A muon for ChatGPT

Tackling the muon g-2 anomaly with the MUonE experiment at CERN

Eugenia Spedicato on behalf of the MUonE collaboration

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Anomalous magnetic moment of the muon

$\overrightarrow{M_l} = g_l \frac{e}{2m_l} \vec{S}$ ⟶ Dirac prediction $g_l = 2$ ⟶ Quantum corrections give the **anomaly**: $a_l = \frac{g_l - 2}{2}$

Can we experimentally test the lattice calculations?

- Experimental average **FERMILAB+BNL**

  VS

  Theoretical **dispersive method** — Discrepancy $> 5\sigma$

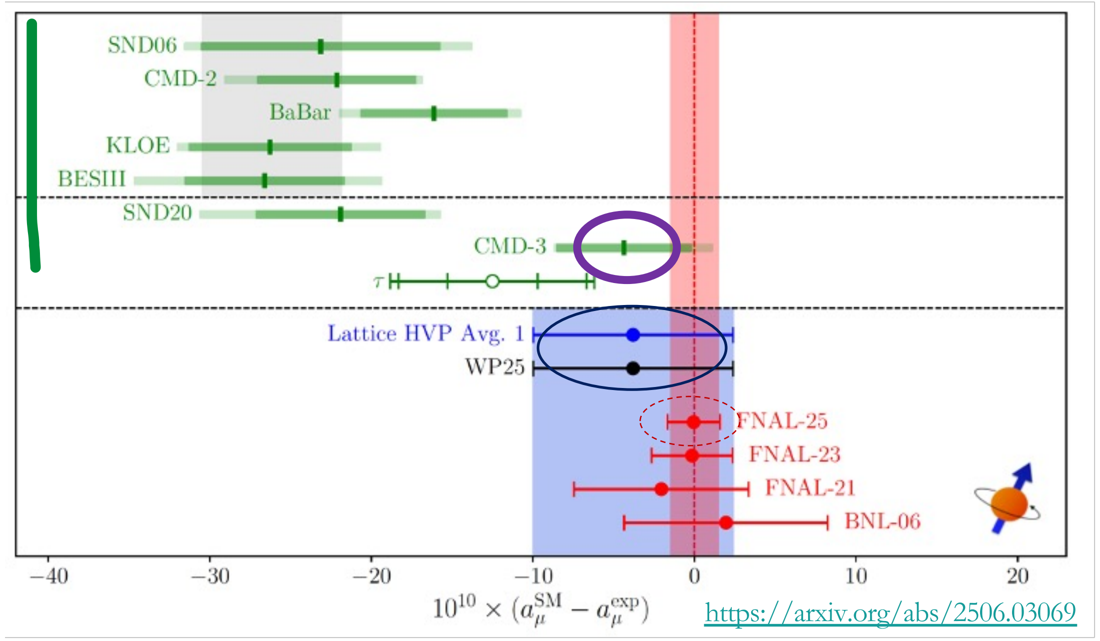
  but…

  LQCD result summarized in Theory intiative White Paper (2025) — Discrepancy $< 1\sigma$

  R. Aliberti et al., (2025) arXiv:2505.21476

  New result from $e^+e^- \to$ hadrons cross section with **CMD-3 data** — Discrepancy $< 1\sigma$

  F. V. Ignatov et al., (2023) Phys. Rev. D 109, 112002



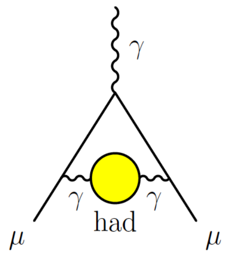
https://arxiv.org/abs/2506.03069

Saskia Charity's talk

1. Reduce the **experimental** error ⟶ Fermilab g-2 goal (124 ppm – new article-)
2. Improve **theoretical** precision ⟶ Dominant uncertainty: **LO hadronic vacuum polarization term** a_μ^{HLO}

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had}$$

0.6%



MUonE proposal

Independent estimate of a_μ^{HLO} through innovative method:

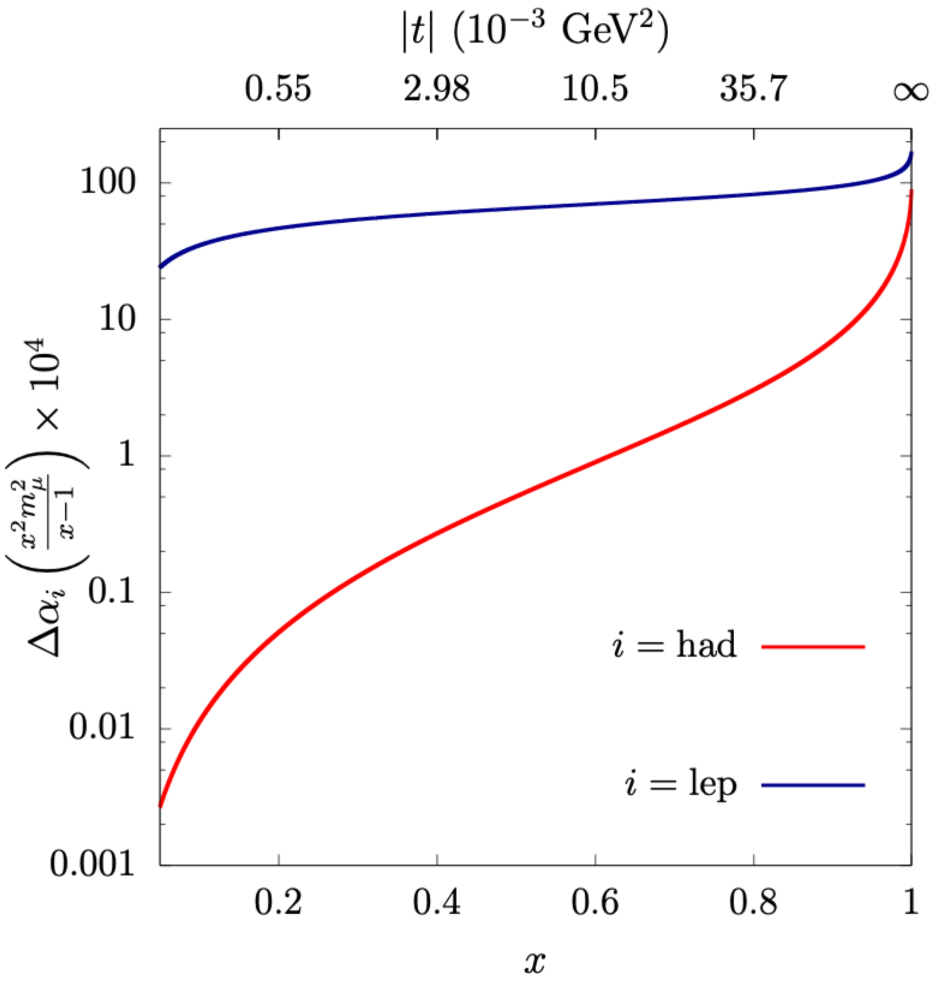
C.M. Carloni Calame, et al. Phys.Lett.B746(2015)325

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

Space-like

Smooth function

B. E. Lautrup et al., Phys. Rept. 3 (1972) 193



Proposed process to measure $\Delta\alpha_{had}$: **elastic scattering**

G.Abbiendi et al., Eur.Phys.J.C77(2017)139

$$\mu\,(160GeV) + e^-(rest) \rightarrow \mu\ + e^-$$

M2 muon beam at CERN SPS

Workflow

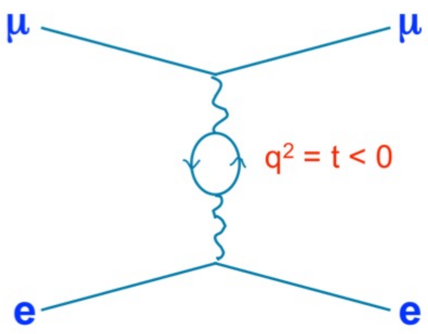
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2 \xrightarrow{\text{Template fit}} \Delta\alpha_{had}(t) \xrightarrow{\text{Master integral}} a_\mu^{HLO}$$

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

Required precision on $a_\mu^{HLO} <$ 1% implies a relative precision of **$\sim 10^{-5}$** on the **shape of the elastic differential cross section**

Great challenge in terms of required **precision!**

$\mu - e$ elastic scattering



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

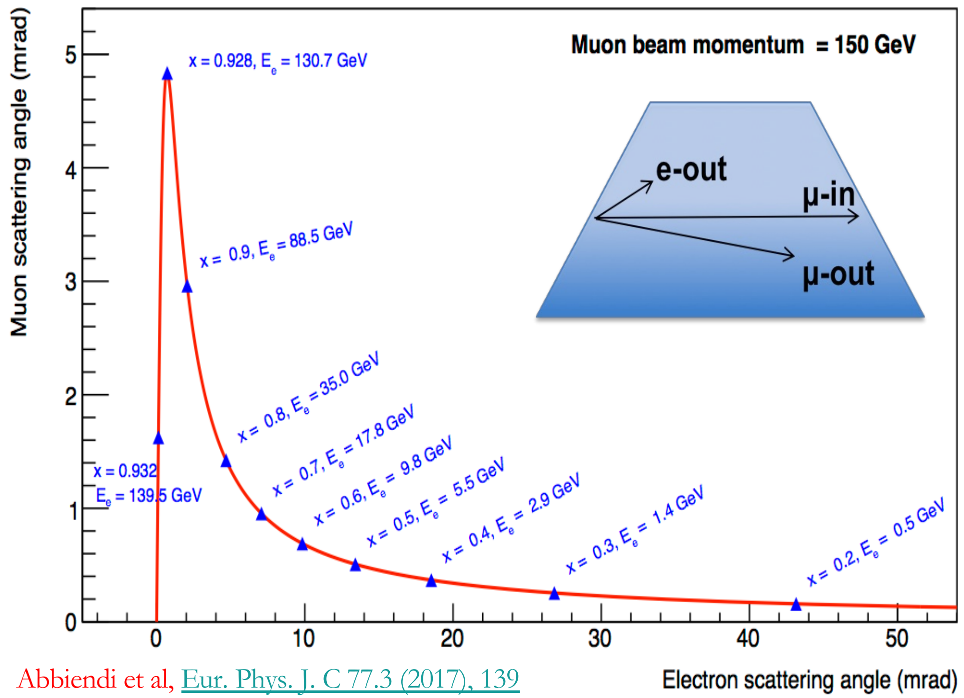
Measuring the **leptons scattering angles**

Precise correlation

Helps in the selection of purely elastic events

$0 < \theta_\mu < 5\ mrad$
$0 < \theta_e \lesssim 50\ mrad$

ELASTIC CURVE

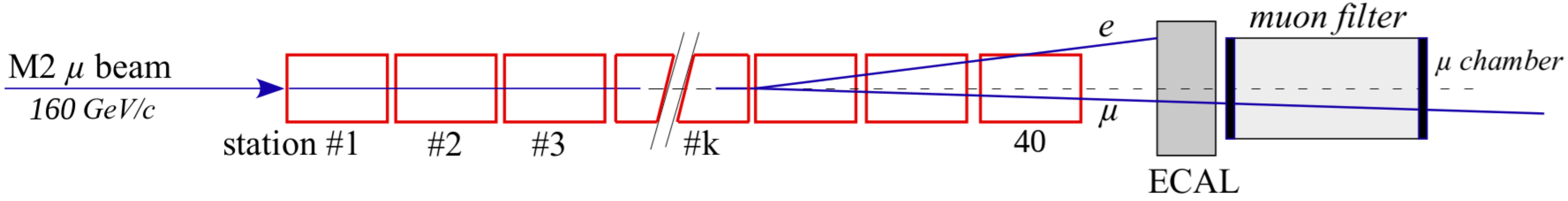


Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

Experimental apparatus

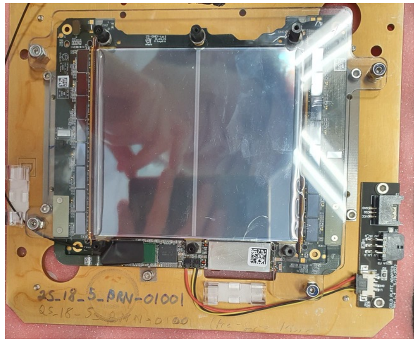
Forseen after CERN Long Shutdown 3 (2027-2029)

40 tracking stations + Electromagnetic calorimeter + Muon filter



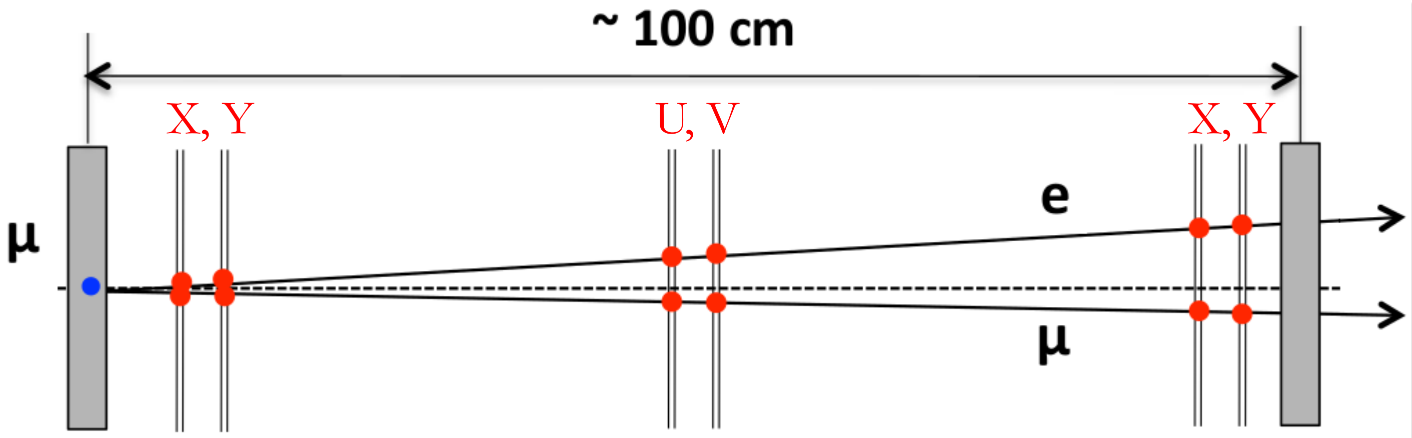
Each **tracking station** behaves as an independent *detector*

- **1** beryllium or carbon target ($1.5 - 1.0\ cm$)
- **6** silicon strip modules (CMS 2S modules)



CERN-LHCC-2017-009

Modular layout to achieve the necessary interaction rate *minimizing* systematic effects (e.g. **Multiple Scattering**)



Letter of Intent: The MUonE Project, SPSC-I-252

More info about 'detectors' in Aldo Arena's talk

Achievable precision

To be **competitive** with previous theoretical estimates:

precision on $a_{\mu}^{HLO} < 1\%$

40 stations
(tot: $\boldsymbol{60\ cm}$ Beryllium)

+

3 years of data taking with an *integrated luminosity* of $\boldsymbol{1.5 \times 10^{7}\ nb^{-1}}$

=

Statistical error on $\boldsymbol{a_{\mu}^{HLO} < 0.5\%}$

The challenge is to control the **systematic effects** at the same level

<u>Main systematics effect</u>:

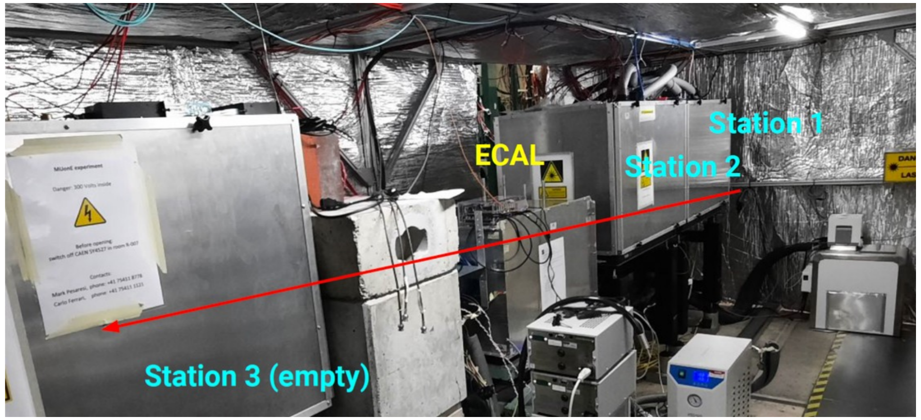
1. Intrinsic **angular** resolution.
2. Multiple **scattering**;
3. **Beam energy** knowledge (few MeV)- **longitudinal** alignment.

Test Runs towards the final experiment

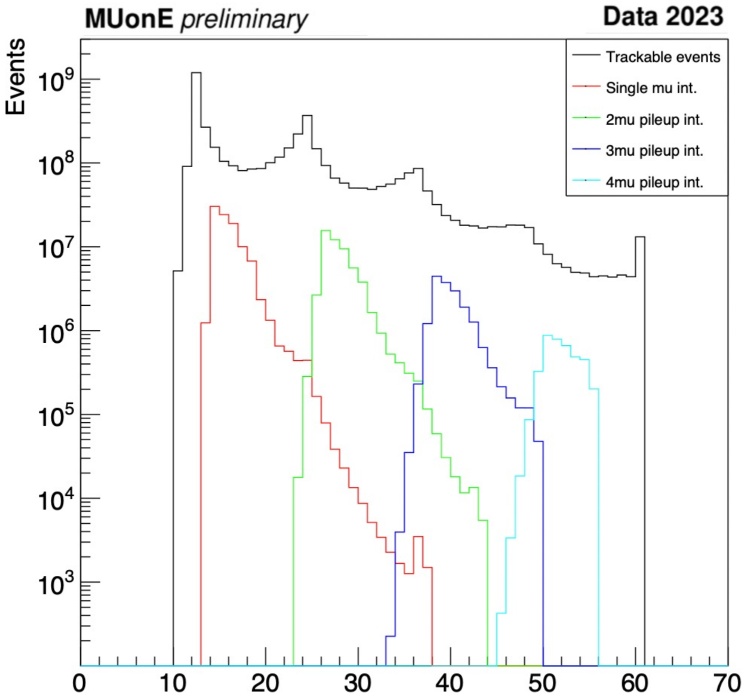
- 2017: dedicated test beam to study multiple scattering
  JINST 15 (2020) P01017
- 2018: test beam to study elastic scattering properties and event selection
  JINST 16 (2021) P06005
- 2021: first joint test CMS-MUonE with a few 2S modules prototypes (parasitic)
- 2022: test 1 tracking station + test the ECAL
- 2023: test with 2 tracking stations + ECAL **Ongoing analysis!**
- 2024: 2 tracking stations (DAQ tests) + calorimeter (characterization)
- 2025: run with a scaled version of the complete apparatus:
  3 tracking stations + ECAL + Muon ID + Beam Momentum Spectrometer (BMS).

Test Run 2023

- 160 GeV muons of **M2 beam** line at CERN North Area;
- Max **asynchronous** rate at 50 MHz ($2\times10^8\mu$ per spill);
- **Setup**: 2 tracking stations + ECAL;
- **Triggerless** DAQ → Large data volumes processed offline.



Future plan: data filter on FPGA**; now** an offline skimming algorithm has been implemented to preselect candidate events from target interaction: base on the hit pattern in the two stations.



CERN-SPSC-2024-015

From **~12 B recorded events**, the skimming procedure reduced the output at ~ $\mathbf{1-2\%}$.

Different classes are well separated:

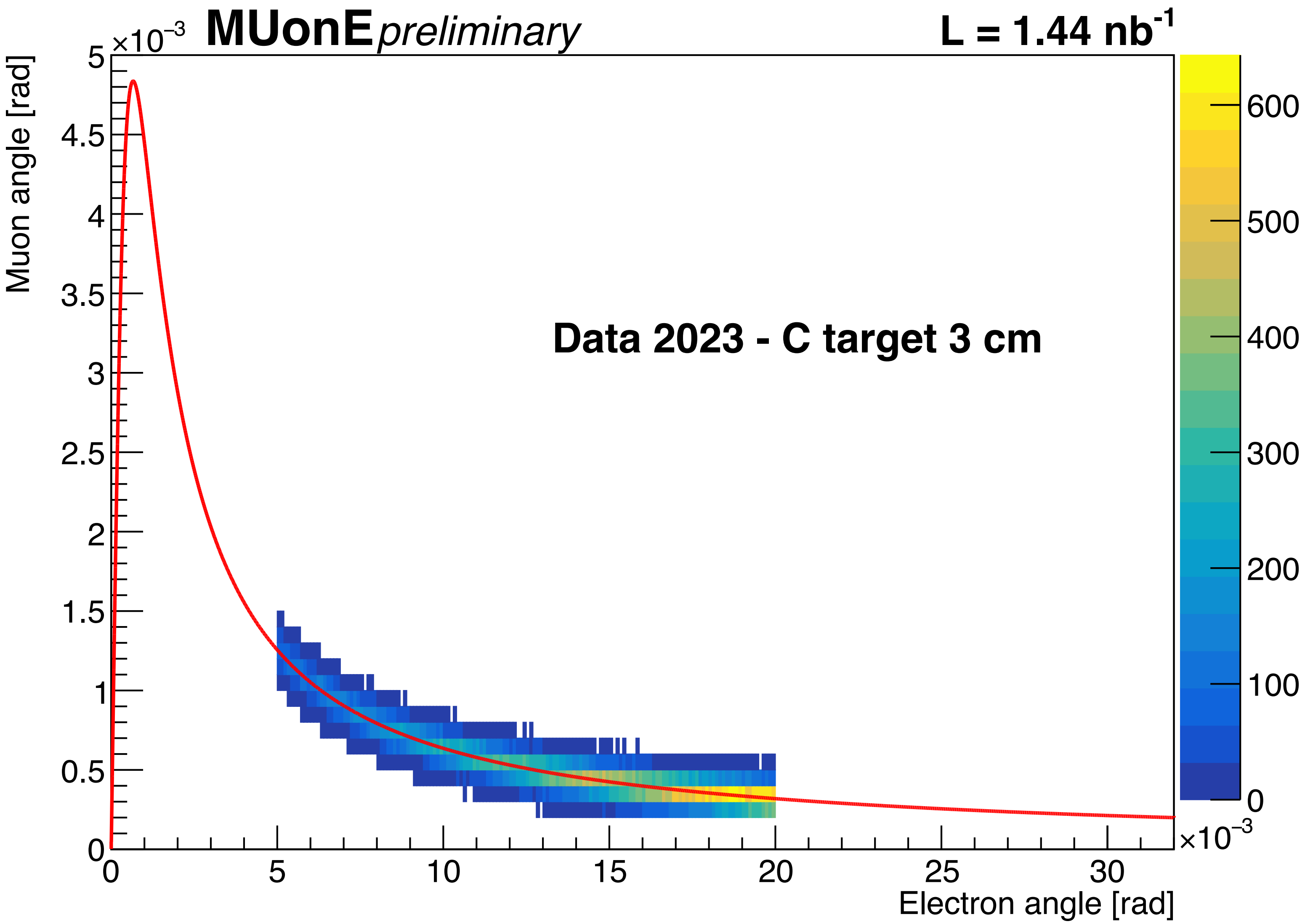
1. Single muon interactions
2. 2,3,4 pile-up muons with interactions

Figure: Fraction of different event multiplicities, in 2023 data, after skimming based on hits patterns.

2D scattering angles plots

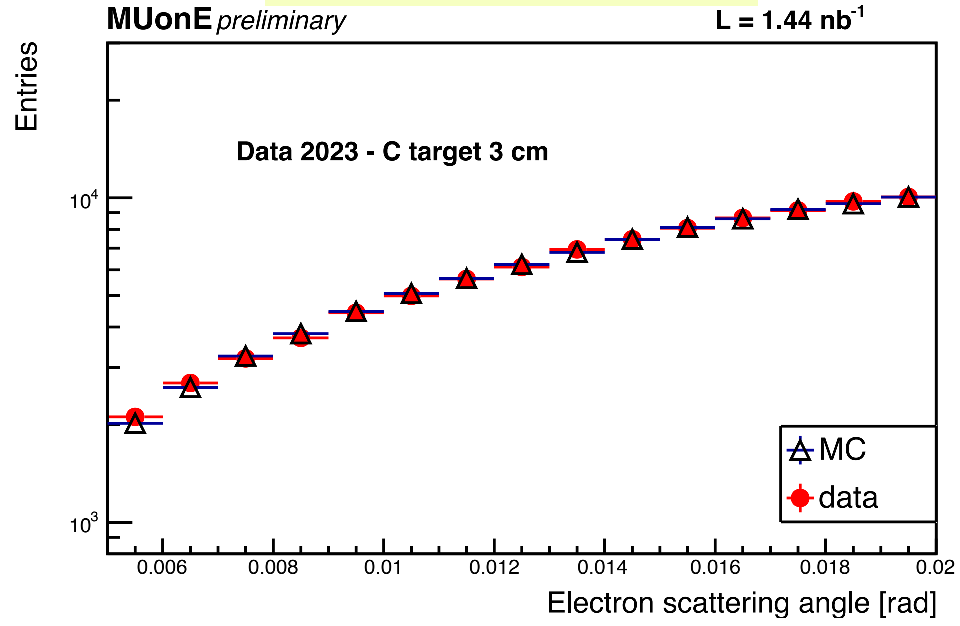
From an elastic sample that passed an elastic selection

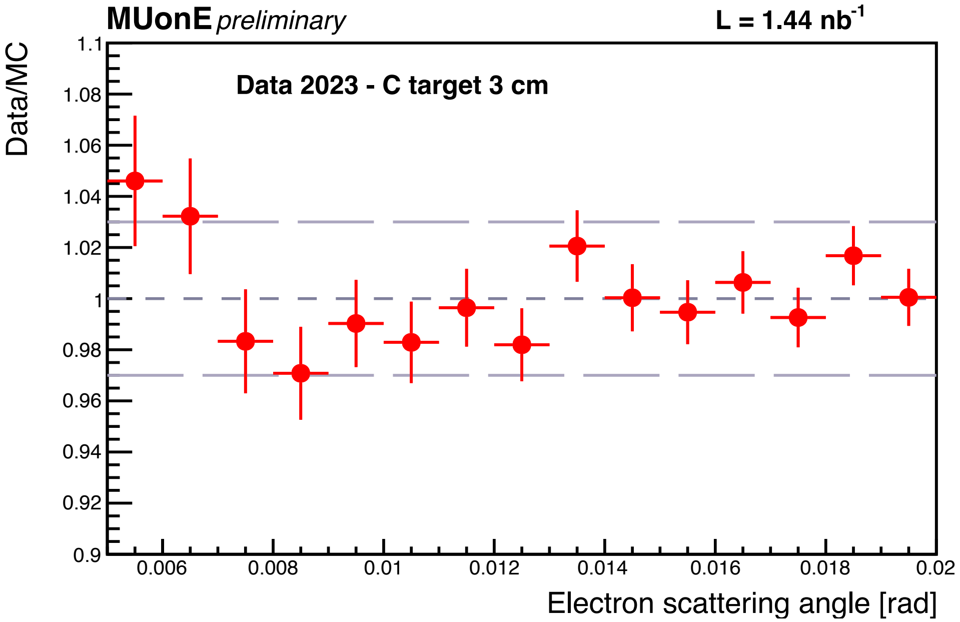
Details in backup



Data/MC comparison of angular distributions after an elastic selection

With resolution correction





$5 < \theta_e < 20\ mrad$

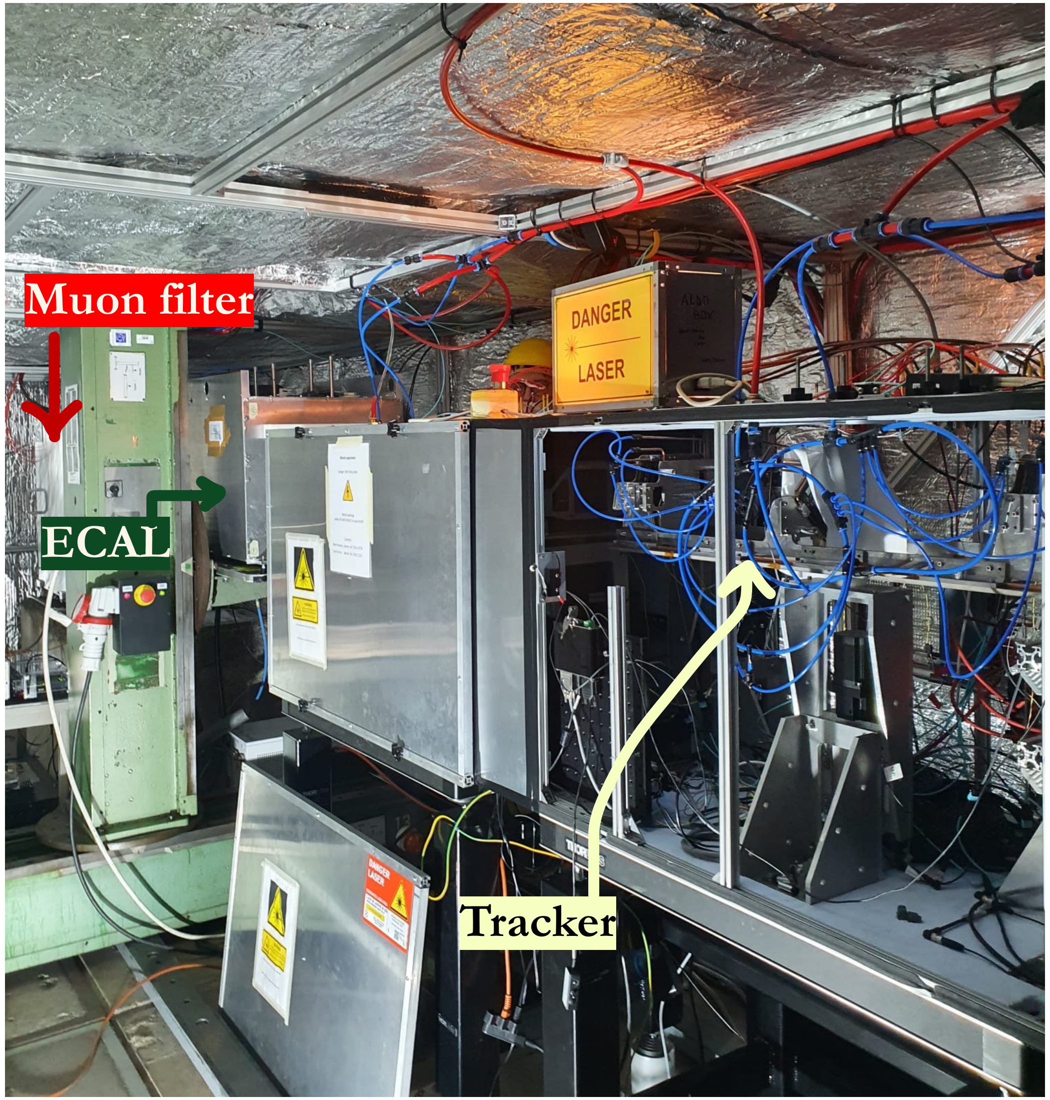
MC normalization to the number of real data events

Data/MC ratio as a function of **electron angle** is mostly within gray limits $\rightarrow$ $\pm 3\%$

NB: For the leptonic running of $\alpha(t)$ to be observed, the MC description of angular shapes must be accurate to at least $\pm \mathbf{0.5\%}$.

Test Run 2025

- From **April to July 2025** possibility to use the M2 beam line at CERN;
- More complete **setup**: 3 tracking station + ECAL + Muon filter + BMS;
- This consists in the **Phase 1 of the MUonE experiment**, presented in this proposal;
- Now, the **setup is all installed** (with the exception of the BMS → July);
- Commissioning has ended, now data taking has started!

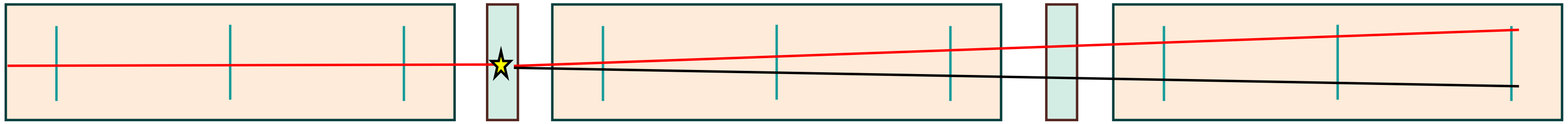


MAIN GOAL: Collect data to make $\Delta\alpha_{had}(t)$ measurement with a ~20% statistical uncertainty, providing elements to optimize a full scale experiment (forseen after LS3)

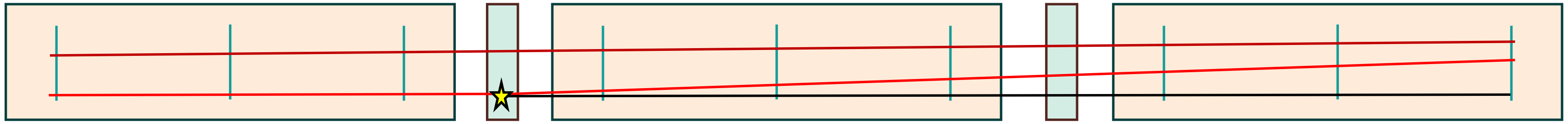
New trigger implemented on FPGA

We are able to directly filter **online** on FPGA different classes of events based on the *hit pattern in the three stations*:

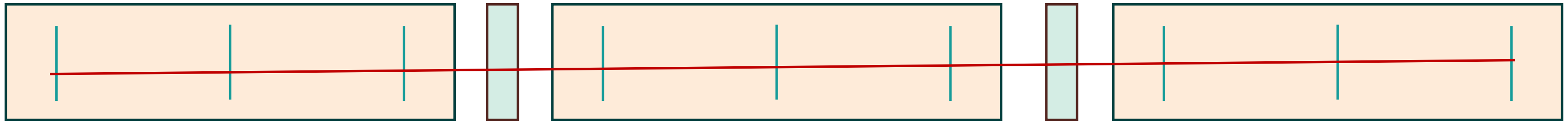
- Single muon interaction first (in the example) /second target



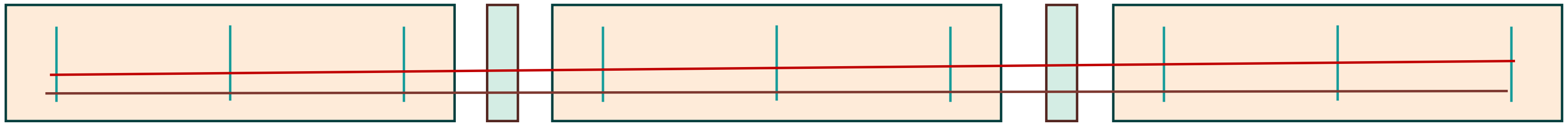
- Pileup muon interaction first (in the example) /second target



- Single passing muon station 1 && 2 / 2 &&3



- Pileup passing muon station 1 && 2 / 2 &&3

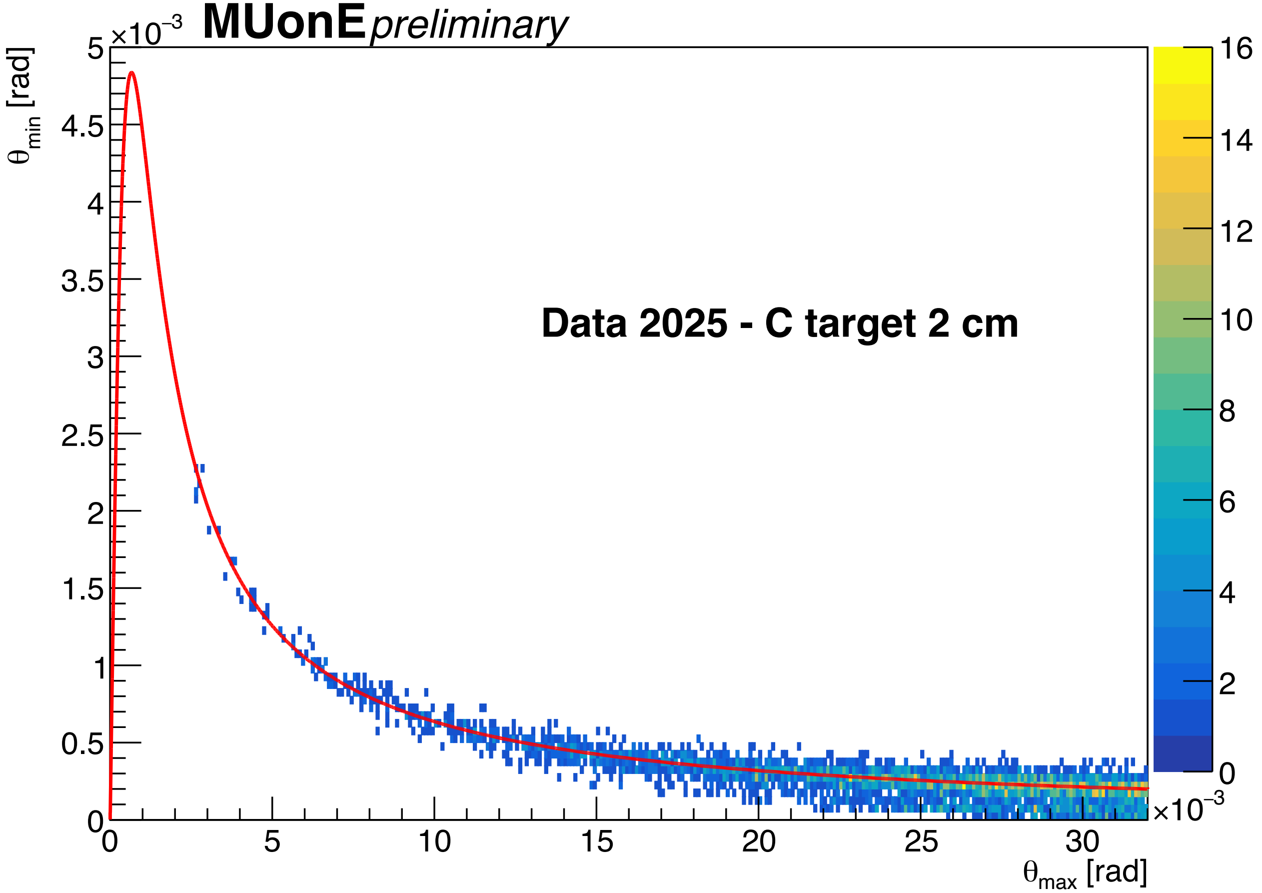


Let's consider events passing the trigger on **single muon interaction** in the **first** target and in the **second** target

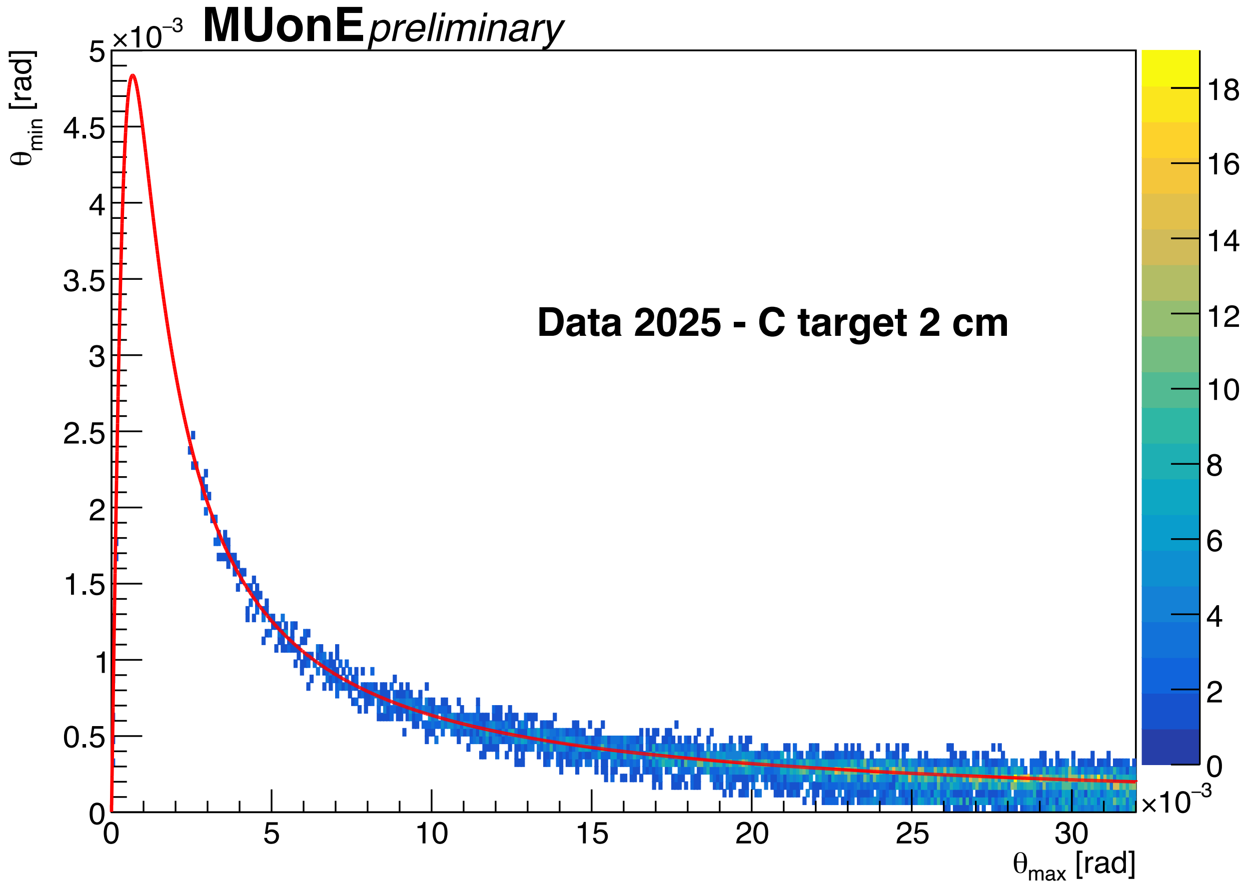
We see elastics!

Details of the selection in backup

first target



second target



Conclusions

- **MUonE** proposes an **innovative and independent method** for the evaluation of the hadronic vacuum polarization term at LO a_μ^{HLO} which is alternative with the *previous ones*. MUonE is the only opportunity to test experimentally the Lattice calculations!
- First results and data/MC comparisons have been done with 2023 TR data;
- **Shapes comparisons** of electron angle distributions stands within $\pm 3\%$ from the MC prediction. However, for the running of $\alpha(t)$ to be observed, the precision on the angular shapes must be accurate to within at least $\pm 0.5\%$. Several improvements are expected next months;
- Next important step:
  2025 **Phase 1**: we presented a technical proposal to the SPSC in June for **4 weeks of running time** in 2025 to study the expected systematic errors and background under realistic conditions and make preliminary measurements of $\Delta\alpha\ (t)$.

Thank you for the attention!

And if you want to join, contact us! ☺
https://web.infn.it/MUonE/

BACKUP

MC generators and reconstruction tools

☼ Dedicated **MC generator** (MESMER) for the **elastic signal** and the main **background** :

- **Background** $\mu^+ N \rightarrow \mu^+ N l^+ l^-$ with $l = e, \mu \rightarrow \sigma_{bkg} \propto Z^2$

  (G. Abbiendi, E. Budassi, C. M. Carloni Calame, A. Gurgone, F. Piccinini; Phys. Lett. B 854 (2024) 138720)

- **Signal+photons** $\mu^+ e^- \rightarrow \mu^+ e^- (\gamma) \rightarrow \sigma_{sig} \propto Z$

  Developed at NNLO (Carloni Calame, C.M. *et al.*; J. High Energ. Phys. 2020, 28)

☼ Detector description for **full simulation**: GEANT4;

☼ Tool for **offline reconstruction**: *FairMUonE* software (based on FairRoot frameworks)

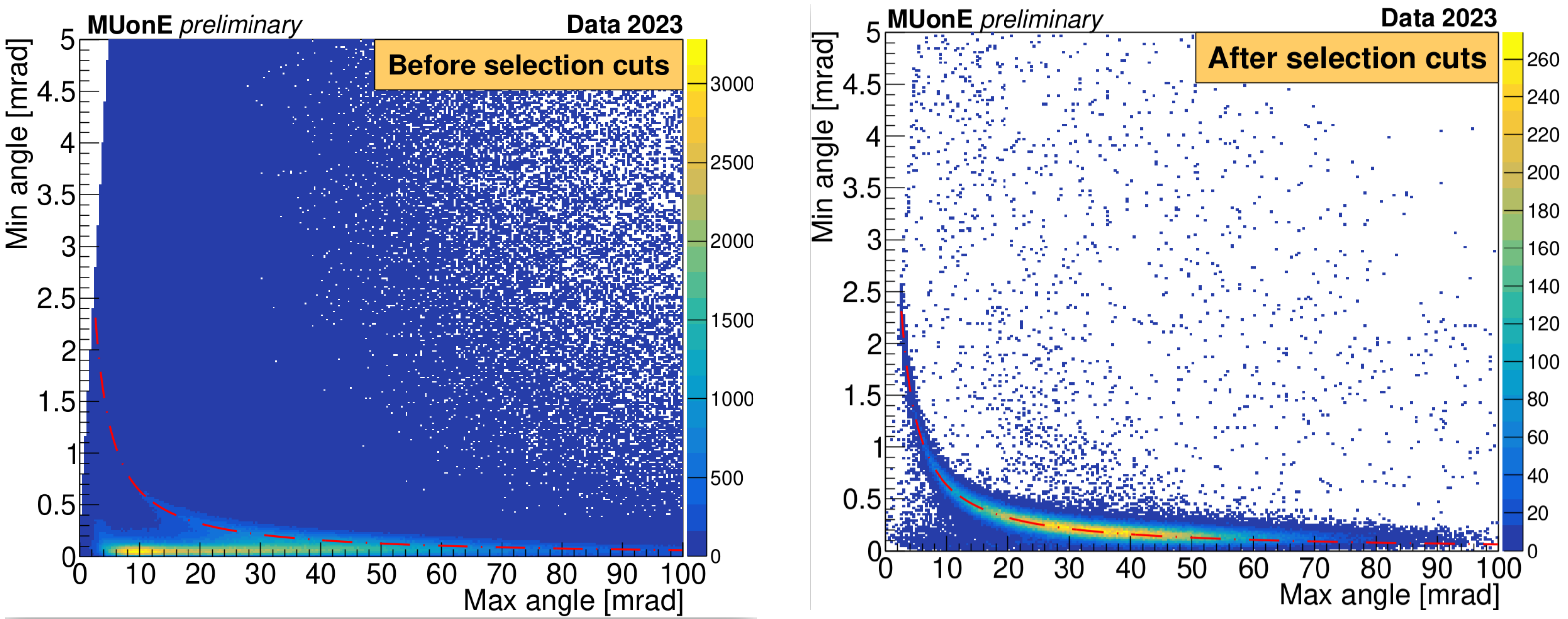


Figure: Skimmed events of a run **from Test Run 2023** (left), remaining reconstructed events after a basic elastic selection (right).

Analysis: $\Delta\alpha_{had}$ parametrization and a_μ^{HLO} estimate

G. Abbiendi, Phys. Scr. 97 (2022) 054007; [arXiv: 2201.13177]

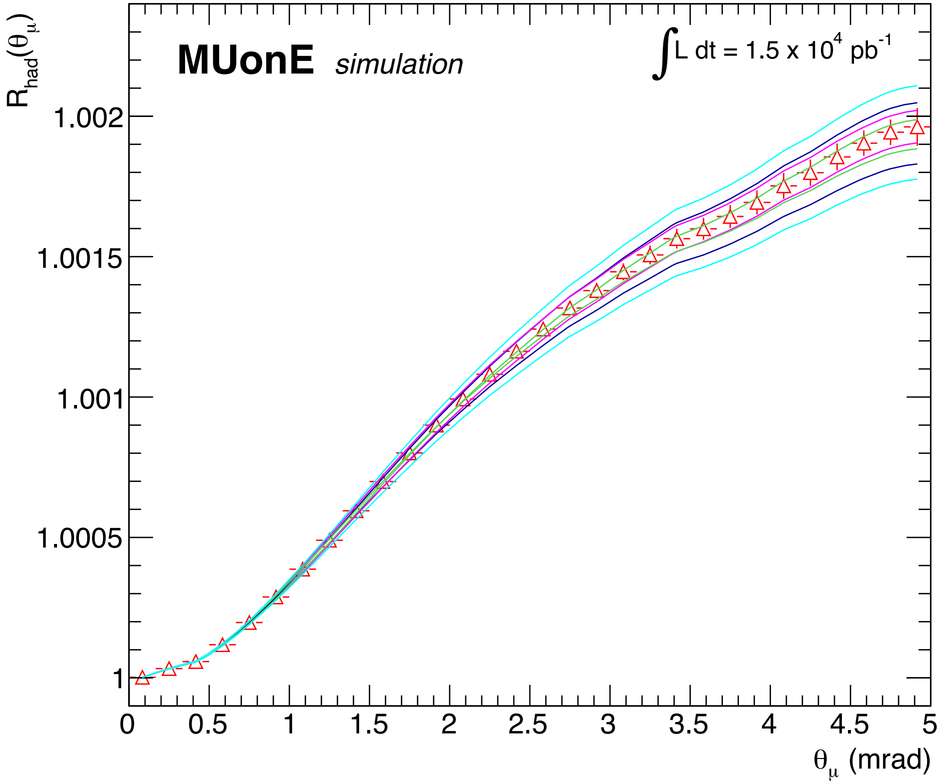
Inspired to the 1-loop QED calculation of the lepton vacuum polarization term

Parametrization with **two** variables K e M:

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

1. ***Template fit***: generation of a grid of points in the parameters space (K, M);
2. R_{had} distribution as a function of the leptons' scattering angle **for different templates**;
3. χ^2 of the data and templates.

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



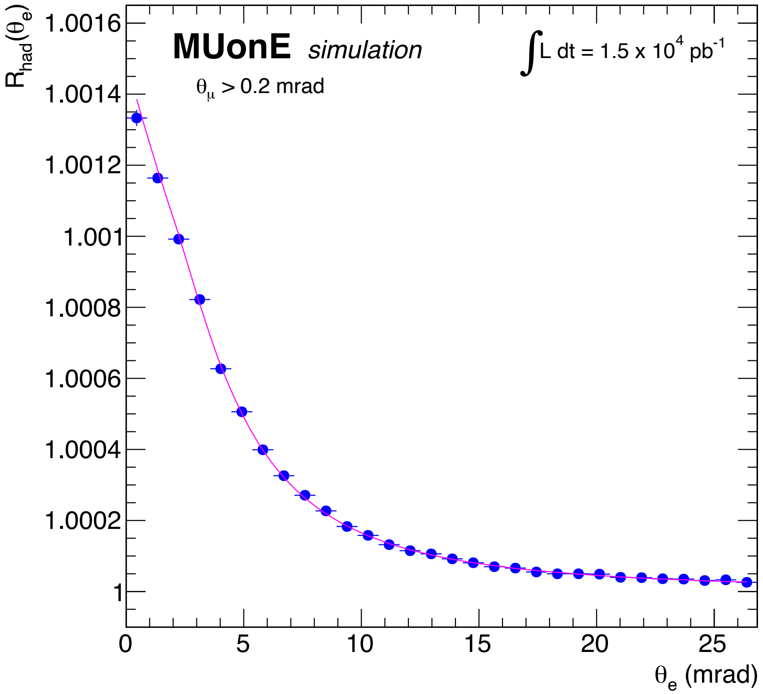
Analysis: $\Delta\alpha_{had}$ parametrization and a_μ^{HLO} estimation

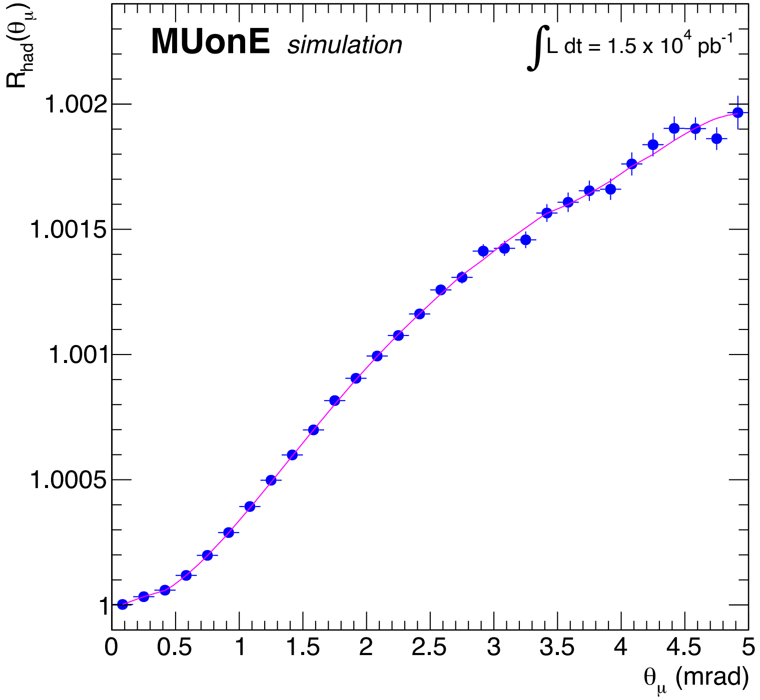
G. Abbiendi, Phys. Scr. 97 (2022) 054007; [arXiv: 2201.13177]

$\Delta\alpha_{had}$ extraction in the final experiment computed using 2D (θ_μ, θ_e)

The value would be inserted in the **master integral** for $\boldsymbol{a_\mu^{HLO}}$

Example of a pseudo-experiment:





Simulation result:

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

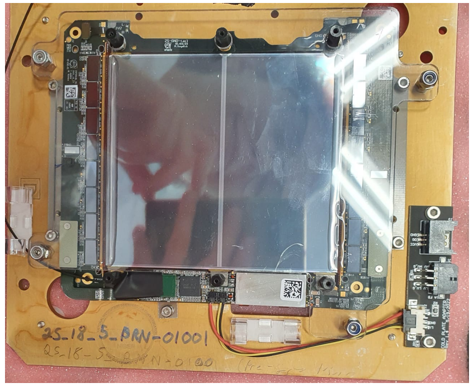
Input value for generation:

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

Experimental apparatus: tracker and ECAL

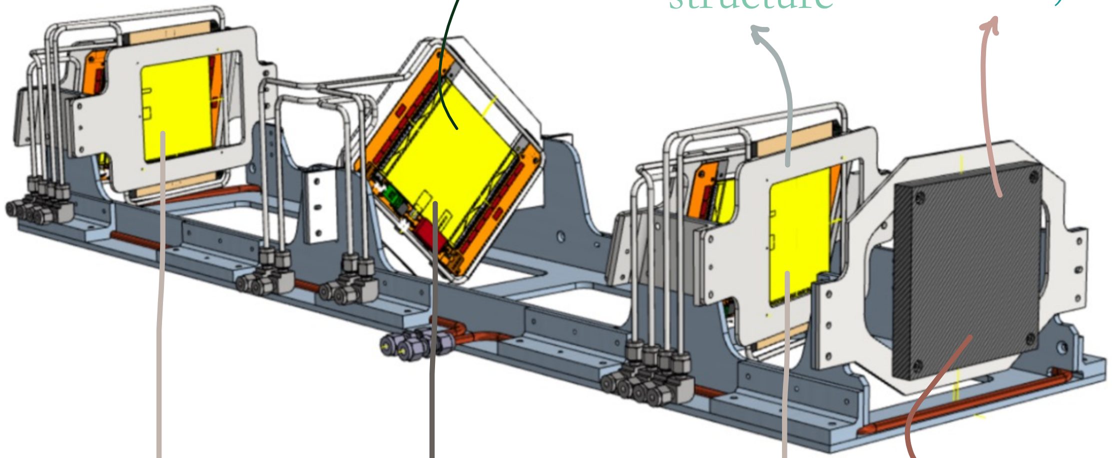
Thickness: $2 \times 320\ \mu m$
Pitch: $90\ \mu m$ ($\sigma_x \sim 26\ \mu m$)
Readout rate: $40\ MHz$
Active area: $10{\times}10\ cm^2$

1 CMS 2S **module** = **2** coupled **silicon strip** sensors (*CMS-Phase2 upgrade*)



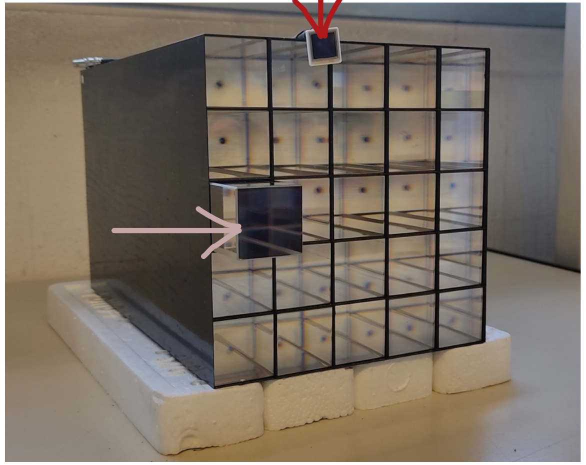
Target Be/C (low Z to reduce MCS)

Invar structure



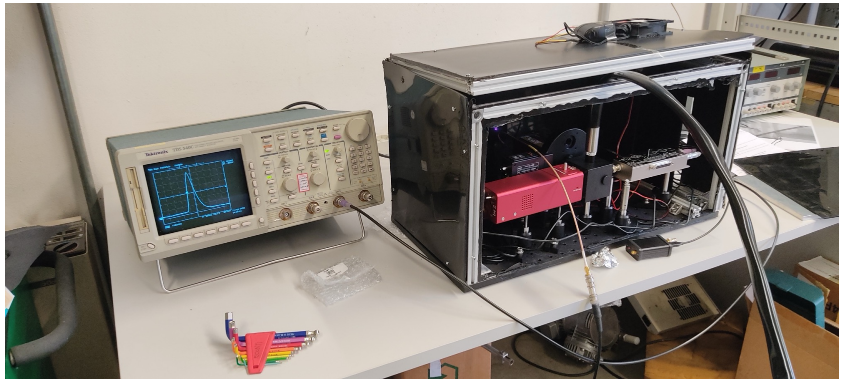
(x, y) (u, v) (x, y)

6 modules pairs



Actually in a **reduced format** for the future **Test Run** aimed at the validation of the experimental proposal:

- 25 cells in $PbWO_4$ ($22\ \chi_0$)
- Surface $\sim 14{\times}14\ cm^2$
- Readout: **APDs** read by 2 **FEBs** connected to a **FC7 board**



Laser pulse system (at **450 *nm***) for APD calibration

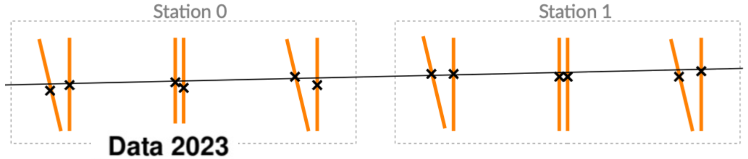
Results with data collected in 2023

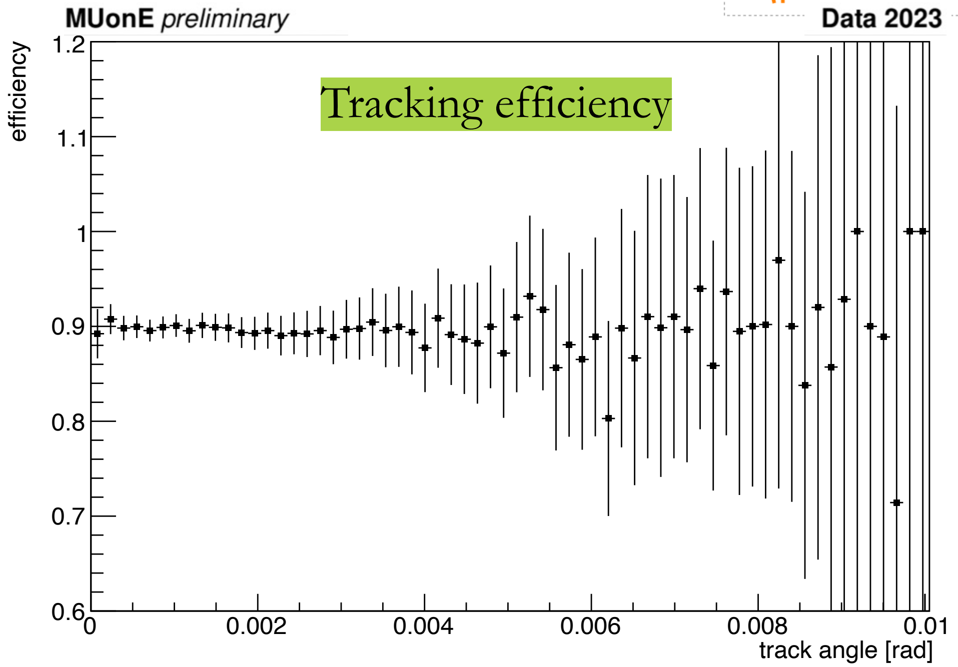
As a function of the angle of selected golden muons:

1. Tracking efficiency:
   - Average module efficiency ~ 98%;
   - Given passing muons with 6 hits in first station, look for reconstructed muon in the second station.

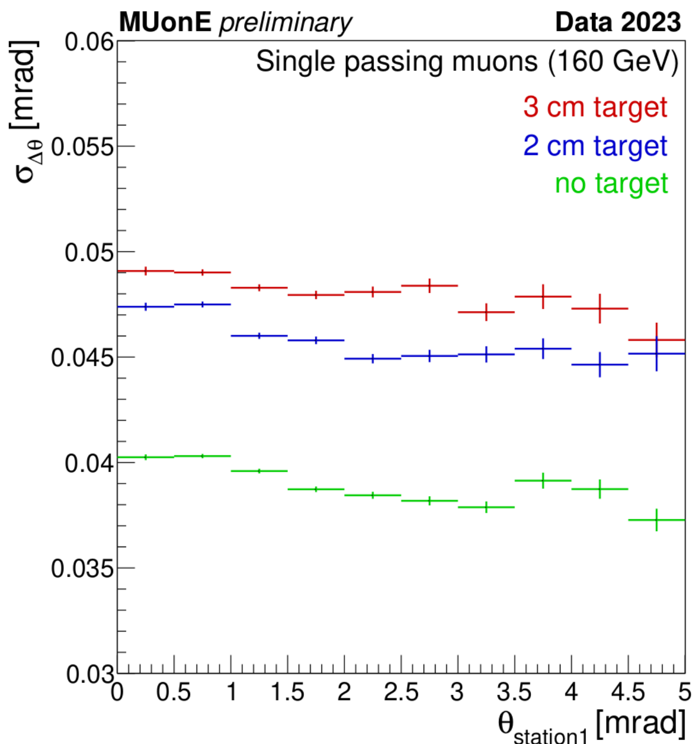
   Result: flat efficiency at ~ 90% → consistent with combinatorial result of individual module efficiencies.
2. Angular resolution for different target thickness:
   - $\Delta\theta = \theta_{st1} - \theta_{st0}$ → Sensitive to: intrinsic resolution, residual misalignment, **multiple scattering (MS)**

   → Estimate of **MS** consistent with **PDG** expectation.





Angular resolution

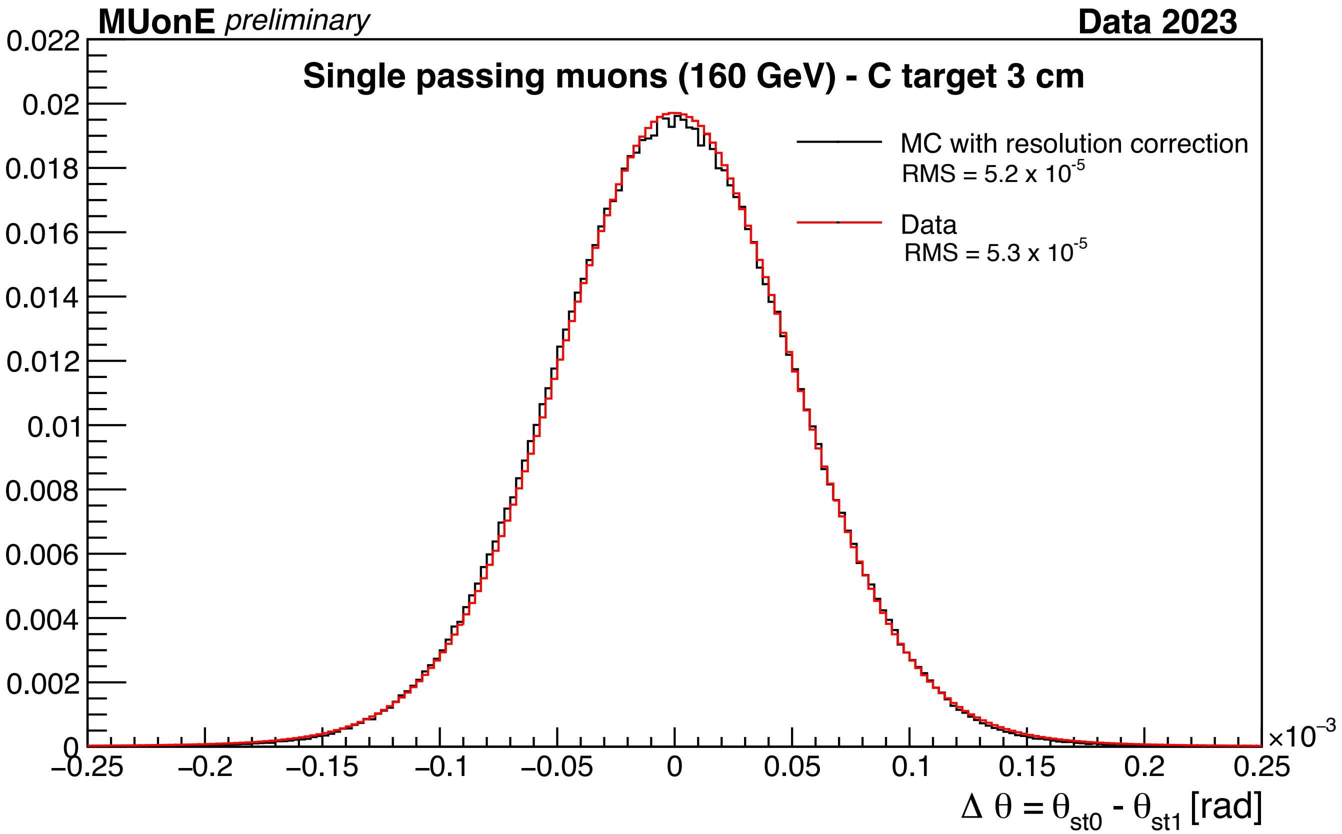


Angular resolution correction for 2023 data

DATA-MC comparison of *angular resolutions*, we found a disagreement of $\sim 20 - 30\%$ (bringing huge *systematics*):

1. Considering just golden muons in first and second station
2. Evaluate difference in angle: $\Delta\theta = \theta_{st0} - \theta_{st1}$
3. The uncertainty on $\Delta\theta$ is: $$\sigma(\Delta\theta) = \sqrt{\sigma_{MS}^2 + \sigma_{int}^2 + \sigma_{alignment}^2}$$
4. Application of **additional and constant** effect to balance data/MC disagreement

MS effects of Silicon and target;
Intrinsic resolution;
Residual misalignment



Angular resolution

- $\sigma(\Delta\theta) = \sqrt{\sigma_{MS}^2 + \sigma_{int}^2 + \sigma_{alignment}^2}$

- Differences between data and MC resolutions

- $\sigma(\Delta\theta_{data})^2 - \sigma(\Delta\theta_{mc})^2 \propto \sigma_{int}^2 + \sigma_{alignment}^2$

is proportional to the difference of data and MC in intrinsic resolution and residual misalignment (MS effects were demonstrated to be quite in agreement in data and mc). This can be treated in MC as an **additional and constant** effect that smears the angular distributions to better describe data → to balance the observed disagreement in angular resolution ($\sim\ 20\%$)

$$\sigma_{residual}(\Delta\theta) = \sqrt{\sigma(\Delta\theta_{data})^2 - \sigma(\Delta\theta_{mc})^2} = 32.\,\mu rad$$

- This is the correction on $\Delta\theta$, so smearing on each individual θ results in:

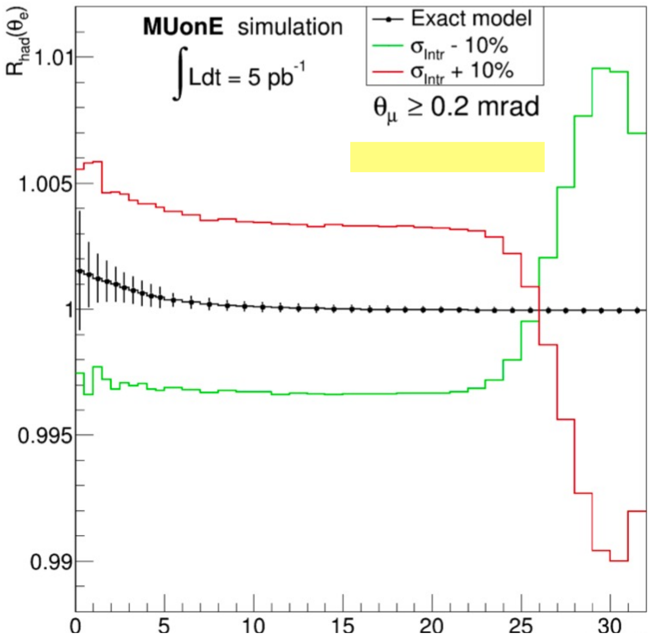
$$\Delta\theta = \theta_1 - \theta_2$$
$$\sigma(\Delta\theta) = \sqrt{\sigma(\theta_1)^2 + \sigma(\theta_2)^2} = \sqrt{2}\,\sigma(\theta)$$

$$\sigma_{residual}(\theta) = \frac{32.2}{\sqrt{2}} = 23.\,\mu rad \rightarrow Smearing\ \theta_X, \theta_Y\ of\ golden\ muon:\ Gaus(0, \sigma_{residual})$$

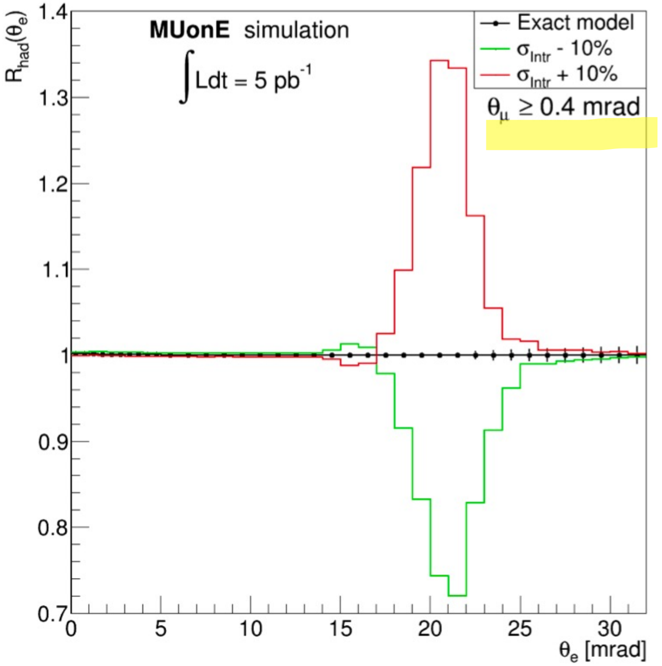
Effect of bad estimate of angular resolution in MC

MC studies in
[Riccardo's thesis]

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



Electron scattering angle

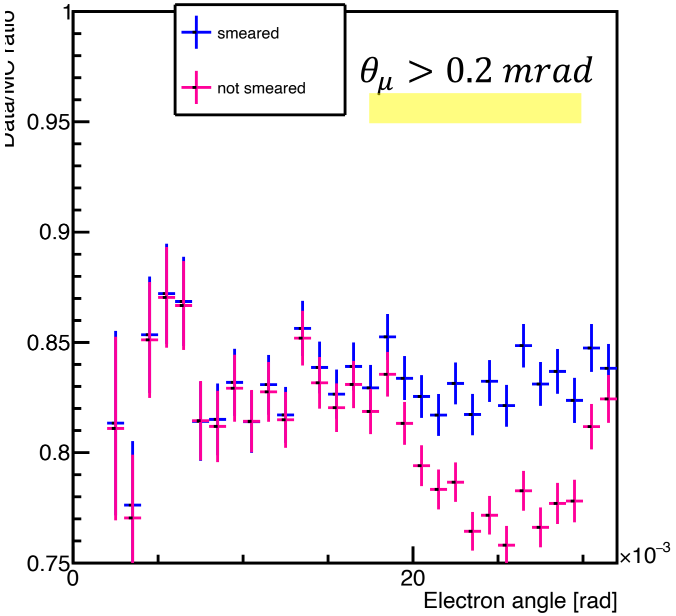


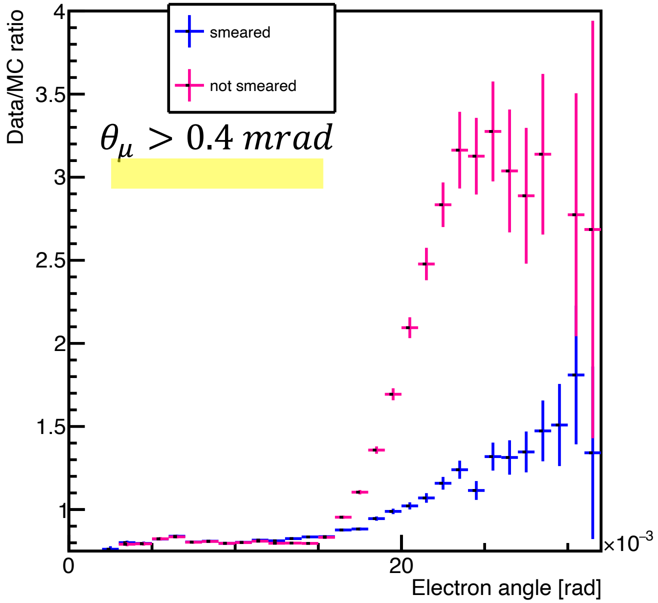
Electron scattering angle

MC with a sigma
of about **10%**
better than real one

$$\frac{data}{MC}\ ratio$$

$$\mathbf{5 < \theta_e < 32\ mrad}$$



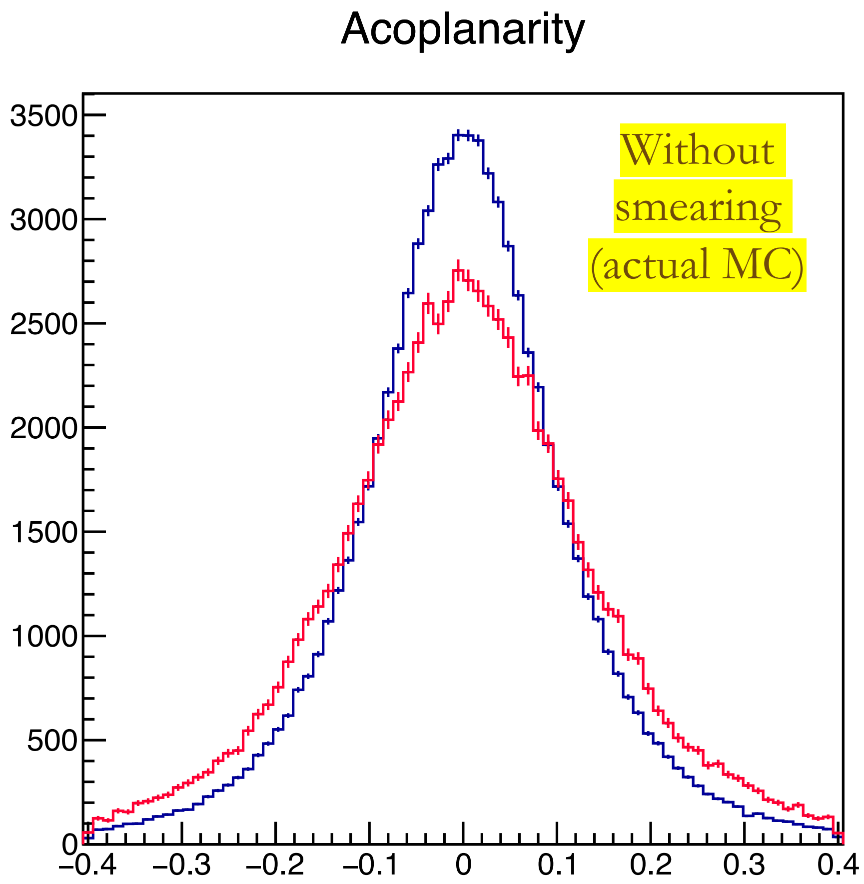


Smeared:
Application of smearing on MC as just described, accounting for **20%** underestimation of real sigma

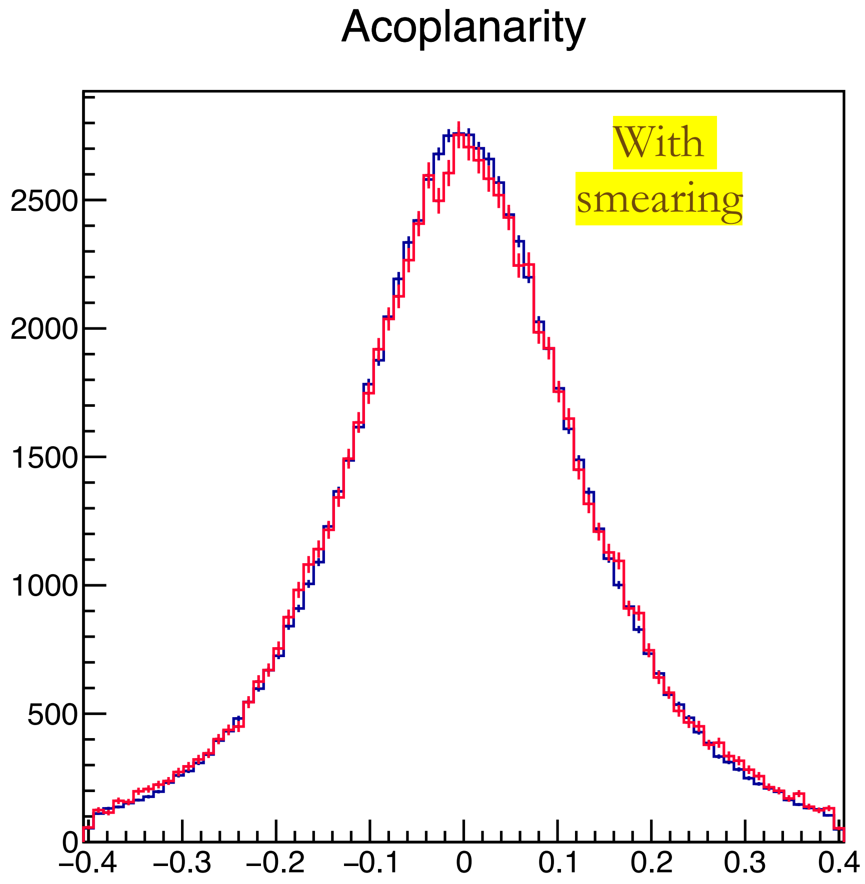
Not smeared: actual MC simulated with **fairmu**

Acoplanarity distribution with and whitout smearing

Acoplanarity distribution of selected sample of elastic events



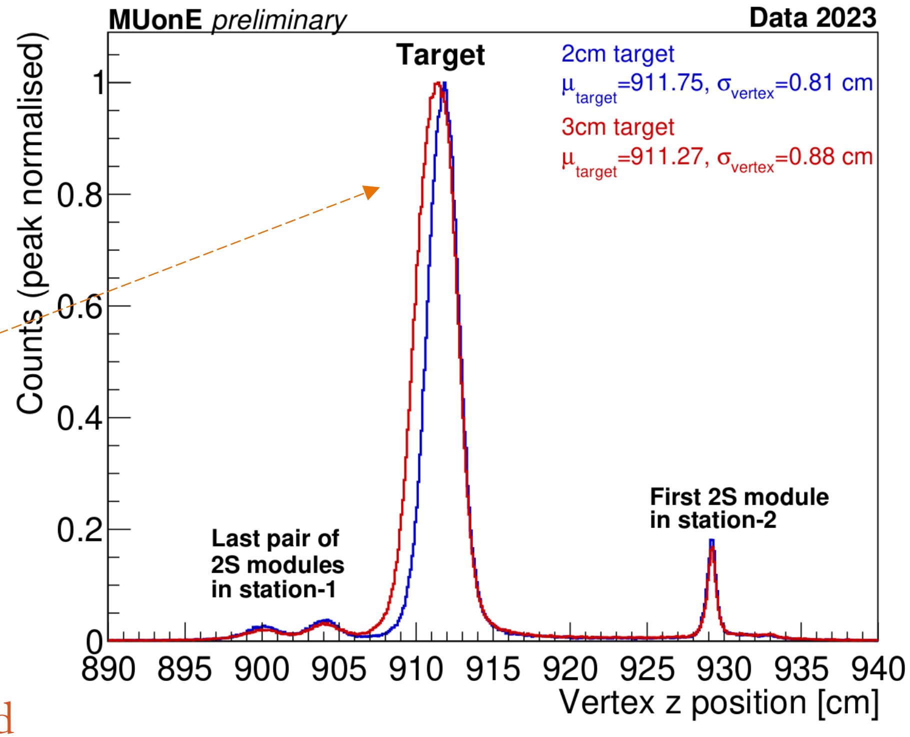
Data
MC



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:

- $\mathrm{N_{hits_{S0}}} = 6$ → 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 $\theta < 4\ mrad$.

Elastic selection:

- $\mathrm{N_{hits_{S1}}} \leq 15$;
- 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:

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

\+

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

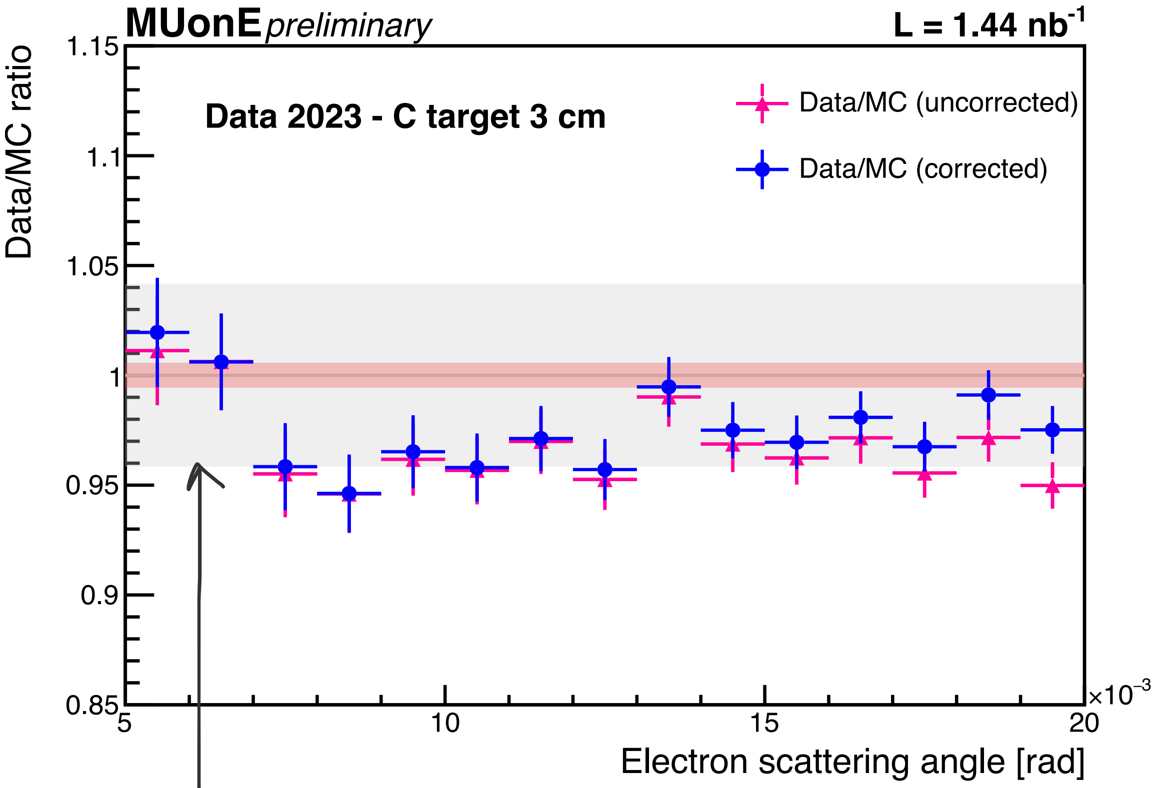
Data/MC ratios
as a function of scattering angles

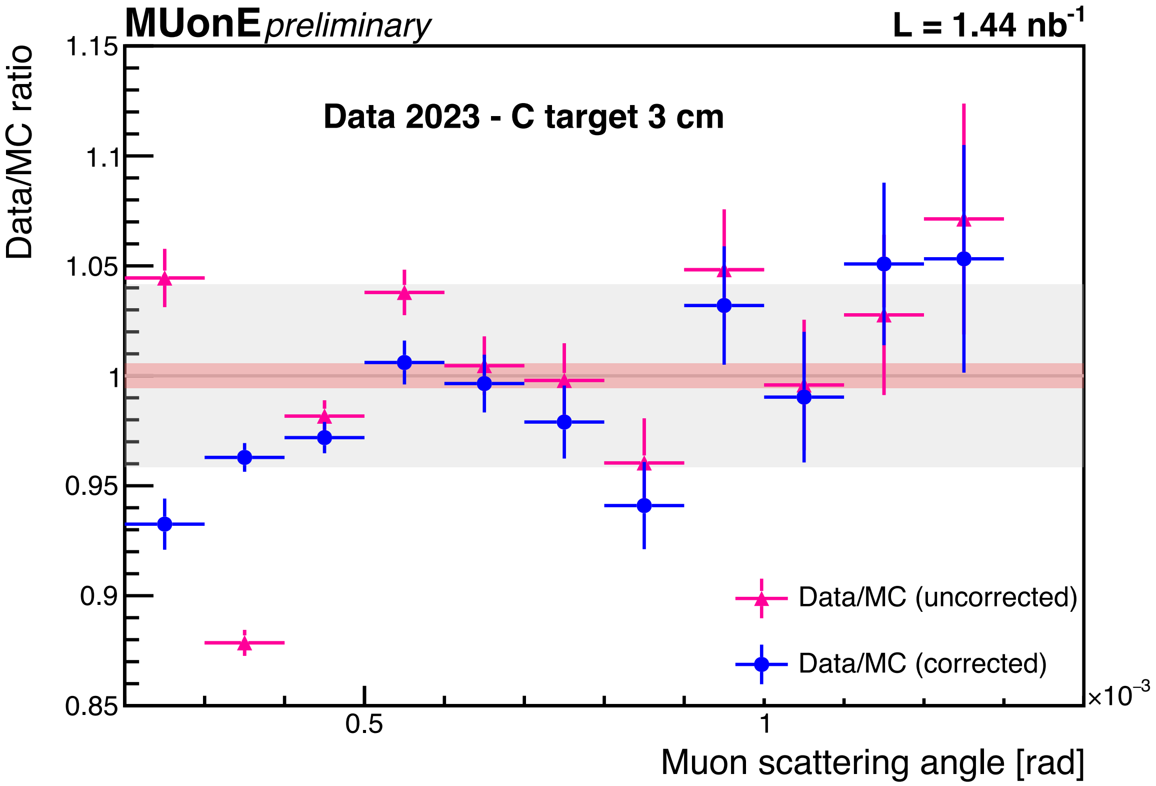
$5 < \theta_e < 20\, mrad$

MC Normalization to the Data Luminosity $\times\ \epsilon_{hw}$

$\epsilon_{hw} = 0.850 \pm 0.035$

Detector efficiency: reconstruct 2 tracks, depends on modules efficiency ($\epsilon_{mod} = 0.980 \pm 0.005$)





Systematic uncertainties bands:

- Luminosity $\sim 0.5\%$
- Detector (ϵ_{hw}) $\sim 4\%$

Ratio **is on average in agreement** with the expected detector efficiency $\boldsymbol{\epsilon_{hw}}$

First cross section measurements

Selected region:
$\boldsymbol{5 < \theta_e < 20\ mrad}$

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

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

Real data cross section within the selection:

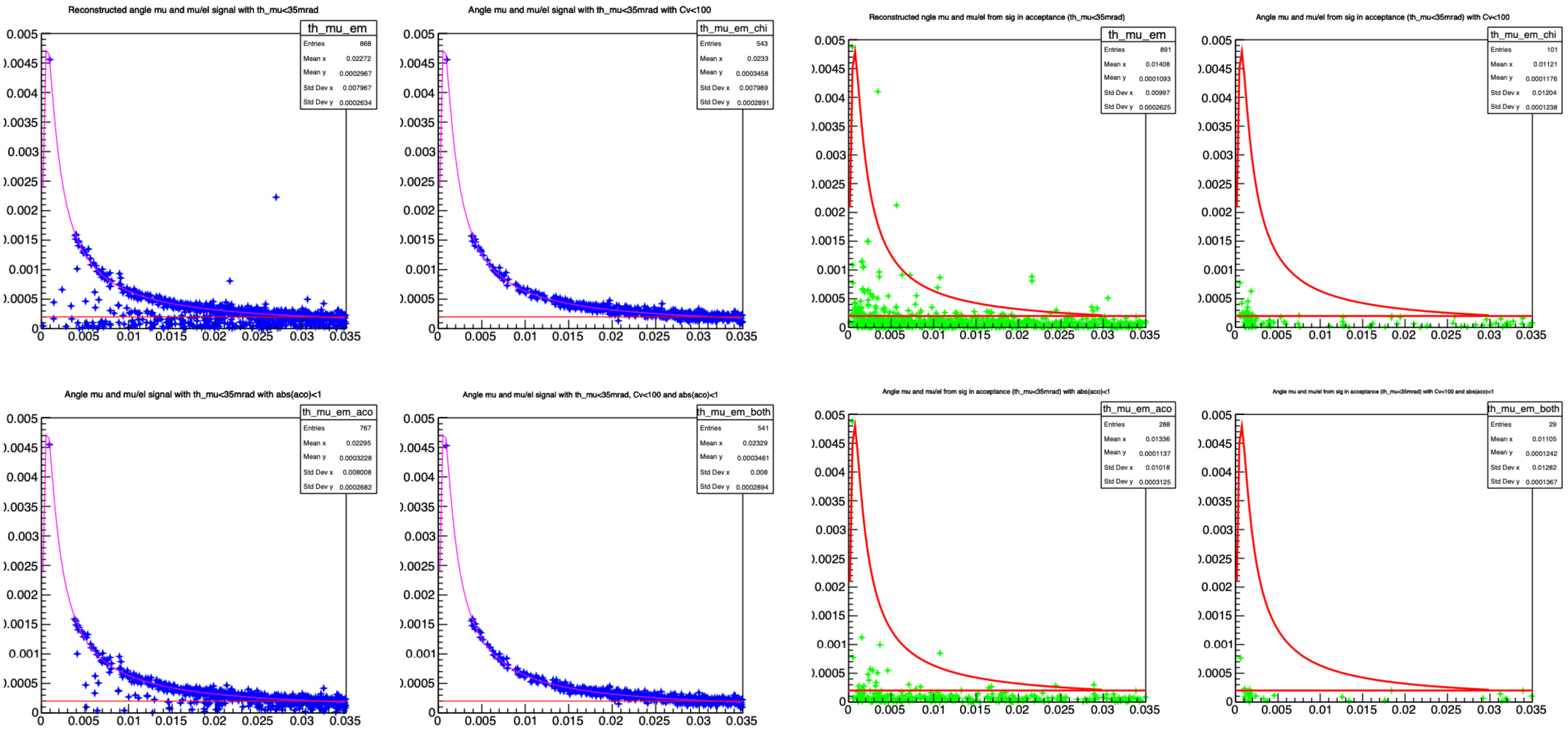
$$\sigma_{data} = 75.1 \pm\ 3.1\ \mu b$$

MC cross section within the selection (selection efficiency $\epsilon = 76.5\%$):

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

First measurement of cross section in the selected region **is consistent** with the MC prediction

Background



Reconstructed angle mu and mu/el signal with th_mu<35mrad
th_mu_em
Entries 868
Mean x 0.02272
Mean y 0.0002967
Std Dev x 0.007967
Std Dev y 0.0002634
Angle mu and mu/el signal with th_mu<35mrad with Cv<100
th_mu_em_chi
Entries 543
Mean x 0.0233
Mean y 0.0003458
Std Dev x 0.007989
Std Dev y 0.0002891
Reconstructed ngle mu and mu/el from sig in acceptance (th_mu<35mrad)
th_mu_em
Entries 891
Mean x 0.01408
Mean y 0.0001093
Std Dev x 0.00997
Std Dev y 0.0002625
Angle mu and mu/el from sig in acceptance (th_mu<35mrad) with Cv<100
th_mu_em_chi
Entries 101
Mean x 0.01121
Mean y 0.0001176
Std Dev x 0.01204
Std Dev y 0.0001238
Angle mu and mu/el signal with th_mu<35mrad with abs(aco)<1
th_mu_em_aco
Entries 767
Mean x 0.02295
Mean y 0.0003228
Std Dev x 0.008008
Std Dev y 0.0002682
Angle mu and mu/el signal with th_mu<35mrad, Cv<100 and abs(aco)<1
th_mu_em_both
Entries 541
Mean x 0.02329
Mean y 0.0003461
Std Dev x 0.008
Std Dev y 0.0002894
Angle mu and mu/el from sig in acceptance (th_mu<35mrad) with abs(aco)<1
th_mu_em_aco
Entries 288
Mean x 0.01336
Mean y 0.0001137
Std Dev x 0.01018
Std Dev y 0.0003125
th_mu_em_both
Entries 29
Mean x 0.01105
Mean y 0.0001242
Std Dev x 0.01282
Std Dev y 0.0001367