MUonE: a direct study of the hadronic vacuum polarization

current status and prospects

Dinko Počanić (for the MUonE collaboration)

University of Virginia

10 June 2025

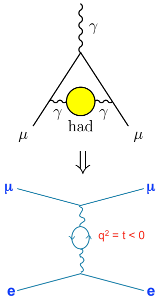
15th Conf. on Intersections of Particle and Nuclear Physics
9 – 13 June 2025
University of Wisconsin, Madison, WI

Outline of the talk

1. Why was MUonE proposed?
   - the muon magnetic anomaly $a_\mu = \frac{1}{2}(g_\mu - 2)$, and
   - the hadronic vacuum polarization (HVP),
   - status of a_μ in 2025.

2. How will MUonE be carried out at CERN?
   - principles of measurement,
   - apparatus,
   - status and plans.

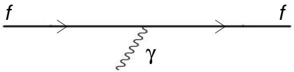
3. The experimental path forward for HVP.



Lepton magnetic dipole moments and the associated anomaly

Dirac's equation (1928) for a point particle g-factor, defined by $\vec{\mu} = g\frac{e}{2m}\vec{S}$, gives $\boxed{g \equiv 2}$, precisely. Quantum fluctuations give rise to the anomalous magnetic moments:

Leading (Dirac) term: g = 2

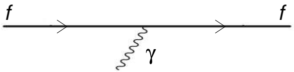


$+$ higher (loop) terms $\Rightarrow$ magnetic anomaly: $\boxed{a = \dfrac{g-2}{2} \neq 0}$.

Lepton magnetic dipole moments and the associated anomaly

Dirac's equation (1928) for a point particle g-factor, defined by $\vec{\mu} = g\frac{e}{2m}\vec{S}$, gives $\boxed{g \equiv 2}$, precisely. Quantum fluctuations give rise to the anomalous magnetic moments:

Leading (Dirac) term: g = 2



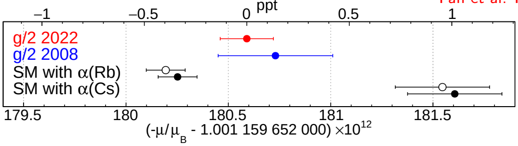
$+$ higher (loop) terms $\Rightarrow$ magnetic anomaly: $\boxed{a = \frac{g-2}{2} \neq 0}$.

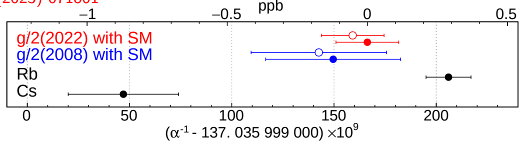
The electron a_e is **extremely well measured**: (Is it now the best measure of α?)

$$a_e = \begin{cases} 0.001\,159\,652\,181\,61\,(23) & [\text{SM}, (\alpha/\pi)^5 \text{ order}] \\ 0.001\,159\,652\,180\,46\,(18) & [\text{experiment}, 0.16\,\text{ppb}] \end{cases}$$

Aoyama, Kinoshita & Nio, Atoms **7** (2019) 1.
Mohr et al., CODATA 2022, (20-May-2024).

Fan et al. PRL 130 (2023) 071801





Until α settles, a_e cannot test the SM critically. Further, low m_e limits coupling to high-E BSM physics.

Muon magnetic anomaly, $a_\mu = \frac{1}{2}(g_\mu - 2)$

Analogous to a_e, but much more sensitive to loops with massive particles:

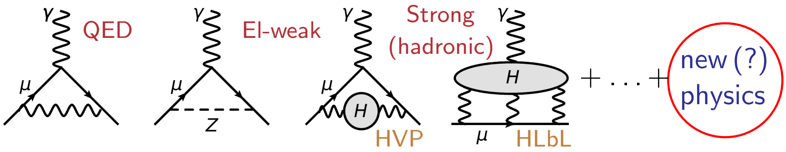
$$\boxed{\text{sensitivity} \propto (m_\mu/m_e)^2 \approx 43,000}$$

Muon magnetic anomaly, $a_\mu = \frac{1}{2}(g_\mu - 2)$

Analogous to a_e, but much more sensitive to loops with massive particles:

$$\boxed{\text{sensitivity} \propto (m_\mu/m_e)^2 \approx 43,000}$$

Leading order processes contributing to a_μ:

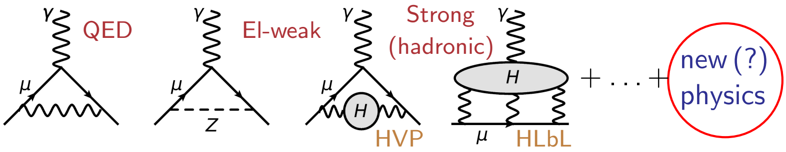


Muon magnetic anomaly, $a_\mu = \frac{1}{2}(g_\mu - 2)$

Analogous to a_e, but much more sensitive to loops with massive particles:

$\boxed{\text{sensitivity} \propto (m_\mu/m_e)^2 \approx 43,000}$

Leading order processes contributing to a_μ:



2020 status of SM calculations of a_μ:

$$\frac{\Delta a_\mu^{SM}}{a_\mu^{SM}} = 369 \times 10^{-9} \quad (369 \text{ ppb})$$

T. Aoyama, et al., Phys. Rep. **887** (2020) 1, and ref's. therein, [Muon $g-2$ Theory Initiative White Paper]

a_μ term	value ($\times 10^{-11}$)	uncert.
QED	116,584,718.931	0.104
El-weak	153.6	1.0
HVP	6 845	40
HLbL	92	18
Total SM	116,591,810	43

⇒ a_μ is a superb probe of the vacuum, i.e., of new physics if it exists.

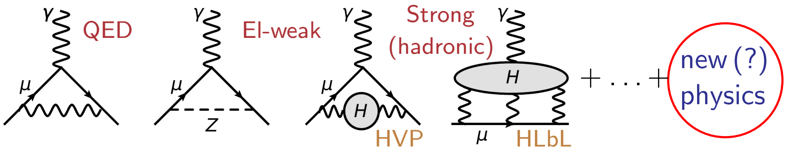
HVP . . . hadronic vacuum polarization; HLbL . . . hadronic light by light scattering.

Muon magnetic anomaly, $a_\mu = \frac{1}{2}(g_\mu - 2)$

Analogous to a_e, but much more sensitive to loops with massive particles:

$\boxed{\text{sensitivity} \propto (m_\mu/m_e)^2 \approx 43,000}$

Leading order processes contributing to a_μ:



2020 status of SM calculations of a_μ:

$$\frac{\Delta a_\mu^{SM}}{a_\mu^{SM}} = 369 \times 10^{-9} \quad (369\ \text{ppb})$$

T. Aoyama, et al., Phys. Rep. **887** (2020) 1, and ref's. therein, [Muon g−2 Theory Initiative White Paper]

a_μ term	value ($\times 10^{-11}$)	uncert.
QED	116,584,718.931	0.104
El-weak	153.6	1.0
HVP	6 845	40
HLbL	92	18
Total SM	116,591,810	43

0.6%

HVP-LO	6931(40)
HVP-NLO	−98.3(7)
HVP-NNLO	12.4(1)

⇒ a_μ is a superb probe of the vacuum, i.e., of new physics if it exists.

HVP . . . hadronic vacuum polarization; HLbL . . . hadronic light by light scattering.

Muon $g-2$ measurements up to 2001 [$\sim 3.5\sigma$ away from SM]

Exp. value dominated by results of BNL E821:

$$a_\mu^{\text{exp}} = 116\,592\,089\,(54)_{\text{stat}}\,(33)_{\text{syst}} \times 10^{-11}\text{, or}$$

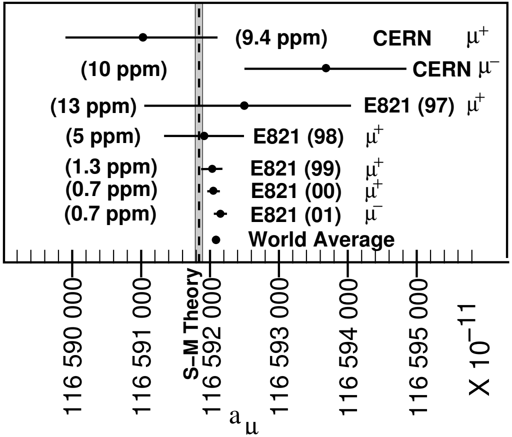
$$a_\mu^{\text{exp}} = 116\,592\,089\,(63)_{\text{tot}} \times 10^{-11}\text{, i.e., a}$$

0.54 ppm result : statistical unc. dominates .

[SM precision comparable, but $\sim 3.5\sigma$ away!]

FNAL E989 set out to improve this result:

- Use the BNL ring in a more intense beam at Fermilab: 21 $\times$ statistics of BNL E821, and
- improve key systematics
- Aim for 4$\times$ lower uncertainty, 0.14 ppm

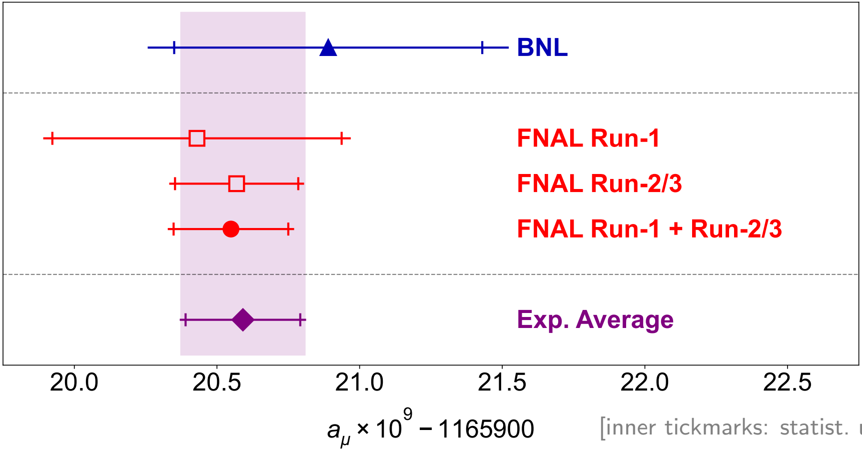


Results after E989 Runs 2/3 analysis (Aug. 2023)

New combined world average:

Aguillard et al., arXiv 2308.06230 / PRL **131** (2023) 16;
Run 2/3 full analysis: arXiv 2402.15410 / PRD **110** (2024) 032009

$$a_\mu(\mathrm{Exp}) = \mathbf{116592059(22)} \times \mathbf{10^{-11}} \quad (\mathbf{0.19}\ \mathrm{ppm}).$$

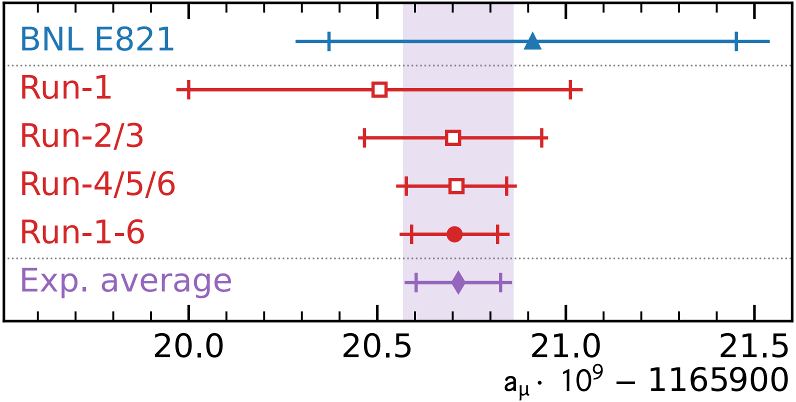


[inner tickmarks: statist. unc. only]

Results after E989 Runs 4/5/6 analysis (3 June 2025)

New combined world average: Aguillard et al., arXiv 2506.03069, submitted to PRL.

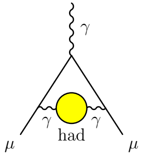
$$\boldsymbol{a_\mu(\mathrm{Exp}) = 1165920715(145) \times 10^{-12} \quad (124\,\mathrm{ppb}).}$$



[see Esra Barlas-Yucel's talk tomorrow]

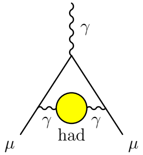
[inner tickmarks: statist. unc. only]

Calculating HVP-LO in the standard model [from exp. cross sections]



In SM, HVP is determined based on measurements of $\sigma(e^+e^- \to \text{hadrons}) \Rightarrow$ ... **timelike processes**.

Calculating HVP-LO in the standard model [from exp. cross sections]

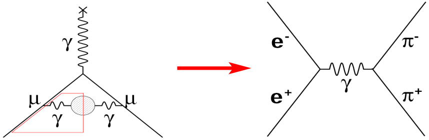


In SM, HVP is determined based on measurements of $\sigma(e^+e^- \to \text{hadrons}) \Rightarrow$ . . . **timelike processes**.

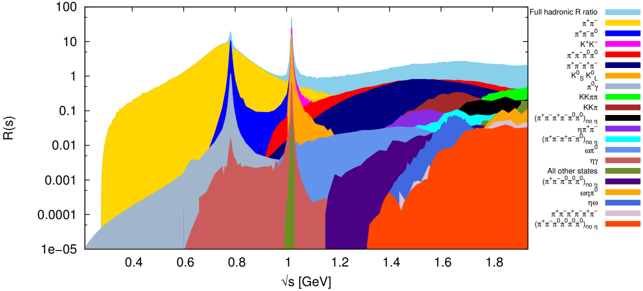
- use dispersion relations: optical theorem and analyticity,
- integral over QCD kernel $K(s)$ heavily weights low $\sqrt{s}$:

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

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



It is mostly $e^+e^- \to \pi^+\pi^-\ /\ \pi^+\pi^-\pi^0\ /\ \pi^0\gamma$; diverse measurements, in many different labs.

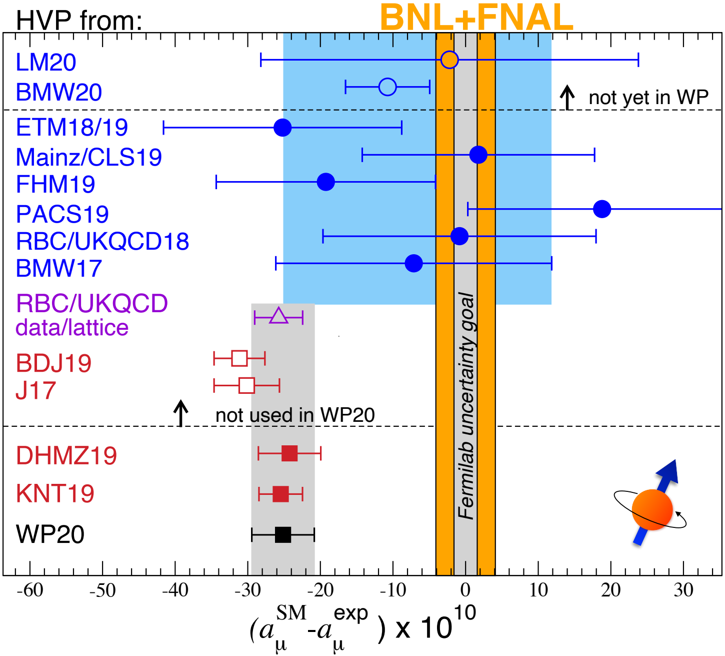


a_μ in the Standard Model

First sub-percent precision LQCD calculation of $a_\mu^{\text{HVP-LO}}$

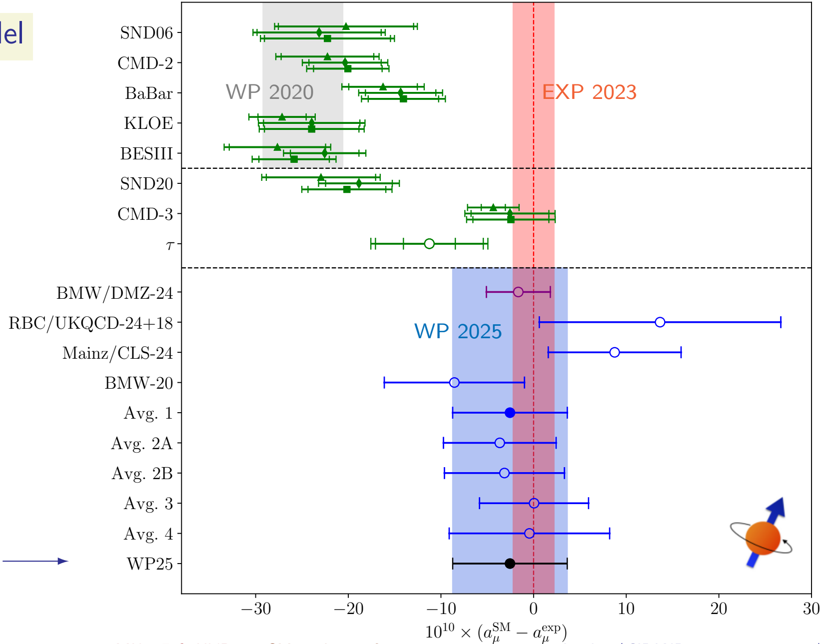
STATUS: 2020

HVP value from $g-2$ Theory Initiative 2020 White Paper [Phys. Rep. **887** (2020) 1]



a_μ in the Standard Model

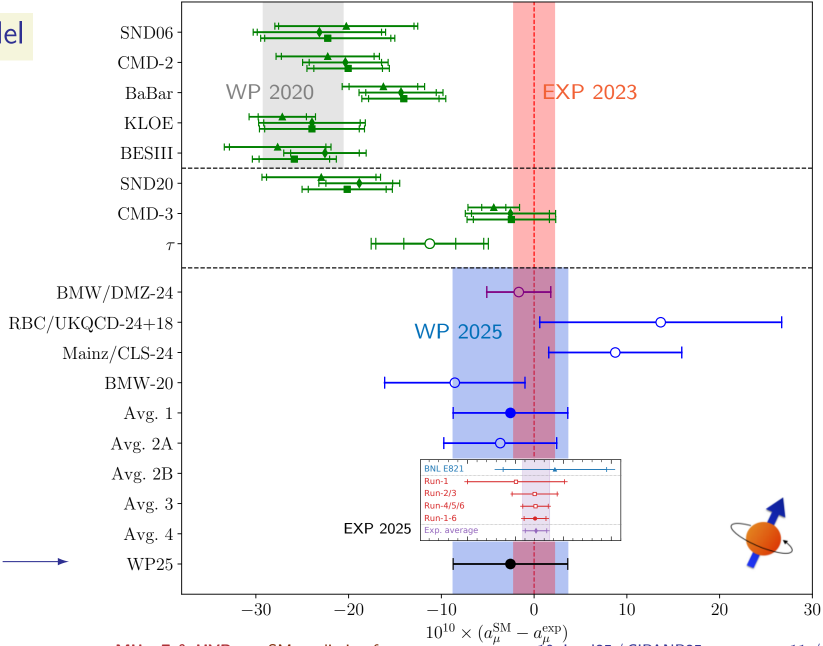
STATUS: 2025



HVP value from $g-2$ Theory Initiative 2025 White Paper [arXiv: 2505.21476]

a_μ in the Standard Model

STATUS: 2025



HVP value from $g-2$ Theory Initiative 2025 White Paper [arXiv: 2505.21476]

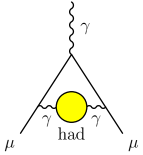
MUonE experiment at CERN:

a direct measurement of HVP-LO through muonic Bhabha scattering

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

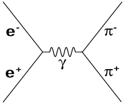
MUonE experiment: **spacelike** determination of a_μ^{HVP}

Instead of the dispersion approach:



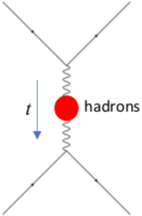
$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\mathrm{had}}(s)\,;$$

$\Rightarrow$



$\left(\begin{array}{c}\text{timelike}\\ \text{channels}\\ \text{[noisy]}\end{array}\right)$

$\Rightarrow$



we swap the s and x integrations:

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha(0)}{\pi}\int_0^1 \mathrm{d}x\,(1-x)\Delta\alpha_{\mathrm{had}}(t)\,;$$

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

Task: measure the change (running) of the eff. FS const. $\alpha(0) \simeq 1/137 \to \alpha(t)$ in a single scattering process $\mu^+ + e^- \to \mu^+ + e^-$:

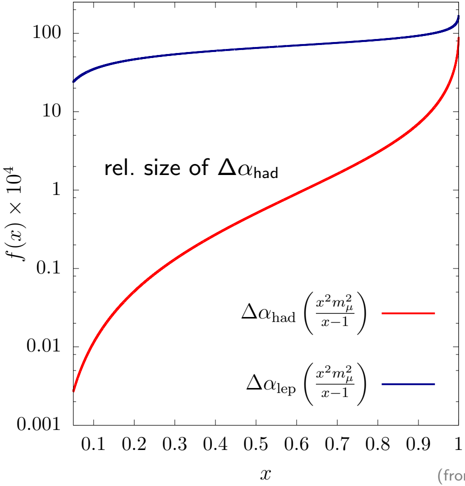
known extremely well

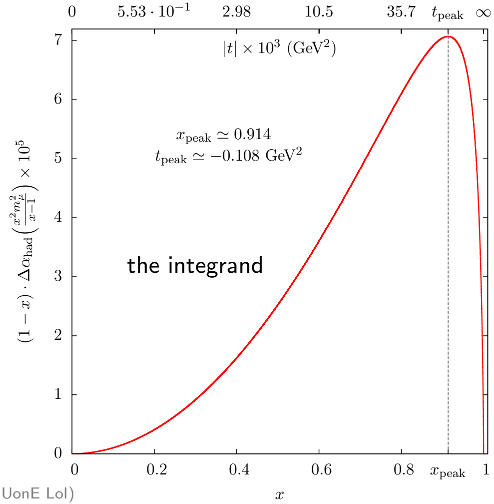
$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}, \quad \text{with} \quad \Delta\alpha = \Delta\alpha_{\mathrm{lepton}} + \Delta\alpha_{\mathrm{hadron}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{weak}}\,.$$

The sole integral is over a single well-behaved, smooth function.

Practical aspects of the measurement

Recall: $$a_\mu^{\text{HVP-LO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\Delta\alpha_{\text{had}}(t)\,; \qquad t \equiv t(x) = \frac{x^2 m_\mu^2}{x-1}$$





(from MUonE LoI)

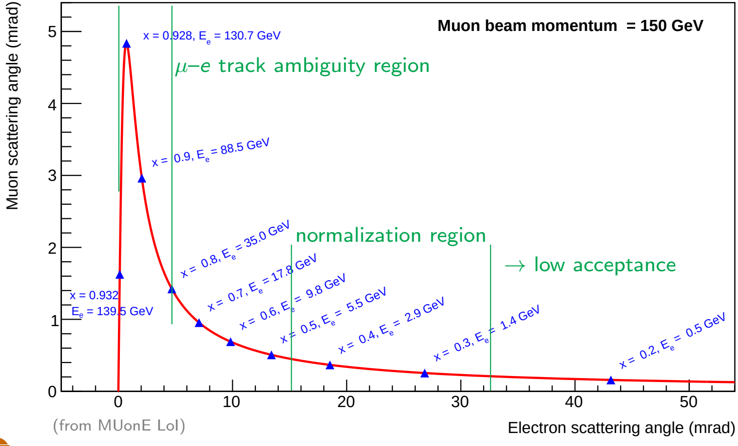
Further practical aspects of the MUonE measurement

- High-energy muon beam on atomic electrons in target
- $d\sigma \propto \alpha^2$ at leading order $\to$ a sensitive observable
- $\Delta\alpha_{\text{had}}$ extracted from **shape** $R_{\text{had}}(t)$ from $d\sigma(t)$
- Elastic events selected using correlated track angles:

from measurement

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

from Monte Carlo sim.



(from MUonE LoI)

Elastic kinematics:

- t is entirely determined by E_e: $t = (p_e^{\text{i}} - p_e^{\text{f}})^2 = 2m_e(m_e - E_e)$
- E_e from track angle and E_μ^{inc}:

$$E_e = m_e \frac{1 + r^2\cos^2\theta_e}{1 - r^2\cos^2\theta_e}$$

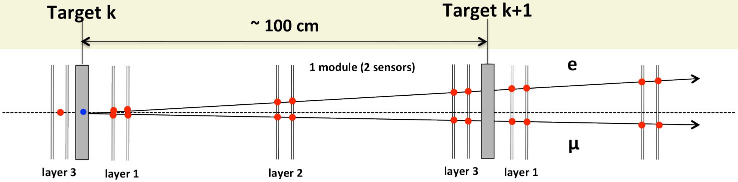
$$r = \frac{\sqrt{(E_\mu^{\text{inc.}})^2 - m_e^2}}{E_\mu^{\text{inc}} + m_e}$$

- $E_\mu^{\text{inc}} \simeq 160$ GeV muon beam
- $x < 0.936 \sim 88\%$ of integral; rest extrapolated.

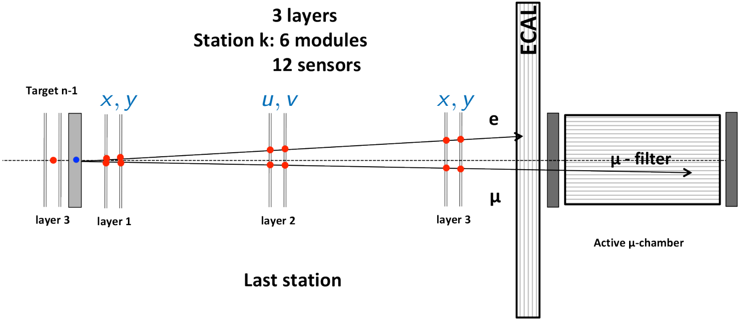
MUonE apparatus

A single tracking station:

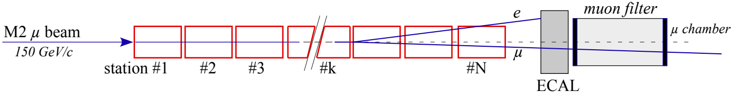
Target: 15 mm/Be or C



The last tracking station:



Full layout (extensible):



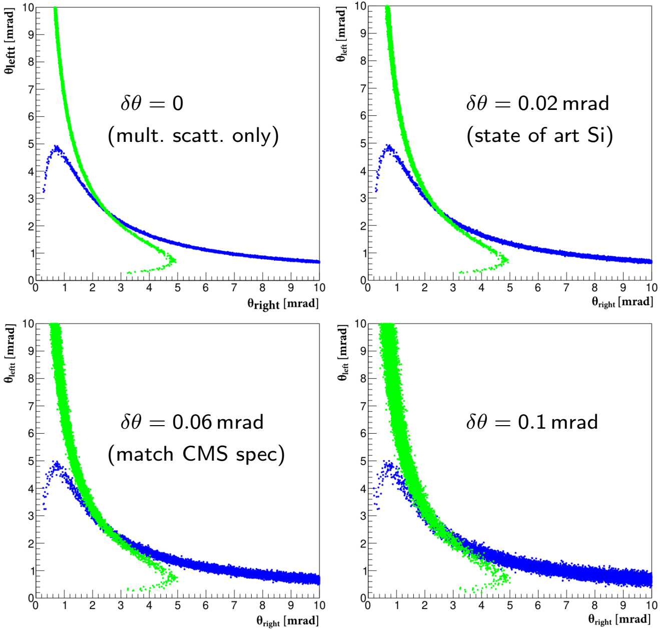
Particle ID from scat. angles alone:

simply sort left- vs. right-angle scattering;

μ-e track ambiguity region grows as $\delta\theta$ increases;

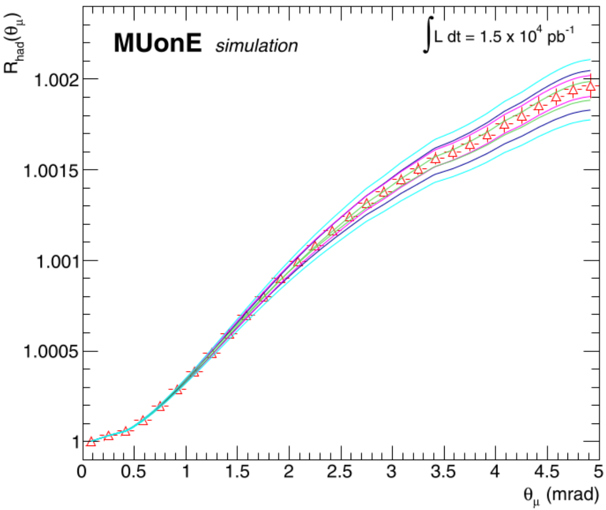
radiative processes $\mu e \to \mu e \gamma$ smear the plots $\Rightarrow$ need good $\delta\theta$ to reject radiative events.

MC simulation of elastic scattering $\Rightarrow$



MUonE analysis approach and challenges

Expected signal size:



Recall that: $R_{\text{had}}^{\text{LO}} \simeq 1 + 2\Delta\alpha_{\text{had}}$.

Critical considerations and requirements:

- θ_μ is robust – primary observable
- detector alignment & its stability
- tracking reconstruction efficiency and accuracy
- detailed understanding of detector response
- optimized cuts to eliminate bgds
- particle ID needed for systematics
- accurate simulation of all processes at goal measurement precision
- reliable event generators for higher order and radiative terms; theory support essential!: Mesmer (Pavia), McMule (PSI).

Theoretical underpinnings for the analysis

MUonE needs: Muon-electron scattering at NLO and (approximate) NNLO and results
NNLO virtual and real leptonic corrections to μ-e scattering and results

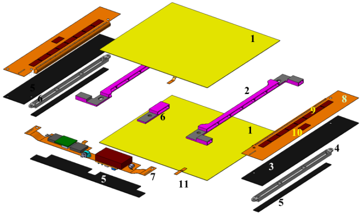
- Carloni Calame et al., PLB 746 (2015), 325
- Mastrolia et al., JHEP 11 (2017) 198
- Di Vita et al., JHEP 09 (2018) 016
- Alacevich et al., JHEP 02 (2019) 155
- Fael and Passera, PRL 122 (2019) 19, 192001
- Fael, JHEP 02 (2019) 027
- Carloni Calame et al., JHEP 11 (2020) 028
- Banerjee et al., SciPost Phys. 9 (2020), 027
- Banerjee et al., EPJC 80 (2020) 6, 591
- Budassi et al., JHEP 11 (2021) 098
- Balzani et al., PLB 834 (2022) 137462
- Bonciani et al., PRL 128 (2022) 2, 022002
- Budassi et al., PLB 829 (2022) 137138
- Broggio et al., JHEP 01 (2023) 112

- A lively theory community is active to provide state-of-the-art calculations to match the required accuracy for meaningful data analysis
- Independent numerical codes (Monte Carlo generators and/or integrators) are developed and cross-checked to validate high-precision calculations. Chiefly
  - ✓ **Mesmer** in Pavia
    `github.com/cm-cc/mesmer`
  - ✓ **McMule** at PSI/IPPP
    `gitlab.com/mule-tools/mcmule`

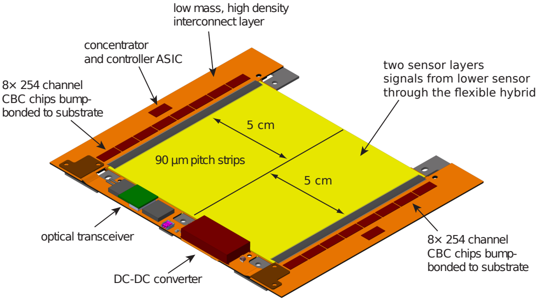
[summary from Carloni Calame, May 2023]

The physical apparatus

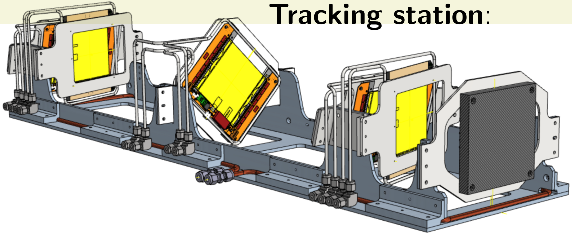
2S tracker modules:



1. 2S silicon sensors
2. Al-CF spacer
3. CF support
4. Al-CF spacer
5. CF stiffener
6. Al-CF short spacer
7. Service Hybrid
8. FE Hybrid
9. CBC
10. CIC
11. HV tab



Tracking station:

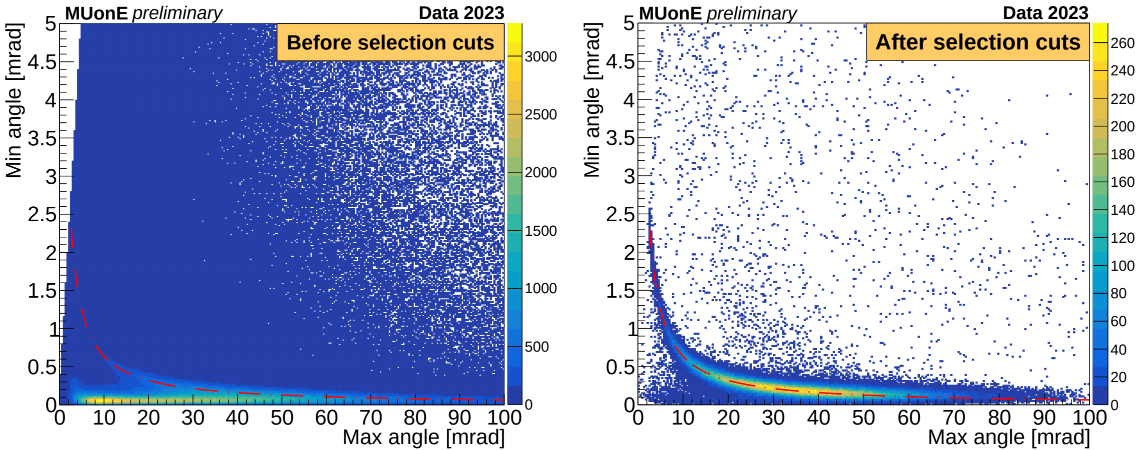


ECAL:

$PbWO_4$
$\sim 3 \times 3\text{cm}^2$
$22X_0$ long;
slightly tapered;
on loan–CMS;
$10\times10\,\text{mm}^2$ APDs
Laser gain monitoring.

MUonE test beam time results 2023 (M2 beamline, SPS/CERN, 160 GeV muons)

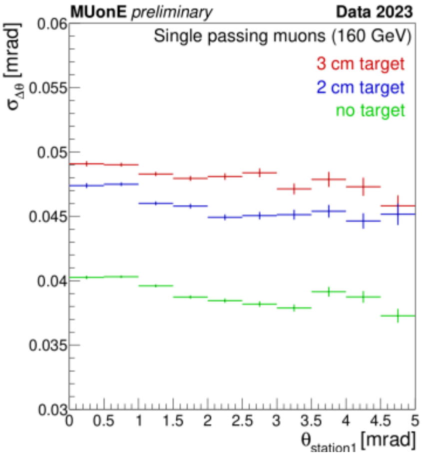
Two tracking stations and ECAL



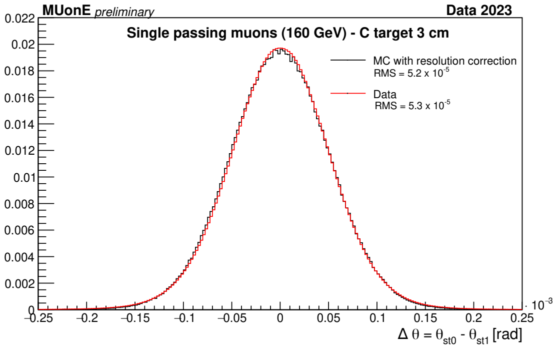
Abundant proof of principle!

Select measures of performance (preliminary)

Angular resolution (muons)



Angular resolution correction (2023 data)



- "golden" muons in 1st and 2nd station only,
- evaluate difference $\Delta\theta = \theta_{\text{st1}} - \theta_{\text{st2}}$,
- $\sigma(\Delta\theta) = \sqrt{\sigma_{ms}^2 + \sigma_{int}^2 + \sigma_{al}^2}$
- *ms*: Si and Tgt (mat. eff.); *int*: intrinsic resol; *al*: residual misalignment.

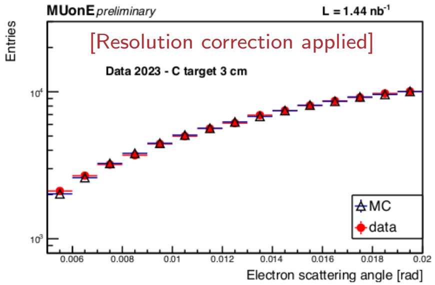
Angular distributions: scattered electrons

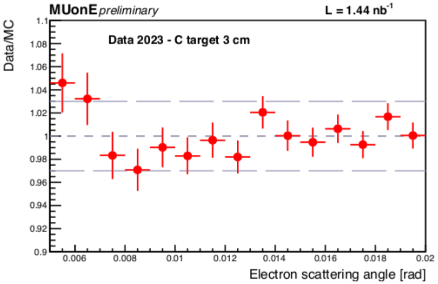
A comparison of 2023 data and MC simulation:
A look at the electron track angular resolution

$$5\,\text{mrad} < \theta_e < 20\,\text{mrad}$$

Data/MC ratio as a function of θ_e mostly contained within the gray limits of $\pm 3\%$.

Note: to ensure proper normalization of the leptonic (QED) running of $\alpha(t)$, the MC description of measured angular distributions must be accurate to $< 0.5\,\%$.



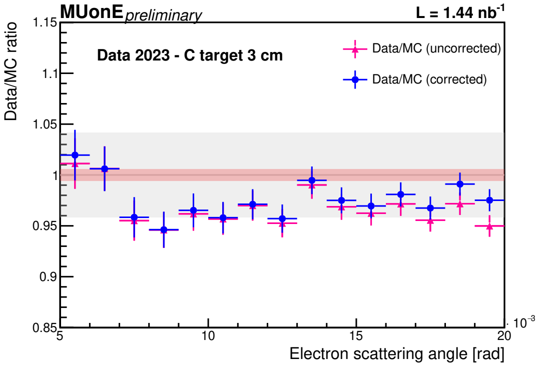


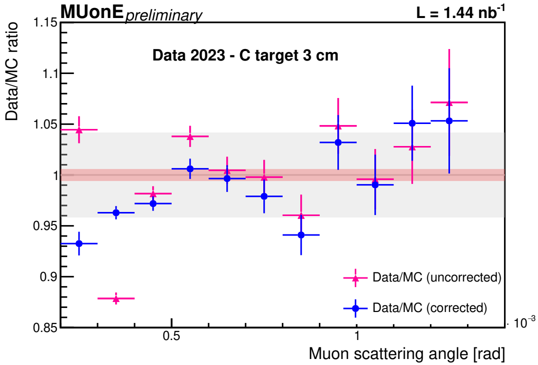
Tracking efficiency as f(scattering angle)

$5\,\text{mrad} < \theta_e < 20\,\text{mrad}$

MC normalized to Data Luminosity $\times\ \epsilon_{\text{hw}}$

Det. efficiency: $\epsilon_{\text{hw}} = 0.850 \pm 0.035$ (2 track); from module efficiency $\epsilon_{\text{mod}} \simeq 0.980 \pm 0.005$.



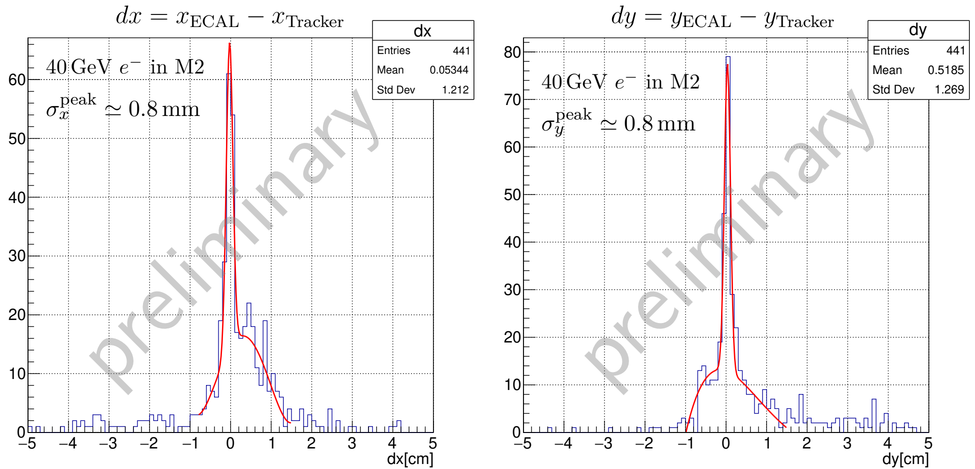


Systematic uncertainty bands:

Luminosity: $\sim$0.5% Detector: $\epsilon_{\text{hw}} \sim 5\%$

On average good agreement with ϵ_{hw}.

Tracker-ECAL position resolution

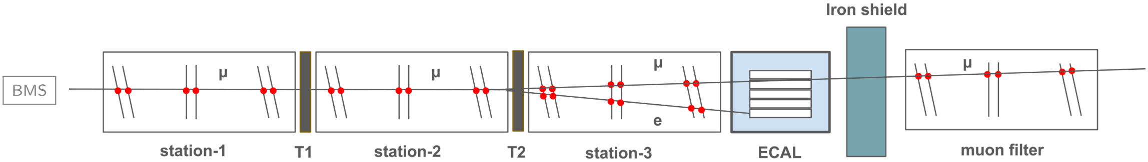


2023 data: x- and y-coordinate differences between the projected Tracker impact points on the ECAL front face, and the reconstructed el-mag shower centers, for synchronised Tracker-ECAL events. Gaussian peaks ($\sigma_{x,y} \simeq 0.8\,\mathrm{mm}$), are consistent with Monte Carlo simulations of the setup. Work in progress.

MUonE goals, status and plans

[LS3 = long accel. shutdown at CERN]

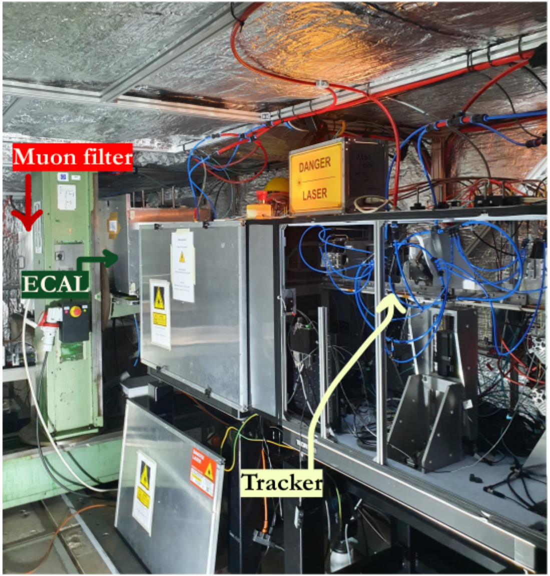
- Long-term goal (post LS3): 40 stations × 3 yrs. of data collection, yielding
  - $1.5 \times 10^7\ \mathrm{nb}^{-1}$, 10 ppm stat. unc. on $\sigma(t)$ measurement at peak of integrand function,
  - $\sim 0.3\%$ on $a_\mu^{\text{HVP-LO}}$ ... competitive with other methods.
- Proof of MUonE measurement principle has been established.
- Full technical proposal approved by CERN SPSC in 2024 for a 2025 interim run.
- 2025 run: 3 tracking st., ECAL, BMS, MF × 4 wks of beam → $\sim 20\%$ on $a_\mu^{\text{HVP-LO}}$, a first physics result before mid-2026 (start of LS3, 3-yr CERN accelerator shutdown):



Phase 1 Run: on the floor in M2/SPS, summer 2025

Fully deployed for the first time:

- 3 tracking stations,
- ECAL,
- a Muon filter prototype,
- a Beam Momentum System (BMS) prototype,
- fully configured Serenity-based DAQ,



Current status, prospects, experimental path forward

- Fermilab E989 Muon $g-2$ final result has exceeded its stated goal and improved a_μ precision by $\sim 4.4\times$ compared to BNL E821.
- While there is no tension w.r.t. LQCD calculations, profound questions surround the dispersion-relation SM evaluation $a_\mu^{\text{HVP-LO}}$, and the underlying data set on $e^+e^- \to$ hadrons.
- MUonE at CERN offers a unique, completely independent way to determine $a_\mu^{\text{HVP-LO}}$.
- E34 at J-PARC will measure a_μ with different systematics from E989, but with far lower event statistics.

With the target, high experimental precision of a_μ achieved, the focus remains on getting a deeper understanding of the HVP!

The current MUonE collaboration

Experimental groups:

INFN Pisa
INFN Bologna
INFN Padova
INFN Università di Perugia
INFN Università di Trieste
University of Rijeka
IFJ PAN Kraków
Imperial College London
Liverpool University
J. Gutenberg Universität Mainz
University of Virginia
Regis University
Northwestern University
Cornell University

Theoretical groups:

Università di Padova
Università di Pavia
Paul Scherrer Institute
Universität Zürich
ETH Zürich

New collaborators are warmly encouraged!