The **MUonE project:**

Measuring the running of $\alpha(t)$ in the space-like region

A proposal for measuring $\alpha_\mu^{\text{HLO}}$ contribution from

$\mu + e \rightarrow \mu + e$ elastic scattering

Clara Matteuzzi
SPSC 21/01/2020

On behalf of the MUonE Collaboration
Physics motivations

Tools to perform the measurement

Request for a pilot run

Plans and tentative timeline

Relevant documents:
MUonE LETTER OF INTENT: http://cds.cern.ch/record/2677471
CERN-SPSC-2019-026, SPSC-I-252

Original article reference:
1. Will measure the running of $\alpha_{em}$ in the space-like region, accessing the leptonic and hadronic contributions

$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\text{lept}}(t) - \Delta\alpha_{\text{had}}(t)}$$

testing QED at unprecedented precision (collaboration with theorists is fundamental)

2. In the context of $(g-2)_{\mu}$, the measurement of the hadronic contribution to the running of $\alpha$ with MUonE is completely independent and complementary to the time-like method, and will make the theoretical expectation more precise
Physics motivations (the running of $\alpha$)

**Time-like evaluation**

$$a_{\mu}^{HLO} = \left( \frac{\alpha m_{\mu}}{3\pi} \right)^2 \int_{4m_{\pi}^2}^{\infty} ds \frac{\hat{K}(s) R_{\text{had}}(s)}{s^2}$$

**Space-like approach**

$$a_{\mu} = \frac{\alpha}{\pi} \int_0^1 dx (1 - x) \Delta\alpha_{\text{had}}(t(x)) \frac{1}{|t|} (10^{-3} \text{ GeV}^2)$$

Time-like evaluation

- Physics motivations
- Space-like approach

$\hat{a}_{\mu}^{HLO}$ is the total area under this curve.
The muon $g-2$ is measured with high precision:

$$a_{\mu}^{\text{exp}} = 116592089(63) \times 10^{-11}$$

G.W.Bennet et al. (Muon g-2 Phys.Rev.D73 (2006)072003

It shows a long standing $\approx 4\sigma$ deviations from the Standard Model prediction:

$$a_{\mu}^{\text{SM}} = 116591783(35) \times 10^{-11}$$

(F.Jegerlehner, MITP Workshop, 19-23 February 2018, Mainz)

$$\Delta a_{\mu} (\text{exp} - \text{SM}) = (306 \pm 72) \times 10^{-11}$$

- New Physics?
- Systematics of the measurement?
- Systematics of the theoretical prediction?

The accuracy of the SM prediction is limited by strong interactions effects.

The present error on the leading order hadronic contribution to muon $g-2$

$$\delta a_{\mu}^{HLO} \approx 4 \cdot 10^{-10}$$

constitutes the main uncertainty of the SM predictions.
Why $\mu + e \rightarrow \mu + e$?

$\mu$ scattering on atomic electrons looks an ideal process:

- It is a pure $t$-channel process:

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha} \right|^2$$

**Differential cross section sensitive to running of $\alpha$ and in particular to the hadronic component $\alpha^{HLO}_\mu$**

- A high intensity ($\sim 1.3 \times 10^7 \mu/s$) muon beam is available in the North Area at CERN with $E_{\text{beam}} \sim 150$ GeV

- The high boosted kinematics allows to access the full kinematic range with small transverse dimension

$$-0.143 \lesssim t < 0 \text{ GeV}^2 \quad 0 < x \lesssim 0.93 \quad \Rightarrow \text{(it spans the peak)}$$

- The same detector can cover **signal** ($x > 0.4 - 0.5$) and **normalization** ($x \leq 0.3$) regions
The constraint is useful to select elastic events, reject background and reduce systematics in $t$ determination around 2-3 mrad $\mu$ and $e$ overlap, to be resolved by $\mu/e$ identification.

Multiple scattering breaks the correlation: simulation and data will help to optimize the detector and reduce the systematics.
A high energy muon beam *(must cover the $t$ range needed)*
the beam M2 at CERN has the characteristics ($E_\mu \approx 150$ GeV, $\sim 1.3 \times 10^7 \mu/s$)
adequate for such a measurement.

The target: atomic electrons must be provided by a light material,
to minimize the e.m. interactions inside the target, but at the same time must provide a high enough number of target electrons
Berillium (or eventually Carbon)

The detector setup:
- A modular target made by 40 layers of Be (C) 15 (10) mm thick, sandwiched in layers of Si tracking planes.
- Need to measure very precisely the angles of the outcoming muons and electrons (to exploit kinematical correlation of the $\mu$-e collision)
- Need to know precisely the direction of the incoming muon
- A simple Particle IDentification (e.m. calorimeter and muon system) will be necessary
Sketch of the final apparatus *(not on scale)*:

40 ‘independent’ stations will provide 60 cm Be target material.
Possible location of at CERN M2

- **Between BSM and COMPASS** *(Studies by J. Bernhard and D. Banerjee)*

1. μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

   - More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)

   - Questions: will require displacements (also removal) of some M2 components.

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m
**M2 Beam parameters for MUonE** (from Dipanwita B., sept 2019)

Need a ‘large’ and ‘parallel’ (=small divergence) beam

Very low divergence

- \( \sigma_x = 1.3 \text{ cm} \)
- \( \sigma_y = 2.2 \text{ cm} \)
- \( E_\mu = 160 \text{ GeV} \)
- \( 0.23 \text{ mrad} \)
- \( 0.24 \text{ mrad} \)
The tracker must provide:
- A very good angular resolution ~ 20 μrad
- High uniformity
- Capable to sustain high rate ~50 MHz

All the Si planes and the electronics will be provided by the CMS Upgrade-II project

Characteristics of the CMS 2S Modules comply with the requirements
Thickness: 2 × 320 μm
Pitch: 90 μm → $\sigma_x = 26 \, \mu m$
Area: 10 cm × 10 cm

The electronics (CBC3 chips) and DAQ (Serenity boards) are also from the R&D of CMS

R/O by 16 CBC3 (8 per side) each reading 254 strips
Efficiency = 99.988 ± 0.008 (CERN-LHCC-2017-009)
Particle Identification based on ECAL is important when both the angles are in the region of 2.5 mrad and $\theta_\mu \sim \theta_e$

Measuring the electron energy would enable:
- Triggering on the calo energy (in OR with the track trigger).
- Performing background studies with data
- Determining the electron (angle, energy) relation
- Checking possible bias, systematic effects, related to the tracks selection.

Calorimeter type is still under study

(philosophy is to recycle existing and working technologies, if possible)

Present ideas are to have
- an Inner ECAL of $\sim 40 \text{ cm} \times 40 \text{ cm}$ of PbWO$_4$ crystals
- an Outer ECAL extending up to $\sim 100 \text{ cm} \times 100 \text{ cm}$ with same/other crystals with ex-OPAL lead glass (rather large size 9.5x9.5 cm) or new PbWO$_4$ new crystals (GEANT4 simulation study under way)
2017: study of Multiple Scattering of electrons of 12 and 20 GeV in H8 area

The study has been concluded with the paper

“Results on multiple Coulomb scattering from 12 and 20 GeV electrons on carbon targets”

published on JINST 15 (2020) P01017

2018: study of $\mu$-e $\rightarrow \mu$-e elastic events

~6 months running with several different configurations,
3 different kinds of calorimeters.

~2M triggers with one target and a PbWO4 crystal calorimeter.

Analysis in progress
Testbeam in 2017 (Multiple Scattering study)

Dedicated test in H8 with electron beams and UA9 apparatus (7 $\mu$m intrinsic resolution)

JINST 15 (2020) P01017

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets

G. Abbiendi$^{d,}$, J. Bernhard$^{d,}$, F. Bettini$^{b,}$, M. Bonanomi$^{d,}$, C. M. Carloni Calame$^{a,}$, M. Garattini$^{b,}$, Y. Gavrilmov$^{d,}$, G. Hall$^{d,}$, F. Iacoangeli$^{b,}$, F. Ignatov$^{d,}$, M. Incaglio$^{b,}$, V. Ivanchenko$^{b,}$, F. Ligabue$^{d,}$, T. O. James$^{d,}$, U. Marconi$^{d,}$, C. Matteuzzi$^{d,}$, M. Passera$^{a,}$, M. Pesaresi$^{d,}$, F. Piccinini$^{d,}$, R. N. Pilato$^{a,}$, F. Pisani$^{b,}$, A. Principe$^{b,}$, W. Scandale$^{b,}$, R. Tenchini$^{b,}$, and G. Venanzoni$^{b,}$

12 GeV electrons, 8 mm graphite
Comparison DATA/GEANT

data/MC

12 GeV electrons, 20 mm graphite
DATA/GEANT

$\theta_{in} - \theta_{out}$ (mrad)
• The setup was located downstream COMPASS 
  *(behind the Tungsten hadrons filter)*

• **Aim to measure** $\mu - e$ *elastic scattering*
  • *Using muons from pions decays (hadron beam) with an estimated beam momentum* $p = (187\pm7)$ GeV
  • *To measure the correlation between the scattering angles: muon angle vs the electron angle;*
  • *Electron energy vs the electron angle correlation and PID.*

• **The detector consists of:**
  – Tracking system: stations equipped with the AGILE silicon strip sensors: 400 micron thick, single sided about 40 $\mu$m intrinsic hit resolution.
  – Electromagnetic calorimeter: 3x3 crystals matrix (CMS PbWO4) $25X_0$, 9.9 cm$^2$
**Testbeam in 2018**

Setup located in the North Area behind the COMPASS detector

**Muon Distribution Downstream (D)**

- **Muon Momentum**

(Courtesy from D. Banerjee)

Beam profile as seen by the upstream planes (y and x)
Testbeam in 2018

40µm hit resolution
~0.100 mrad angular

$\theta_\mu$ vs $\theta_e$

Elasticity curve: beam momentum at 187 GeV

Tracking algorithm applied.
~ 2 million incoming muons in the chosen configuration

→ ~8600 reconstructed events with wanted topology
~ 1500 after all cuts on Vx and acoplanarity

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The challenge for MUonE will come from the main issue to control the systematic error at the same level as the statistical one.

Tools to do the measurement

**Strategy:**

- measure $\Delta\alpha_{\text{had}}(t)$ in the reachable experimental kinematic range determined by $E_\mu$

- get large $x$ values from theory (pQCD, lattice)

- get the integrand function and the value of $\alpha_H^{\text{LO}}$ and $a_\mu$

(A non exhaustive list of syst contributions....)

**Acceptance**
- Efficiencies and corrections (from trigger, selection, ...)
- Effects of the $E_e$ energy cut
- Background subtraction and background modelling (from data as much as possible)
  *It requires a implementation in GEANT4 of the major background processes (pair production and bremsstrahlung)*

**Uncertainty in the location of interaction vertices** (will be inside the target but also in the Si planes)
**Uncertainty in the muon beam momentum scale** (see next slide)
**Effects of Multiple Scattering:** first results in 2020_JINST_15_P01017

The pilot run will give first and fundamental information on the experimental systematics intrinsic in the detector design.
Measuring the incoming beam mean energy $<E_\mu>$

- Sensitivity to the hadronic contribution as a function of the $<E_\mu>_\text{in}$ mean energy for the full integrated luminosity.

- Determine the $<E_\mu>_\text{in}$ from the energy-angles relation around the equal angle condition

$$\theta_{eq} \simeq \sqrt{\frac{2m_e}{P_{beam}}}$$

**corresponding to 2.5 mrad at 150 GeV** → $\theta = \theta(E_\mu) = \frac{1}{2}(\theta_1 + \theta_2) = 2-3\text{mrad}$

- $\chi^2$ test comparing $\theta$ distribution of simulated data samples *(templates)* to the measurement

$\chi^2(E_\mu)$ scan with $10^6$ events

$\sim 40$ hours needed to collect $10^6$ events with a single MUonE’s station

minimum at $150.000\pm0.002$ GeV
QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group)


First results obtained for the NNLO box diagrams contributing to \(\mu\)-e scattering in QED (Padova group):

M. Fael, arXiv:1808.08233;
M. Fael, M. Passera arXiv:1901.03106;

resummation (effects beyond fixed-order perturbation theory) and mass effects including the electron mass (PSI group) → differential cross section (A. Signer, Y. Ulrich)

An unprecedented precision challenge for theory: a full NNLO MC generator for \(\mu\)-e scattering (10⁻⁵ accuracy) → International efforts under way, a report is in preparation
The MUonE Pilot Run

In the LoI, the MUonE requests the M2 beam

- **Location:**
  upstream COMPASS after the Beam Momentum Station (BMS)

- **3 weeks at the end of 2021** *(due to the Si planes availability)*
  ➡️ to run with 2 full stations in the configuration:

  ![Incoming muon tracking diagram](image)

  ➡️ the apparatus will be in a thermalized volume
  at the end of the 2 stations, a calorimeter ~ 20x20 cm² under study

The pilot run should provide ~ 10⁸ elastic events
Ongoing studies and test for the mechanics

In September 2019 105 keuro were granted for 2020 by the INFN committee (mainly for mechanics study and test) for the preparation of a Pilot Run in 2021.

Special attention in the mechanics studies is put in having an easy and quick roll-in and roll-out system (expected ~1 day).
The aims of the Pilot Run (*quoted from the LoI*):

### 13.2 Pilot run motivations

Aim of the Pilot Run is to demonstrate the validity of the design and the operation of the MUonE project. The main objectives are:

- Confirm the system engineering, i.e. assembly, mounting and cooling;
- Assessing the detector counting rate capability;
- Checking the signal integrity in the process of data transfer for the DAQ;
- Proving the validity of the trigger-less operation mode;
- Evaluate the FPGA real-time processing, to distinguish muons passing stations without interacting, to demonstrate the ability to identify and reconstruct $\mu - e$ events in real time.
- Testing the procedure for the alignment of the sensors: tools and methodology;
- Monitoring mechanical and thermal stability;

If good data taken ($\mathcal{O}(10^8)$ elastic events) *they will be used to perform a test measurement of the leptonic contribution $\Delta \alpha_{\text{lept}}$ to the running of $\alpha$.*

*The accurate evaluation of the experimental systematics on this parameter, will give the information on the potentiality of the detector design on the final measurement.*
The measurement of $\Delta\alpha_{\text{lept}}$ with the pilot run data

Very preliminary!

$\delta\Delta\alpha_{\text{lept}} \approx 6\%$ with Pilot run data

Fit with

$\Delta\alpha_{\text{lept}} = A + B \times \log(t/t_0)$

$t_0 = -0.0015$
**Tentative time profile schedule**

**If the Pilot Run will validate** the design and the performance, then MUonE will request (a *very* tentative schedule...):

- **2022** Some time (*of the order of 4 weeks*) with ½ of the apparatus towards the end of the running time (due to availability of the Si modules and their mounting/aligning on the supports)

- **2023 – 2024** Consistent time of running to collect as much statistics as possible. The total amount of necessary statistics corresponds to ~ 10^7 s of running time (*~3 years assuming the present parameters of the M2 at 150 GeV*)

The beam requests are related to the scheduled delivery by CMS (*has to produce/test the full tracker apparatus, 280 Si modules*):
- 50% of stations by spring **2022**
- 50% of stations by end of **2022**

Need to collect ~ 3.5 x 10^{12} elastic events with E_e> 1 GeV to achieve a statistical error of ~0.3 %
Status of MUonE

🌟 15 institutions *(12 exp, 3 only theory)*

🌟 Collaboration still under construction

  II Collaboration meeting on 12-13 February 2020 at CERN

🌟 Approval of the pilot run will help to make real and operative the expressions of interest from several groups

The Letter of Intent has been submitted to the SPSC on 6\textsuperscript{th} June 2019: [https://cds.cern.ch/record/267747?ln=it](https://cds.cern.ch/record/267747?ln=it)

We have been assigned three referees: M.Bona, A. Ferrari and U. Wiedemann

On the 30\textsuperscript{th} September we presented the financing request to the INFN committee, for the preparation of a Pilot Run in 2021. 105 keuro were granted for 2020 *(mainly for mechanics study and test)*.
INFN Bologna
G. Abbiendi, L. Capriotti, G. Galli, U. Marconi, C. Patrignani, A. Principe,

INFN Firenze
G. Sguazzoni,

Imperial College, London
J. Borg, K. Uchida, G. Hall, A. Howard, M. Pesaresi,

Krakow IFJ Pan
M. Baszczyk, P. Dorosz, M. Kucharczyk, M. Witek, M. Zdybal,

INFN Milano Bicocca
A. Broggio, C. Matteuzzi, M. Paganoni, M. Soldani, L. Trentadue,

Budker Institute, Novosibirsk
S. Eidelman, I. Logashenko, F. Ignatov,

INFN Padova
A. Bragagnolo, E. Conti, S. Di Vita, M. Fael, S. Laporta, P. Mastrolia, G. Ossola,
P. Paradisi, M. Passera, M. Presilla, A. Primo, P. Ronchese, U. Schubert, G. Simi,
F. Simonetto, R. Stroili, W.J. Torres-Bobadilla,

INFN Pavia
C. Carloni Calame, M. Chiesa, G. Montagna, O. Nicrosini, F. Piccinini,

INFN Pisa
G. Bagliesi, C. Ferrari*, M. Incagli, F. Ligabue, F. Palla, R.N. Pilato, P. Spagnolo, R. Tenchini,
G. Venanzoni, P. G. Verdini,

INFN Trieste
G. Cantatore, M. Karuza,

Shanghai Jiao Tong University
L. Li,

Paul Scherrer Institute
A. Signer, Y. Ulrich

University of Dublin
M.K. Marinkovic,

University of Liverpool
T. Bowcock, K. Rinnert, T. Teubner,

University of Virginia
D. Pocanic

CERN
D. Abbaneo, J. Bernhard, D. Banerjee, S. Mersi
Conclusions

We propose to measure $\mu e \rightarrow \mu e$ scattering in the space-like region with the existing CERN North Area $\mu$ beam and a detector which should not require R&D for new technologies.

The experiment is very challenging from the experimental point of view considering the systematic uncertainty which must be achieved.

The MUonE collaboration presents a request for a pilot run in 2021 to assess in the best and convincing way possible the validity of the setup design and feasibility of the measurement. A first measurement of the leptonic contribution to the running seems possible with the first collected data.
Approach: space-like evaluation

\[ |t| \ (10^{-3} \text{ GeV}^2) \]

\[ \Delta \alpha_{\text{lep}} \]

\[ \Delta \alpha_{\text{had}} \]

Very small contribution!

\[ x_{\text{peak}} \approx 0.914 \]

\[ t_{\text{peak}} \approx -0.108 \]

\[ \Delta \alpha_{\text{had}}(t_{\text{peak}}) = \mathcal{O}(10^{-3}) \]

integrand function: \((1 - x) \Delta \alpha_{\text{had}}(t(x))\)

is the total area under this curve.
Approach: space-like evaluation

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

\[ t(x) = -\frac{x^2 m_{\mu}^2}{1 - x} \]

\[ t = \begin{cases} 
0^- & \text{for } x \to 0^+ \\
-\infty & \text{for } x \to 1^- 
\end{cases} \]

\[ \alpha(t) = \frac{\alpha}{1 - \Delta \alpha_{\text{lept}}(t) - \Delta \alpha_{\text{had}}(t)} \]

★ Strategy:
- measure \( \Delta \alpha_{\text{had}}(t) \) in the reachable experimental kinematic range determined by \( E_\mu \)
- get large \( x \) values from theory (pQCD, lattice)
- get the integrand function and the value of \( a_{\mu}^{\text{HLO}} \)
To be competitive with the current evaluations, $\Delta \alpha_{\text{had}}(t)$ needs to be measured at the % level.
Testbeam in 2018

$\theta_\mu$ vs $\theta_e$ correlation

Effect of the resolution with GEANT4

Signal (elastic) Background (pair production)

7 µm (2017 TB)

40 µm (2018 TB)

Final detector MUST have the best resolution possible to be achieved with a Si tracker

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Monitoraggio olografico della distanza e della posizione relative tra i piani di tracciamento

- Materiale ottico di base per l’equipaggiamento di una “station” di prova
  - laser 532 nm (P~mW)
  - 2x fibre ottiche multimodo
  - 2x beamsplitter (BS)
  - 4x specchi
  - 2x sensori CCD

![Diagram](image)