Experiment update – MUonE –

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8th Plenary Workshop of the Muon g-2 Theory Initiative
IJCLab, 12th September 2025

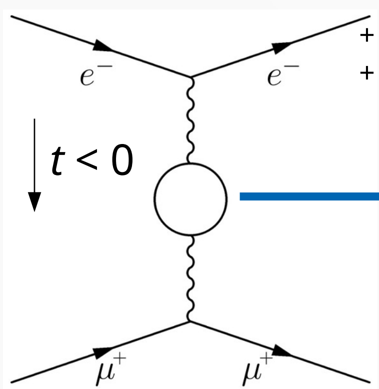
The MUonE experiment

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

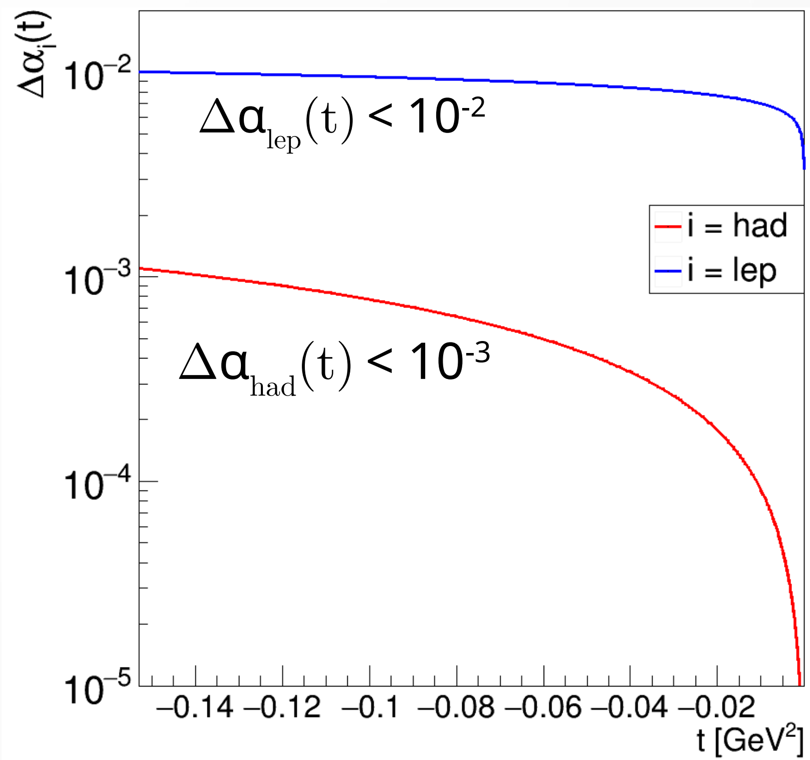
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)] \qquad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

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



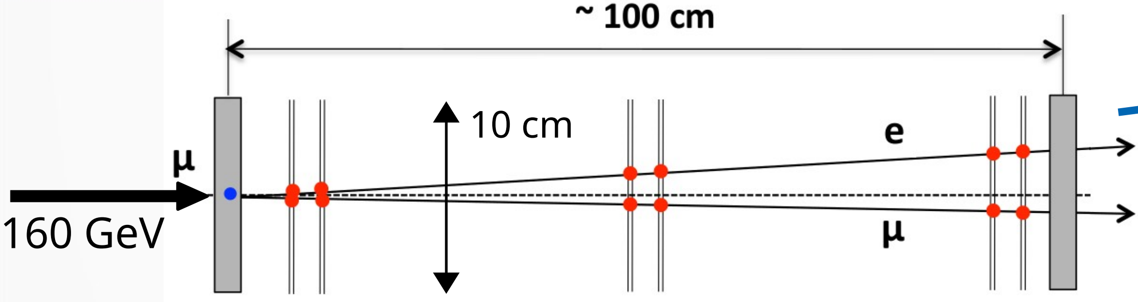
+ higher orders
+ radiative corrections

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



MUonE kinematic range

The MUonE experiment



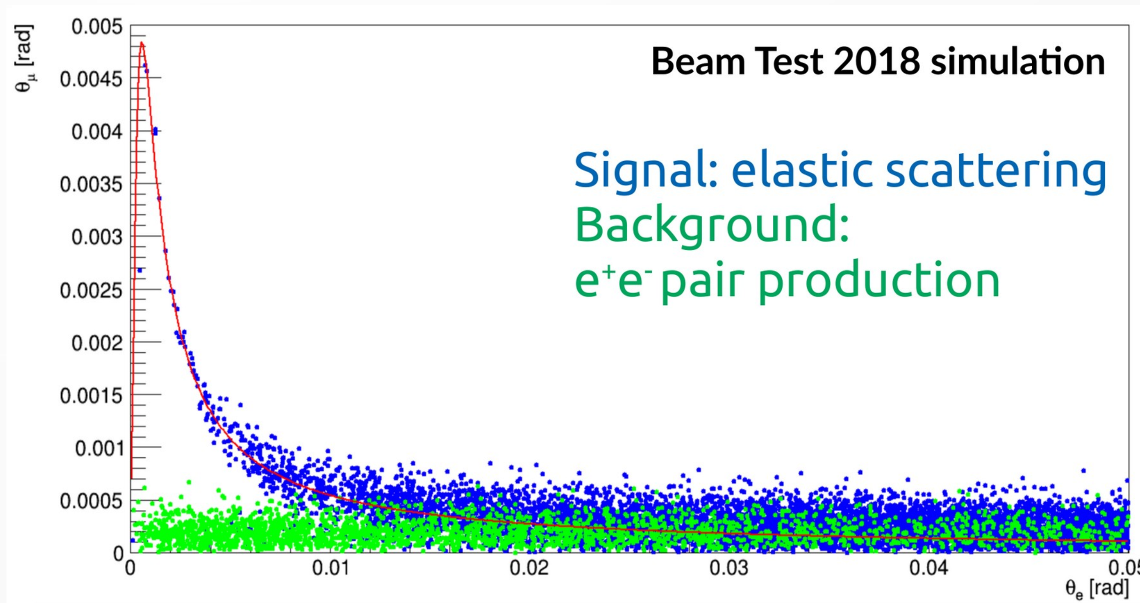
low-Z target
~1.5 cm

6 Si strip detectors (3 XY points)

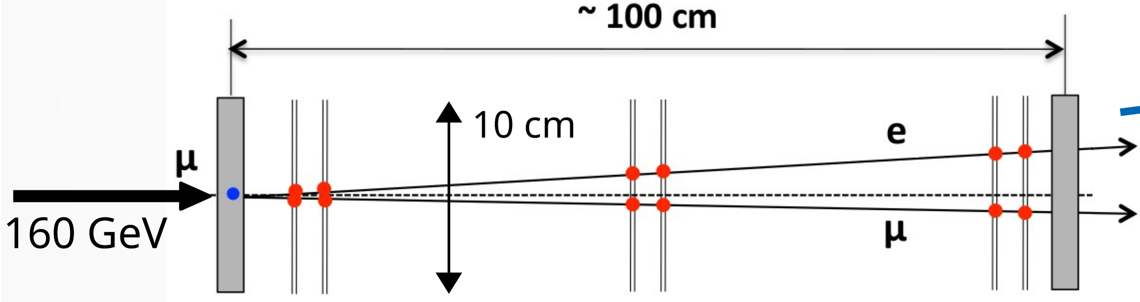
$$\frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}}=0)} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$

From MC

- Observables: (θ_e, θ_μ)
- Exploit (θ_e, θ_μ) correlation to reject background (main source: μ N → μ N e^+e^-)

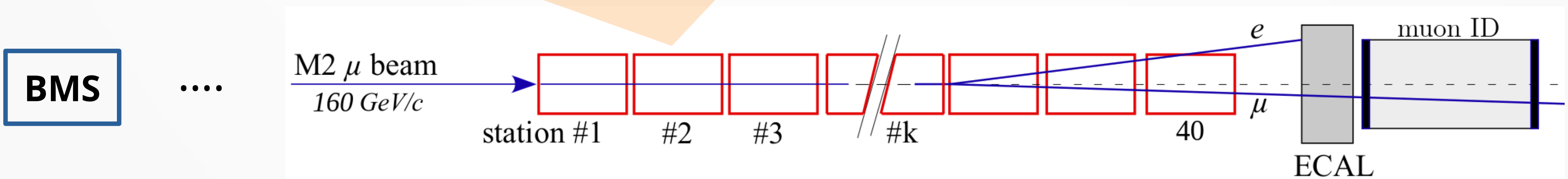


The MUonE experiment



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

From MC



- 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:

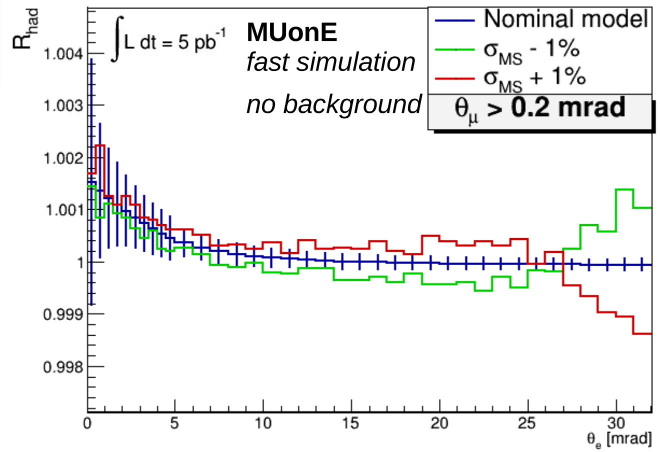
- ~3 years post LS3 (>2030)
- 40 stations
- $a_\mu^{\mathrm{HVP,LO}} < 0.5\%$

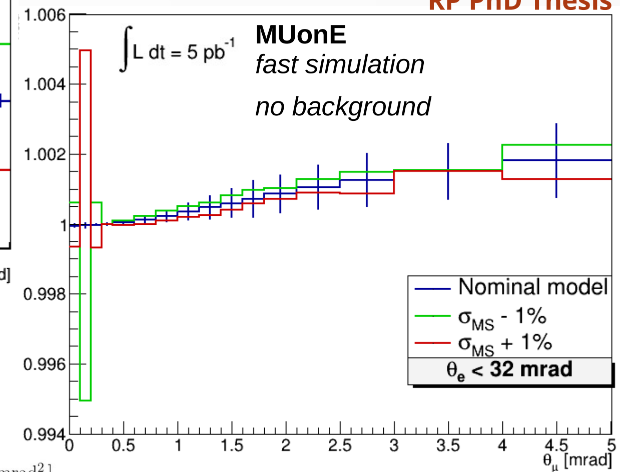
Systematic error goal: 10 ppm

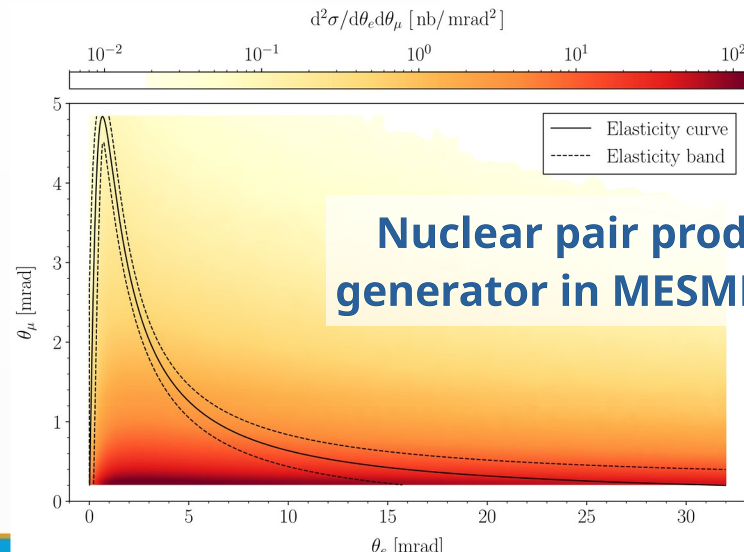
- 10 μm longitudinal alignment
- Beam energy measured to few MeV
- Multiple scattering 1%
- Angular intrinsic resolution
- Uniform detector response over full angular range
- Need of dedicated MC generators: signal (>NNLO), main backgrounds

multiple scattering ±1% systematic effect

Phys. Scr. 97 (2022) 054007
RP PhD Thesis







Phys. Lett. B 854 (2024)

Nuclear pair production event generator in MESMER (also signal)

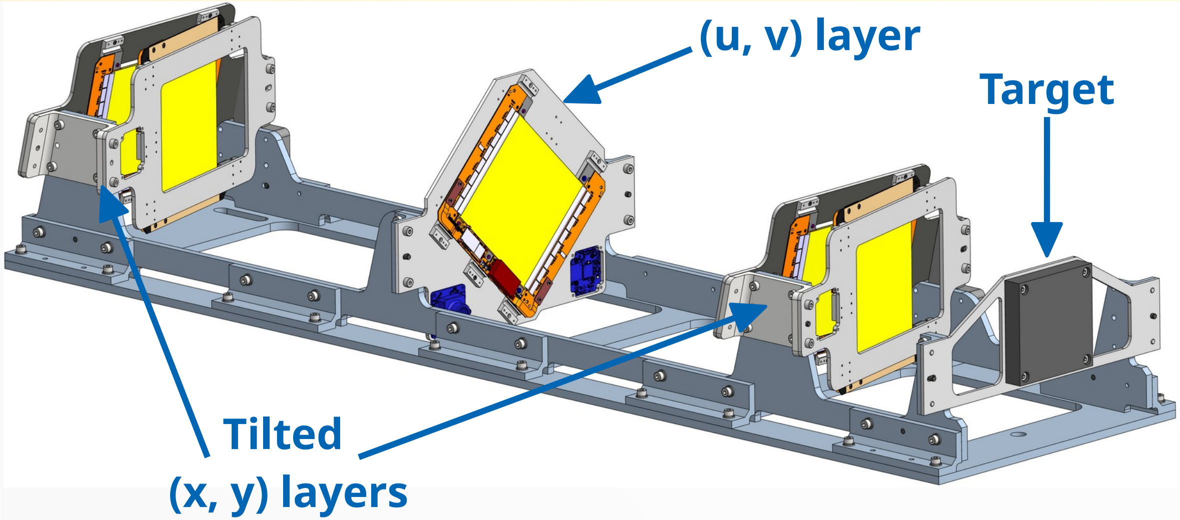
MESMER
McMule

Staged approach towards the full experiment

- 2017: test beam, multiple scattering studies JINST 15 (2020) P01017
- 2018: test beam, elastic scattering properties and event selection studies JINST 16 (2021) P06005

- 2021: first joint test CMS-MUonE
  with 4 2S modules prototypes (parasitic)
- 2022:
  - test 1 tracking station
  - test the calorimeter
- **2023**: test with 2 tracking stations + calorimeter
- 2024: 2 tracking stations (DAQ tests) + calorimeter (characterization)
- **2025**: run with a scaled version of the complete apparatus

Tracking system

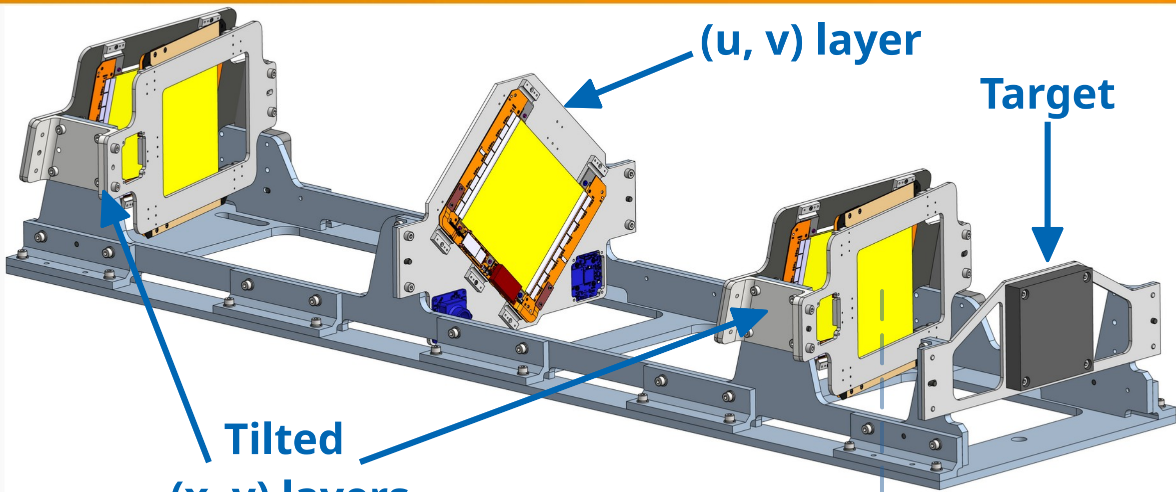


INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

Laser holographic system
to monitor stability

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

Tracking system

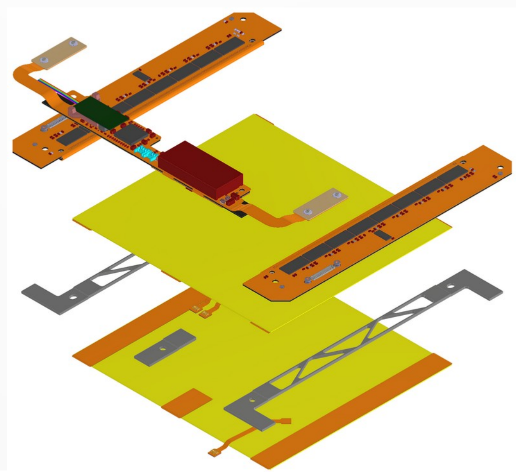


INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

Laser holographic system
to monitor stability

2S modules
(CMS Phase2 upgrade)

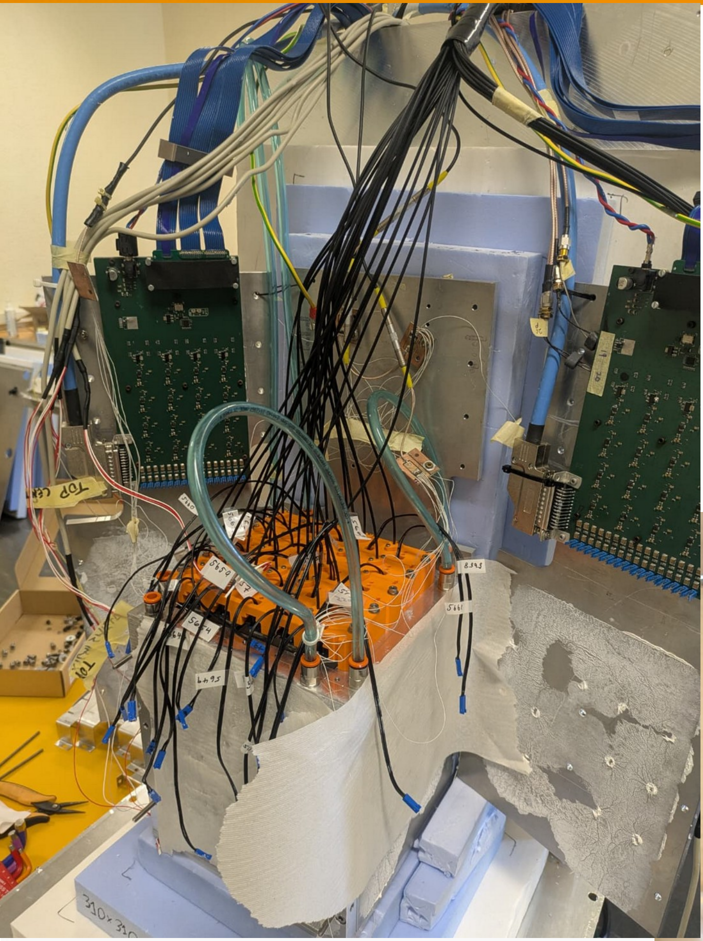
TDR CMS Tracker Phase2 Upgrade



- (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



- 5x5 $PbWO_4$ crystals, used in the 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

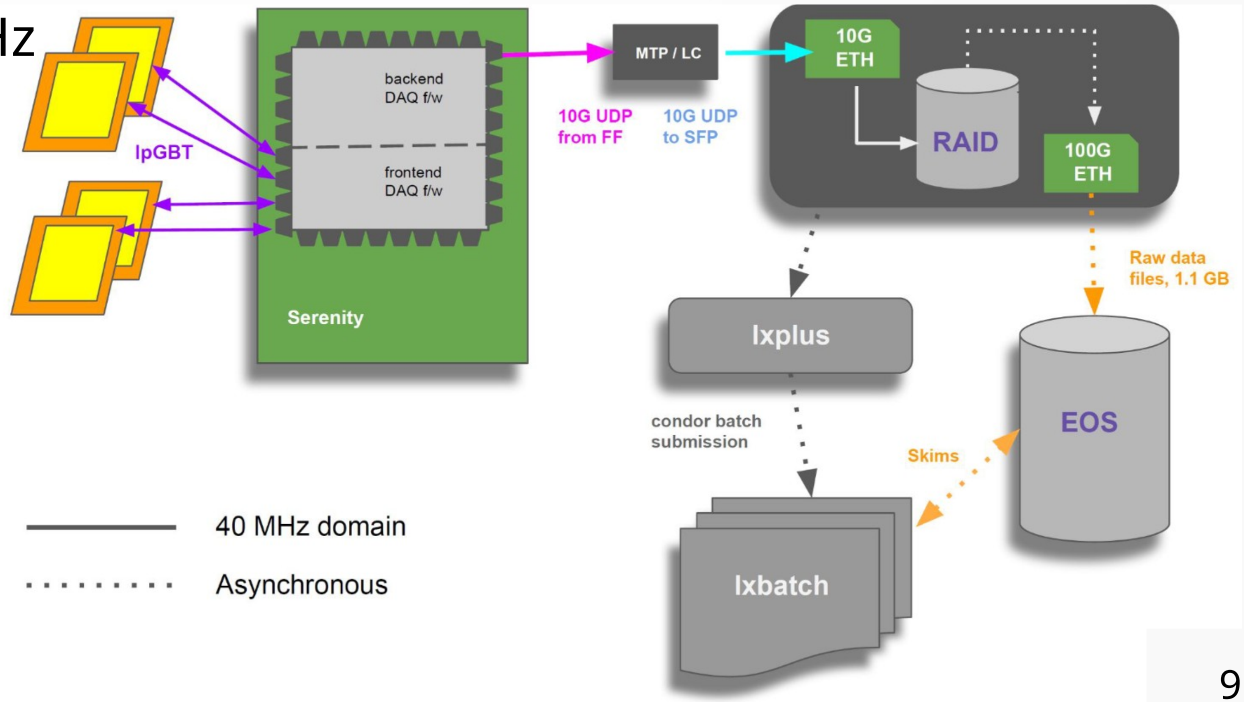
- End of TR 2023: ECAL data integrated in the main DAQ
- TR 2025: tracker-ECAL time sync achieved

DAQ system

M2 beam line at CERN:
unique environment

- High intensity: ~$2\times10^{8}\,\mu^{+}$ / 5s spill → **~40 MHz**
- **Beam asynchronous to DAQ clock**

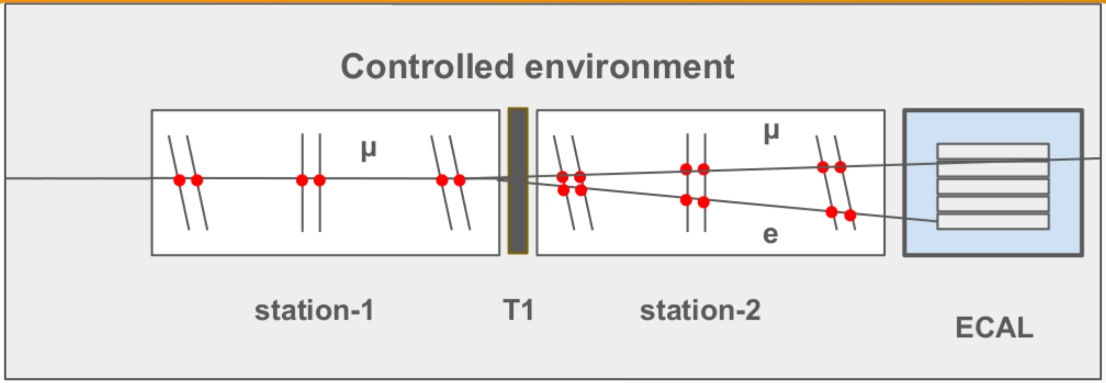
- Serenity board (developed for CMS Phase2 Upgrade)
- Triggerless readout @ 40 MHz
- Event aggregator on FPGA
- Data aggregation on 4 PCs
- Transmission to EOS into 1GB files

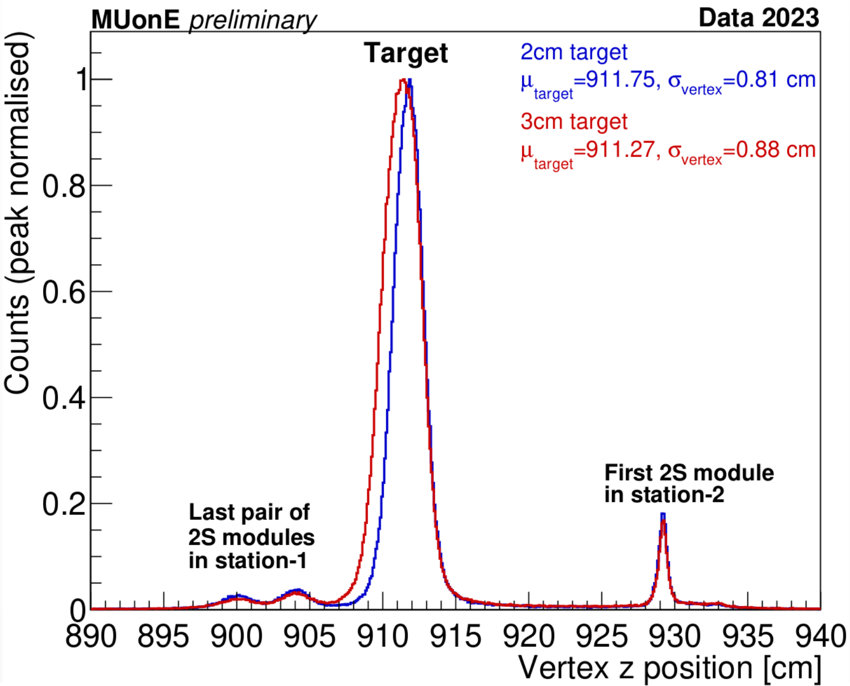


Test Run 2023

- 2 tracking stations
- C target
  (2 or 3 cm thickness used)
- ECAL

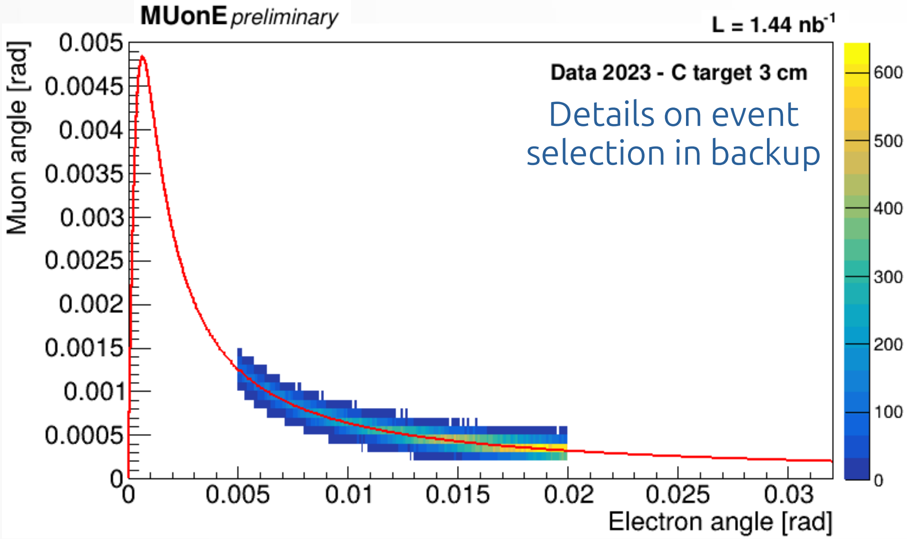
- **Demonstrated continuous readout @40 MHz.**
- Study detector performance, reconstruction algorithms, event selection.





Test Run 2023 – Data/MC comparison

Select elastic events in a clear region

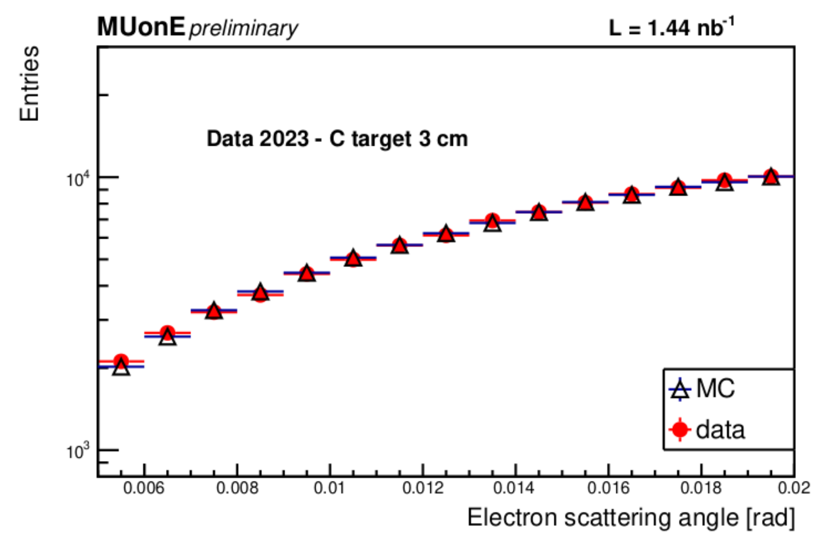


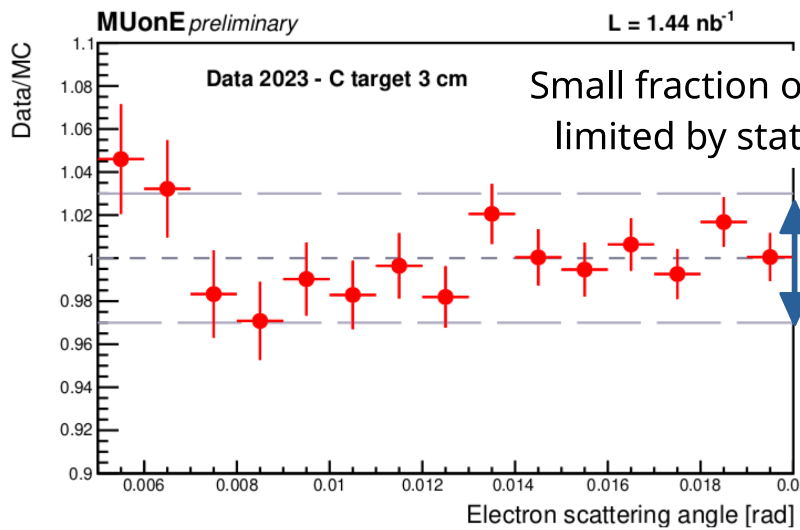
Count N_μ on target → luminosity estimate

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

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

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



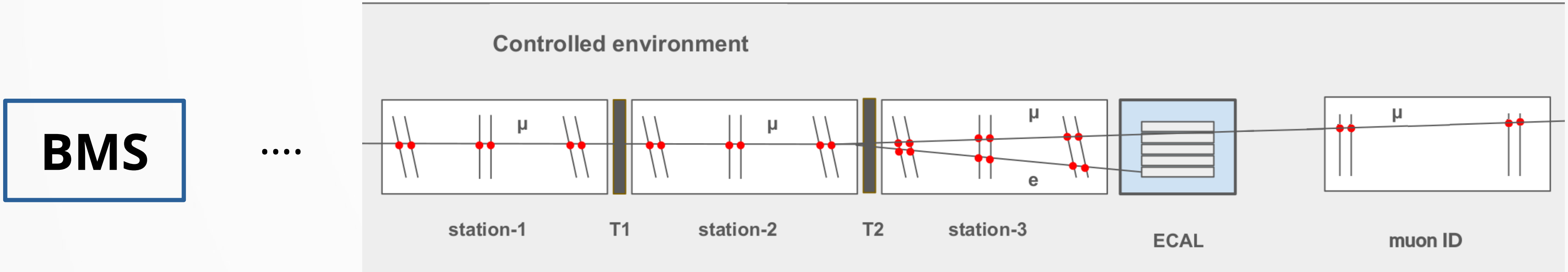


Small fraction of data: limited by statistics

± 3%

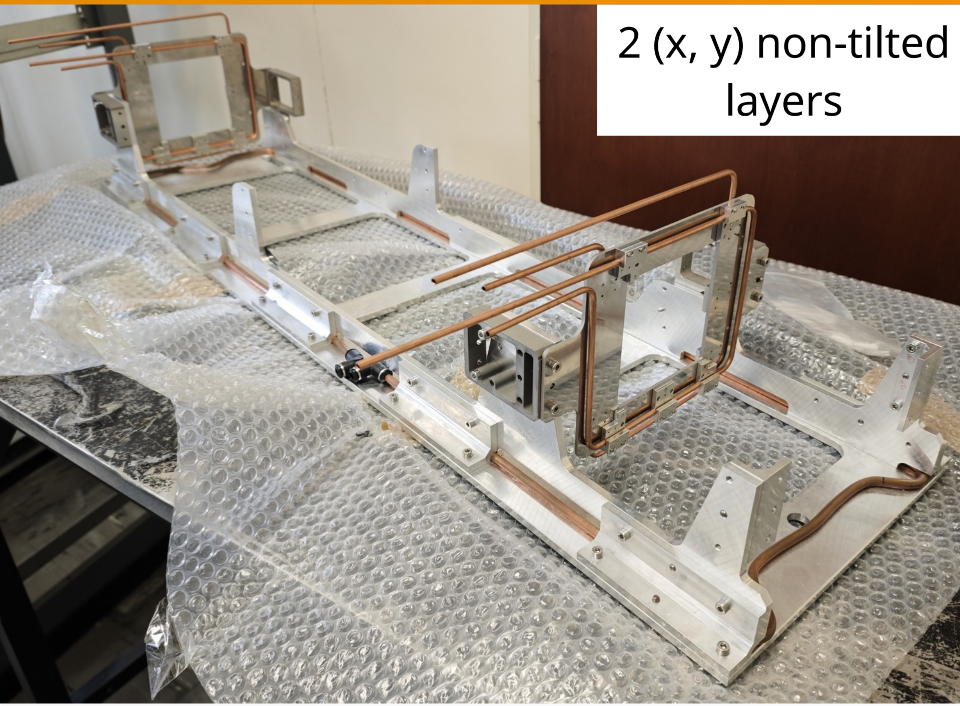
MUonE Phase-1: Test Run 2025

Proposal for Phase 1 of the MUonE experiment

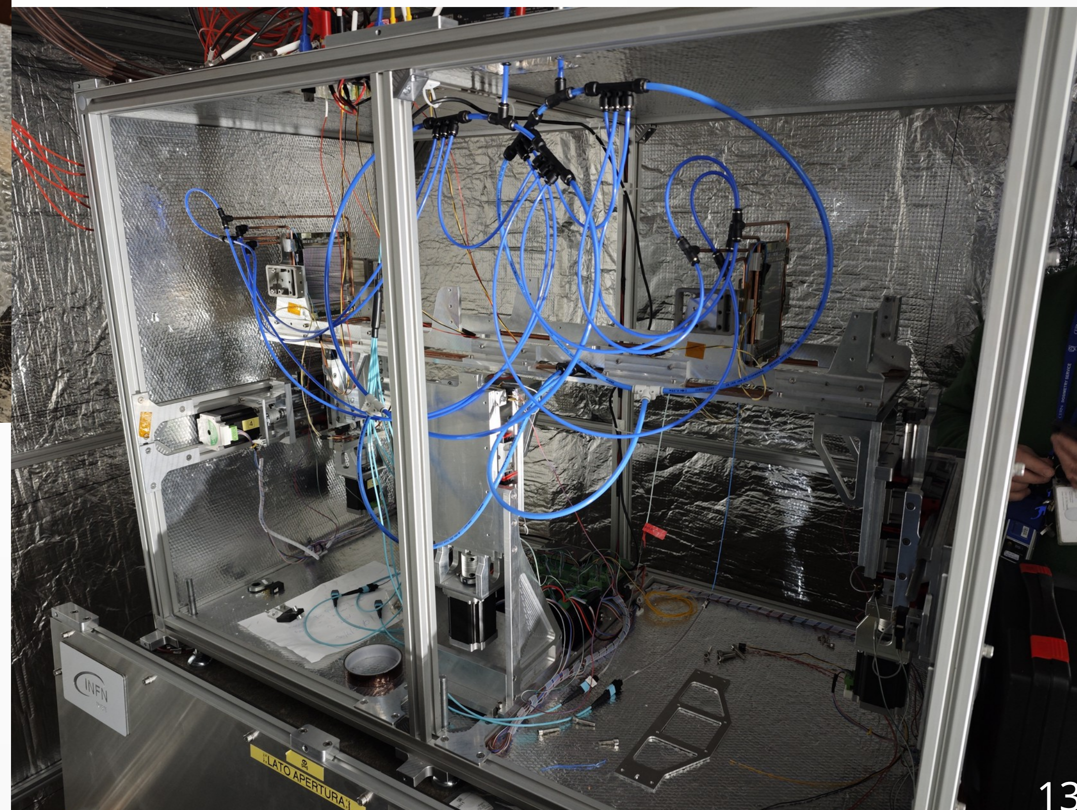


- 3 × tracking stations, each equipped with 6 pre-production 2S modules
- 2 × C targets (each 2 cm thick)
- ECAL: e^- PID + E_e measurement
- Timing detector: time of arrival of muons. 2 plastic scintillators before and after the tracking stations
- Muon ID: μ PID. Equipped with 4 prototype 2S modules
- BMS: measure $p\mu$ event by event. 2 × tracking stations, each equipped with 4 prototype 2S modules

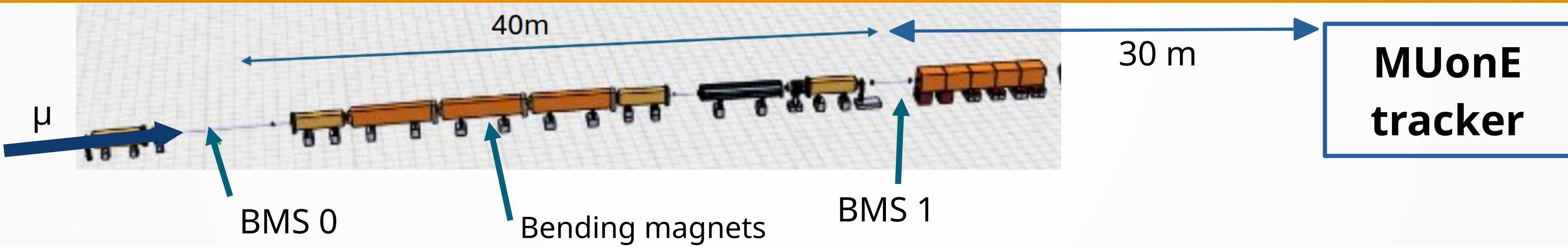
Muon ID



2 (x, y) non-tilted layers

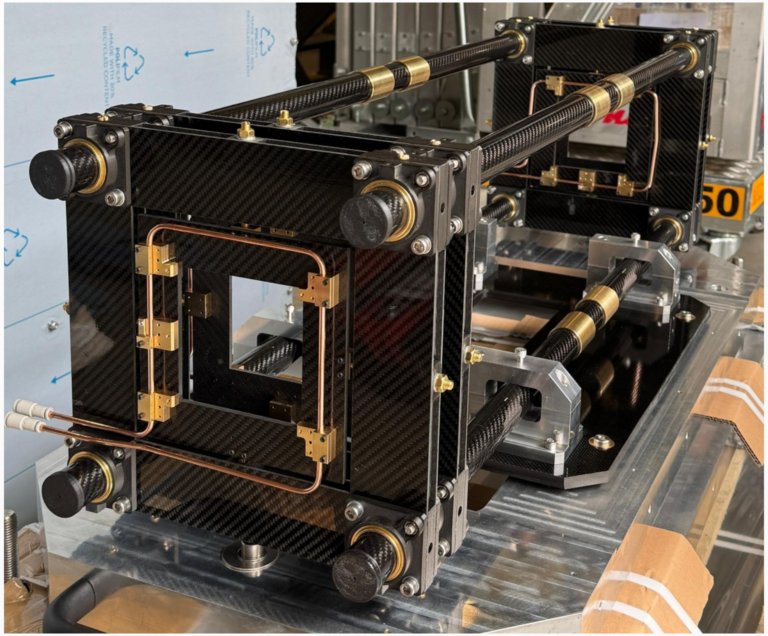


BMS (Beam Momentum Spectrometer)



- Bending power: 16 T*m
  (30 mrad @160 GeV)
- Proof of concept in 2025.
  Challenges:
  - Time synchronisation
    with the rest of the system
  - Alignment
  - B-field monitoring

New Carbon Fibre structure

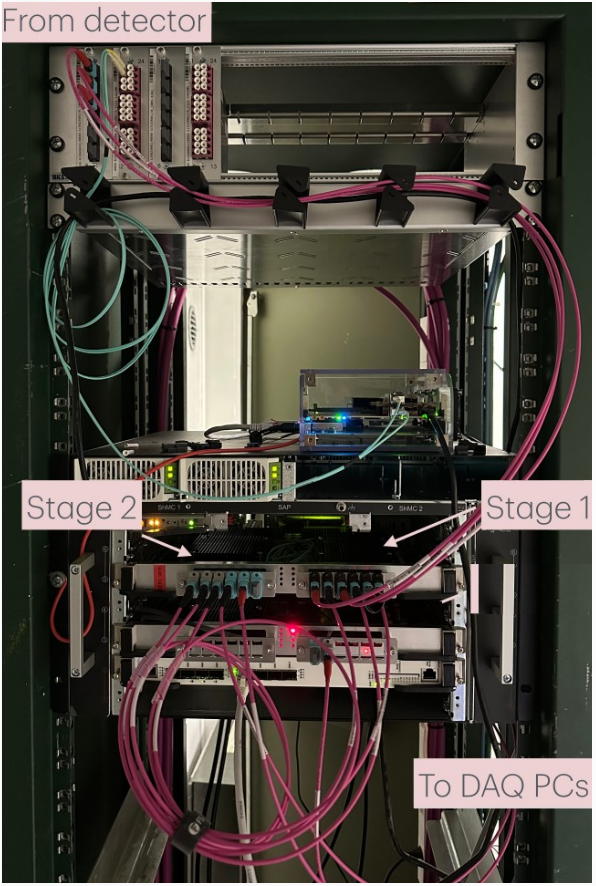


×2

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

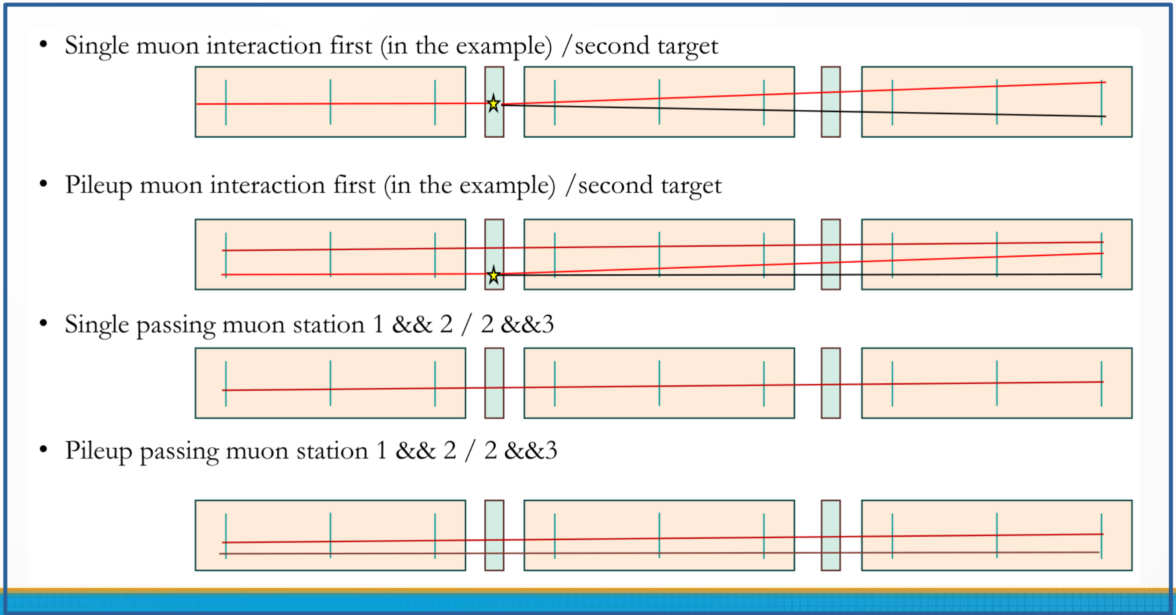
System increasing in complexity...

Move to a 2 stages DAQ design



- **Stage 1:** 36 communication links with subdetectors
  - 30×2S modules
  - 2×Timing Detector
  - 4×ECAL
- Online selection based on tracker modules occupancy. ~×100 reduction of recorded events compared to 2023.

Event topologies



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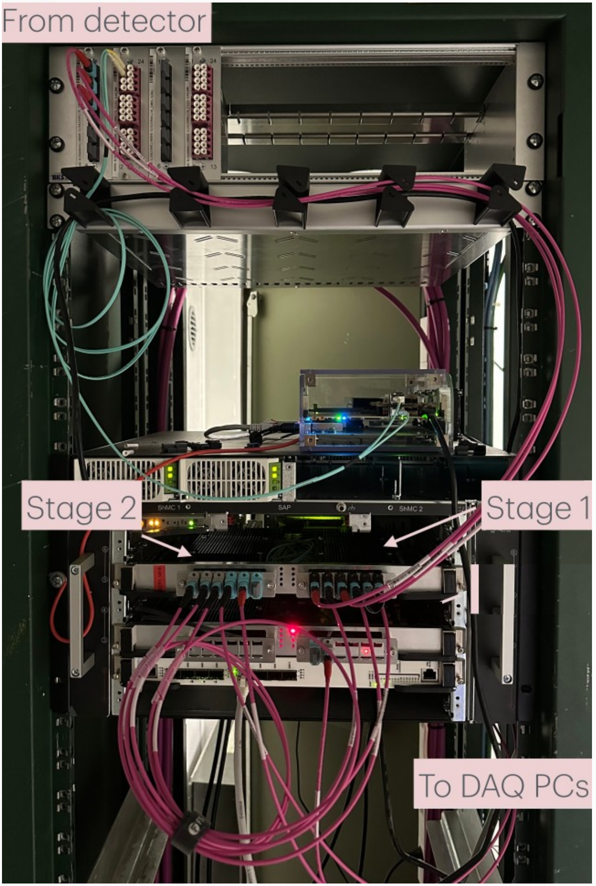
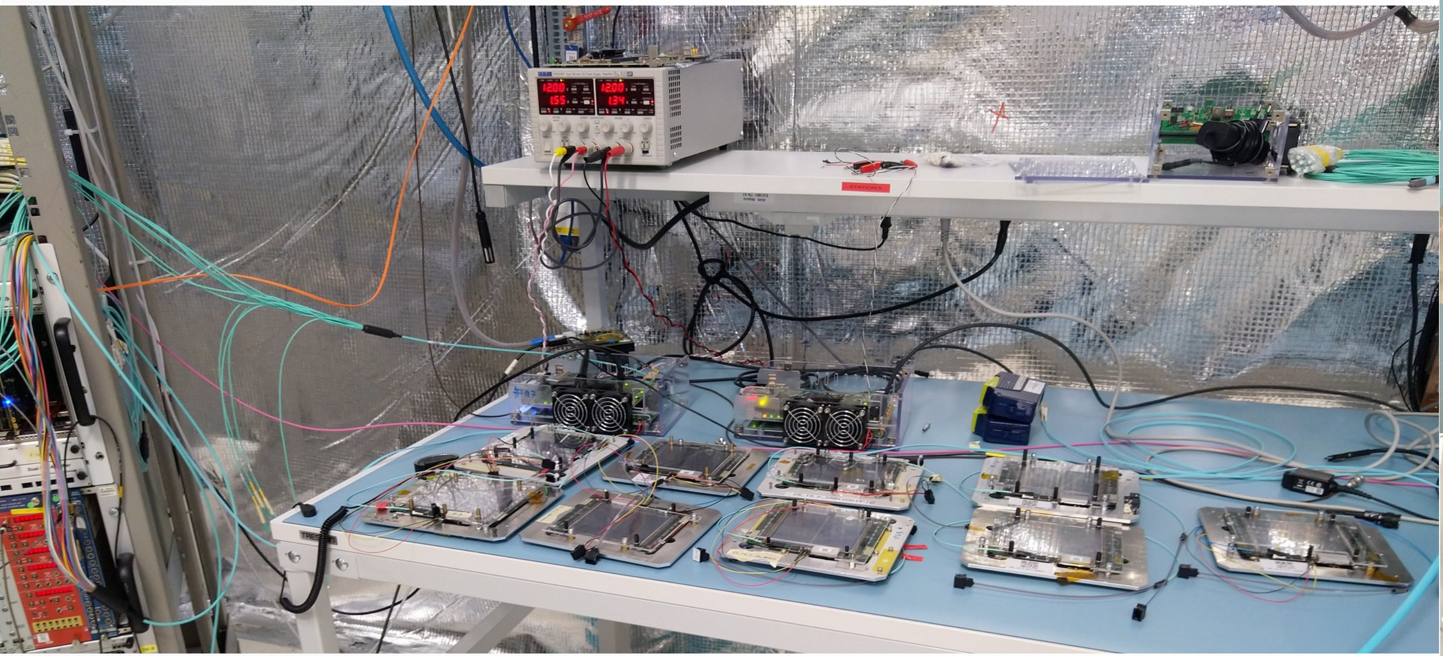


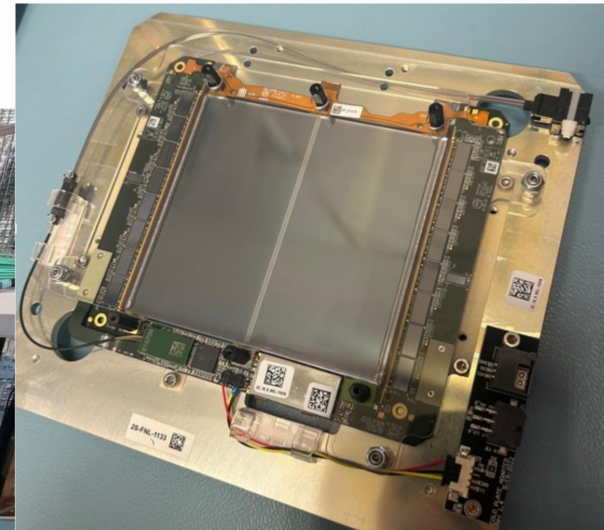
- **Stage 1:** 36 communication links with subdetectors
  - 30×2S modules
  - 2×Timing Detector
  - 4×ECAL
- Online selection based on tracker modules occupancy. ~×100 reduction of recorded events compared to 2023.
- **Stage 2:** event building.
  - Group information from all subdetectors in a time-coherent packet of data.
- Online decoding of data provides ready-to-use ntuples for DQM and prompt analysis.

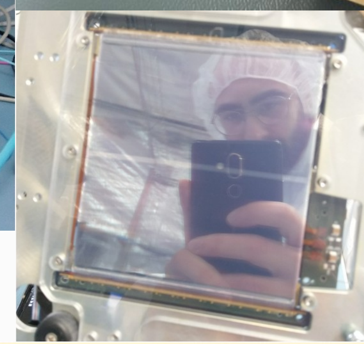
Test Run 2025 – timeline

	March	April	May	June	July	August
2S modules characterisation in lab						

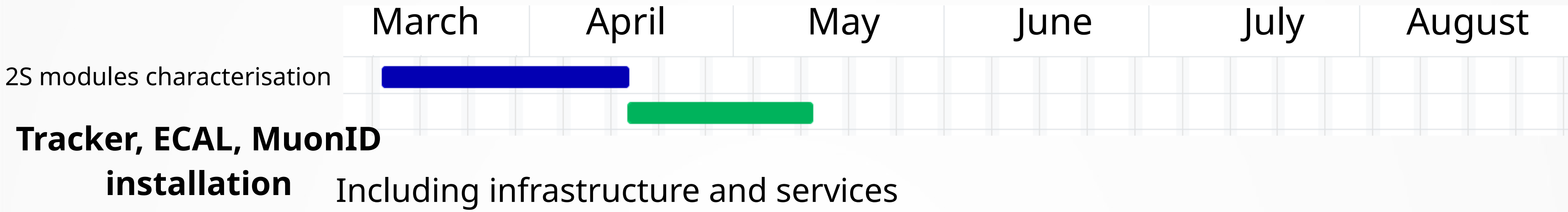
Noise tests + modules grading

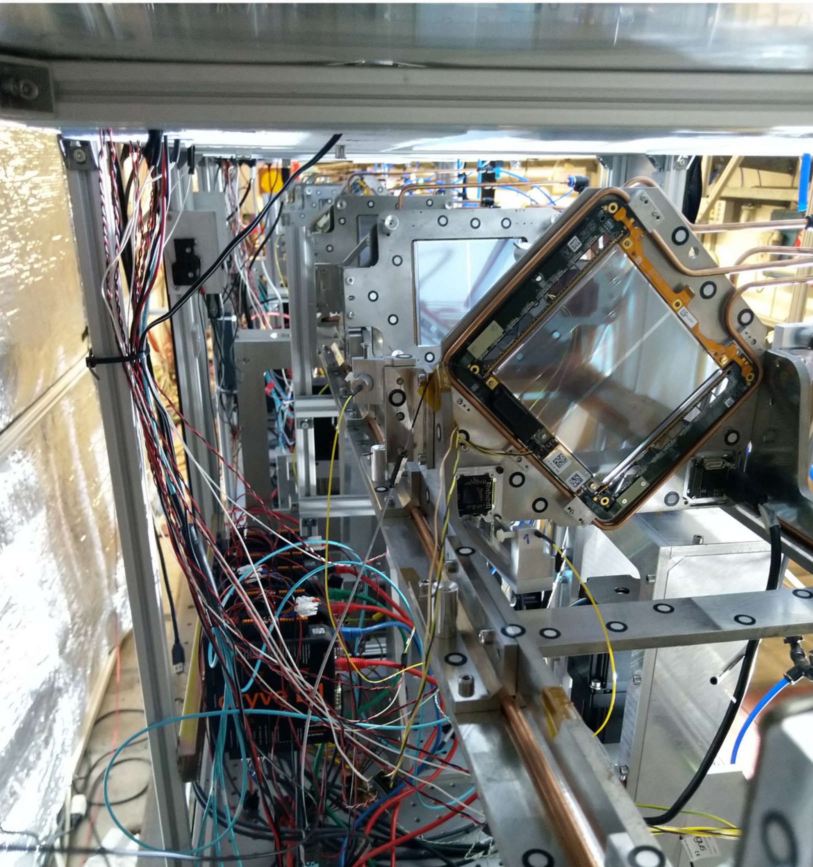


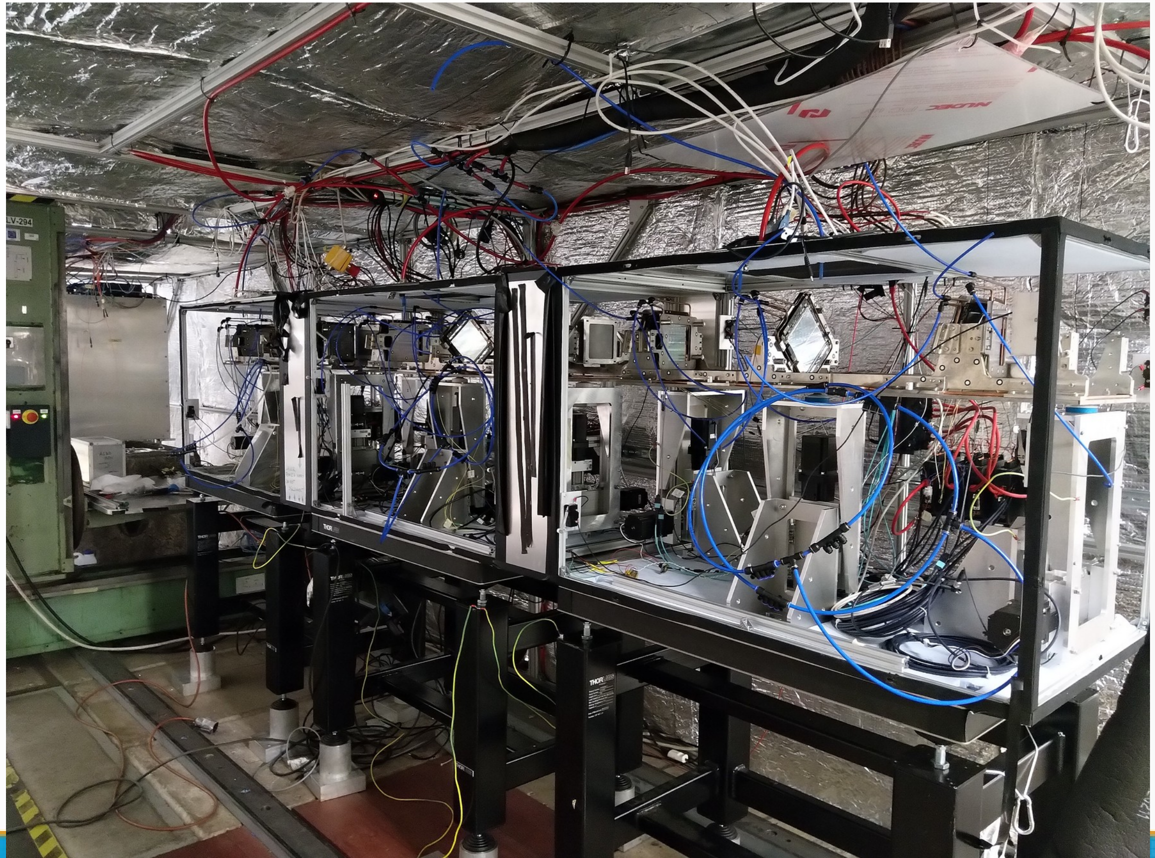




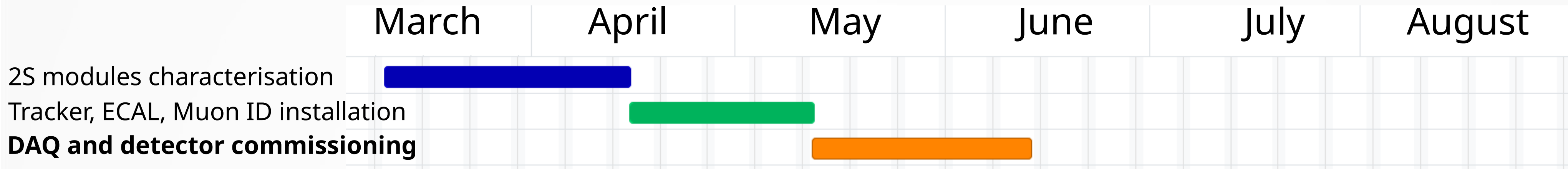
Test Run 2025 – timeline







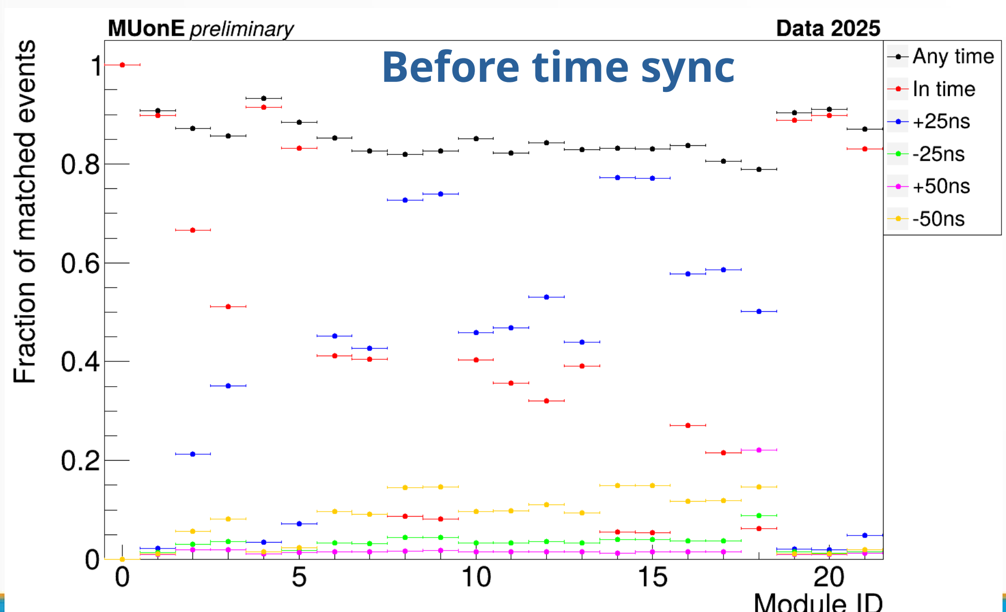
Test Run 2025 – timeline

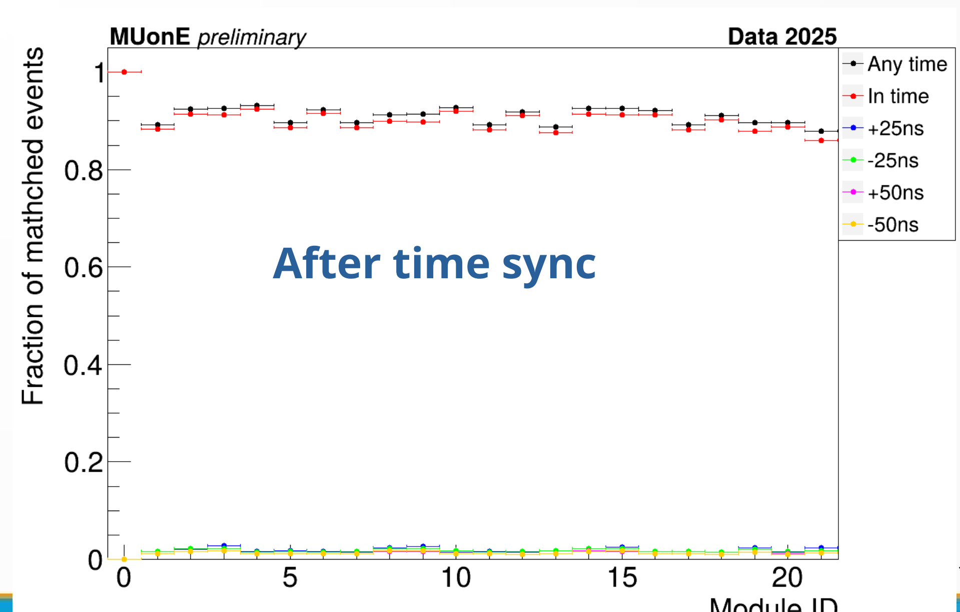


Numerous tests accomplished despite technical challenges (...and SPS inefficiencies)

Tracker time synchronisation

Fix the internal clock of a reference module, then scan the possible delays of the other modules to maximise their coincidences with reference





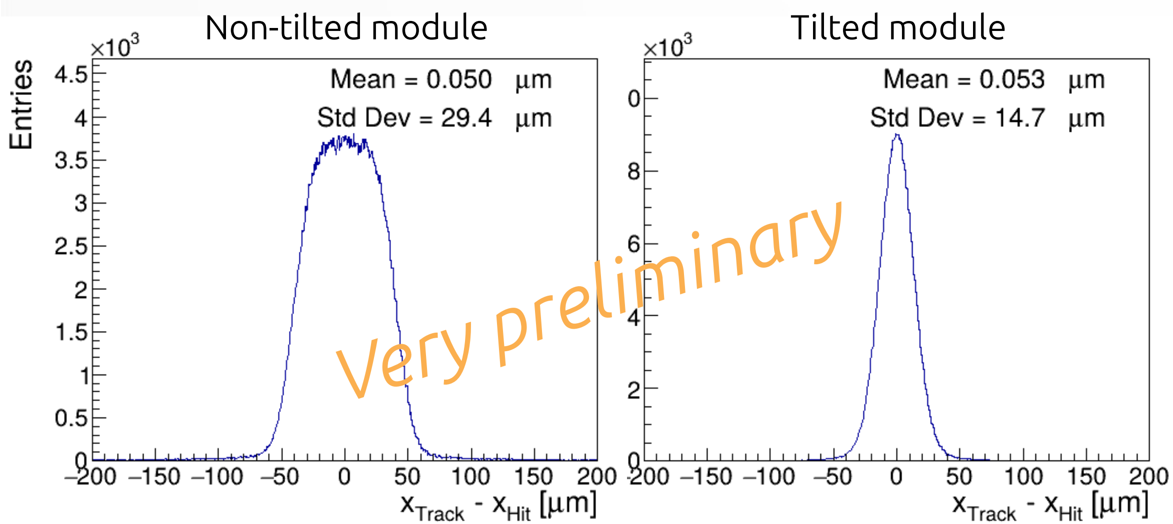
DAQ and detector commissioning

Alignment

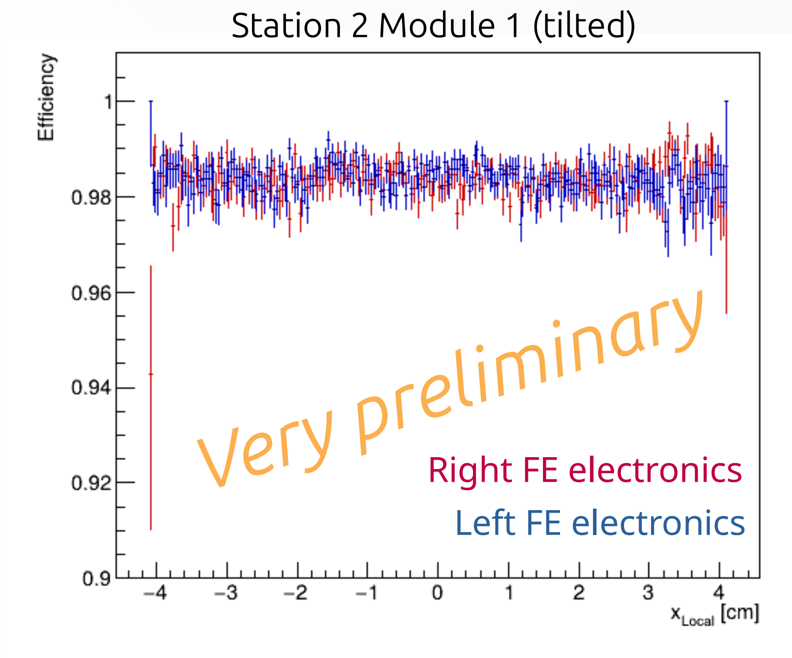
- Hardware (stepper motors):
  center the beam profile on each module, then align the 3 stations one relative to the other.
- Software:
  local χ^2 minimization on a sample of single passing muons.

Examples of residuals

*Std Dev is <u>not</u> the hit resolution: track fit error to be subtracted



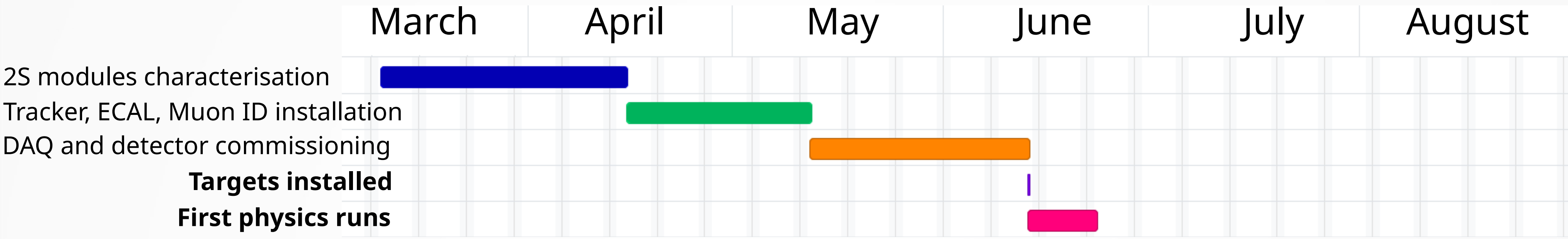
Module efficiency

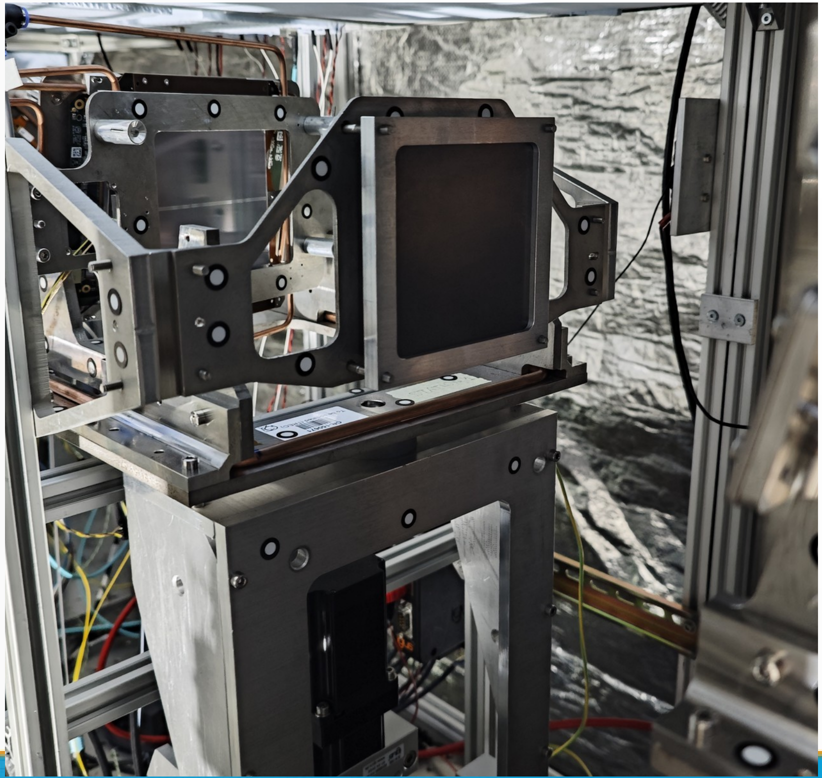


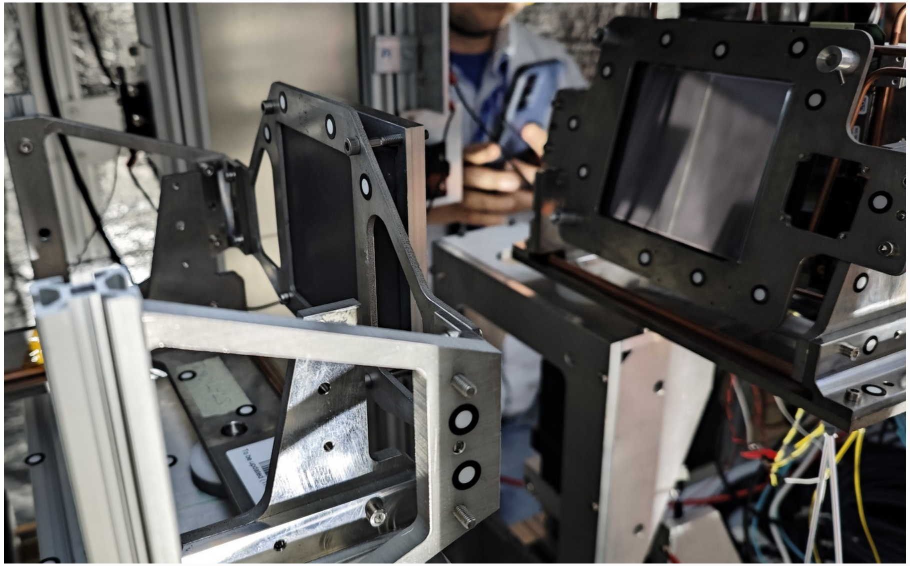
Uniform efficiency
over the entire modules surface

Work in progress: efficiency time uniformity over the entire data taking

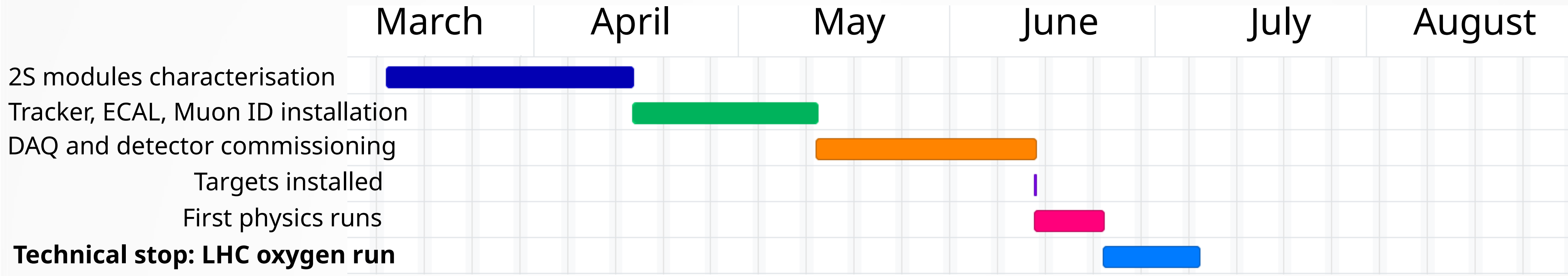
Test Run 2025 – timeline





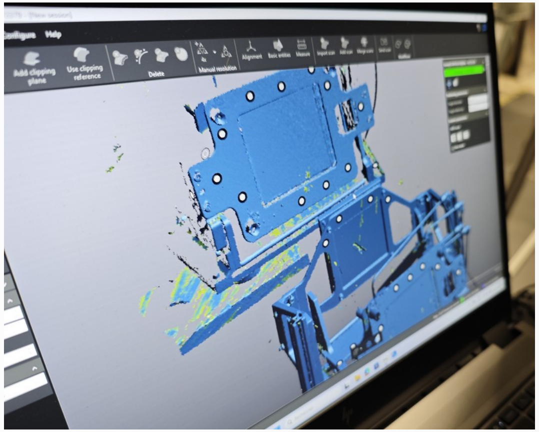


Test Run 2025 – timeline

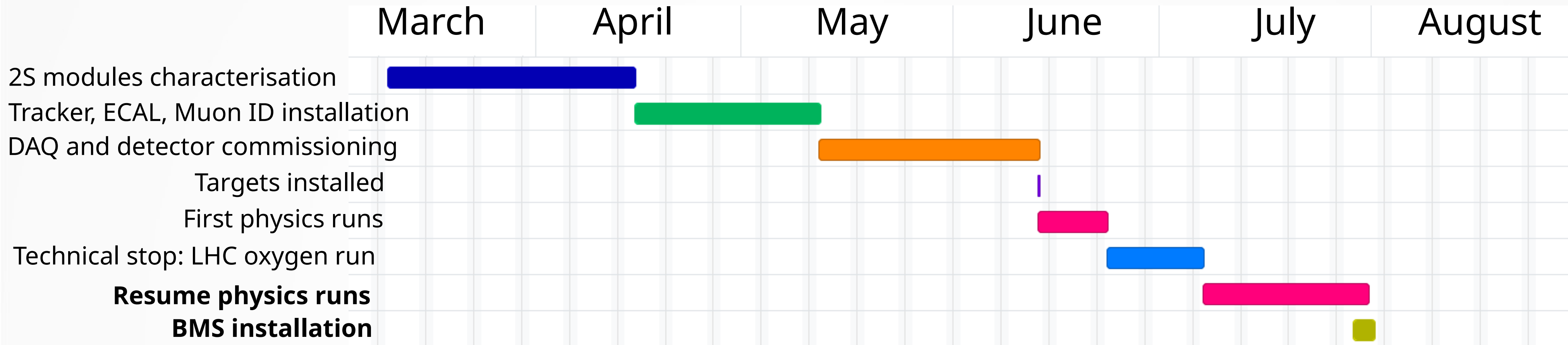


Metrology measurements of the detector (100 µm precision)

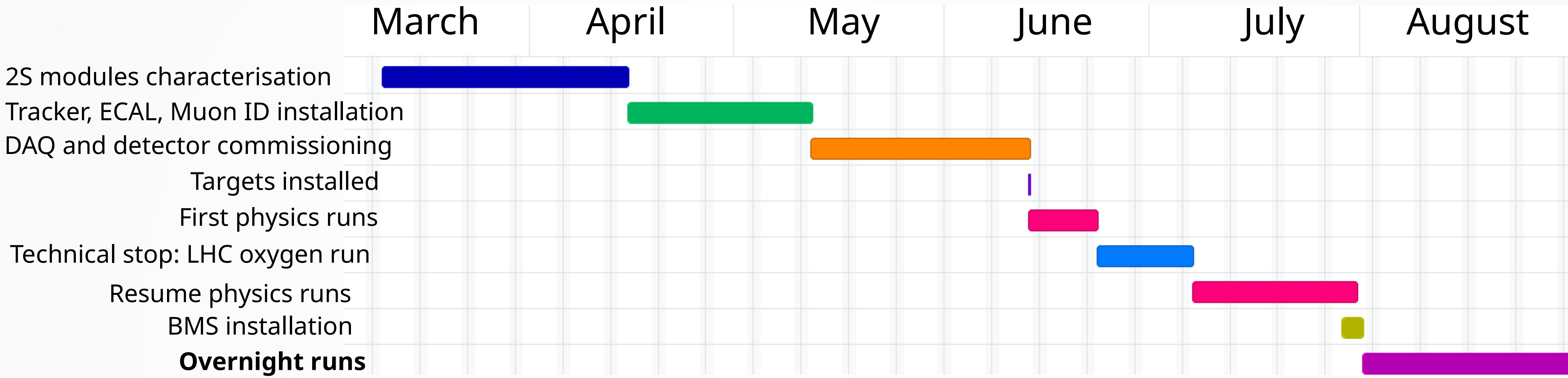
- <u>3D scanner photogrammetry</u>: position and orientation of each module within a station
- <u>Laser survey</u>: relative position of the different subdetectors; absolute position with respect to beam elements
- To be used as starting point of software alignment



Test Run 2025 – timeline

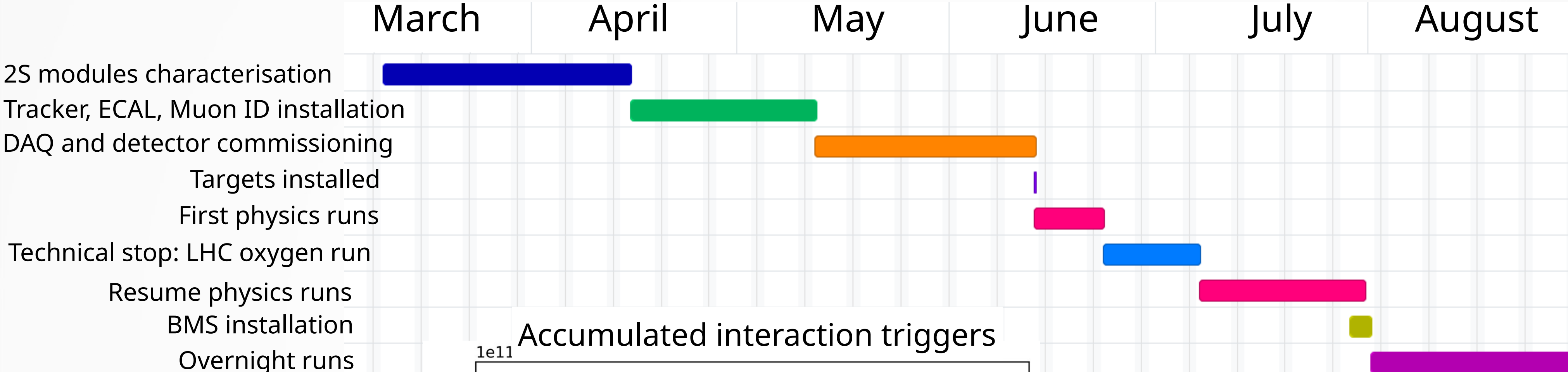


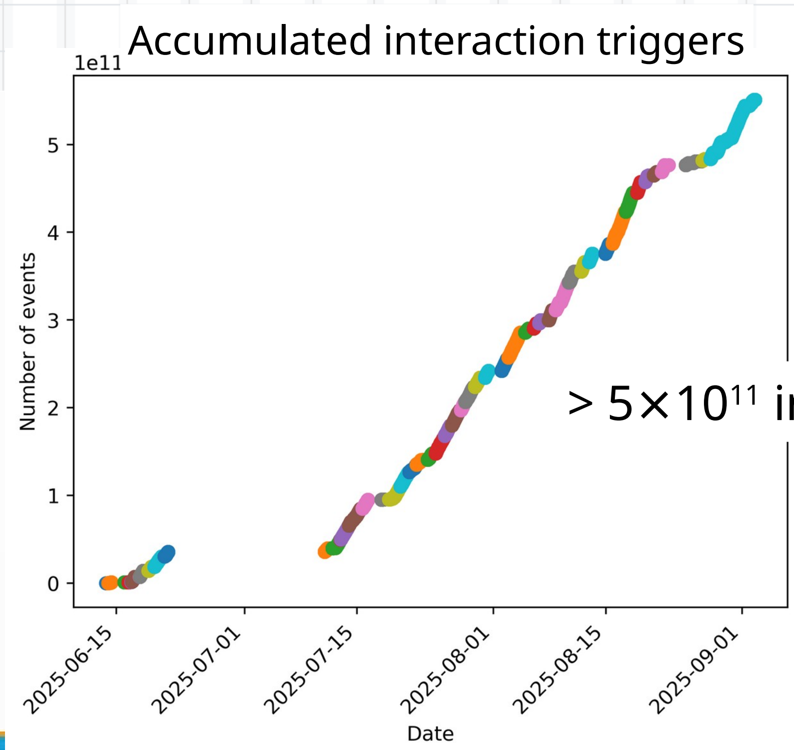
Test Run 2025 – timeline



AMBER takes over as main user.
They kindly agreed that MUonE could continue to take data during nights, while they exploit daytime to install new hardware

Test Run 2025 – timeline

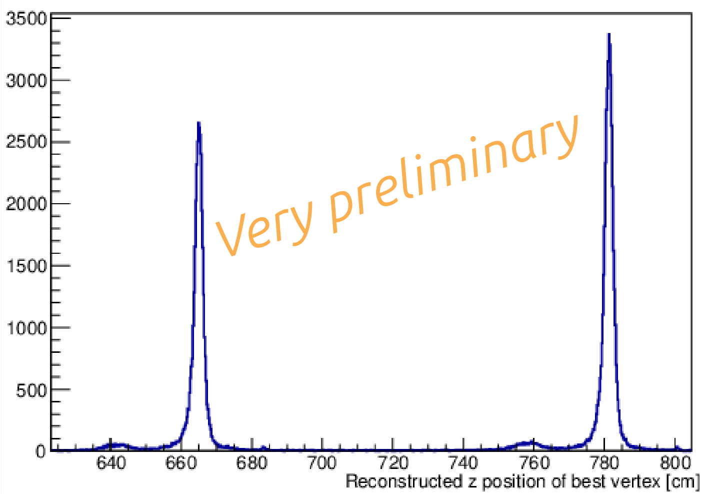




> 5×10^{11} interaction triggers recorded!

Elastic scattering events

Elastic events from both targets

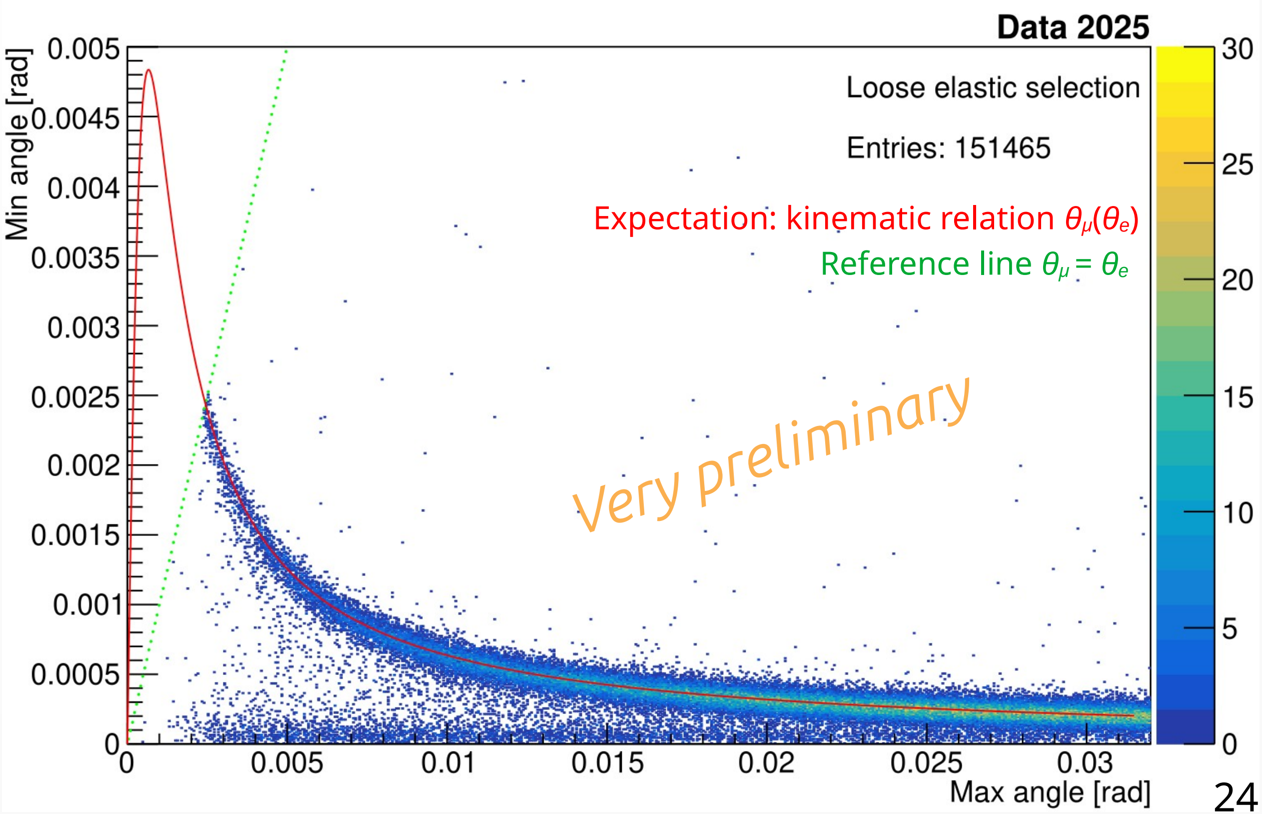


Can use ECAL or MuonID to resolve the ambiguity

Tracker-only analysis of elastic events

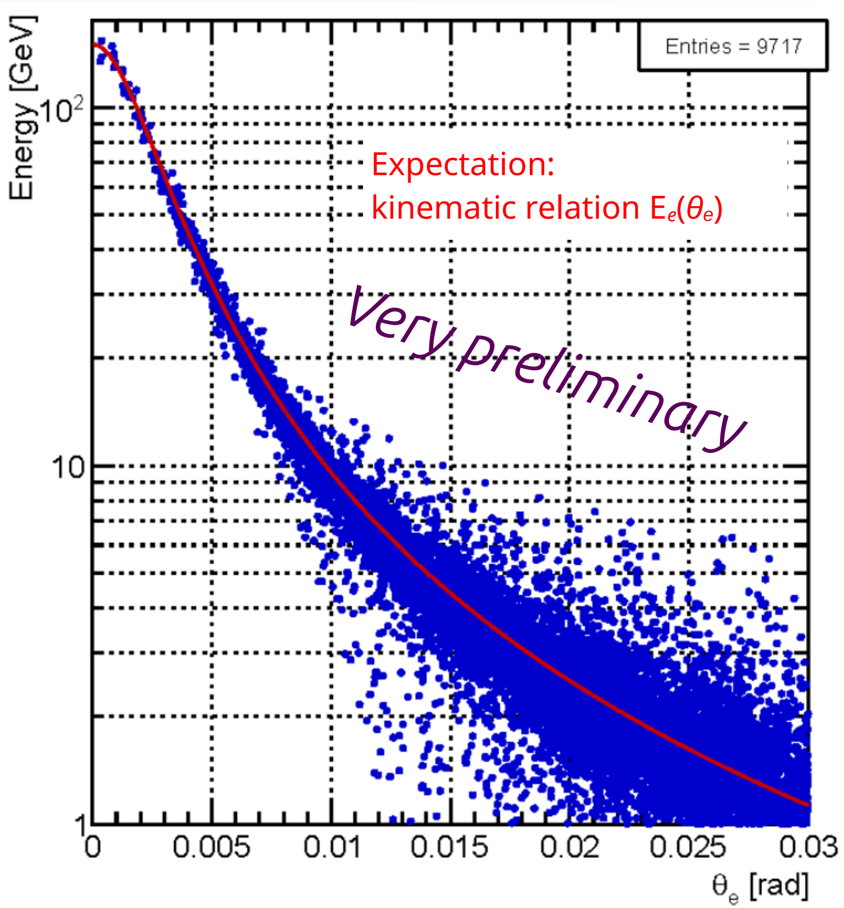
Not able to discriminate between μ and e^-:

plot θ_{max} vs θ_{min} to avoid misidentification when θ_e < 5mrad

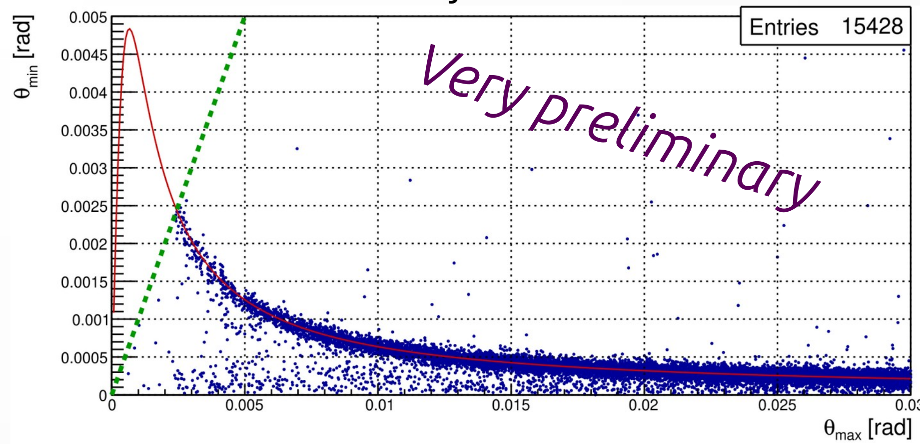


ECAL-based PID

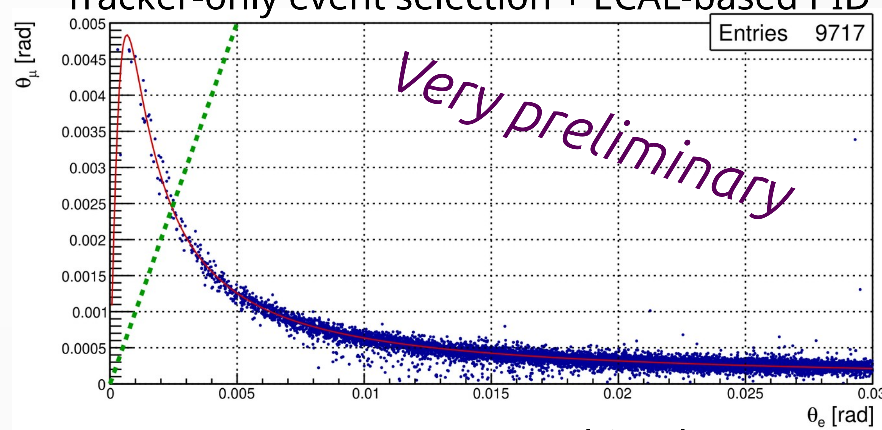
Correlation between ECAL energy deposit and θ_e reconstructed in the tracker



Tracker-only event selection



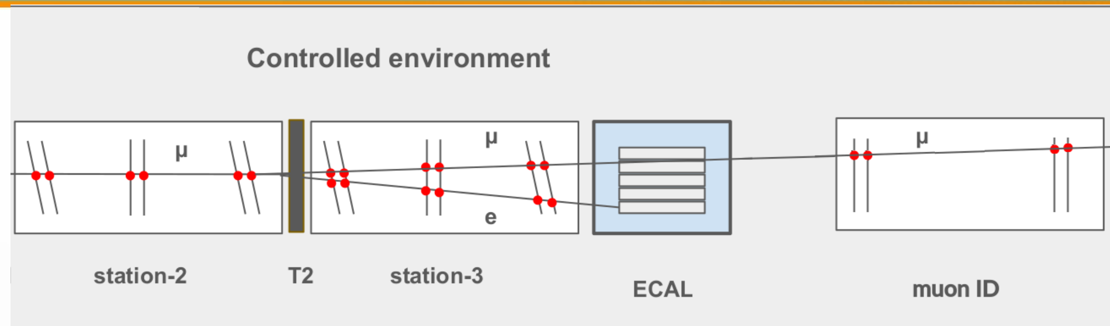
Tracker-only event selection + ECAL-based PID



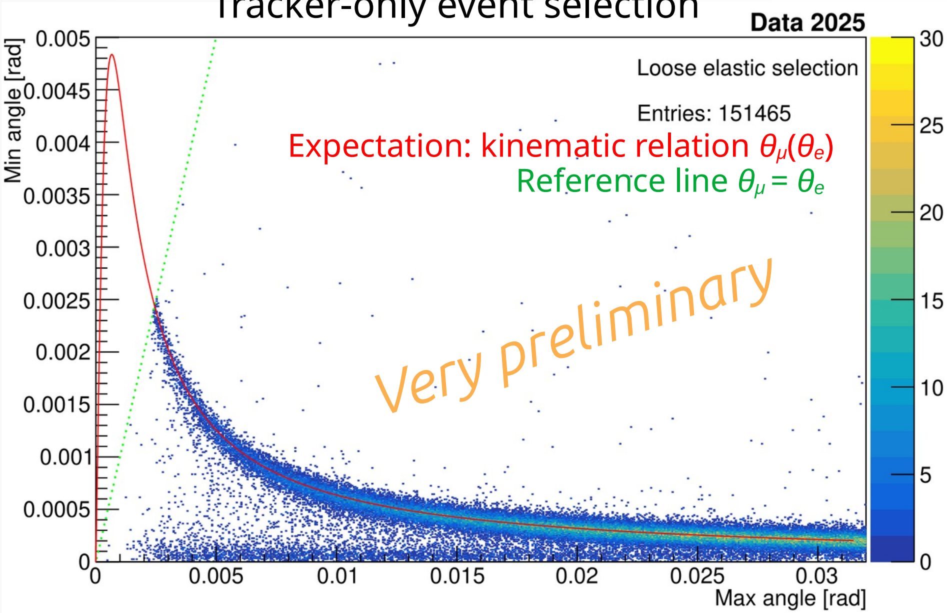
- ECAL energy > 1 GeV
- Loose elastic selection
- Matching between candidate e^- track and ECAL cluster centroid

Muon ID-based PID

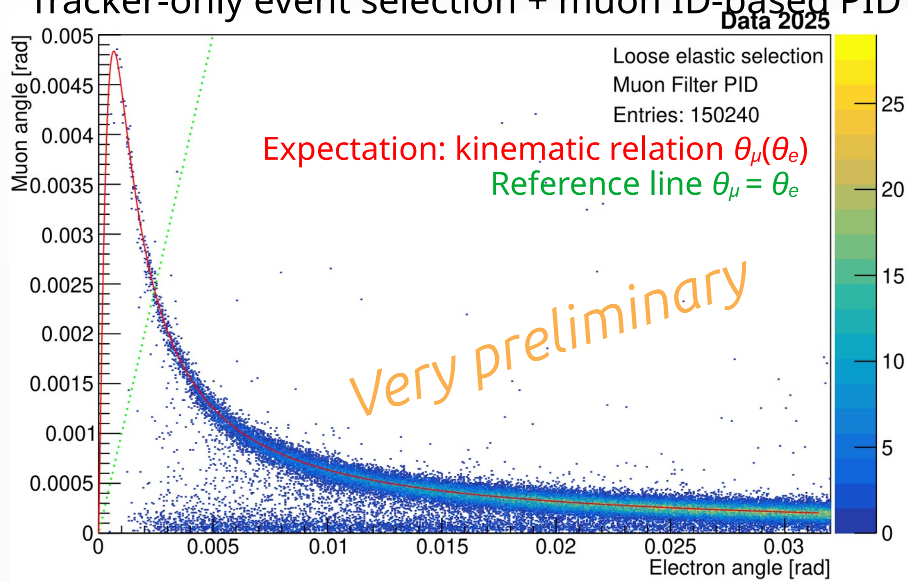
- Propagate tracks to the Muon ID
- Look for matching between a track and muon ID hits: select the muon track



Tracker-only event selection



Tracker-only event selection + muon ID-based PID

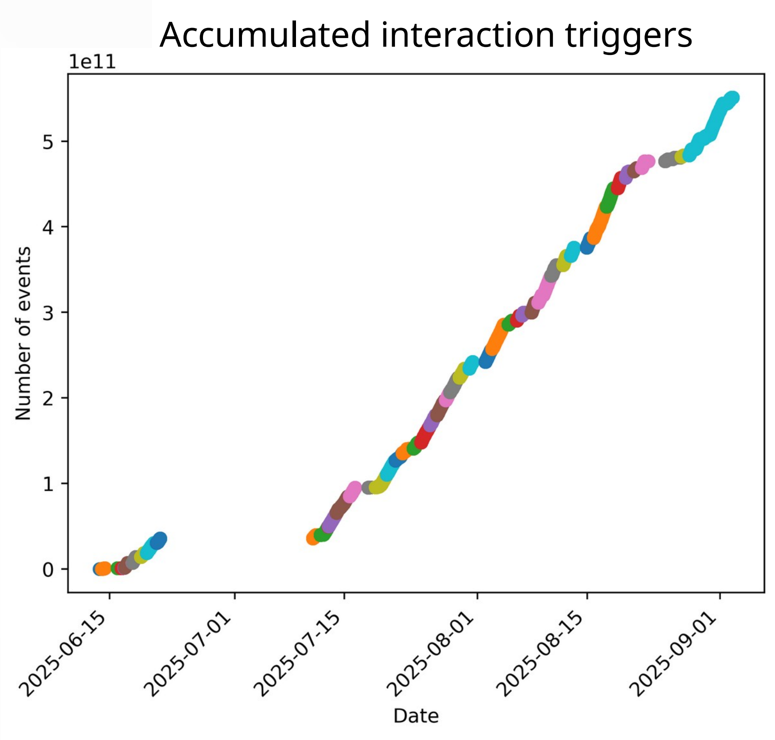


Work in progress: ECAL + muon ID combined PID

Conclusions

MUonE web site

- MUonE 2025 Test Run:
    - Successful ~3 months data taking with 3 stations (2 targets), ECAL and muon ID.
    - Integration of the BMS in the main DAQ in the last few days of run.
    - Opportunity to run further tests parasitically in September (no ECAL).



- Analysis campaign underway. Goals:
    - Proof of principle measurement of $\Delta\alpha_{lep}(t)$ (and comparison with 2023 data).
    - Preliminary measurement of $\Delta\alpha_{had}(t)$ (~20% statistical error + similar systematic).
    - Study systematic effects.

- 2025 data will serve as a basis for the full-scale experiment proposal (40 tracking stations + ancillary detectors) to be prepared during the CERN Long Shutdown 3.

BACKUP

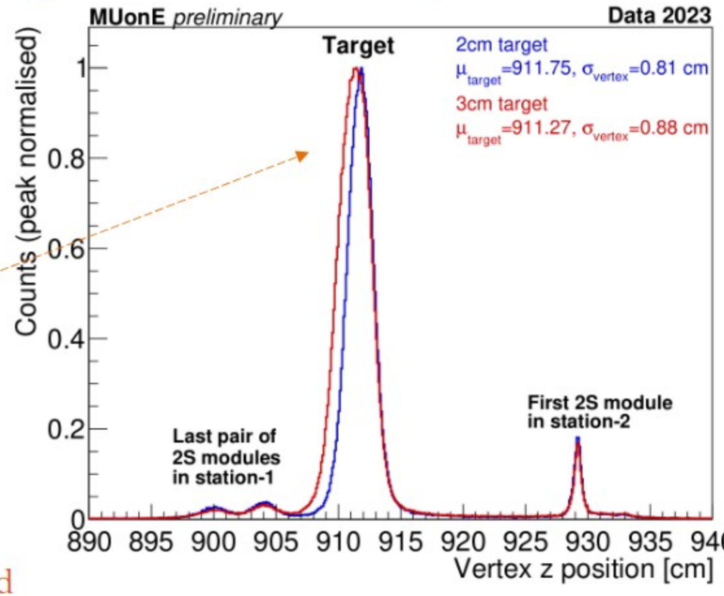
Data-MC comparison of elastic events

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:

$$\rho = (1.83 \pm 0.01) g/cm^3$$
+
$$d_{target} = (3.000 \pm 0.001)\ cm$$

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

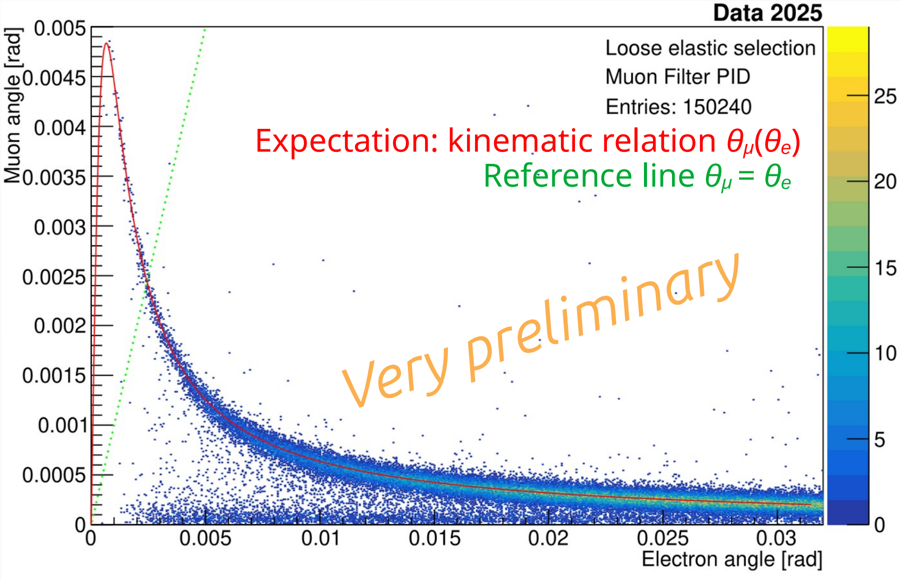
$\epsilon_{hw} = 0.850 \pm 0.035$:
2 tracks reconstruction efficiency which depends on modules efficiency
($\epsilon_{mod} = 0.980 \pm 0.005$)

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

Muon ID-based PID event selection

- 1stub/module for each track
- 1 track in the station before target; 2 tracks in the station after target
- No stubs shared between different tracks
- $|z_{vtx} - z_{target}| < 2$ cm
- Reject acoplanar events (acoplanarity < 0.4 rad)

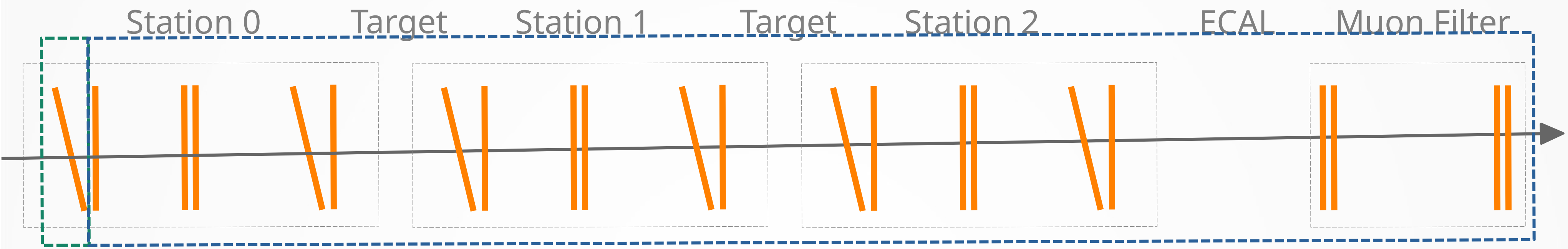
Tracker-only event selection + muon ID-based PID



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

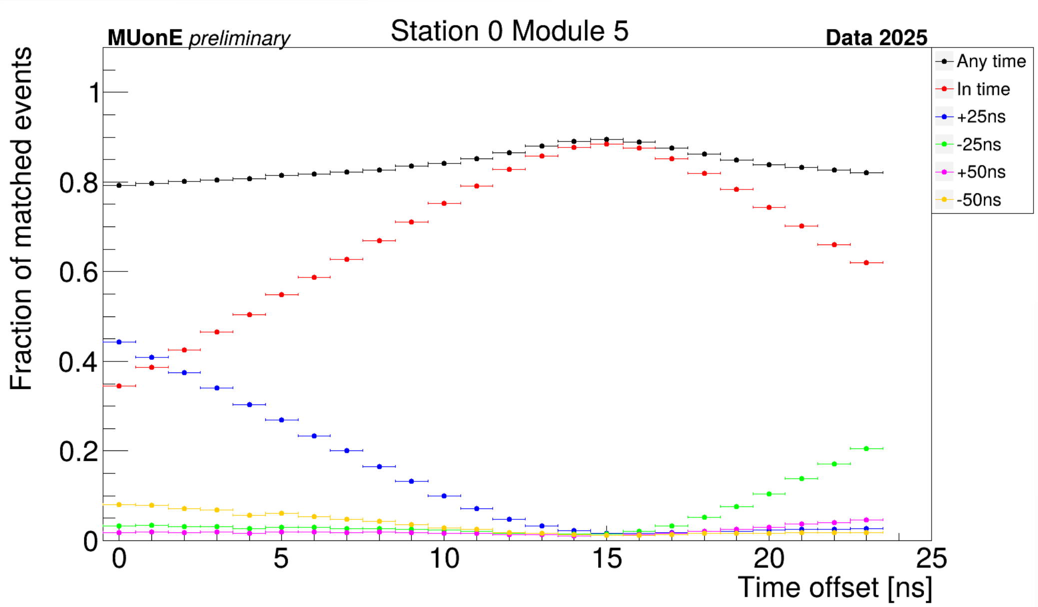
Source of systematic error	Uncertainty on the systematic source	Uncertainty on $\Delta\alpha_{had}$	Uncertainty on $d\sigma$
Intrinsic angular resolution	0.5%	10%	200 ppm
Multiple scattering	1%	10%	200 ppm
Beam energy scale	25 MeV	10%	200 ppm
z coordinate	100 μm	10%	200 ppm
Beam energy spread (3.75%)			
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**

TR 2025 – tracker time synchronisation



Delay:
12 ns

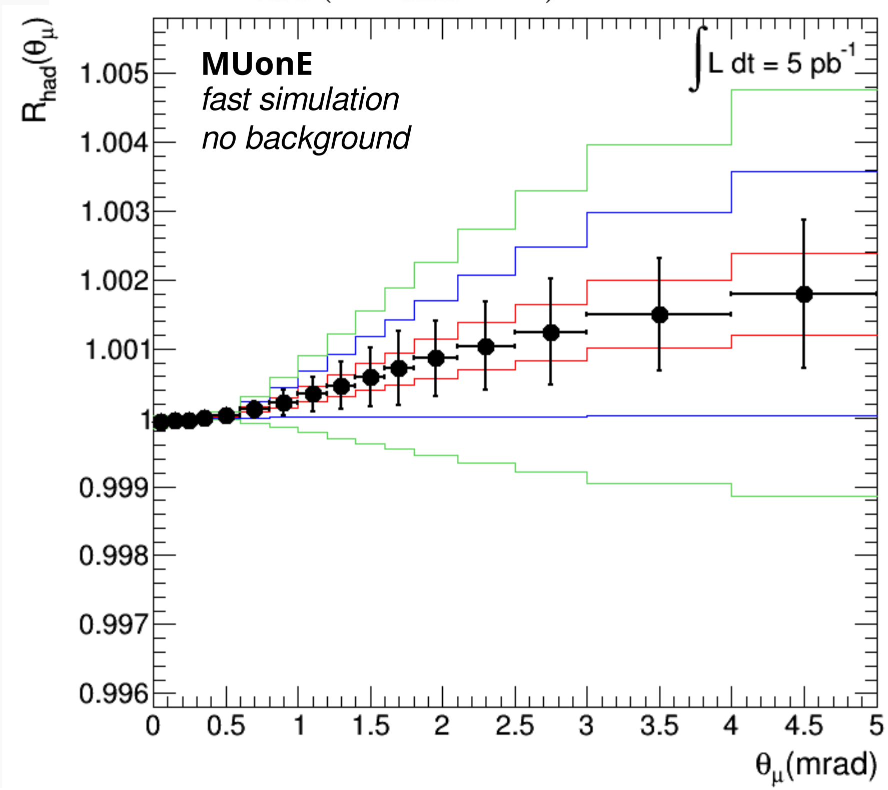
Delay scanned [0, 24] ns



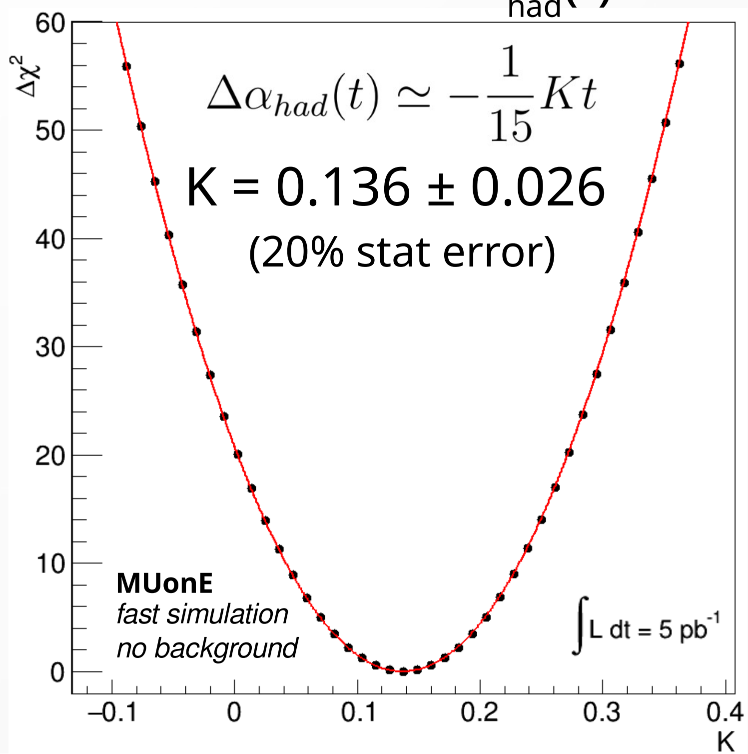
First measurement of $\Delta\alpha_{had}(t)$

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

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



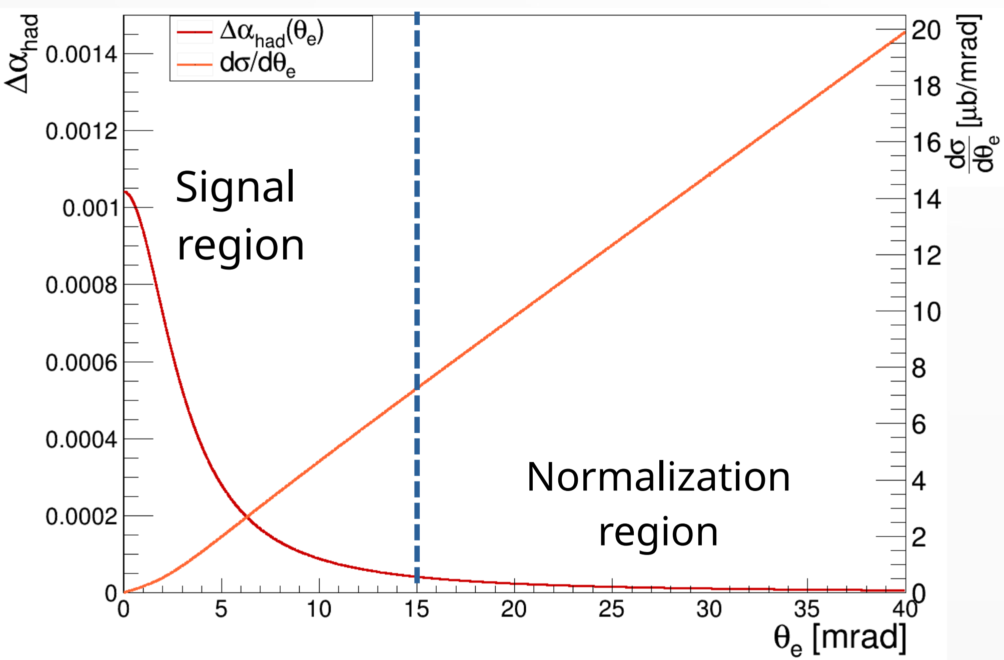
Template fit procedure
to extract $\Delta\alpha_{had}(t)$



Strategy for the systematic effects

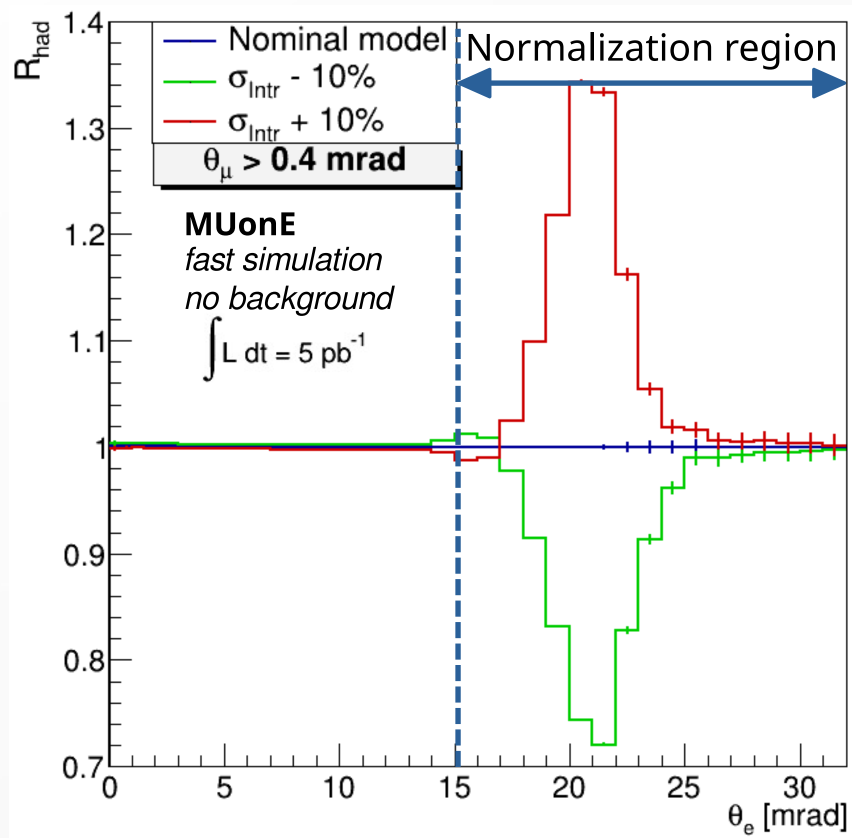
Promising strategy:

- 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:

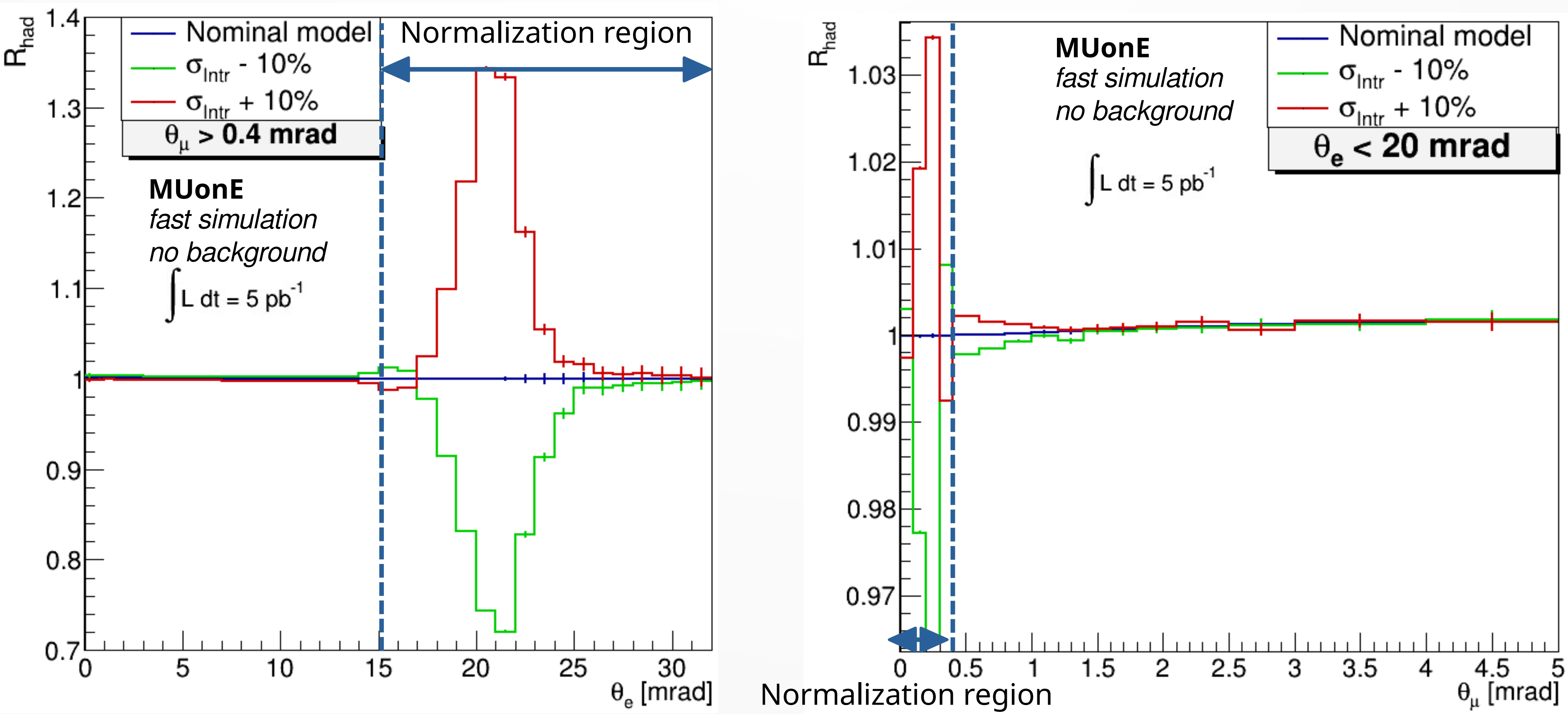
±10% systematic error on the angular intrinsic resolution



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

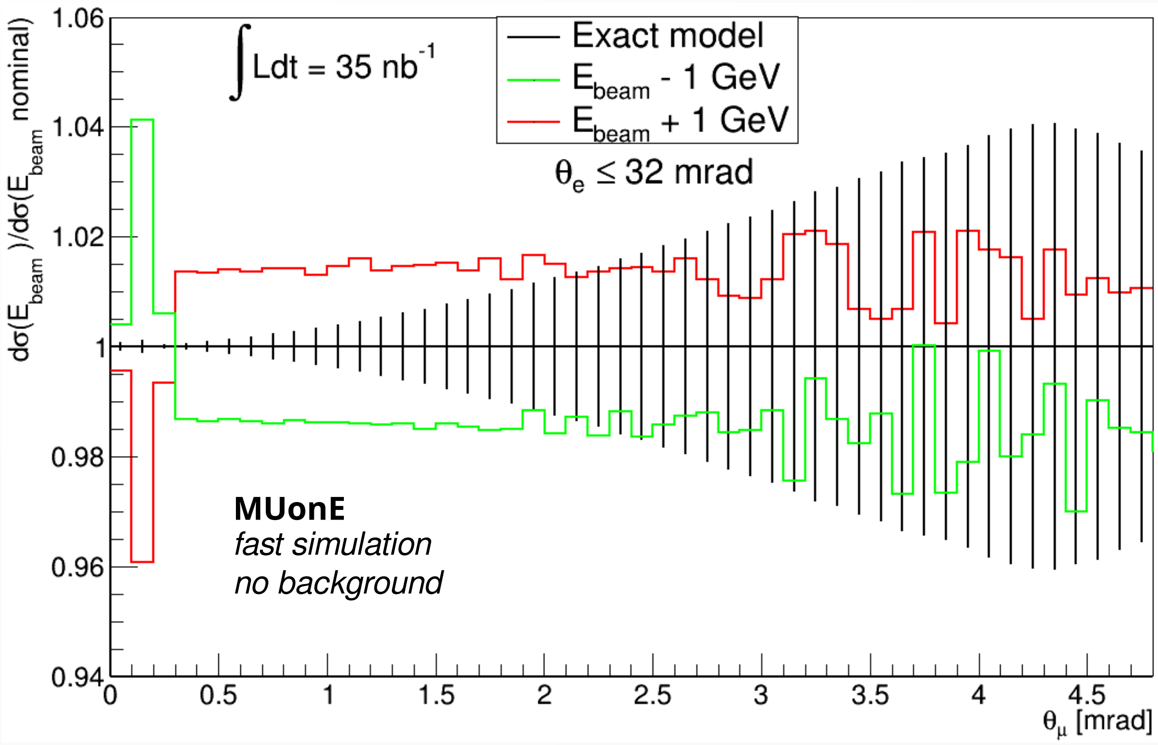
Example: ±10% error on the angular intrinsic resolution



Systematic error on the muon beam energy

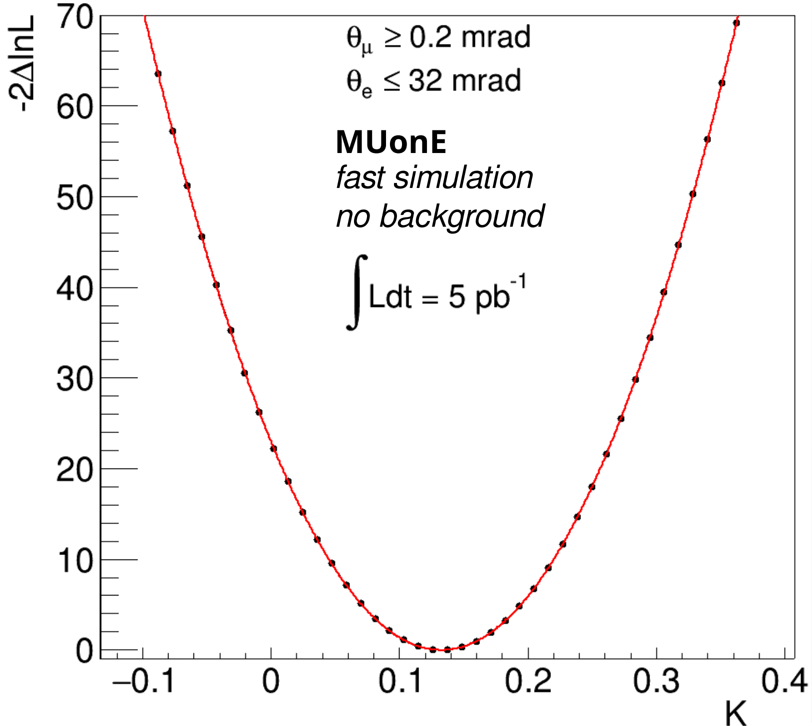
Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV)

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

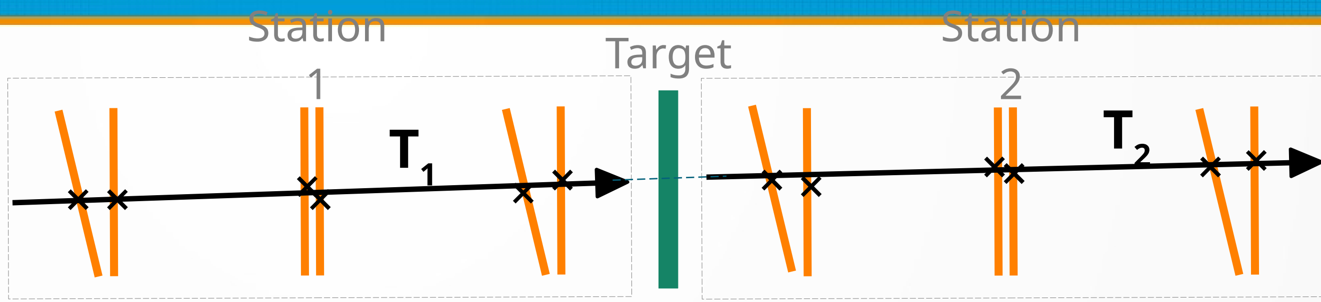
Selection cuts	Fit results
$\theta_e \leq 32\,\text{mrad}$ $\theta_\mu \geq 0.2\,\text{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\text{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\text{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\text{E}_\text{Beam}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$

Similar results also for different selection cuts

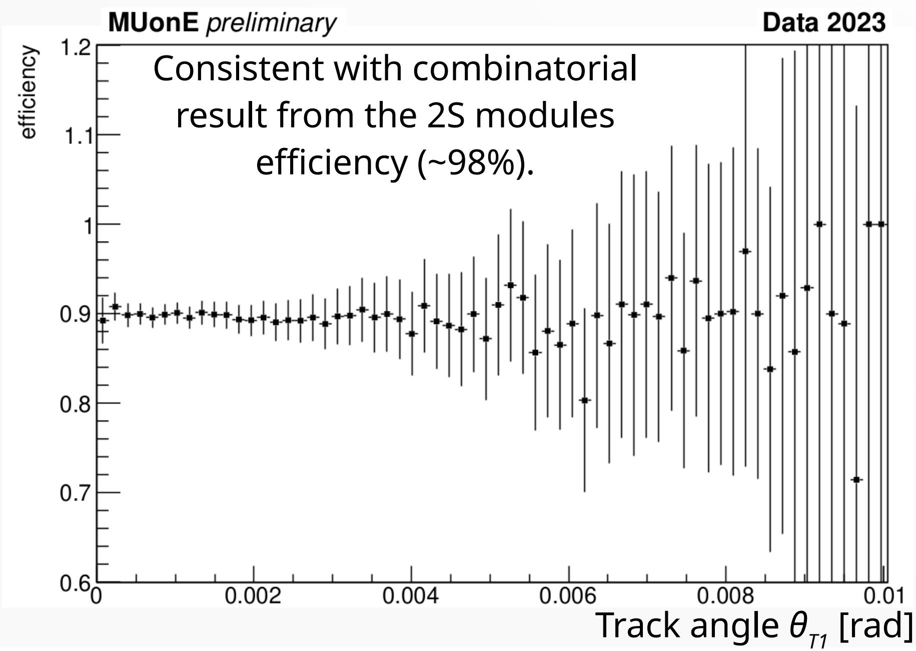
Input shifts identified correctly.
No degradation on the signal parameter

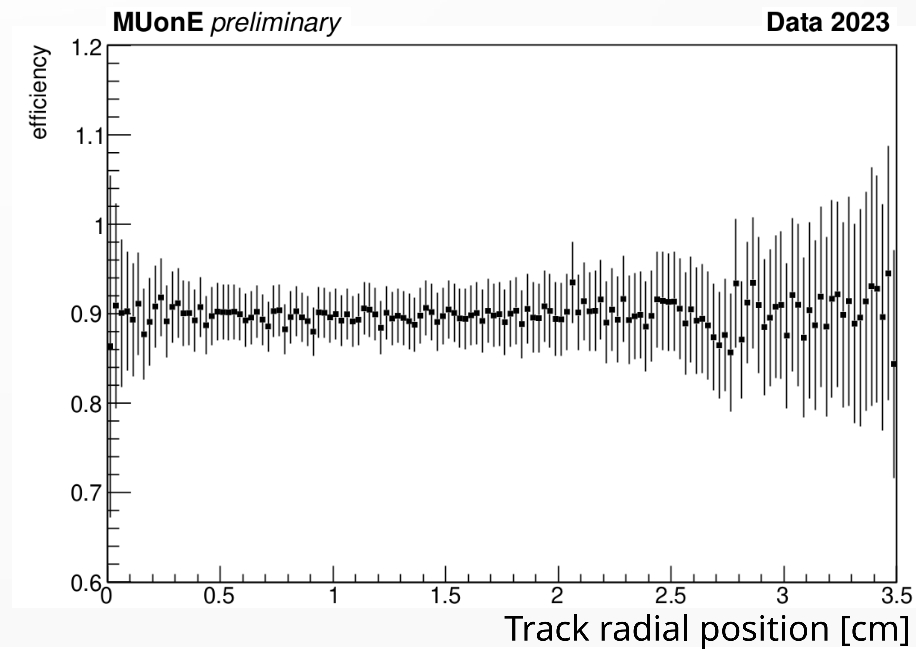
TR 2023 – tracking efficiency

Select events with <u>single passing muons</u>.



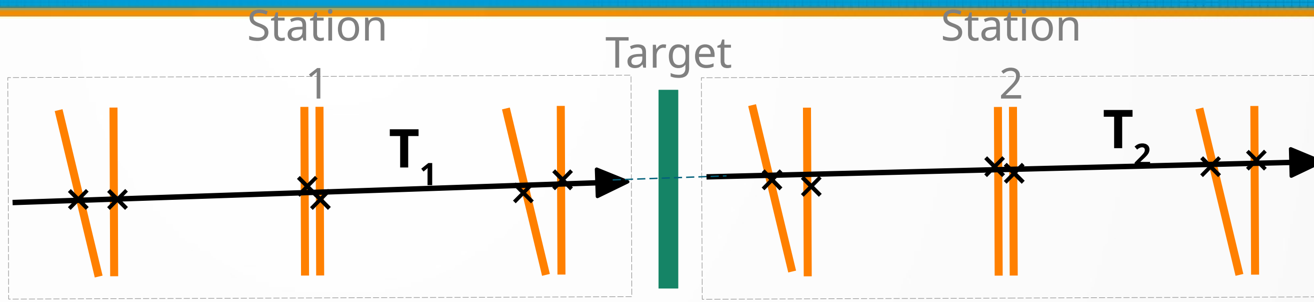
$$\text{Tracking efficiency} = \frac{N(T_2 \cdot T_1)}{N(T_1)}$$

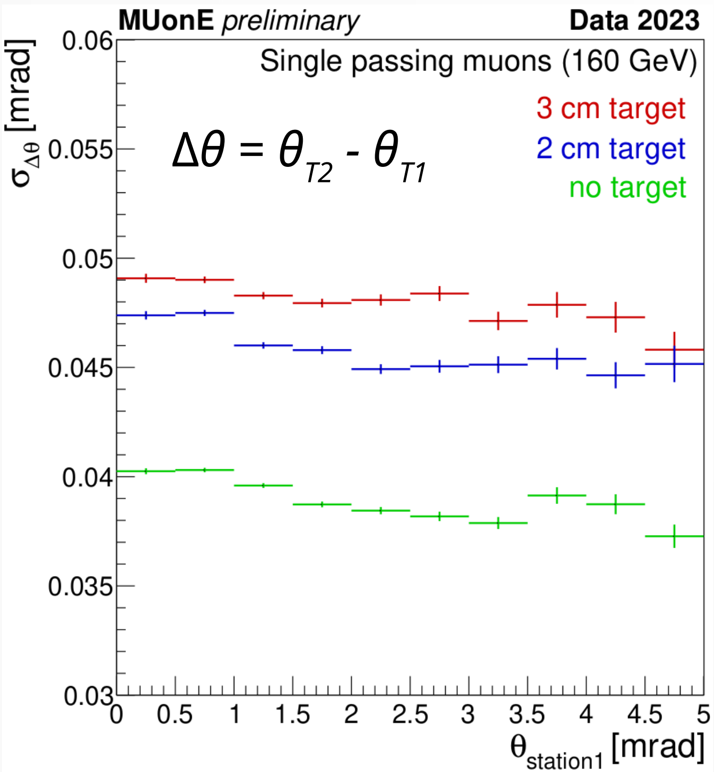




TR 2023 – angular resolution and MS effects

Select events with <u>single passing muons</u>.

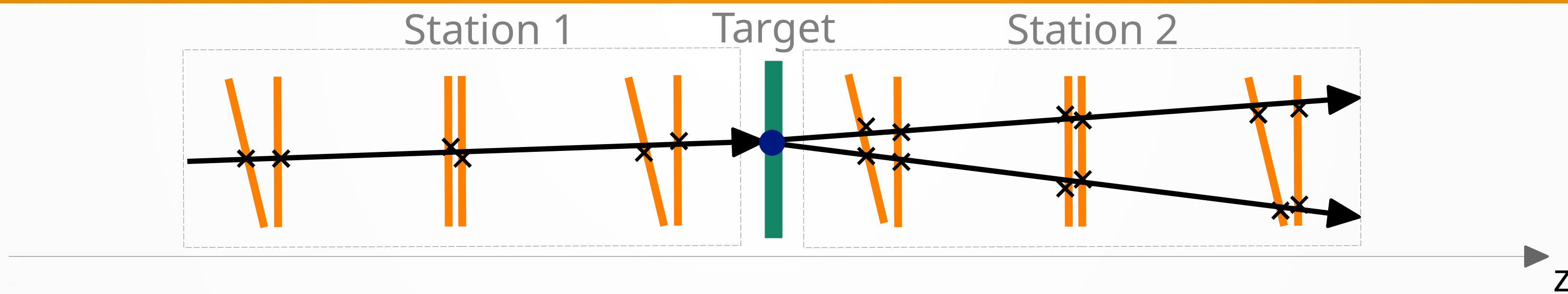


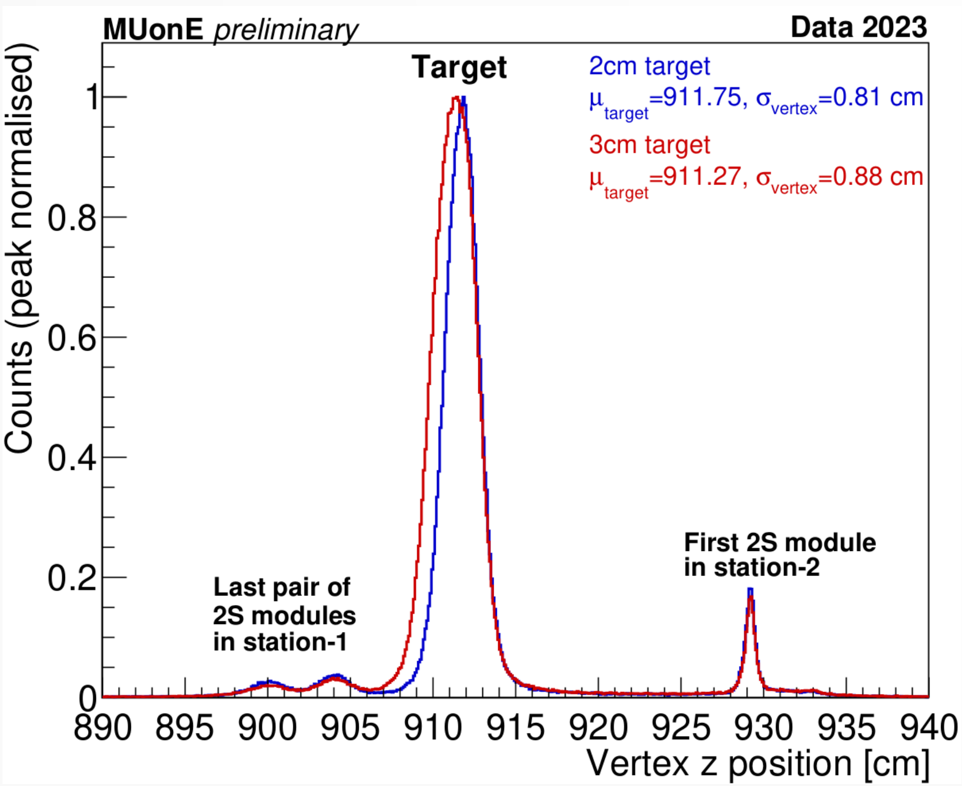


Target	$\sigma_{\Delta\theta}$ [μrad]	σ_{MS}(target) [μrad]	σ_{MS}^{PDG}(target) [μrad]
3 cm C	48.9 ± 2.1	28.1 ± 0.6	28.2
2 cm C	46.8 ± 2.1	24.3 ± 1.4	22.6
No Target	40.0 ± 2.2		

- Angular resolution of a station: ~28 μrad
- Target MS effects:
  good agreement with the expectations

TR 2023 – vertexing



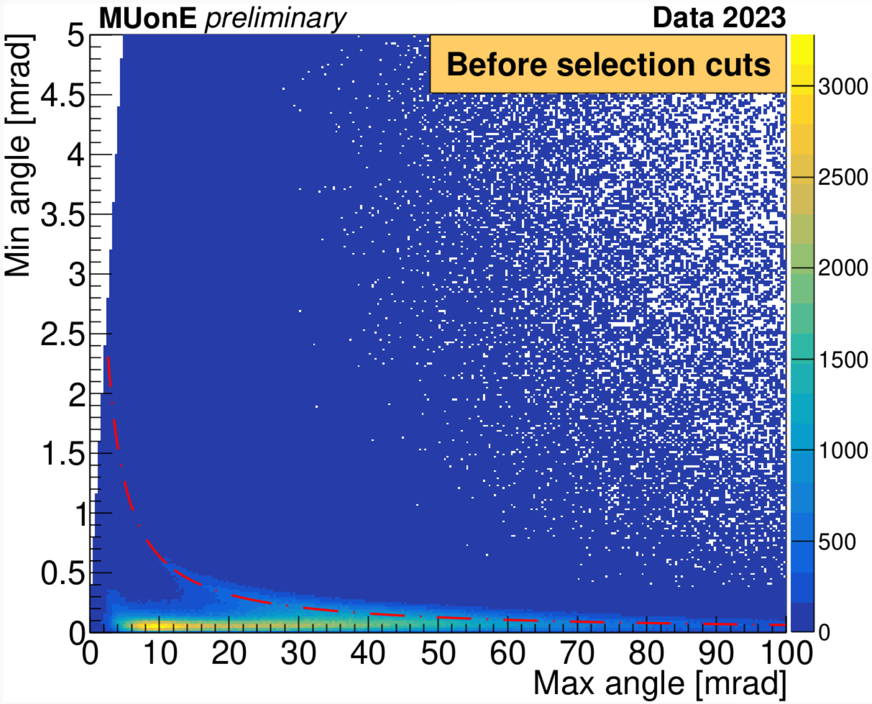


- Simple selection: events with 2 outgoing tracks within geometrical acceptance (0.2 – 32 mrad)
- The target center is shifted by 0.5 cm by changing between 3 cm and 2 cm target
- Interactions in the Si sensors are visible
- Vertex resolution: ~8 mm

TR 2023
μ-e elastic scattering event selection

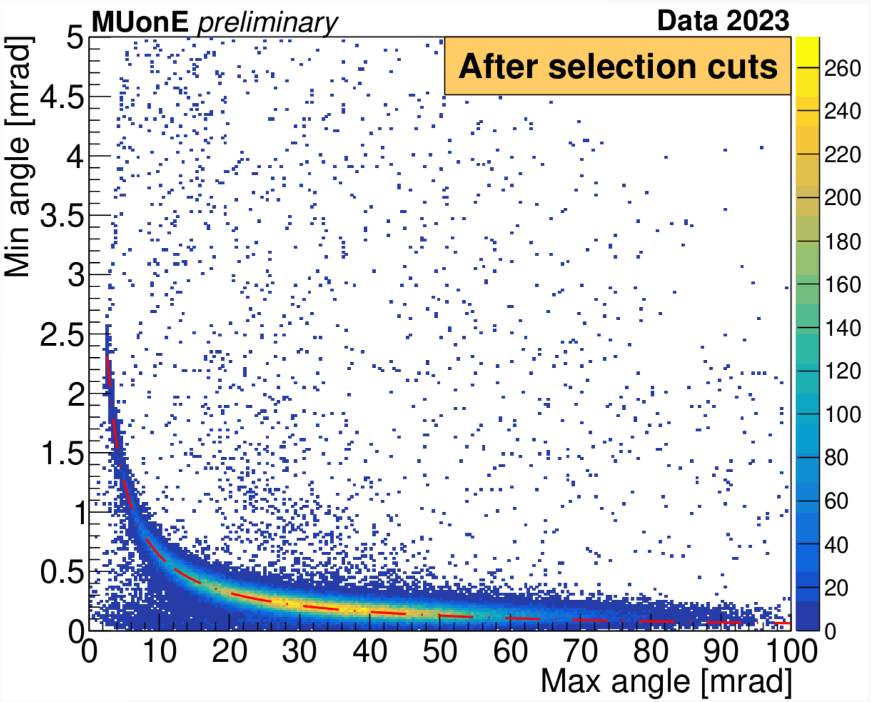
Pre-selection

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

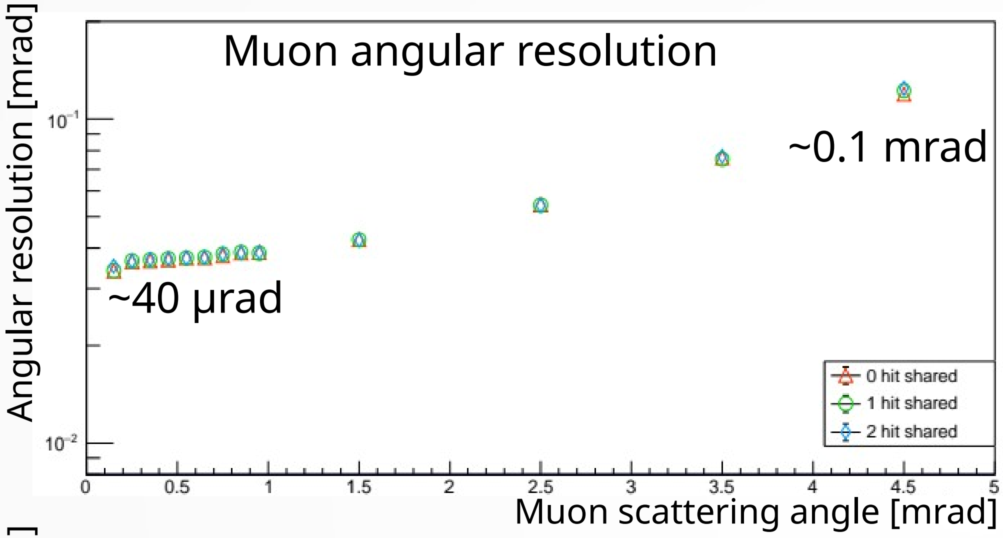


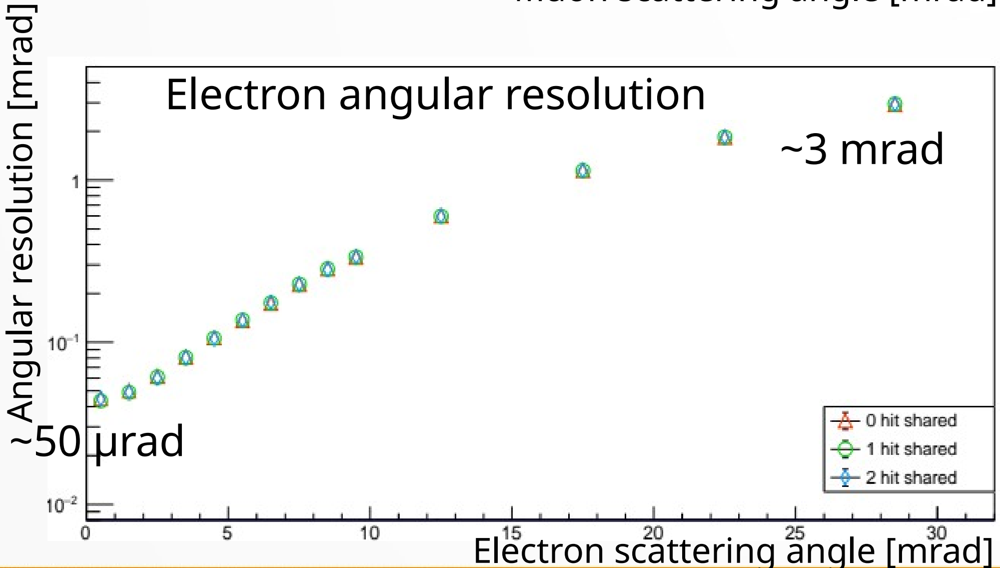
Initial event selection

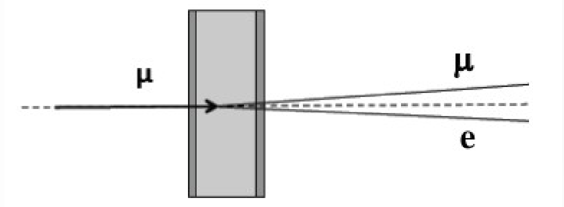
- ≥ 1 hit/module
- Cut on N_{hits}(station2)
- $|z_{vtx} - z_{target}| < 3$ cm
- Acoplanarity cut



TR 2023 - MC performance: angular resolution of scattered particles

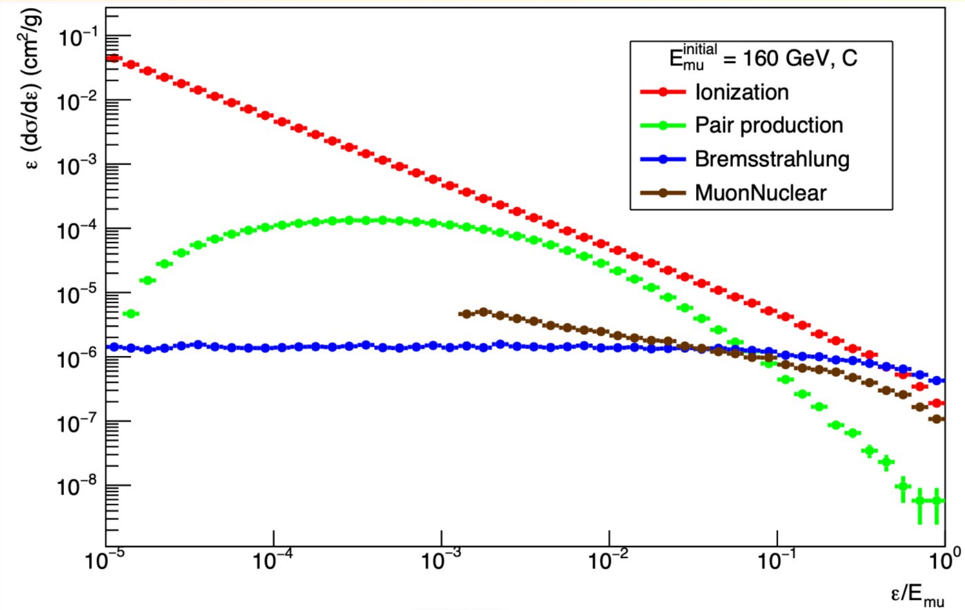


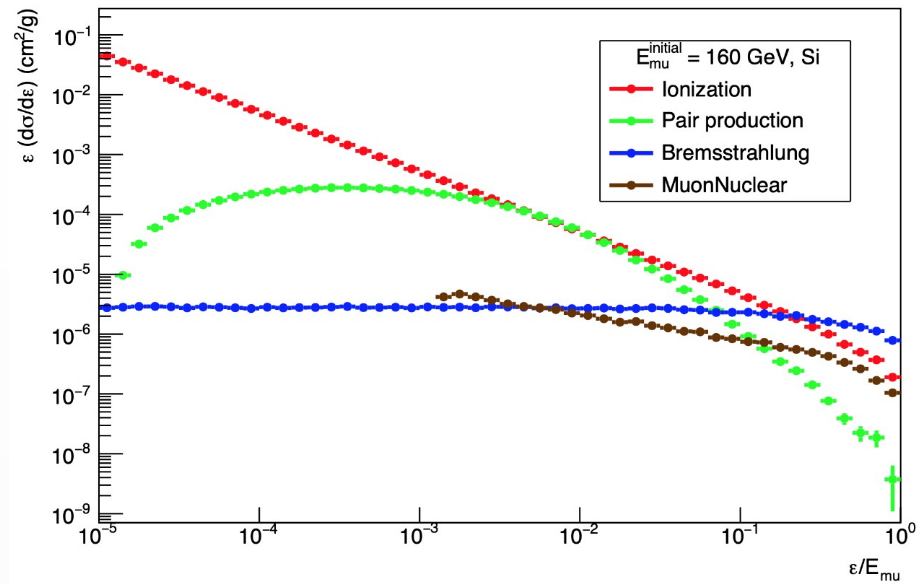




- Compare track reconstruction with MC truth.
- Muon angle: ~40 μrad resolution for small scattering angles.
- Electron angle: stronger impact of MS. Resolution is ~3 mrad for large scattering angles (E_e ~1–2 GeV).

Backgrounds





θ_e [mrad] 32 0

MESMER

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

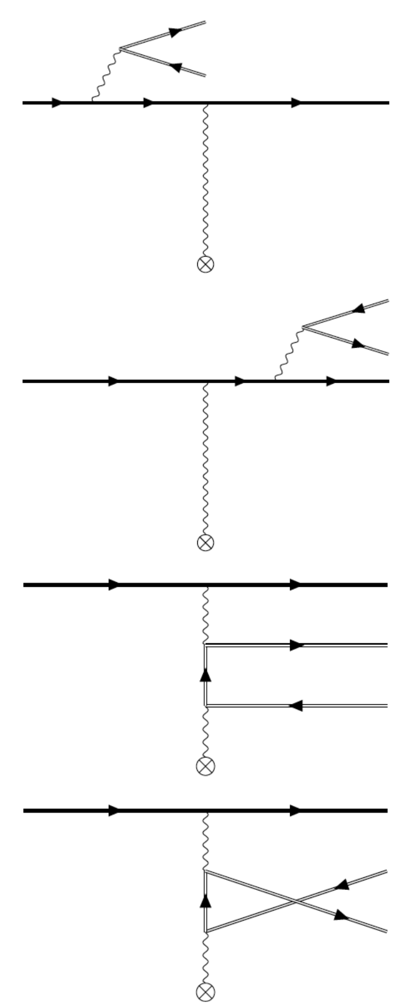
$l = e, \mu$

GEANT4

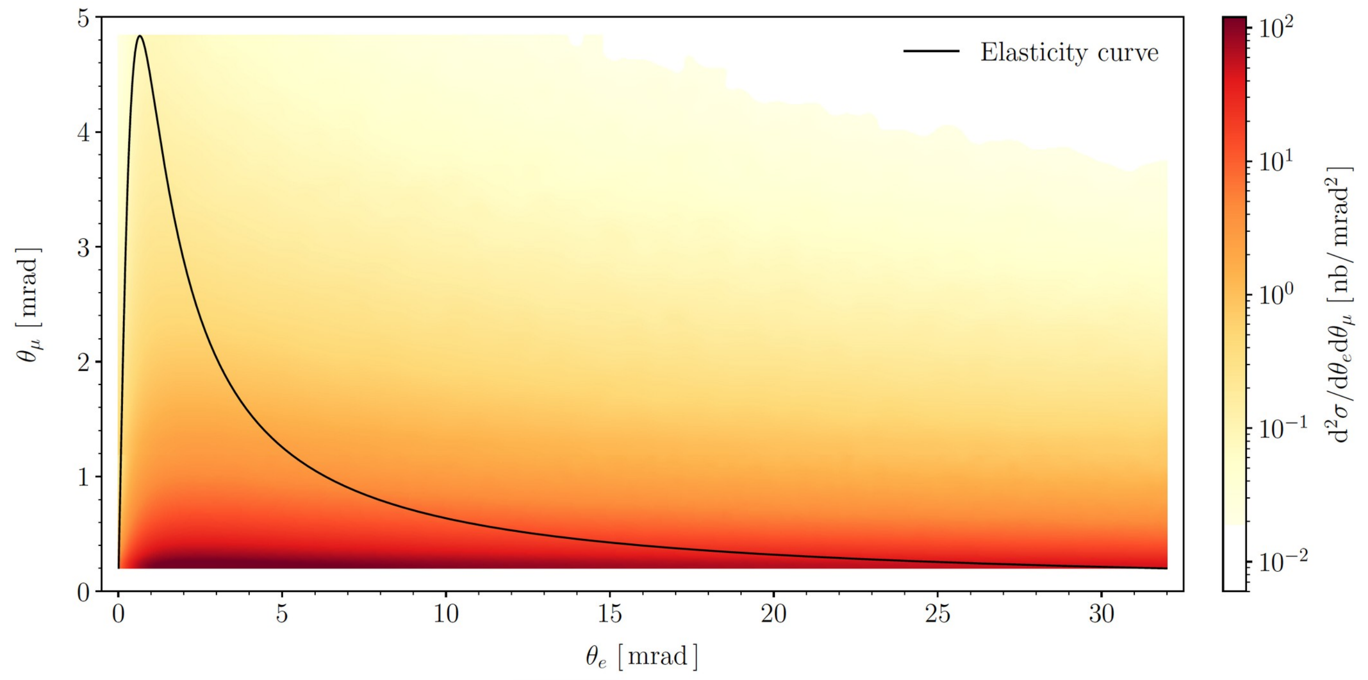
- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$

New Background MC generator

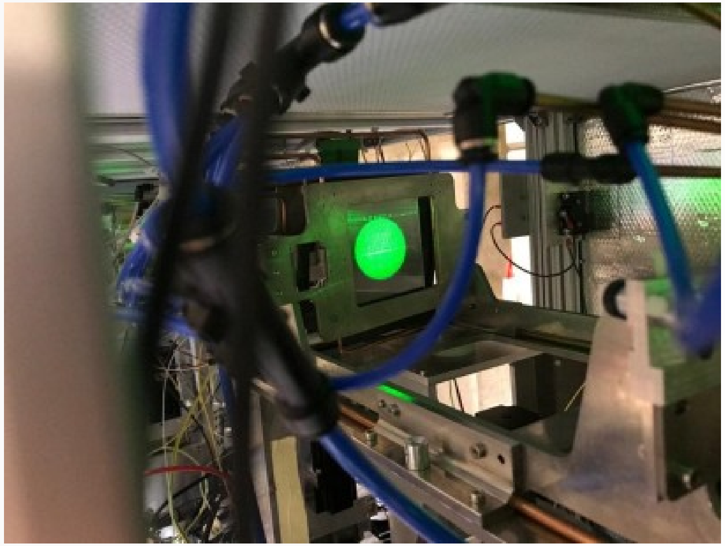
Main background: e+e- pair production
Implemented in MESMER
and interfaced with the MUonE detector simulation



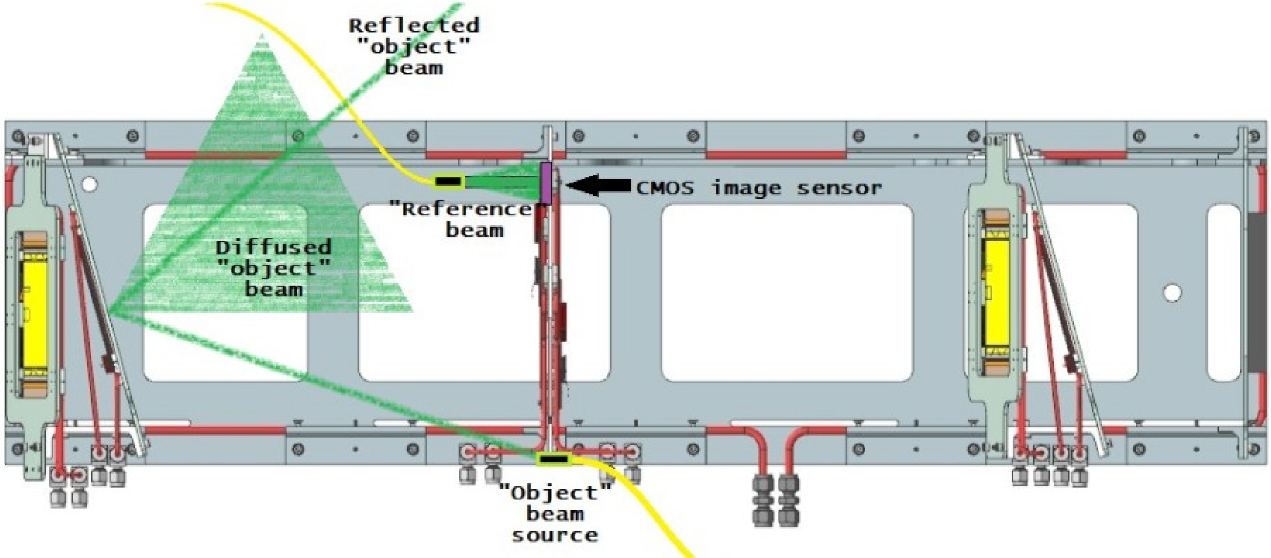
Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)



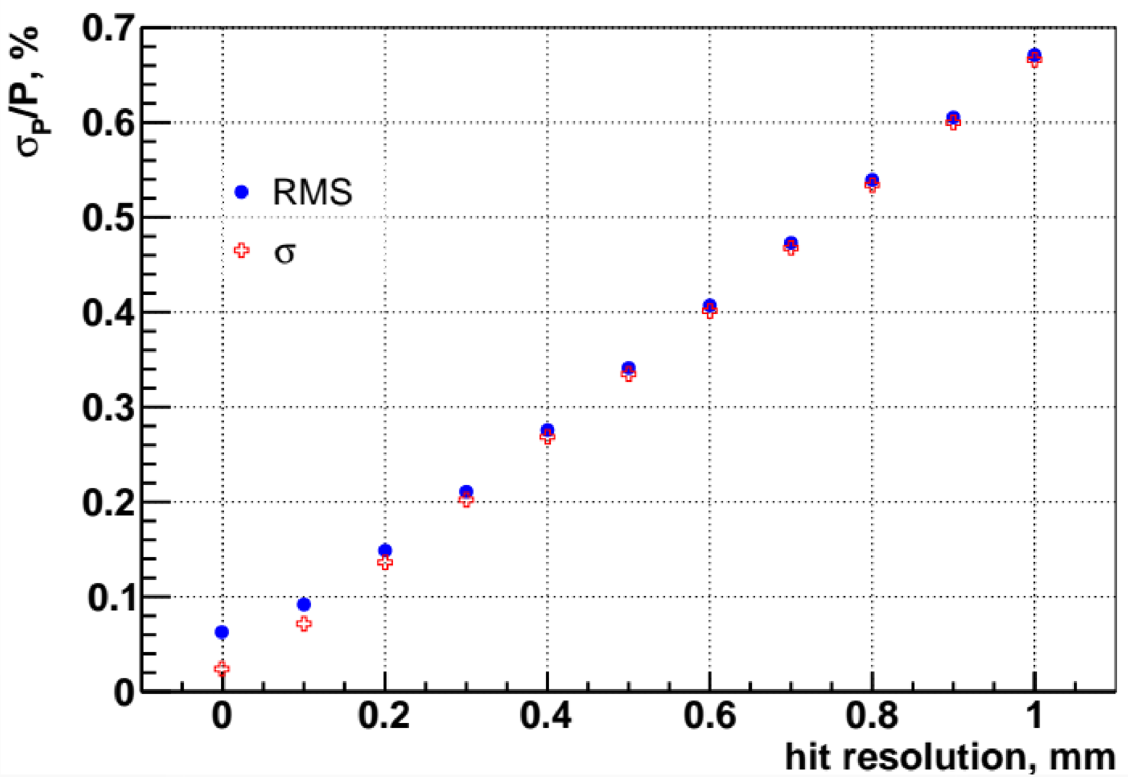
Laser holographic system



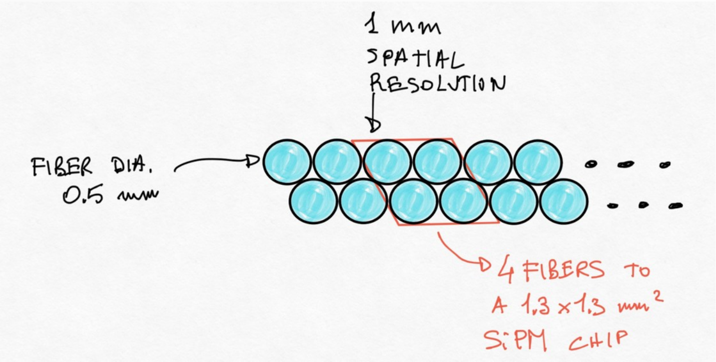
- Compare holographic images of the same object at different time
- Fringe pattern is related to deformations of the mechanical structure
- 532 nm fiber-coupled laser.
  Resolution: ~0.25 μm (half wavelength)
- Current limitation: Si sensors are sensitive to visible light → continuous monitoring is not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



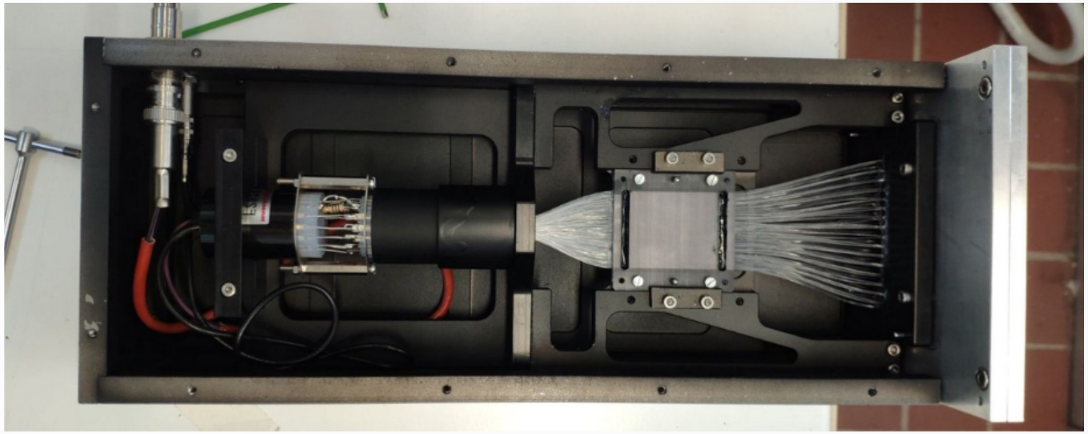
BMS (Beam Momentum Spectrometer)



Muon ID – SciFi



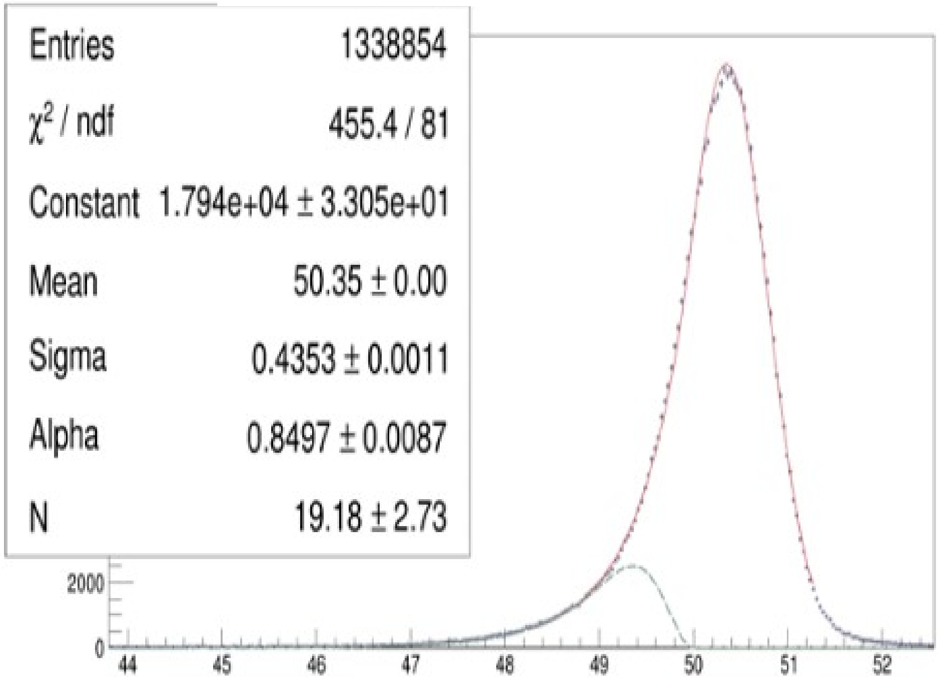
prototype



- Polistyrene round fibres. 4 fibres coupled to 1 SiPM.
- <0.5 ns timing resolution.
- Pitch: 1.25mm. Expected resolution: ~360 μm
- Same technology could be used as timing detector between BMS and main tracker.

e^- beam, 50 GeV

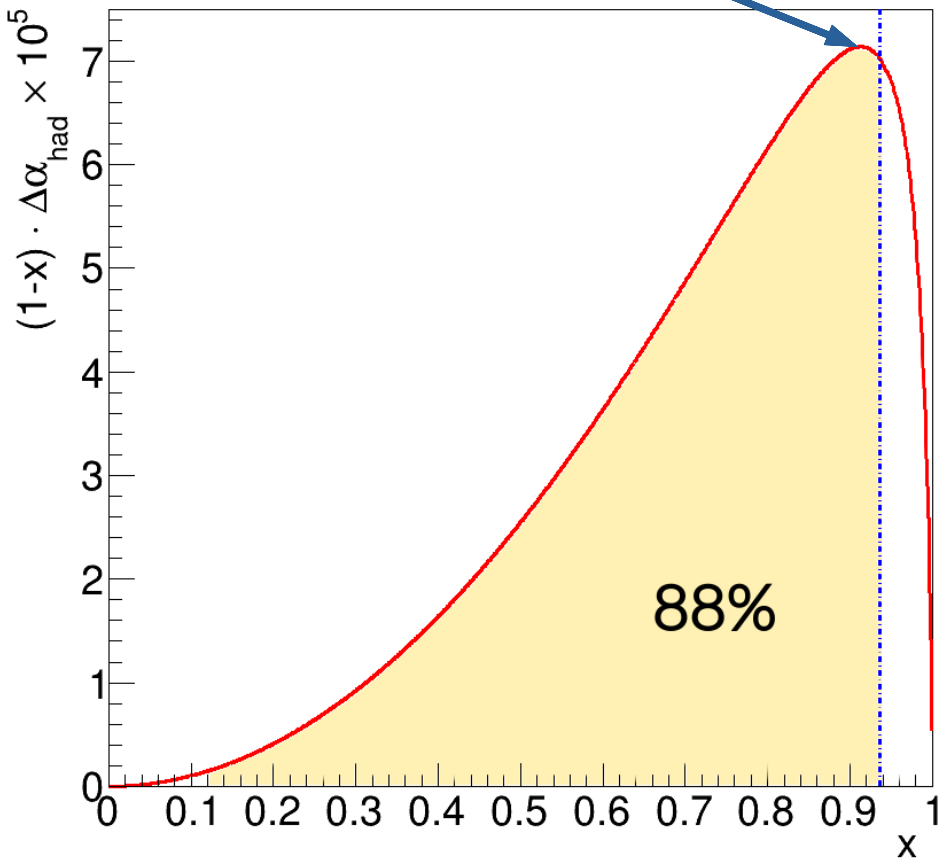
TB 2024, M2 beamline

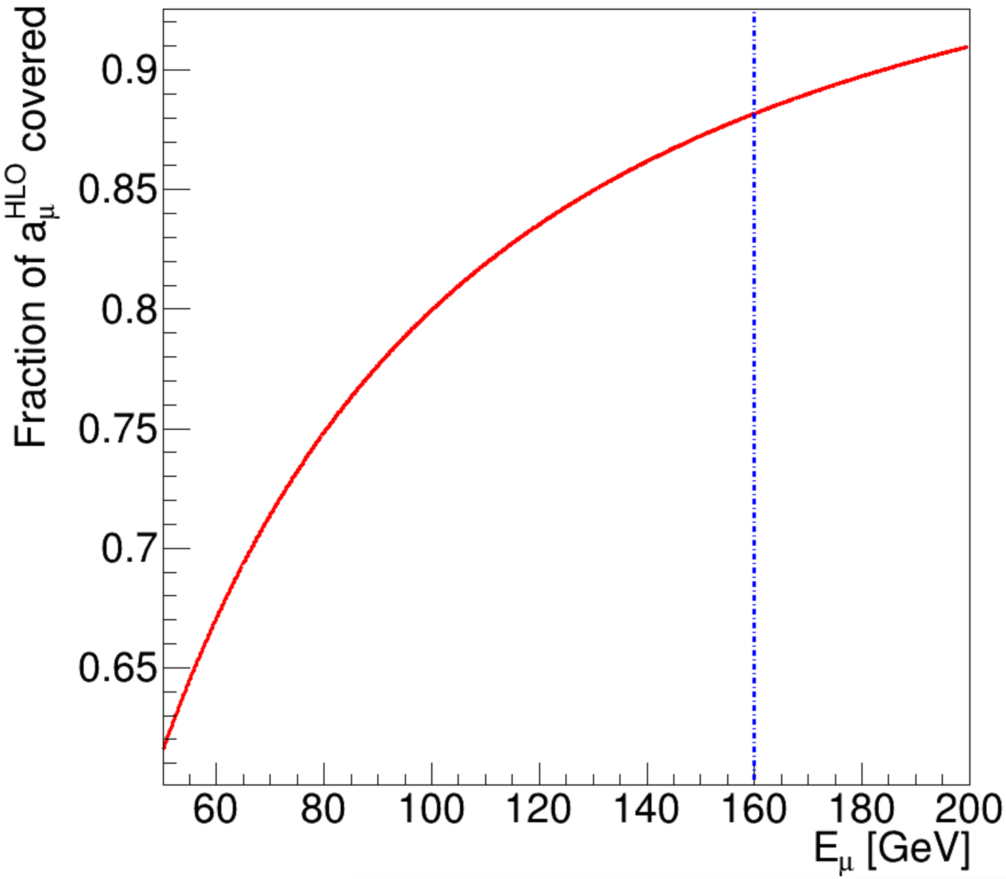


Energy 3x3 cluster in the ECAL [GeV]

$x < 0.936$

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



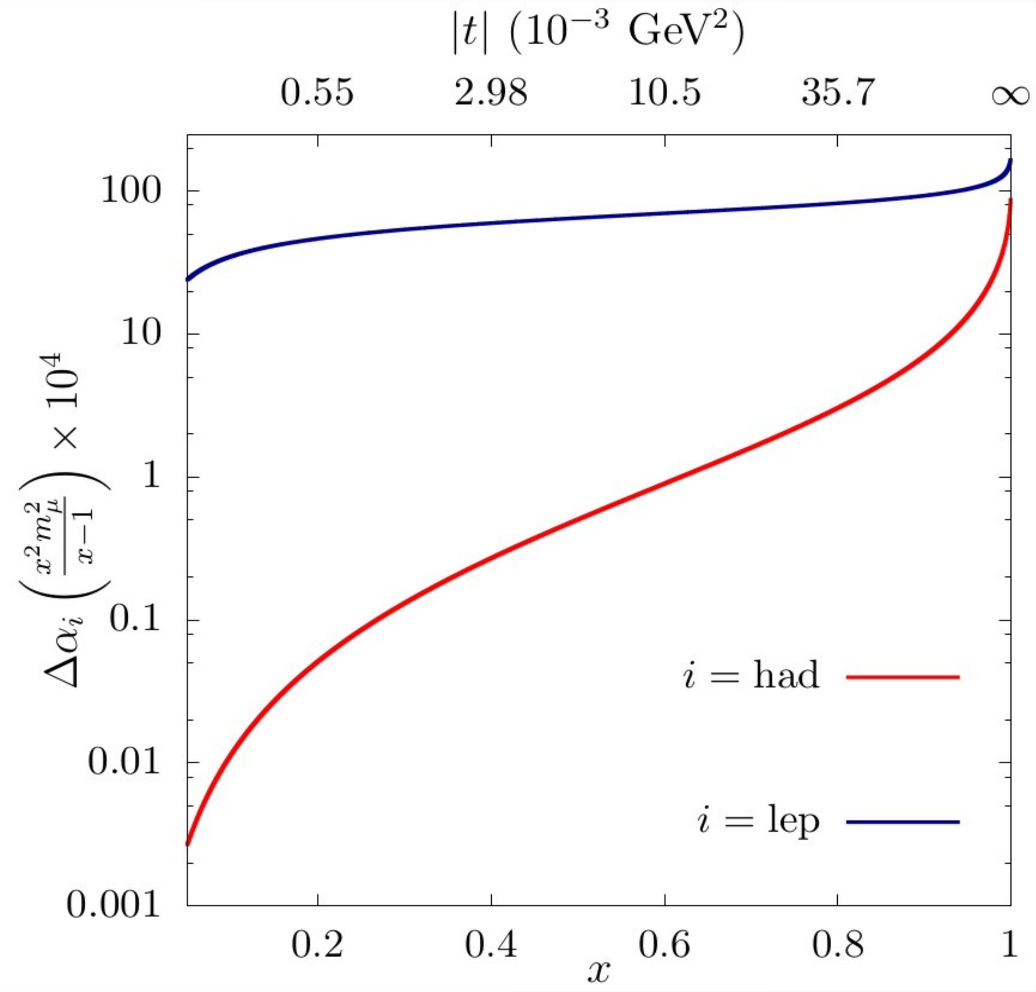


- 160 GeV muon beam on atomic electrons.

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

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

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



$\Delta\alpha_{had}$ parameterization

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

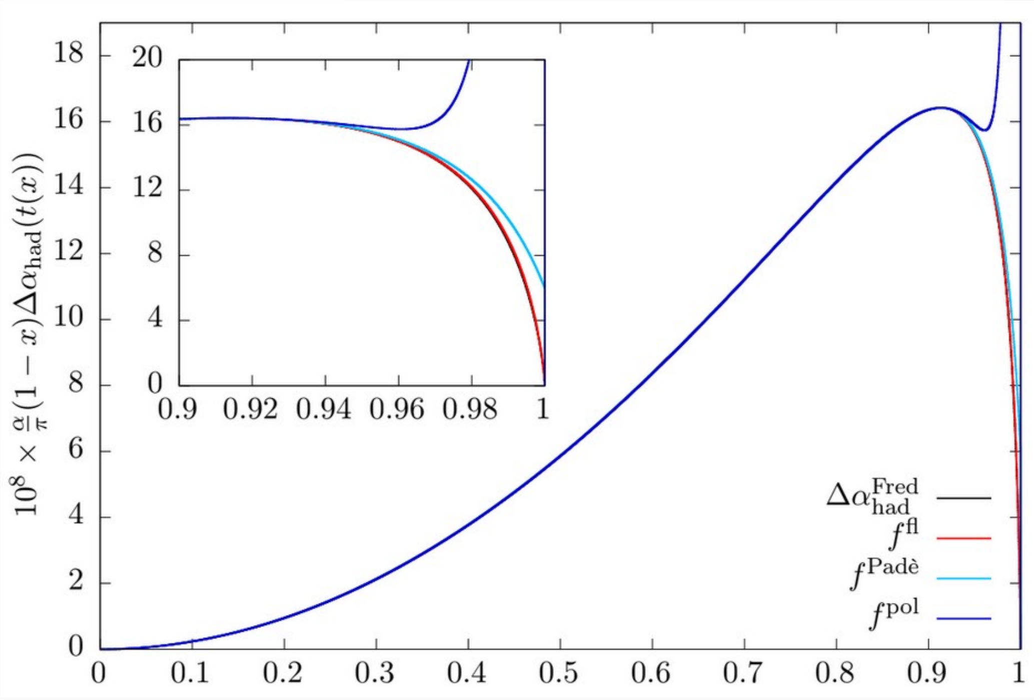
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

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

Dominant behaviour in the MUonE kinematic region:

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

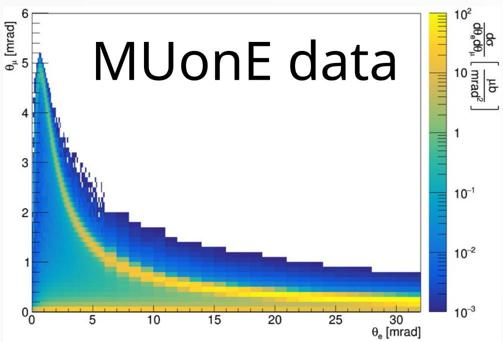


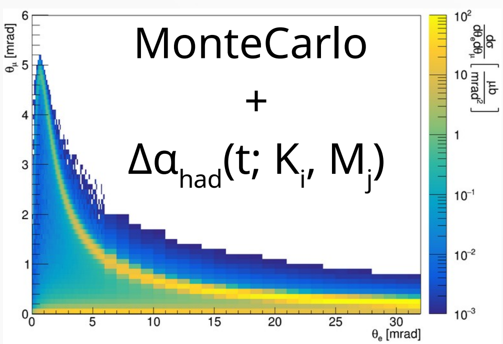
Extraction of $\Delta\alpha_{had}(t)$

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

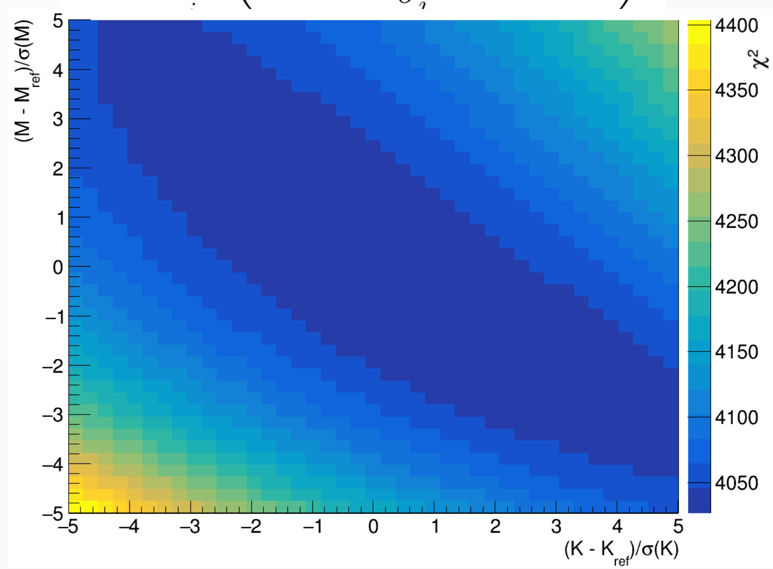
2 parameters:
K, M

Template fit to the 2D (θ_e, θ_μ) distribution:





$$\chi^2 = \sum_i^{\text{bins}}\left(\frac{\text{data}_i - \text{templ}(K, M)_i}{\sigma_i^{\text{data}}}\right)^2$$



Extraction of a_μ^{HLO}

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

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

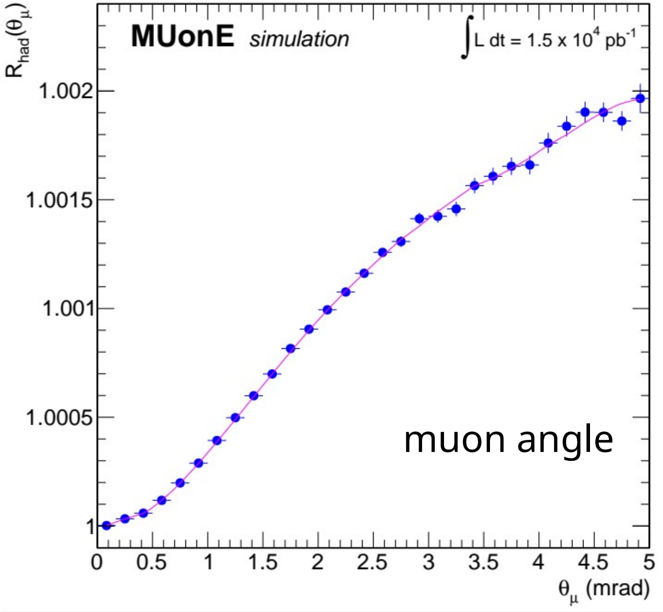
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

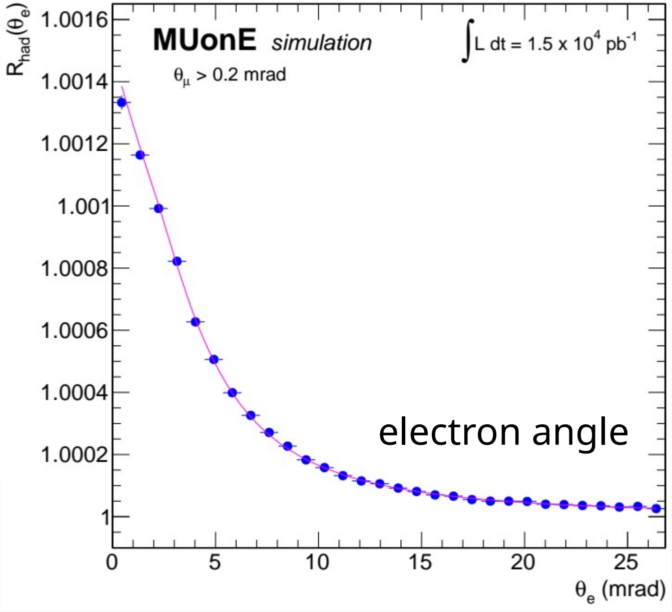
Results from fast simulation assuming the final statistics:

$a_\mu^{HLO} = (688.8 \pm 2.4)\ 10^{-10}$

Input value:

$a_\mu^{HLO} = 688.6\ 10^{-10}$





Alternative method to compute $a_\mu^{\rm HLO}$ from MUonE data

Ignatov, RP, Venanzoni, Teubner, Phys. Lett. B 848 (2024) 138344

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

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

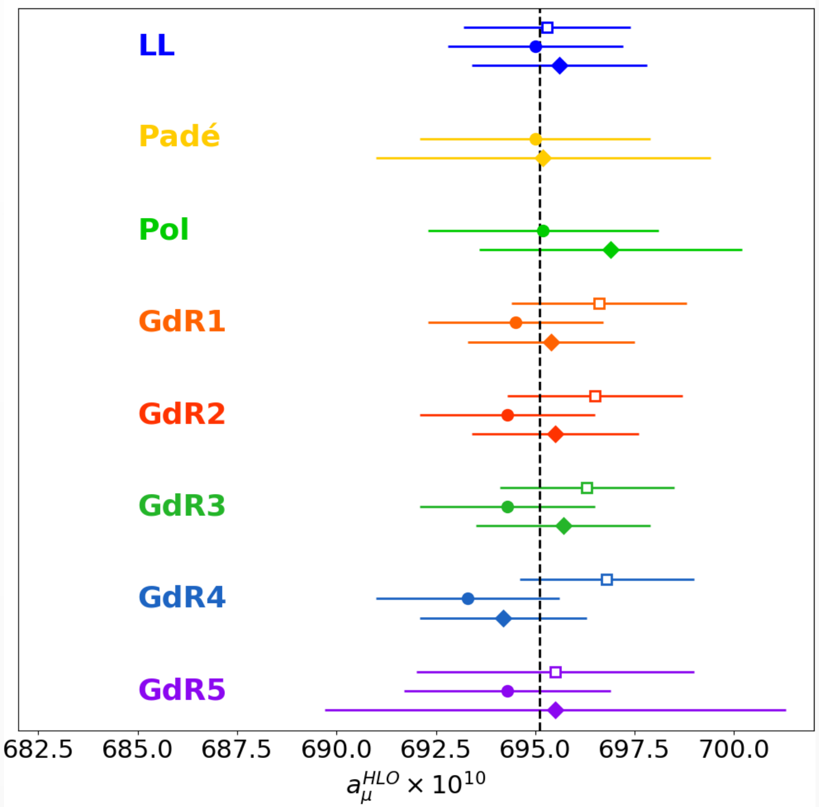
MUonE 99%

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

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

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

Time-like data + pQCD 1%



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