The MUonE experiment
proposal, status and plans

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on behalf of the MUonE collaboration

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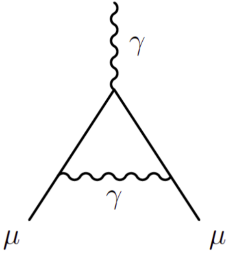
THE MUON ANOMALOUS MAGNETIC MOMENT

The muon anomalous magnetic moment

The anomalous magnetic moment of the muon $\frac{g_\mu - 2}{2} = a_\mu$ is calculated as sum of three contributions:

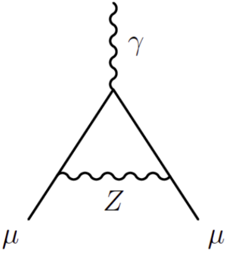
a_μ^{QED}

QED corrections
Known up to 5 loops
$\sigma_{rel} = 7 \times 10^{-10}$



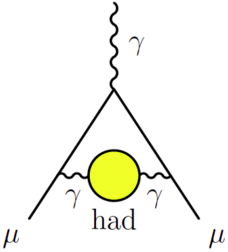
a_μ^{EW}

Electroweak corrections
Contribution $\sim 10^{-9}$
$\sigma_{rel} < 1\%$



a_μ^{H}

Hadronic corrections
Contribution 7×10^{-8}
$\sigma_{rel} \simeq 0.35 - 0.60\%$



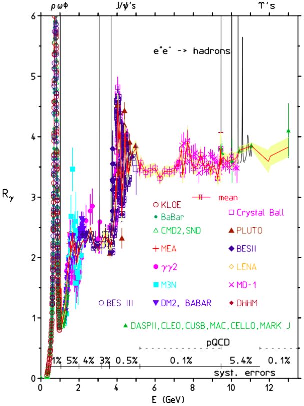
Not calculable in pQCD
Dominant theoretical syst

Hadronic vacuum polarisation

Main contribution to hadronic correction: LO vacuum polarisation
Traditionally calculated via data-driven approach + optical theorem:

$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{E_{cut}} ds \frac{K(s)R_\gamma(s)}{s^2}$$

$$R_\gamma = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

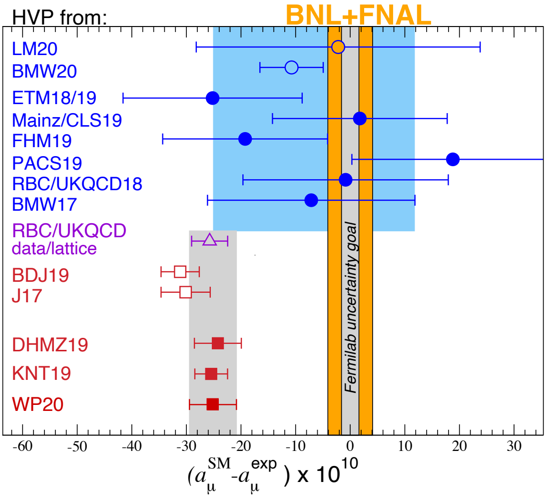


- Low-energy region subject to large fluctuations for high number of resonances
- Large number of measurements

Alternatively, lattice QCD calculations are becoming more and more precise

[EPJ WoC 118 (2016) 01016]

Latest theoretical and experimental results



BNL + FNAL combination gives 4.2σ deviation from data-driven theory.
Discrepancy between data-driven approach and lattice QCD calculations?

[arXiv:2203.15810]

A new method: space-like approach

MUonE will use a new, independent evaluation of a_μ^{HLO}

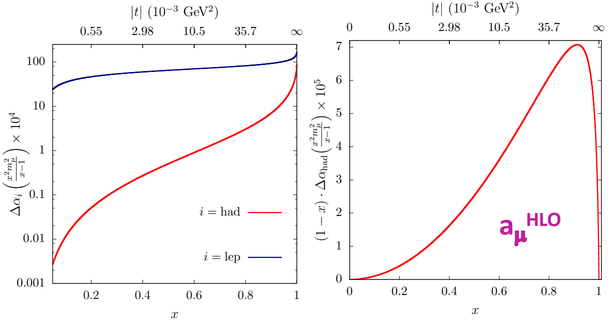
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

$\Delta\alpha_{had}$: hadronic contribution to the running of α in the space-like region

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

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



$\Delta\alpha_{had}(t)$ can be extracted from the shape of $\mu e \to \mu e$ differential cross section

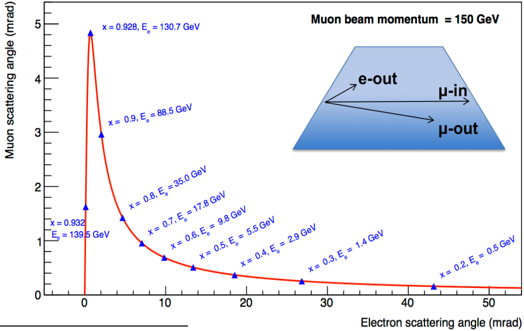
[PLB 746 (2015) 325]

THE MUonE EXPERIMENT

The MUonE experiment

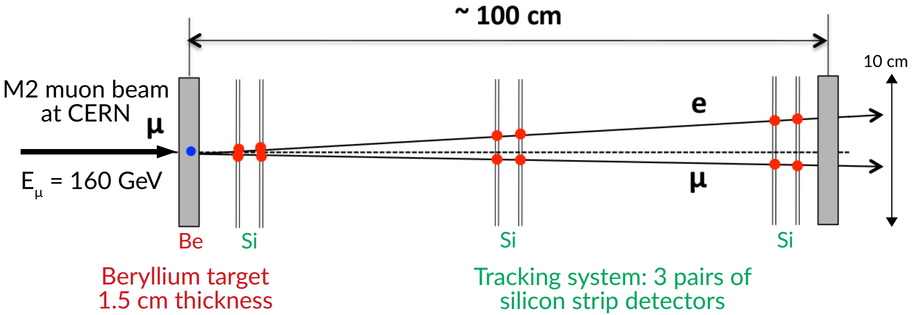
MUonE will measure the differential cross-section of elastic μe scattering with $E_\mu = 160$ GeV muons colliding on atomic electrons of a fixed target with low Z

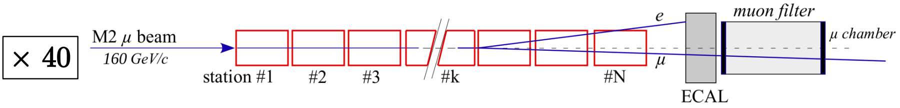
- High-intensity CERN M2 beam: $5 \times 10^7 \mu/s$
- Highly-boosted final states: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad
- Correlation between muon and electron angles allows to select elastic events and reject background (i.e. pair production)
- Phase space covers 87% of the a_μ^{HLO} integral ($x < 0.93$)



[EPJC 77 (2017) 139]

MUonE detector layout





[Letter of Intent: the MUonE project]

Tracking modules: CMS 2S modules

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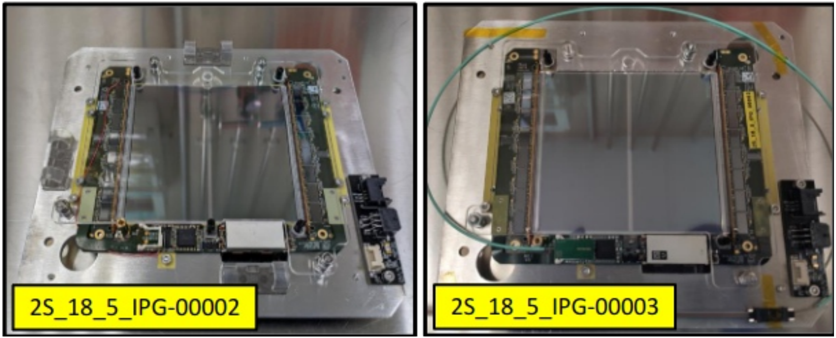
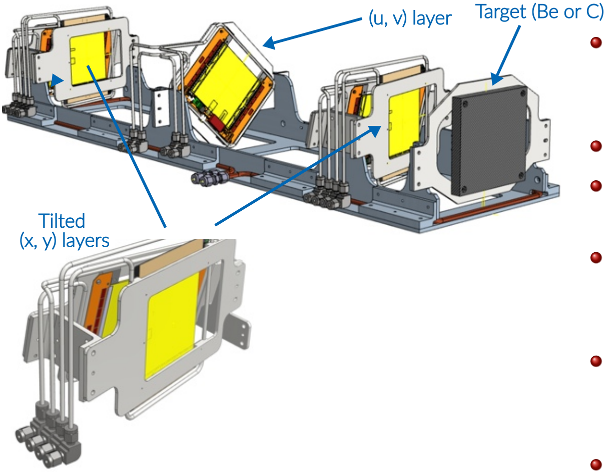


- CMS 2S modules in production for CMS-Phase2 upgrade
- Two layers of silicon strip sensors, each with back and front readout
- A stub is formed by two hits, one in each layer, with small distance
- Dimensions: 10x10 cm^2, 2x320 μm thickness, 90 μm pitch ($\sigma_x \sim 26\mu$m)
- Four modules assembled by CMS Perugia for MUonE, 5th coming soon
- Difference with LHC: signal is asynchronous, the sampling runs at 40 MHz

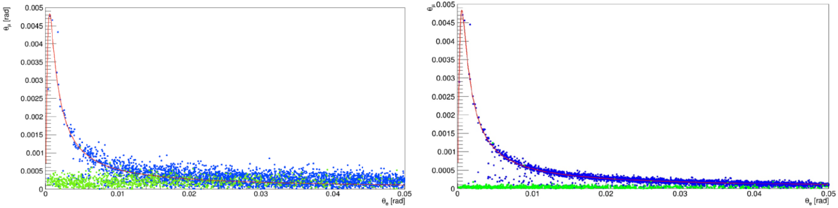
[CMS Tracker Upgrade TDR]

MUonE tracking station



- Stringent request: relative position within a station must be stable at 10 µm
- Low CTE material: INVAR
- Laser holographic system to monitor stability
- (x,y) layers tilted by 233 mrad to improve single hit resolution $\sigma \sim 8\mu m$
- Cooling system, room temperature stabilised within 1-2 °C
- FE electronics linking with Serenity board for DAQ

Importance of small single-hit resolution

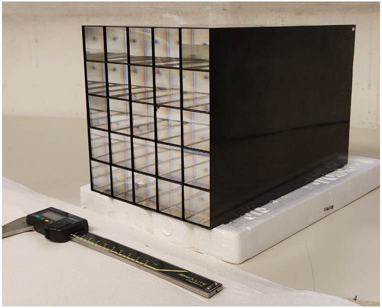


- Simulation (Geant4) of events with 2 tracks, 150 GeV muon energy
- Blue: elastic μe scattering
- Green: e^+e^- pair production (background)
- Red: ideal elastic scattering curve
- Left: $\sigma = 25\mu$m , right $\sigma = 8\mu$m
- Tilting the (x,y) layers has a huge effect on sensitivity!

Calorimeter

PbWO4 crystals used by the CMS ECAL in a 5x5 array (14x14 cm^2)

- Mainly used for particle ID
- Cell size: 2.85x2.85 cm^2
- Lenght 22 cm corresponding to 24.7 X_0
- Cooling system, insulation, $\Delta T < 0.1$ °C
- Readout: Hamamatsu APD sensors
- Laser for calibration and monitoring (APD and FEE gain)
- FE electronics linking with Serenity board for DAQ

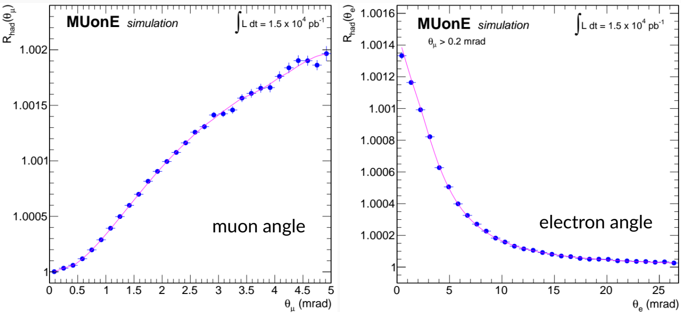


Extraction of a_μ^{HLO}

$\Delta\alpha_{had}(t)$ parametrisation inspired by the 1-loop QED contribution at $t < 0$

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

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



$L = 1.5 \times 10^7\ \text{nb}^{-1}$
(3-year run)

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

Stat. error
0.35%

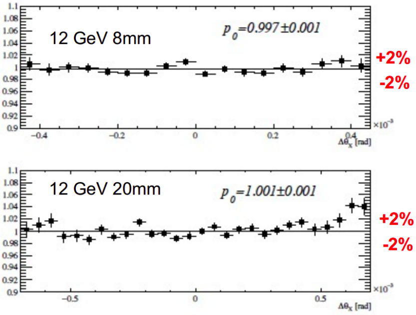
$$R_{had} = \frac{d\sigma(\Delta\alpha_{had}(t))}{d\sigma(\Delta\alpha_{had}(t)=0)}$$

TEST BEAMS RESULTS AND PROSPECTS

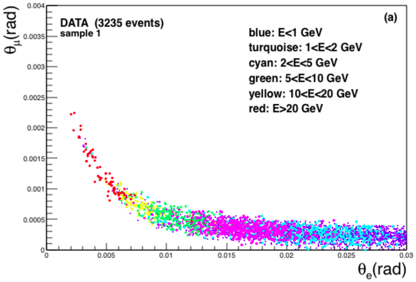
Test Beams 2017 and 2018

Test Beam 2017
Multiple scattering analysis
[JINST 15 (2020) P01017]

data/MC

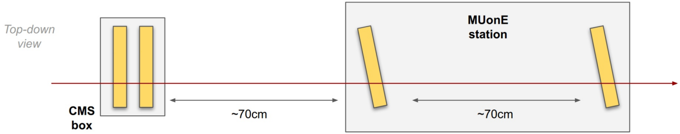


Test Beam 2018
$\mu - e$ elastic scattering
[JINST 16 (2021) P06005]

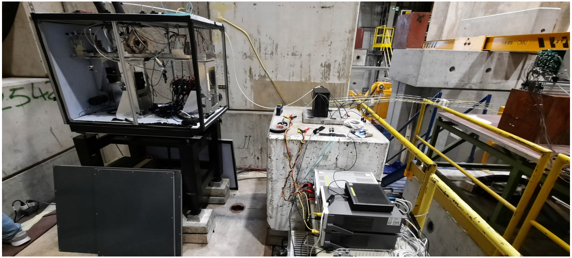


Test Beam October 2021

Parasitic test beam at the CERN M2 beam line: 3 weeks in October 2021



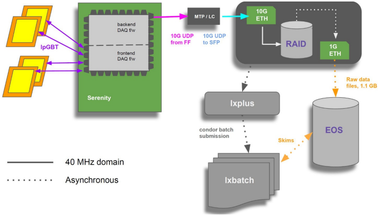
- Joint test with CMS tracker, located downstream of COMPASS
- 160 GeV muons with asynchronous rate of $\sim$ 16 kHz
- Two modules built for MUonE in the MUonE station
- Two modules built for CMS tracker in the CMS box



Test Beam October 2021

First complete check of the full DAQ chain with the M2 asynchronous beam

- Continuous stream of 40MHz data from 2S modules written on disk
- Reliable readout over >6h runs
- 30 TB of raw data collected, ∼1 TB after empty packets removal
- Offline analysis ongoing: check data integrity and modules synchronization, beam behaviour, track reconstruction...



Test Beam July 2022

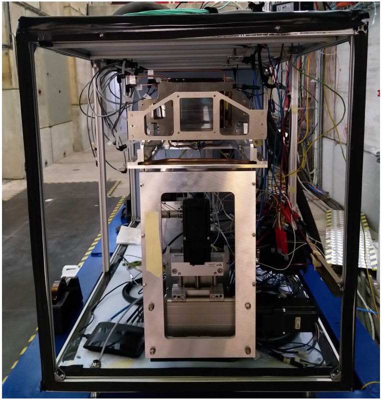
First performance test of the calorimeter at the CERN T9 $e^{\pm}$ line

- Positrons with E_e in the range [1, 10] GeV
- Testing sensitivity, linearity, optimisation of APD and gain
- Using the old CMS multigain amplifier (MPGA) with a new commercial ADC
- Study of energy resolution, expected to be dominated by low light yield
- Study of the acquisition rate with a laser pulse
- DAQ rate $\sim$ 1.5 kHz, similar to elastic scattering rate for $E_e > 1$ GeV

Test Beam October 2022

One week at the CERN M2 muon beam line: tracking station + calo

- Confirm the detector design, proof of concept
- Define the procedures for alignment, readout chain, trigger strategy
- Test synchronism between tracking and calo acquisitions
- With full beam intensity expected $\sim 1\ \text{pb}^{-1}$/day once the station has been completely commissioned



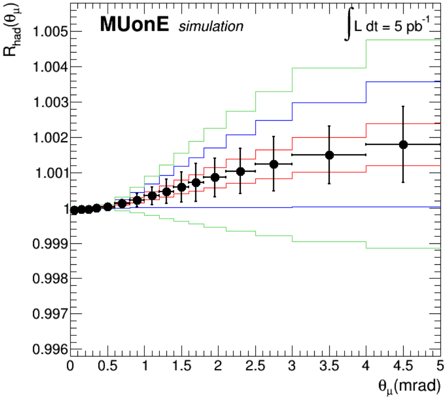
Test Run 2023 - expected sensitivity

At leading order

$$R_{had} = \frac{d\sigma(\Delta\alpha_{had}(t))}{d\sigma(\Delta\alpha_{had}(t)=0)} \simeq 1 + 2\Delta\alpha_{had}(t)$$

and for small t, i.e. the dominant behaviour in the MUonE kinematic region

$$R_{had} \simeq 1 + 2\Delta\alpha_{had}(t) \simeq 1 - \frac{2}{15}Kt$$



- Three weeks at the CERN M2 muon beam line
- Expected 3 stations + calo
- In one week $\sim 5\ \text{pb}^{-1}$
- Sensitive to the leptonic running, but low sensitivity to the hadronic running

$$K = 0.136 \pm 0.026$$

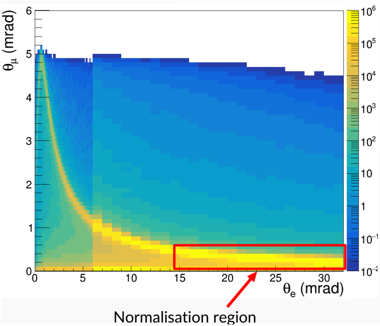
(19% stat. error)

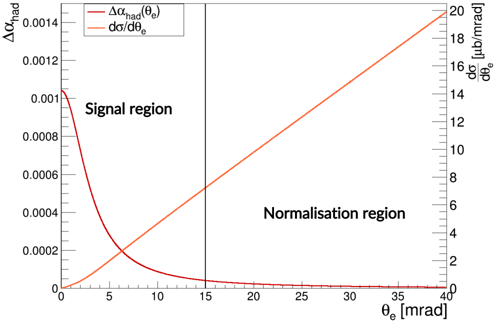
STUDY ON SYSTEMATIC EFFECTS

Normalisation region

The largest systematic effects have a major impact in the large θ_e region

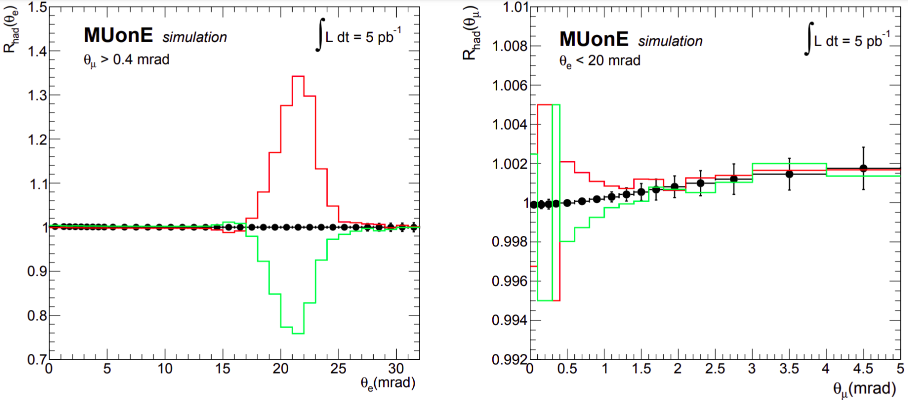
- No sensitivity to $\Delta\alpha_{had}$ in that region
- Very large statistics
- We can use it as normalisation region to calibrate the systematic effects





Intrinsic angular resolution

Effect of a ±10% systematic error on the intrinsic angular resolution



Multiple Coulomb scattering

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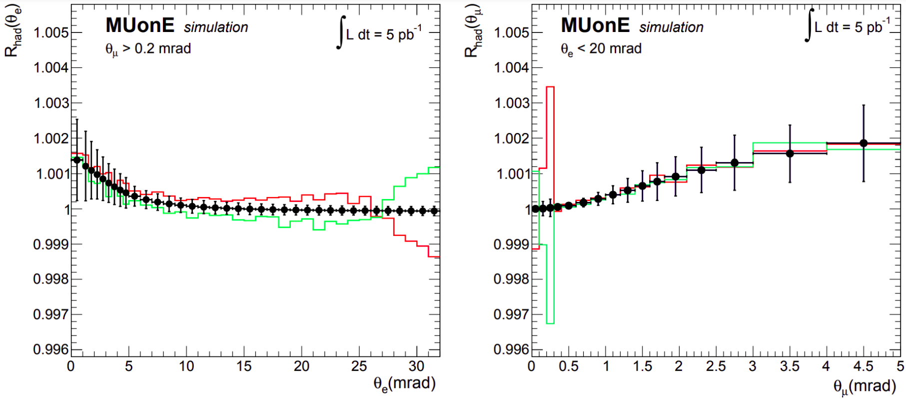
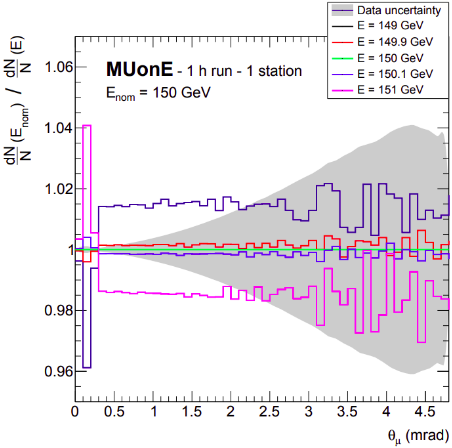
Effect of a ±1% systematic error on the assumed width of the core of the MCS distribution



Beam energy scale calibration

Effect of a $\pm(0.1 - 1)$ GeV shift in the average beam energy



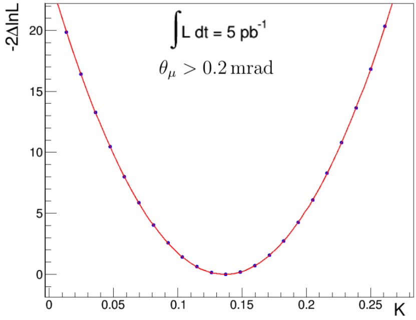
Can be calibrated with elastic μe events with equal scattering angles

The final detector should be able to calibrate the average beam energy scale with a precision better than 3 MeV in less than one week

Calibration of systematic effects

- Fitting data in the control region and correct the distributions
- The residual systematic uncertainties are then included as nuisance parameters in a likelihood fit
- Determined simultaneously with the signal parameters

Example: introduce +0.5% shift in multiple scattering



Fit results ($\theta_\mu > 0.2\,\mathrm{mrad}$)
$K = 0.136 \pm 0.028$
$\mu_{MS} = (0.508 \pm 0.013)\%$

- Both signal and systematic effect identified with good precision
- Almost no degradation on signal parameter (21% vs 20% error)
- Method tested against all sources mentioned above at the same time

CONCLUSIONS

Conclusions

- Discrepancy in the long-standing puzzle of muon g-2 confirmed at 4.2σ
- Theory error dominated by LO hadronic vacuum polarisation contribution
- The alternative method to determine a_μ^{HLO} proposed by MUonE is independent, complementary and competitive with the latest evaluations
- CERN has recognised the fundamental interest and approved a Test Run as a condition to move on towards the full-scale experiment

Conclusions

- Challenge: control of systematic effects at the level of statistical precision
- Towards the full experiment: 10 stations before LS3 (2026) with 4 months data taking and $\sim 2\%$ (stat) measurement of a_μ^{HLO}
- Impressive progress on theory: [NLO MC generator developed], great effort towards a full NNLO generator (10^{-5} accuracy)
- Interesting "secondary" physics programme: search for displaced vertices, FB asymmetry, LFV, search for light mediators...

We are looking for collaborators, please get in touch if you are interested to join us!

[https://web.infn.it/MUonE]

BACKUP

Useful documentation

Some BSM papers on MUonE:

- K. Asai et al, *Probing the L_μ-L_τ Gauge Boson at the MUonE Experiment*
  - [https://arxiv.org/abs/2109.10093]
- I. Galon, D. Shih, I. R. Wang, *Dark Photons and Displaced Vertices at the MUonE Experiment*
  - [https://arxiv.org/abs/2202.08843]
- G. Grilli di Cortona, E. Nardi, *Probing light mediators at the MUonE experiment*
  - [Phys. Rev. D 105 (2022) L111701]

Recent developments on the theory side presented at ICHEP 2022:

- E. Budassi, *High precision calculations for the MUonE experiment*
  - [Link to slides]
- S. Laporta, *NLO and NNLO hadronic vacuum polarization contributions to the muon $g-2$ in the space-like region*
  - [Link to slides]
- C. L. Del Pio, *Neutral pion production in μe scattering at MUonE*
  - [Link to poster]

CERN M2 muon beam line

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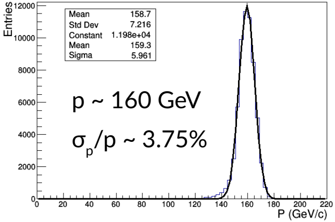
- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 3×10^8 μ^+/spill).

Beam momentum



Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm