Status of the MUonE experiment

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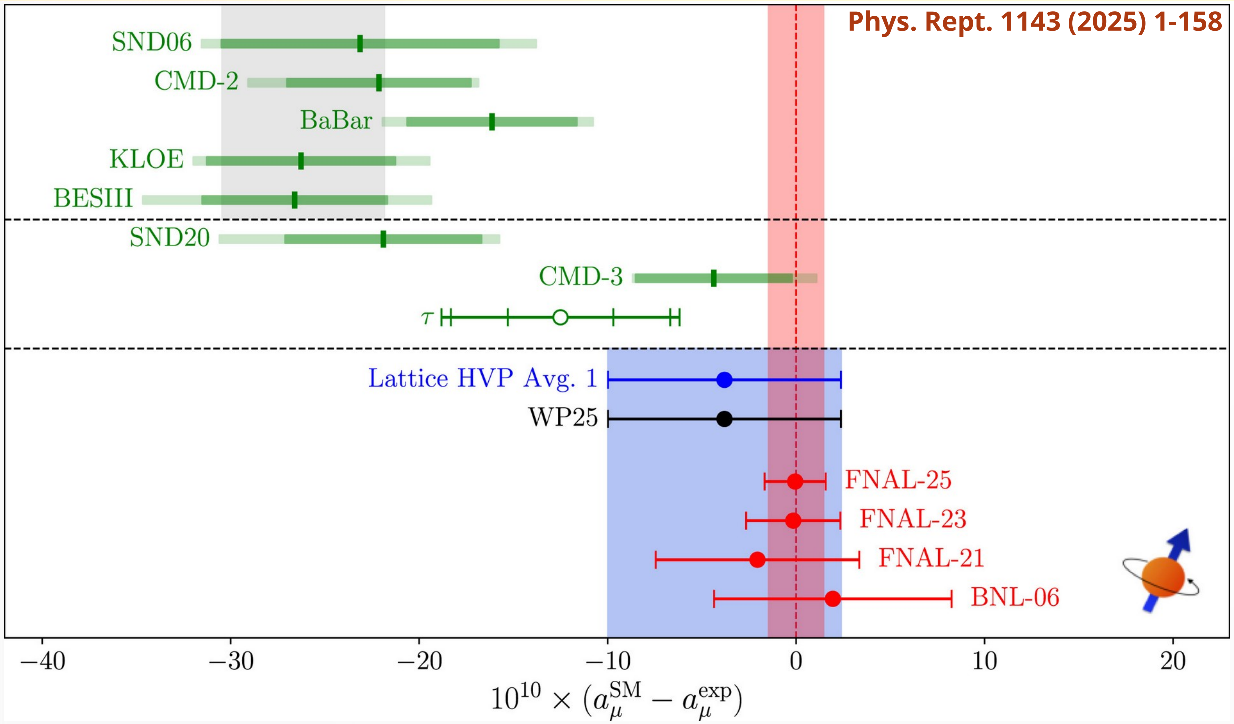
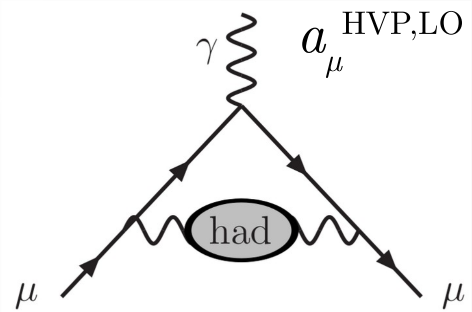
Workshop on Flavour changing and conserving processes
Anacapri, 30th September 2025

Muon g-2: current status





Main source of uncertainty of the theoretical prediction

Tensions in the evaluation of $a_\mu^{HVP,LO}$ using lattice QCD (WP2025) or e^+e^- hadronic cross sections

A clarification of the theoretical prediction is needed

The MUonE experiment

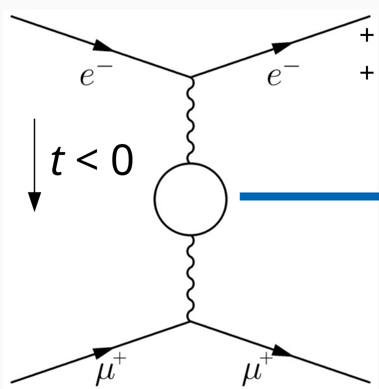
Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026
Proposal for Phase 1 of the MUonE experiment

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

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

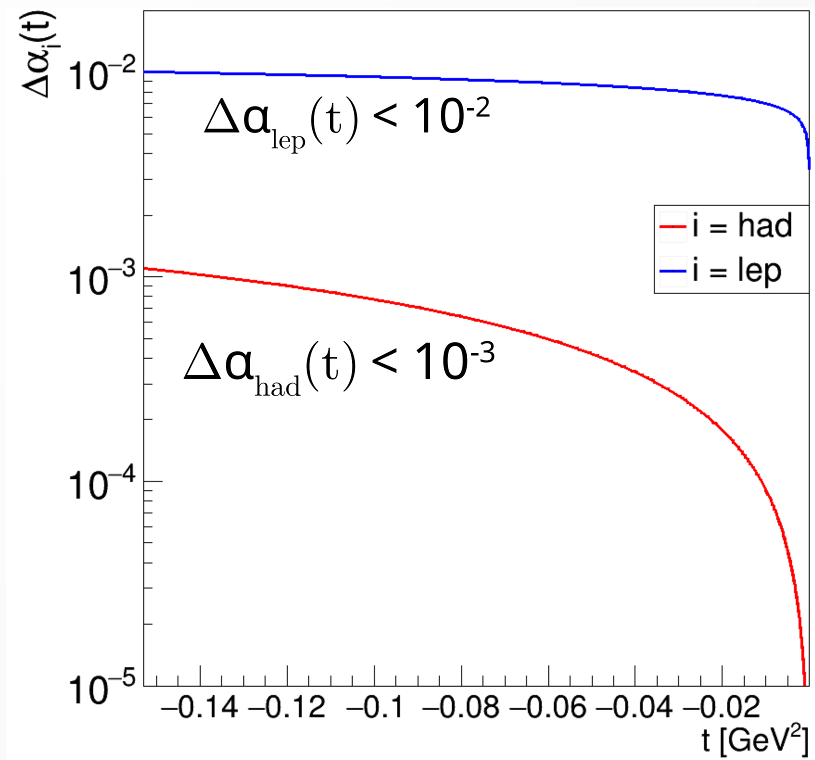
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

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



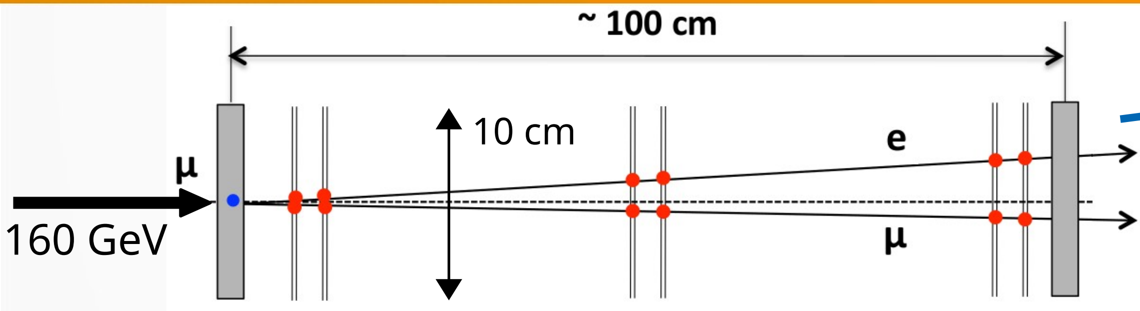
+ higher orders
+ radiative corrections

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



MUonE kinematic range

The MUonE experiment



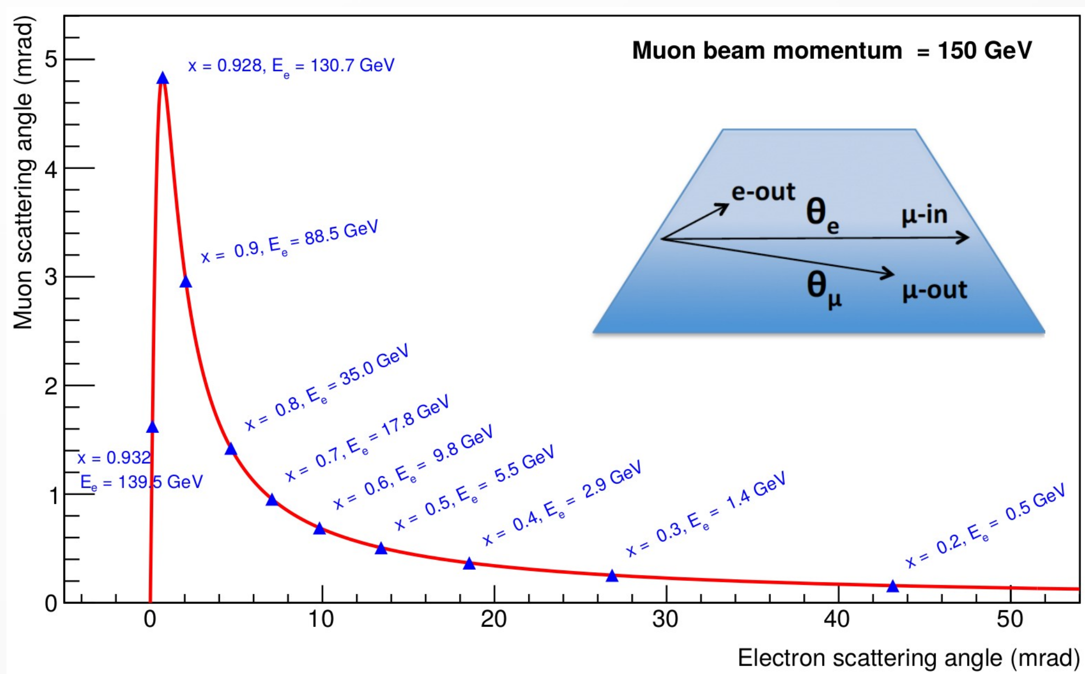
$$\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

From MC

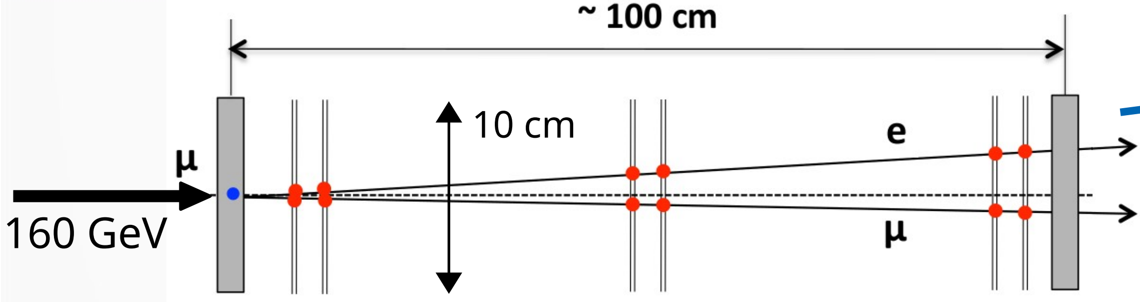
low-Z target ~1.5 cm

6 Si strip detectors (3 XY points)

- Observables: (θ_e, θ_μ)
- Exploit (θ_e, θ_μ) correlation to reject background (main source: μ N → μ N e^+e^-)
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad



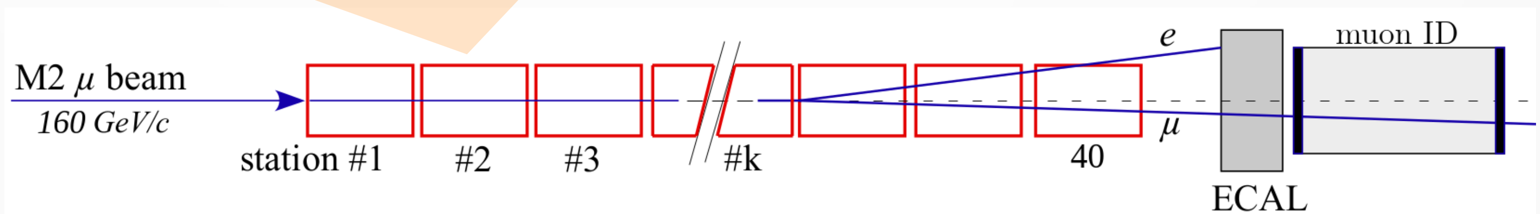
The MUonE experiment



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

From MC

BMS ....



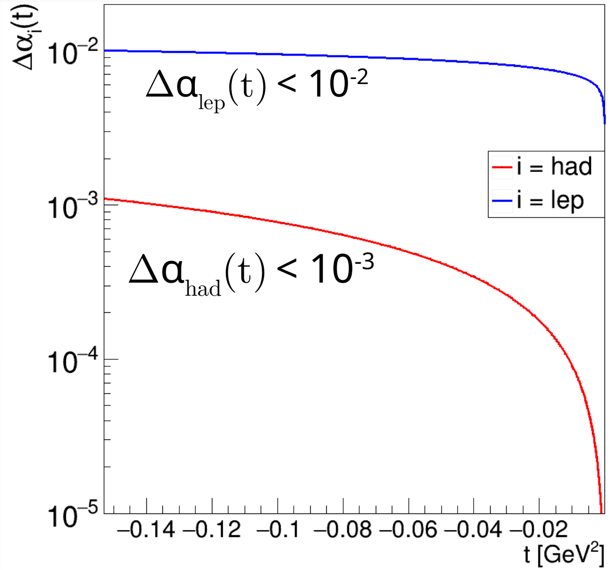
- Modular layout:
  each station measures
  the incident muon direction
  for the following one
- ECAL: PID + *e* energy
- Muon ID: PID
- BMS: beam momentum spectrometer

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)

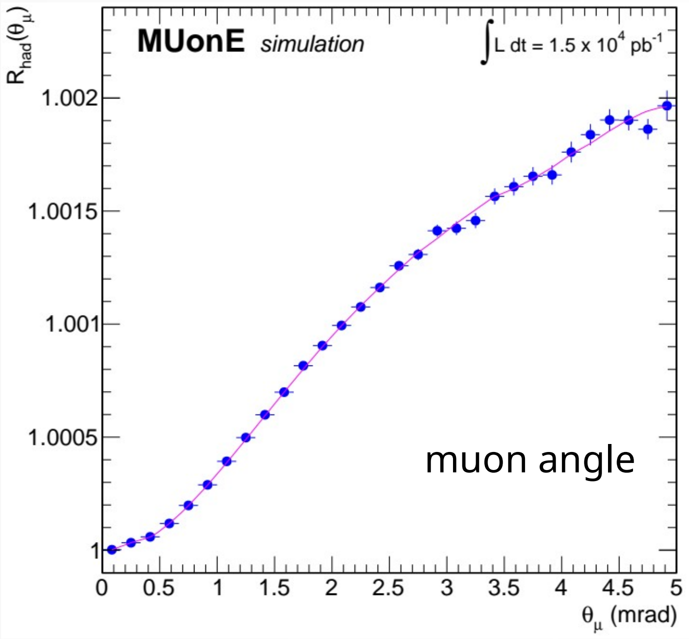


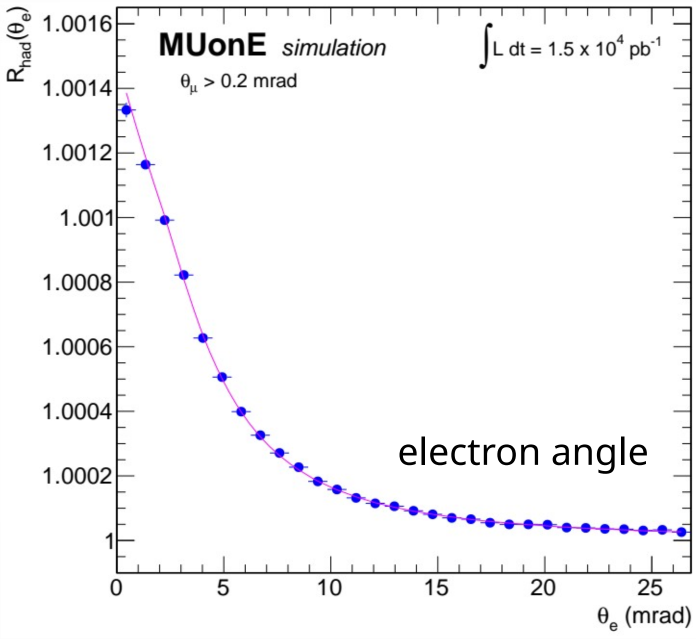
Systematic error goal:

10 ppm on the shape of the differential cross section

- 10 μm longitudinal alignment
- 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

Sensitivity to $\Delta\alpha_{had}(t)$





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

$$R_{had} \sim 1 + 2\Delta\alpha_{had}(t)$$

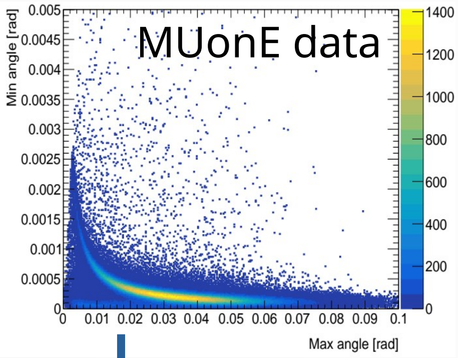
$\Delta\alpha_{had}(t)$ parameterization: inspired from the 1 loop QED contribution at $t < 0$:

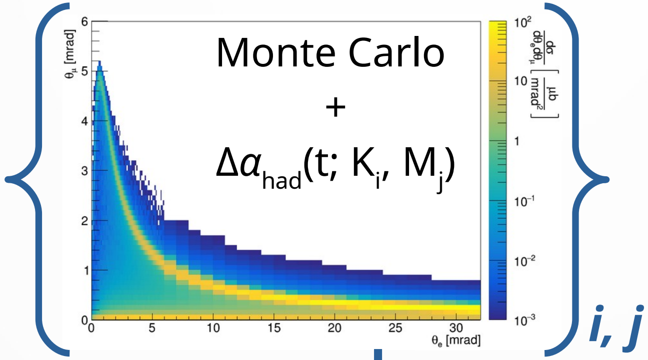
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters:
K, M

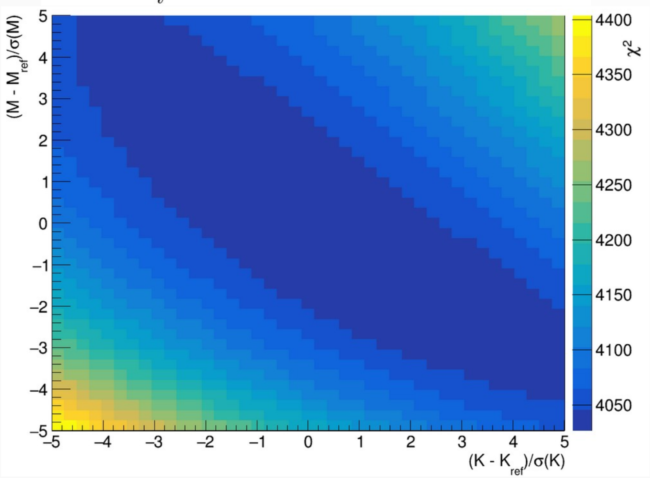
Extraction of $a_\mu^{\mathrm{HVP,LO}}$: current workflow

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





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



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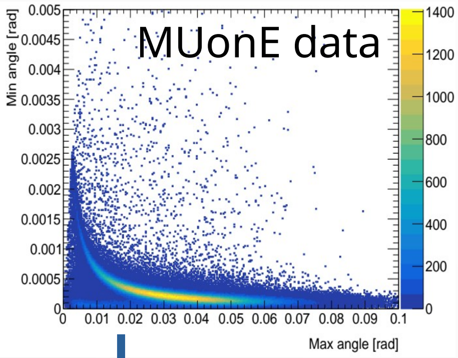
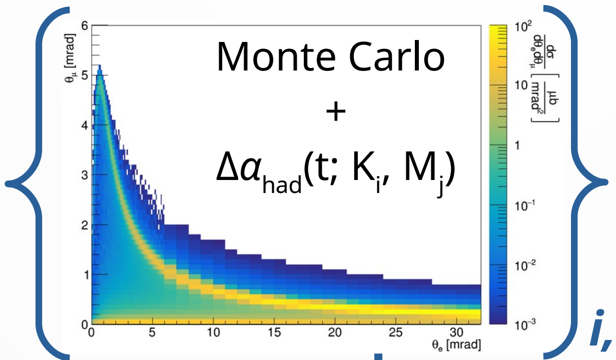
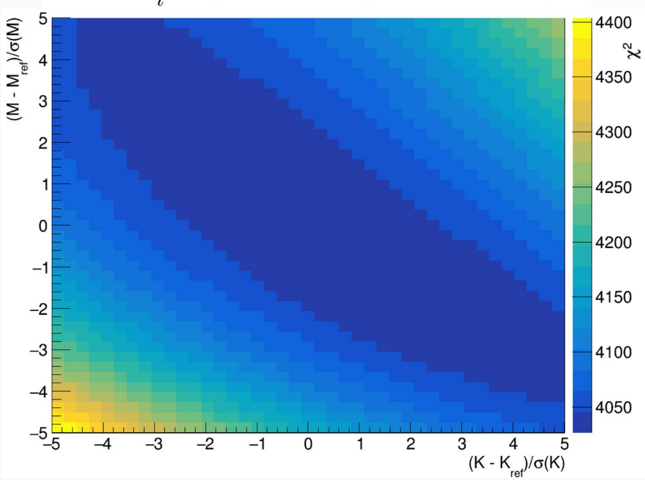




i, j

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



(K_{best}, M_{best})

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

MUonE fast simulation, final statistics:

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

Input value (FJ17):

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

Alternative method to compute $a_\mu^{\text{HVP,LO}}$ 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

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

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

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

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

MUonE 99%

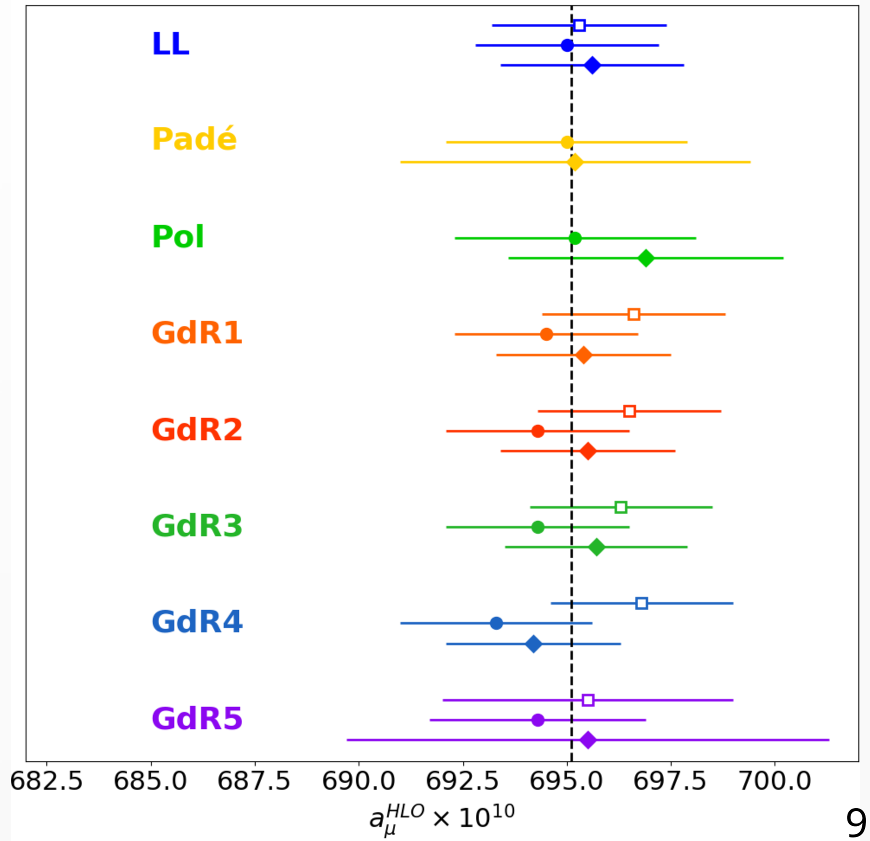
$$a_\mu^{\text{HLO (II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\text{pQCD}}$$

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

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

Time-like data + pQCD 1%

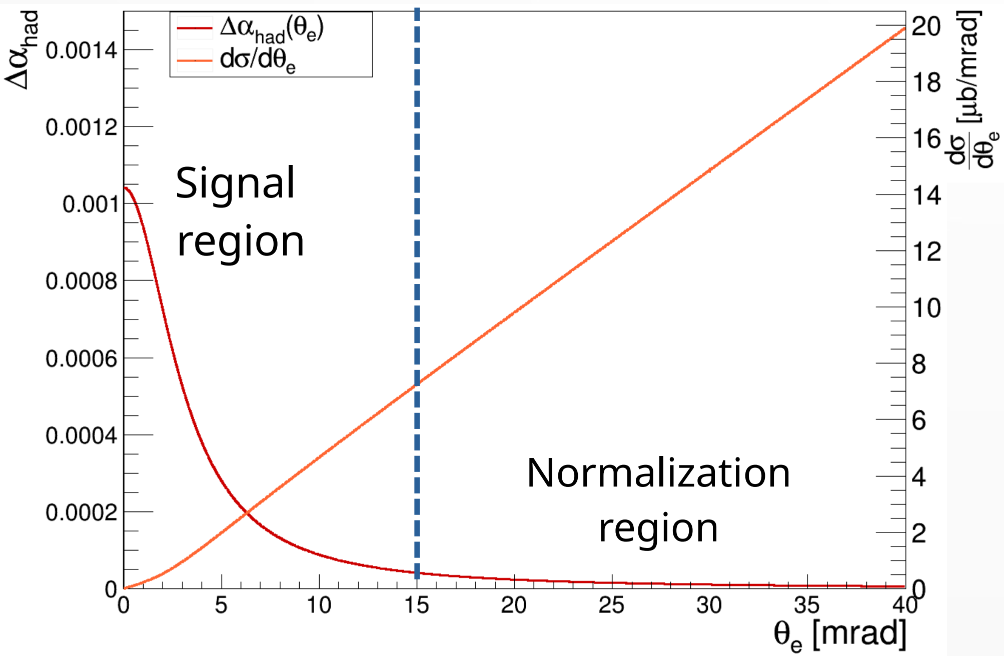
Competitive results independently of the $\Delta\alpha_{\text{had}}$(t) parameterization



Strategy for the systematic effects

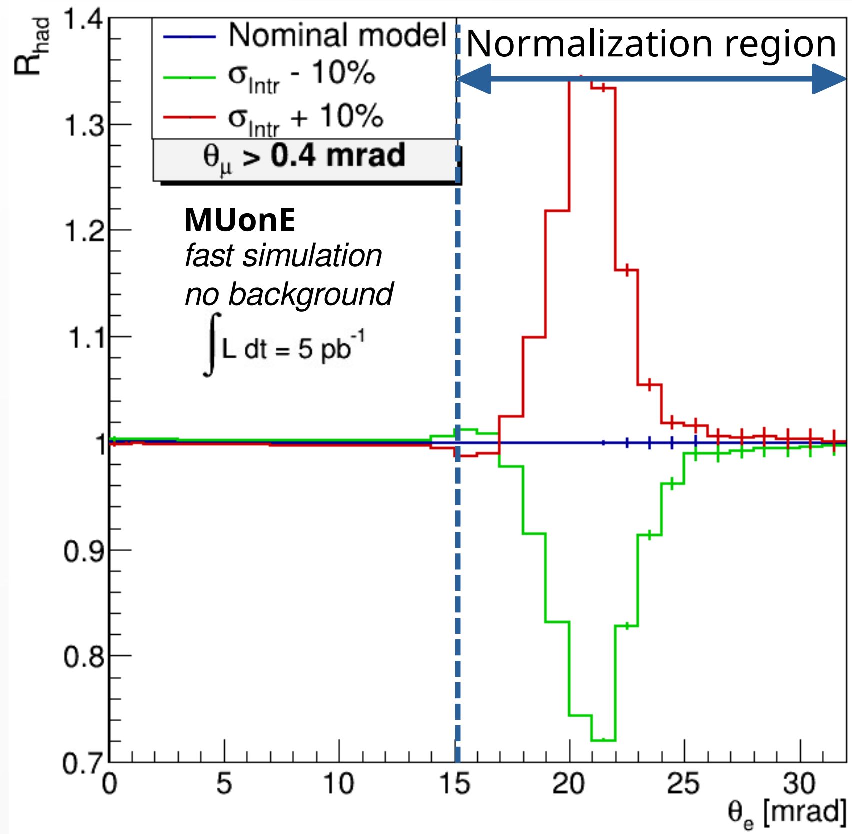
Promising strategy:

- 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:

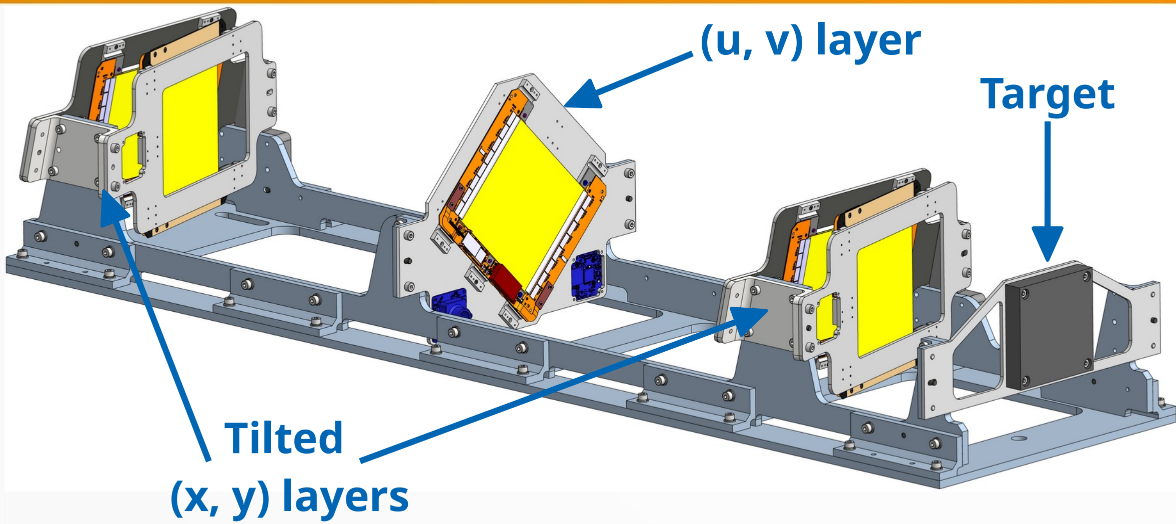
±10% systematic error on the angular intrinsic resolution



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

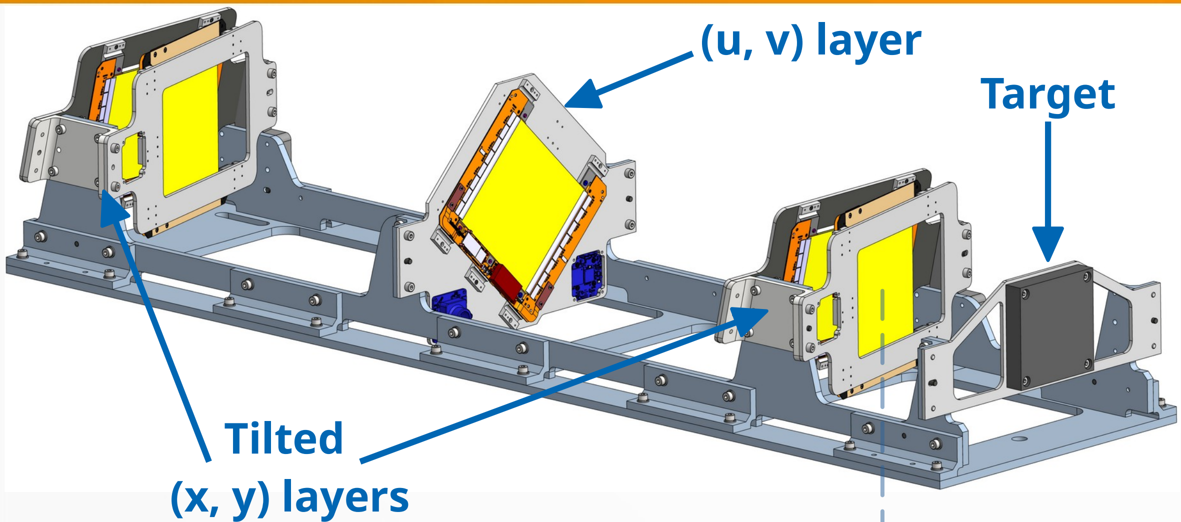


INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

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



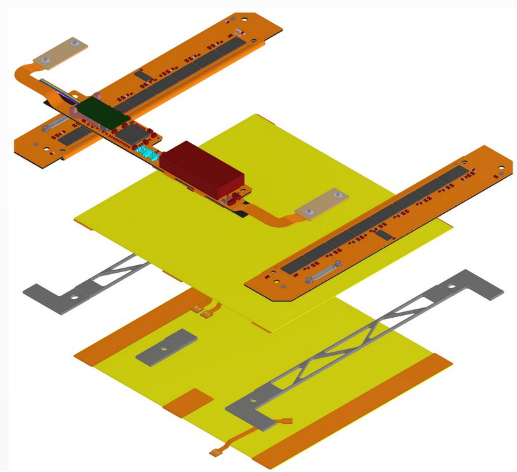
INVAR (Fe/Ni alloy)
CTE ~ 1.2 ppm/K

Laser holographic system
to monitor stability

2S modules
(CMS Phase2 upgrade)

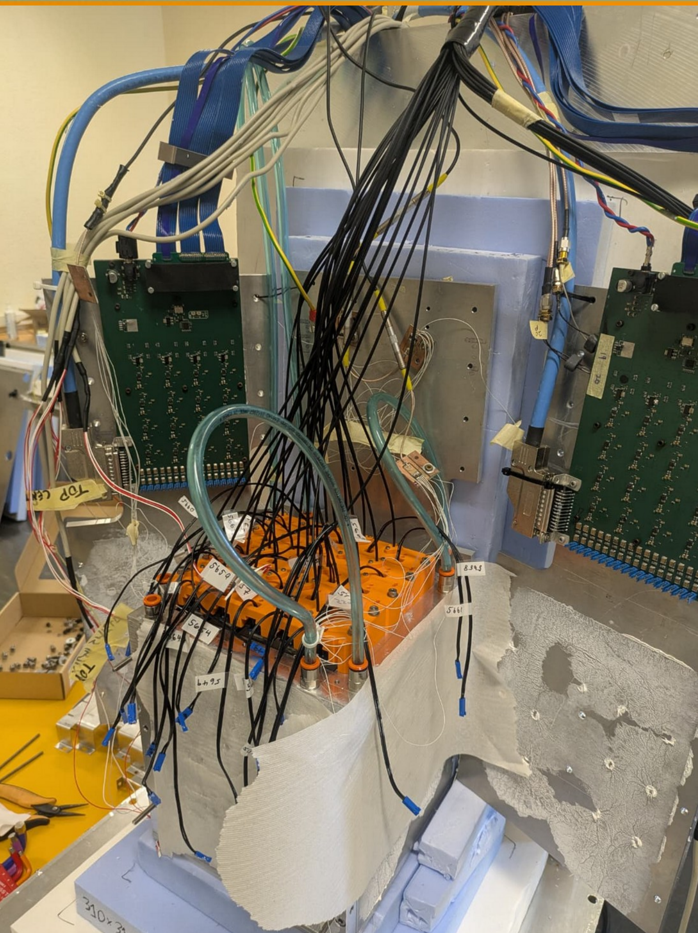
TDR CMS Tracker Phase2 Upgrade

- (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

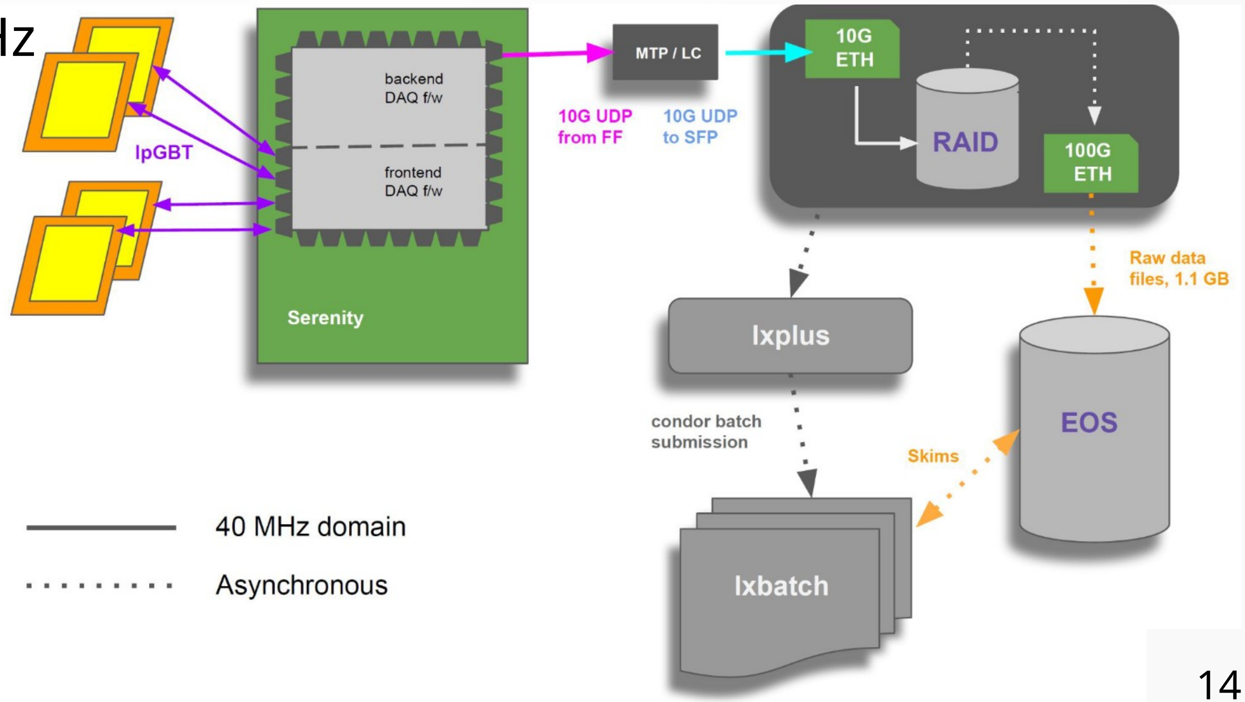
- End of TR 2023: ECAL data integrated in the main DAQ
- TR 2025: tracker-ECAL time sync achieved

DAQ system

M2 beam line at CERN:
unique environment

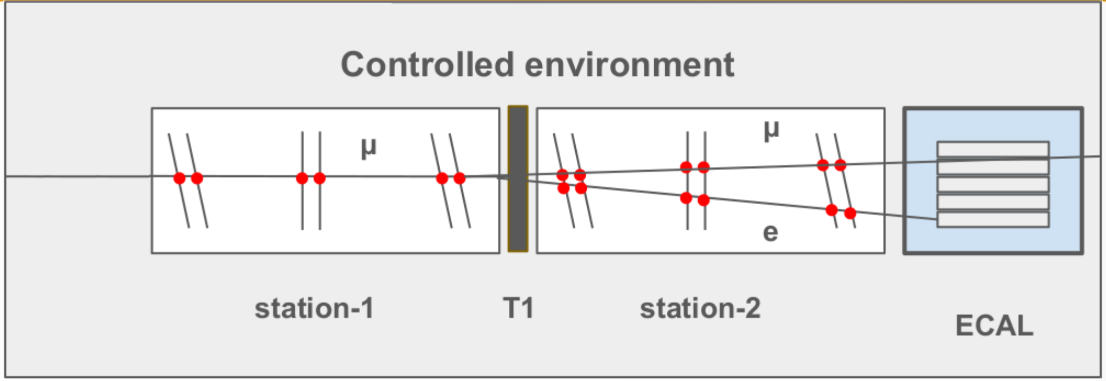
- High intensity: ~$2\times10^{8}\,\mu^{+}$ / 5s spill → **~40 MHz**
- **Beam asynchronous to DAQ clock**

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

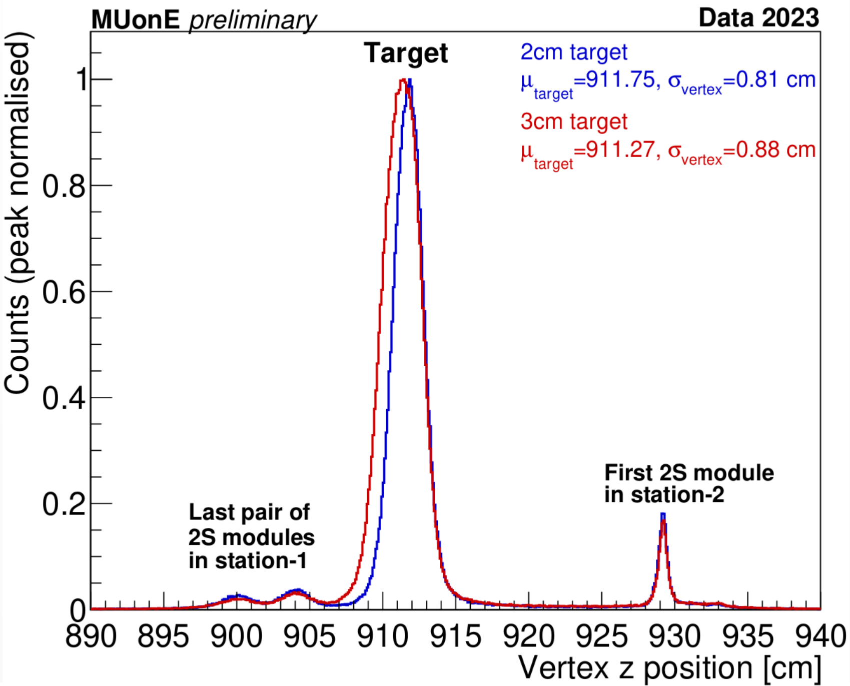


Test Run 2023

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

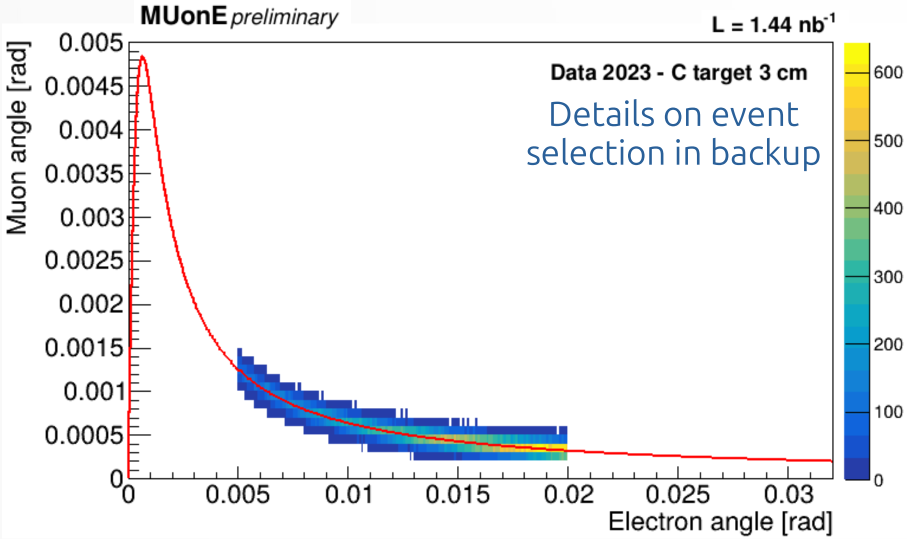


- **Demonstrated continuous readout @40 MHz.**
- Study detector performance, reconstruction algorithms, event selection.



Test Run 2023 – Data/MC comparison

Select elastic events in a clear region

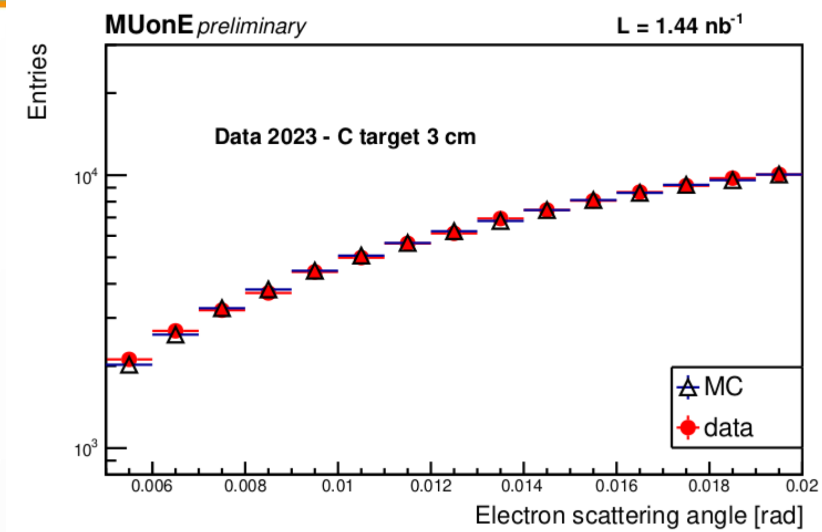


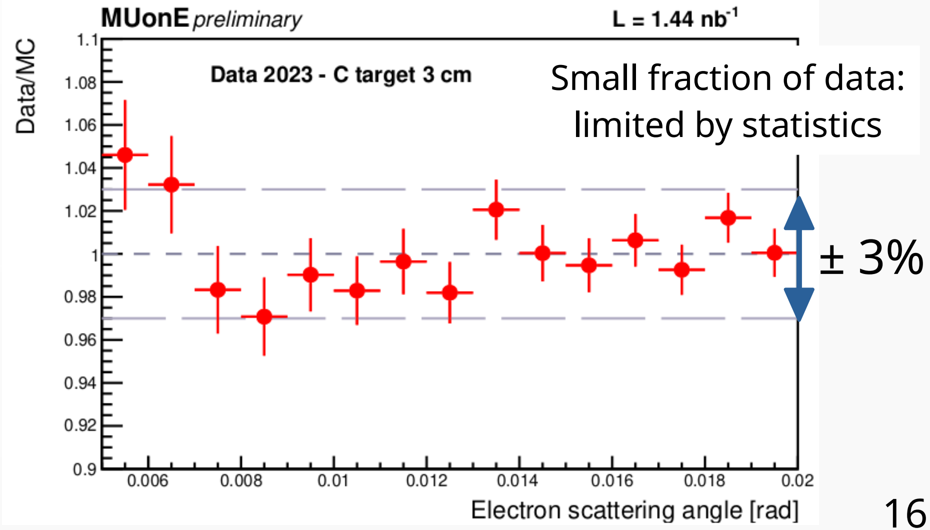
Count N_μ on target → luminosity estimate

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

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

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

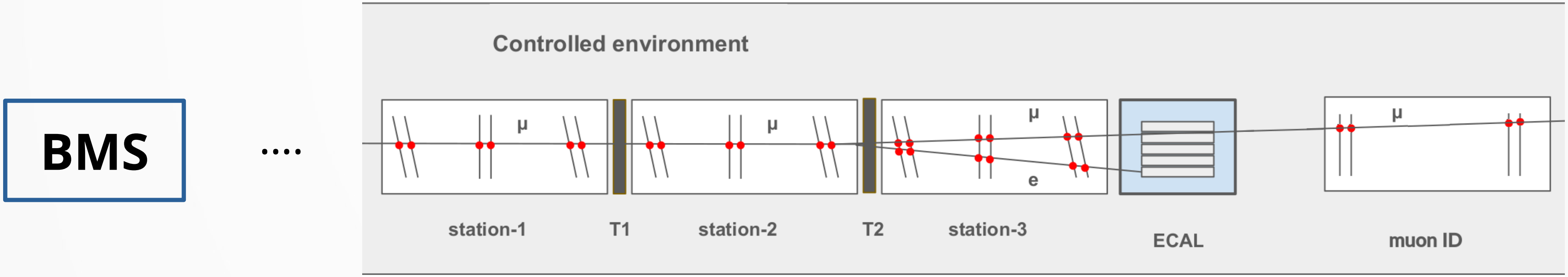




Small fraction of data: limited by statistics

MUonE Phase-1: Test Run 2025

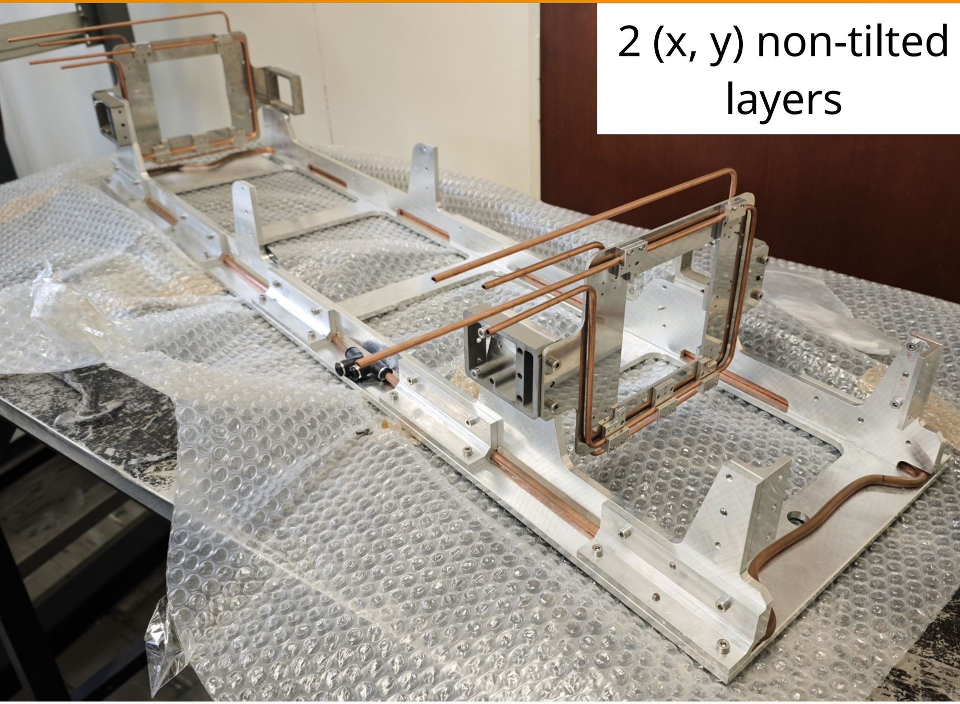
Proposal for Phase 1 of the MUonE experiment

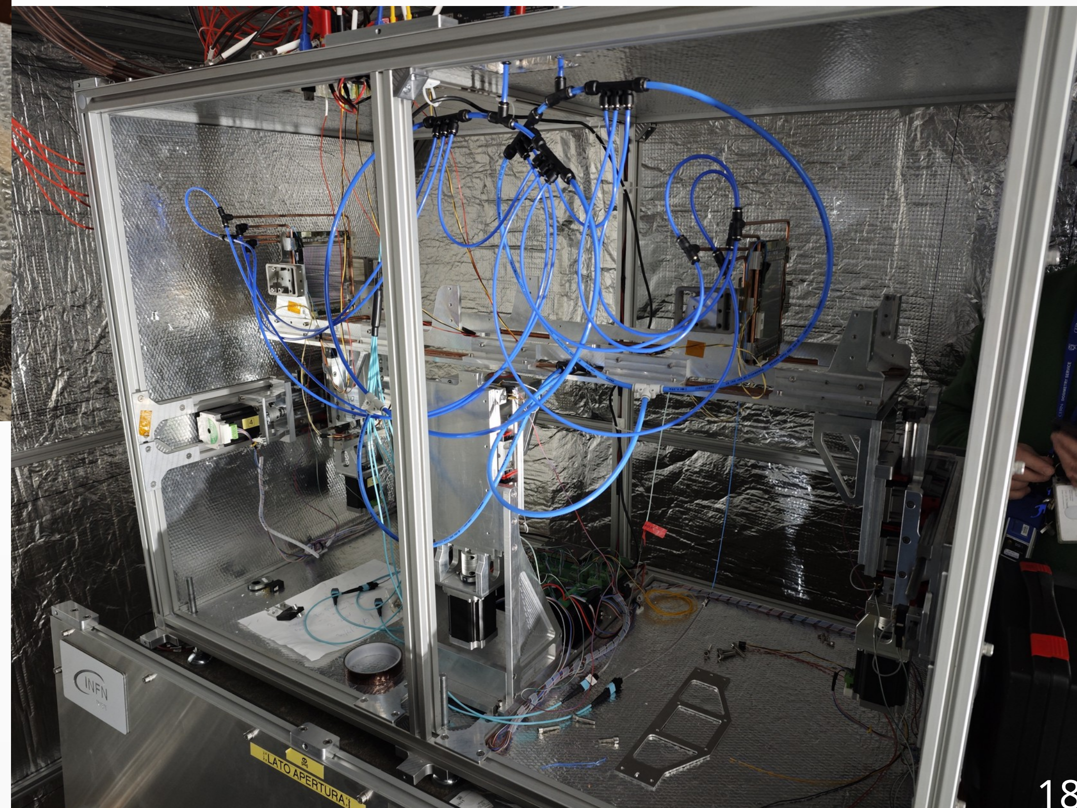


- 3 × tracking stations, each equipped with 6 pre-production 2S modules
- 2 × C targets (each 2 cm thick)
- ECAL: e^- PID + E_e measurement
- Timing detector: time of arrival of muons. 2 plastic scintillators before and after the tracking stations
- Muon ID: μ PID. Equipped with 4 prototype 2S modules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

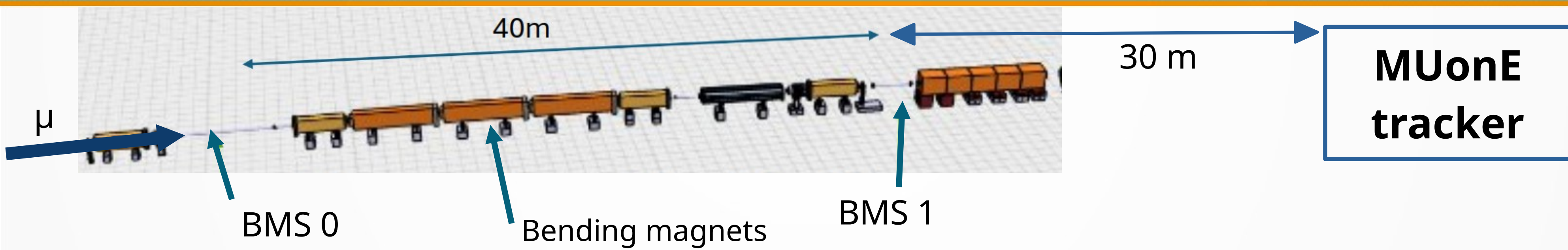
Muon ID

2 (x, y) non-tilted layers



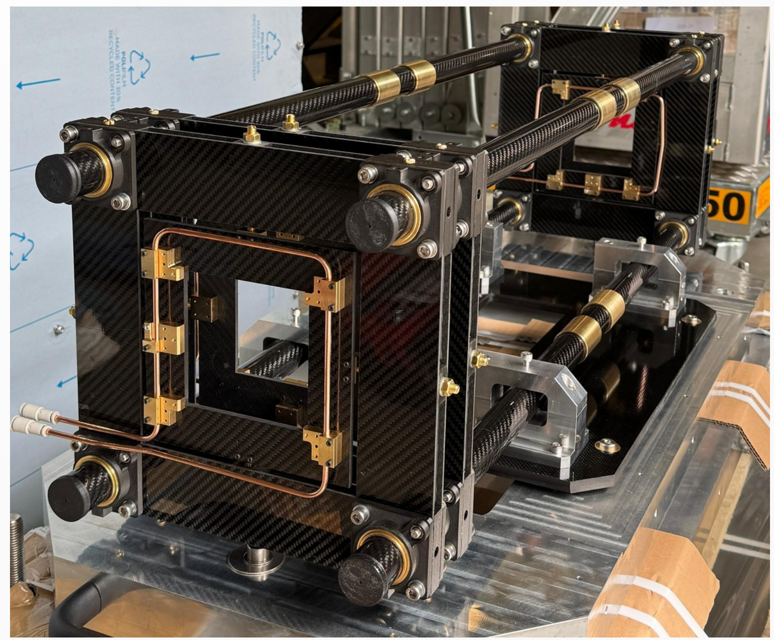


BMS (Beam Momentum Spectrometer)



- 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

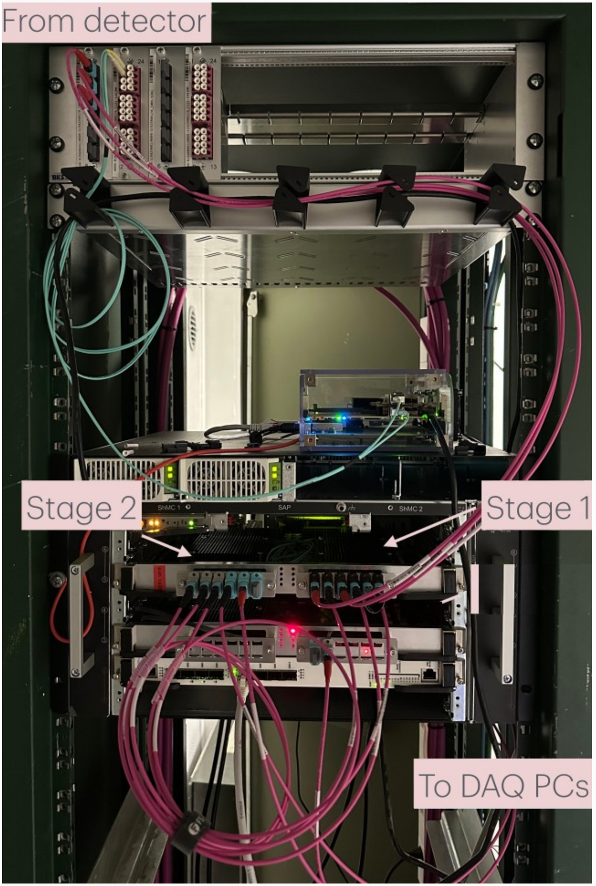


×2

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

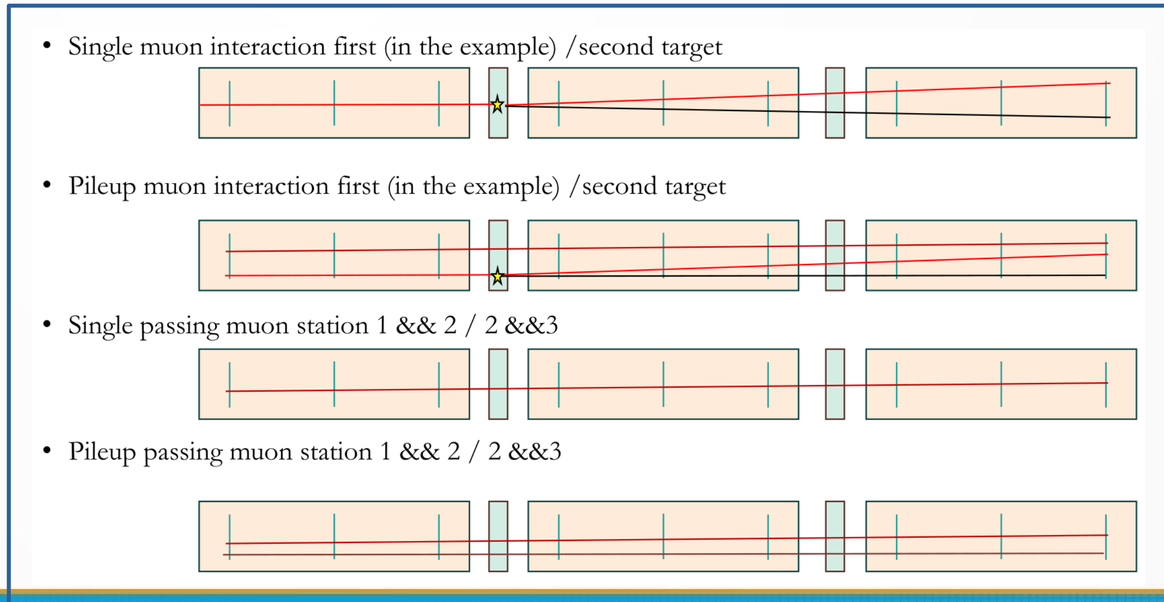
System increasing in complexity...

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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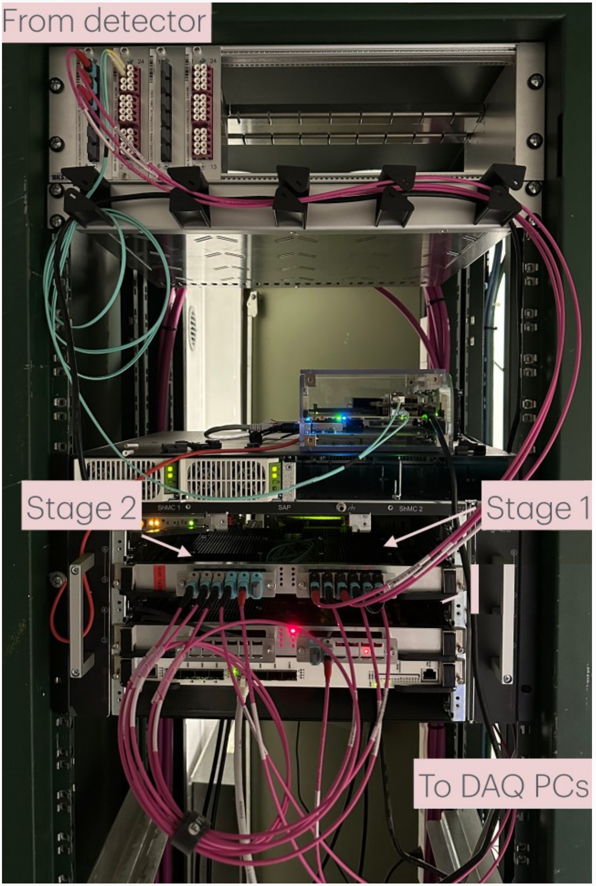
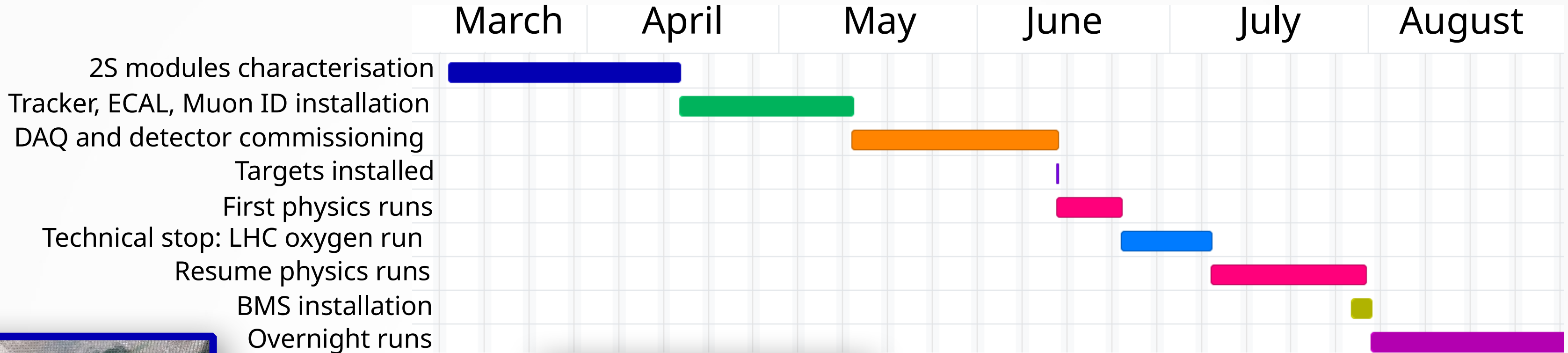
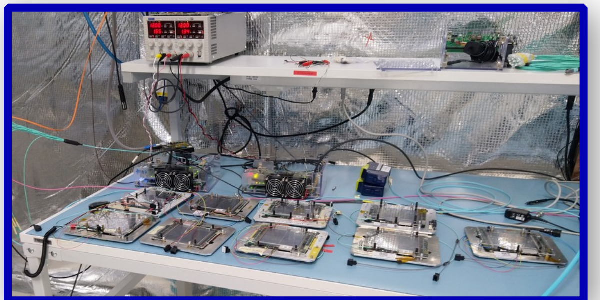
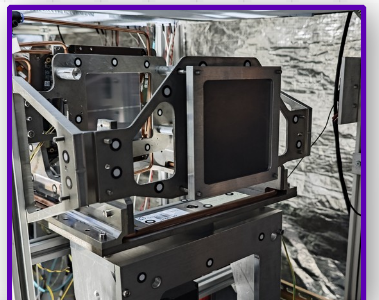


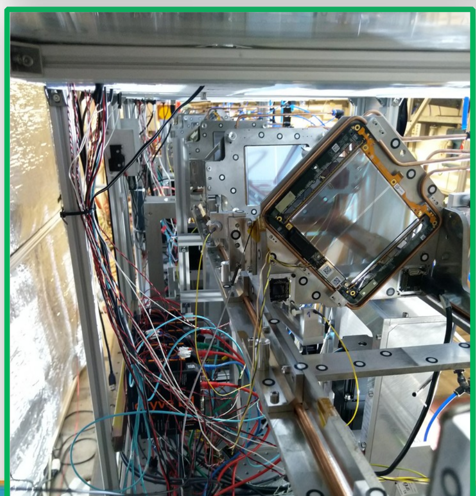
- **Stage 1:** 36 communication links with subdetectors
  - 30×2S modules
  - 2×Timing Detector
  - 4×ECAL
- Online selection based on tracker modules occupancy. ~×100 reduction of recorded events compared to 2023.
- **Stage 2:** event building.
  - Group information from all subdetectors in a time-coherent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

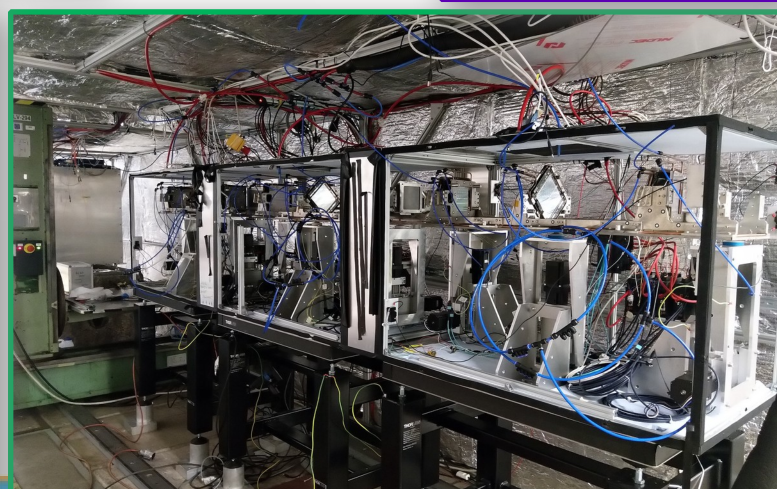
Test Run 2025 – timeline



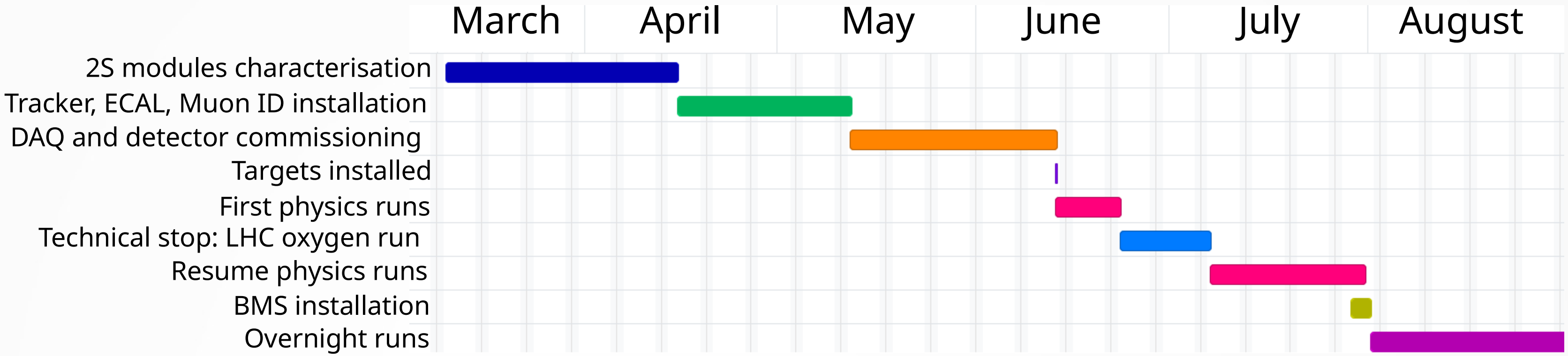


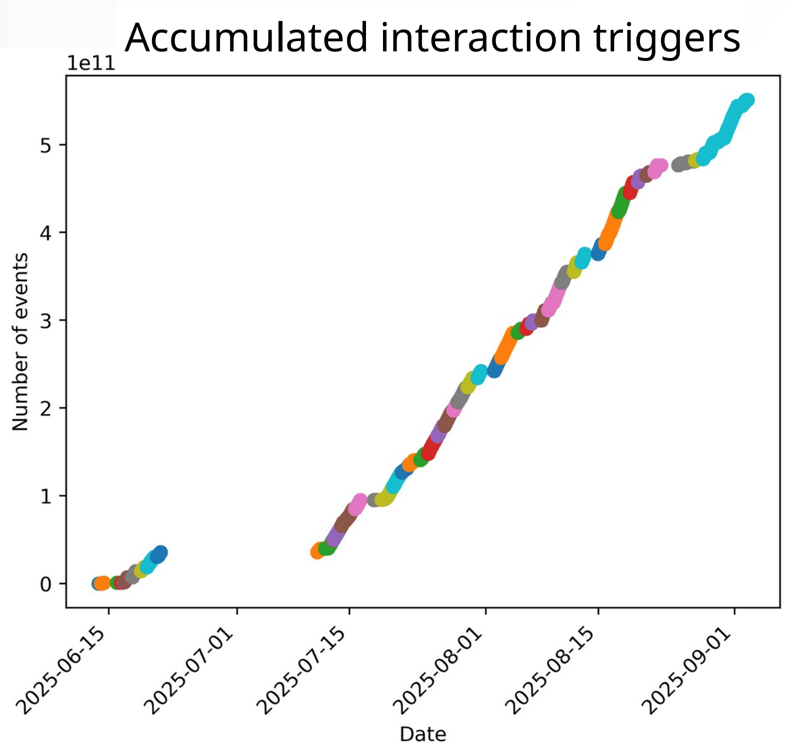






Test Run 2025 – timeline

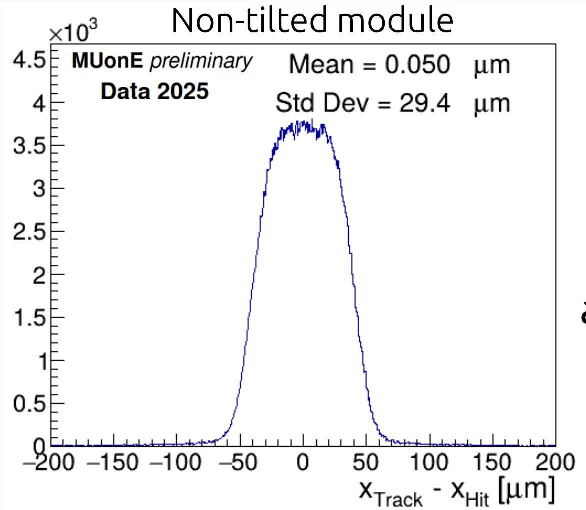


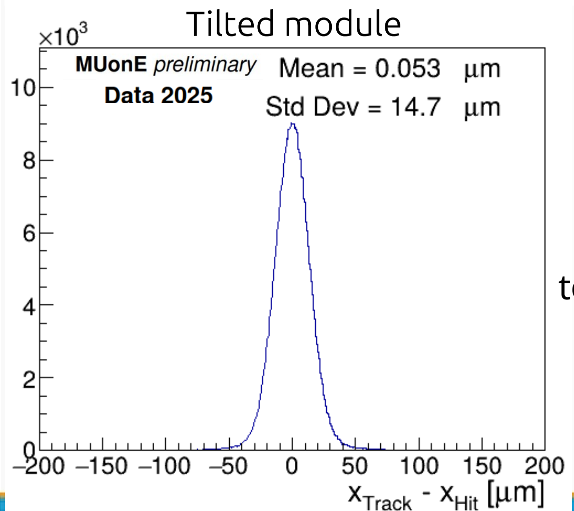


more than 5×10^{11} interaction triggers recorded!

Tracker performance

Unbiased residuals

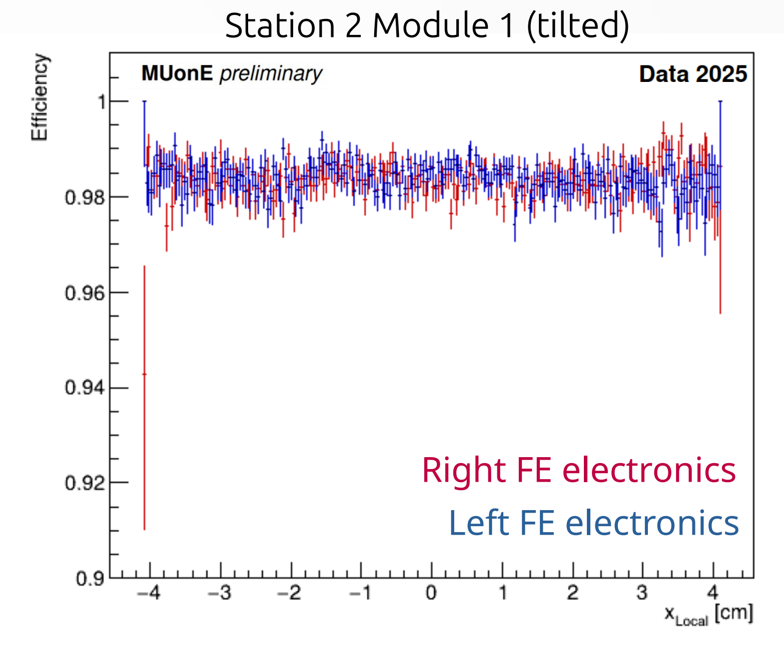




Clear difference in the resolution of tilted and non-tilted modules

*Track fit error to be subtracted from Std Dev to isolate the intrinsic resolution (work in progress)

Module efficiency

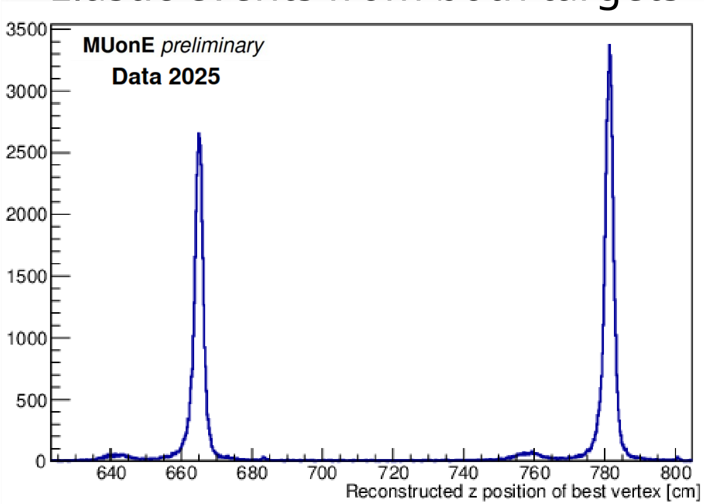


Uniform efficiency over the entire modules surface

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

Elastic scattering events

Elastic events from both targets

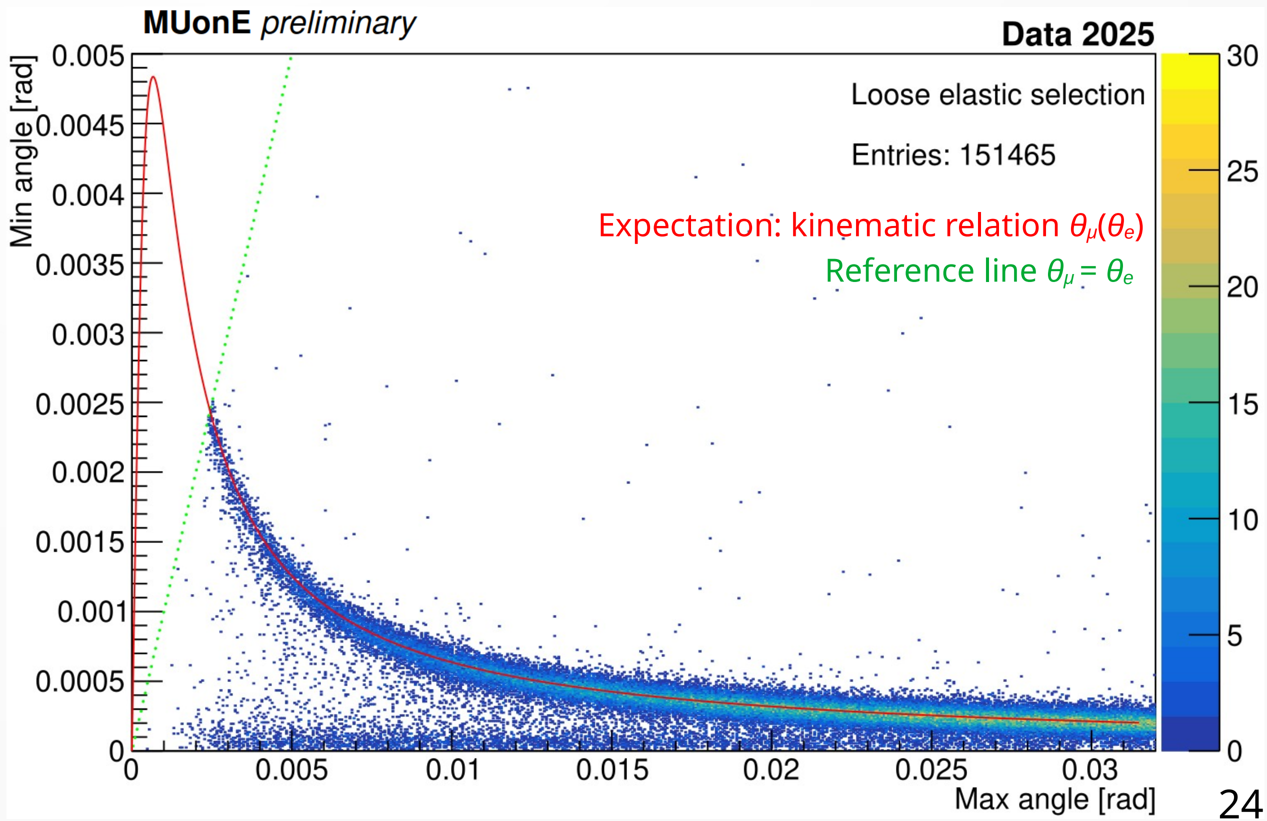


Can use ECAL or MuonID to resolve the ambiguity

Tracker-only analysis of elastic events

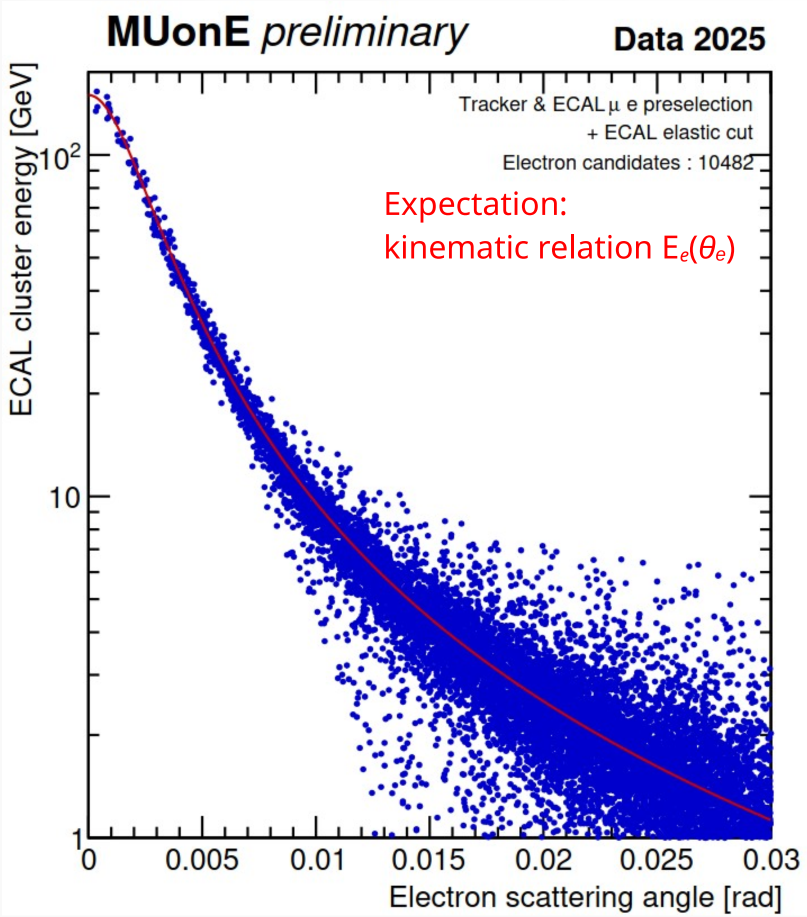
Not able to discriminate between μ and e^-:

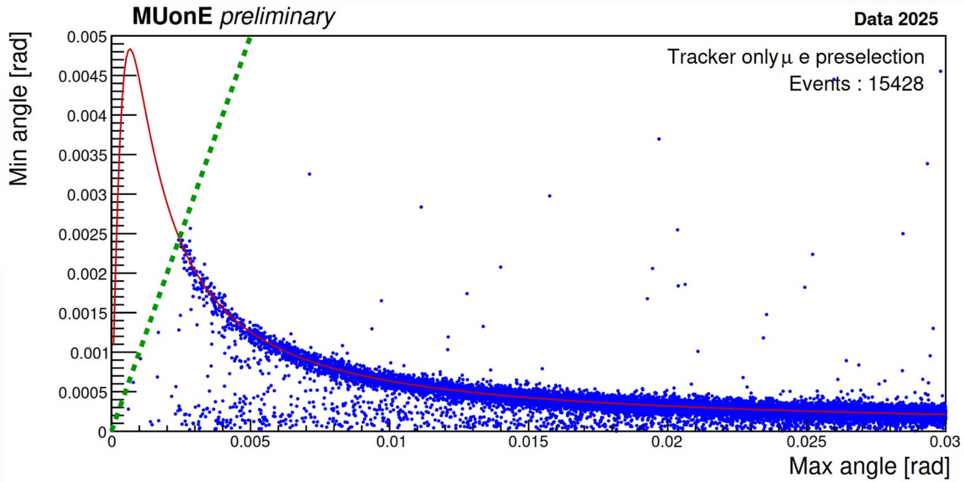
plot θ_{max} vs θ_{min} to avoid misidentification when θ_e < 5mrad

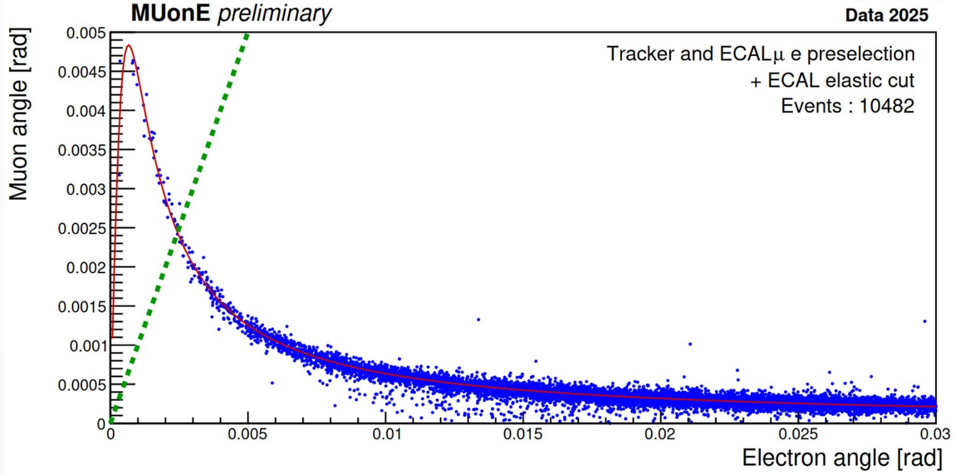


ECAL-based PID

Correlation between ECAL energy deposit and θ_e reconstructed in the tracker



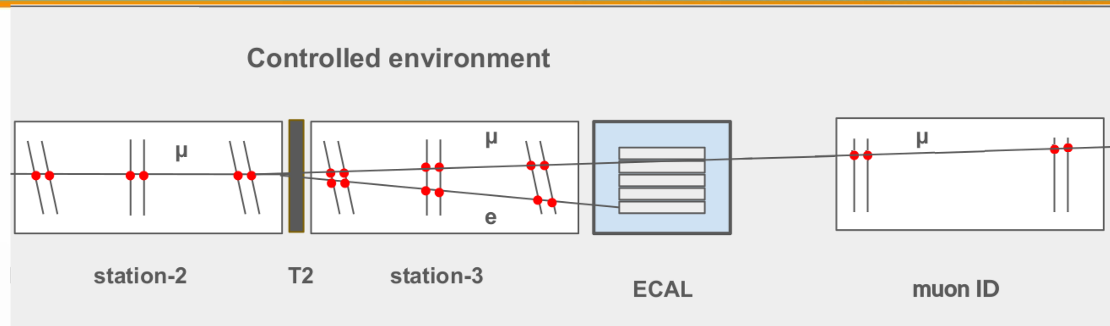




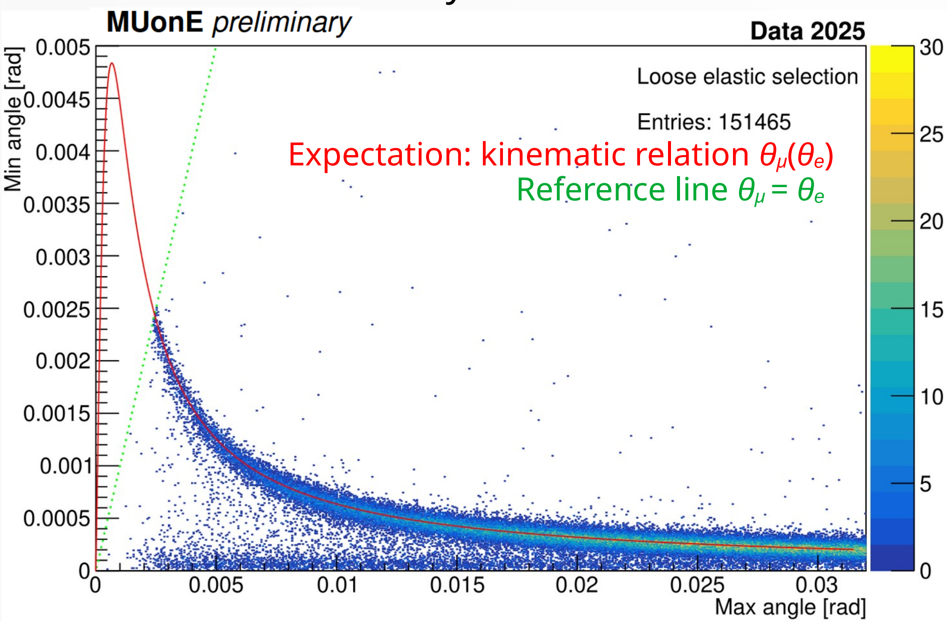
- ECAL energy > 1 GeV
- Loose elastic selection
- Matching between candidate e^- track and ECAL cluster centroid

Muon ID-based PID

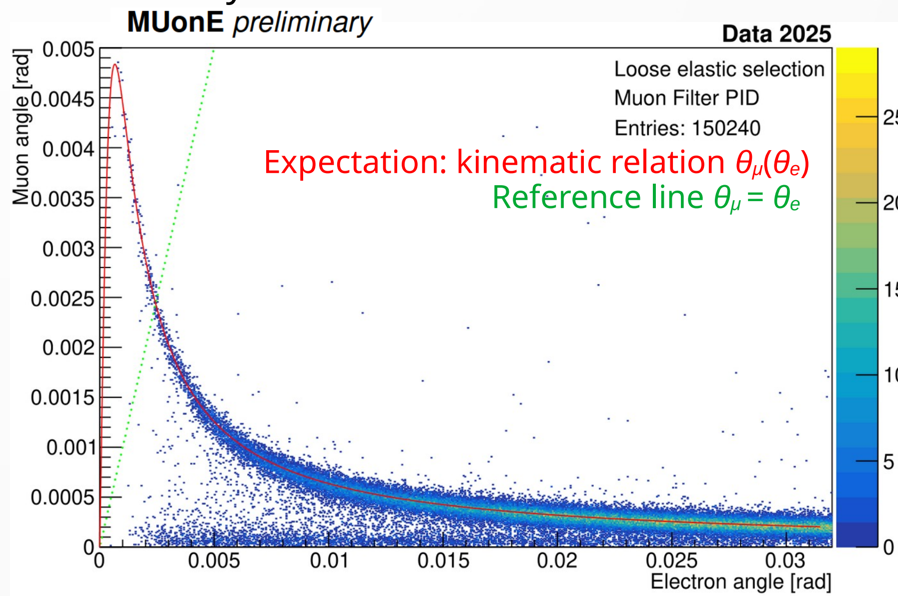
- Propagate tracks to the Muon ID
- Look for matching between a track and muon ID hits: select the muon track



Tracker-only event selection



Tracker-only event selection + muon ID-based PID

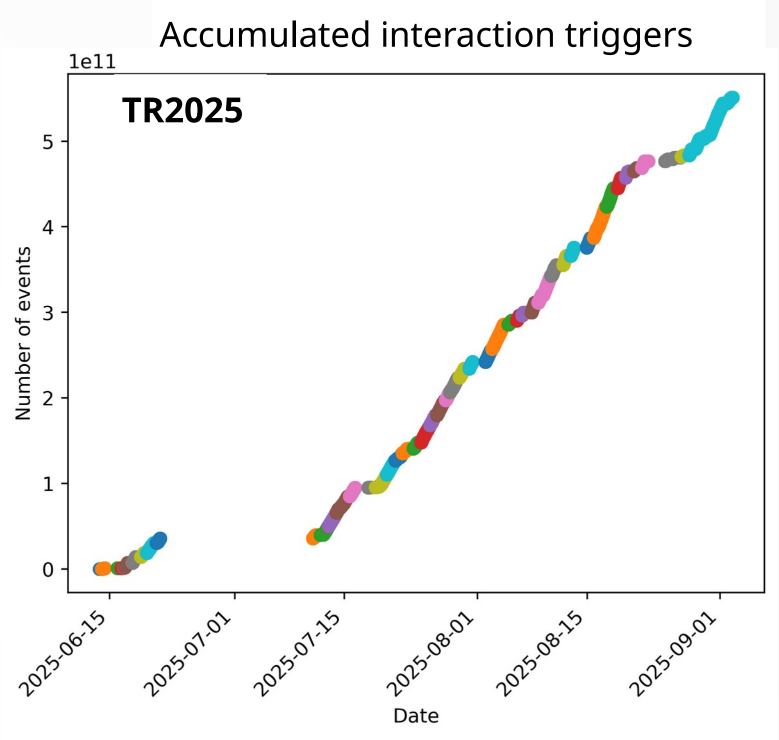


Work in progress: ECAL + muon ID combined PID

Conclusions

MUonE web site

- MUonE aims to provide an independent evaluation of $a_\mu^{\mathrm{HVP,LO}}$ competitive with the latest results.
- 2025 Test Run:
  - Successful ~3 months data taking with 3 stations (2 targets), ECAL and muon ID.
  - Integration of the BMS in the last few days of run.
- 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

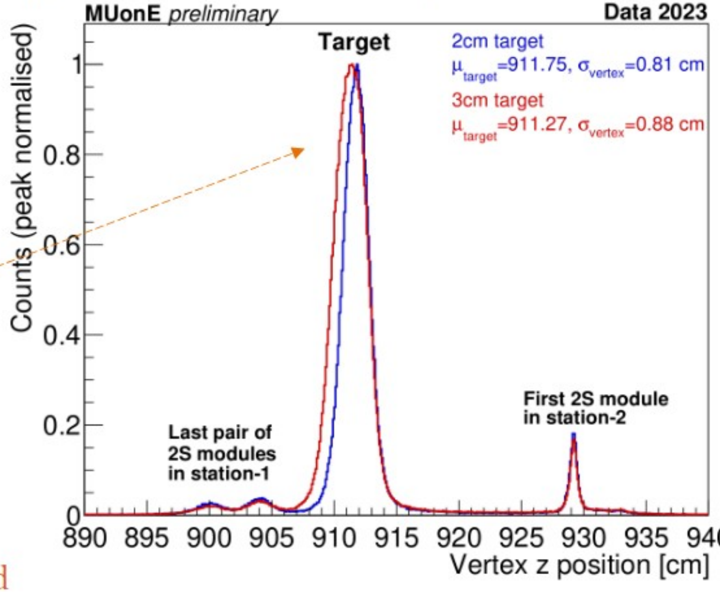
MC sample: MESMER generated signal elastic events → 16.5×10^6 to be reconstructed with **realistic misalignment scenario** (simulated geometry from real metrology followed by track-based alignment as with real data)

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:
$N_{hits_{S0}} = 6$ → 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:
$\rho = (1.83 \pm 0.01) g/cm^3$
+
$d_{target} = (3.000 \pm 0.001)\ cm$

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

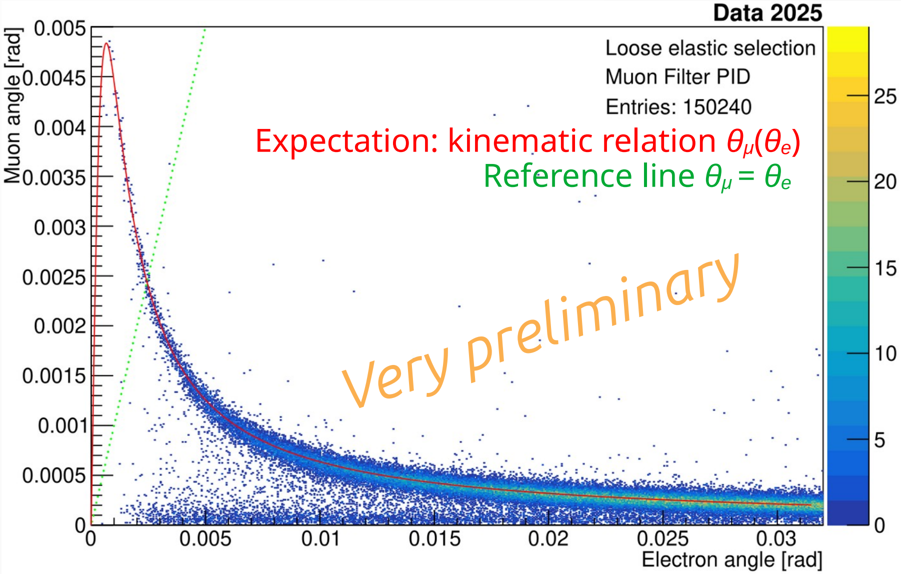
$\epsilon_{hw} = 0.850 \pm 0.035$:
2 tracks reconstruction efficiency which depends on modules efficiency
($\epsilon_{mod} = 0.980 \pm 0.005$)

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)

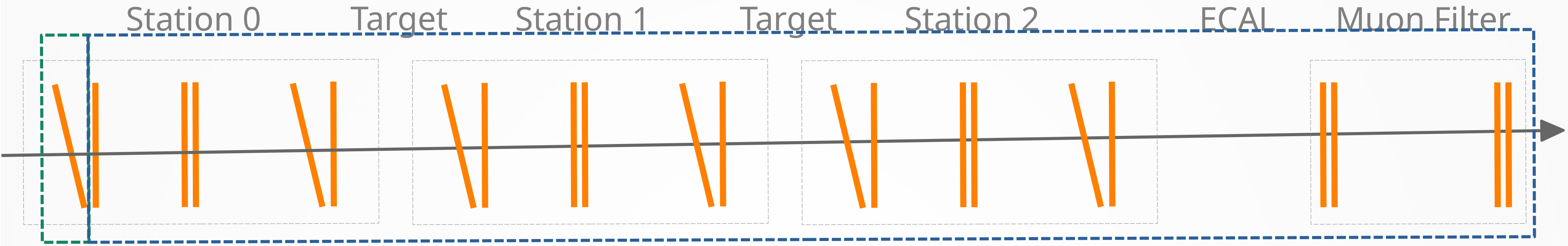
Tracker-only event selection + muon ID-based PID



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

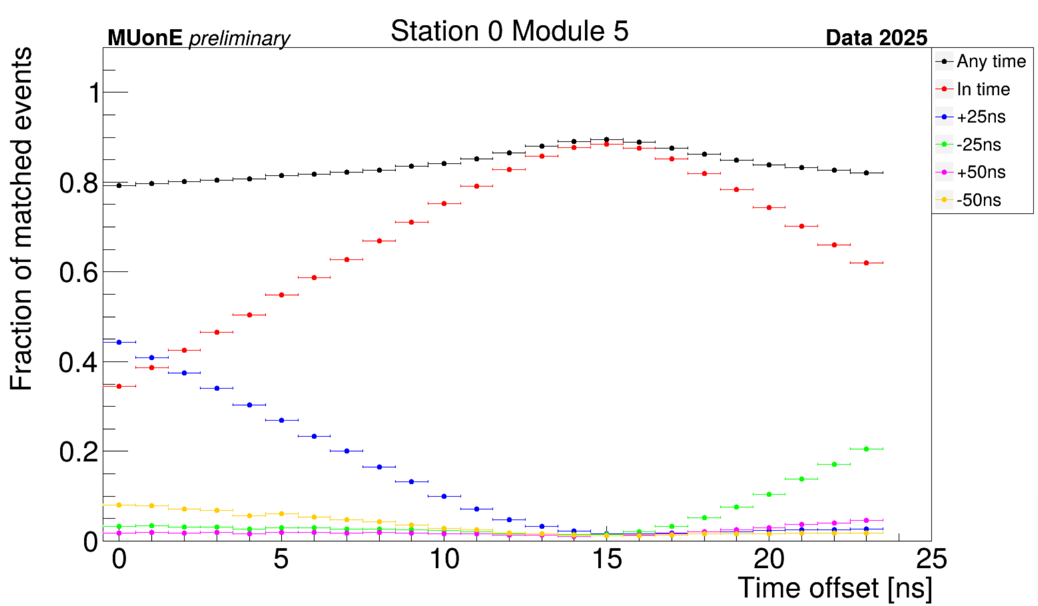
Source of systematic error	Uncertainty on the systematic source	Uncertainty on $\Delta\alpha_{had}$	Uncertainty on $d\sigma$
Intrinsic angular resolution	0.5%	10%	200 ppm
Multiple scattering	1%	10%	200 ppm
Beam energy scale z coordinate	25 MeV 100 μm	10% 10%	200 ppm 200 ppm
Beam energy spread (3.75%)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

TR 2025 – tracker time synchronisation

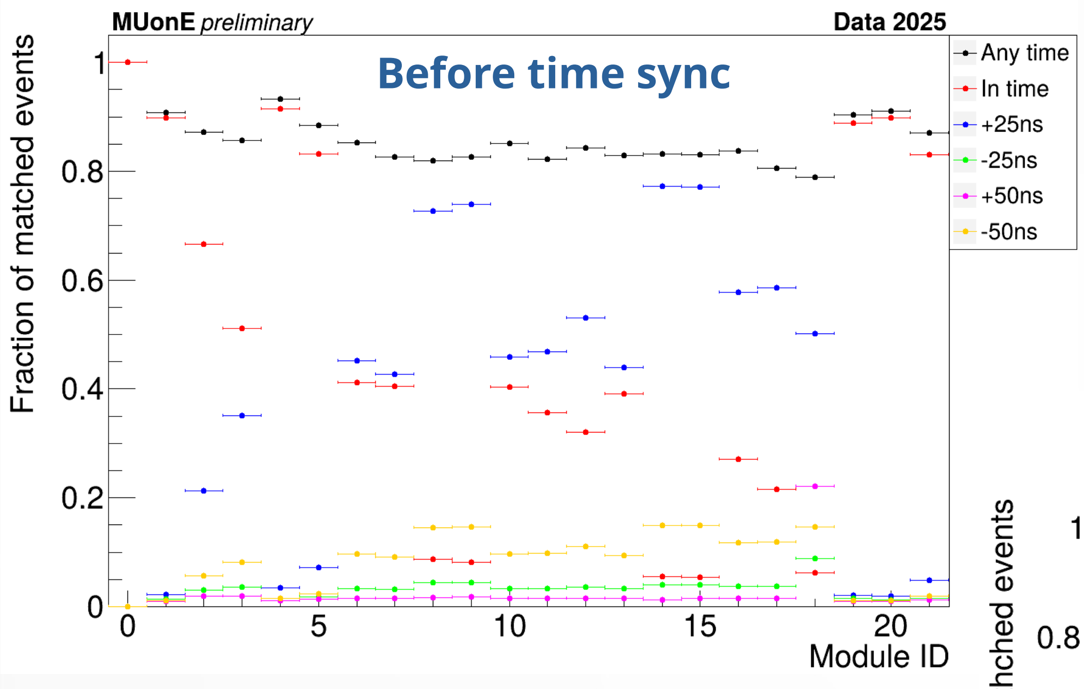


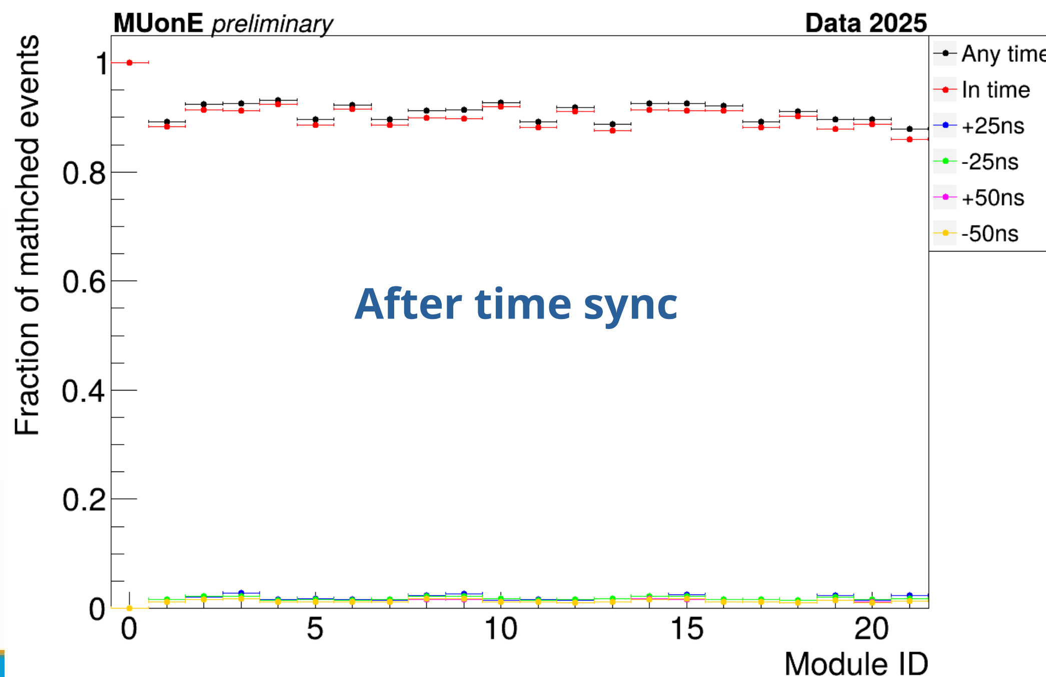
Delay:
12 ns

Delay scanned [0, 24] ns



TR 2025 – tracker time synchronisation



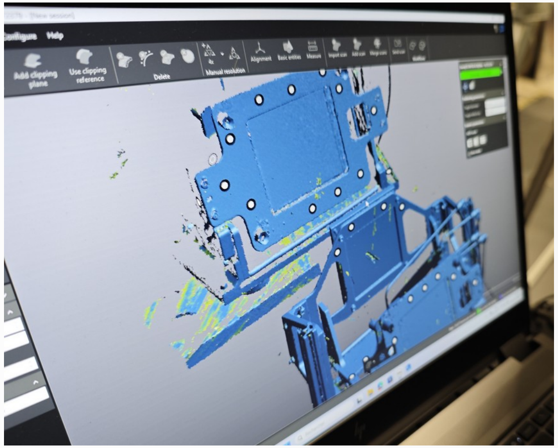


Alignment

- 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)

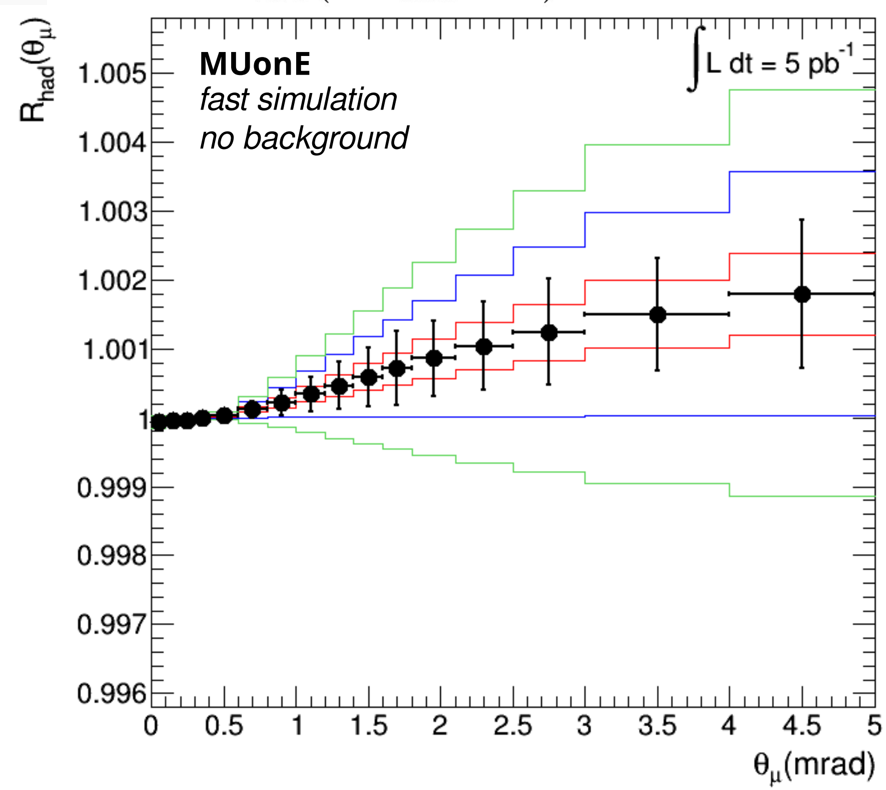
- 3D scanner photogrammetry: position and orientation of each module within a station
- Laser survey: relative position of the different subdetectors; absolute position with respect to beam elements
- To be used as starting point of software alignment



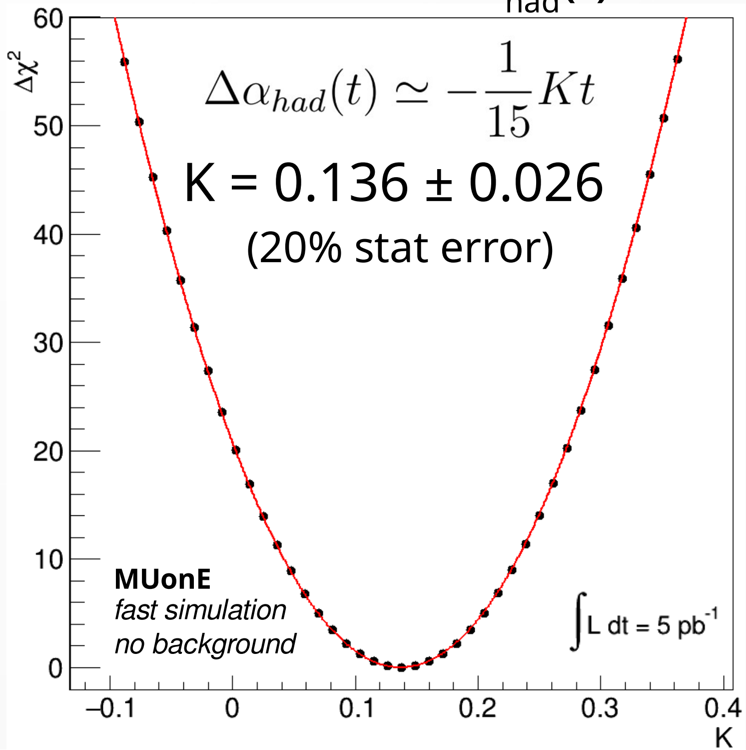
First measurement of $\Delta\alpha_{had}(t)$

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

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



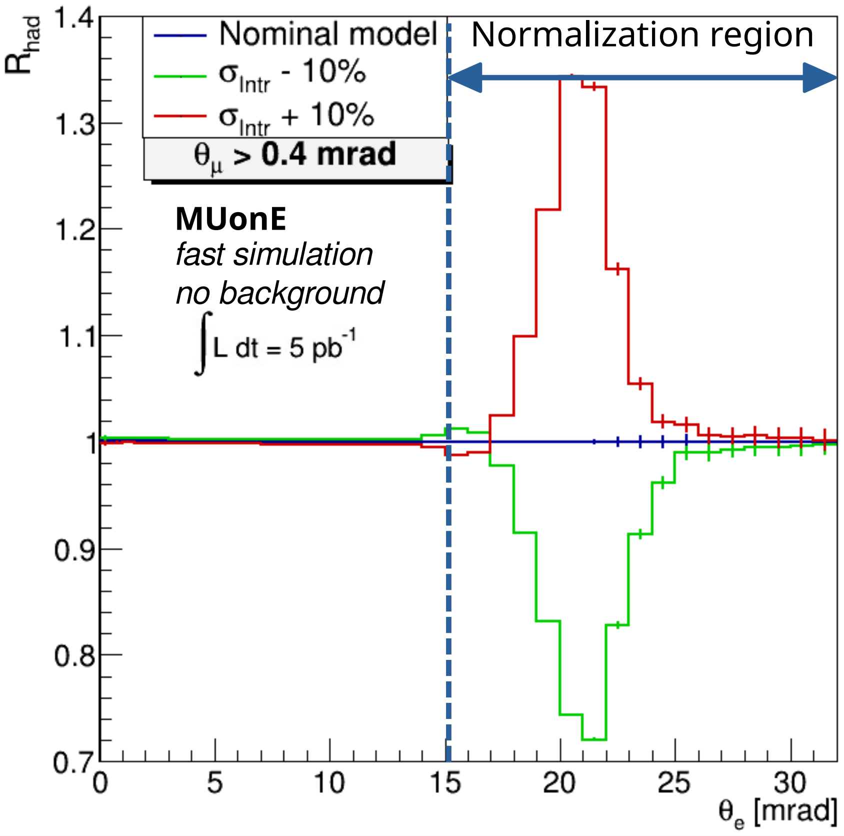
Template fit procedure
to extract $\Delta\alpha_{had}(t)$

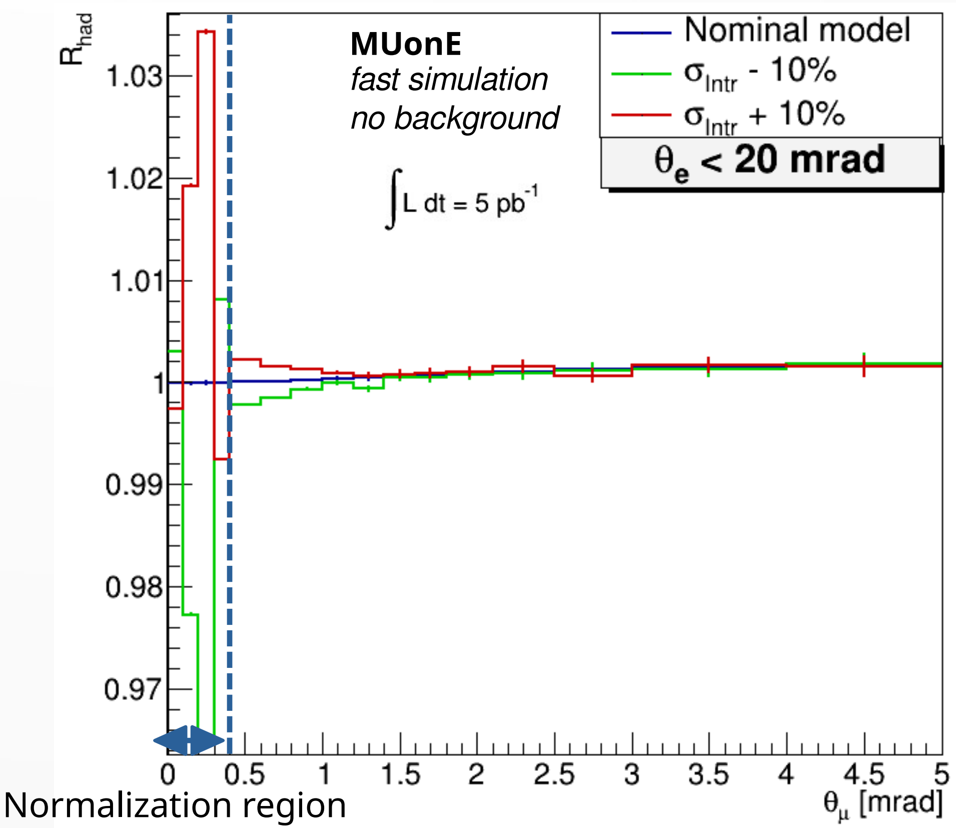


The need of including systematic effects in the analysis

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

Example: ±10% error on the angular intrinsic resolution

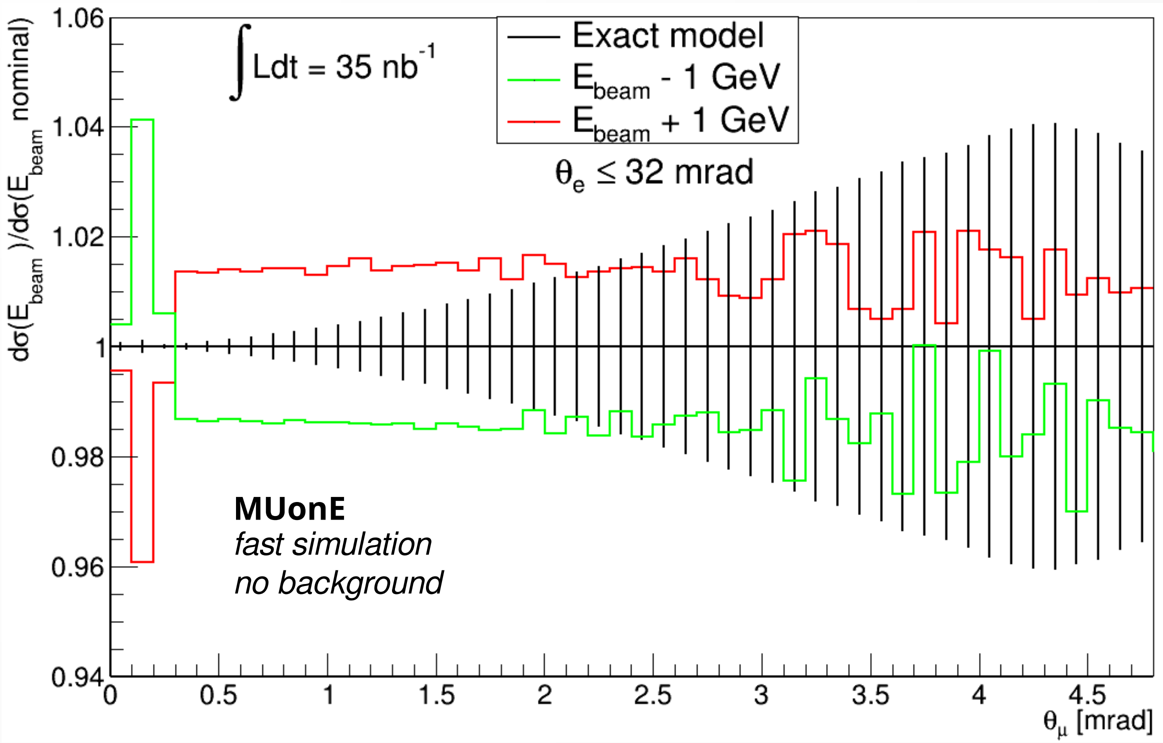




Systematic error on the muon beam energy

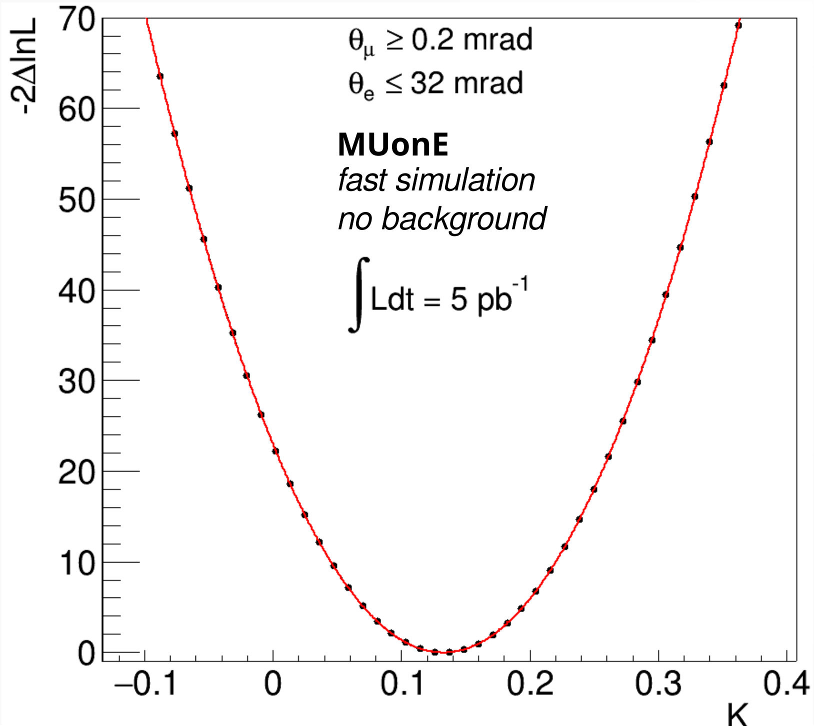
Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV)

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

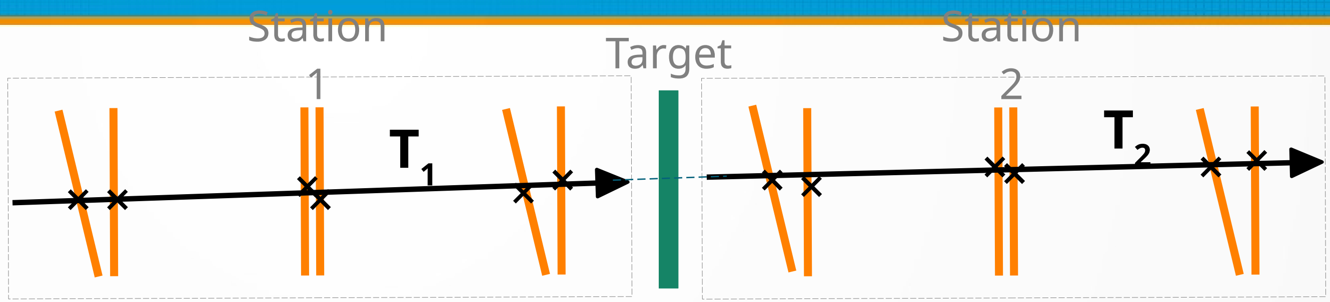
Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$ $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\mathrm{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\mathrm{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\mathrm{E_{Beam}}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$

Similar results also for different selection cuts

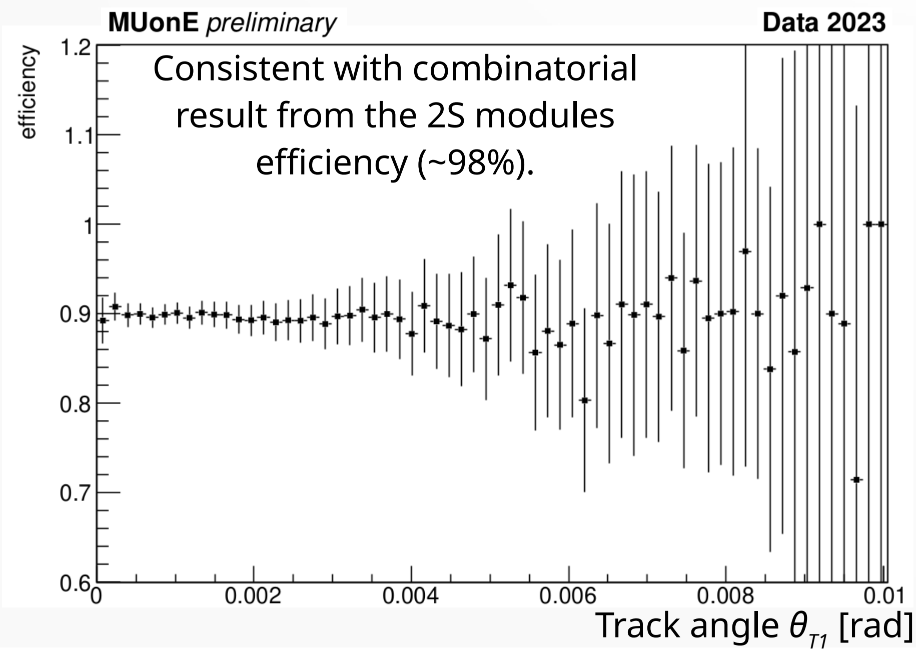
Input shifts identified correctly.
No degradation on the signal parameter

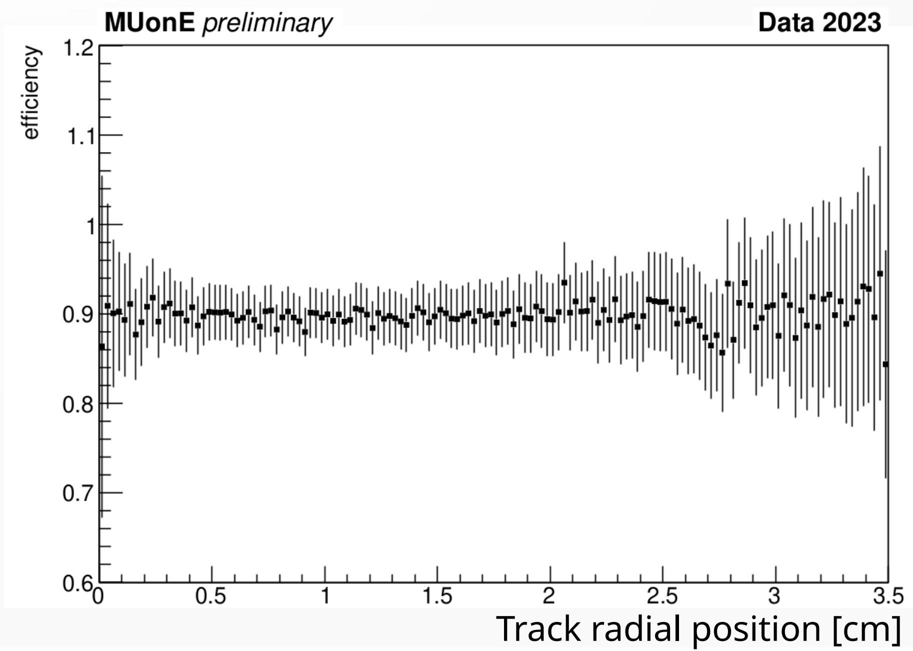
TR 2023 – tracking efficiency

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

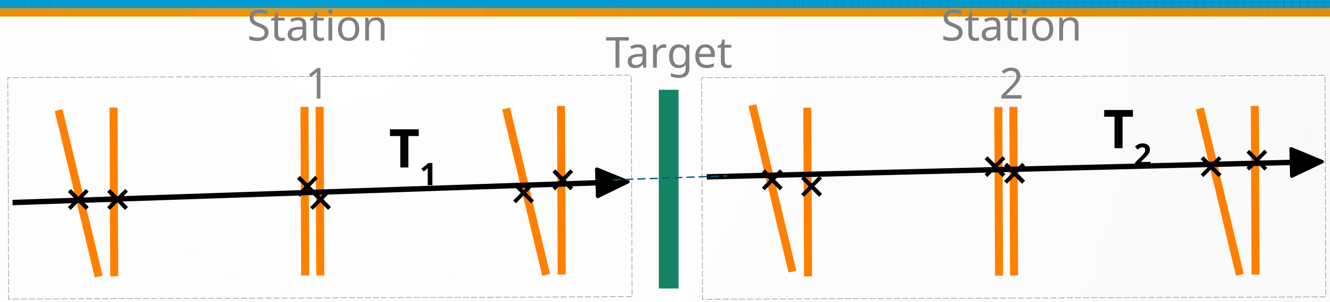


$$\text{Tracking efficiency} = \frac{N(T_2 \cdot T_1)}{N(T_1)}$$

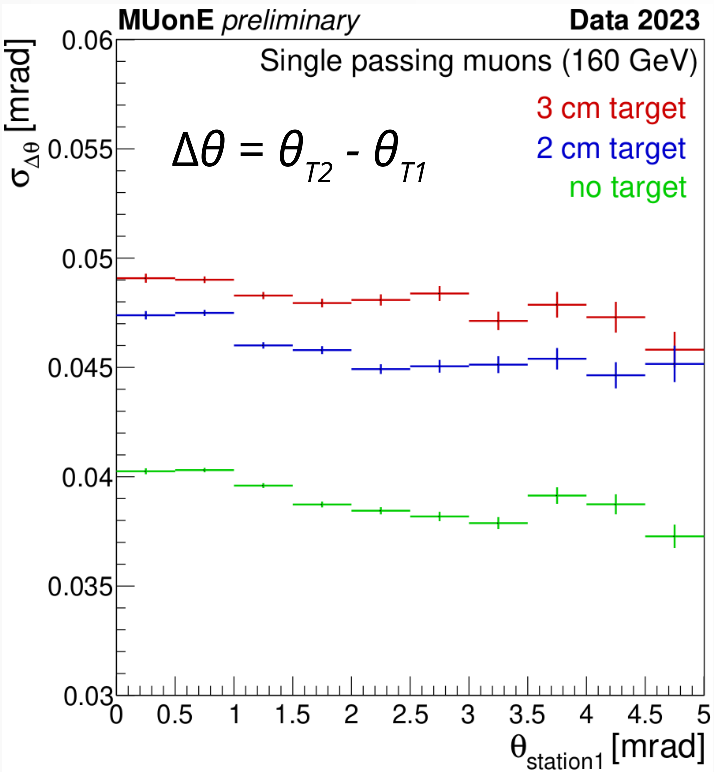




TR 2023 – angular resolution and MS effects



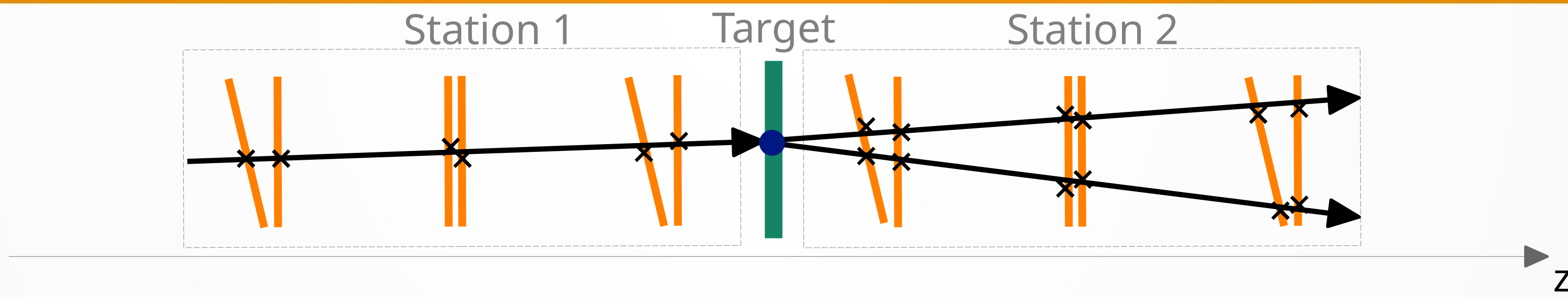
Select events with <u>single passing muons</u>.

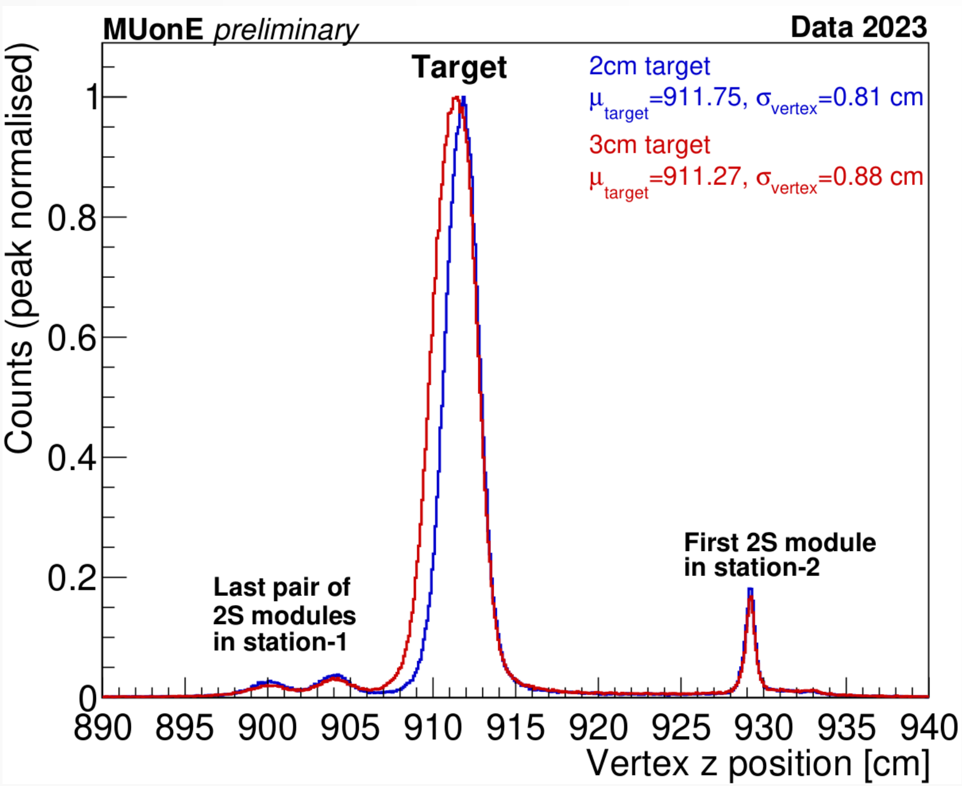


Target	$\sigma_{\Delta\theta}$ [μrad]	σ_{MS}(target) [μrad]	σ_{MS}^{PDG}(target) [μrad]
3 cm C	48.9 ± 2.1	28.1 ± 0.6	28.2
2 cm C	46.8 ± 2.1	24.3 ± 1.4	22.6
No Target	40.0 ± 2.2		

- 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

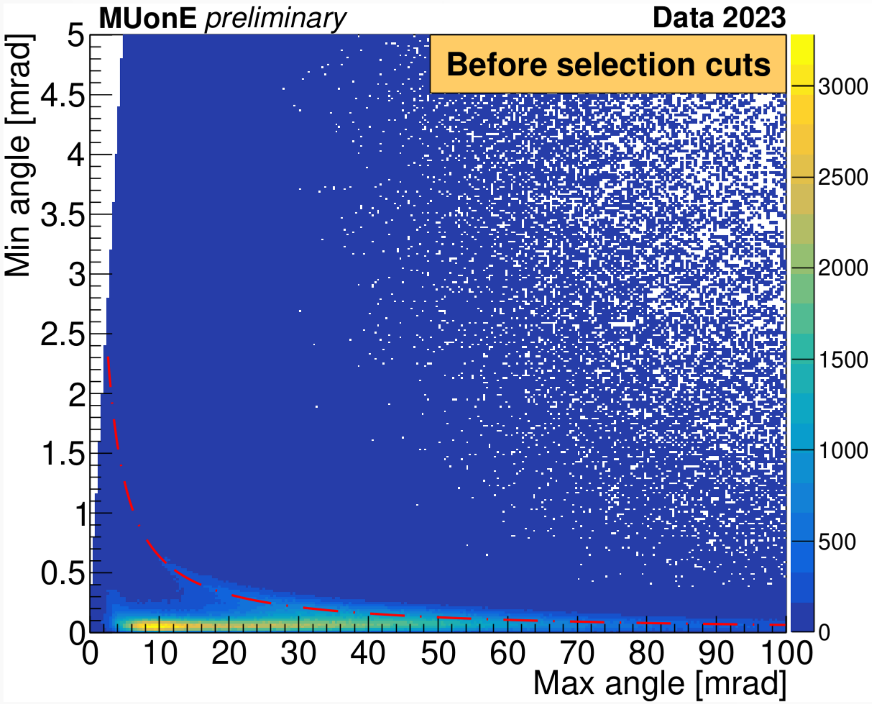
TR 2023
μ-e elastic scattering event selection

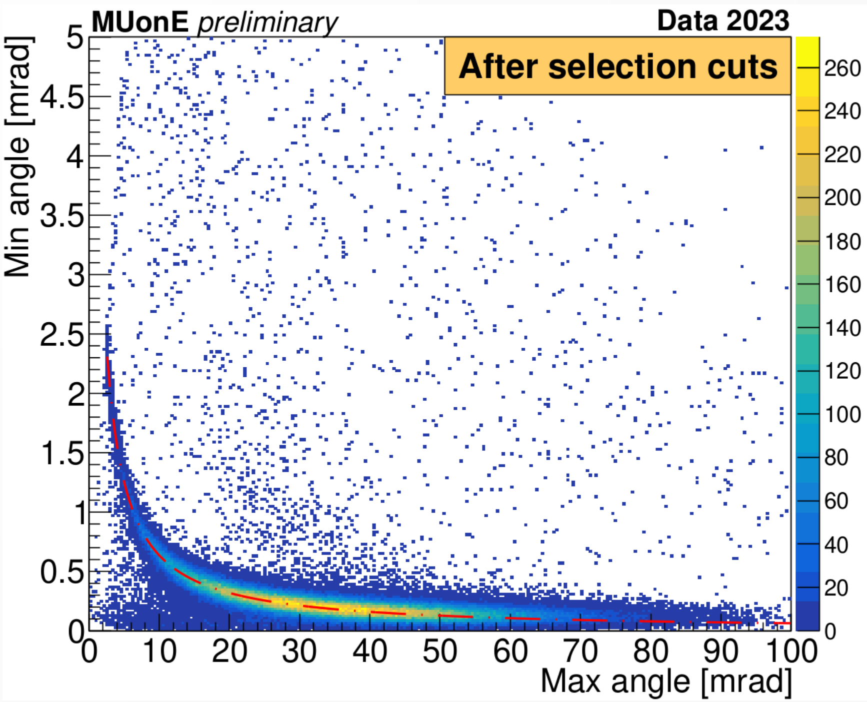
Pre-selection

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

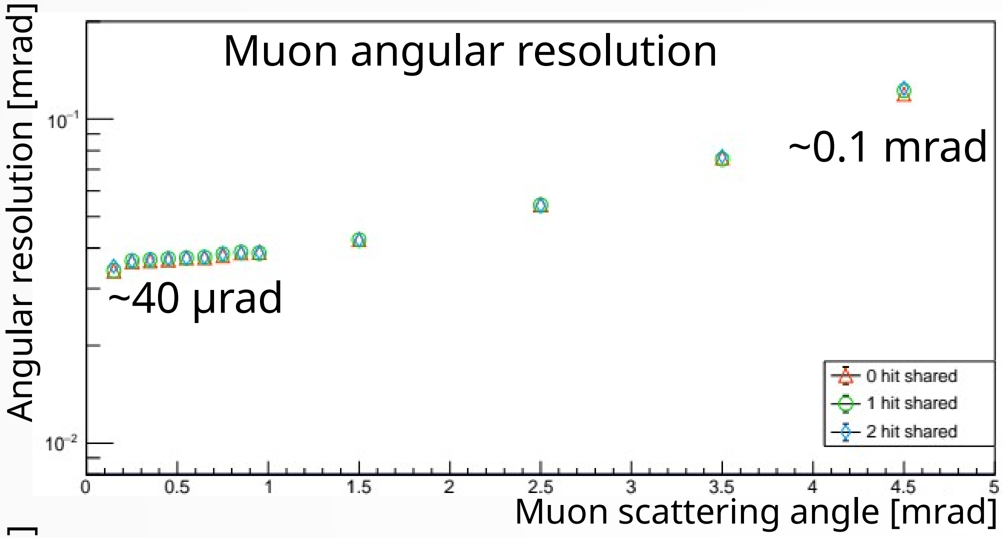
Initial event selection

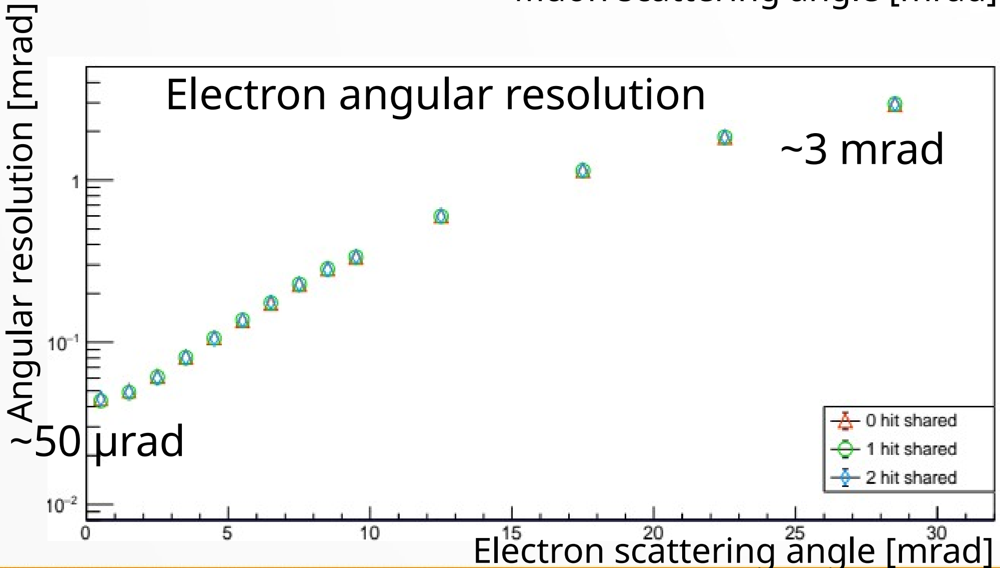
- ≥ 1 hit/module
- Cut on N_{hits}(station2)
- $|z_{vtx} - z_{target}| < 3$ cm
- Acoplanarity cut

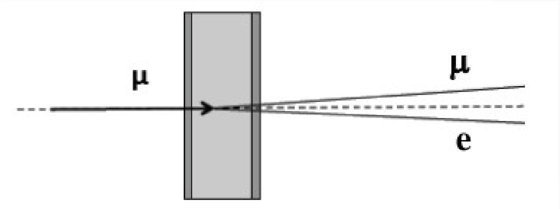




TR 2023 - MC performance: angular resolution of scattered particles

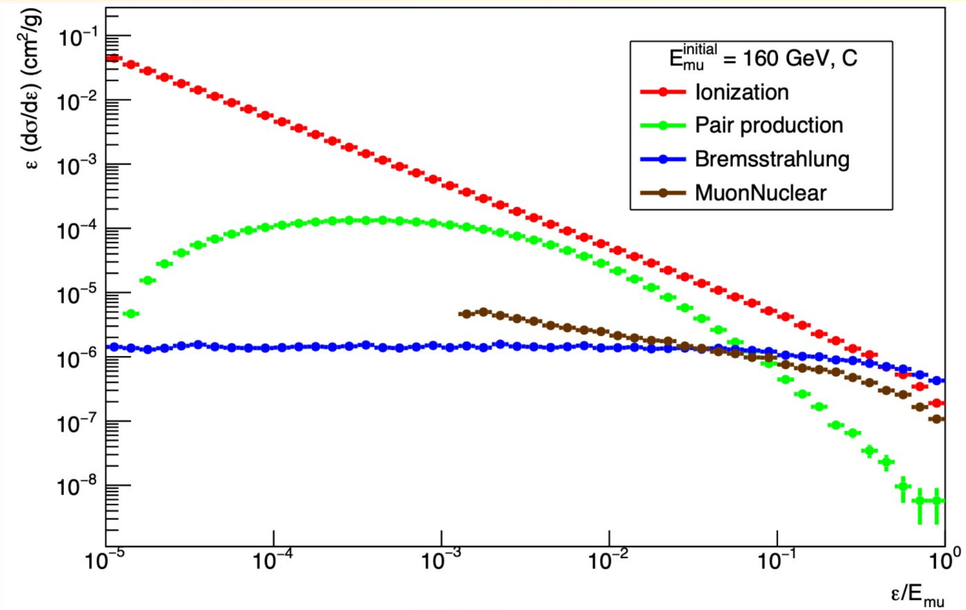


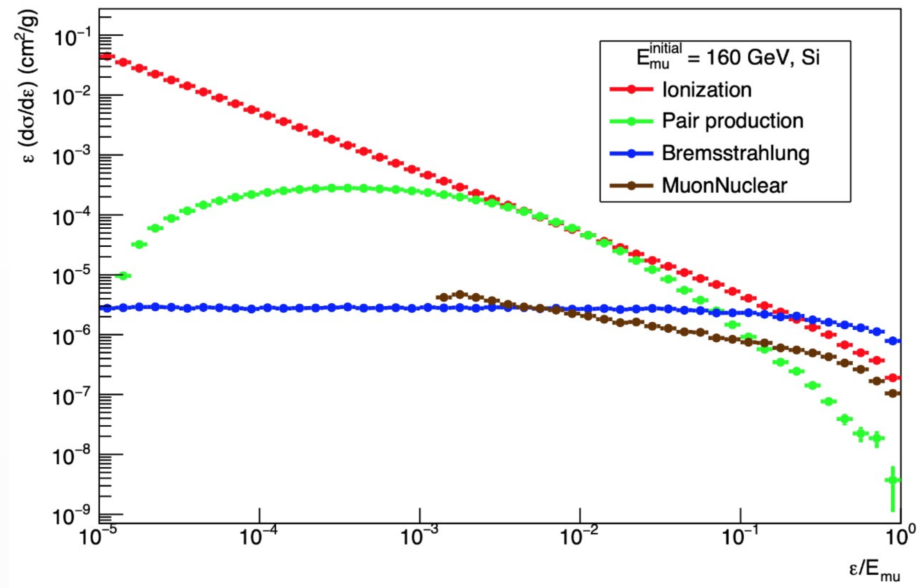




- Compare track reconstruction with MC truth.
- Muon angle: ~40 μrad resolution for small scattering angles.
- Electron angle:
  stronger impact of MS.
  Resolution is ~3 mrad for large scattering angles (E_e ~1–2 GeV).

Backgrounds





θ_e [mrad] 32 0

GEANT4

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

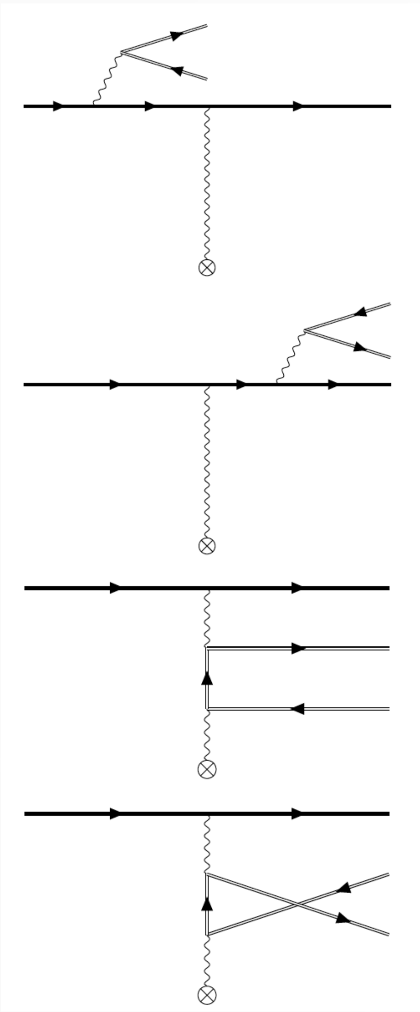
MESMER

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

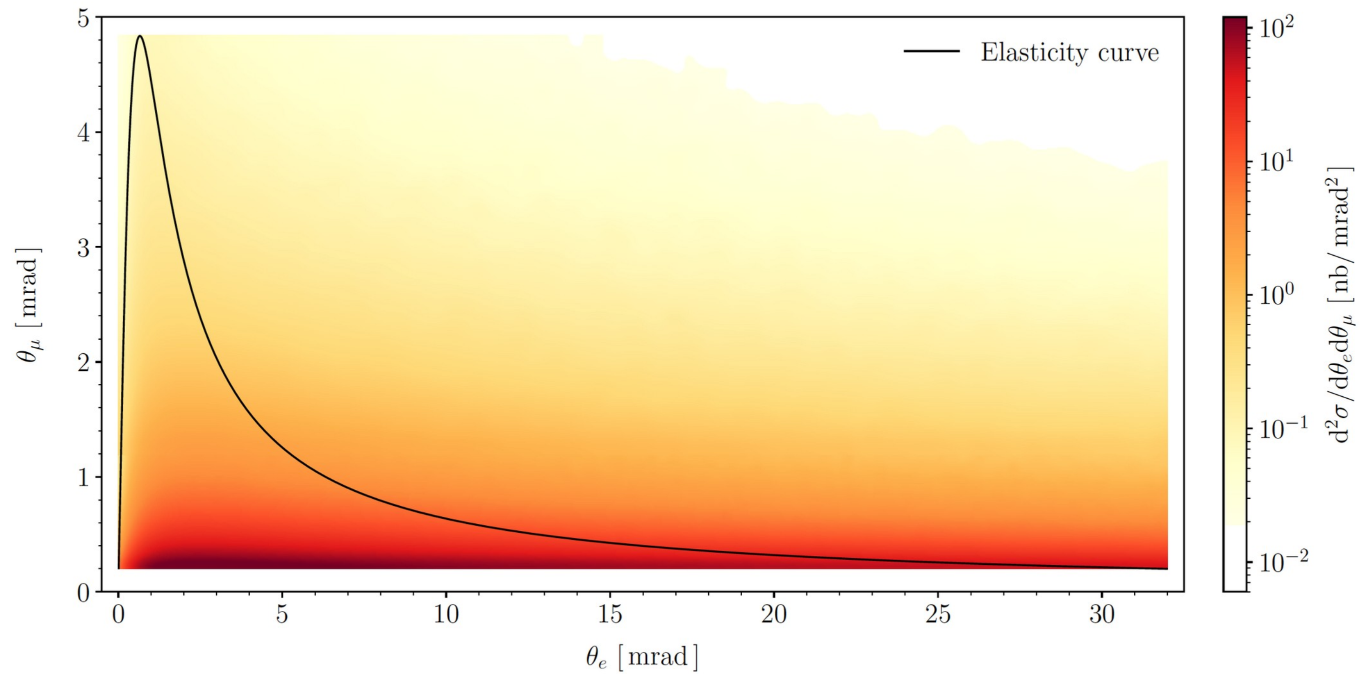
$l = e, \mu$

New Background MC generator

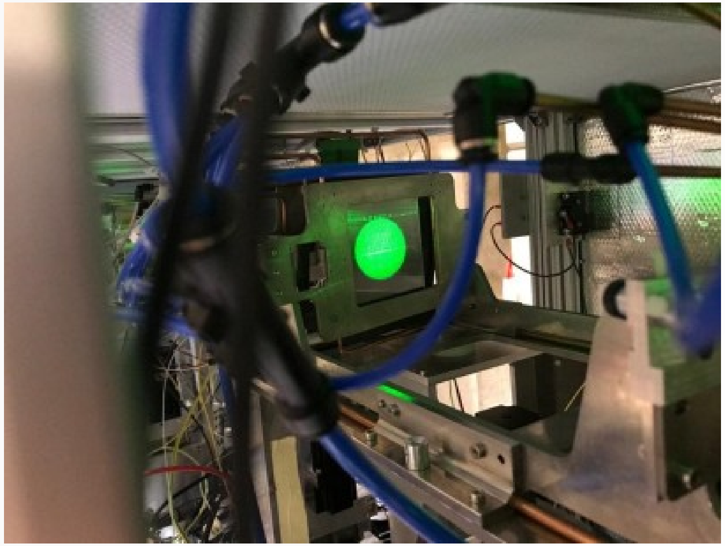
Main background: e+e- pair production
Implemented in MESMER
and interfaced with the MUonE detector simulation



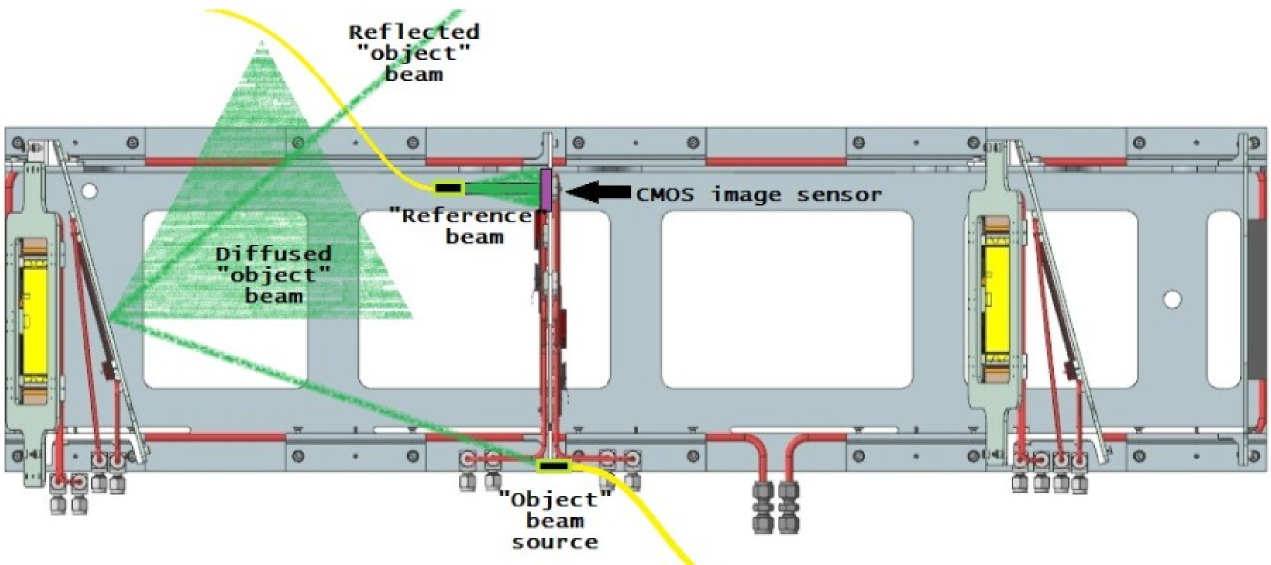
Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)



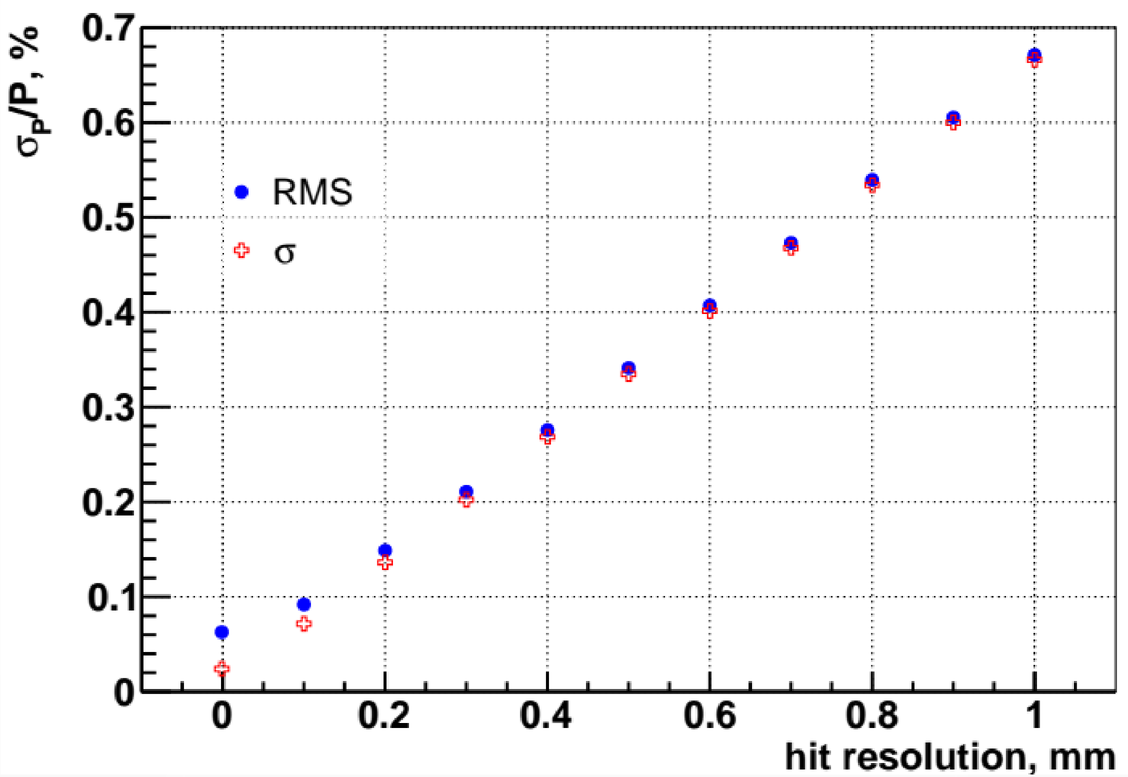
Laser holographic system



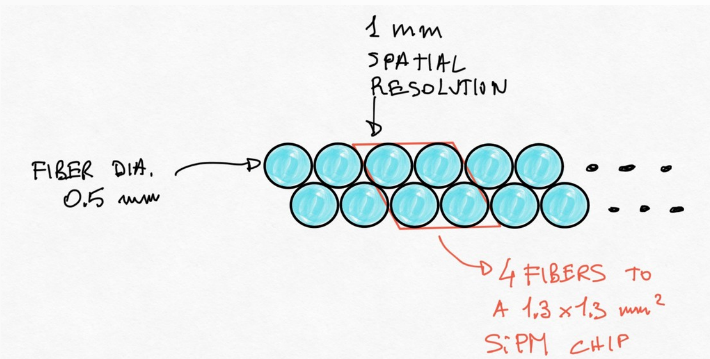
- Compare holographic images of the same object at different time
- Fringe pattern is related to deformations of the mechanical structure
- 532 nm fiber-coupled laser.
  Resolution: ~0.25 µm (half wavelength)
- Current limitation: Si sensors are sensitive to visible light → continuous monitoring is not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



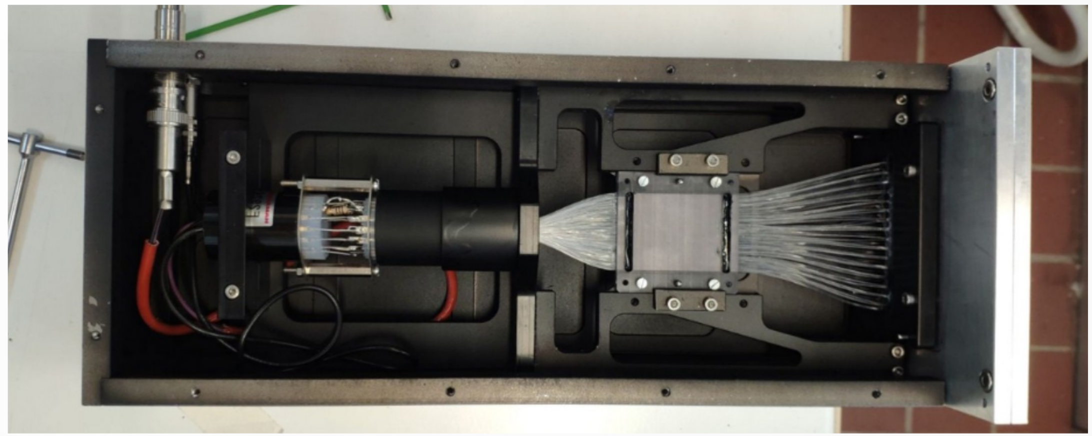
BMS (Beam Momentum Spectrometer)



Muon ID – SciFi



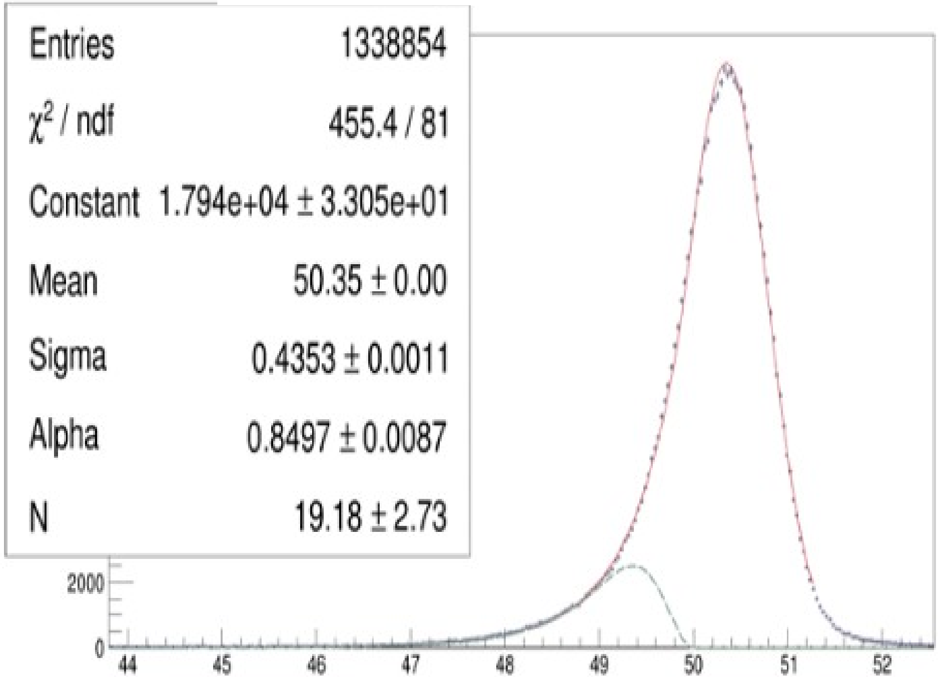
prototype



- 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

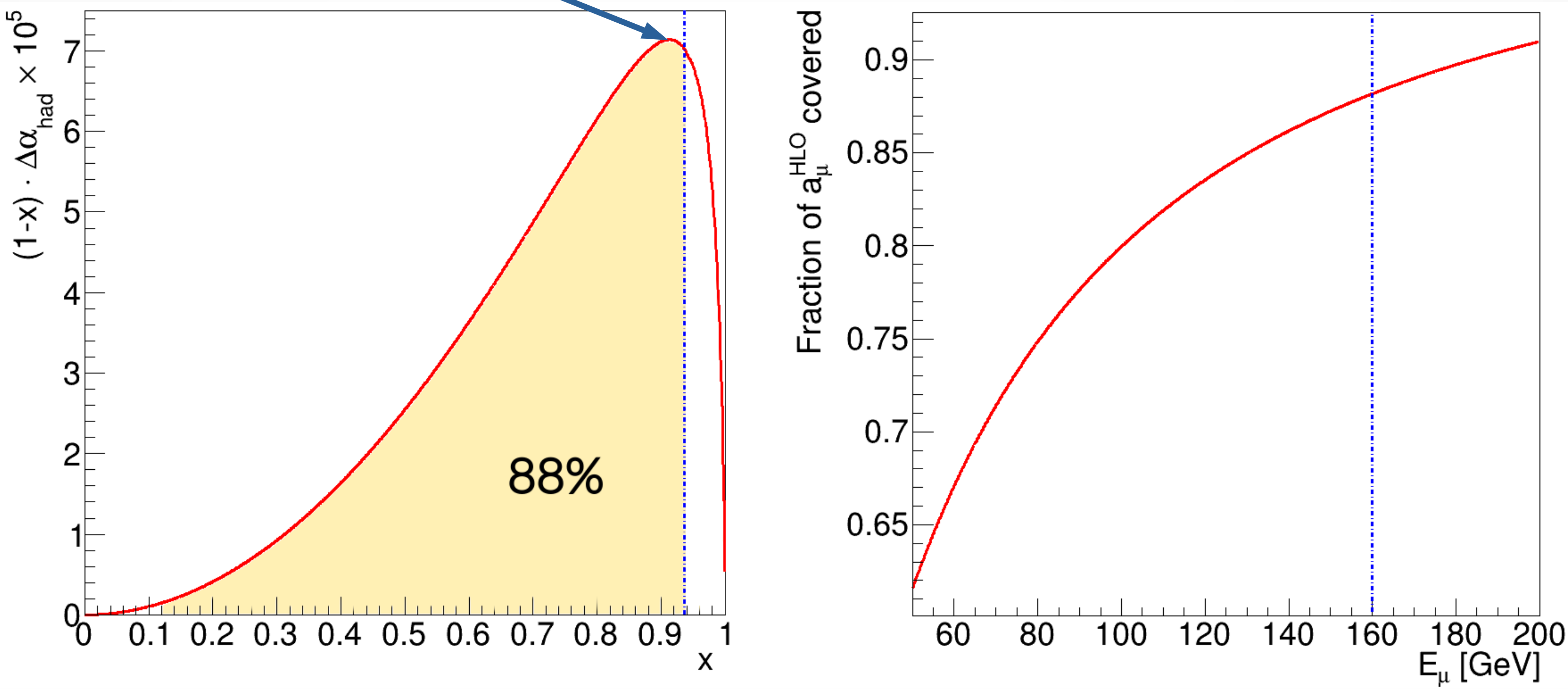
TB 2024, M2 beamline



Energy 3x3 cluster in the ECAL [GeV]

$x < 0.936$

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

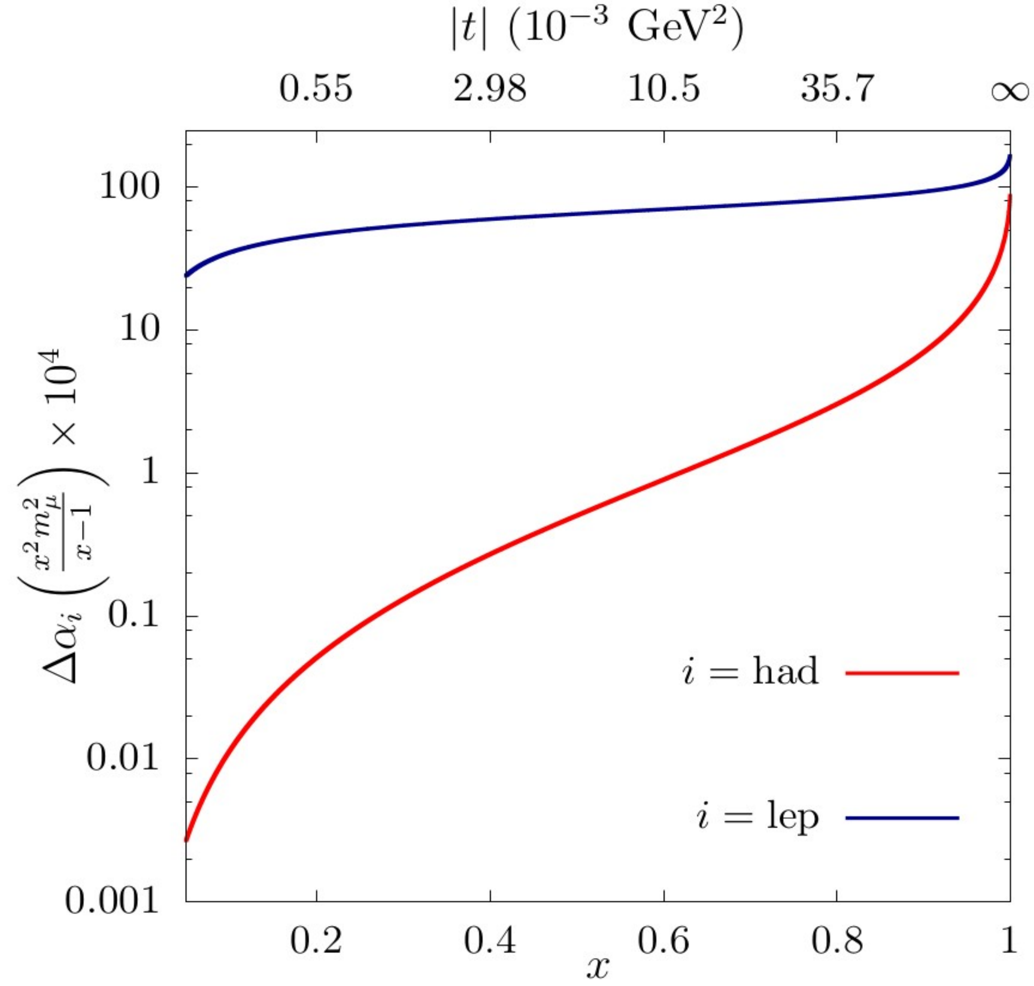


- 160 GeV muon beam on atomic electrons.

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

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

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



$\Delta\alpha_{had}$ parameterization

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

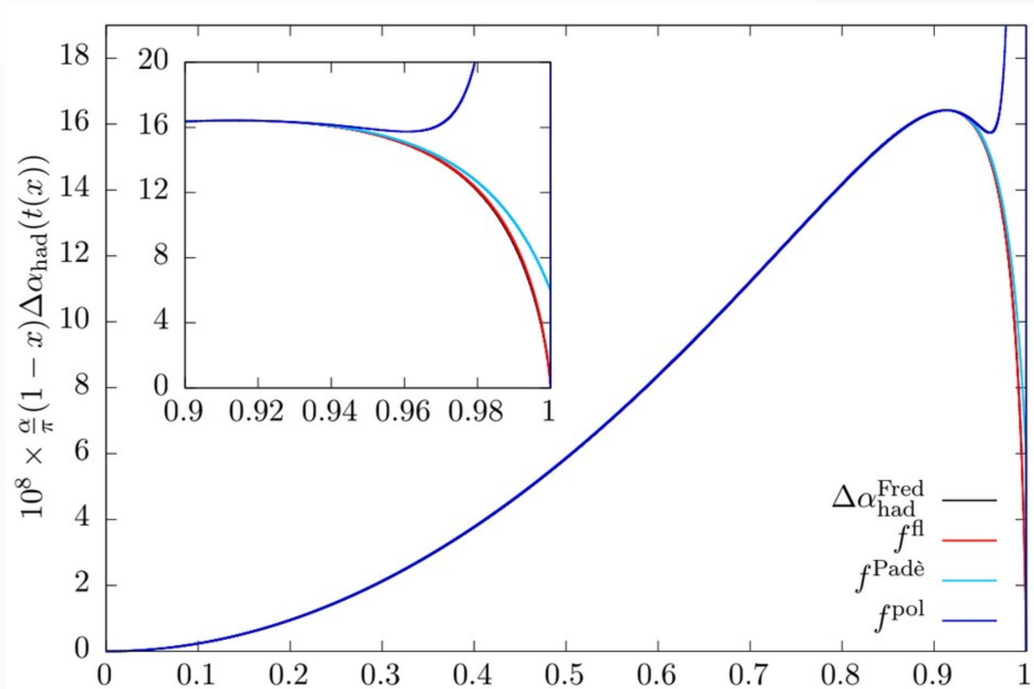
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

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 $a_\mu^{\text{HVP,LO}}$ from MUonE data

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

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2}$$

$$R(s) \propto \sigma(e^+e^- \to \text{hadrons})$$

$$s_{\text{th}} = m_{\pi^0}^2$$

$$s_0 \gtrsim (2\,\text{GeV})^2$$

$$\frac{\alpha^2}{3\pi^2}\int_{s_{\text{th}}}^{s_0}\frac{ds}{s}K(s)R(s) + \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}K(s)R(s)$$

pQCD

$$-\text{Im}\Pi_{had}(s) = \frac{\alpha}{3}R(s)$$

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

Low energy integral

$$\int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} K(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} =$$

$$\int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} [K(s) - K_1(s)] \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} + \boxed{\int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} K_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi}}$$

$$K_1(s) = a_0 s + \sum_{n=1}^{3} \frac{a_n}{s^n}$$

$K_1(s)$ approximates $K(s)$ for $s < s_0$.

Meromorphic function:

no cuts, poles in $s = 0$.

Two different techniques to get $K_1(s)$:

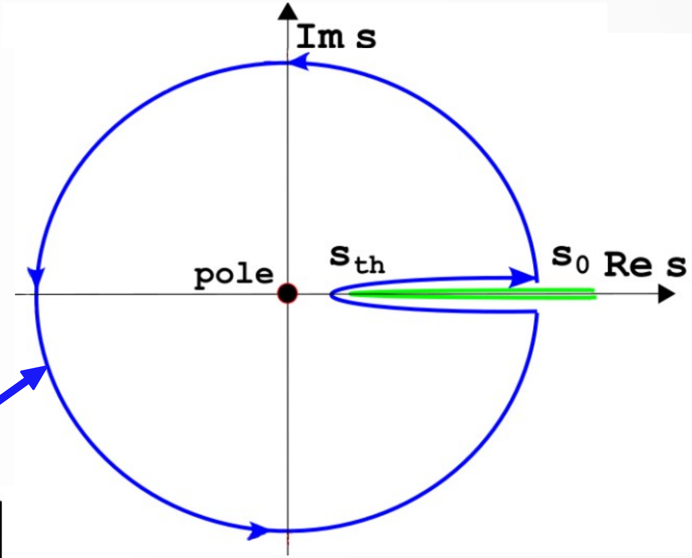
1) Least squares minimization

2) Minimize $\int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} |K(s) - K_1(s)| R(s)$

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

Low energy integral

Use Cauchy's theorem



$$\int_{s_{\mathrm{th}}}^{s_0} \frac{ds}{s} K_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} =$$

$$\mathrm{Res}\left[\Pi_{had}(s)\frac{K_1(s)}{s}\right]_{s=0} - \frac{1}{2\pi i}\oint_{|s|=s_0} \frac{ds}{s} K_1(s)\Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$\mathrm{Res}\left[\Pi_{had}(s)\frac{K_1(s)}{s}\right]_{s=0} = \sum_{n=1}^{3} \frac{c_n}{n!}\frac{d^{(n)}}{ds^n}\Pi_{had}(s)\Big|_{s=0} = \sum_{n=1}^{3} \frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

From MUonE

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

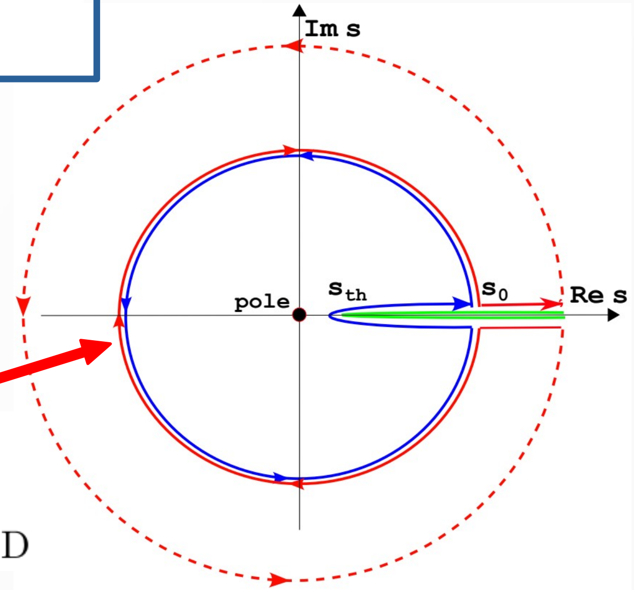
High energy integral

Similar strategy for the high energy part

$$\int_{s_0}^{\infty} \frac{ds}{s} K(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} =$$

$$\int_{s_0}^{\infty} \frac{ds}{s} [K(s) - \tilde{K}_1(s)] \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} + \boxed{\int_{s_0}^{\infty} \frac{ds}{s} \tilde{K}_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi}}$$

$$\tilde{K}_1(s) = K_1(s) - c_0 s$$



$$\int_{s_0}^{\infty} \frac{ds}{s} \tilde{K}_1(s) \frac{\mathrm{Im}\Pi_{had}(s)}{\pi} = \frac{1}{2\pi i} \oint_{|s|=s_0} \frac{ds}{s} \tilde{K}_1(s) \Pi_{had}(s) \Big|_{\mathrm{pQCD}}$$