MUonE experiment at SPS

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Outlook:

Anomalous magnetic moment of a muon

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S},$$

Lande g-factor can be determined for fermions from the Dirac equation. For elementary, pointlike fermions it gives:

$$g = 2.$$

But, including additional effects related to electromagnetic, weak and strong forces:

$$g > 2.$$

Thus, an anomalous magnetic moment can be defined:

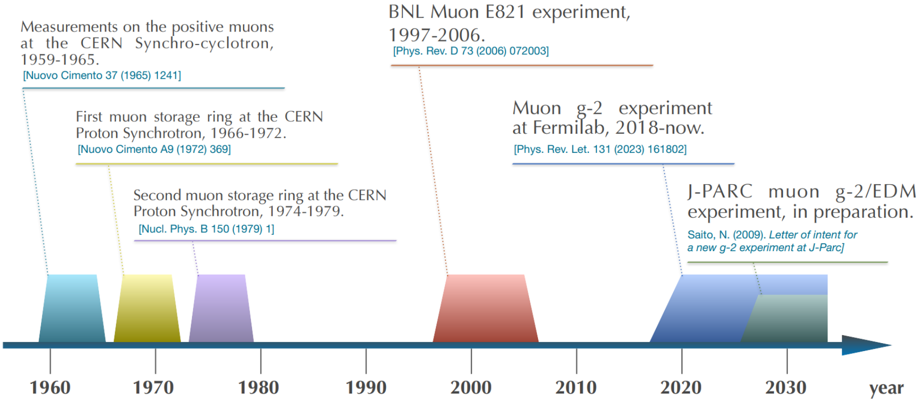
$$a_\mu = \frac{g-2}{2}.$$

The anomalous magnetic moment of a muon can be referred as:

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}.$$

- One of the most precisely measured quantities,
- precisely determined in Standard Model,
- good test for various theoretical aspects.

Over 60 years of muon g-2...



Muon g-2 timeline.

Results of Muon g-2 experiments

Experimental average:
[Phys. Rev. Let. 131 (2023) 161802]

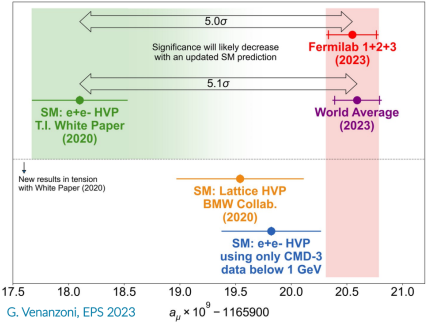
$$a_\mu(\text{exp}) = 116592059(22) \times 10^{-11}$$

Prediction for the SM value:

[Phys. Rep. 887 (2020) 1]

$$a_\mu^{\text{SM}} = 116591810(43) \times 10^{-11}$$

a_μ^{QCD} determined from dispersive relation.



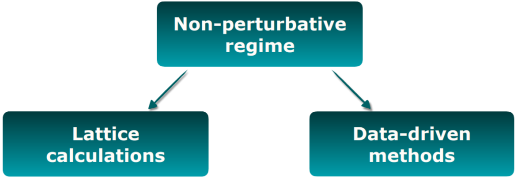
Current experimental average shows a 5σ discrepancy according to the theoretical value of the Muon g-2.

Hadronic contribution a_μ^{HLO}

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}.$$

- QED corrections known up to 5 loops, $\sim 0.001\%$ of $\sigma(a_\mu^{\mathrm{SM}})$.
- EW known up to 2 loops, $\sim 0.2\%$ of $\sigma(a_\mu^{\mathrm{SM}})$.
- Hadronic - non-perturbative QCD, $\sim 99.8\%$ of $\sigma(a_\mu^{\mathrm{SM}})$.

Main source of uncertainty - hadronic vacuum polarisation (HVP) contribution to theoretical value of a_μ.



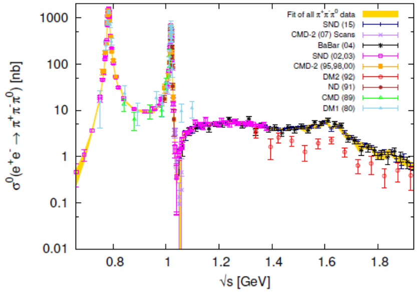
- Lattice calculation of HVP by BMW Collaboration [Nature 593 (2021) 51]

- a_μ^{SM} takes HVP term from multiple measurements of $e^+e^- \to$ hadrons cross-sections.
- Preliminary results from CMD-3 experiment - $e^+e^- \to \pi^+\pi^-$ cross section.[arXiv:2302.08834]

Hadronic contribution a_μ^{HLO}

The Standard Model prediction of a_μ uses the data-driven method based on the dispersion relation to determine a_μ^{HLO} term.

[Phys. Rev. D 97 (2018) 114025]



$$a_\mu^{HVP,LO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2 c^4}^{\infty} ds\, K(s)\, \sigma^{(0)}(s)$$

$\sigma^{(0)}$ - total x-section $e^+e^- \to$ hadrons, $K(s) \sim 1/s$

- $\sigma^{(0)}$ from multiple experiments, subtracted from ISR and vacuum polarization corrections.
- Low-energy region highly fluctuating.
- Hadron resonances and thresholds effects.
- Accuracy $\sim 0.6\%$.

MUonE experiment - the new approach to determine a_μ^{HLO}

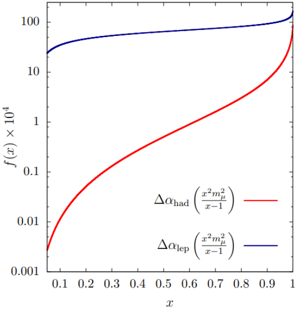
MUonE experiment - the new approach to determine a_μ^{HLO}

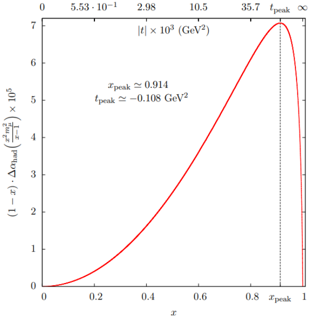
MUonE experiment uses a novel, independent method to determine a_μ^{HLO} by measuring hadronic contribution to running fine-structure constant value.

$$a_\mu^{HVP,\,LO} = \left(\frac{\alpha_0}{\pi}\right)^2 \int_0^{0.932} dx(1-x)\Delta\alpha_{had}[t(x)].$$

- $\Delta\alpha_{had}[t(x)]$ is a smooth function and is the hadronic contribution to the running α.
- The integrand is a smooth function free of resonance poles (in contrast to the dispersive integral).

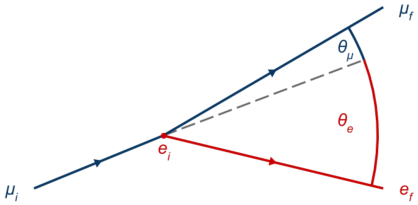
Letter of Intent SPSC-I-252 (2019)





$\Delta\alpha_{had}[t(x)]$ can be measured in the $\mu - e$ elastic scattering process.

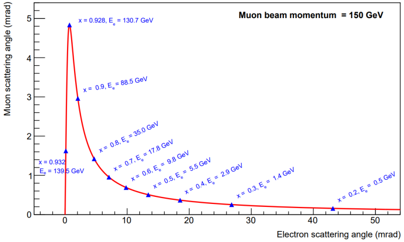
- Scattering of high-energy muons on atomic electrons on a low-Z target through the elastic process.



running of α

$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

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

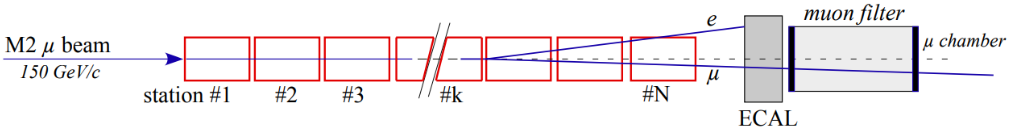


[Eur. Phys. J. C77 (2017) 139]

- The angles of scattered particles are related to the differential cross section.
- The elastic scattering signal region located closer to the peak.
- The reference region dominated by the multiple scattering background far from the peak (angular correlation is minor).
- The ratio of above allows to significantly reduce the systematic uncertainty.

Experimental apparatus

MUonE needs to control very well both systematic and statistical errors.



- Located at SPS.
- 160 GeV incoming muon beam.
- Modular structure made by up to 40 tracking stations.
- Each station consists of a target and 6 tracking modules.
- Targets made of a Low-Z material (Be or C) to minimize distortions of the outgoing e/μ trajectories.
- Tracking layers made of Si tracking planes.
- Precise measurement of the outcoming electrons and muons angles.
- Precise measurement of the incoming muon direction.
- Systematic effects known at $\sim$ 10 ppm.
- Intrinsic hit resolution $\sim$ 10 μm.

Tracking system

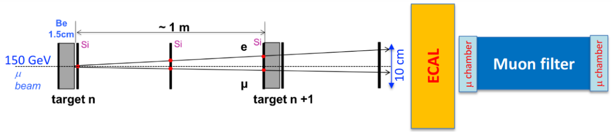
Up to 40 tracking stations in the final detector layout.

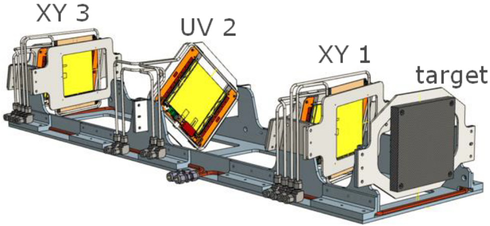
Each tracking station consists of:
- target,
- 6 tracking modules.

Each tracking module consists of:
- pair of close Si layers.

MUonE will use the CMS 2S Si sensors developed for CMS Outer Tracker upgrade.
[CMS-CR-2023-146]

[not on scale]





Test Run 2018

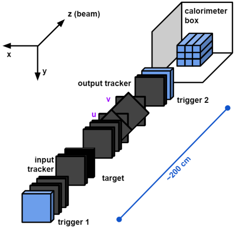
Published in JINST 16 (2021) P06005

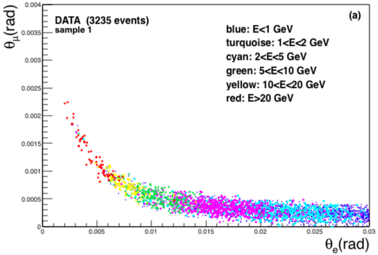
First complex proof of concept was performed downstream COMPASS in 2018, with muons coming from the pion decays.
Beam rate - few kHz.

(Different sensors and detector layout)

Aimed mainly to explore the ability to select a clean sample of elastic scattering events in view of designing the final experiment.

- Also - specify the outlines for the final MUonE experimental setup.





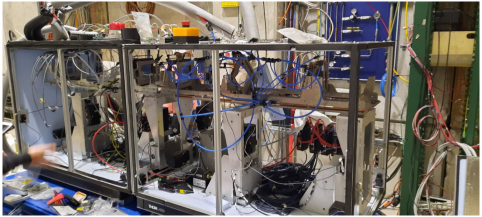
Conclusion: a clean sample of elastic events was obtained even if the resolution worse than the final one for MUonE.

Ongoing analyses of 2022/23 Test Runs

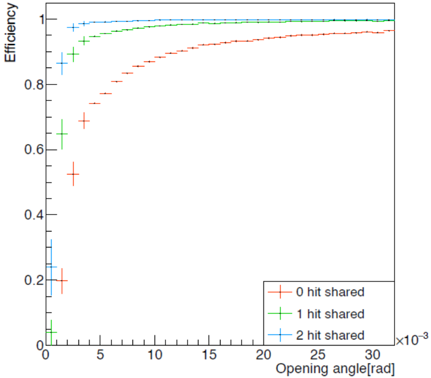
- M2 muon beam in the CERN North Area.
- 160 GeV muons, beam rate - 40 MHz.
- Stations consisting of a thin graphite target and 6 CMS tracking layers.
- One station after target and one station upstream detector for tracking the incoming muons.
- In 2023 $\sim 10^8$ elastic events were collected and under analysis.

Main goals:

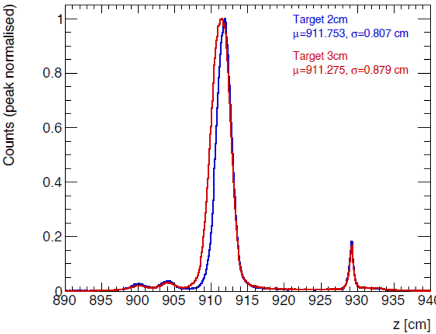
- confirm the system engineering,
- test DAQ system,
- test the tracking and vertex reconstruction,
- evaluate the FPGA real-time processing,
- test the procedure for the alignment of the sensors.



Results from 2023 Test Run analysis



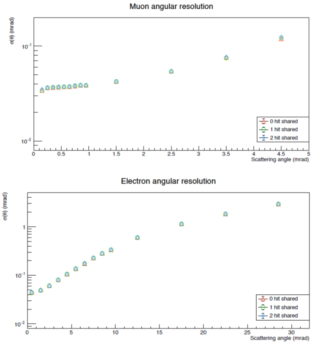
Reconstruction efficiency for the elastic event as a function of the $e-\mu$ opening angle.



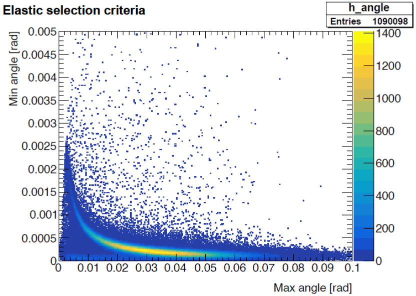
Vertex z position determined for events with two outgoing tracks.

[CERN-SPSC-2024-015; SPSC-P-370]

Results from 2023 Test Run analysis



Angular resolution as a function of the scattering angle for the outgoing muon (top) and electron (bottom), obtained by fitting the residual distribution of the reconstructed angle using MC truth.



2D distribution of candidate scattering events after the loose elastic selection.

[CERN-SPSC-2024-015; SPSC-P-370]

Development of new tools - Machine Learning methods for MUonE

[Computer Science 20(4) (2019) 477-493]
[DCAI 2021 Lecture Notes, vol. 2, p 202-205]
[Computer Science, 25 (2024) 1]

Track finding with the Deep Neural Networks for MUonE

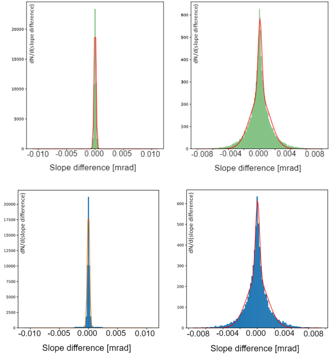
Simultaneous development of a new tool that can be applied to:

- pattern recognition
- track reconstruction

Goal: speed up the online reconstruction process - solve the CPU time consumption problem.

Three-dimensional DNN based track reconstruction for Test Beam 2018 - comparable results to the classical method.

Work on ML based methods is currently continuing (full reconstruction in 3D, PID, alignment).



Particle	DNN based	Classical
Muon	$\sigma = 0.000018$ mrad	$\sigma = 0.000019$ mrad
Electron	$\sigma_1 = 1.290$ mrad, $\sigma_2 = 0.245$ mrad	$\sigma_1 = 1.230$ mrad, $\sigma_2 = 0.244$ mrad

Summary

The most recent results from Fermilab indicate a 5σ discrepancy according to Standard Model prediction of a_μ. Currently, the Hadronic Vacuum Polarization contribution to a_μ^{SM} is determined with the dispersive integral using $e^+e^- \to$ hadrons.

- Preliminary results from CMD-3 experiment disagrees with other e^+e^- data.
- Lattice results are closer to the experimental one.

Independent determination of HVP term by measurement of the hadronic part of running fine-structure constant proposed by MUonE experiment - great opportunity to clarify the situation.

- Test Run 2018 - clean sample of elastic events was obtained - very optimistic!
- Ongoing analysis of Test Run 2022/23 data taken with the final target and CMS tracking layers.
- Start of data collecting for miniMUonE planned for 2025:
  - 2 CMS 2S stations after target and 1 station upstream detector for tracking the incoming muons,
  - calorimeter, muon filter and incoming muon momentum measurement (BMS).

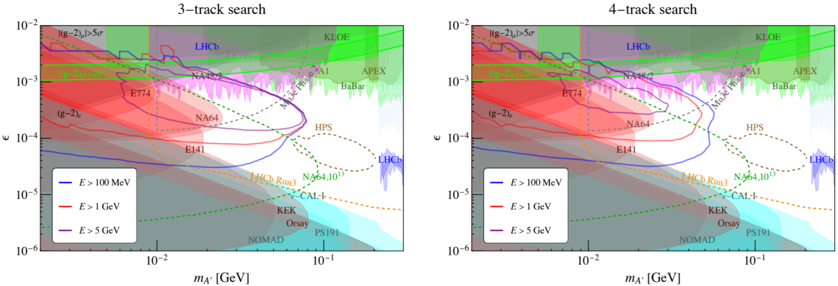
Supported by the National Science Centre NCN (Poland) under the contract no. 2022/45/B/ST2/00318

Backup - secondary studies

The MUonE detector is sensitive to hypothetical long-lived particles and covers parts of phase-space unreachable to other experiments.
In particular - dark photons:

$$\mu + e \to \mu + e + A'(\to e^+e^-),$$

expected to decay between the target and the first tracking module.



[arXiv:2202.08843]