The MUonE experiment

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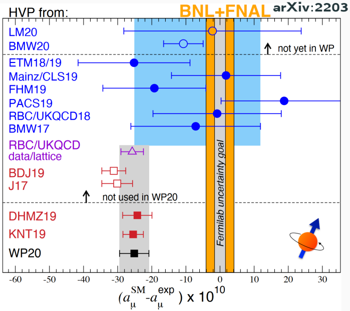
Muons anomalous magnetic moment – current picture

Muon anomalous magnetic moment, defined as $a_\mu = \frac{g-2}{2}$ $(\vec{\mu} = g\frac{e}{2m}\vec{S})$, measured by Fermilab seems to be in disagreement with the SM prediction. Uncertainties are big due to non-perturbative contributions.



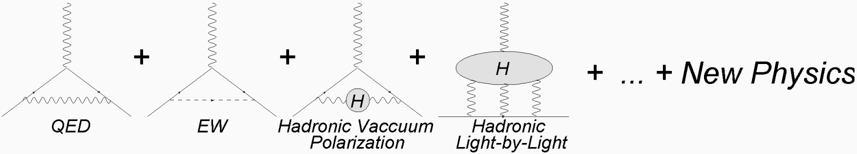
arXiv:2203.15810

circles – lattice, squares – data driven

The difference with SM data-driven predictions has a significance of 4.2σ!

Lattice results are closer to Fermilab's, but this tension is not yet understood.

Muons are much more sensitive to strong contributions and massive loops than electrons, for which QED corrections are usually enough.

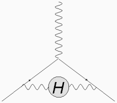


contribution	exact corrections	value $[\cdot 10^{-11}]$	σ	σ/σ_{total} [%]
QED	5 loops	116’584’718.931	0.104	0.001
EW	2 loops	153.6	1.0	0.2
HVP	non-perturbative	6’845	40	99.8
HLbL	non-perturbative	92	18	
Total SM		116’591’810	43	

The Hadronic Vacuum Polarization contribution dominates the SM uncertainty.

MUonE experiment – a spacelike approach to HVP

The novel approach, proposed by MUonE, removes the most challenging part of data driven calculations – integration of hadronic cross-sections.



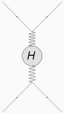
$$a_\mu^{HVP,LO} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} ds\, K(s)\, \sigma_{had}(s)$$

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

$$\Longrightarrow$$

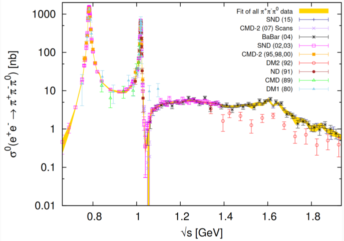
$$a_\mu^{HVP,LO} = \frac{\alpha(0)}{\pi}\int_0^1 dx\,(1-x)\Delta\alpha_{had}(t)$$

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

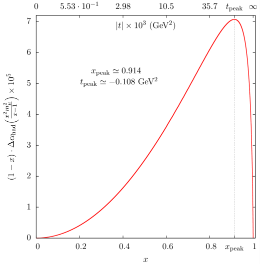


The integrand now depends on the change of the hadronic part of the effective fine structure constant and is a smooth, well-behaved function.

arXiv:1802.02995



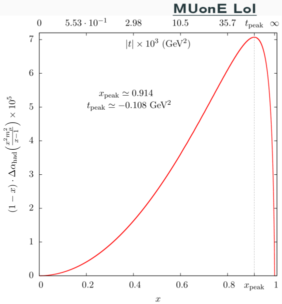
MUonE LoI

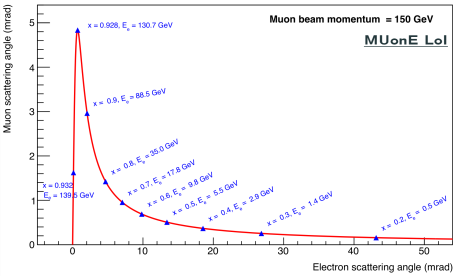


Experimentally, the problem is reduced to a measurement of the running of α in a single scattering process – $\mu + e \to \mu + e$.

$$\frac{\alpha(t)}{\alpha(0)} = \frac{1}{1-\Delta\alpha(t)}, \quad \Delta\alpha = \Delta\alpha_{lepton} + \Delta\alpha_{hadron} + \Delta\alpha_{top} + \Delta\alpha_{weak}$$

where all contributions, except $\Delta\alpha_{hadron}$, are known very precisely.

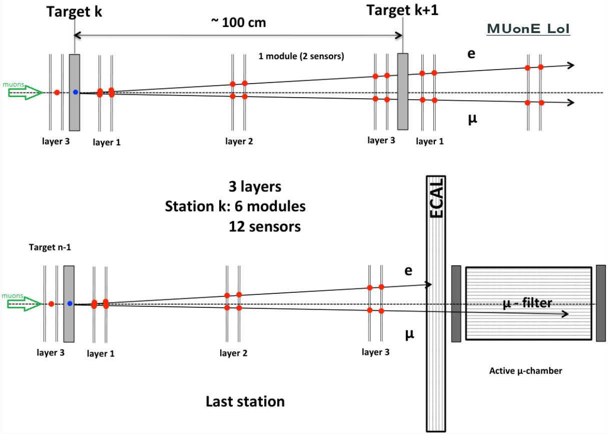




88% of integral covered with $E_\mu^{inc} \simeq 160$ GeV, rest can be extrapolated.

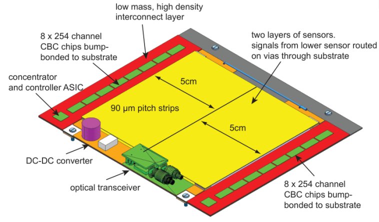
MUonE detector

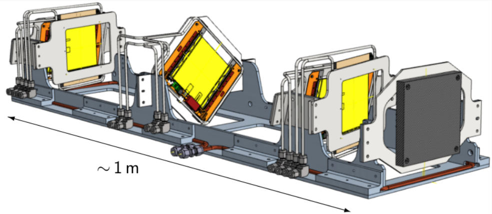
The detector has to be as simple as possible to keep the systematics low.



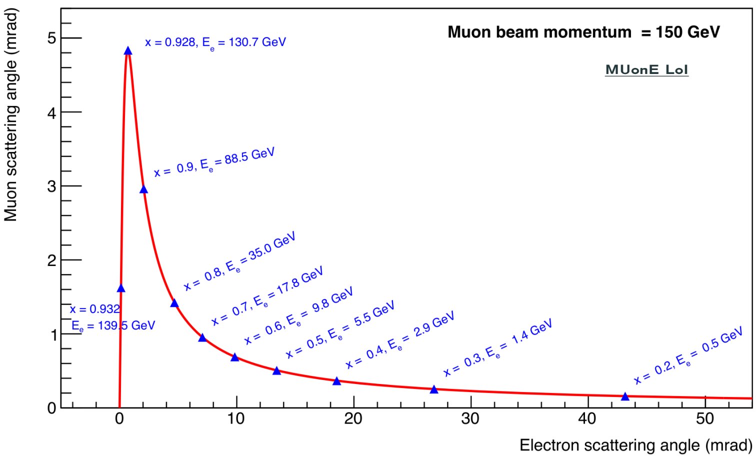
40 tracking stations are planned in total (each w/ 1.5 cm Be target), but the modular design allows for flexibility and running in stages. MUonE will be utilizing the M2 line at CERN (160 GeV muons).

Each station contains 6 prototype 2S silicon strip modules designed for the CMS upgrade (CMS-TDR-014) in an Invar (Fe/Ni alloy) frame, which can maintain required dimensional stability with temperature changes.





The modules are paired to provide measurement in two perpendicular directions with one pair rotated 45° to solve combinatorial ambiguities. A tilt around the strip axis may be introduced to further increase resolution.



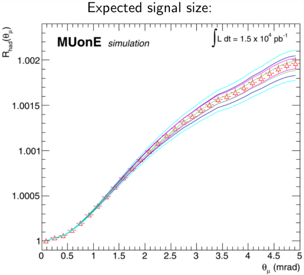
Since the system is boosted, the modules cover entire acceptance (roughly $\theta_e < 32$ mrad and $\theta_\mu < 5$ mrad). The position resolution of 10-20 μm translates to roughly 0.02 mrad of angular resolution.

Analysis strategy

The easiest way of extracting the hadronic running of α is by taking the ratio of a measured scattering cross-section and MC cross-section with no hadronic running. At LO:

$$R^{LO}_{had}(t) = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had} = 0)} \simeq 1 + 2\Delta\alpha_{had}$$

The analysis will employ a template fit to the 2D distribution of scattering angles (θ_μ, θ_e) using a *lepton-like* parametrization of $\Delta\alpha_{had}$, inspired by the calculable lepton pair contribution.

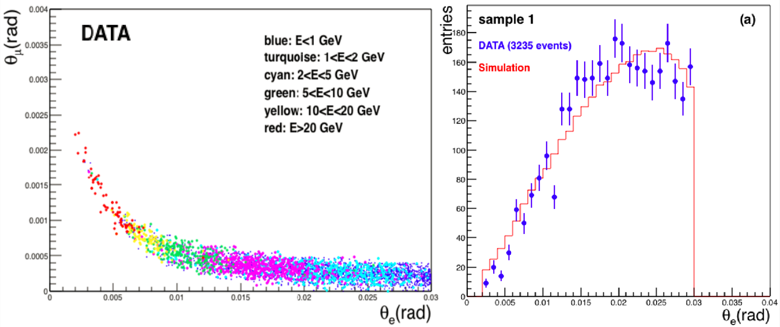


Expected signal size:

marks – central value with stat. uncert.
colored curves – representative templates

Test Runs – 2018

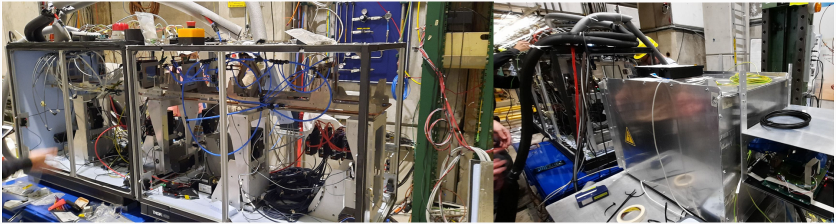
A number of test runs have been performed using some of the final components and beam. In 2018 the early proof of concept (different modules and configuration) was tested on the M2 beam line.



Conclusions – elastic signal can be extracted from data reasonably well, even with resolution lower than final, but calorimeter is crucial. Results published in JINST 16 (2021) P06005.

Test Runs – 2022

In 2022, the test involving a full tracking station, using CMS modules, and combined with a calorimeter was performed on the M2 beamline.



Data acquisition tested, successful and stable operation at high intensity. Limited physics possibilities due to lack of incoming muon tracking, but lots of data on module performance collected.

A joint publication with CMS will soon follow.

Test Runs – 2023

A Pilot Run is planned for the end of September, this time with 2-3 fully instrumented stations.

- full integration of ECAL and tracker DAQ
- test a simplified on-line selection for data reduction in real time
- background study with final detector configuration
- test of global alignment
- study of beam energy calibration
- measurement of the leptonic running of α

Results will be used to prepare the full experiment proposal.
Submission to the SPSC planned for 2024.

Summary and future

Fermilab results on a_μ indicate a 4.2σ discrepancy with data driven prediction of the SM. Lattice results are closer to the experimental one, but don't explain the tension of data-driven methods.

The uncertainty of SM value is dominated by non-perturbative contributions, in particular the Hadronic Vacuum Polarization.

MUonE aims to provide a complementary measurement of α_μ^{HVP-LO} with a competitive precision of $\sim 0.3\%$ (better by a factor of 2) by exploiting a novel approach to calculations.

- short term goal – 2-3 stations, 2023 Test Run → measurement of leptonic running
- medium term goal – 10 stations, 4 months → $\sim 2\%$ precision before CERN shutdown in 2026
- long term goal – 40 stations, 3 years → $\sim 0.3\%$ precision
- systematics controlled at the 10 ppm level

Being formed
still growing up

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

CERN
Exp-Th

Imperial College (London), Liverpool U. *Exp-Th*
Durham U.

Krakow IFJ Pan
Exp

μONe

Cornell U.,
Northwestern U.,
Regis U.,
Virginia U.
Exp

Shanghai Jiao Tong U.
Exp

The MUonE Collaboration

Demokritos INPP (Athens) *Exp-Th*

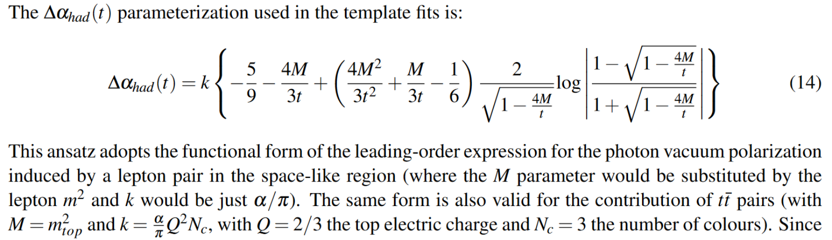
PSI (Villigen),
U.Zürich, ETH Zürich
Th

Mainz U.,
Max-Planck Inst.
Exp-Th

+ other involved theorists from: New York City Tech (USA), Vienna U. (A)

Backup – lepton-like parametrization

MUonE LoI



The $\Delta\alpha_{had}(t)$ parameterization used in the template fits is:

$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\} \tag{14}$$

This ansatz adopts the functional form of the leading-order expression for the photon vacuum polarization induced by a lepton pair in the space-like region (where the M parameter would be substituted by the lepton m^2 and k would be just α/π). The same form is also valid for the contribution of $t\bar{t}$ pairs (with $M = m_{top}^2$ and $k = \frac{\alpha}{\pi}Q^2N_c$, with $Q = 2/3$ the top electric charge and $N_c = 3$ the number of colours). Since