The MUonE experiment at CERN:

a determination of hadronic vacuum polarization $\Delta\alpha_{\mathrm{had}}$ through scattering

Dinko Počanić, (for the MUonE collaboration)

Institute for Nuclear and Particle Physics, University of Virginia

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Venice, Italy,
29 – 31 May 2023

Outline of this talk

Motivation: unresolved issues concerning the muon magnetic anomaly

Basic measurement approach of MUonE

Proposed analysis method

Experimental method, apparatus and collaboration

Precision goals and future plans

Lepton magnetic dipole moments, and the associated anomaly

Our story begins with Dirac's result for a point particle g-factor, defined by $\vec{\mu} = g\frac{e}{2m}\vec{S}$, i.e., $\boxed{g \equiv 2}$, precisely. Quantum fluctuations give rise to the anomalous magnetic moments:

$$a = \frac{g-2}{2} \neq 0.$$

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For example, the electron magnetic anomaly is **extremely well reproduced by QED**:

$$a_\mathrm{e} = \begin{cases} 0.001\,159\,652\,181\,61\,(23) & [\mathrm{SM},\ (\alpha/\pi)^5\ \mathrm{order}]^* \\ 0.001\,159\,652\,181\,28\,(18) & [\mathrm{experiment},\ 0.16\,\mathrm{ppb}]^\dagger \end{cases} \quad ; \ \text{agreement:} \ \sim 1.1\sigma$$

insensitive to massive particle loops ($\Rightarrow a_\mathrm{e}$ provides an alternative measurement of α_em)
We therefore focus on $\boldsymbol{a_\mu}$ as it is much more sensitive than a_e to massive loops.

* Aoyama, Kinoshita & Nio, Atoms **7** (2019) 1.

† Mohr et al., CODATA 2018, posted online 20 May 2019, to be published.

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

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

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

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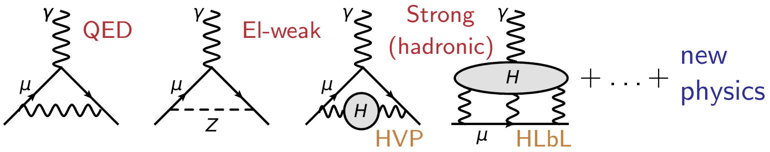
Leading order processes contributing to a_μ:



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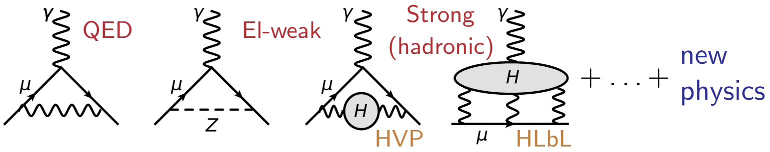

Current status of SM calculations of a_μ:

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

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.

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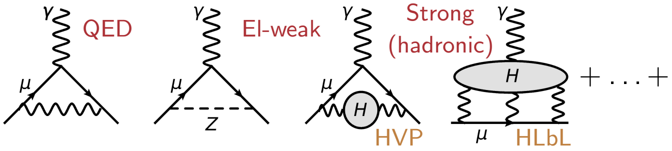

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HVP-LO	6931(40)
HVP-NLO	−98.3(7)
HVP-NNLO	12.4(1)

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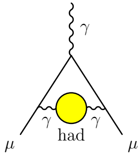
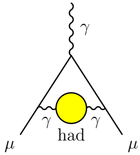


In SM, HVP is determined based on measurements of $\sigma(e^+e^- \to \text{hadrons}) \Rightarrow$ . . . **timelike processes**.

Calculating HVP-LO in the standard model



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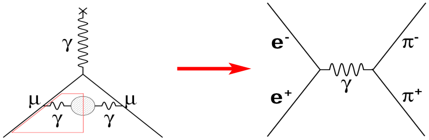
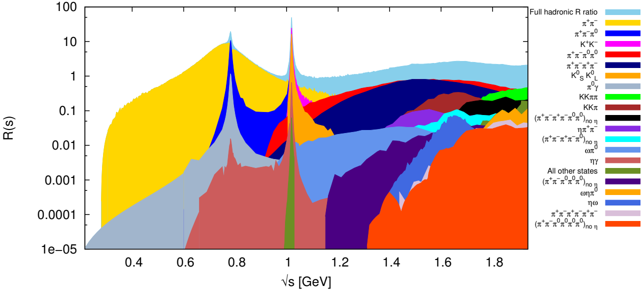


- use dispersion relations: optical theorem and analyticity,
- integral over QCD kernel $K(s)$ heavily weights low $\sqrt{s}$:

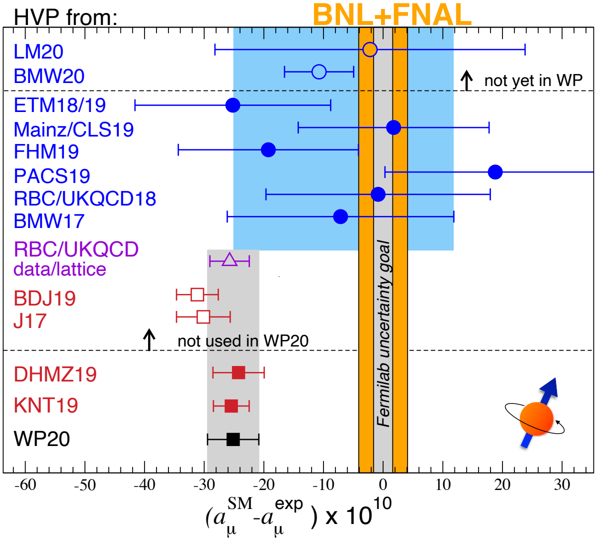
$$a_\mu^{\text{HVP-LO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\text{had}}(s)\,;$$

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

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



Present status of the hadronic vacuum polarization

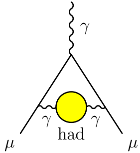


[from Snowmass 2022, arXiv:2203.15810]

Strong impetus for a completely new measurement approach provided by:

- persistent discrepancy between experimental and Standard Model determinations of a_μ, and
- the arguably unsatisfactory status of the HVP-LO contribution,

$\Rightarrow$ **MUonE**.

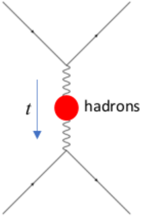


Instead of the dispersion approach:

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

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

$\Rightarrow$



we swap the s and x integrations:

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

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

The task is reduced to a measurement of the change (running) of the effective fine structure constant $\alpha(0) \simeq 1/137 \to \alpha(t)$ in a single scattering process $\boldsymbol{\mu + e \to \mu + e}$:

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

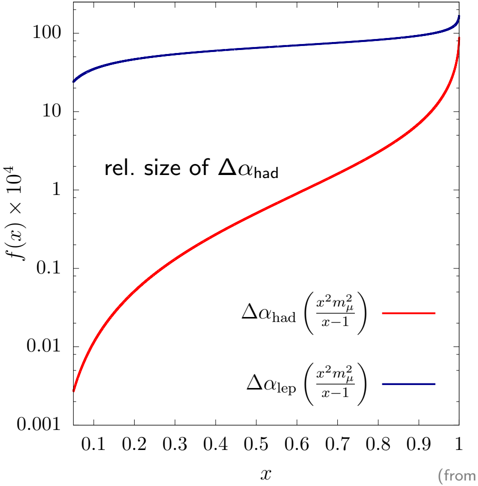
where all terms except $\Delta\alpha_{\mathrm{hadron}}$ are known extremely well.

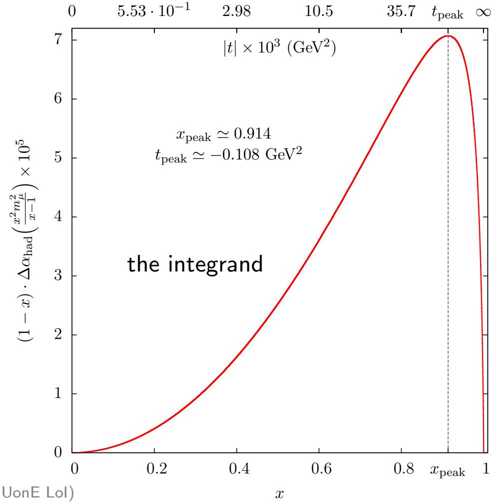
The sole integral is over a well-behaved, smooth function.

MUonE will measure hadron-related changes in the running of α in scattering of μ^+ on e^-.

Practical aspects of the measurement

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





(from MUonE LoI)

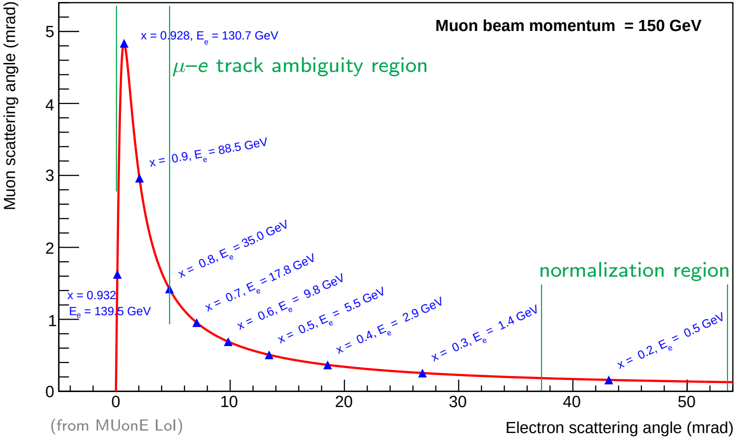
Further practical aspects of the measurement

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

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

from measurement

from Monte Carlo sim.



(from MUonE LoI)

Elastic kinematics:

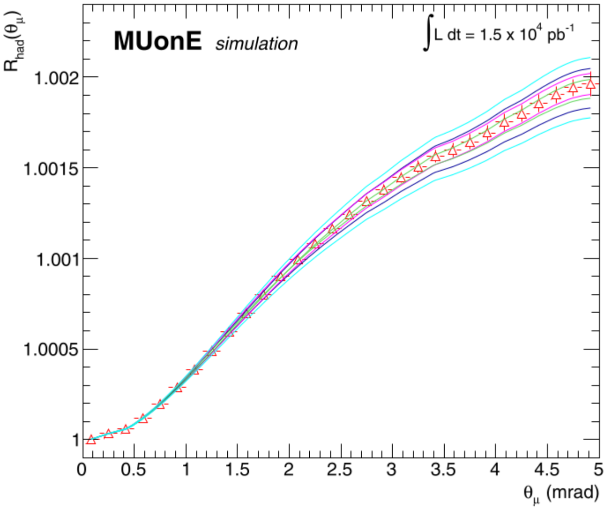
- t is entirely determined by E_e: $t = (p_e^{\rm i} - p_e^{\rm f})^2 = 2m_e(m_e - E_e)$
- E_e from track angle and $E_\mu^{\rm inc}$:

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

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

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

Expected signal size:



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

Critical considerations:

- 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 useful, not indispensable
- accurate simulation of all processes at goal measurement precision
- reliable event generators for higher order and radiative terms

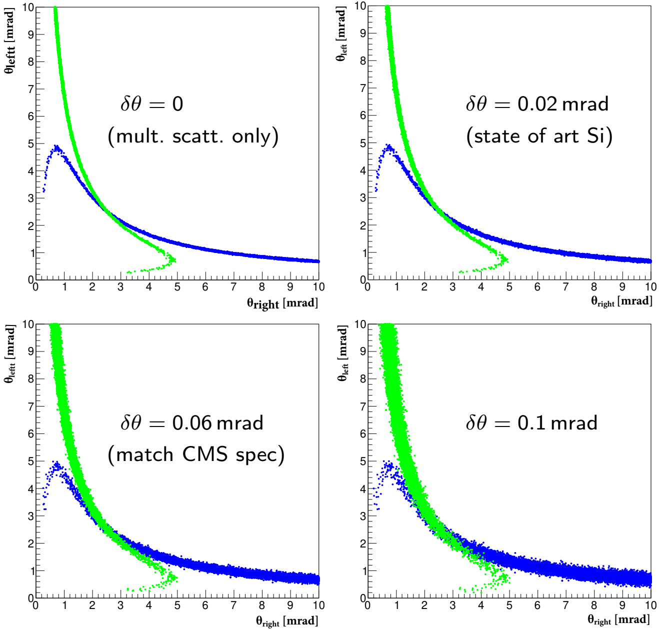
Particle ID from scattering angles:

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 $\Rightarrow$



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]

Mesmer Monte Carlo event generator

1. Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini
   Muon-electron scattering at NLO, JHEP 02 (2019) 155
2. Carloni Calame, Chiesa, Hasan, Montagna, Nicrosini, Piccinini
   Towards muon-electron scattering at NNLO, JHEP 11 (2020) 028
3. Budassi, Carloni Calame, Chiesa, Del Pio, Hasan, Montagna, Nicrosini, Piccinini
   NNLO virtual and real leptonic corrections to muon-electron scattering, JHEP 11 (2021) 098
4. Budassi, Carloni Calame, Del Pio, Piccinini
   Single π^0 production in μe scattering at MUonE, PLB 829 (2022) 137138

End result: the "template" fit

✓ Everything implemented in the **`Mesmer`** Monte Carlo event generator

Muon Electron Scattering with Multiple Electromagnetic Radiation

and also a 18th-century *alchemist and astronomer!*

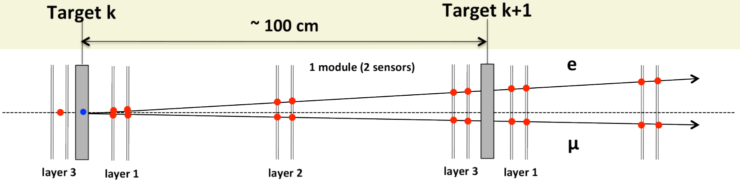
`github.com/cm-cc/mesmer`

[from Carloni Calame, May 2023]

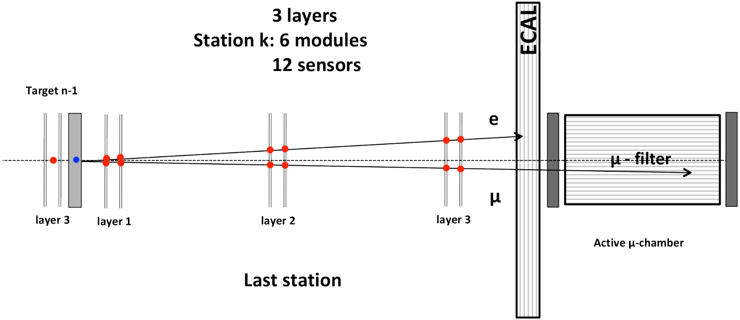
MUonE apparatus

A single tracking station:

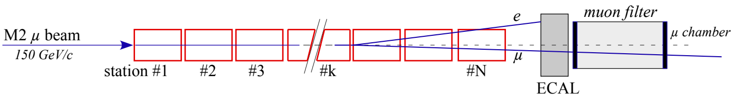
Target: 15 mm/Be or C



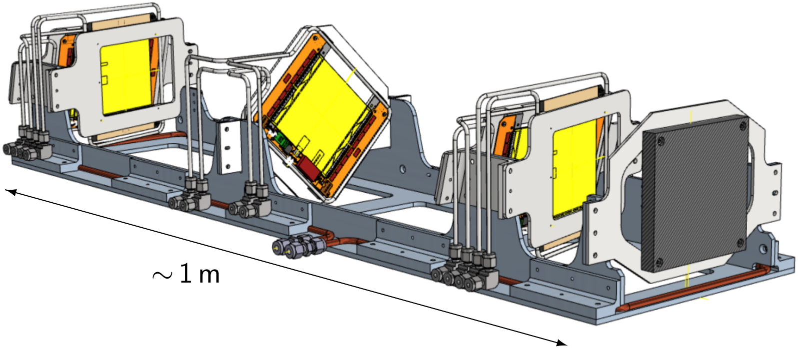
The last tracking station:



Full layout (extensible):

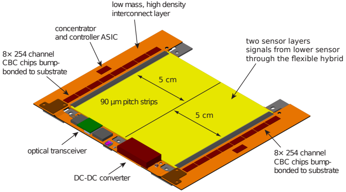


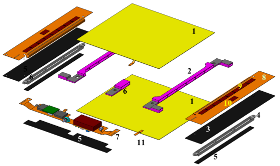
MUonE tracking stations



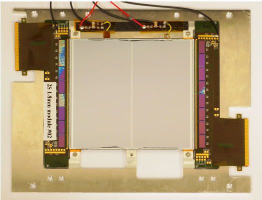
- 3 pairs of LHC 2S silicon strip modules
- modules may be tilted to reduce effective pitch; effect on alignment under study,
- frames made from Invar Fe/Ni alloy to maintain dimensional stability within 10 μm,
- monitored by holographic laser system (see below),
- temperature controlled environment.

The CMS 2S Si-strip modules



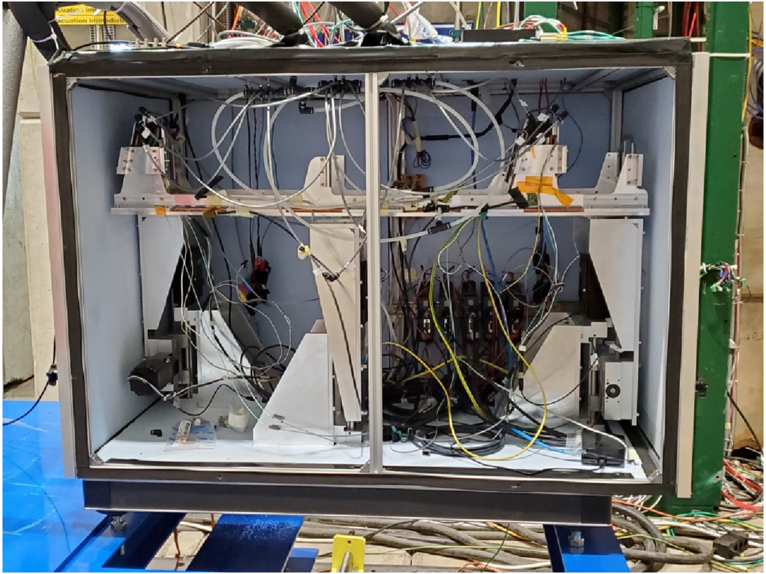


1. 2S silicon sensors
2. Al-CF spacer
3. CF support
4. Al-CF spacer
5. CF stiffener
6. Al-CF short spacer
7. Service Hybrid
8. FE Hybrid
9. CBC
10. CIC
11. HV tab

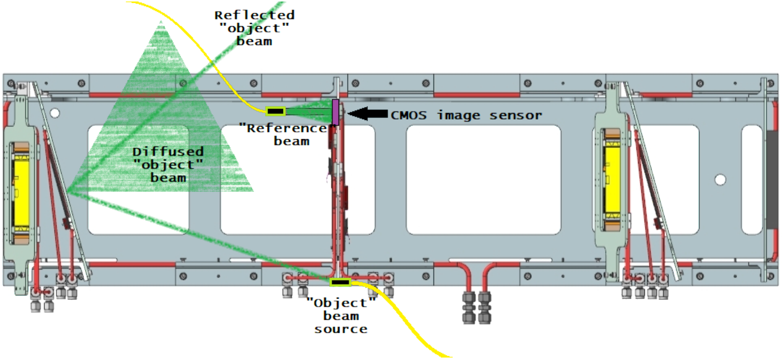


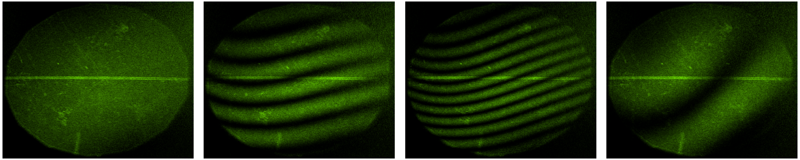
- "2S" Si strip prototypes for the outer CMS HL-LHC upgrade largely satisfy CMS requirements; MUonE needs differ:
  - continuous high rate of asynchronous particles;
  - high alignment precision and high tracking resolution ;
- $10 \times 10\,\mathrm{cm}^2$ active area; $320\,\mu$m thick; $90\,\mu$m strip pitch;
- 2 planes for one coordinate 1.8 mm apart to reject backgrounds and large-angle tracks;
- significant delivery delays (component shortages) are impacting MUon goals schedule [Pisa, Bruxelles, soon Fermilab];
- under consideration: option to use one sensor only per plane, i.e., "1S" (?).

MUonE tracking station in experimental hall



Holographic alignment monitor (HAM)





(a) (b) (c) (d)

Time-dependent interferometry by digital superposition of raw holographic images taken at different time t. Sensors must be off for HAM DAQ.

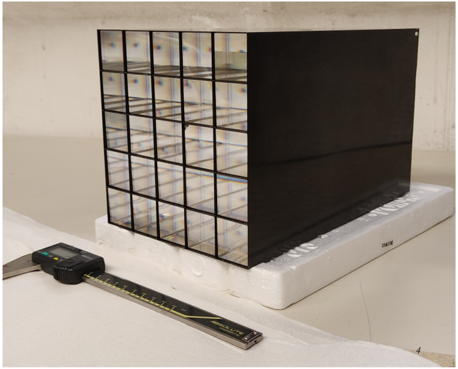
Displacements of the object, due to temp. changes, produce interference fringes modulo $(\lambda/2)$.

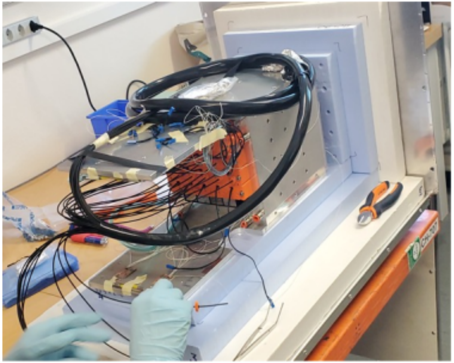
$\Leftarrow$ a sequence of four HAM recordings over a 24h period.

[INFN Trieste]

ECAL in MUonE

A filter to select elastic events by breaking the e-μ track ambiguity; check on E_{dep} inferred from track angles.





- Lead tungstate ($PbWO_4$) crystals lent by CMS: $2.85 \times 2.85\,\text{cm}^2$, 22 cm long ($25X_0$), read out by APDs.
- Current array is 5×5 crystals; final size of ECAL is under study.
- Assembled and characterized in dedicated test beam run in July 2022; used in October 2022 M2 test run with trackers; test runs scheduled in June and Sept. 2023.

MUonE test beam runs: past and future

Several test runs **with beam** were carried out since 2017, with part, or all, of the main MUonE components.

Most notable:

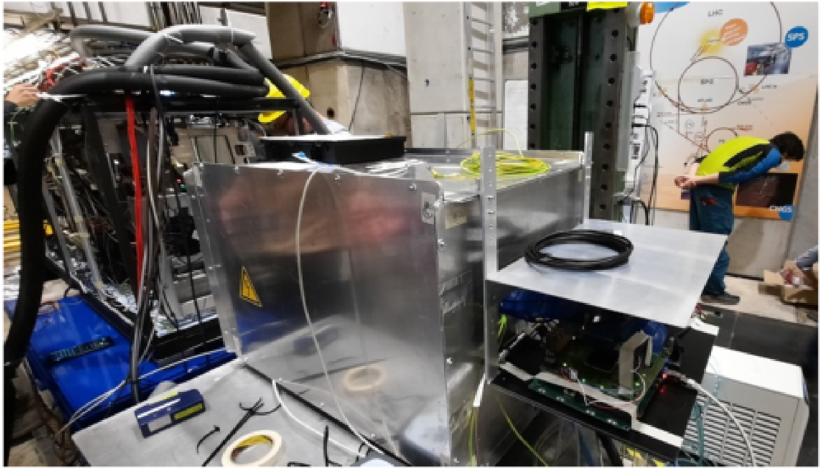
- July 2022: first in-beam test of fully assembled ECAL, in a dedicated week in the T9 test beamline,
- October 2022: first combined in-beam test of **a tracking station and ECAL**, in the M2 beamline, in a mix of primary user (one week) and occasional short periods in parasitic mode (during COMPASS running).

Much analysis of the data acquired in test-runs has been done, with focus on understanding and optimizing the fundamentals of detector response, resolution, noise, cuts, etc.

A joint publication with CMS will eventually present details of the relevant performance parameters of the 2S modules.

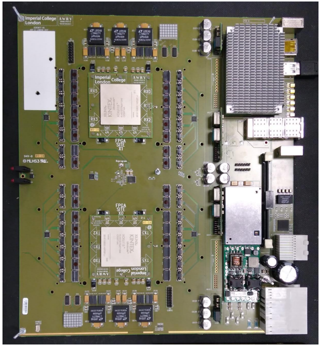
October 2022 test run

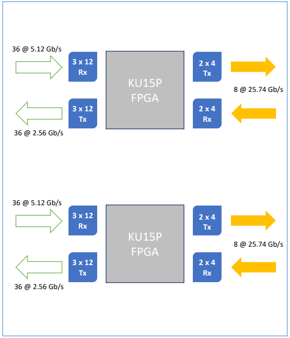
- one week as primary user;
- one full tracking station + ECAL calorimeter;
- detector and DAQ operated at high beam rate of up to $2.8 \times 10^8\ \mu$/spill;
- many important insights gleaned.



Data acquisition system

At the heart of DAQ is the **Serenity** ATCA[1] **development platform** intended for use primarily in CMS, with two FPGA daughter cards mounted on interposers. ⇒





Serenity will also handle MUonE ECAL data.

A number of significant developments of the system remain, in order to make it meet MUonE requirements for data rate/volume, event processing and reduction at the FPGA level, etc.

The DAQ system remains under intense study and continued active optimization.

[1] Advanced Telecommunications Computing Architecture standard

The current MUonE collaboration

Experimental groups:

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

Theoretical groups:

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

New collaborators are warmly invited!

Goals and future plans

- Long-term goal: 40 stations $\times$ 3 years of data collection, which yields
  - $1.5 \times 10^7\ \mathrm{nb}^{-1}$,
  - 10 ppm statistical uncertainty on $\sigma(t)$ measurement at peak of integrand function,
  - $\sim 0.3\%$ on $a_\mu^{\text{HVP-LO}}$... competitive with other methods.
- Medium term goal: 10 stations $\times$ 4 months of data collection $\to \sim 2\%$ on $a_\mu^{\text{HVP-LO}}$, a first physics result before 3-year CERN accelerator shutdown starting in 2026.
- Systematics to be controlled at the 10 ppm level, including on the shape. Principal sources:
  - detector alignment, especially longitudinal,
  - multiple scattering,
  - intrinsic tracker angular resolution,
  - muon beam energy.
- Past and planned test runs are demonstrating feasibility of this novel attempt to resolve the Muon $g-2$ anomaly,
- A full technical proposal is under preparation; completion planned for 2024.