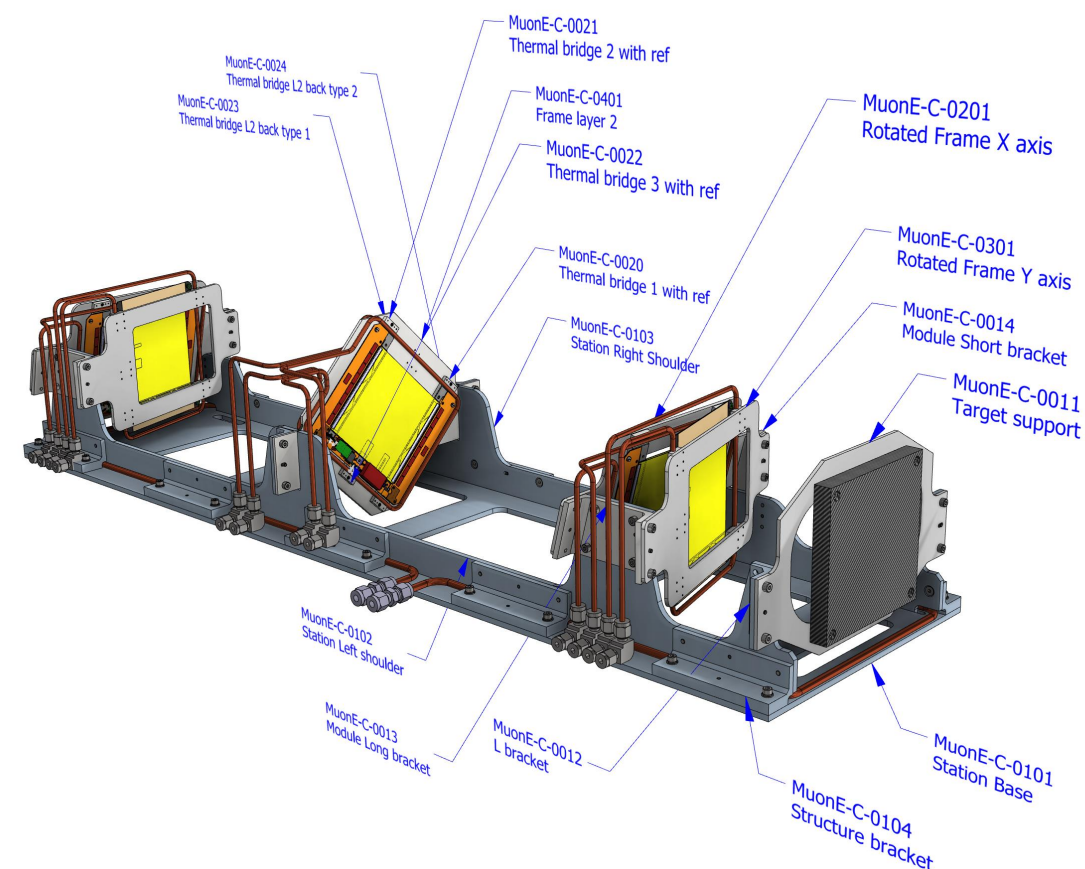


Precision requirements

- Uncertainty on theoretical estimates $\Delta\alpha_{\mu}^{HLO} < 1 \%$
- MUONE precision goal $\Delta\alpha_{\mu,exp}^{HLO} < 0.5 \%$
- With 40 stations (60 cm Be target total thickness) and 3 yrs of data with integrated luminosity $1.5 \cdot 10^7 \text{ nb}^{-1} \Rightarrow \Delta\alpha_{\mu,stat}^{HLO} < 0.5 \%$
- **Critical challenge:** control systematic effects at the same level
- **Main systematics**
 - intrinsic angular resolution
 - multiple Coulomb scattering
 - knowledge of beam energy - longitudinal alignment (few MeV level)

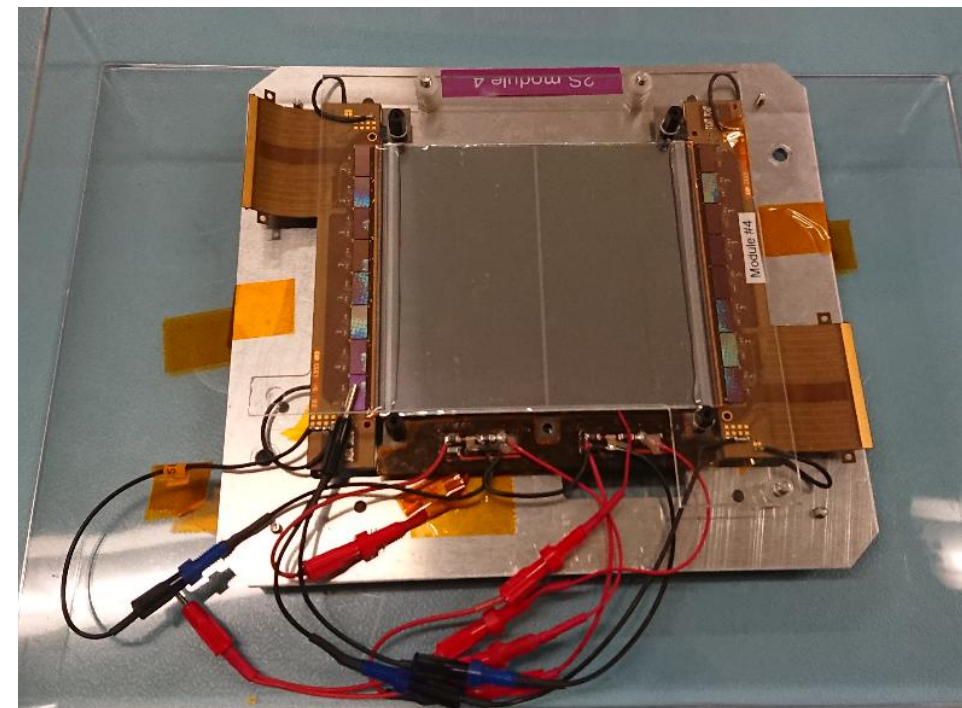
- “Gondola”

- InVar constuction (Fe/Ni alloy with 1.2 ppm/K CTE)
 - requirement: 10 μm stability
 - Holographic Alignment Monitor
- 6 x 2S Si tracking modules from CMS Phase 2
 - 2 tilted pairs for x-y coordinates
 - 1 pair (u,v coords) to solve ambiguities
 - global resolution $\sim 20 \mu\text{m}$
 - Gondola mounted on a 3-point motorized support system
 - Entire assembly enclosed in an environmental box with dry air flux for temperature and humidity control



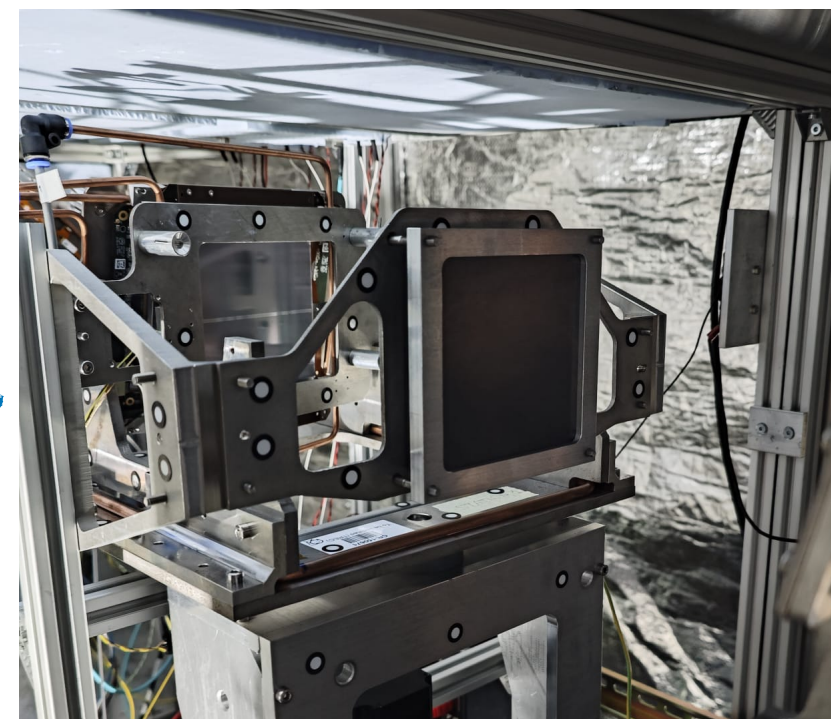
- **2S tracking module from CMS Phase2 upgrade**

- ~90 cm² active area
- 2 × 320 μm thickness
- 40 MHz, binary readout
- 90 μm pitch
- ~26 μm hit resolution
- **MUonE workhorse detector**



- **target**

- Be or C (graphite)
- interchangeable to vary thickness



HAM system

• Holographic Alignment Module - HAM

- monitors distance changes between tracking planes at the **sub- μm level**
- lens-less, fiber coupled digital holographic inteferometry

• Monitoring protocol

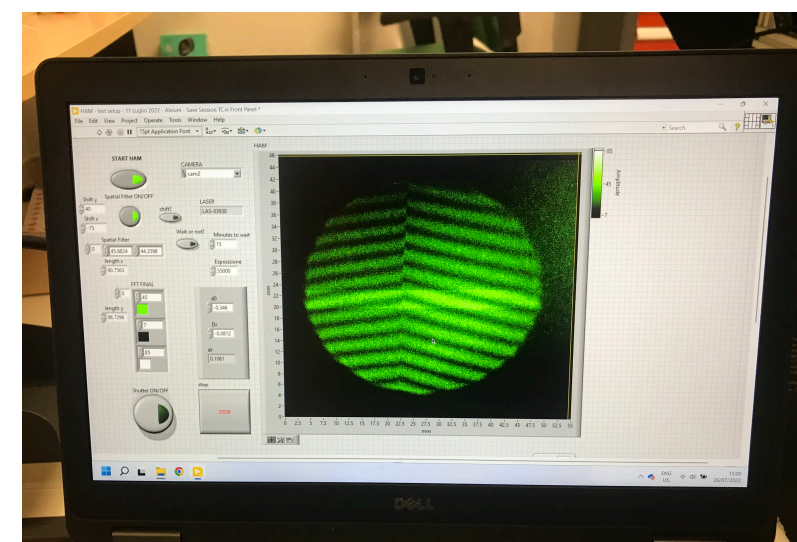
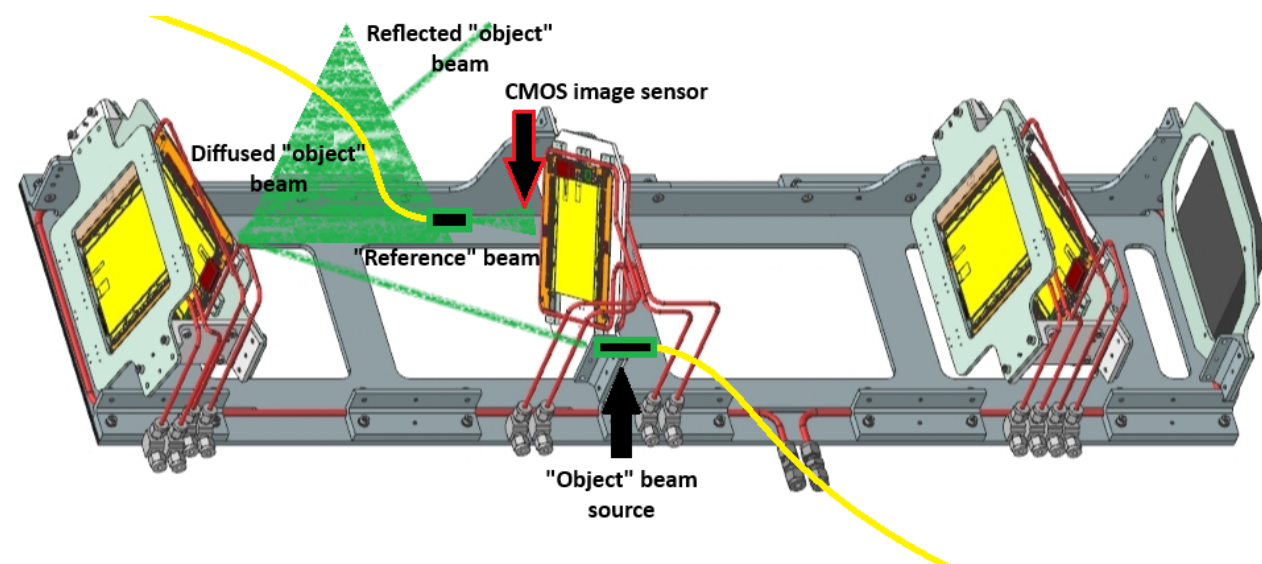
- time-lapse holographic images compared with an initial reference image
- interference fringes evidence relative movements, 1 fringe = $\lambda/2$ displacement

• Visible HAM

- 532 nm $\Rightarrow$ 0.25 μm sensitivity
- monitoring possible when trackers are off

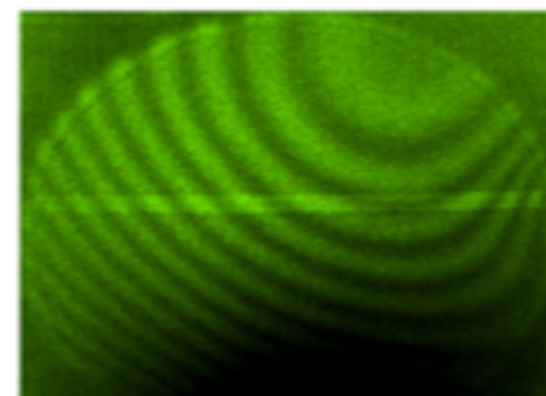
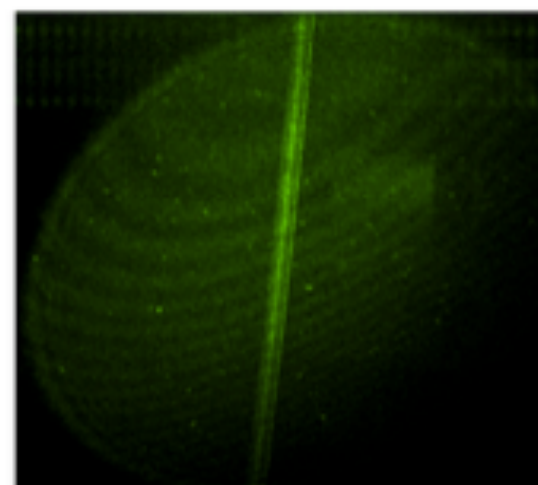
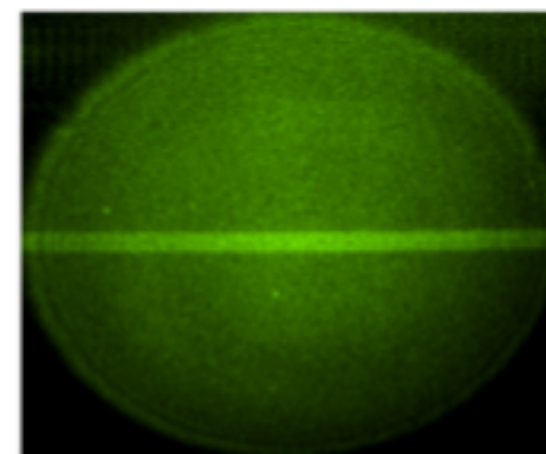
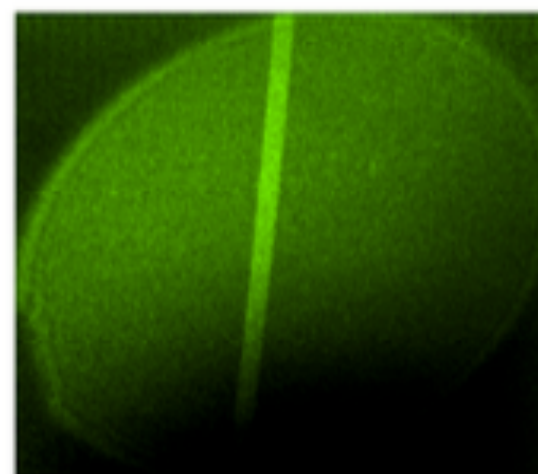
• IR HAM

- testing phase, next upgrade
- 1550 nm $\Rightarrow$ 0.75 μm sensitivity
- **continuous monitoring during data taking**

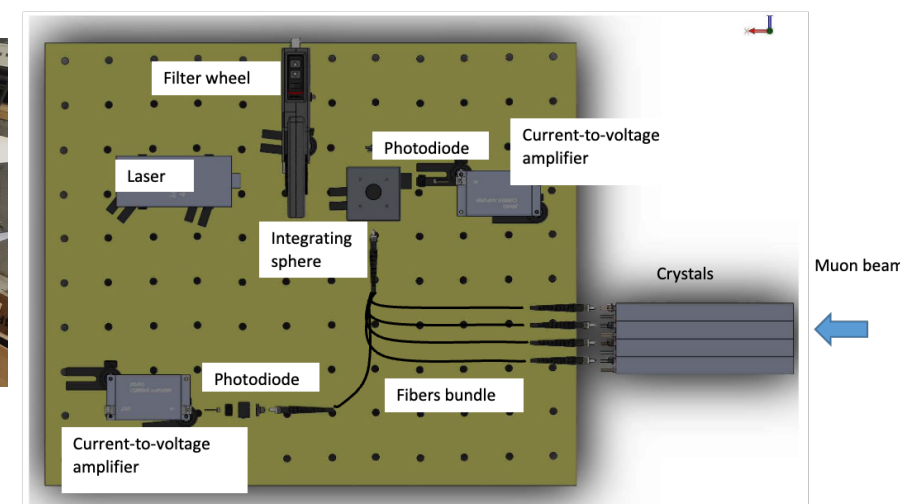
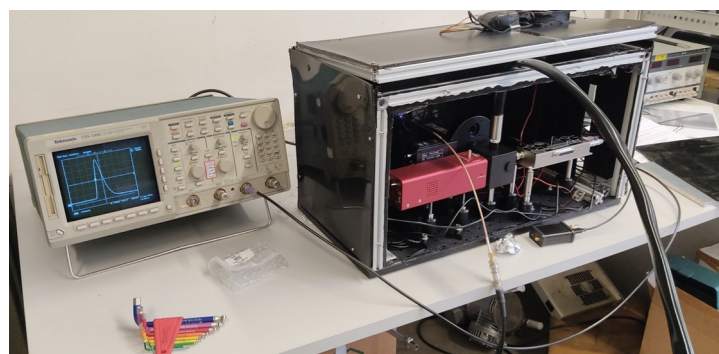


HAM imaging sample

- HAM system illuminating the external surface of a 2S module
- Time-lapse holographic interferometry
 - upper row
 - initial images of two different modules in the same gondola
 - lower row
 - image superposition after target installation
 - 13 fringes (rightmost image)
 - displacement of $13 \cdot (532 \text{ nm}/2) = 3.4 \text{ }\mu\text{m}$



- 25 PbWO_4 crystals (as used in the CMS ECAL)
 - (2.85 cm)x(2.85 cm) cross section
 - 23 cm long ($\sim 26 X_0$)
- light readout with APDs directly coupled to the crystals
- calibrated with a fiber-coupled laser system *à la E989 - Muon g-2*
- measures 1-150 GeV electron energies
- energy resolution $< 5\%$
- filters inelastic events by verifying energy deposition inferred from track angles
- will be larger in the final 40-station setup (1 m)x(1 m)

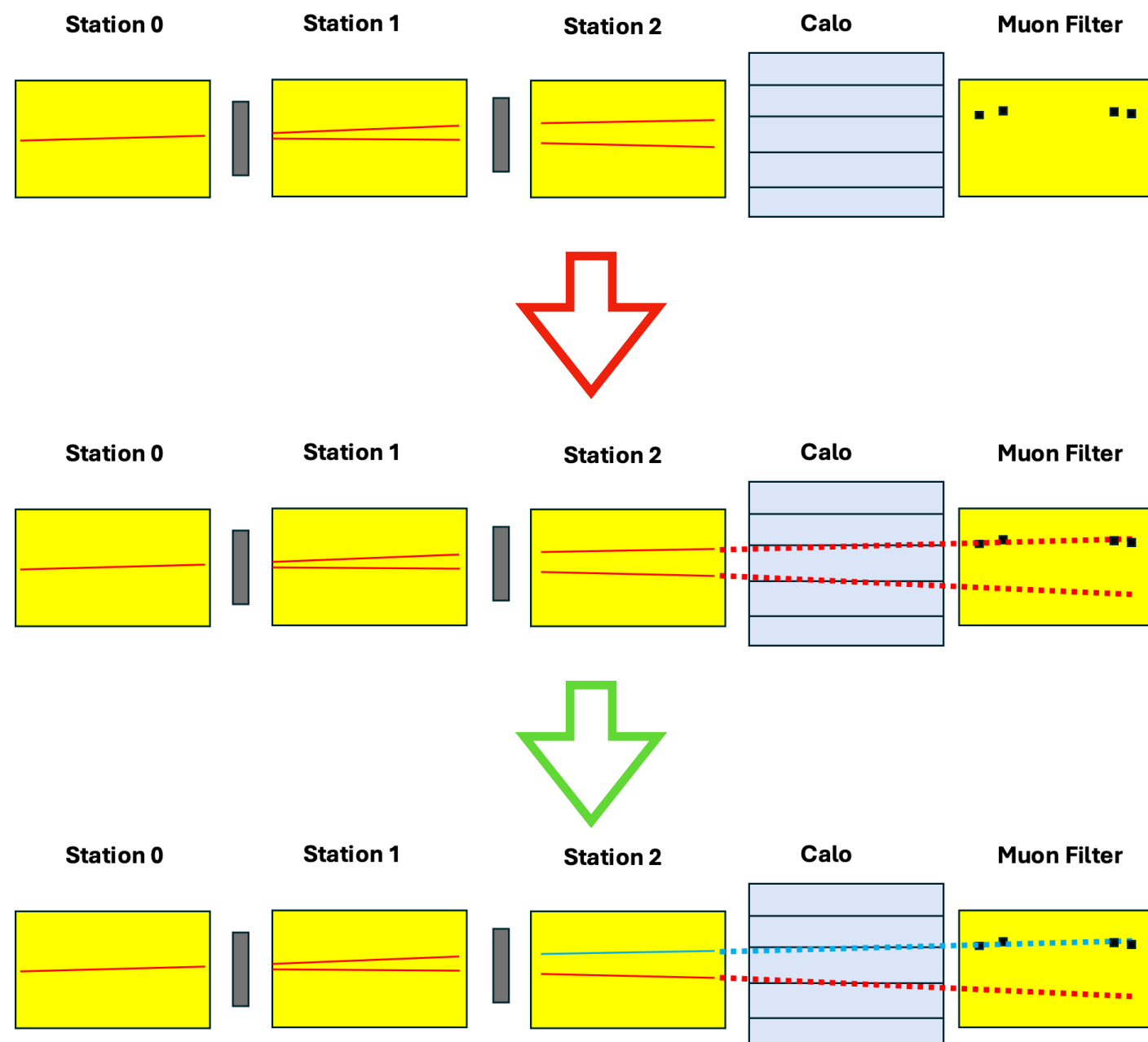


Muon Filter PID

- **Muon Filter PID - endline tracking station without target**

- reconstruct muon tracks after the ECAL
- connect with tracks before the ECAL $\Rightarrow$ **PID at small angles < 5 mrad**
- must cover entire beam cross section after the ECAL
- requires 2 pairs of x-y coordinates $\Rightarrow$ 4 tracking planes

MF track ID principle



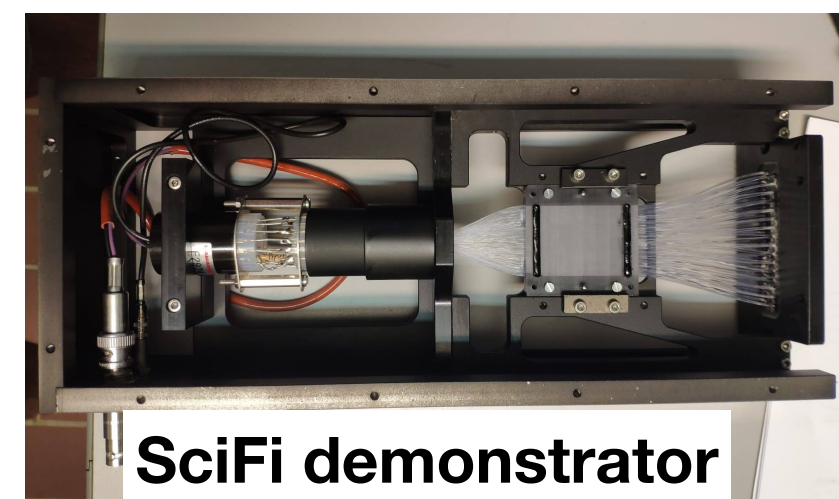
Muon Filter station - 2025

- 2025 “baseline” hardware

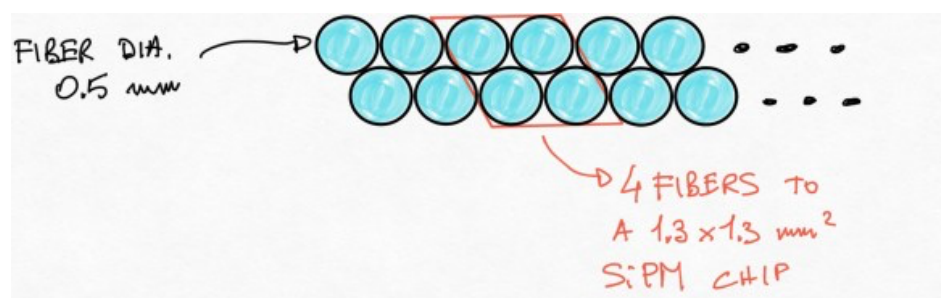
- standard gondola with motorized alignment mounts
- 2 pairs of non-tilted 2S modules ~60 cm apart
- cross section coverage (90 mm)x(90 mm) $\Rightarrow$ sufficient for the 2025 test run setup with 3 stations

- SciFi Muon Filter upgrade - 2026 $\rightarrow$

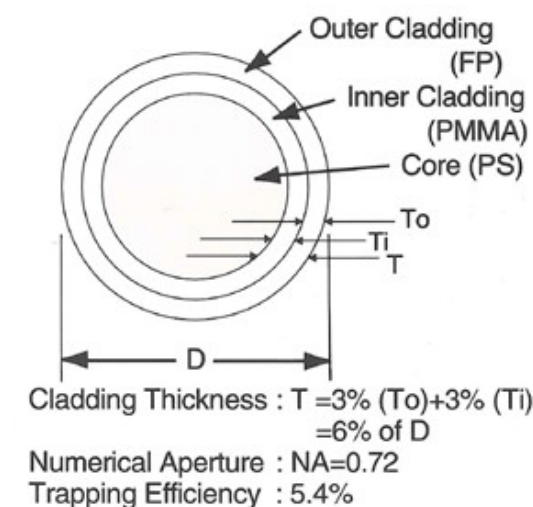
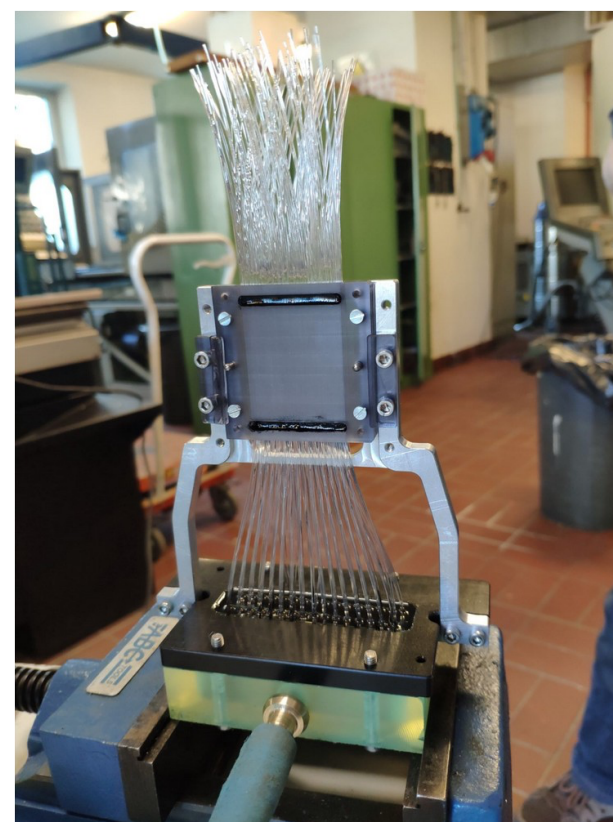
- Scintillating Fiber tracking planes
 - 1.25 mm pitch, scalable area
 - SiPM readout
 - PMT trigger signal from fiber bundle



SciFi Muon Filter



- Polystyrene (PS) round fibers, multi cladding (6% of the thickness)
- 88% of mechanical efficiency for single layer SciFi array
- Used double and shifted layers array – 4 fibers coupled to 1 SiPM
- Pitch 1.25 mm – resolution $\sim 360 \mu\text{m}$



07/07/25

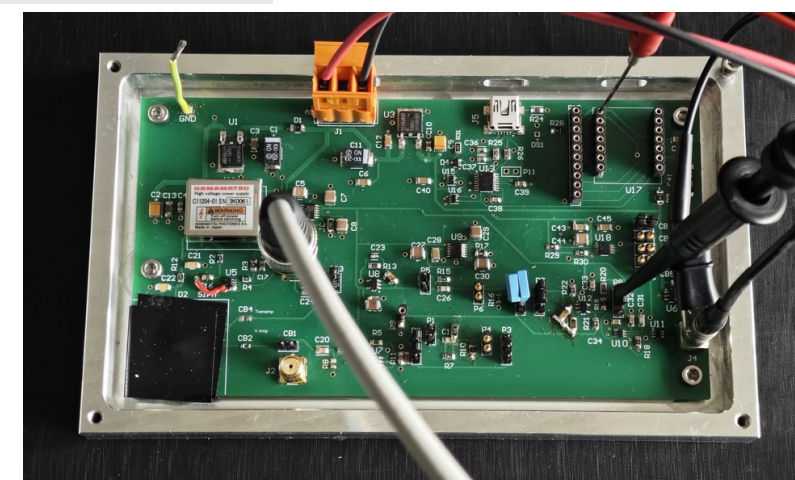
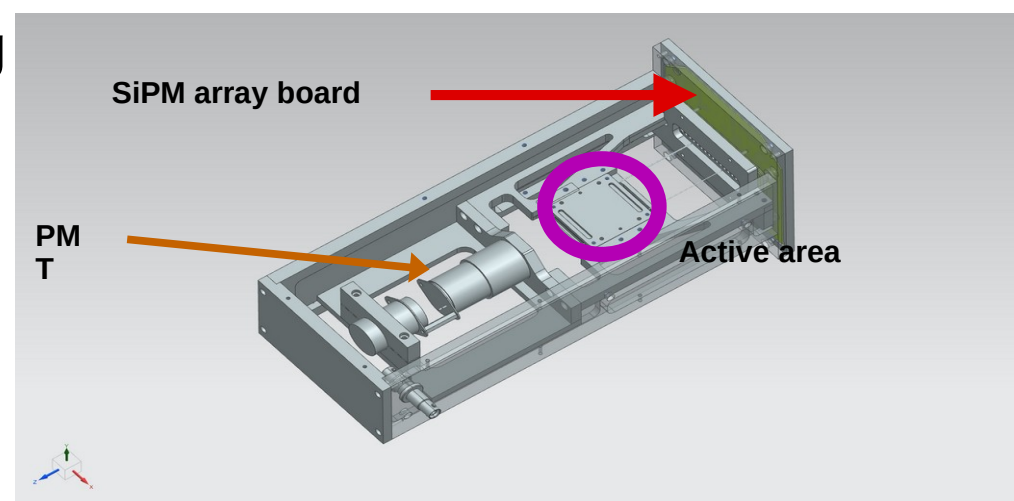
MUonE detector at CERN, EPS-HEP 2025

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Slide courtesy of A. Arena

SciFi Muon Filter Prototype

- 0.5mm dia. plastic scintillating fibers (Kuraray SCSF-78)
- SiPMs 1.3x1.3 mm² (Hamamatsu S13360-1350)
- PMT (Hamamatsu R1924A)
- Easy to cover large beam cross sections – easily scalable
- “Simple” mechanics
- Custom Front-End electronics in development



07/07/25

MUonE detector at CERN, EPS-HEP 2025

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Slide courtesy of A. Arena

Beam Momentum Spectrometer - 2025

- Eveny by event muon momentum measurement with 2 BMS stations

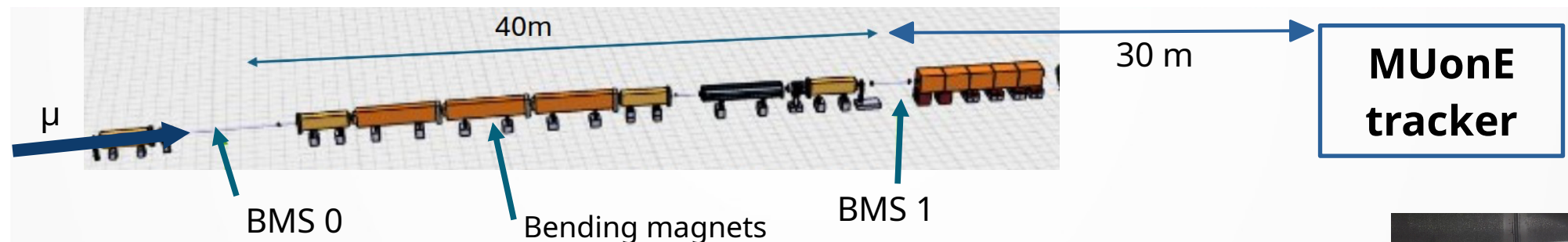
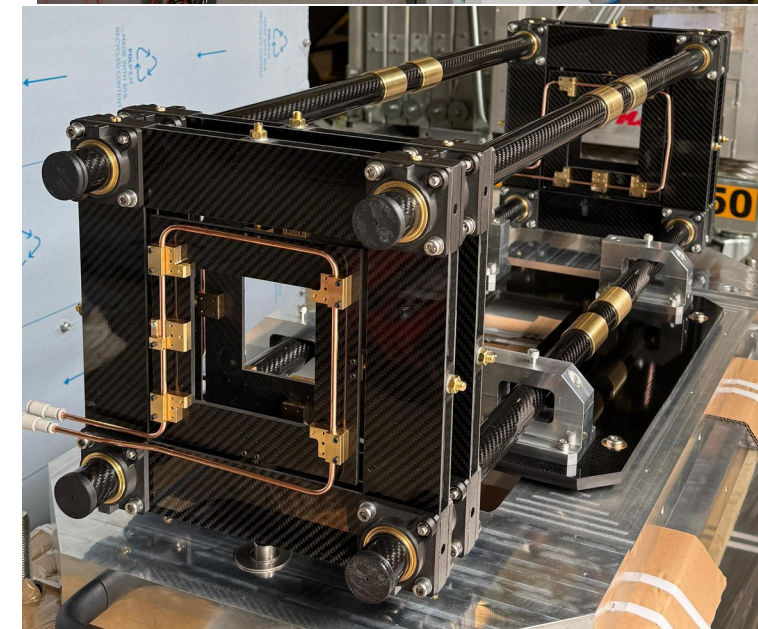


Figure from R. Pilato, FCCP workshop, Anacapri, Italy 2025

- Goal resolution $< 0.5 \%$
 - Bending power: 16 T·m, 30 mrad at 160 GeV
 - 1 m long carbon fiber structure
 - 2 x-y non tilted tracking planes equipped with 2S modules
- First tests in Jul-August 2025



DAQ system



M2 beam line at CERN:
unique environment

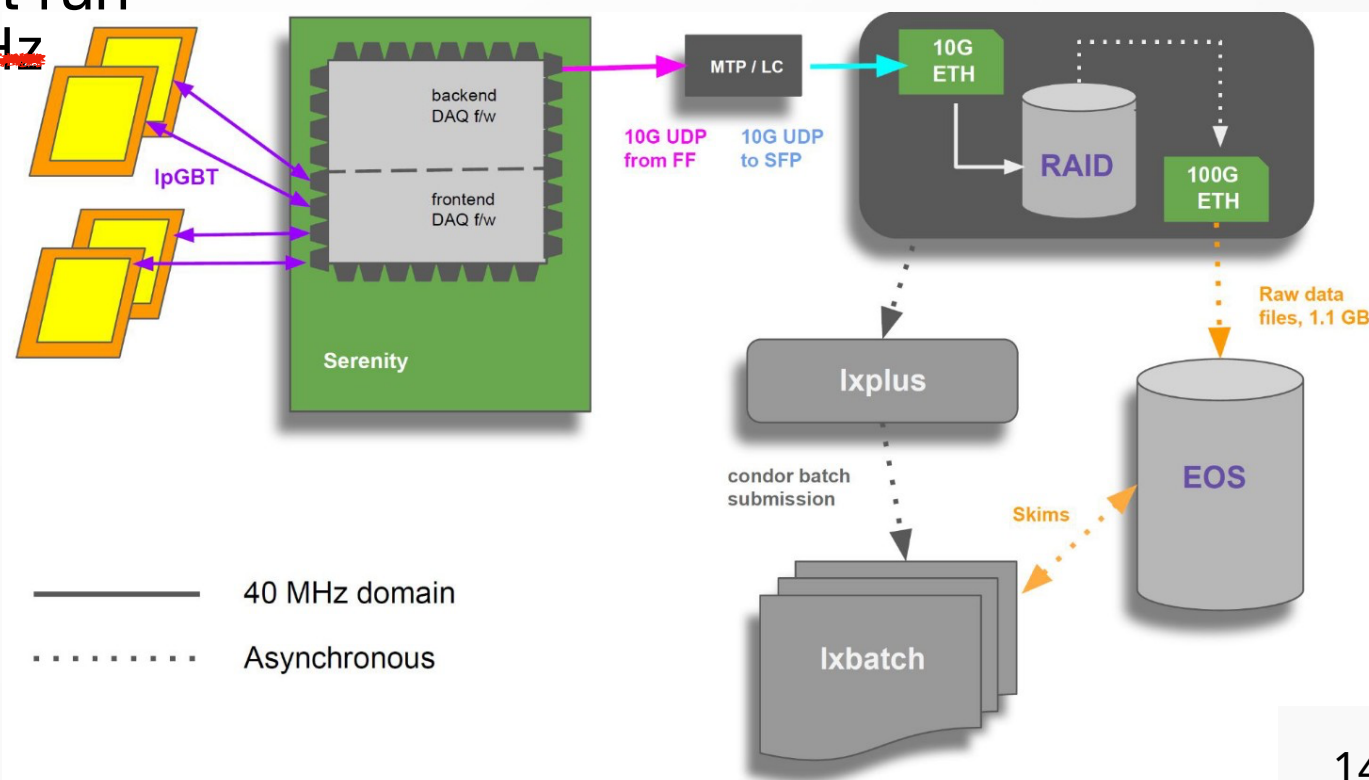
- High intensity: $\sim 2 \times 10^8 \mu^+ / 5\text{s spill} \rightarrow \sim 40 \text{ MHz}$
- **Beam asynchronous to DAQ clock**

- **Serenity** board (developed for CMS Phase2 Upgrade)

Triggered readout in the 2025 test run

- ~~Triggerless readout @ 40 MHz~~

- Event aggregator on FPGA
- Data aggregation on 4 PCs
- Transmission to EOS for permanent storage

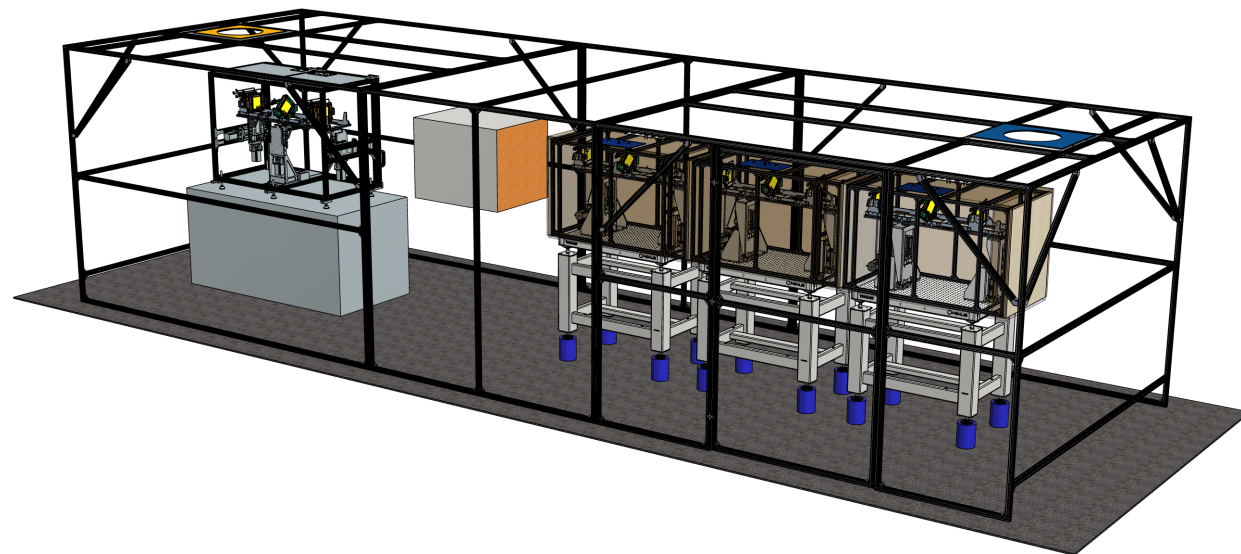


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Slide from R. Pilato - Workshop on Flavour changing and conserving processes
Anacapri, 30th September 2025

MUonE 2025 test run

- July-August 2025: test run at the CERN M2 beamline with 160 GeV muons
- main goals
 - demonstrate detection integration
 - validate DAQ chain
 - demonstrate elastic event identification
 - bonus goal: collect enough data for a $\Delta\alpha_{had}(t)$ measurement with ~20% statistical uncertainty
- beamline layout
 - BMS (2 stations)
 - 3 tracking stations, 2 stations equipped with 2 cm thick C targets
 - ECAL
 - Muon Filter PID
 - timing scintillators at both ends of the station line
 - DAQ chain



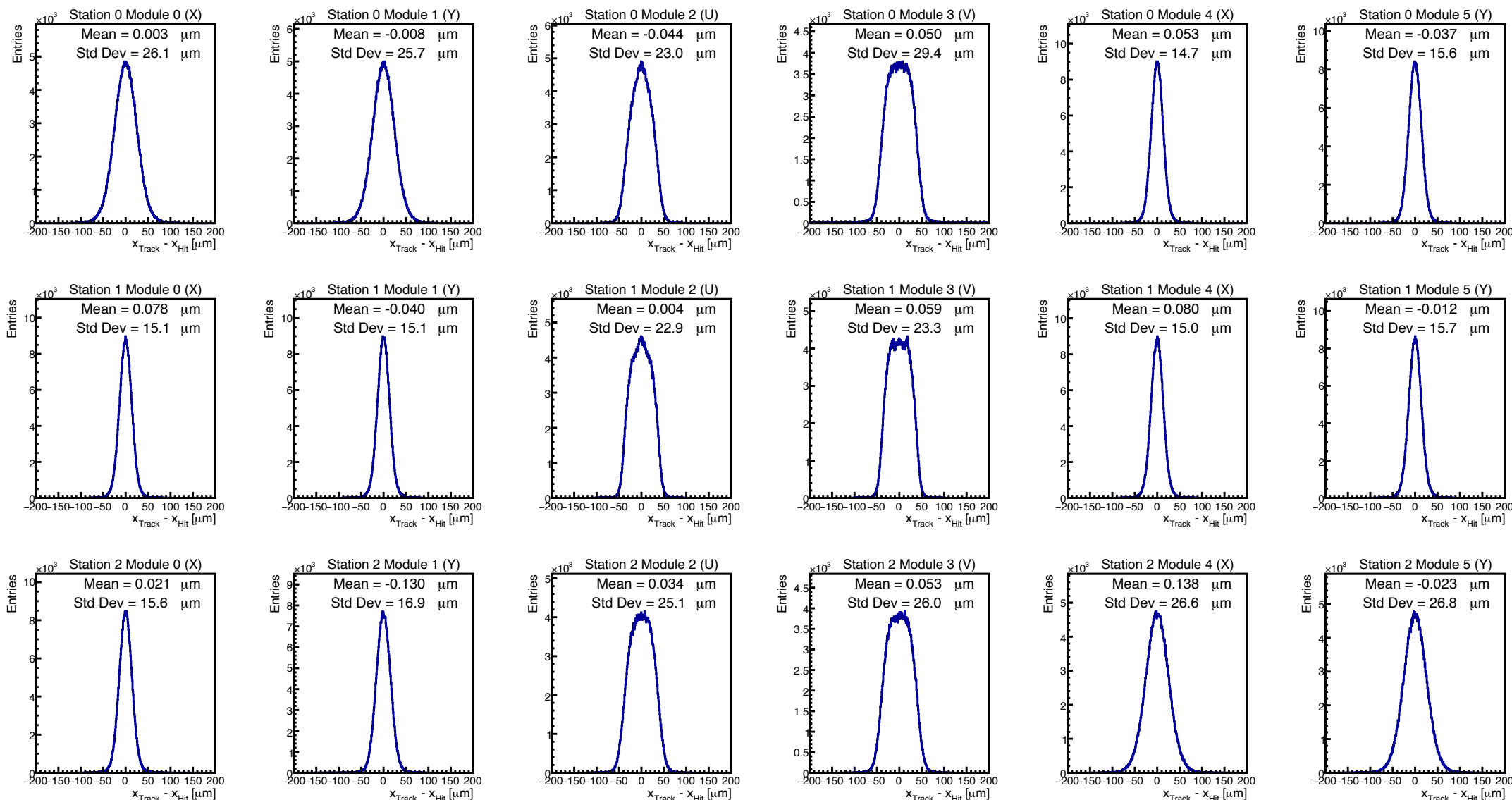


- **Analysis effort is ongoing**
- **Selected plots from the 2025 MUonE test run**
 - **tracker**
 - resolution - 20-25 μm
 - timing - 90% timing efficiency
 - efficiency - 99% stub efficiency
 - **ECAL PID sample**
 - **MF PID sample**
- **DAQ performance**
 - online selection on stub pattern implemented in the FPGA $\Rightarrow$ event rate reduced from 40 MHz to 500 kHz

2025 Tracker “residuals”

- difference between reconstructed track position and hit position

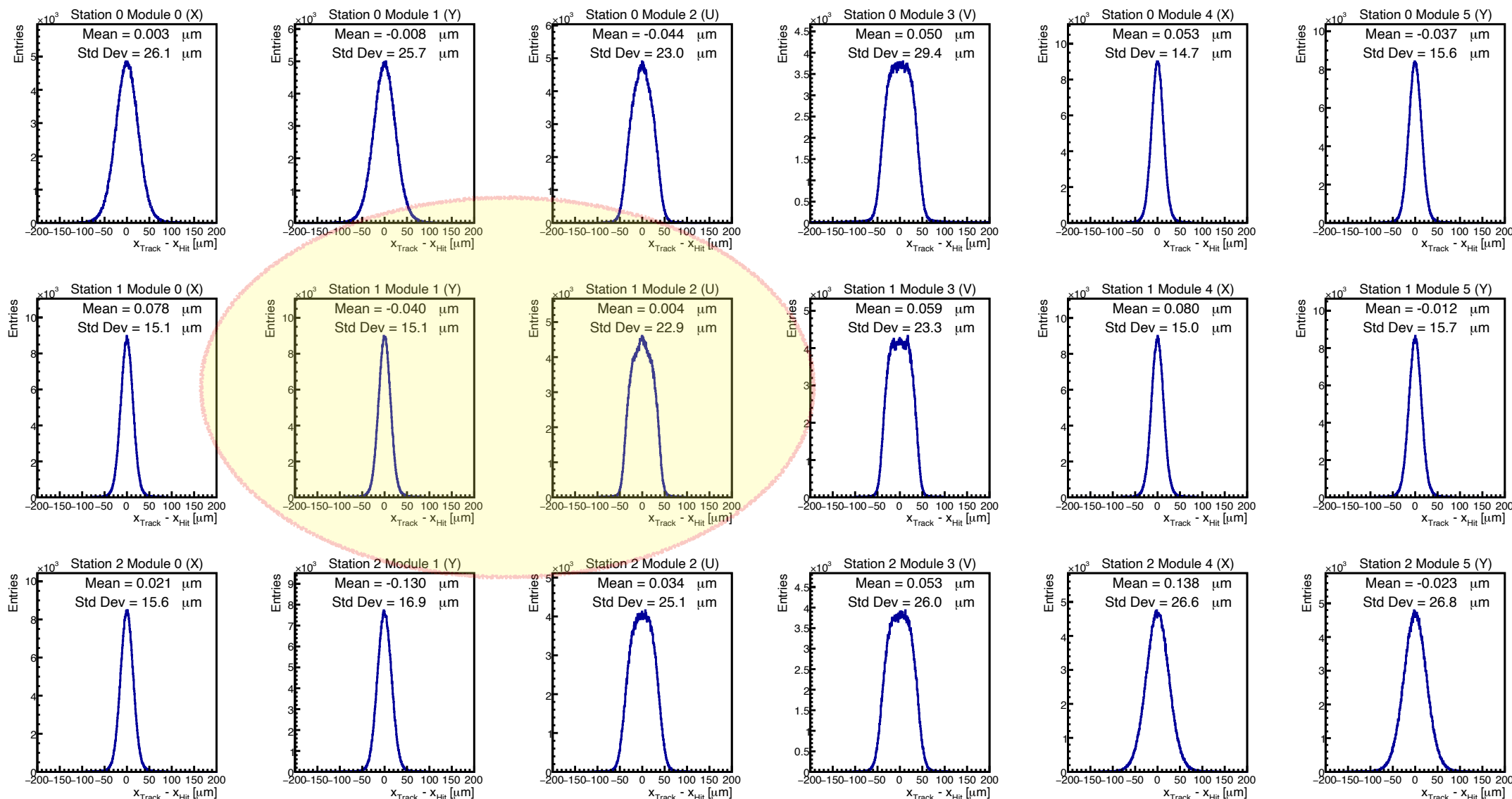
- station 0, no target
- stations 1 and 2, 2 cm C target
- X,Y - tilted modules
- U,V - rotated non tilted modules



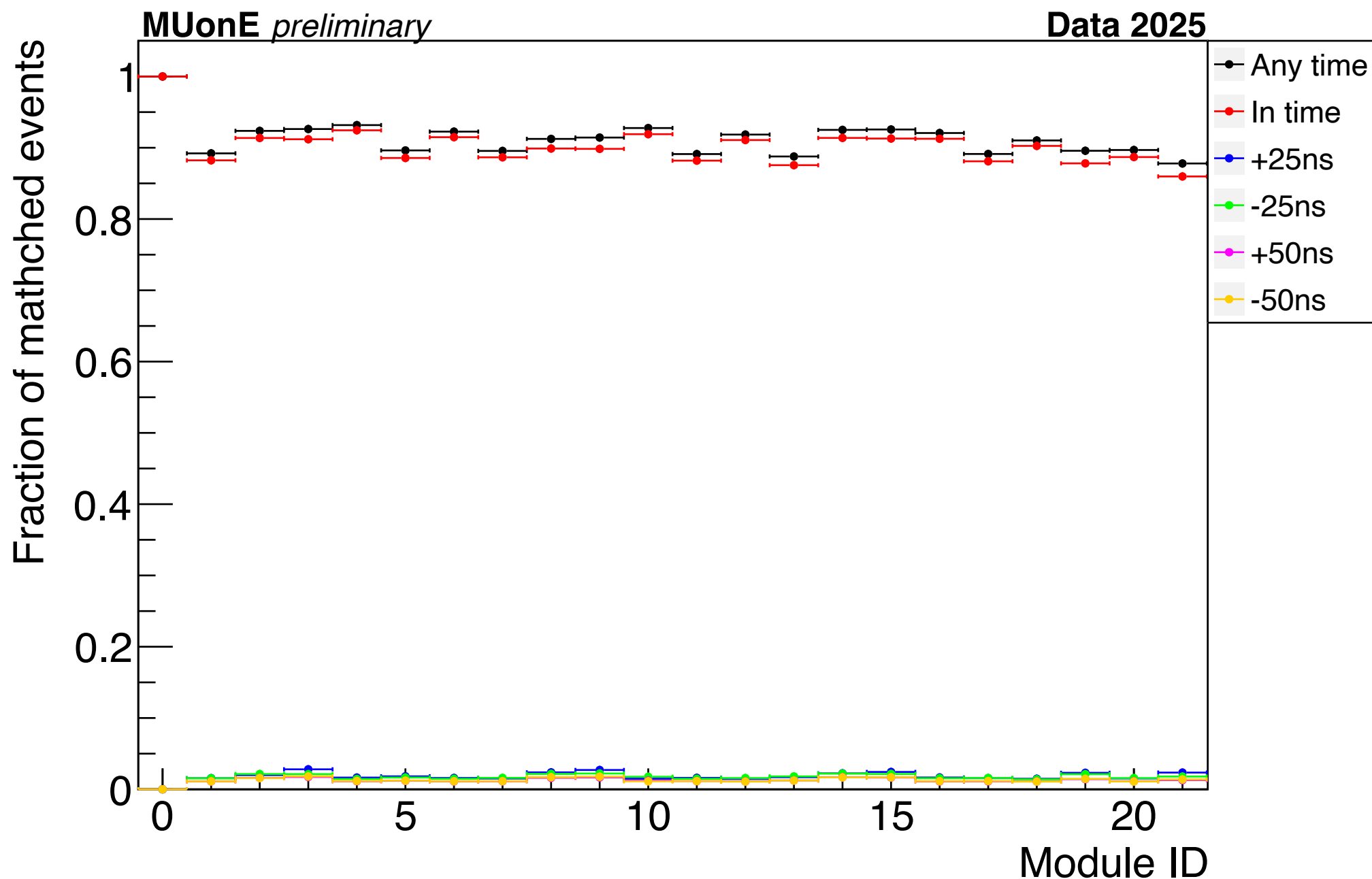
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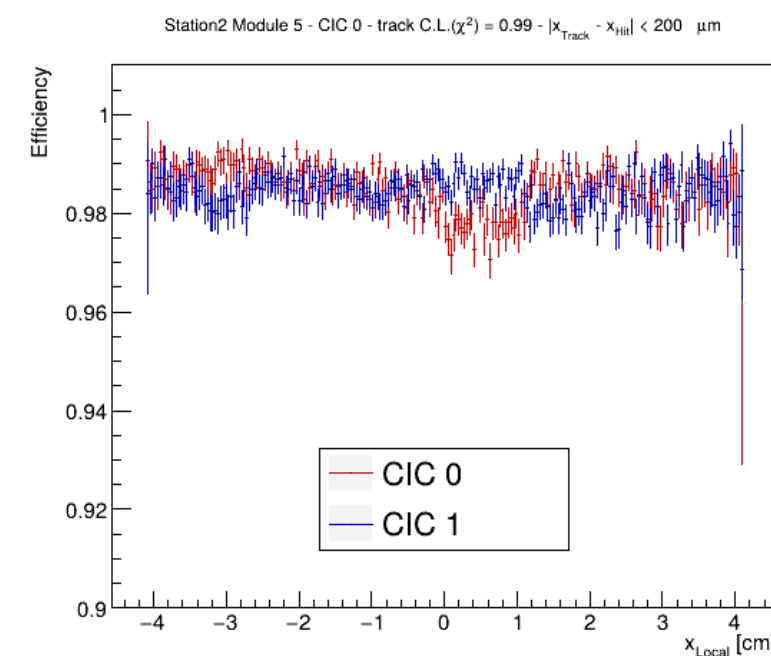
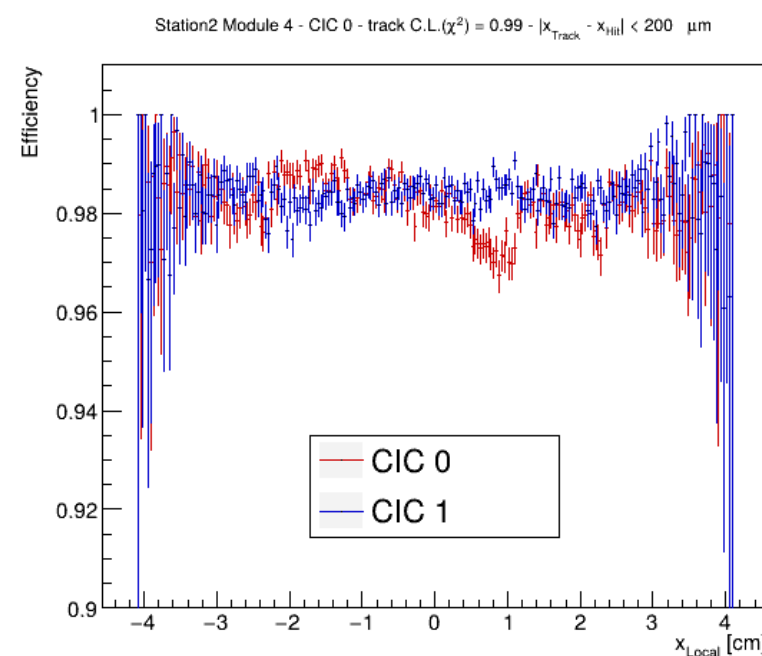
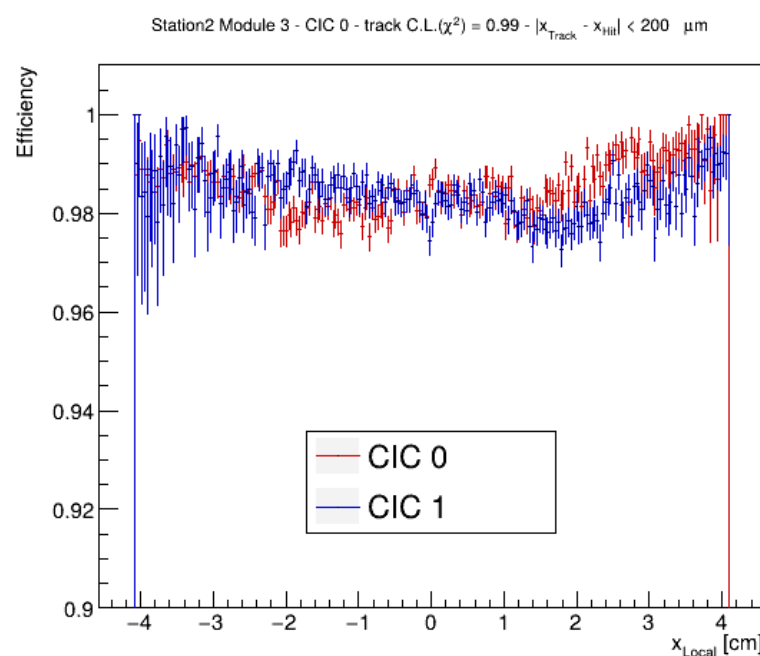
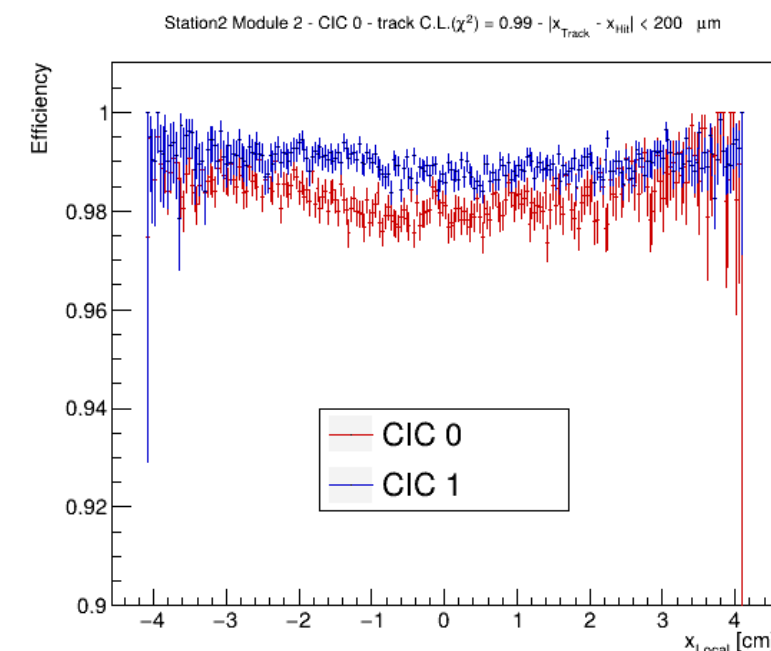
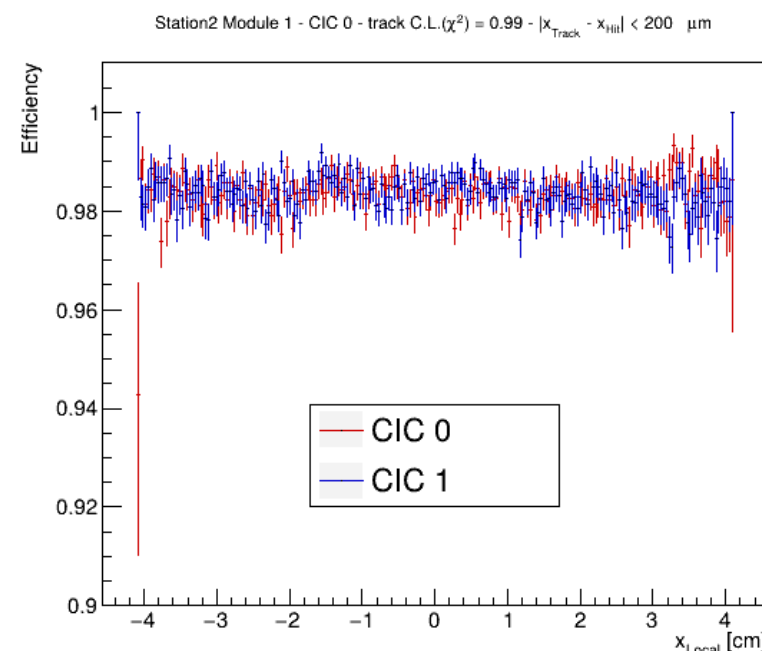
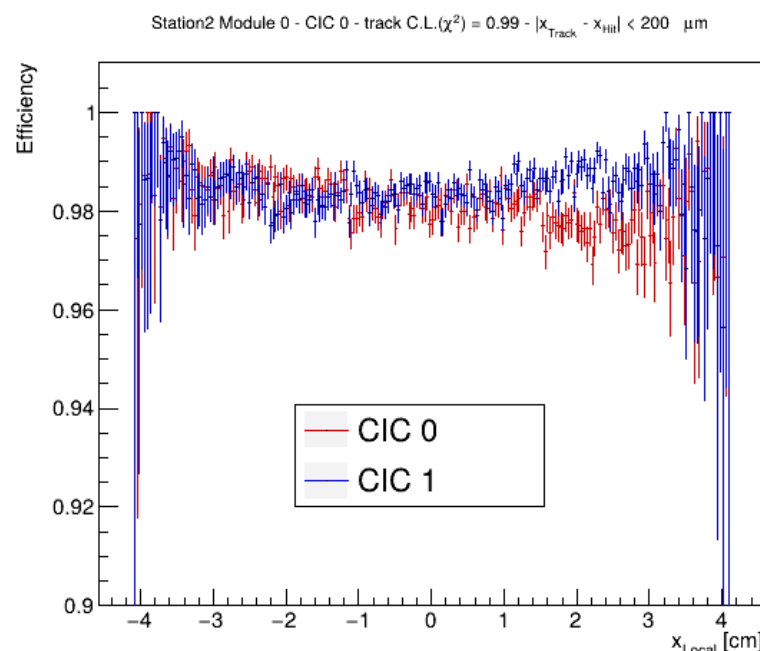
- station 0, no target
- stations 1 and 2, 2 cm C target
- X,Y - tilted modules
- U,V - rotated non tilted modules



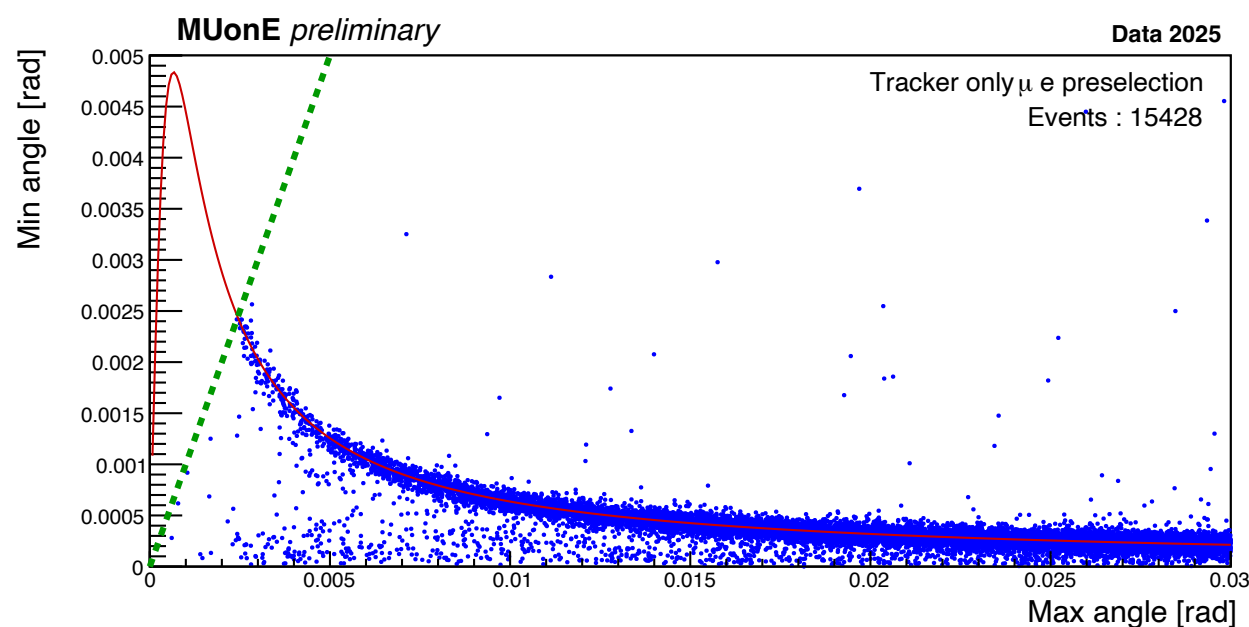
- Ratio of events with a stub in a given module when a single stub is seen in the reference module (station 0 module 0 in this case) for all the 22 2S modules



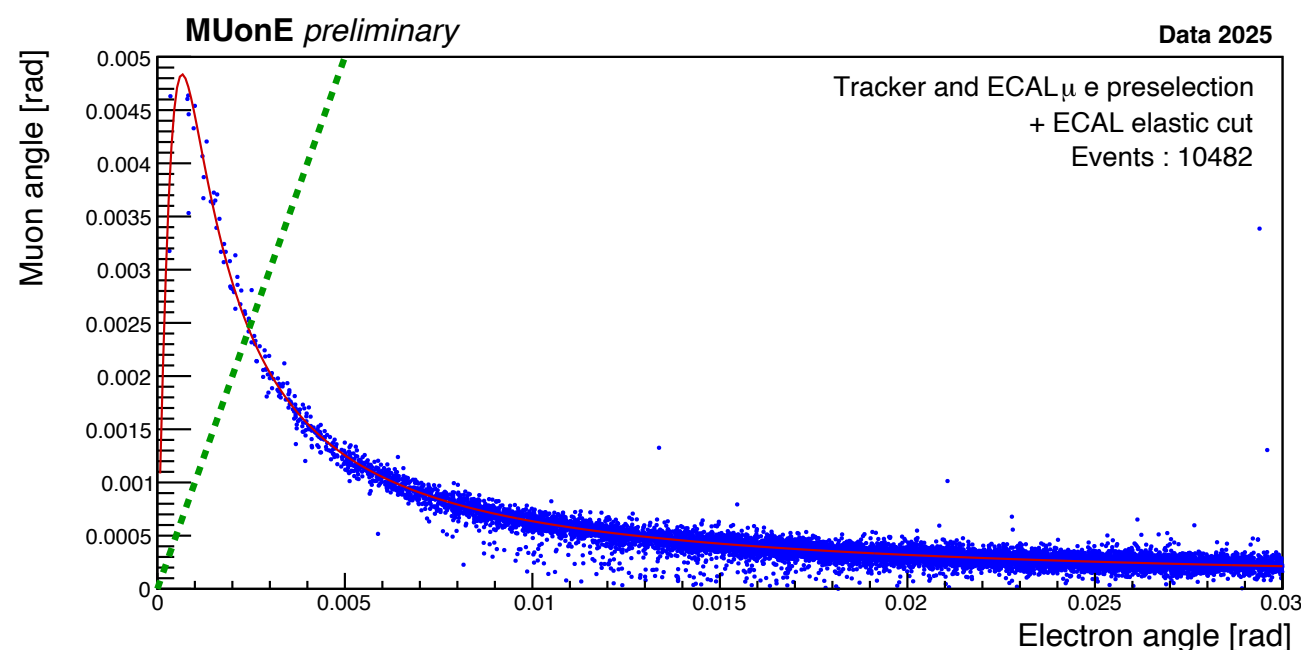
- Stub efficiency - 2S modules in station 2 vs. reconstructed track position. Red and blue represent the two CICs on a 2S module.



- 2D distributions of the muon and electron scattering angles at different selection stages.
 - green dashed lines $\Rightarrow$ to equal scattering angles.
 - red curves $\Rightarrow$ expected elastic scattering kinematic correlation at 160 GeV.

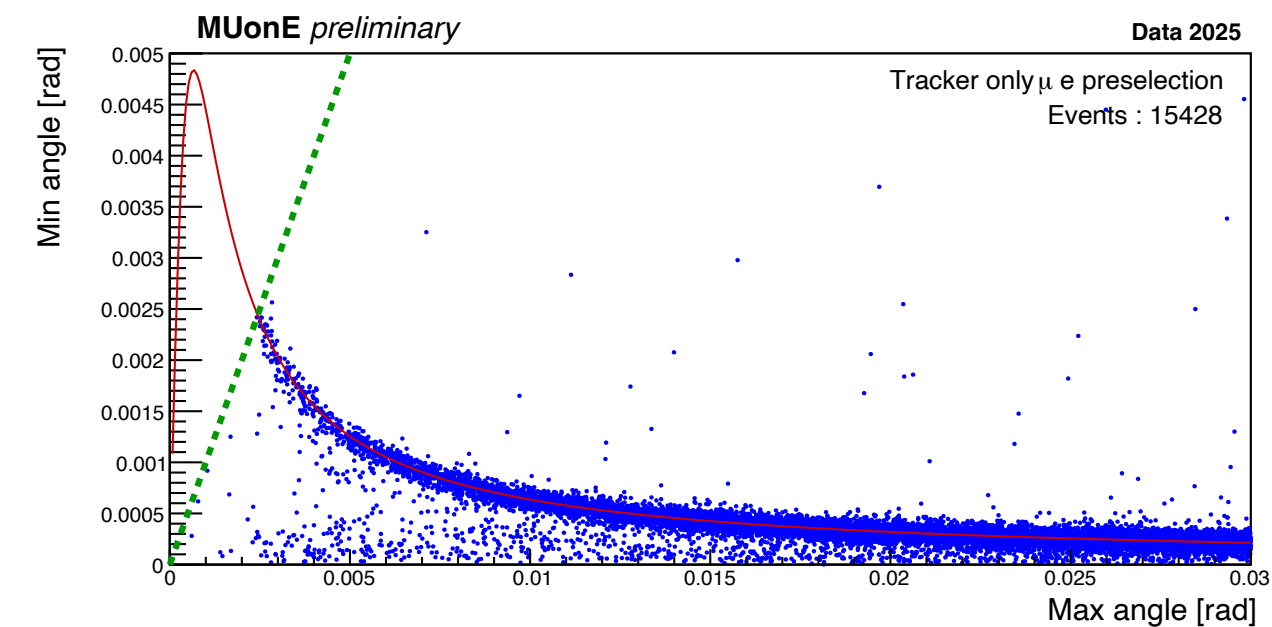


Tracker only selection

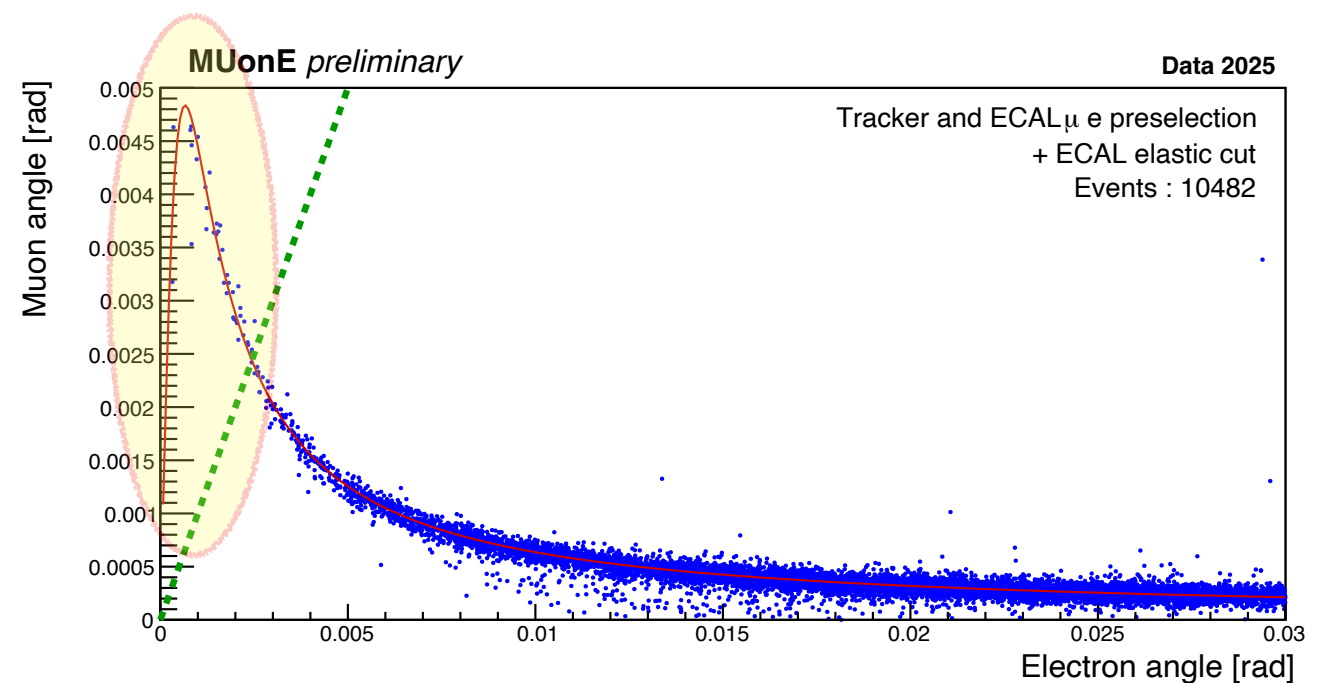


Tracker selection
ECAL selection
ECAL elastic cut

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Tracker only selection



Tracker selection
ECAL selection
ECAL elastic cut

• 2025 test run

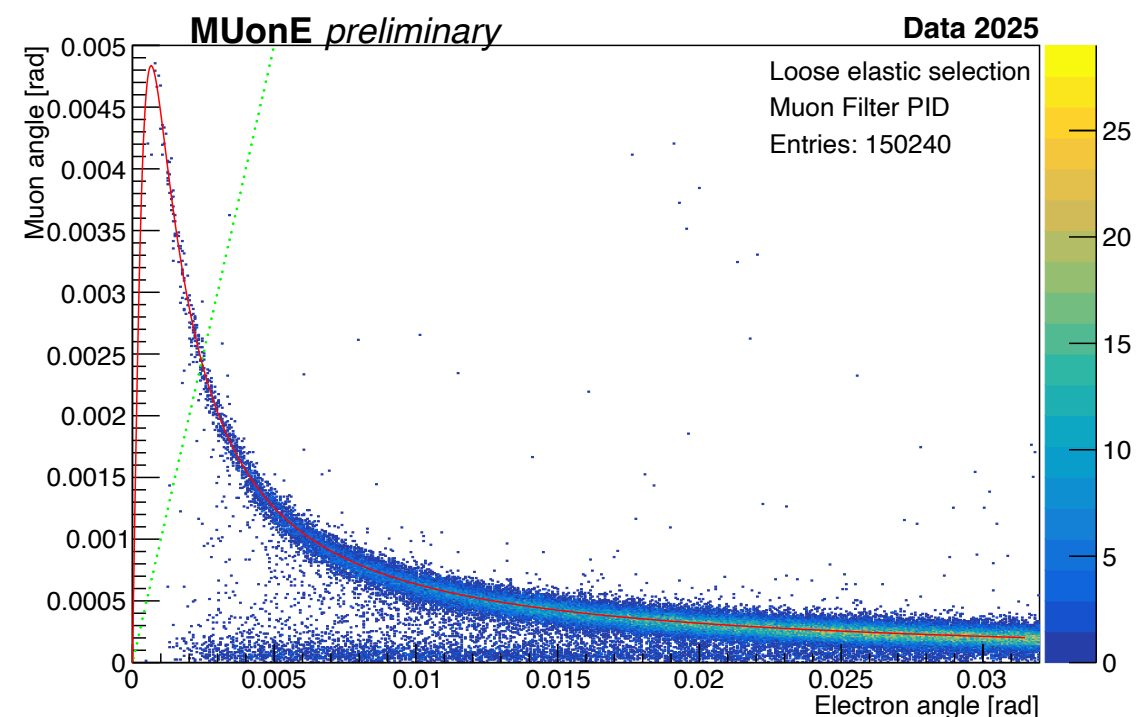
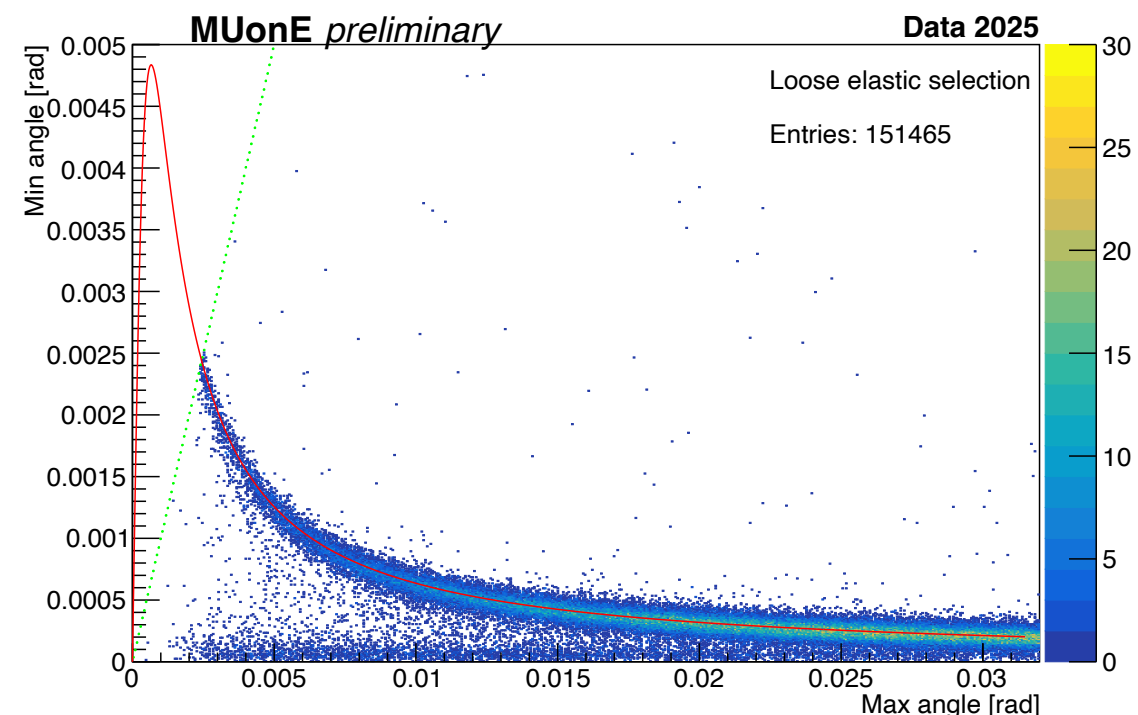
- several weeks of data taking with a fully integrated pilot apparatus
- demonstrated online event selection - factor 80 reduction in event rate
- **preliminary sample**
 - elastic events
 - small angle PID

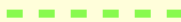
• Ongoing analysis campaign

- study systematic effects
- preliminary measurements of $\Delta\alpha_{had}(t)$ at ~20 % level (syst. & stat.)

• Main directions 2026 →

- overall detector review
- detailed proposal to SPSC
- goal: achieve full setup after the LHC long shutdown (2029 →)



 $\theta_\mu = \theta_e$ reference
 $\theta_\mu - \theta_e$ kinematic relation

• 2025 test run

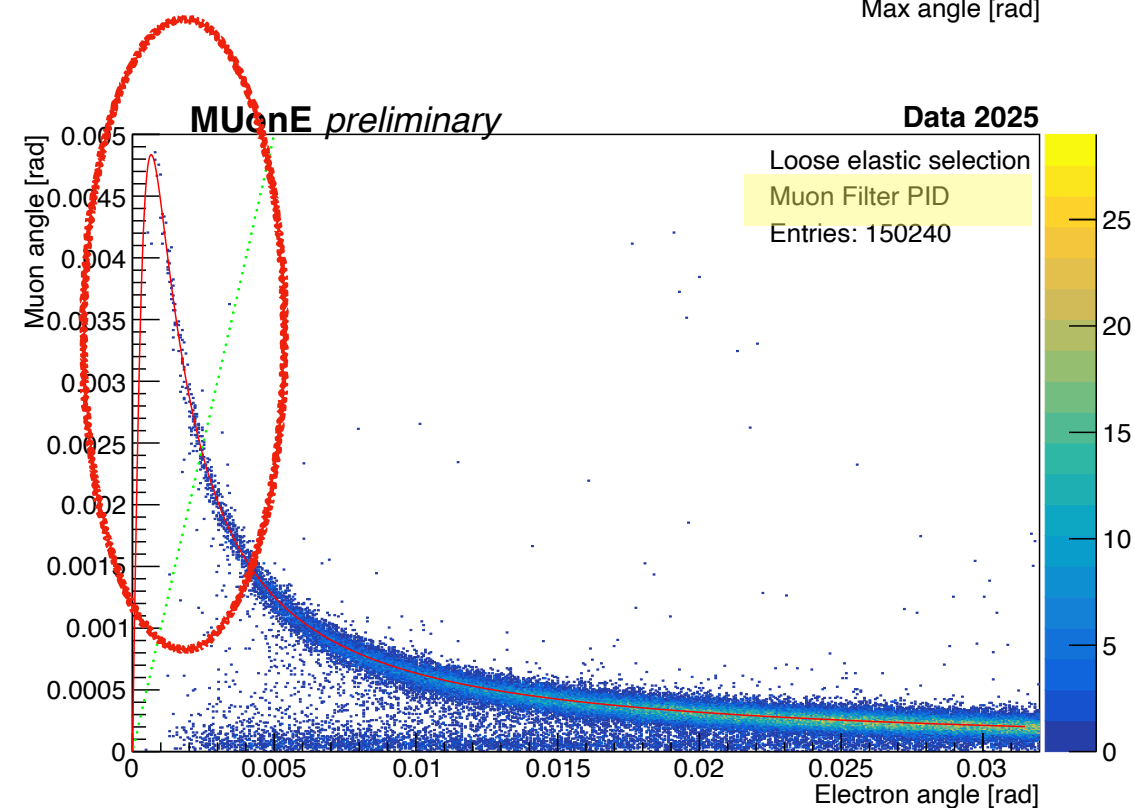
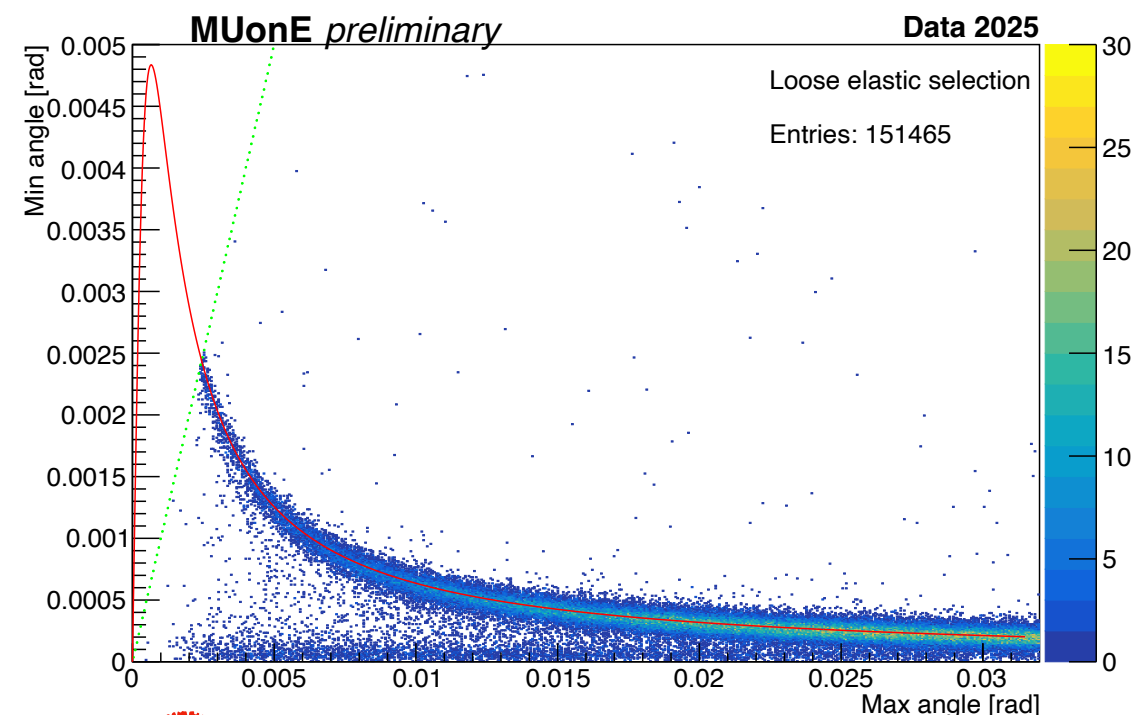
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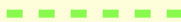
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Conclusions

- The **high precision experimental value of a_μ** recently released by E989 at Fermilab is a solid benchmark. **It is not, however, the end of the story.**
- **Discrepancies** between lattice and data-driven calculations and unresolved **tensions** in the current experimental determinations of the leading **hadronic vacuum polarization** contribution, call for a new independent measurement. The **MUonE experiment** at CERN tries to address this concern.
- The **2025 MUonE test run** at the CERN M2 beamline validated the concept of the experimental setup and provided valuable insights and lessons about the performance of the apparatus
- **MUonE** enters now a critical internal review phase with the goal of preparing a complete proposal for the CERN SPSC in view of data taking with a complete apparatus after the LHC long shutdown

“Before I came here I was confused about this subject.

Having listened to your lecture I am still confused, but on a higher level.”

