Status of the MUonE experiment

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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**: $a_l = \frac{g_l - 2}{2}$

Are those **discrepancies** still real? Hint of **new physics?**

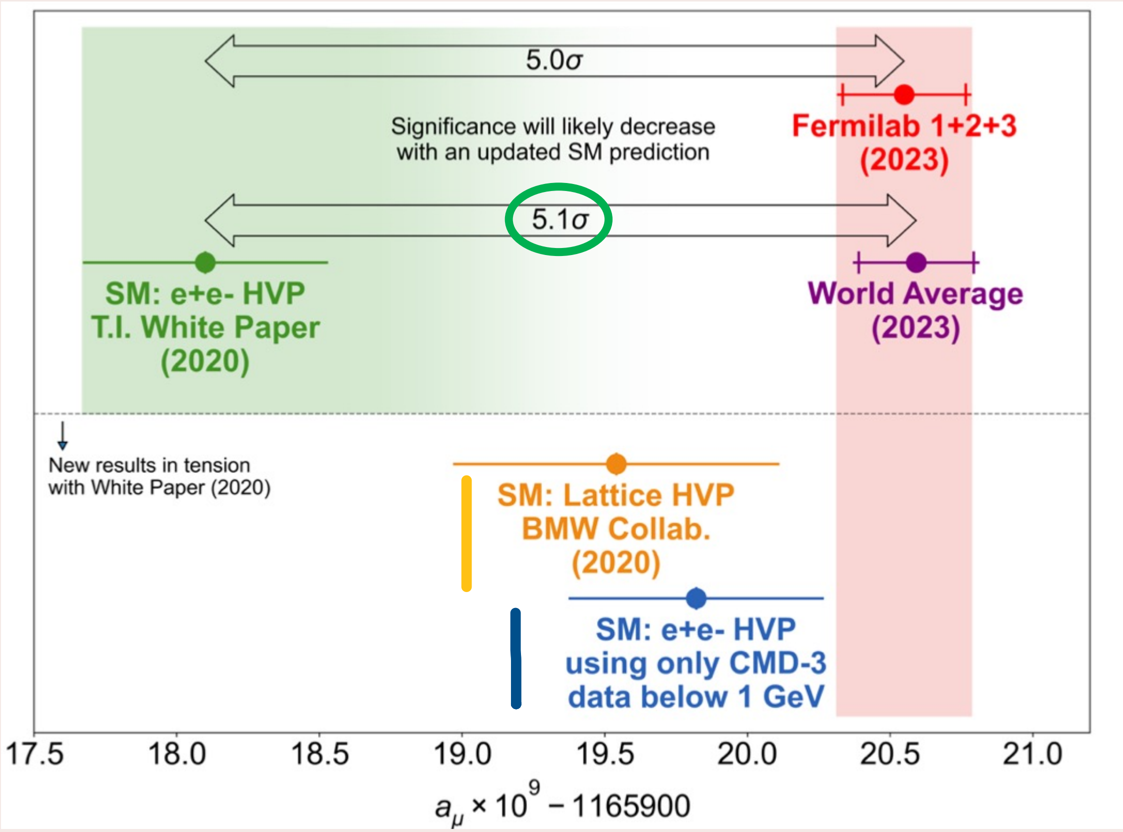
Experimental average **FERMILAB+BNL**
P. B. Aguillard et al., (2023) arXiv:2308.06230

Theoretical **reference value (WP)**
T. Aoyama et al., (2020) arXiv:2006.04822

but…

Most precise **LQCD** result
T. Borsanyi et al., (2021) arXiv:2002.12347v3

New result from $e^+ - e^- \rightarrow$ had cross section with **CMD-3 data**
F. V. Ignatov et al., (2023) arXiv:2302.08834



1. Reduce the **experimental** error ⟶ Fermilab g-2 goal (0.54 ppm (BNL) → 0.20 ppm $\xrightarrow{goal}$ 0.14 ppm)
2. Improve **theoretical** precision ⟶ Dominant contribution: **LO hadronic vacuum polarization term**

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had} \rightarrow \boldsymbol{a_\mu^{HLO}} \rightarrow \mathbf{0.6\%}$$

MUONE PROPOSAL

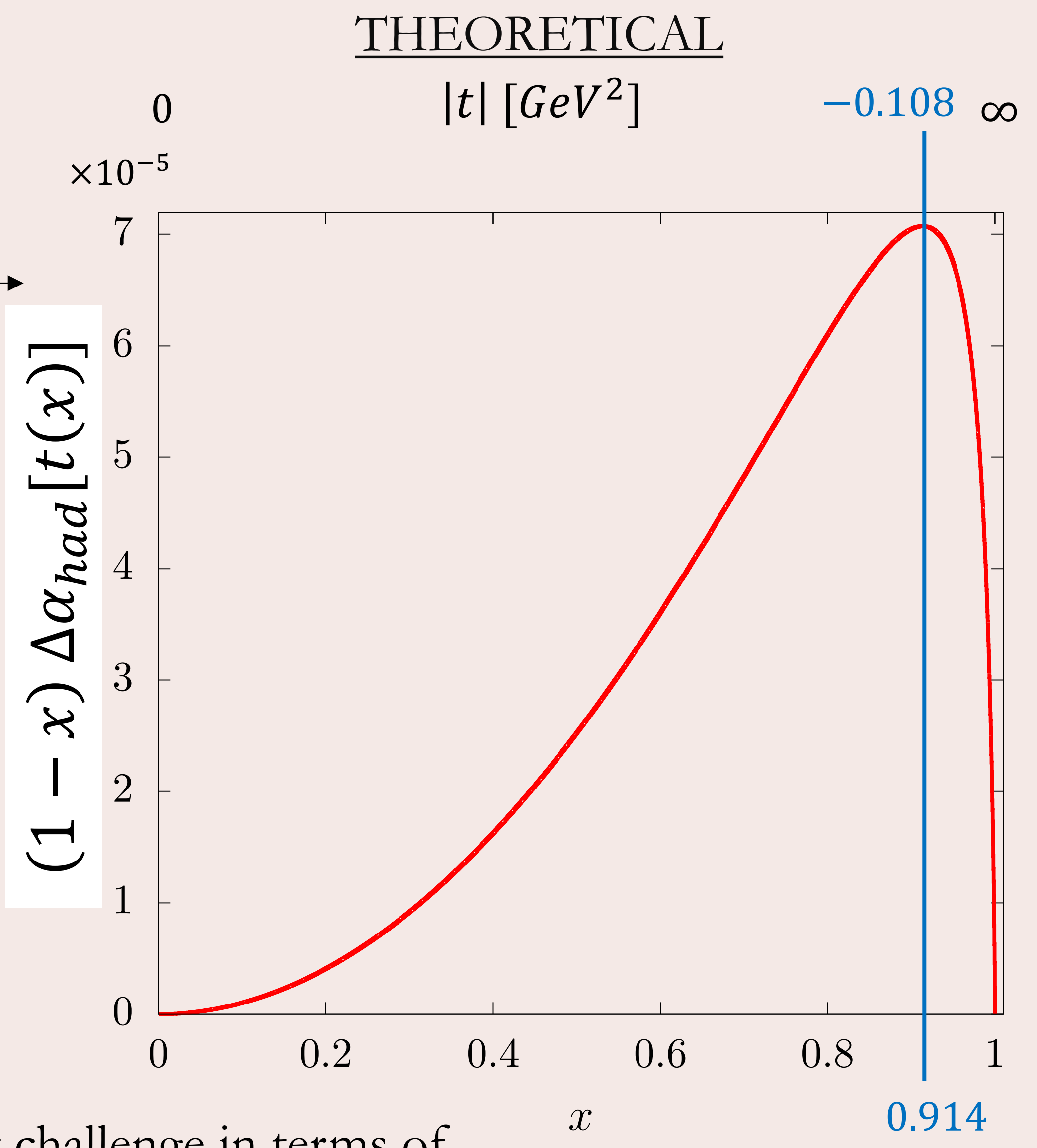
Independent estimate of a_μ^{HLO} through innovative method:

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 →



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

G.Abbiendi et al., Eur.Phys.J.C77(2017)139 ; B. E. Lautrup et al., Phys. Rept. 3 (1972) 193

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

M2 muon beam at CERN SPS

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

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

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

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

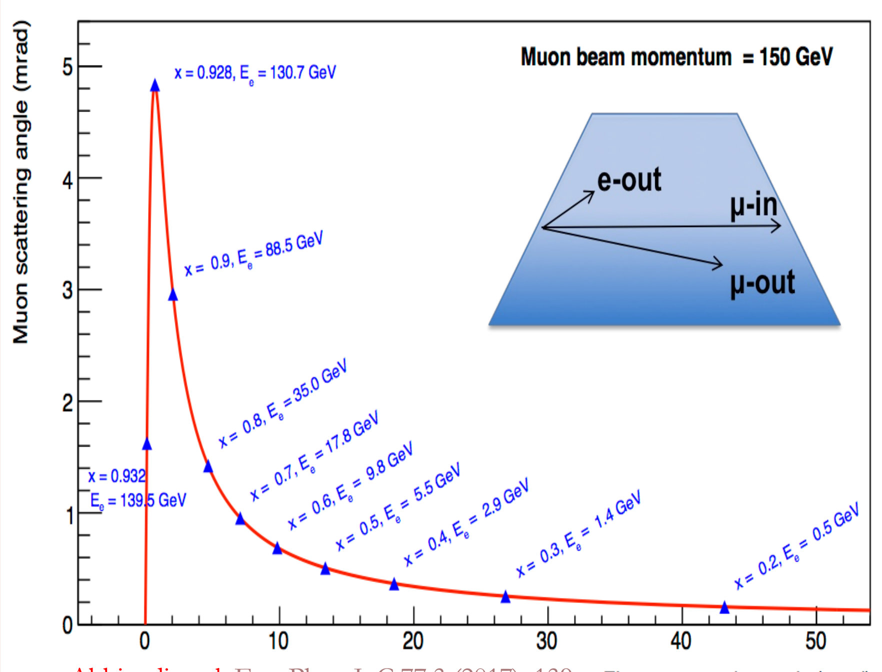
EXPERIMENTAL APPARATUS

Simple kinematics relations ($t \leftrightarrow \theta_l$)

$$\frac{d\sigma_{el}}{dt} \longleftrightarrow \frac{d\sigma_{el}}{d\theta_l}$$

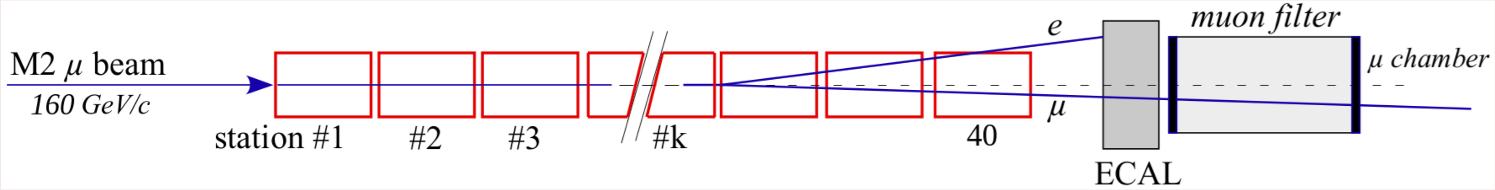
Measuring the **leptons scattering angles**

ELASTIC CURVE



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

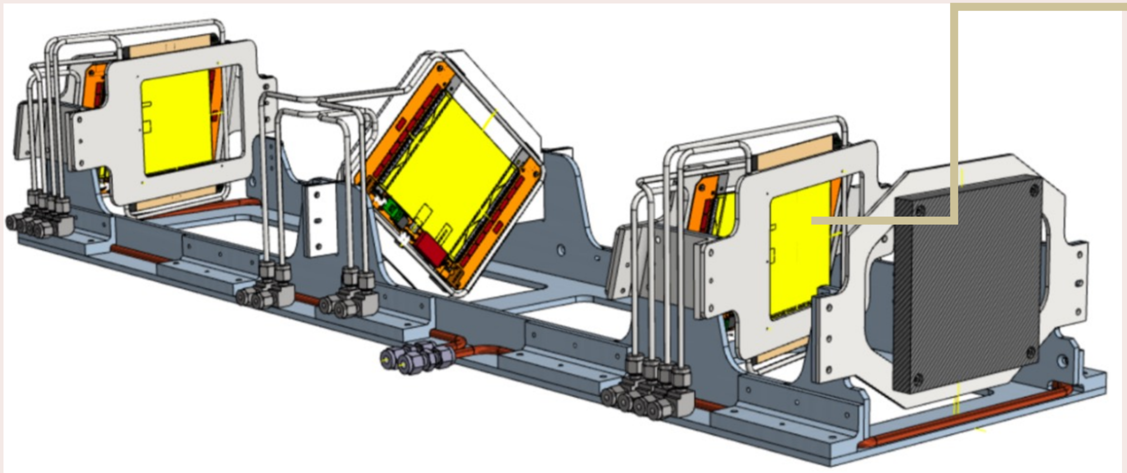
40 tracking stations + Electromagnetic calorimeter + Muon chamber



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

- **1** beryllium or carbon target
- **6** silicon strip modules

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

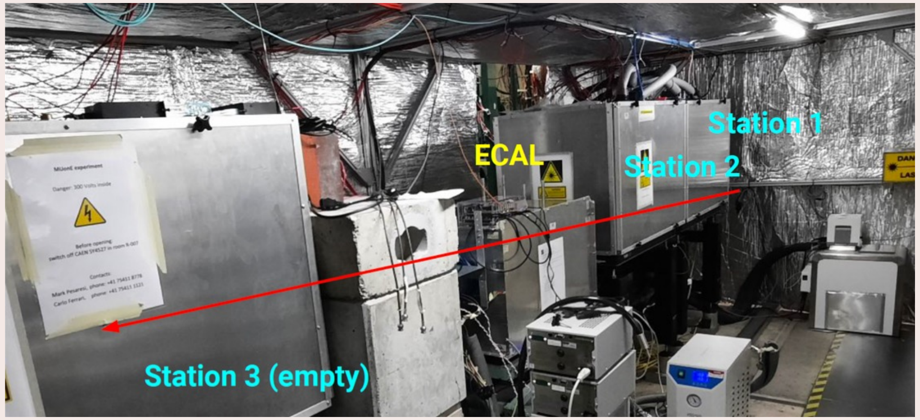


CMS 2S module:
2 coupled **silicon strip** sensors
(*CMS-Phase2 upgrade*)

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

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 (6 modules each) + ECAL;
- **Triggerless** DAQ at 40 MHz → Large data volumes processed ***offline***.



- **Plan** is to have data filter on **FPGA;** *now* an offline skimming algorithm has been implemented to preselect candidate events from target interaction: base on number of hits in the two stations
  On **~12 B** merged events, the skimming procedure reduced the output at ~ $\boldsymbol{few\%}$.

  Different *classes* of candidate events are well separated:

  1. Single muon interactions:
     compatible with ***1 incoming muon*** in station0 + some *interaction* in station1
  2. 2,3,4 pile-up muons with interaction
     compatible with ***N incoming muons*** in station0 + some *interaction* in station1

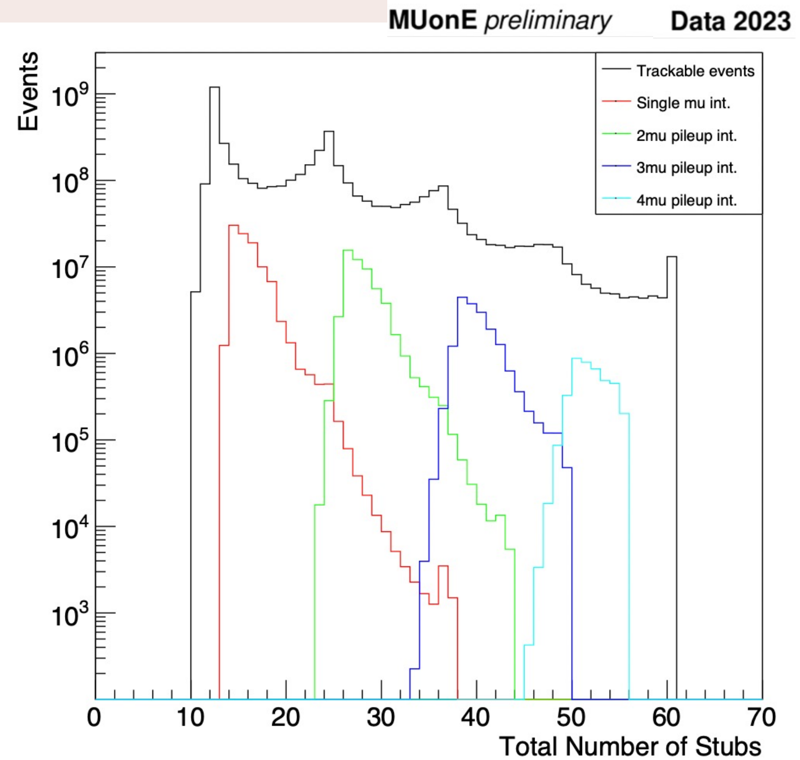
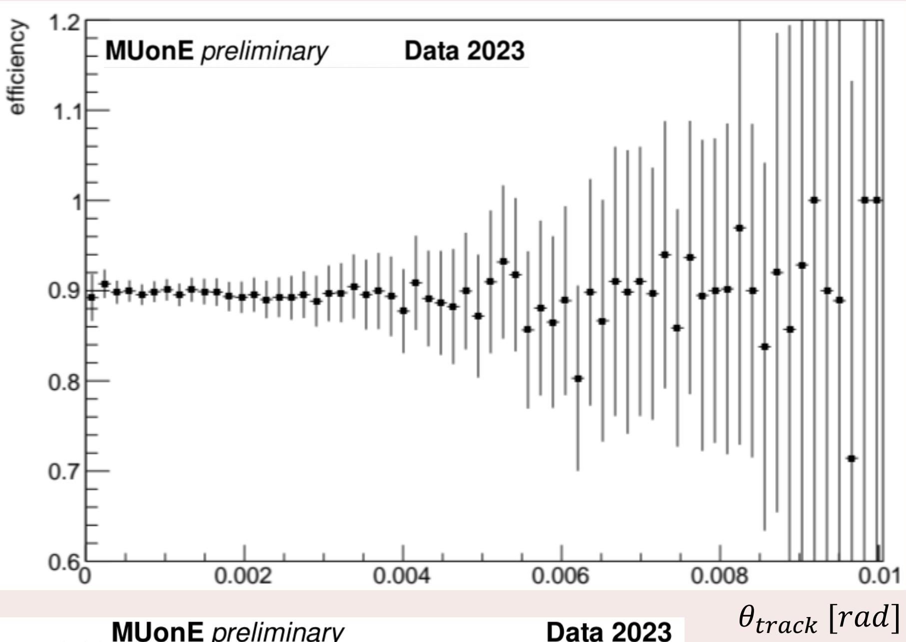


Fig: Fraction of different event multiplicities, in 2023 data, after skimming ***based on hits patterns***.

SOME RESULTS WITH DATA COLLECTED IN 2023

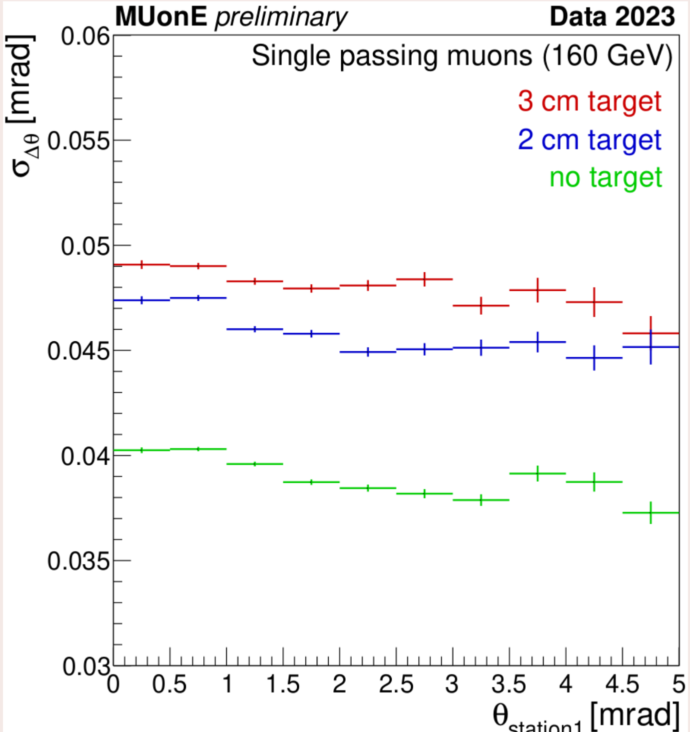
1. Tracking efficiency as a function of selected golden muon's angle :
   - Average module efficiency ~ **98%**;
   - Given passing muons with 6 hits in first station, look for reconstructed muon in the second station.

   Result: *flat* efficiency at ~ **90%** → consistent with combinatorial result of individual module efficiency.



2. Angular resolution as a function of selected golden muon's angle for different target sizes:
   - $\Delta\theta = \theta_{st1} - \theta_{st0}$ → Sensitive to: intrinsic resolution, residual misalignment, **multiple scattering (MS)**

   → Estimate of **MS** consistent with calculation with **PDG** MS prediction.

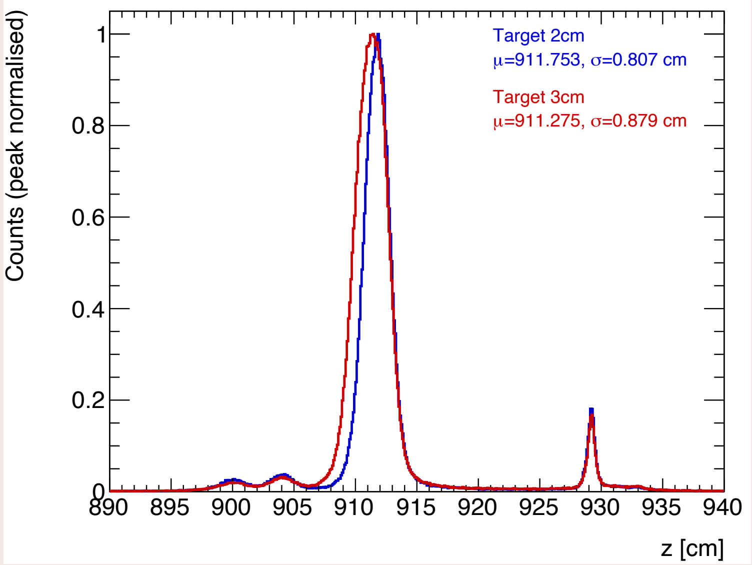


SEARCHING FOR **ELASTIC EVENTS**

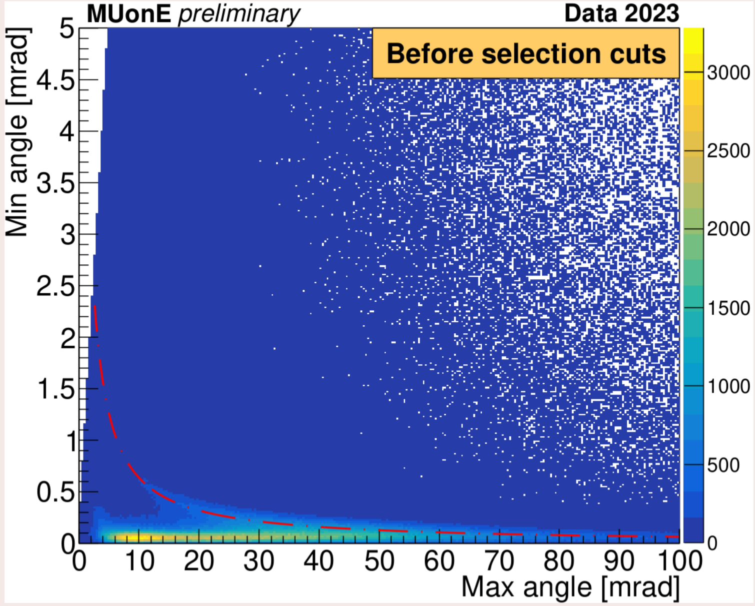
Analysis of one run of TB2023 → Data taken with 2 and 3 *cm* target

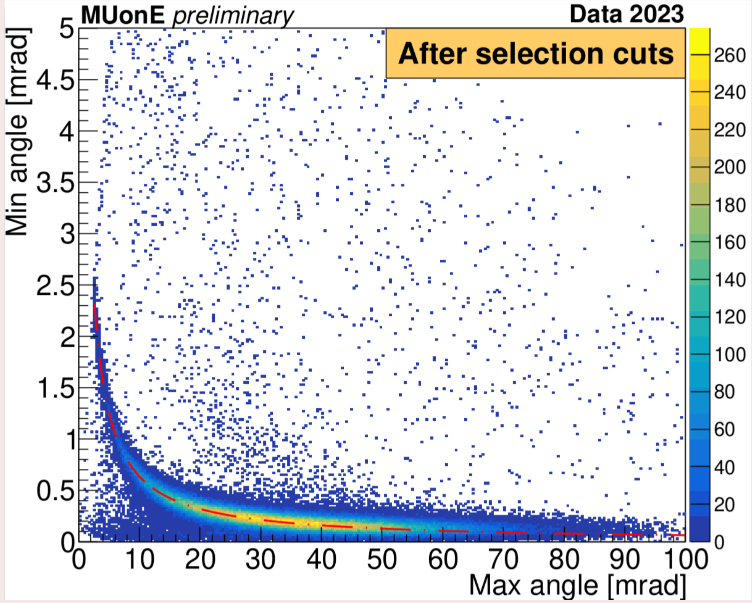
First studies done on sample compatible with **single muon interactions**

Distribution of <u>reconstructed vertx Z position</u> in candidate events with 2 and 3 cm target runs



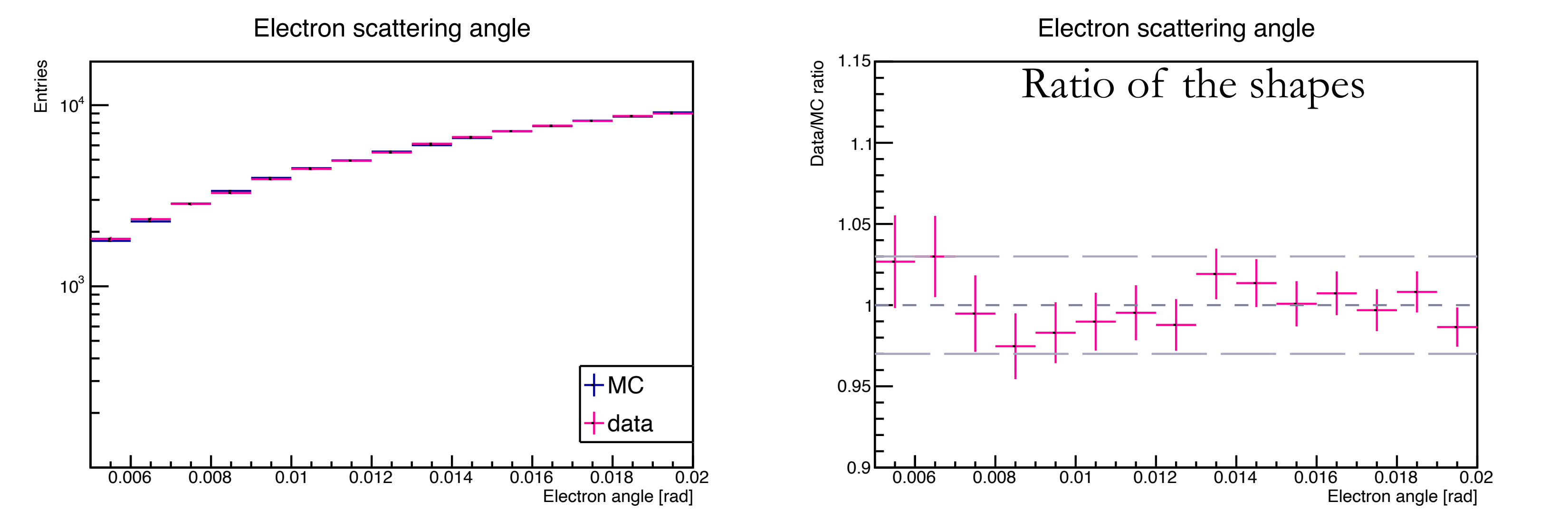
2D distribution of <u>scattering angles</u> in candidate events of the run before and after a *basic elastic selection*





DATA/MC COMPARISON USING TR 2023 DATA: **FIRST STUDIES**

1. Run of 97×10^6 filtered events (single mu interaction) compared with MC sample of 10.5×10^6 *weighted* elastic events
2. **Fiducial** and **elastic** selections (details in backup) are applied
3. To compare the **shapes** of the angular distributions, **normalization is to the number of real data events**.



First studies: Data/MC shapes as a function of **electron angle** is within gray band → **±3%**

For the running of $\alpha(t)$ to be observed, the MC description of angular shapes must be accurate to within at least $\pm 0.5\%$ → **work in progress to improve the comparison**. Next months important developments are attended!

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*. Great possibility to *shade some light* on this intriguing **puzzle**!
- First results and data/MC comparisons have been done with 2023 TR data;
- **Shapes comparisons** of electron angle distributions stands within $\pm 3\%$. However, for the running of $\alpha(t)$ to be observed, the MC description of angular shapes *must be accurate* to within at least $\pm 0.5\%$. Several improvements are attended 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

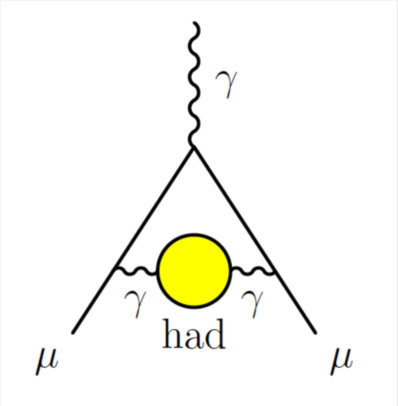
BACKUP

Anomalous magnetic moment of the muon

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

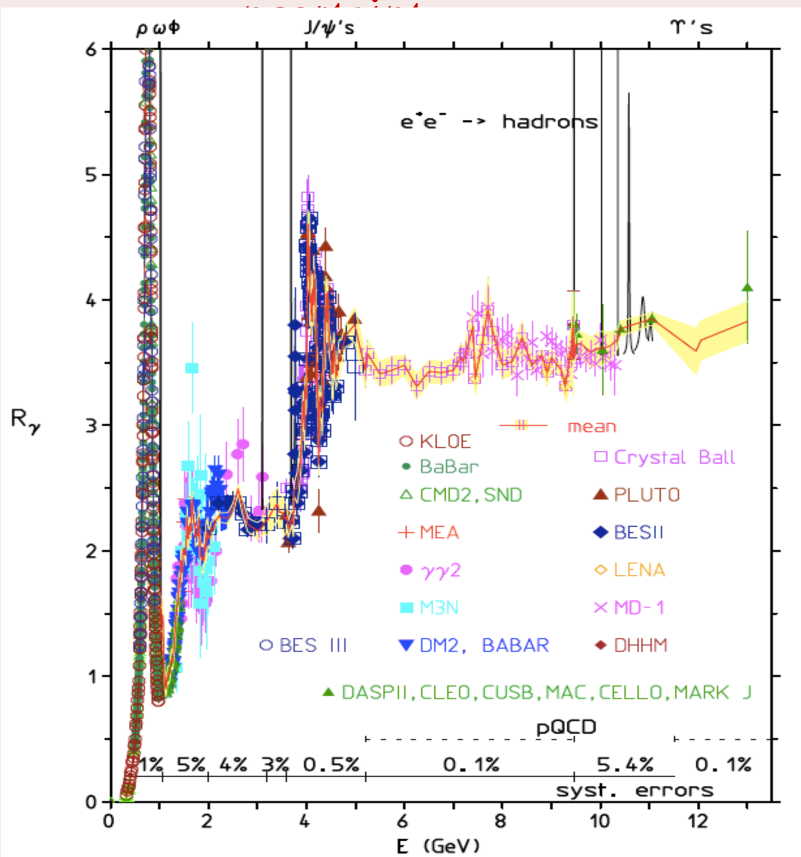
Precise estimates from perturbation theory

$a_\mu^{had} \rightarrow a_\mu^{HLO}$ + *higher order terms*



Hadronic contribution to the LO vacuum polarization term a_μ^{HLO} is not calculable through pQCD

Dominates theoretical → **0.6%**



F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016

<u>Reference</u> approach (WP before BMW) is **data-driven**:

$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2} \longrightarrow R_{had}(s) \propto \sigma(e^- e^+ \rightarrow had)$$

measurements

Alternative methods are needed

<u>Main contribution</u>: region of *low energies*, highly *fluctuating* because of **hadronic resonances** and **threshold effects**

The new estimate of a_μ^{HLO} from <u>LQCD</u> (BMW) ***weeken*** $\Delta a_\mu(th - exp)$ discrepancy, **but** introduces some ***tensions*** with the <u>data-driven</u> method.

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

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

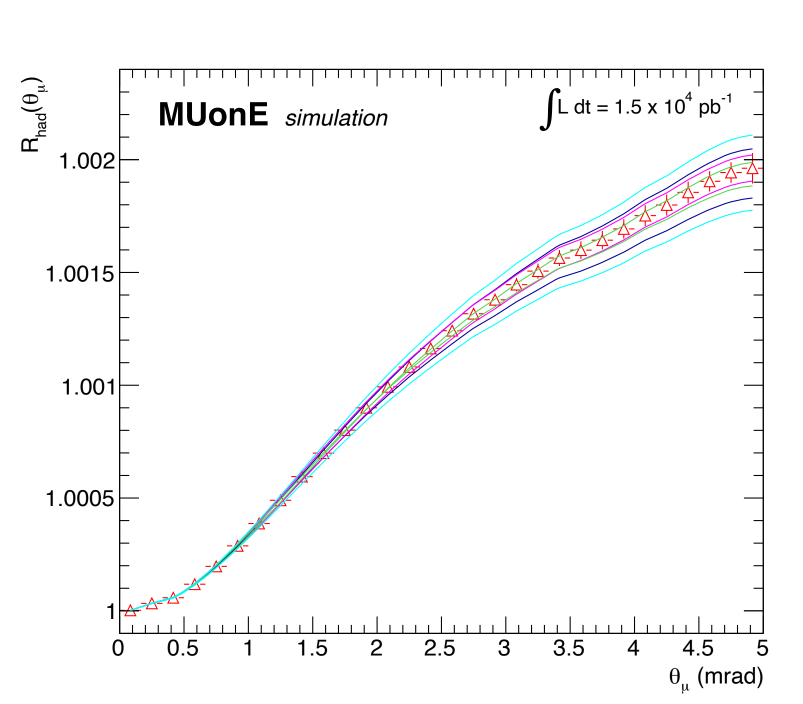
Inspired to the 1 loop QED calculation of the leptonic and $t\bar{t}$ pair vacuum polarization term

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.

$$R_{had} = \frac{d\sigma_{data}\,(\Delta\alpha_{had})/d\theta}{d\sigma_{MC}(\Delta\alpha_{had} = 0)/d\theta}$$



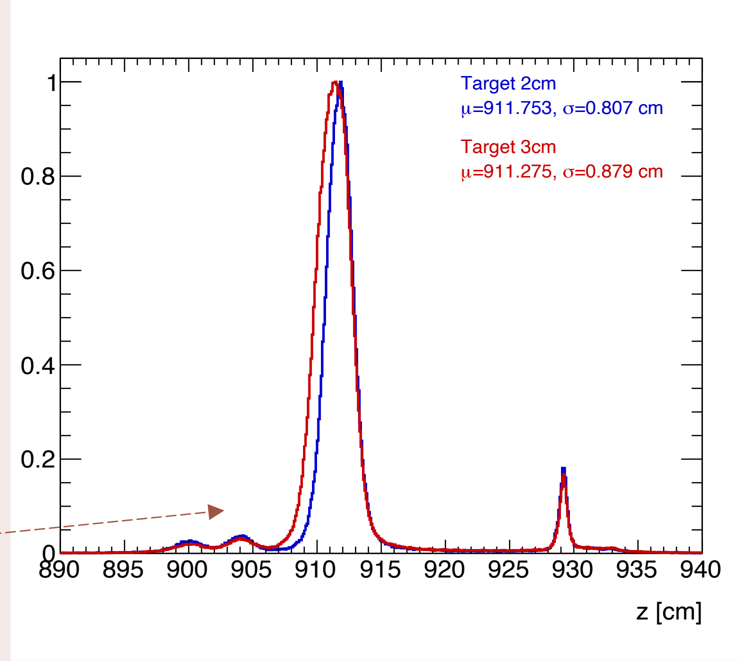
DATA-MC COMPARISON

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

MC sample: MESMER signal → 10.5×10^{6} generated signal events to be reconstructed with **realistic geometry** (*misalignment* from metrology are introduced)

Fiducial selection:

- $\mathrm{N_{stubs}}_{S0} = 6$ → 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 $\theta < 4\ mrad$;
- Reconstructed GM track $\chi^2 < 2$.



Elastic selection:

- $\mathrm{N_{stubs}}_{S1} \leq 15$;
- Reconstructed vertex with $z_{vrtx} > 906\ cm$;
- $\theta_\mu > 0.2\ mrad\ +\ 5 < \theta_e < 32\ mrad$;
- $|A_\phi| < 0.4\ mrad$
- Elasticity condition: $|\theta_\mu^{rec} - \theta_\mu^{th}(\theta_e^{rec})| < 0.2\ mrad$

>5 mrad: Avoid ambiguities in PID

<32 mrad: geometrical acceptance to have flat efficency

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

DATA/MC COMPARISON USING TR 2023 DATA

1. Run of 97×10^6 filtered events (single mu interaction) is compared with a MC sample of 10.5×10^6 *weighted* elastic events
2. **Fiducial** and **elastic** selections (details in backup) are applied
3. To have an absolute comparison, normalization of MC to the **absolute luminosity**:

Events passing fiducial selection
Elastic cross section from MC generator ⟵

$$L_{MC} = \frac{\sum_j w_j(fiducial)}{\sigma_{el}}$$

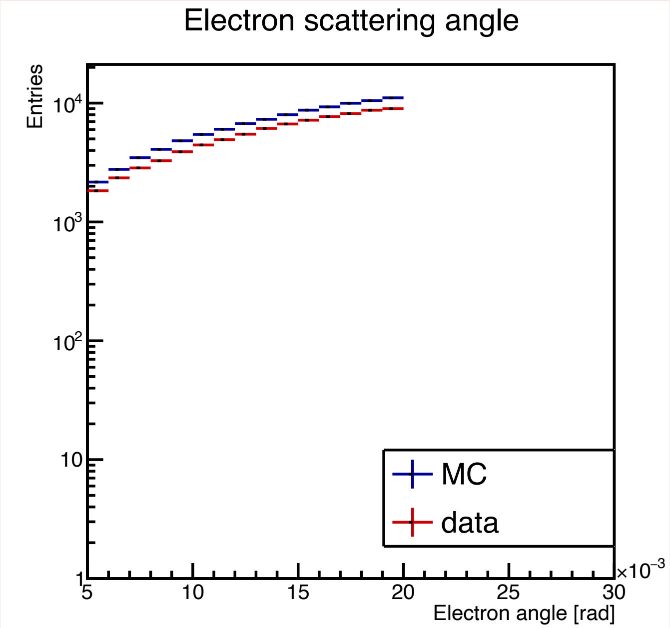
$$L_{RD} = N_{\mu oT} \cdot d_{target} \cdot \rho^e_{target}$$

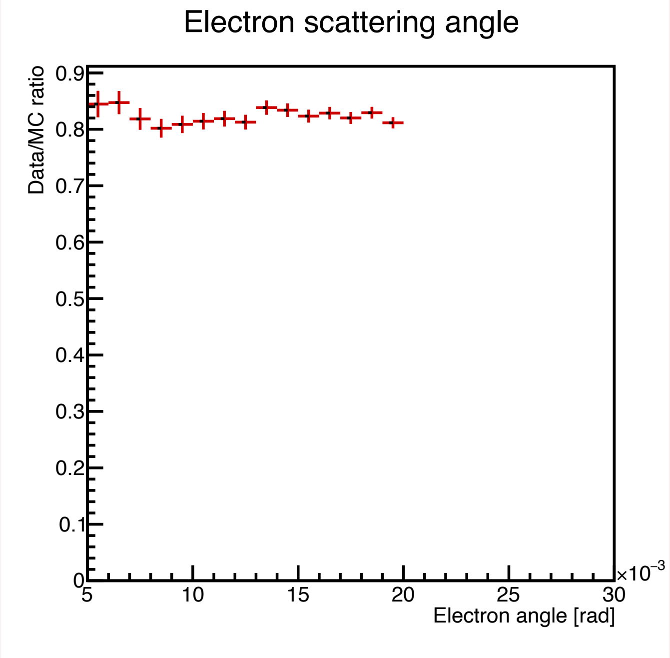
⟶ Golden muons on target
Thickness target
Electron density target

4. To compare the shapes of the angular distributions **normalization to the number of real data events**.

DATA/MC COMPARISON USING TR 2023 DATA

ABSOLUTE NORMALIZATION





Flat region of $\mathbf{5\,mrad < \theta_e < 20\,mrad}$

2 tracks reconstruction efficiency, given modules efficiency $\boldsymbol{\epsilon = 0.980 \pm 0.005}$:

$$\epsilon_{2t} = \epsilon_{1t} \times \epsilon_{1t} = 0.850 \pm 0.035$$

where

Track with at least 5 stubs, without any hit shared → $\epsilon_{1t} = \epsilon^6 + 2(1-\epsilon)\epsilon^5$