UNIVERSITY OF LIVERPOOL

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The MUonE experiment: status and plans

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μONe

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University of Connecticut, 03-07 August 2026

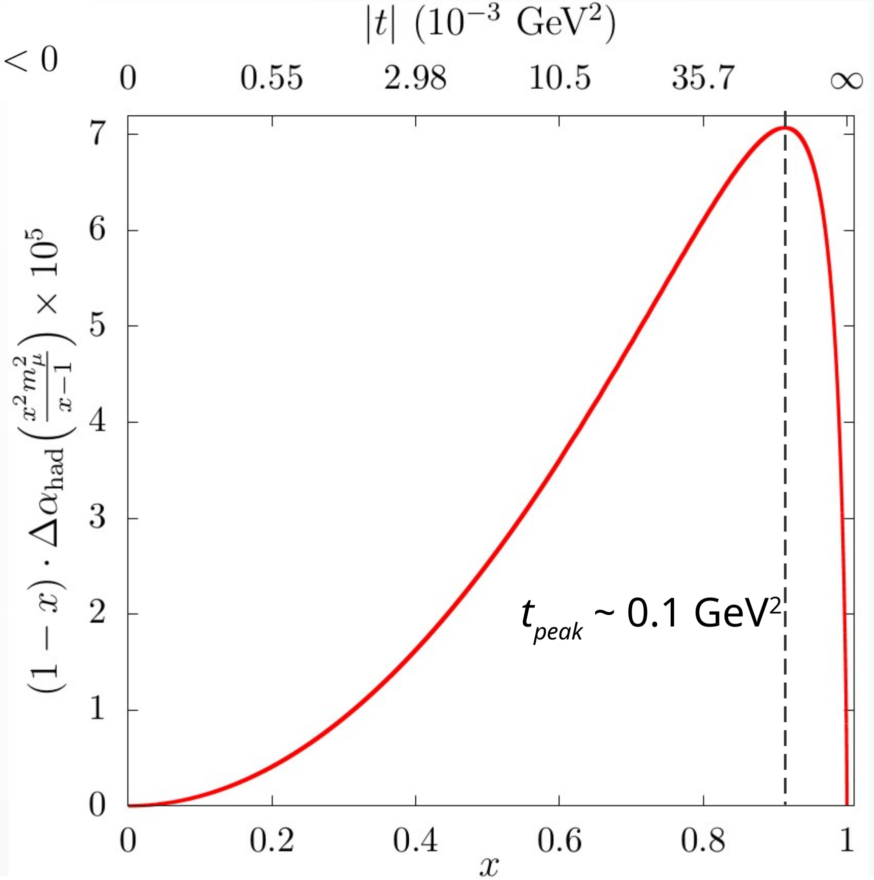
The MUonE experiment

Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026
Proposal for Phase 1 of the MUonE experiment

New independent evaluation of $a_\mu^{HVP,LO}$, based on the measurement of $\Delta\alpha_{had}(t)$ in the space-like region

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

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$



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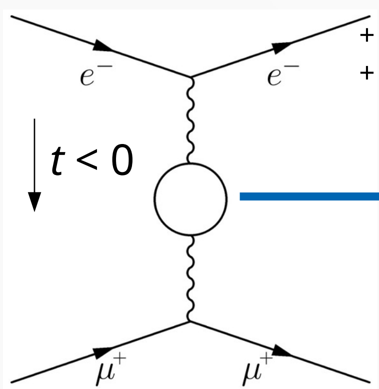
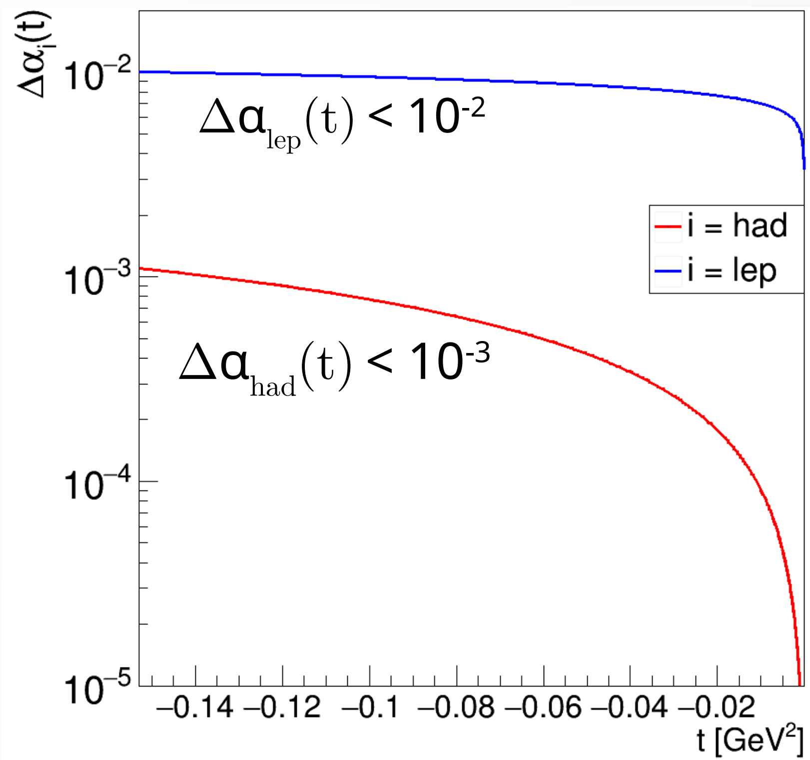
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)] \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Extract $\Delta\alpha_{had}(t)$ from the *shape* of ***μe → μe*** differential cross section



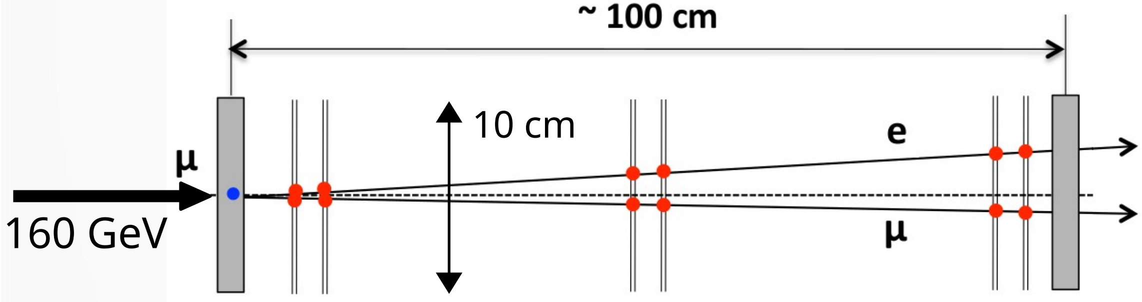
+ higher orders
+ radiative corrections

$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t) + \Delta\alpha_{top}(t)$$



MUonE kinematic range

The MUonE experiment

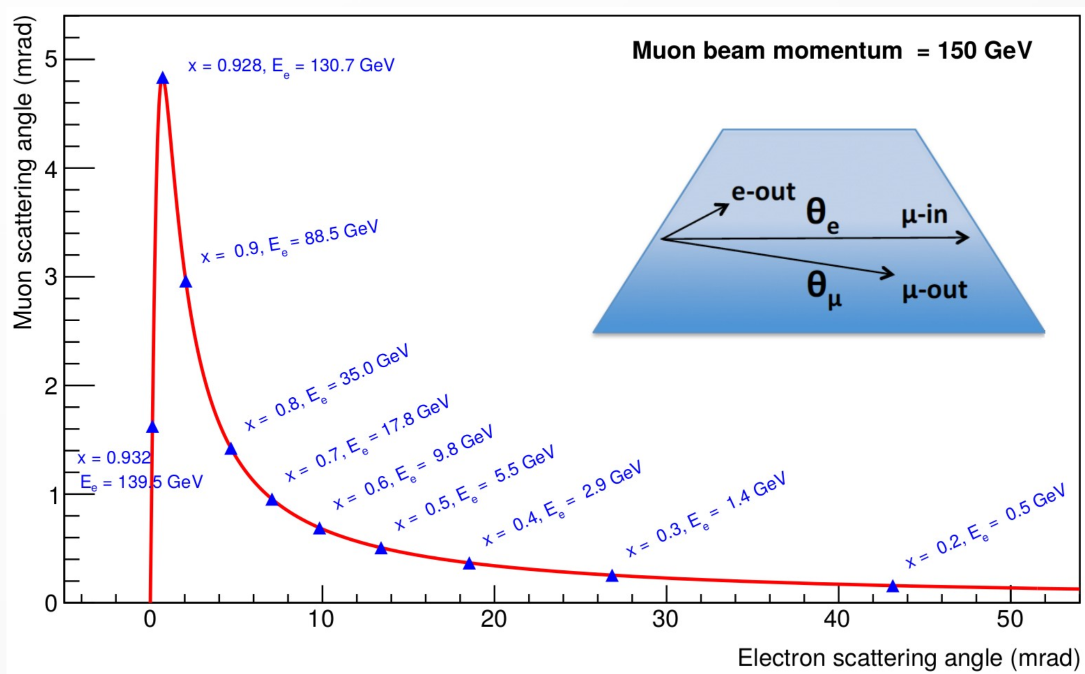


$$R_{\rm had} = \frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

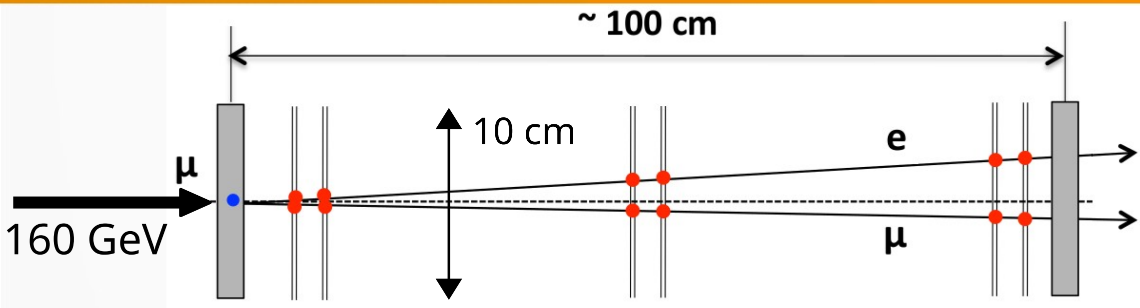
low-Z target ~1.5 cm

6 Si strip detectors (3 XY points)

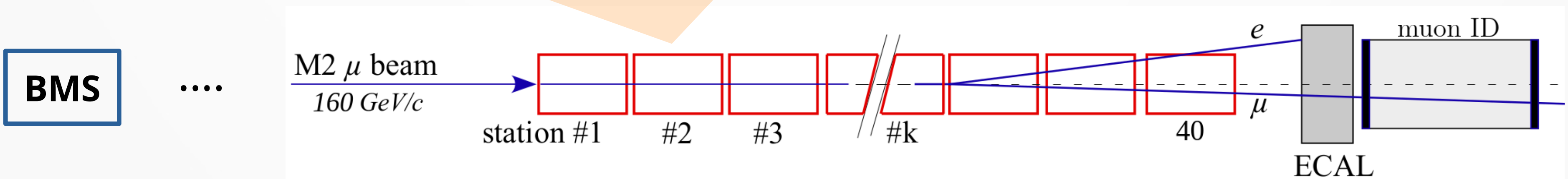
- Observables: (θ_e, θ_μ)
- Exploit (θ_e, θ_μ) correlation to reject background (main source: $\mu\, N \rightarrow \mu\, N\, e^+e^-$)
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad



The MUonE experiment



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



- Modular layout:
  each station measures
  the incident muon direction
  for the following one

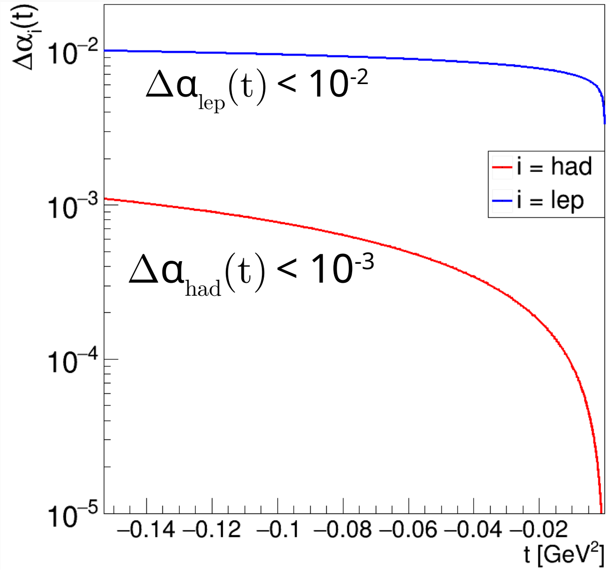
- ECAL: PID + *e*⁻ energy
- Muon ID: PID
- BMS: beam momentum spectrometer

The MUonE experiment

MUonE final goal:

- ~3 years post LS3 (>2030)
- 40 stations
- 4×10^{12} elastic events
- $a_\mu^{\mathrm{HVP,LO}} < 0.5\%$
- ~1% precision on $\Delta\alpha_{had}(t)$

(error on $\Delta\alpha_{had}(t)$: 10^{-5} in the signal region)



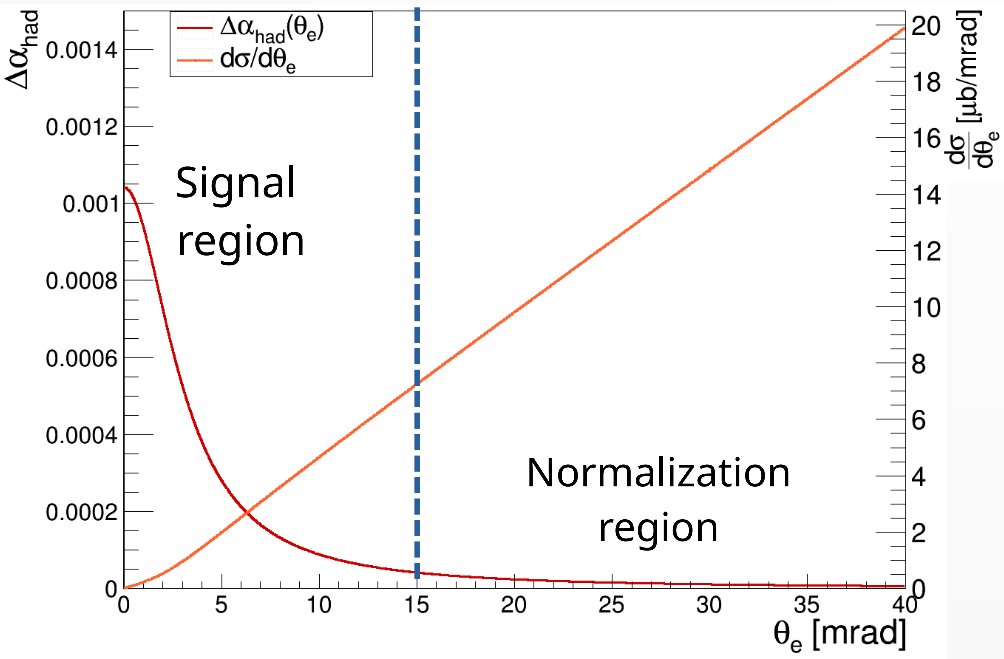
Systematic error goal:
10 ppm on the shape of
the differential cross section

- 10 μm longitudinal alignment
- Measure beam energy at few MeV
- Multiple scattering ~1%
- Angular intrinsic resolution
- Uniform detector response over full angular range
- Need of dedicated MC generators: signal (>NNLO), main backgrounds

Strategy for the systematic effects

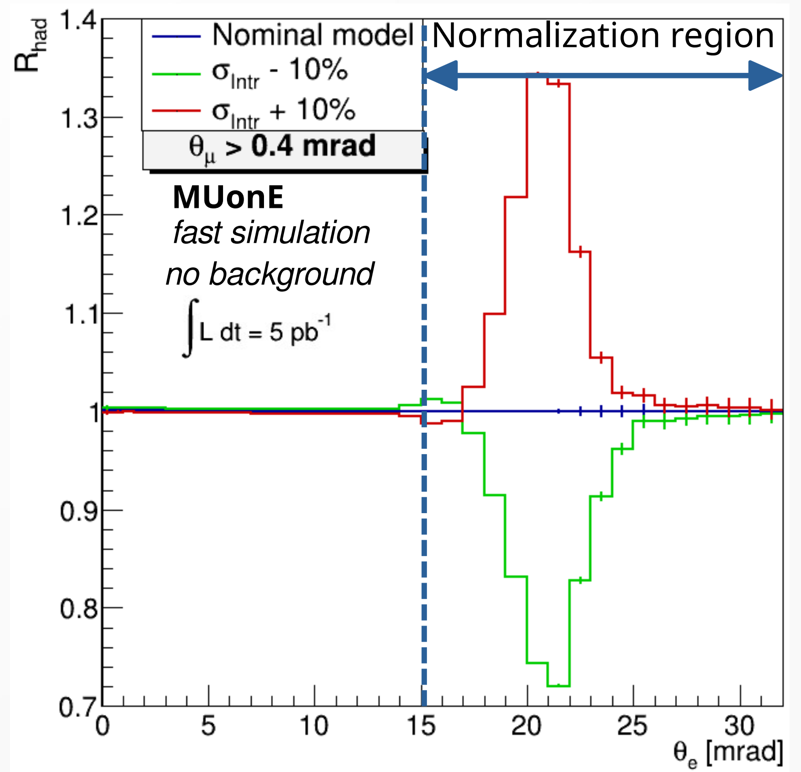
Promising strategy:

- Study the main systematics in the normalization region: large systematic effects but no sensitivity to $\Delta\alpha_{had}$
- Include residual systematics as nuisance parameters in a combined fit with signal



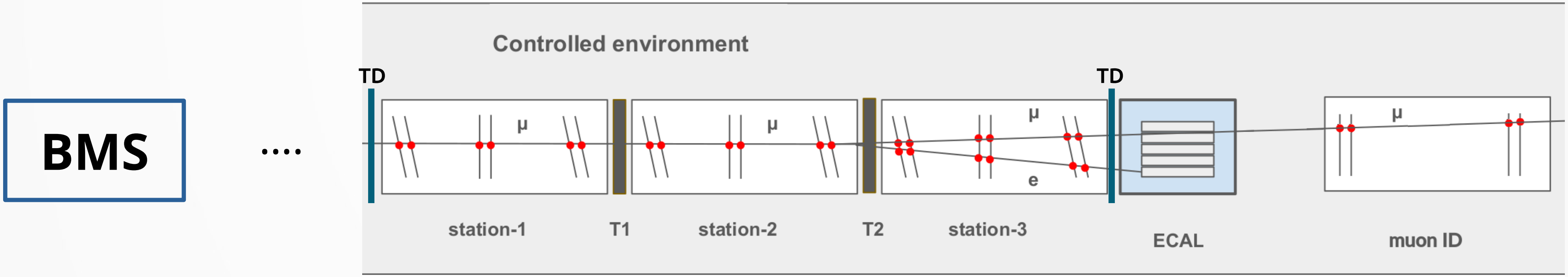
Example: ±10% systematic error on the angular intrinsic resolution

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



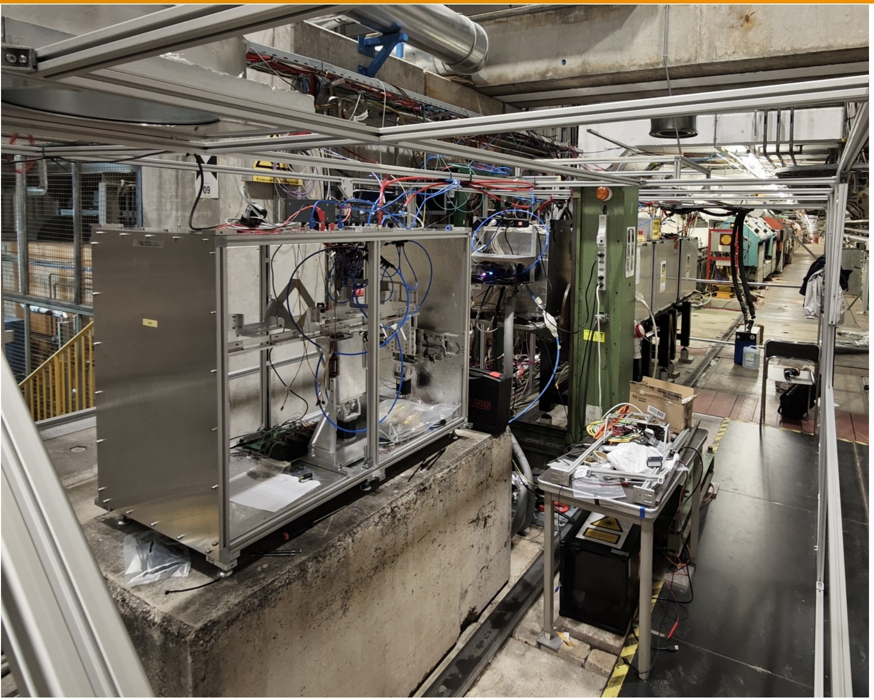
MUonE Phase-1: Test Run 2025

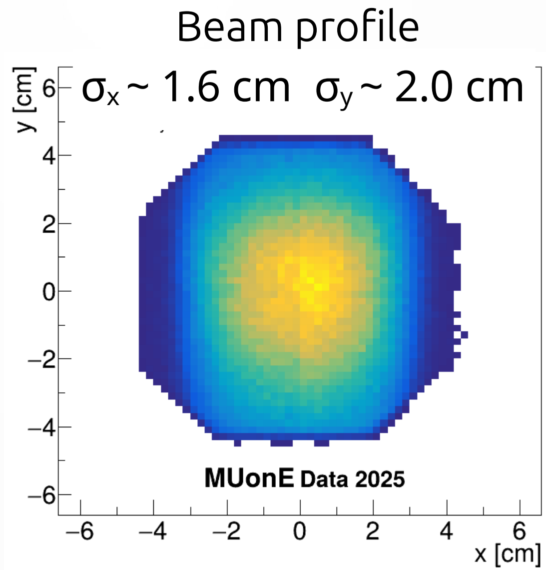
[Proposal for Phase 1 of the MUonE experiment]

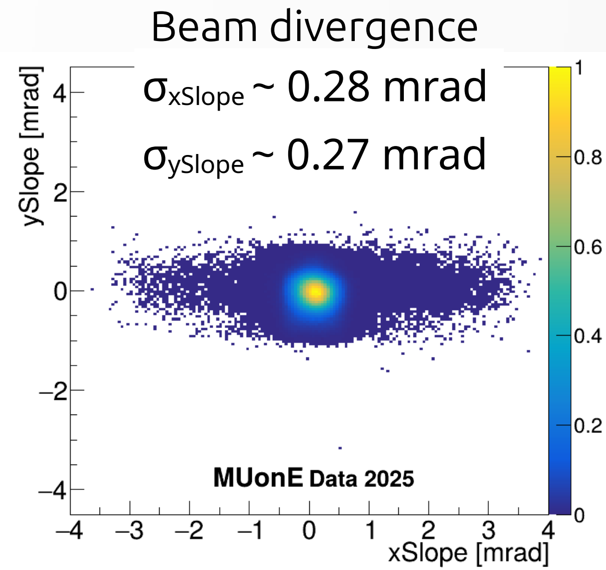


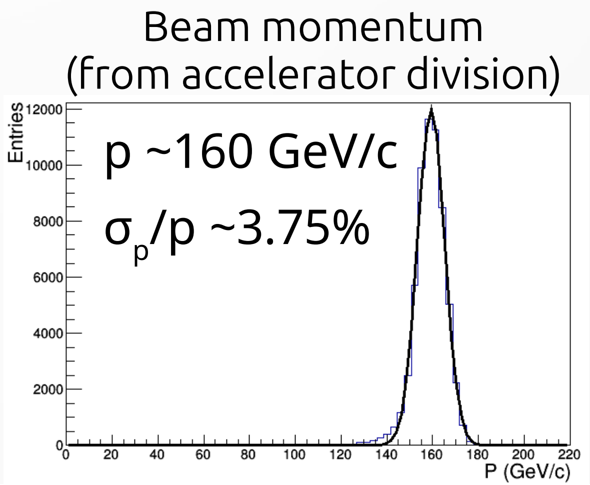
- 3 × tracking stations:
  muon beam direction
  and angles of the interaction products
- 2 × C targets
  (each 2 cm thick)
- ECAL: e^- PID + E_e measurement
- Timing detector: time of arrival of muons.
  2 plastic scintillators before and after the tracking stations
- Muon ID: μ PID. Equipped with
  4 prototype 2S modules
- BMS: measure p_μ event by event.
  2 × tracking stations, each equipped with
  4 prototype 2S modules

M2 beamline at CERN North Area



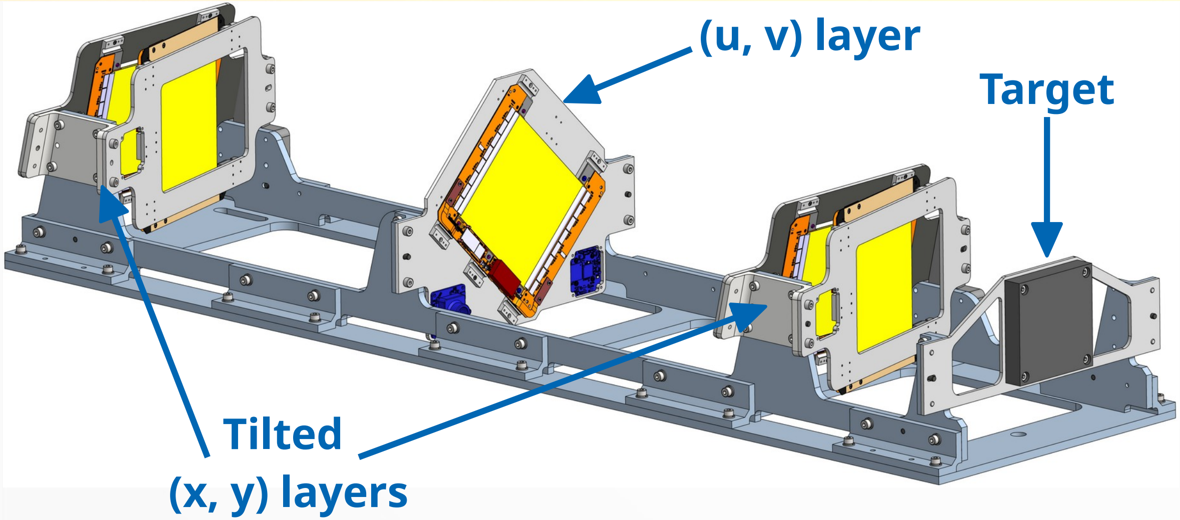






- MUonE location:
  upstream of the AMBER detector
- Spill duration 4.8 s, ~ 25% duty cycle
- $\sim 2\times10^8$ μ^+/spill → $\sim 4\times10^7$ μ^+/s
- Muons **asynchronous** to the DAQ clock

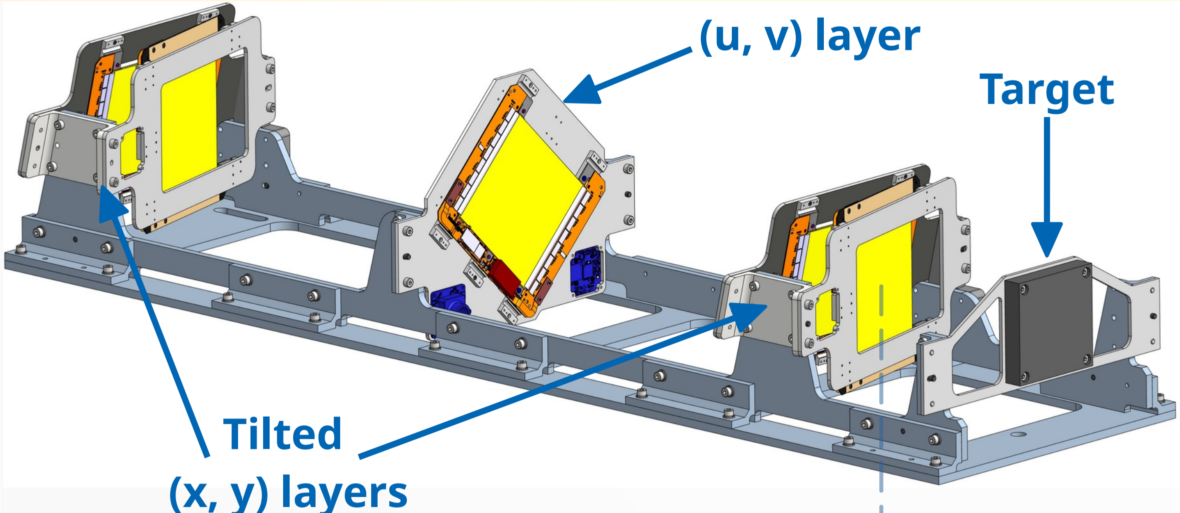
Tracking system



INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

- (x, y) layers:
  tilted by 233 mrad → ~2× hit resolution improvement
- (u, v) layers:
  solve reconstruction ambiguities

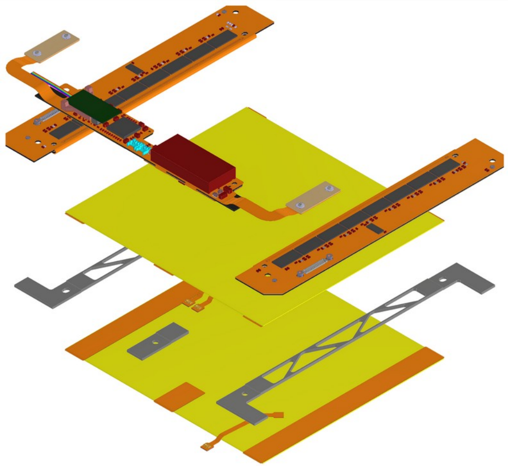
Tracking system



INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

2S modules (CMS Phase2 upgrade)

TDR CMS Tracker Phase2 Upgrade

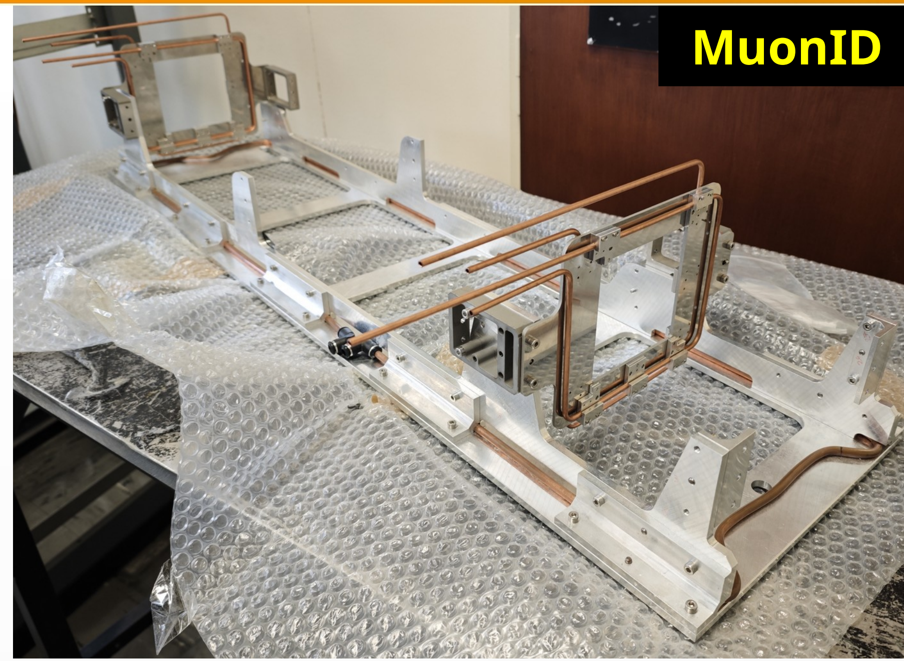


- (x, y) layers:
  tilted by 233 mrad → ~2× hit resolution improvement
- (u, v) layers:
  solve reconstruction ambiguities

- ~90 cm^2 active area
- 2 × 320 μm thickness
- 40 MHz, binary readout
- 90 μm pitch
  (~26 μm hit resolution)

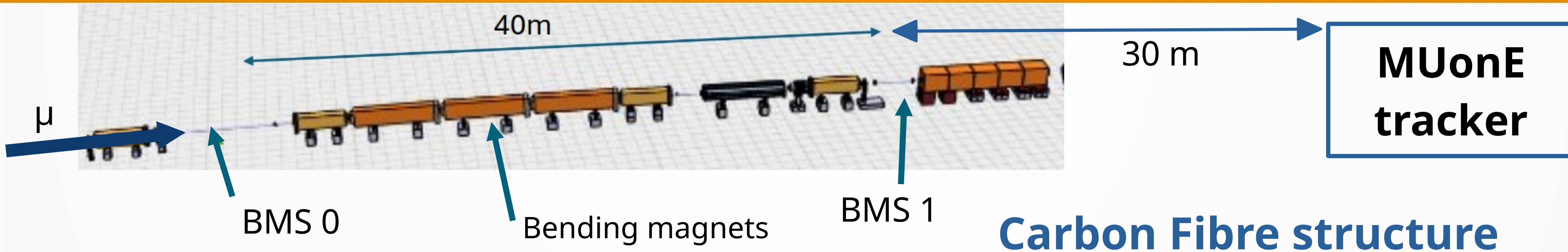
Calorimeter & MuonID: E_e + PID

- 5x5 $PbWO_4$ crystals (CMS ECAL)
  - area: 2.85×2.85 cm^2
  - length: 23 cm (~25 X_0)
- Total ECAL area: ~14×14 cm^2
- Readout: 10x10 mm^2 APD



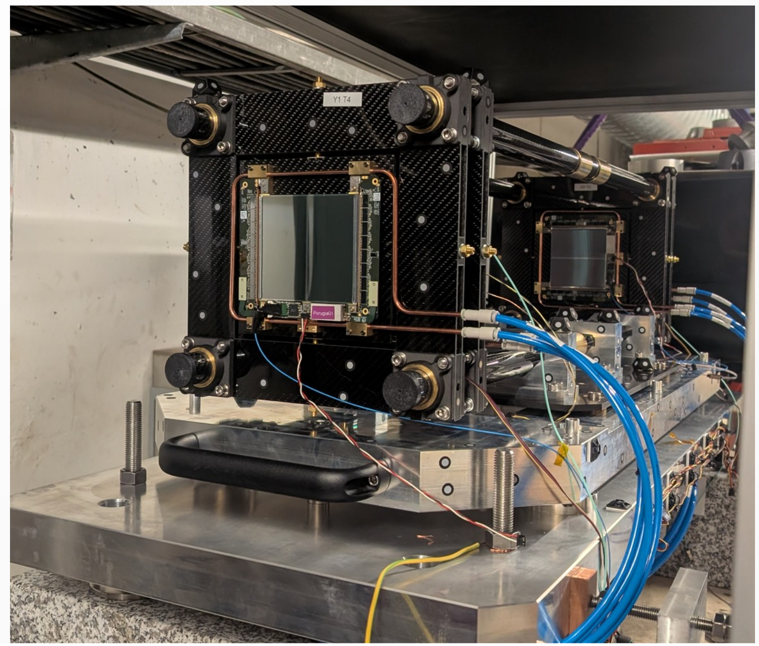
- Aluminum tracking station
- 4×2S modules (2 non-tilted XY pairs)
- Alternative solution R&D: scintillating fibres

BMS (Beam Momentum Spectrometer)



- Bending power: 16 T*m
  (30 mrad @160 GeV)
- Two tracking stations before/after bending magnets to measure deflection
- Proof of concept in 2025.
  First analysis ongoing. Challenges:
  - Alignment
  - B-field monitoring

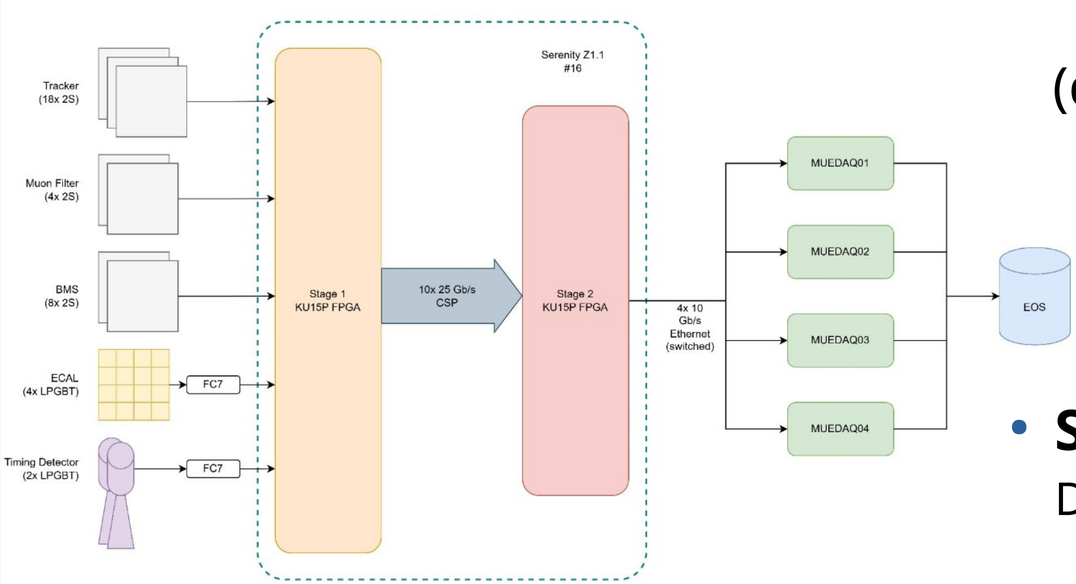
Carbon Fibre structure



×2

Each tracking station 1 m long
2 (x, y) non-tilted layers

DAQ system

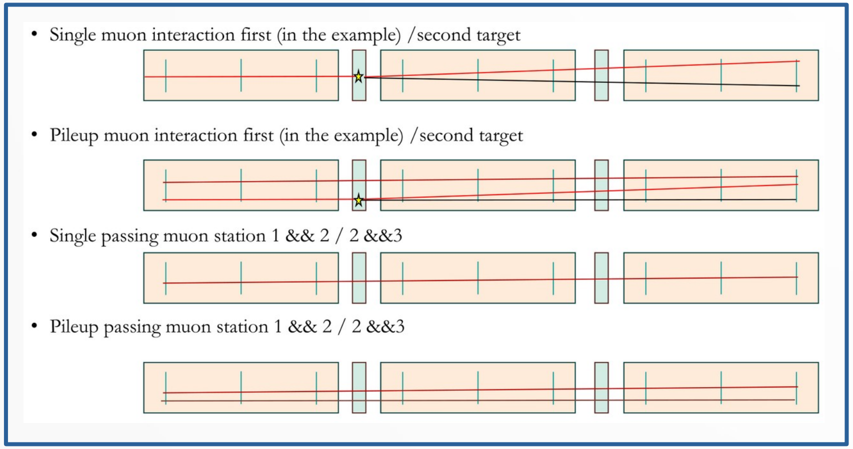


Based on the Serenity platform
(developed for CMS Phase-2 Upgrade)

Two stages firmware design
triggerless readout @40MHz

- **Stage 1:**
  Data aggregation per sub-detectors:
  - 3×tracking stations
  - MuonID
  - ECAL
  - 2×BMS
  - Timing detectors
- Online selection based on tracker occupancy
  Event rate reduced from 40 MHz to ~500 kHz
- **Stage 2:**
  event building, grouping information from all sub-detectors in time-coherent packets

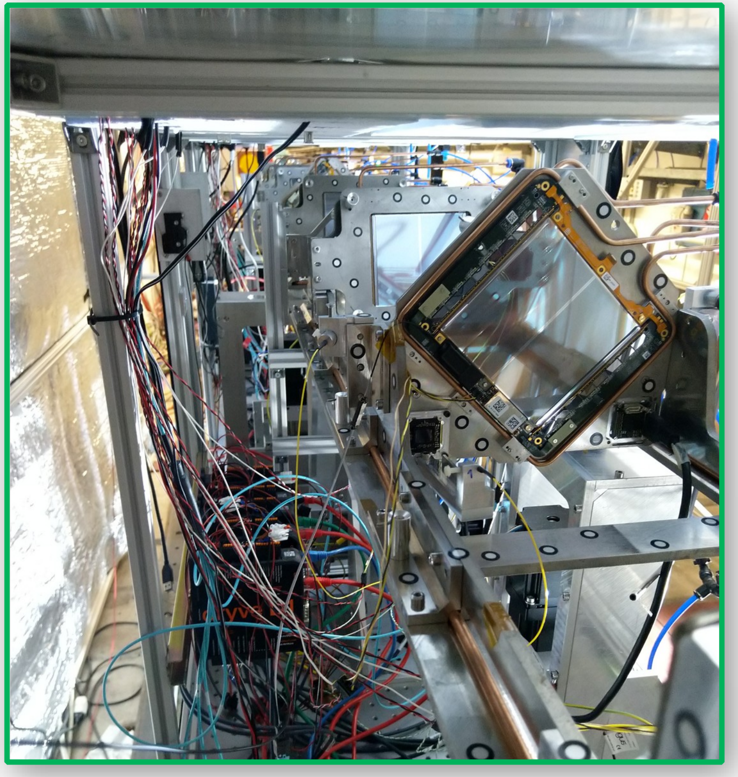
Online trigger event topologies

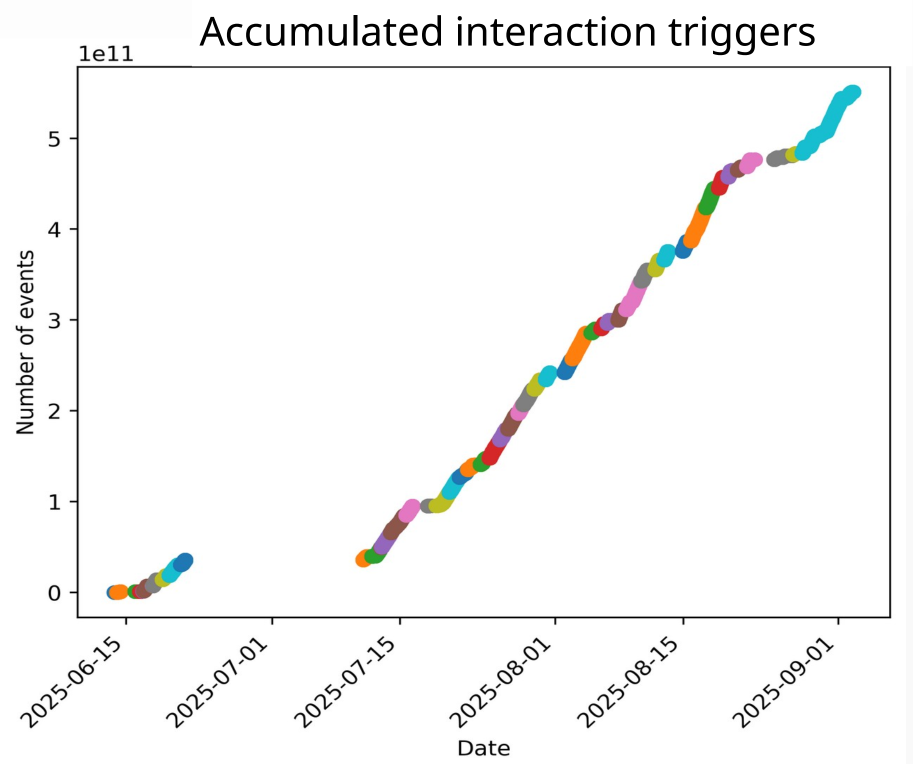


Phase-1 final statistics

3-months data taking (June-August 2025)

- more than 5×10^{11} interaction triggers recorded (~500 TB disk space)
- ~10^8 elastic scattering events after selection

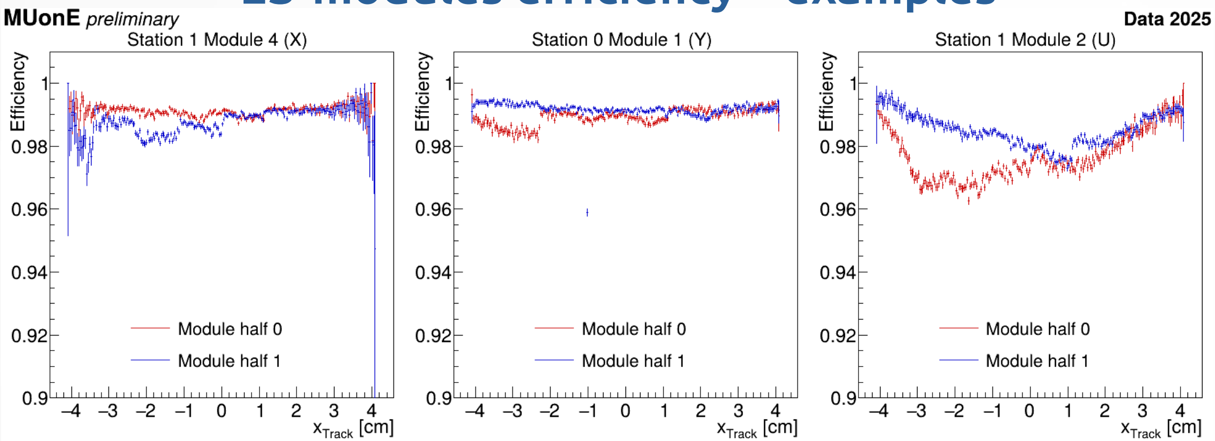




Tracking performance – efficiency

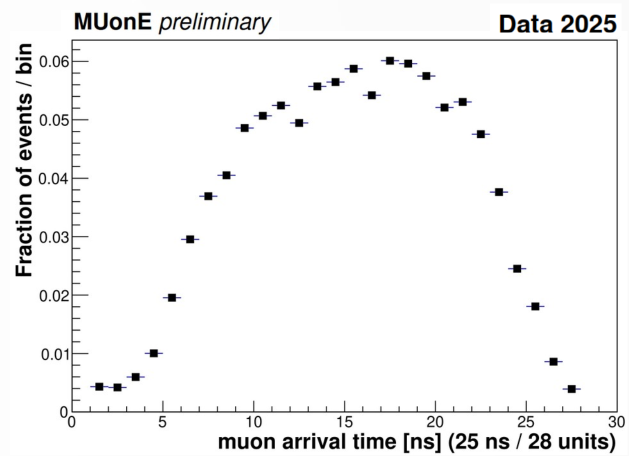
Paper about 2S-modules performance in preparation
(joint paper with the CMS tracker group)

2S-modules efficiency – examples



- Typical average efficiency: ~98%-99%
- Space uniformity: ~0.3%-0.6%.
  Steps due to non-optimal threshold equalisation across different chips
- Spatial profiles included in MC to account for non-uniformities

Effects of the asynchronous beam on the efficiency



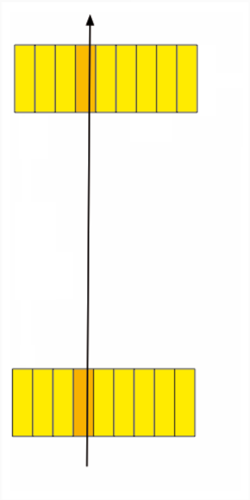
- Timing detector used to correlate the efficiency with particles arrival time
- Efficiency loss at clock edges
- Modules efficiency is ~99.5% if in-time particles are selected

Tracking performance – resolution

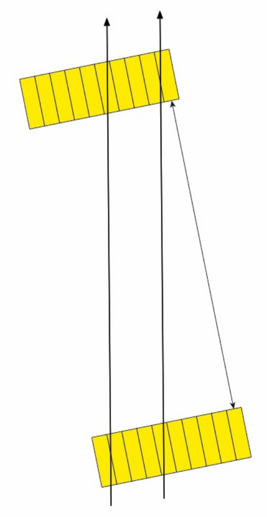
Paper about 2S-modules performance in preparation

(joint paper with the CMS tracker group)

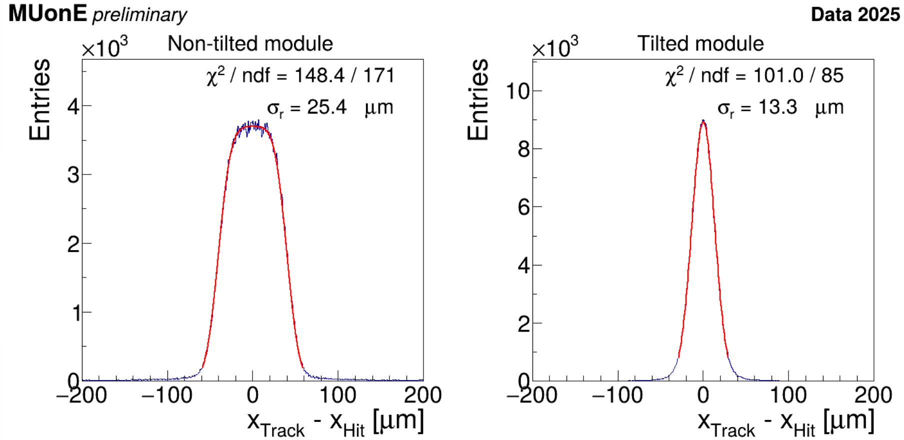
Non-tilted module

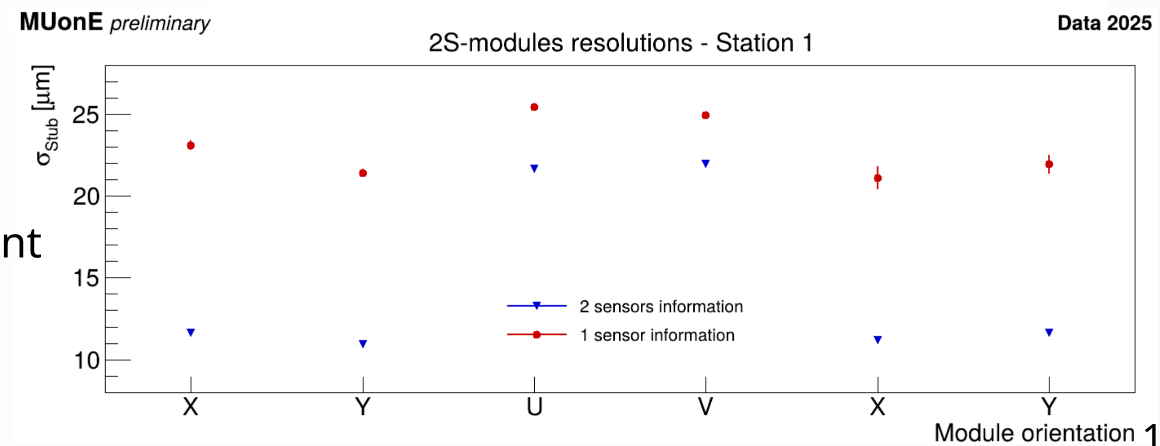


Tilted module



2S-modules residuals – examples





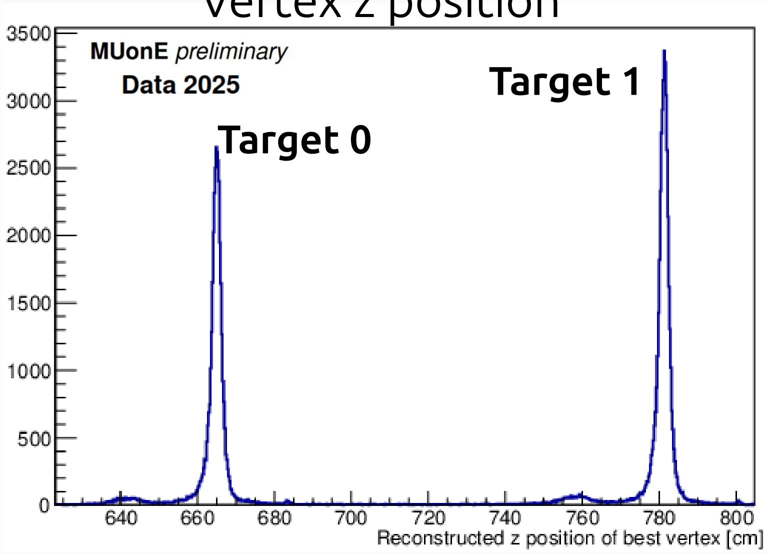
- Tilting the 2S-modules: two uncorrelated position measurements → resolution improvement
- **Non-tilted modules (UV): σ_{hit} ~ 22 µm**
- **Tilted modules (XY): σ_{hit} ~ 12 µm**

Elastic scattering events

Tracker event selection

- 1 incoming track, 2 outgoing tracks
- No shared hits between tracks
- No extra hits in the stations
- Reject non-planar events (background suppression)

Vertex z position



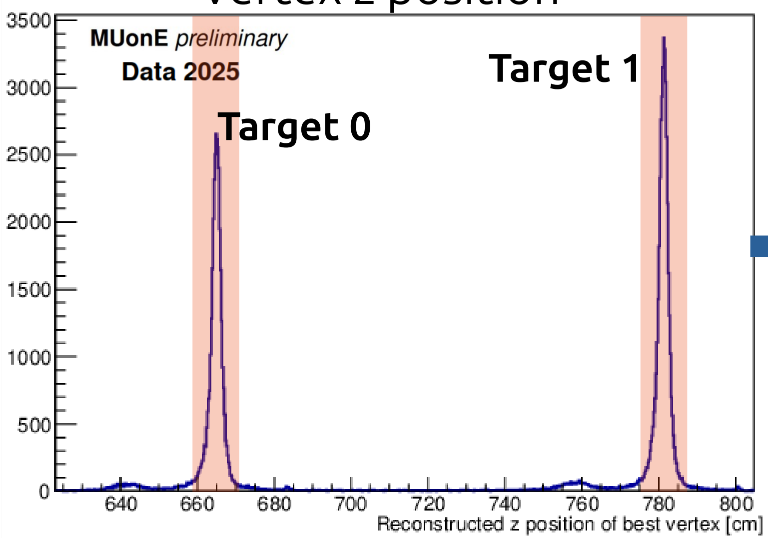
Elastic scattering events

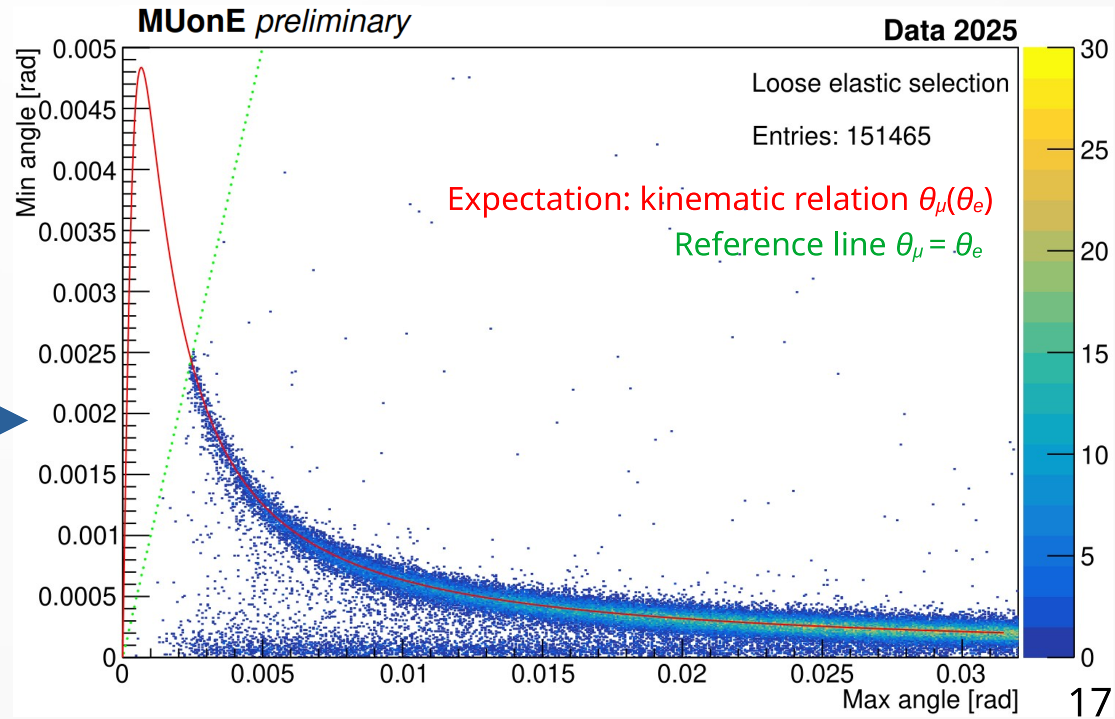
Tracker event selection

- 1 incoming track, 2 outgoing tracks
- No shared hits between tracks
- No extra hits in the stations
- Reject non-planar events (background suppression)

Not able to discriminate between μ and e^-: plot θ_{max} vs θ_{min} to avoid misidentification when $\theta_e < 5$ mrad

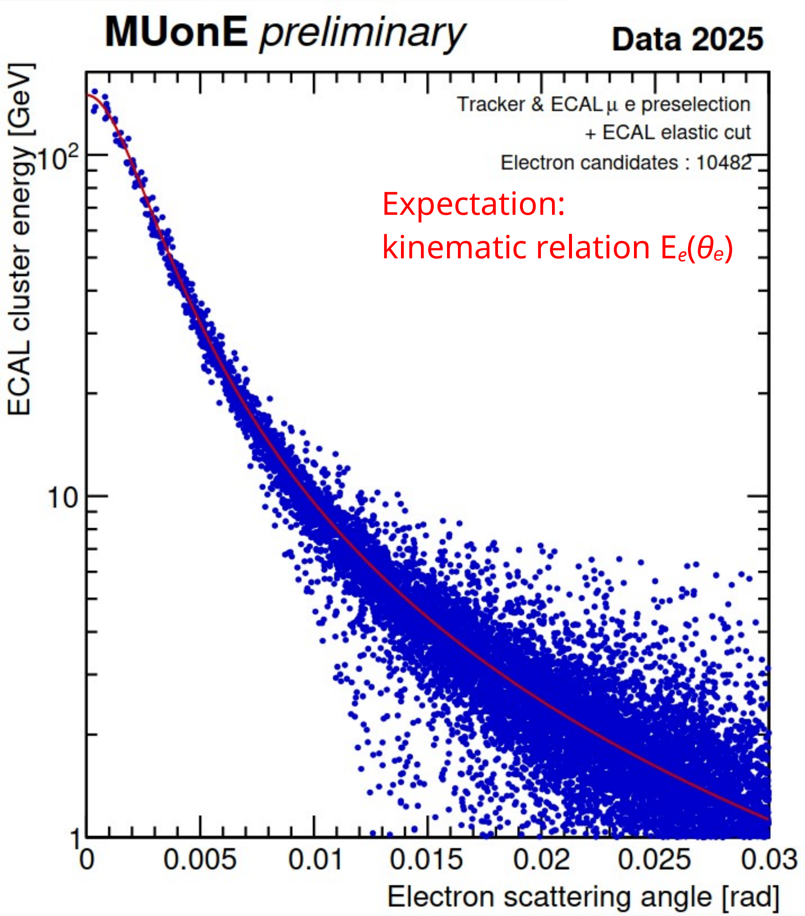
Vertex z position

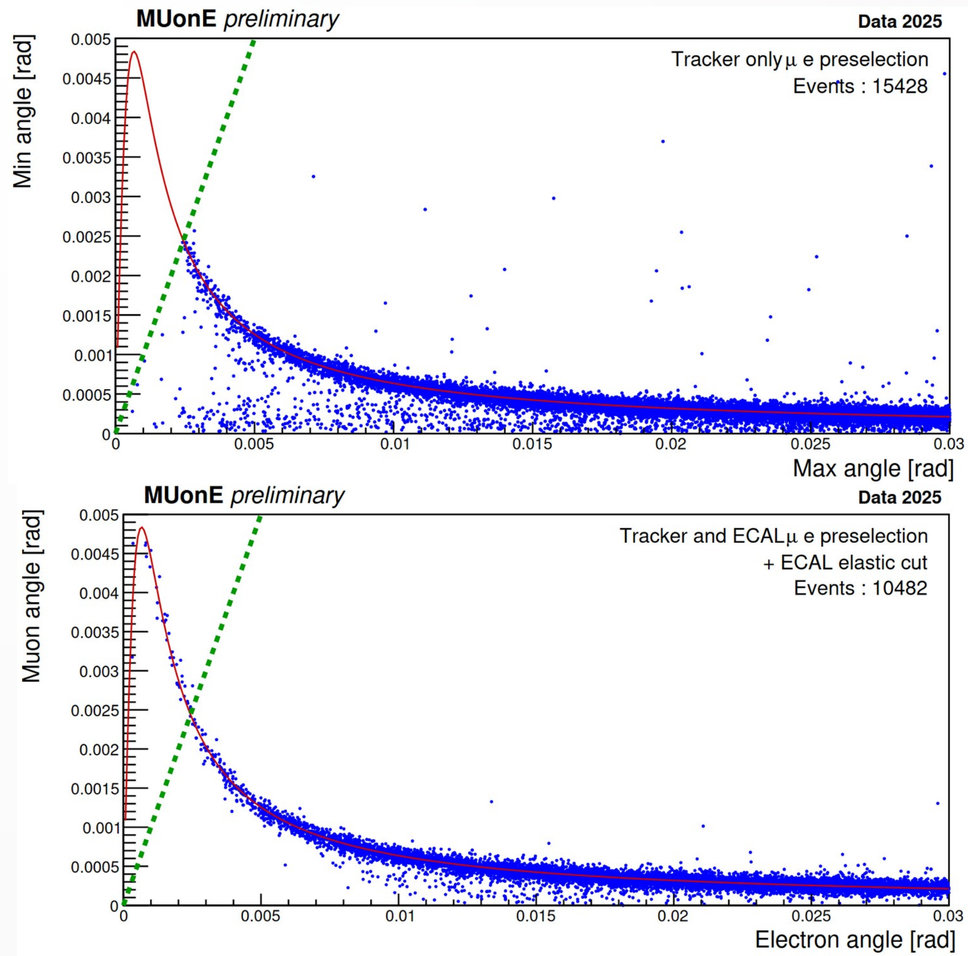




ECAL-based PID

Correlation between ECAL energy deposit and θ_e reconstructed in the tracker

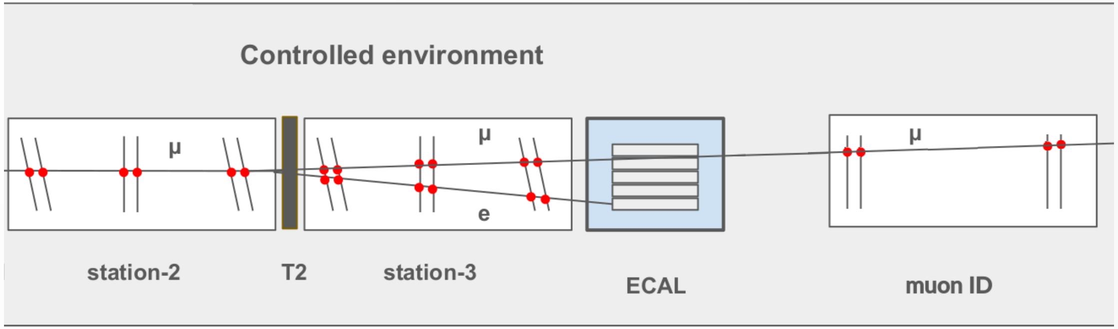




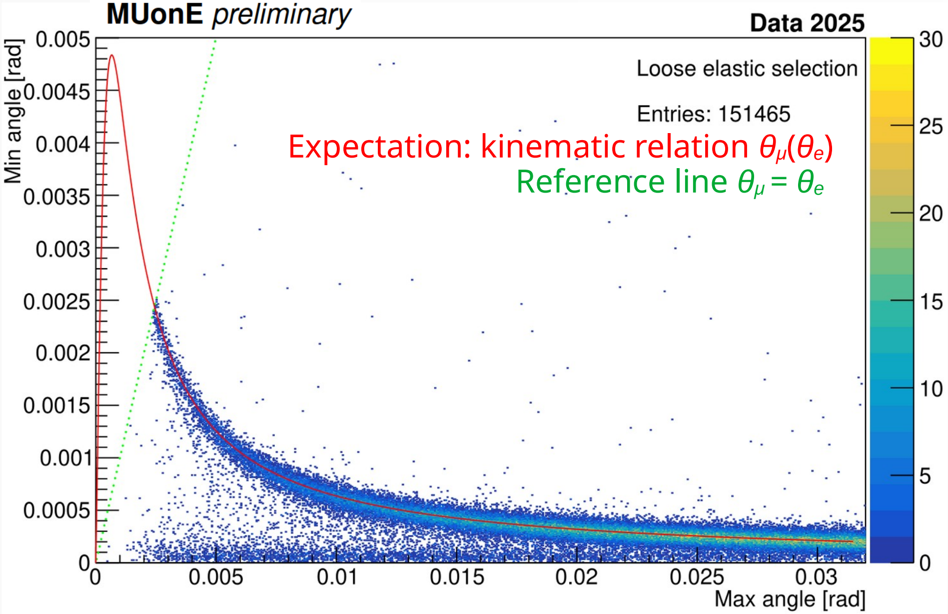
- ECAL energy > 1 GeV
- Loose elastic selection
- Matching between candidate e^- track and ECAL cluster centroid

Muon ID-based PID

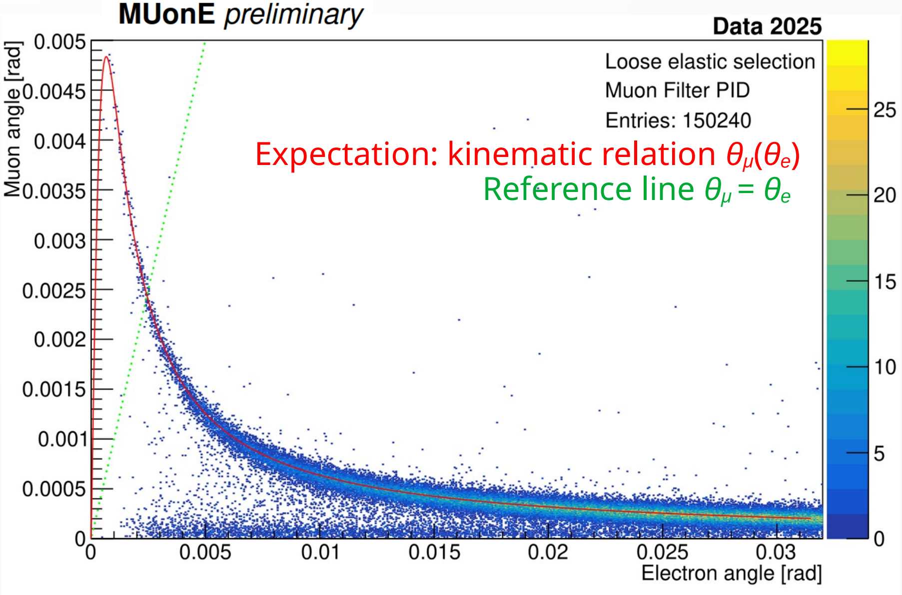
- Propagate tracks to the Muon ID
- Look for matching between a track and muon ID hits: select the muon track



Tracker-only event selection



Tracker-only event selection + muon ID-based PID



Conclusions and outlook

MUonE web site

- 2025 Test Run: 3 months data taking.
  Tested operations of all sub-detectors with a scaled version of the final apparatus.

- Paper about 2S-modules performance in preparation.

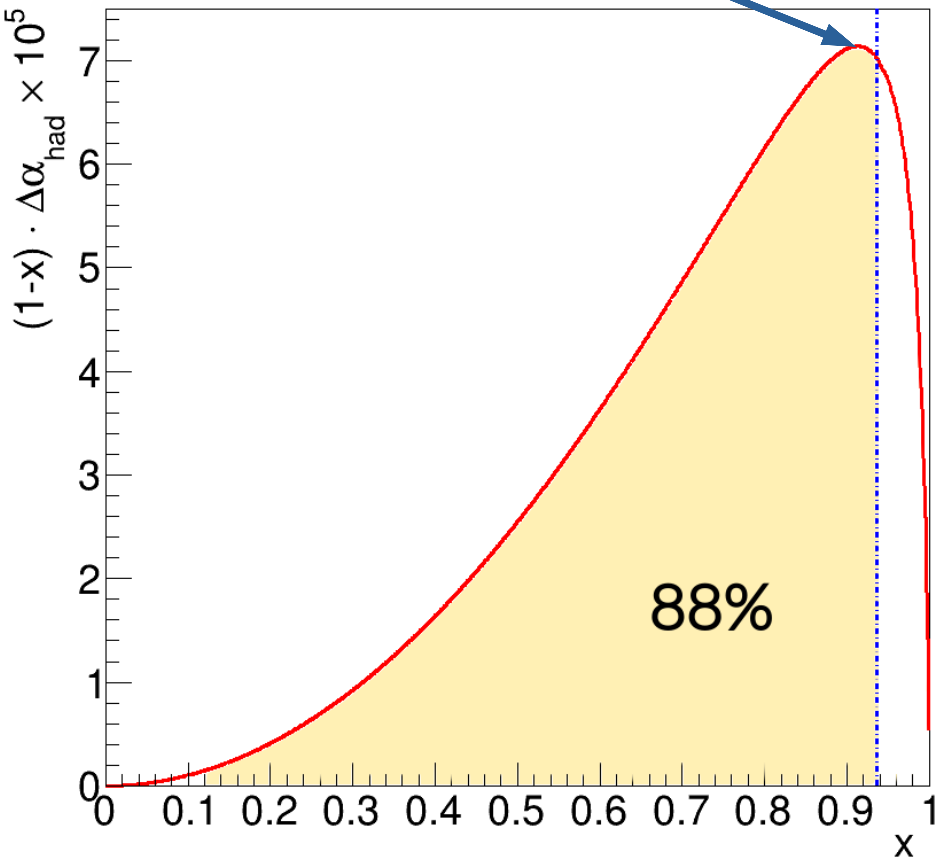
- Analysis campaign underway
  - Huge effort to improve the MC simulation (2S-modules electronics response, realistic beam profile, asynchronous beam effects…)
  - First data/MC comparison expected in the next months using a fraction of the total dataset, corresponding to ×50 more statistics than data analysed in 2023.
  - Goals: proof of principle measurement of $\Delta\alpha_{lep}(t)$; preliminary measurement of $\Delta\alpha_{\mathrm{had}}(t)$ targeting $O(20\%)$ precision; systematic effects assessment.

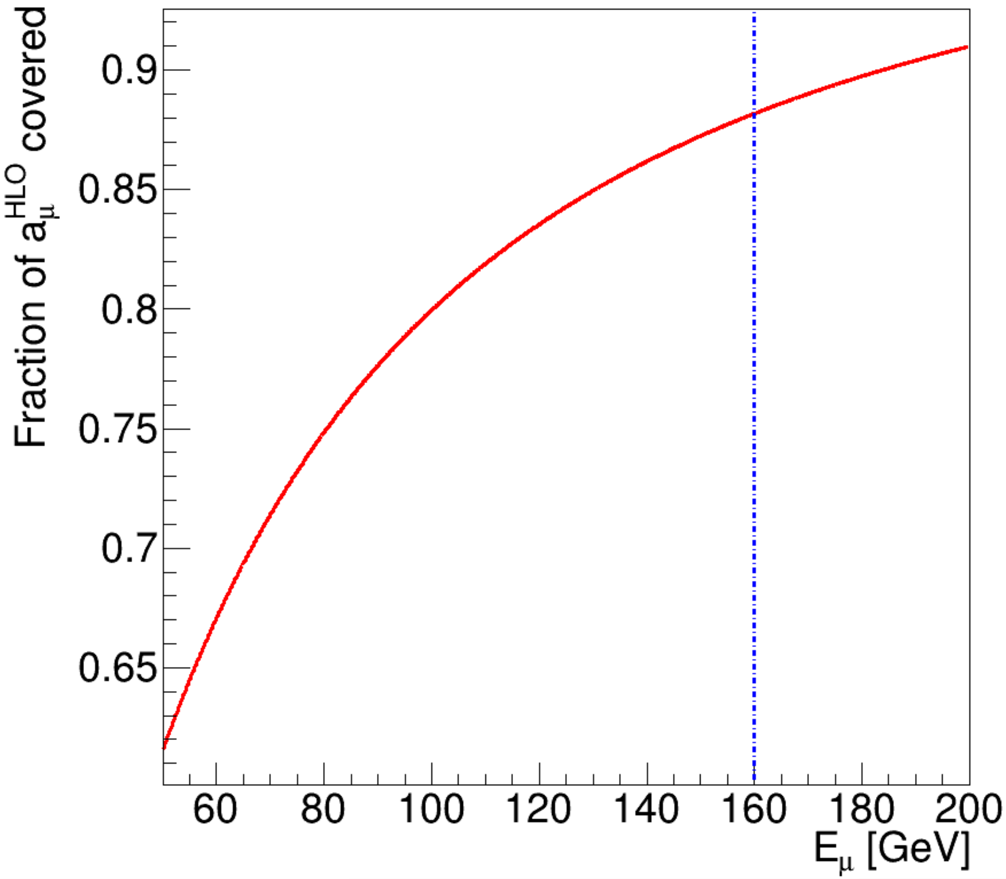
- Full-scale experiment proposal (40 tracking stations + ancillary detectors) to be prepared during CERN LS3 based on 2025 results.

BACKUP

$$x < 0.936$$

$t_{peak} \sim -0.108\ \text{GeV}^2$ $x_{peak} \sim 0.92$



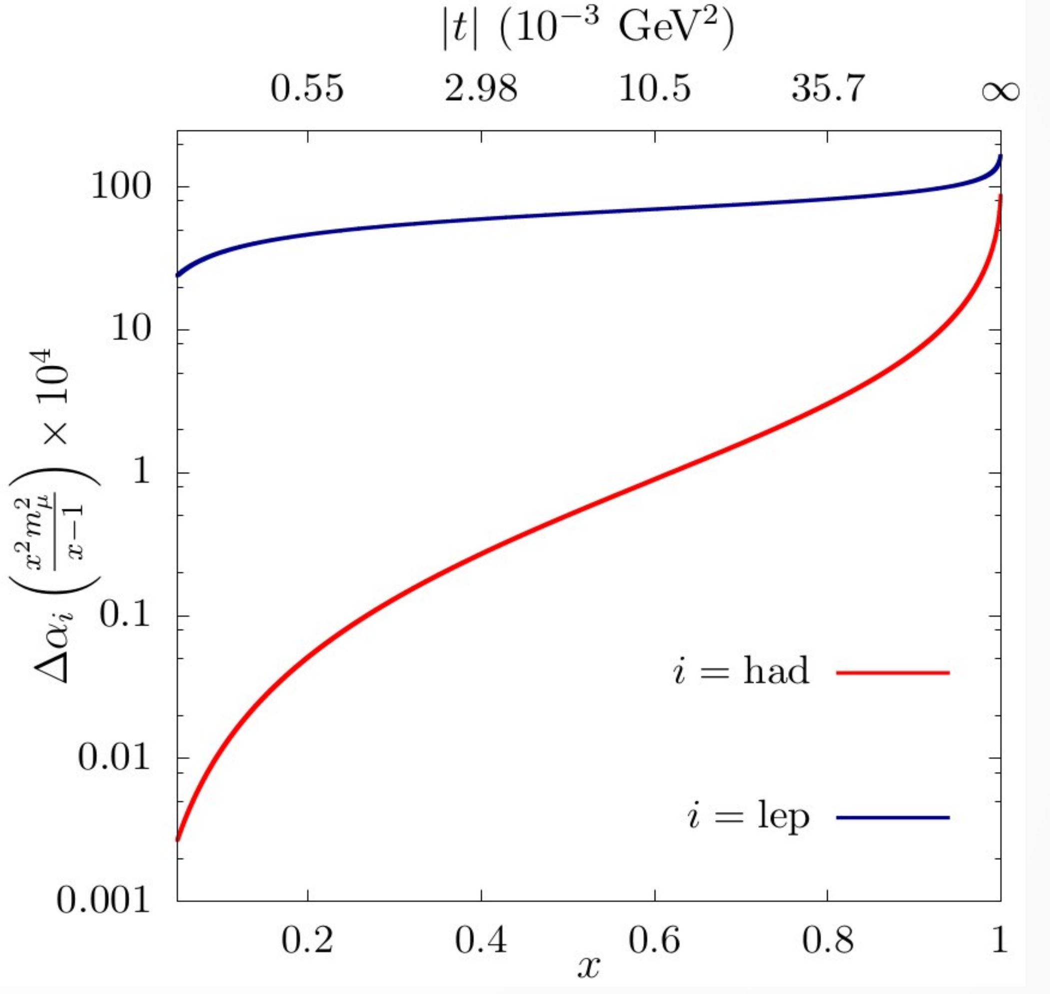


- 160 GeV muon beam on atomic electrons.

$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



$\Delta\alpha_{had}$ parameterization

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

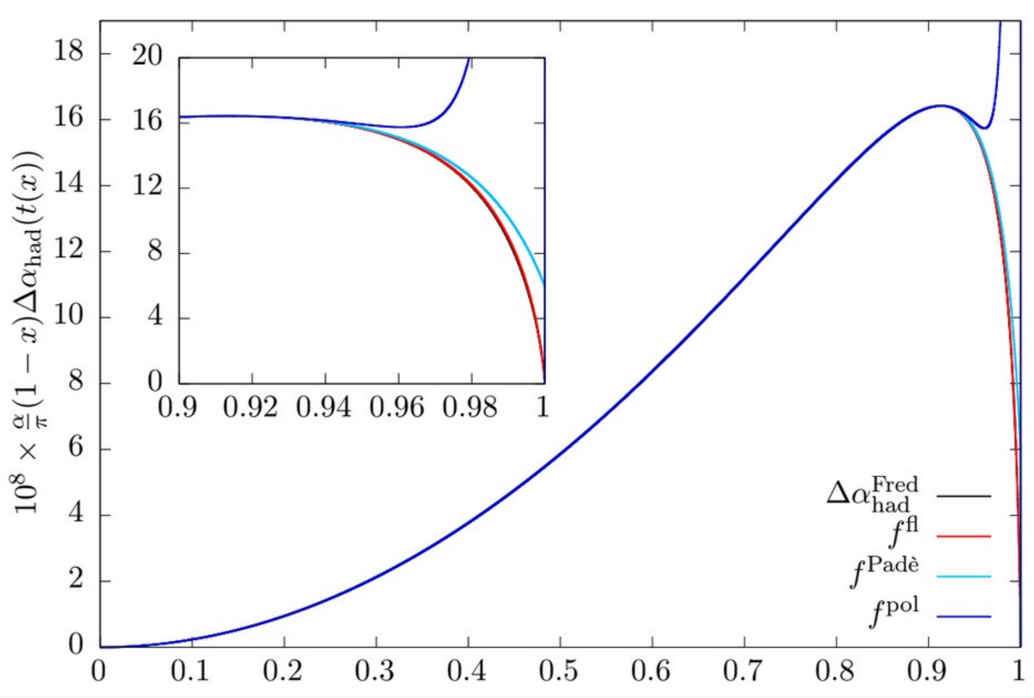
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

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

Dominant behaviour in the MUonE kinematic region:

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



Alternative method to compute $a_\mu^{\mathrm{HVP,LO}}$ from MUonE data

Based on **Phys. Rev. D 85 (2012)** **Phys. Rev. D 96 (2017)** **Phys. Lett. B 848 (2024)**

Start from the dispersive integral

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{\infty}\frac{ds}{s}K(s)R(s)$$

Approximated kernel + Cauchy theorem to remove the problematic low energy part

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO\,(I)}} + a_\mu^{\mathrm{HLO\,(II)}} + a_\mu^{\mathrm{HLO\,(III)}} + a_\mu^{\mathrm{HLO\,(IV)}}$$

$$a_\mu^{\mathrm{HLO\,(I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

MUonE 99%

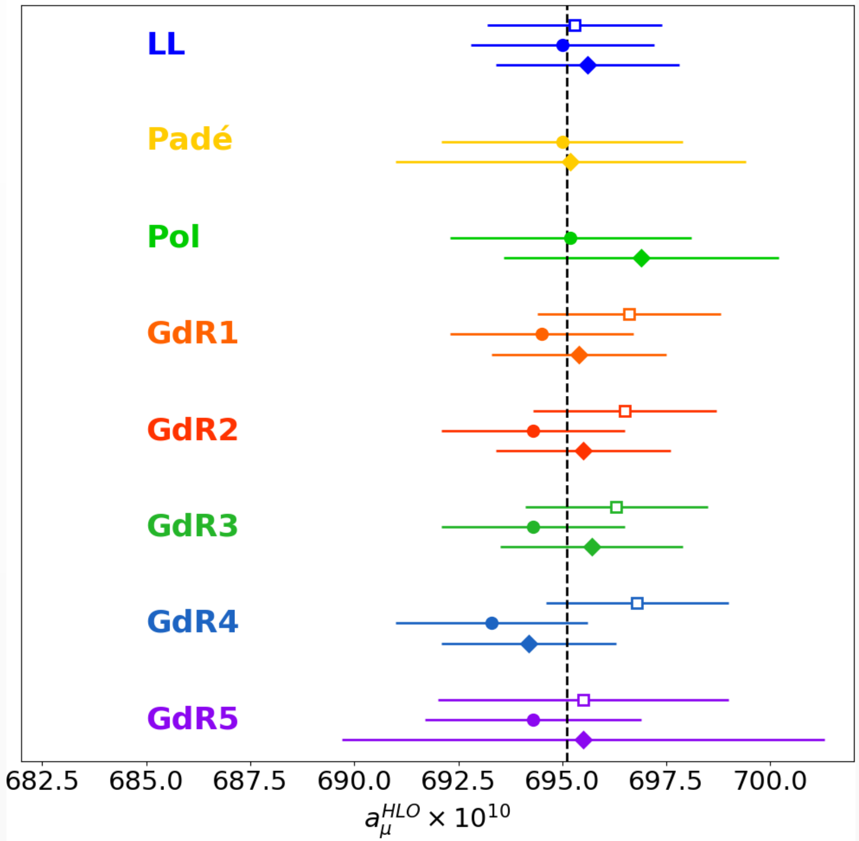
$$a_\mu^{\mathrm{HLO\,(II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO\,(III)}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s)-K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO\,(IV)}} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s)-\tilde{K}_1(s)]R(s)$$

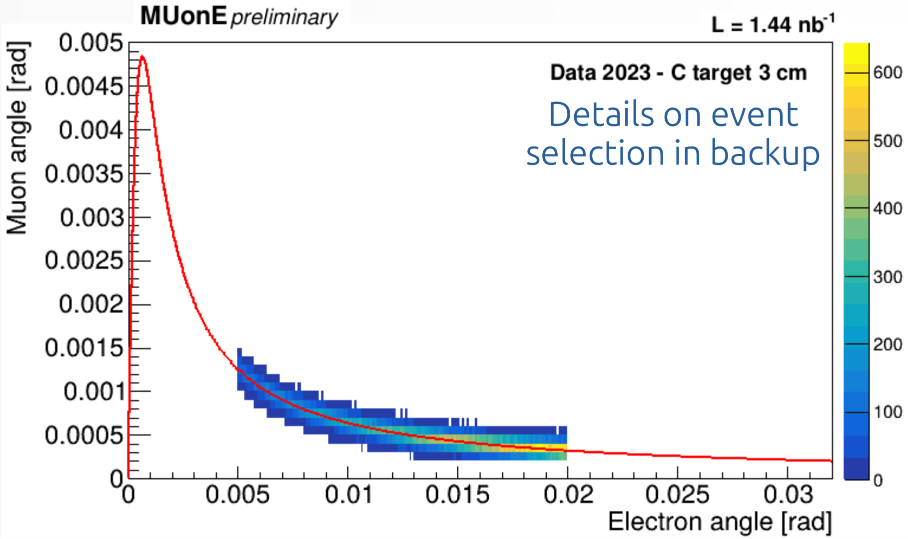
Time-like data + pQCD 1%

Competitive results independently of the $\Delta\alpha_{\mathrm{had}}(t)$ parameterization



Test Run 2023 – Data/MC comparison

Select elastic events in a clear region



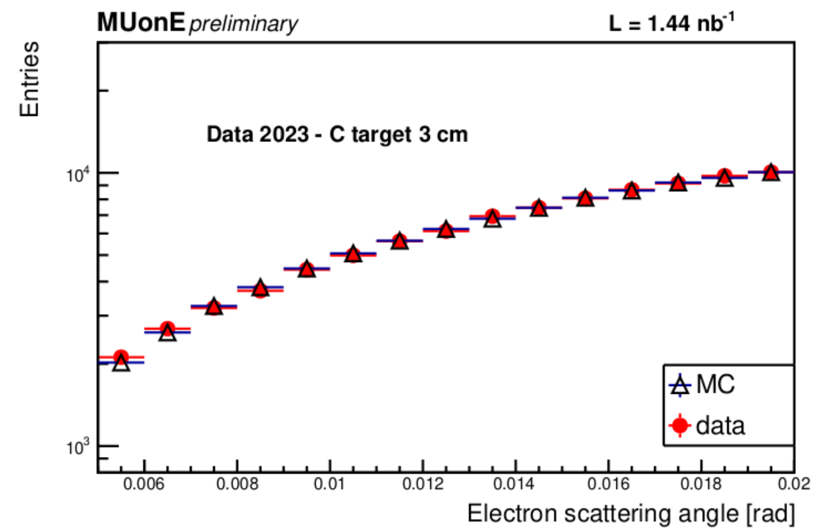
Details on event selection in backup

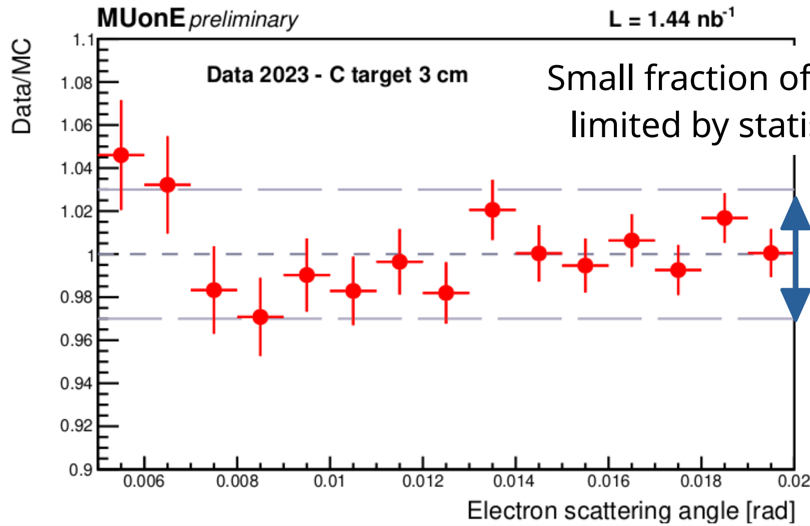
Count N_μ on target → luminosity estimate

Data/MC comparison of the cross section within event selection:

$$\sigma_{data} = (75.1 \pm 3.1)\ \mu b$$

$$\sigma_{MC} = (77.75 \pm 0.14)\ \mu b$$





Small fraction of data: limited by statistics

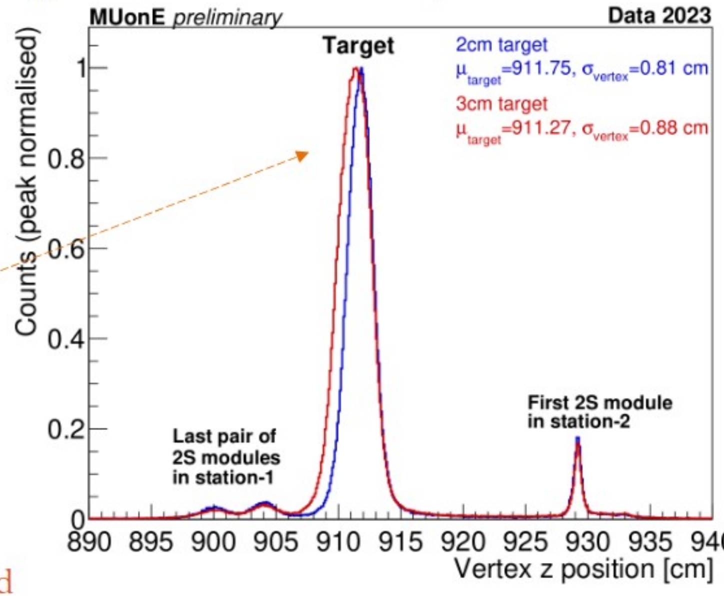
Data-MC comparison of elastic events

Data sample: **run 6** → 97×10^6 events **after skimming** to be reconstructed

MC sample: MESMER generated signal elastic events → 16.5×10^6 to be reconstructed with **realistic misalignment scenario** (simulated geometry from real metrology followed by track-based alignment as with real data)

Fiducial selection:

- $N_{hits_{S0}} = 6$ → 1 per module: golden muon (GM);
- GM impinges last 2 modules in S0 within $\pm1.5\ cm$ from centre in X and Y ;
- Reconstructed GM with $\theta < 4\ mrad$.



Elastic selection:

- $N_{hits_{S1}} \leq 15$;
- Reconstructed Z vertex $> 906\ cm$;
- $\theta_\mu > 0.2\ mrad, 5 < \theta_e < 20\ mrad$;
- Acoplanarity $|A_\phi| < 0.4\ rad$;
- Elasticity condition: $|\theta_\mu - \theta_\mu^{exp}(\theta_e)| < 0.2\ mrad$

>0.2 mrad: main background removed

>5 mrad: Avoid ambiguities in PID

<20 mrad: region less affected by systematics

$$\theta_\mu^{exp}(\theta_e) = \arcsin\left\{\sin\theta_e\sqrt{\frac{E_e^2(\theta_e)-m_e^2}{[E_\mu+m_e-E_e(\theta_e)]^2-m_\mu^2}}\right\}$$

Absolute luminosity normalization

From the **knowledge of the number of golden muons** (passing the fiducial selection) that can potentially interact in the target, we can estimate luminosity:

Fiducial selection:
$N_{hits_{S0}} = 6 \rightarrow 1$ per module: golden muon (GM);
GM impinges last 2 modules in S0 within $\pm 1.5\ cm$ from centre in X and Y ;
Reconstructed GM with $\theta < 4\ mrad$.

Luminosity **real data**:

$$L = N_{\mu oT} \cdot d_{target} \cdot \rho^{e}_{target} =$$

Golden muons on target
Target thickness
Electron density target $\rho^{e}_{target} = \rho \cdot \frac{Z}{A} \cdot N_A$

Run 6 $= (1443.0 \pm 8.0)\mu b^{-1}$

Main error on:

$$\rho = (1.83 \pm 0.01) g/cm^3$$

+

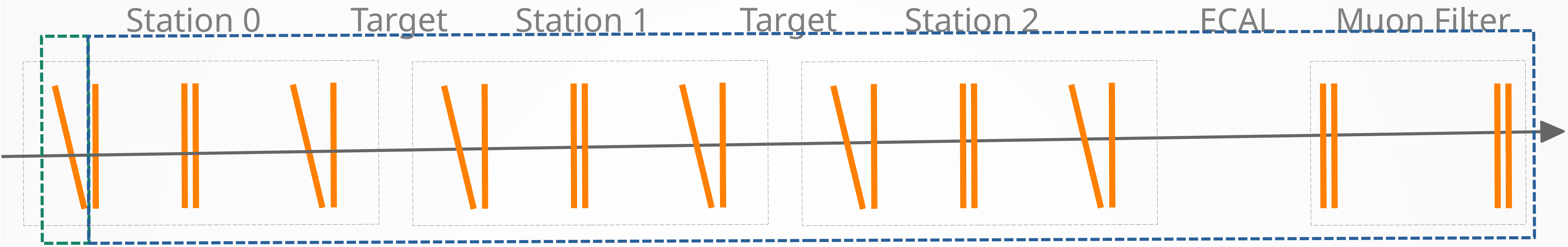
$$d_{target} = (3.000 \pm 0.001)\ cm$$

$$\sigma = \frac{N_{elastic}}{\epsilon_{hw} L}$$

$\epsilon_{hw} = 0.850 \pm 0.035$:
2 tracks reconstruction efficiency which depends on modules efficiency
($\epsilon_{mod} = 0.980 \pm 0.005$)

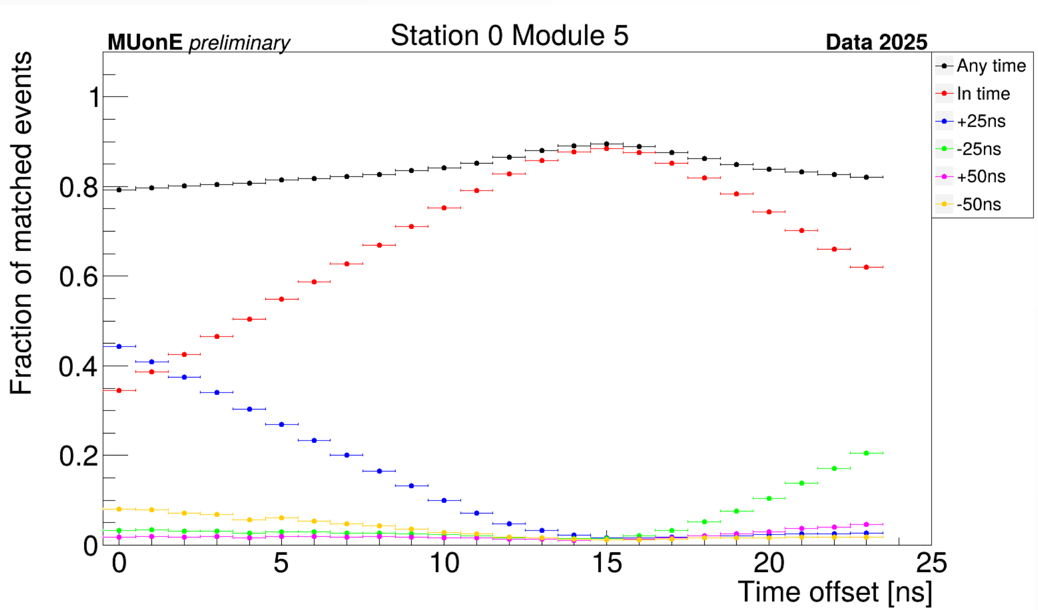
MC selection efficiency on σ_{MC} estimate: 76.5%

TR 2025 – tracker time synchronisation

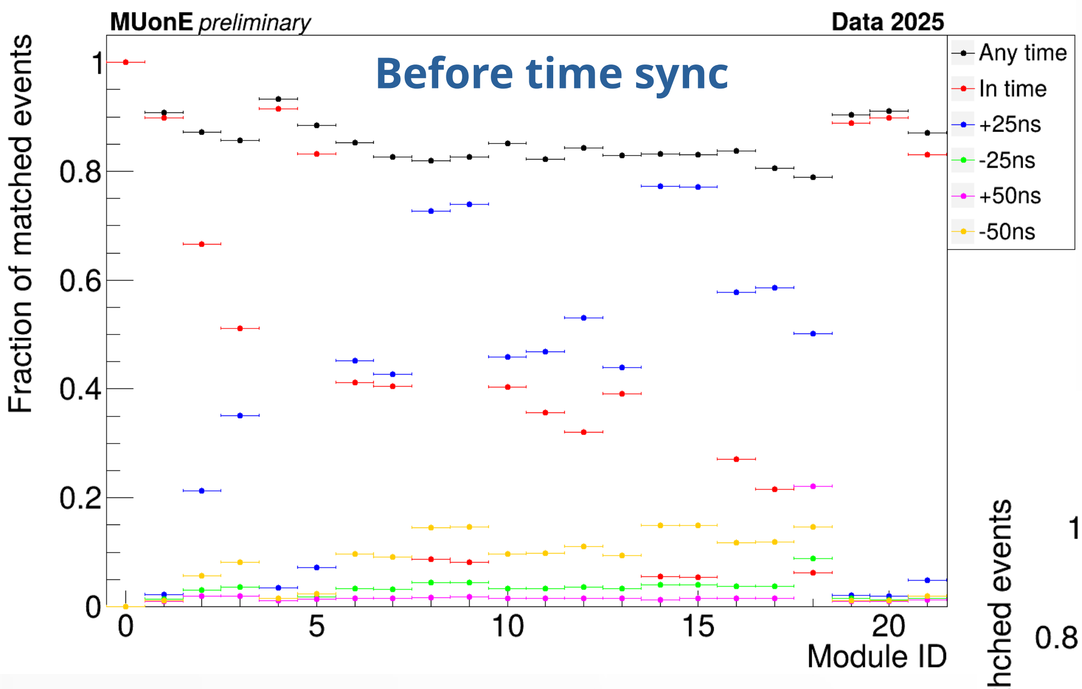


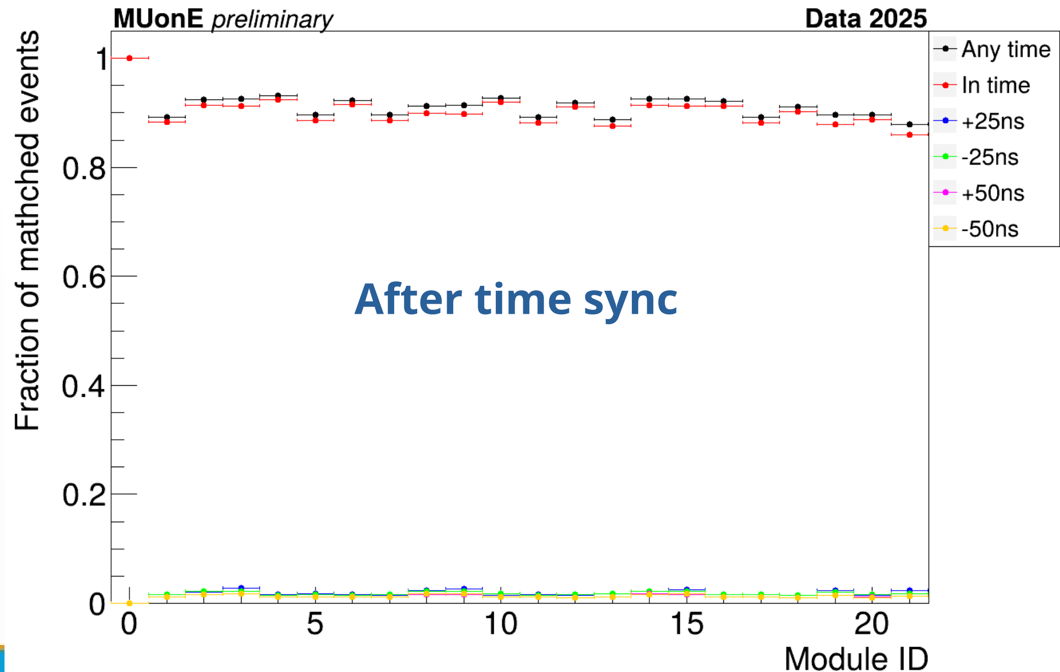
Delay:
12 ns

Delay scanned [0, 24] ns



TR 2025 – tracker time synchronisation





Alignment

- Hardware (stepper motors):

  center the beam profile on each module (< 500 µm)

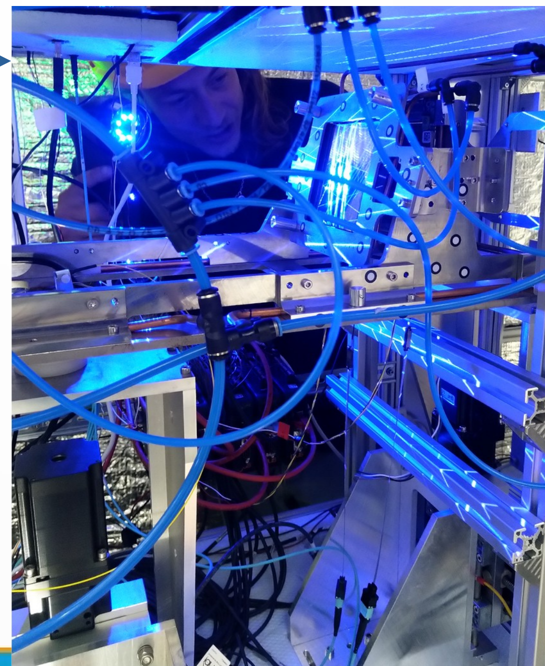
  align the longitudinal axis of each station to the beam axis (< 0.5mrad)

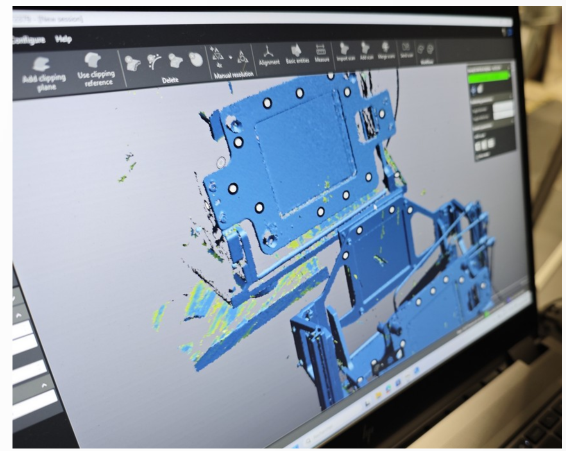
  align the 3 stations one relative to the other (< 200 µm)

- Software: local χ^2 minimization on a sample of single passing muons.

Metrology measurements of the detector (< 100 µm precision)

- 3D scanner photogrammetry: position and orientation of each module within a station
- Laser survey: relative position of the different subdetectors; absolute position with respect to beam elements
- To be used as starting point of software alignment





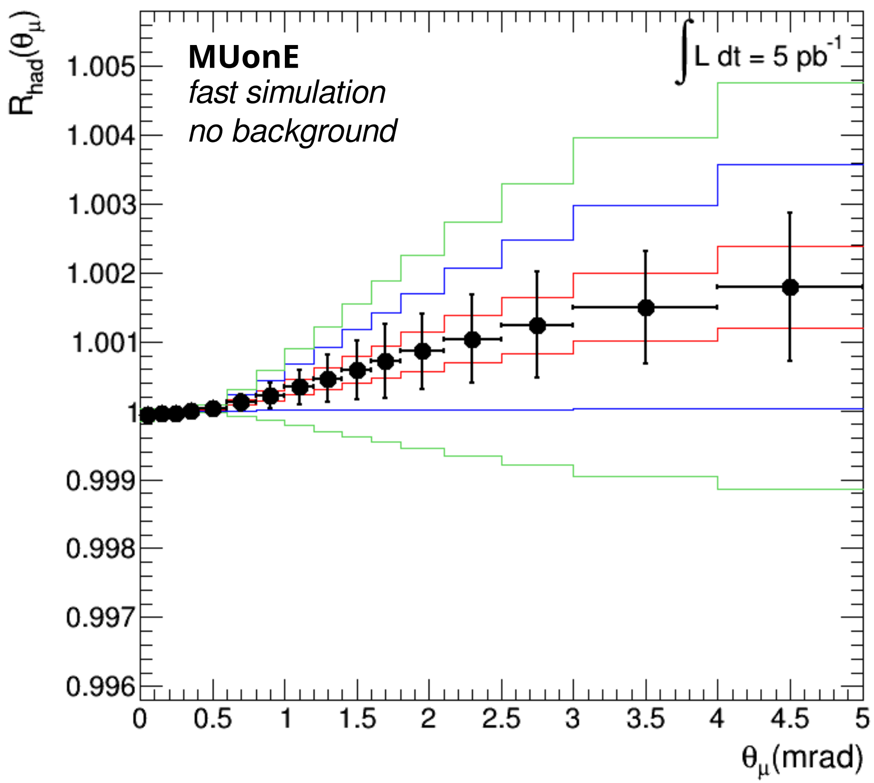
Summary of the main sources of systematic errors and corresponding uncertainties for the 2025 run

Source of systematic error	Uncertainty on the systematic source	Uncertainty on $\Delta\alpha_{had}$	Uncertainty on $d\sigma$
Intrinsic angular resolution	0.5%	10%	200 ppm
Multiple scattering	1%	10%	200 ppm
Beam energy scale	25 MeV	10%	200 ppm
z coordinate	100 μm	10%	200 ppm
Beam energy spread (3.75%)			
current BMS	4% ($\sigma_p/p \sim 1\%$)	1%	20 ppm
upgraded BMS	1% ($\sigma_p/p < 0.5\%$)	$< 0.5\%$	5ppm
Other contributions (i.e. tracking efficiency and reconstruction uniformity, residual background)		15%	300 ppm
Total		**25%**	**500 ppm**

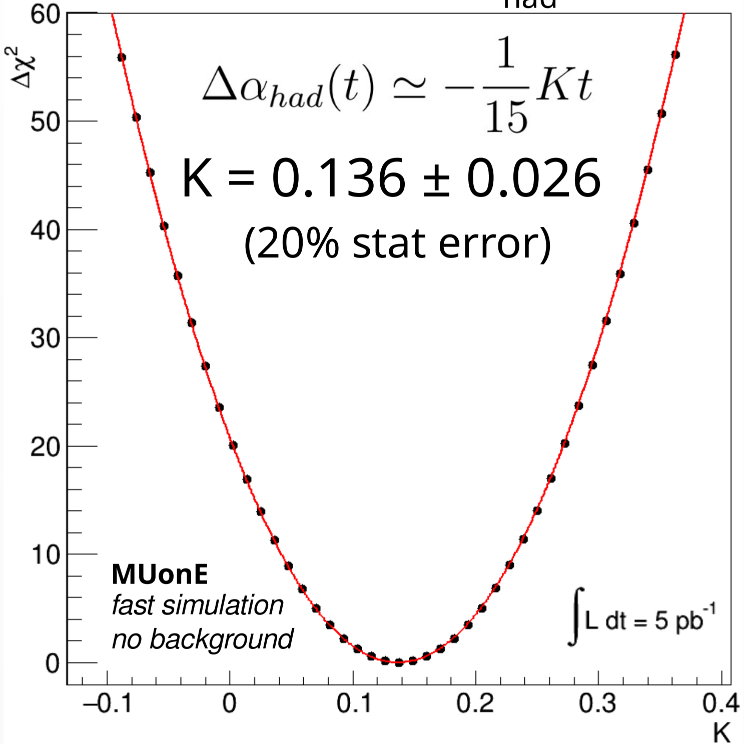
First measurement of $\Delta\alpha_{had}(t)$

Expected event yield: ~10^9 elastic events within acceptance
(one order of magnitude larger than 2023)

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



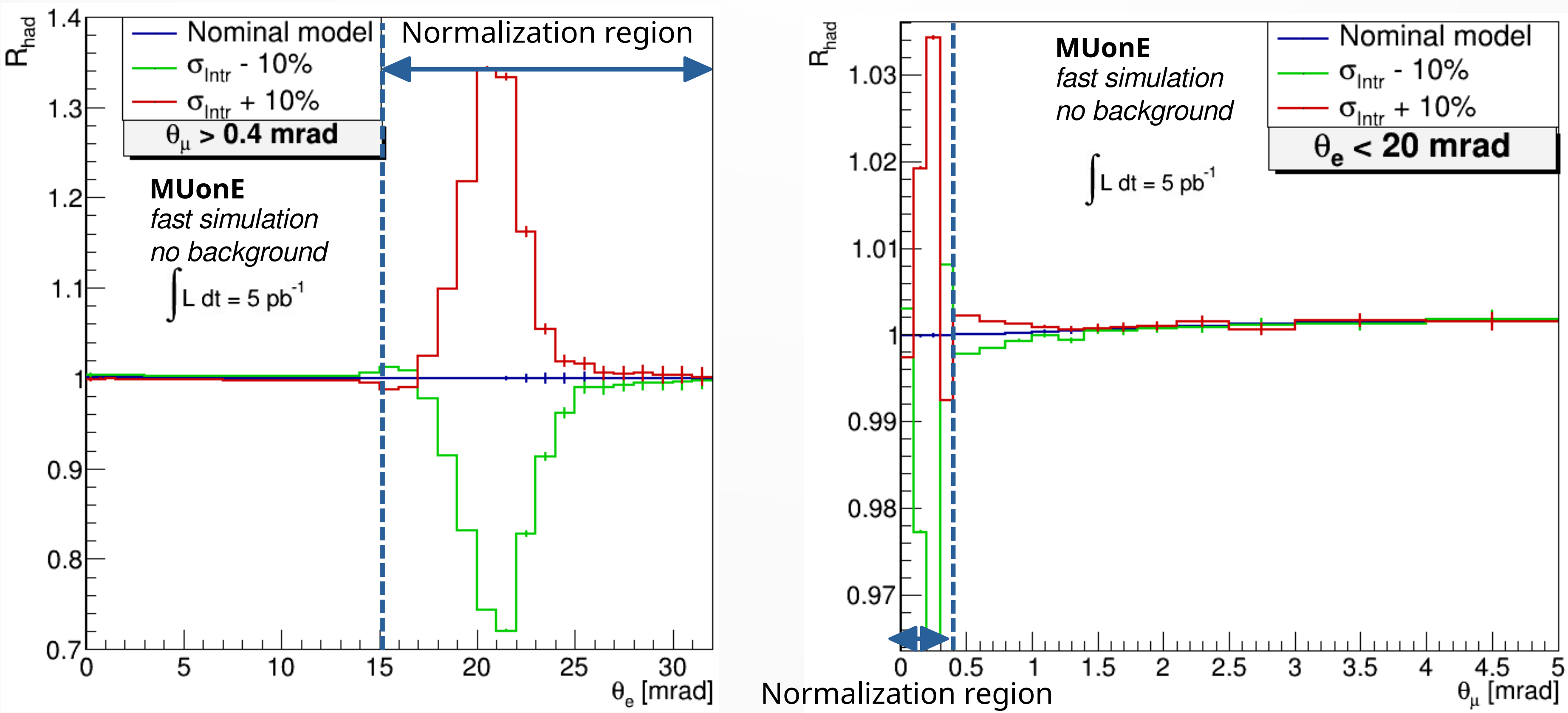
Template fit procedure
to extract $\Delta\alpha_{had}(t)$



The need of including systematic effects in the analysis

Some systematic effects can produce huge distortions in the shape of the elastic scattering cross section

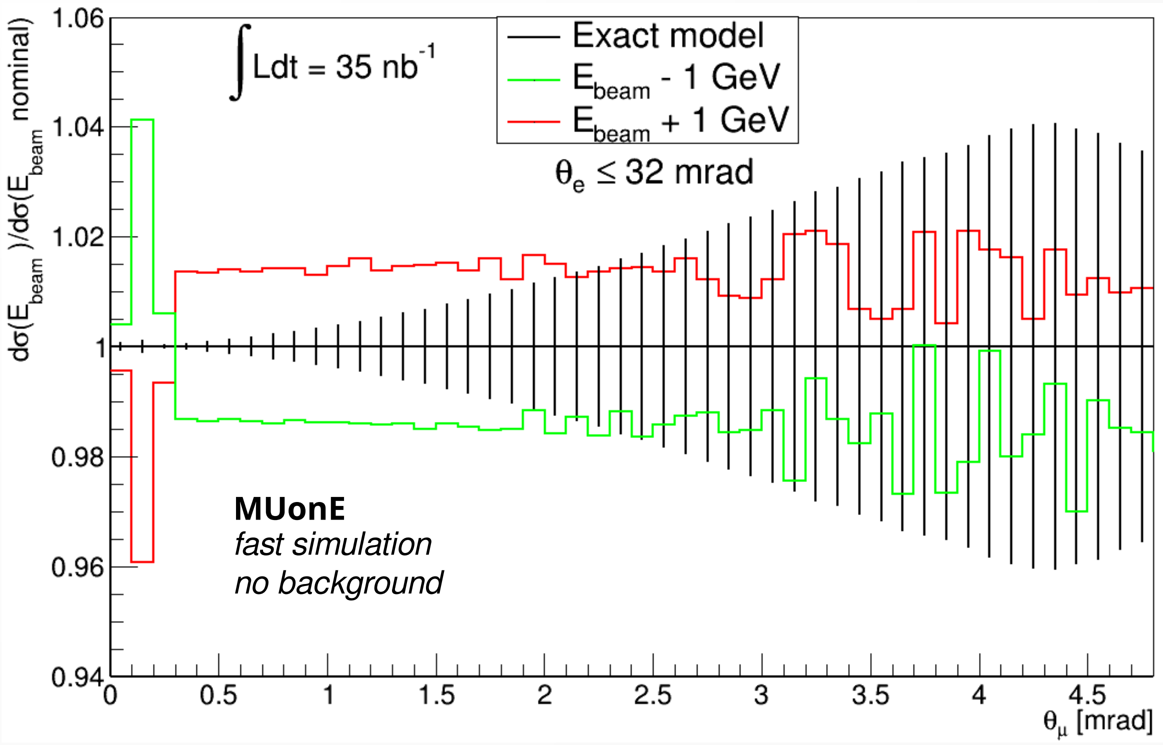
Example: ±10% error on the angular intrinsic resolution



Systematic error on the muon beam energy

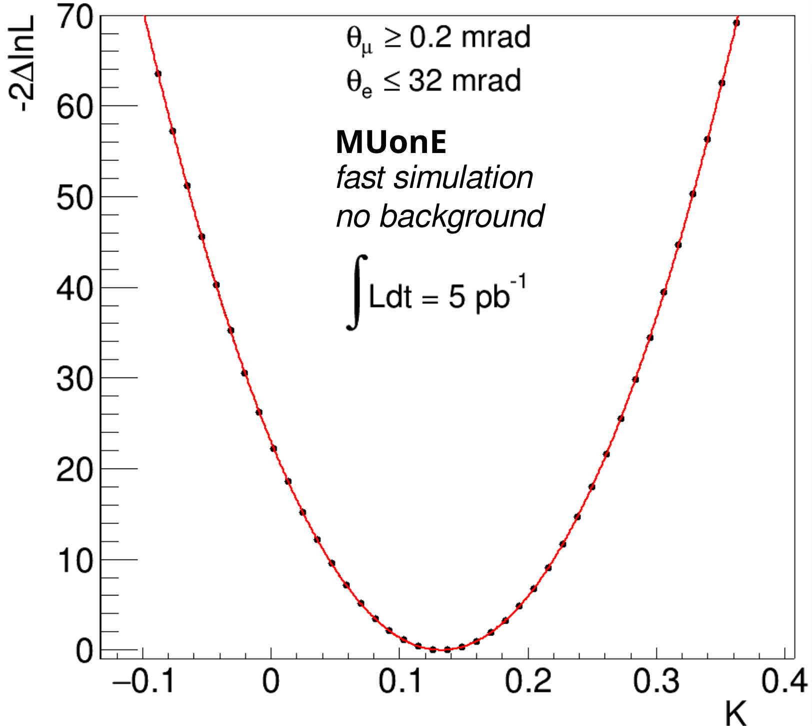
Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV)

This effect can be seen from our data in 1h of data taking per station



Combined fit
signal + systematics

- Include residual systematics as nuisance parameters in the fit.
- Simultaneous likelihood fit to K and systematics using the Combine tool.



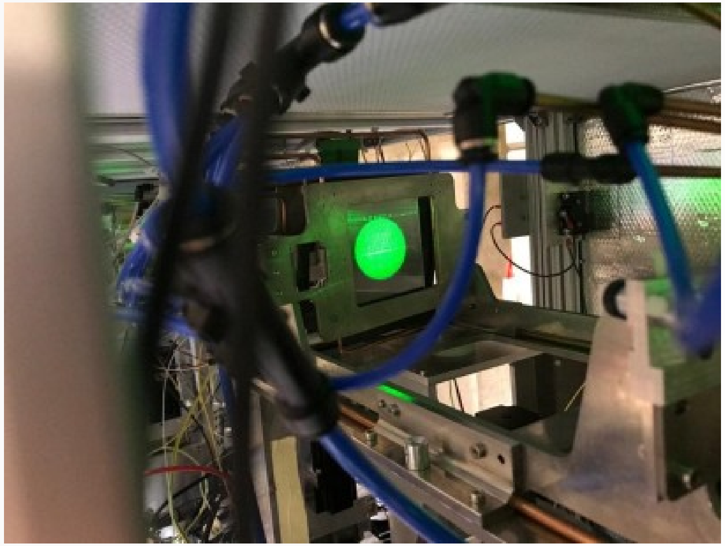
- K_{ref} = 0.137
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$, $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\mathrm{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\mathrm{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\mathrm{E_{Beam}}} = (6.5 \pm 0.5)\ \mathrm{MeV}$ $\nu = -0.001 \pm 0.003$

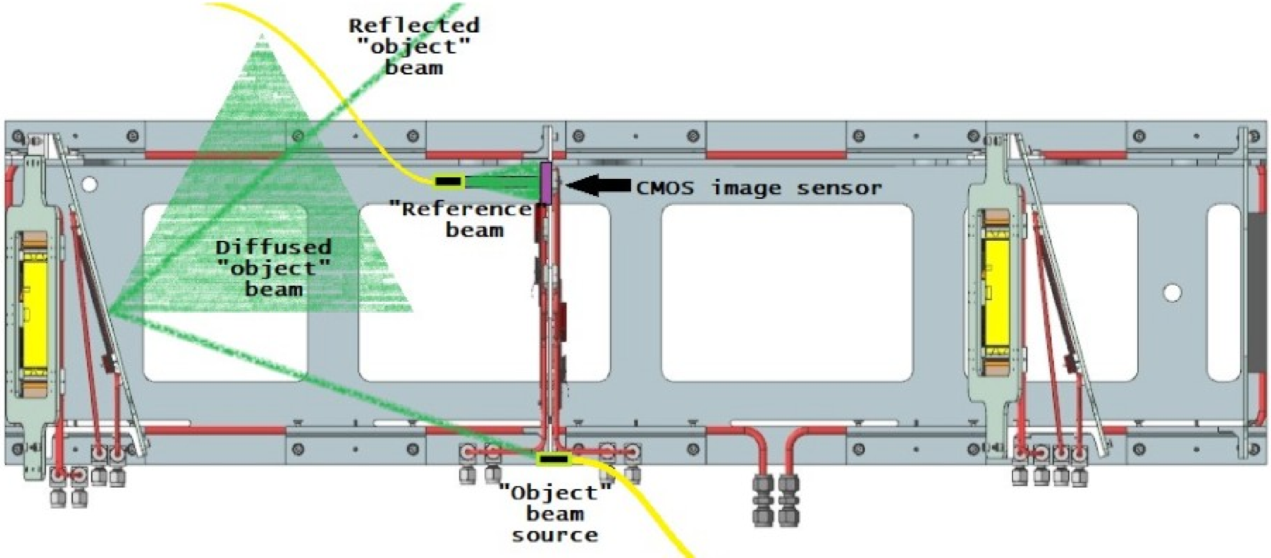
Similar results also for different selection cuts

Input shifts identified correctly.
No degradation on the signal parameter

Laser holographic system

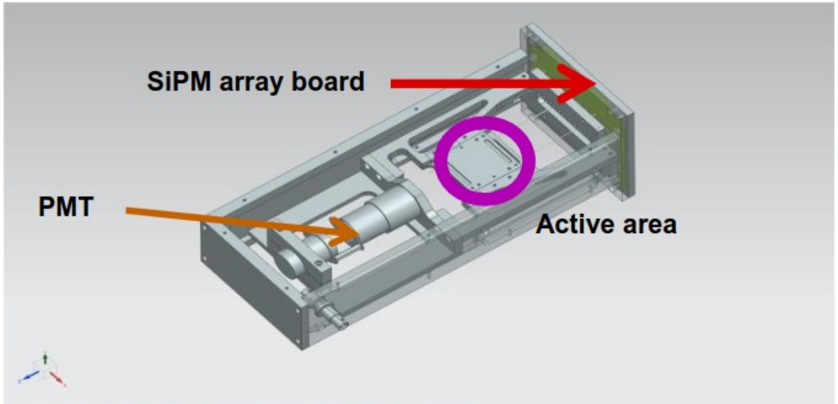


- Compare holographic images of the same object at different time
- Fringe pattern is related to deformations of the mechanical structure
- 532 nm fiber-coupled laser.
  Resolution: ~0.25 μm (half wavelength)
- Current limitation: Si sensors are sensitive to visible light → continuous monitoring is not possible
- Improvement: use >1500 nm laser (IR)



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



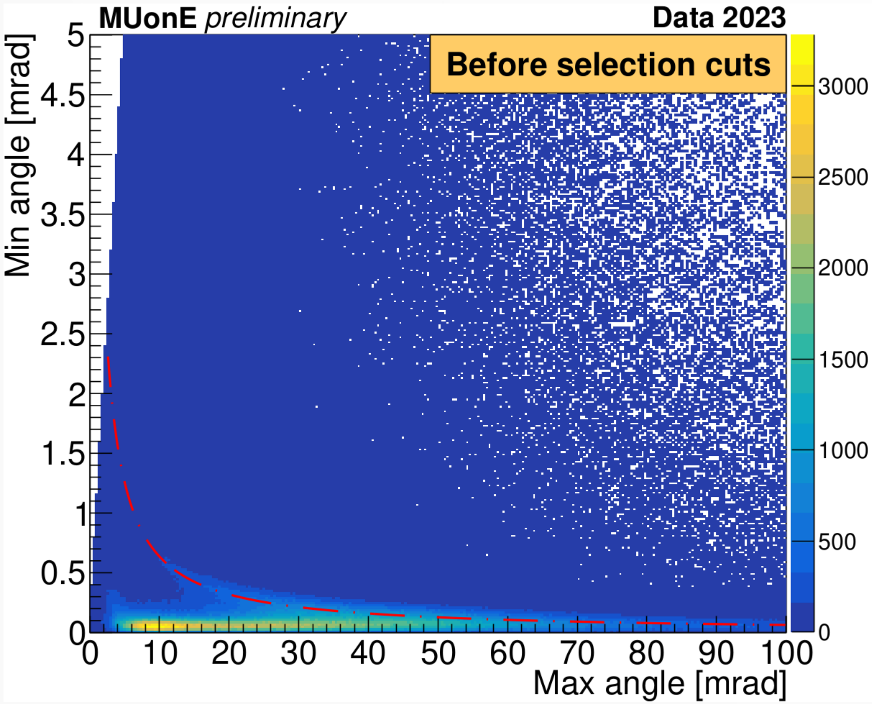
TR 2023
μ-e elastic scattering event selection

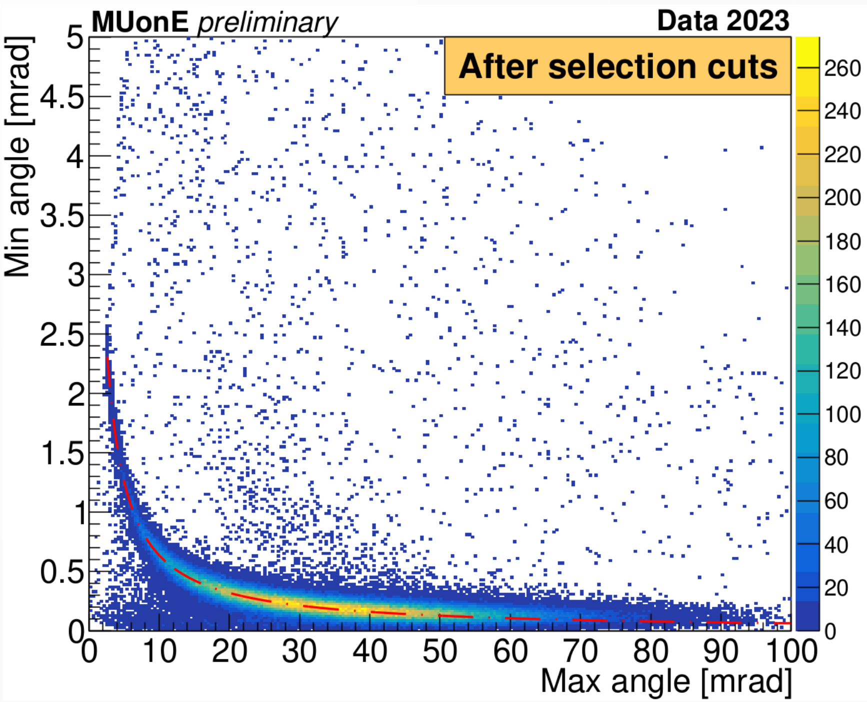
Pre-selection

- Single μ_{in} candidate
- μ_{out}, e_{out} pair candidate

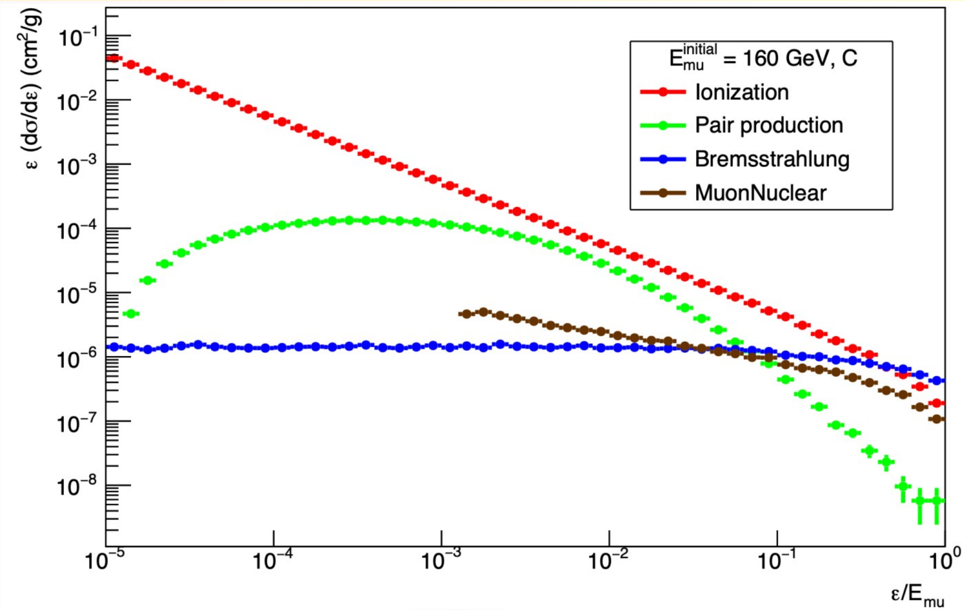
Initial event selection

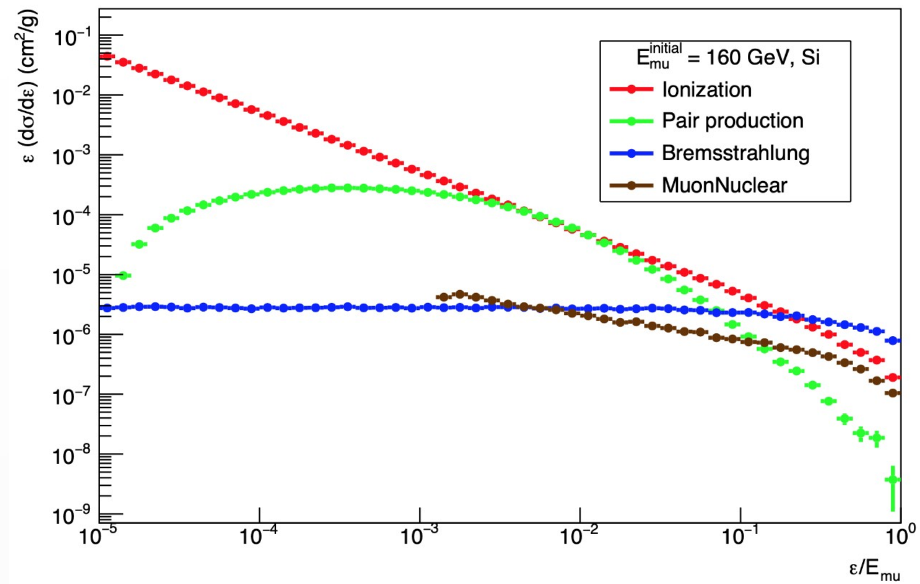
- ≥ 1 hit/module
- Cut on N_{hits}(station2)
- $|z_{vtx} - z_{target}| < 3$ cm
- Acoplanarity cut





Backgrounds





θ_e [mrad] ← 32 … 0

MESMER

- $\mu e^- \to \mu e^- \gamma$
- $\mu e^- \to \mu e^- l^+ l^-$
- $\mu N \to \mu N l^+ l^-$

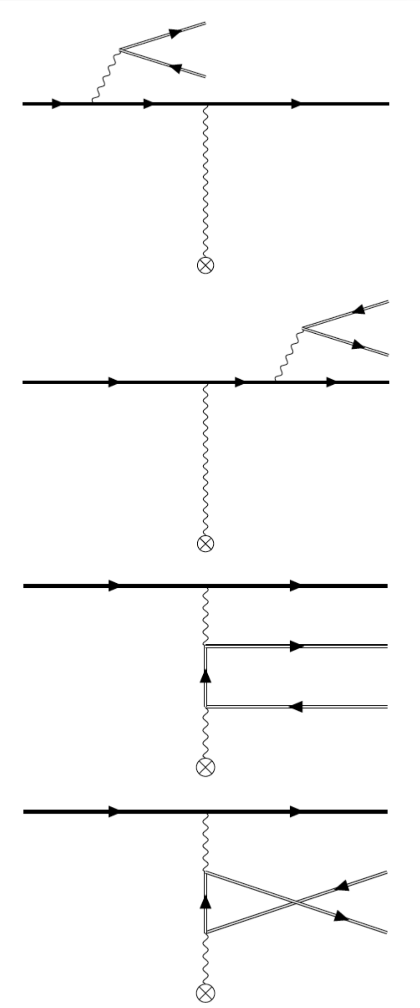
$l = e, \mu$

GEANT4

- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$

New Background MC generator

Main background: e+e- pair production
Implemented in MESMER
and interfaced with the MUonE detector simulation



Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)