Status of the MUonE experiment

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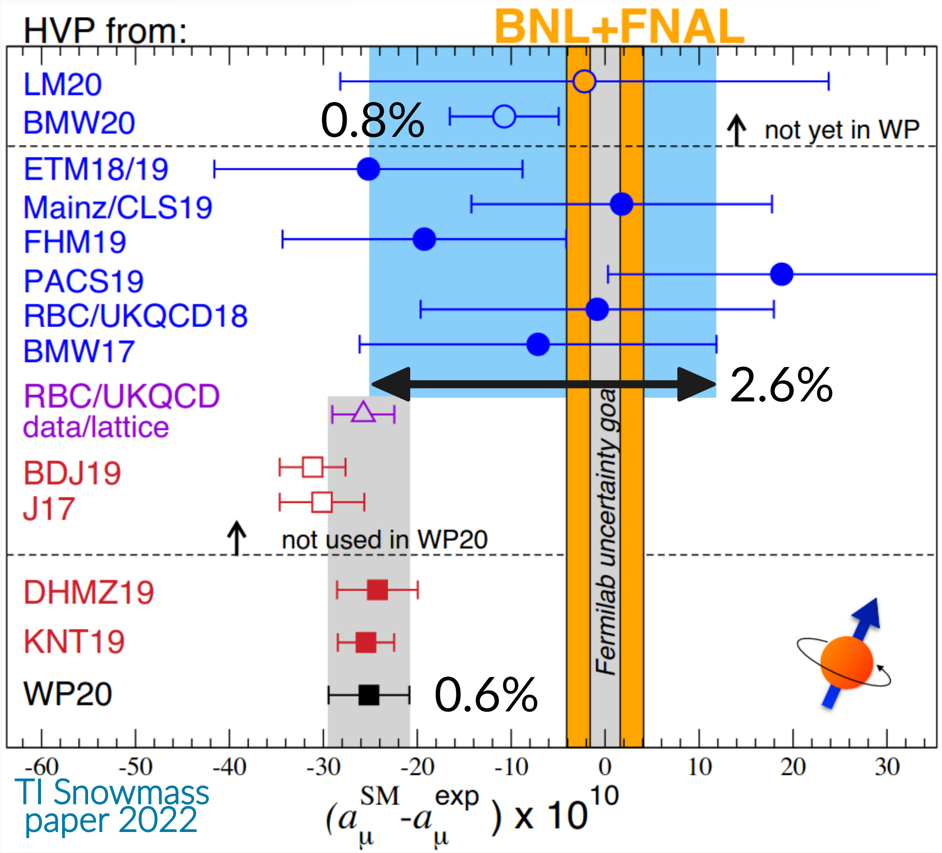
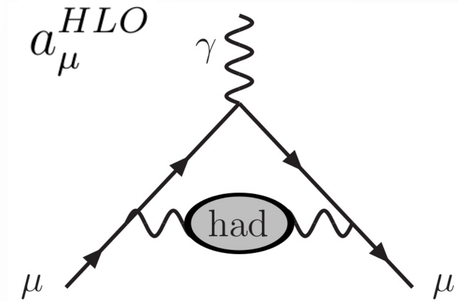
for the MUonE Collaboration

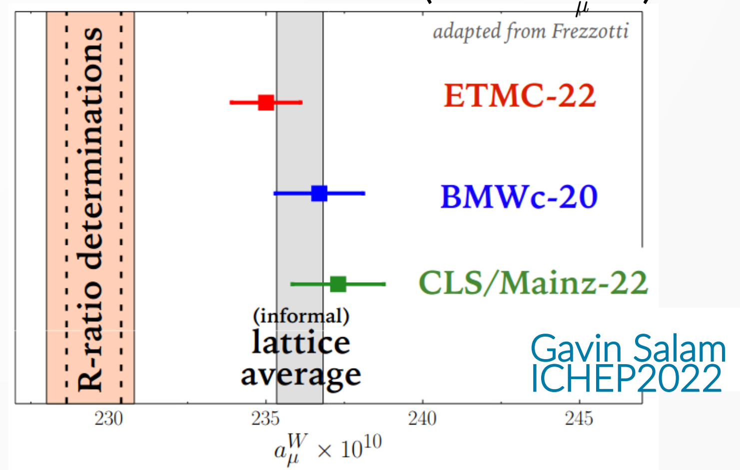
The 13th International Workshop on e^+e^- collisions from Phi to Psi
Shanghai, 16th August 2022

a_μ^{HLO} : present status





New lattice results in the intermediate window (~30% a_μ^{HLO}):



"Further insights into these connections will be provided by another complementary method for HVP, which is expected to become available over the next years at the MUonE experiment". (TI Snowmass paper 2022)

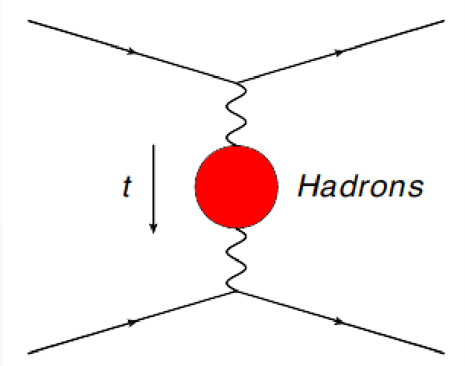
a_μ^{HLO} : space-like approach

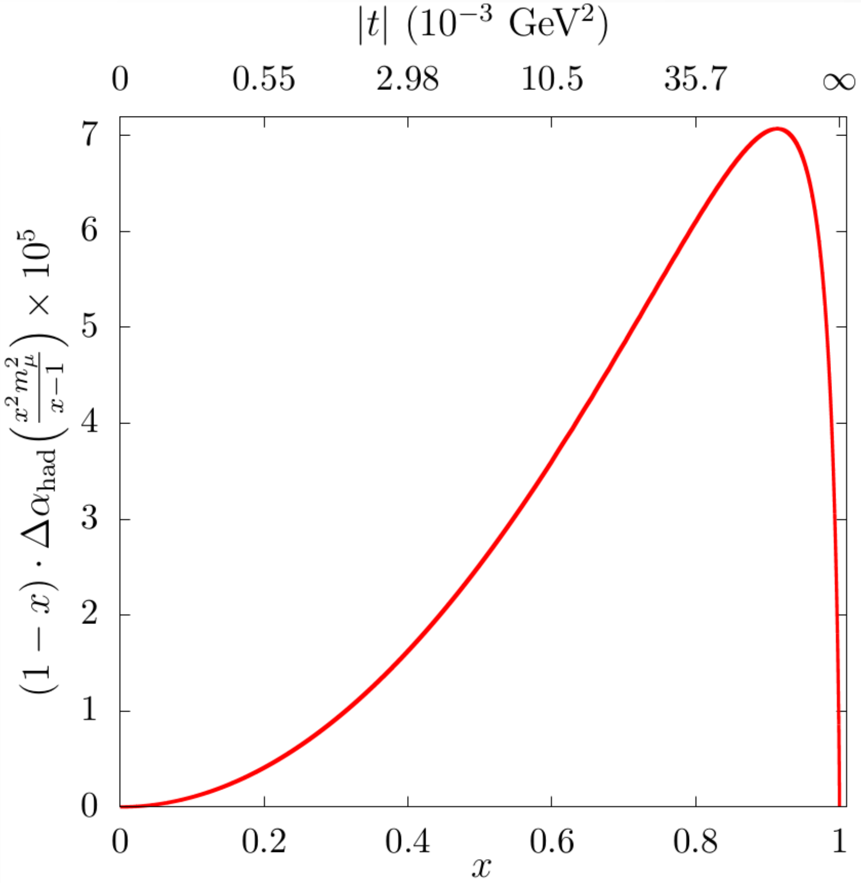
MUonE: a new independent evaluation of a_μ^{HLO}

$$\boxed{a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]}$$

Lautrup, Peterman, De Rafael, Phys. Rep. C3 (1972), 193

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



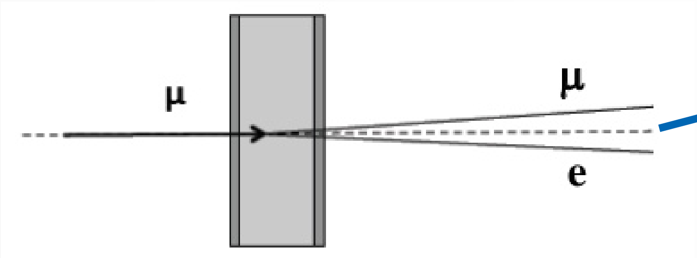


Carloni Calame, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015), 325

Based on the measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.

The MUonE experiment

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

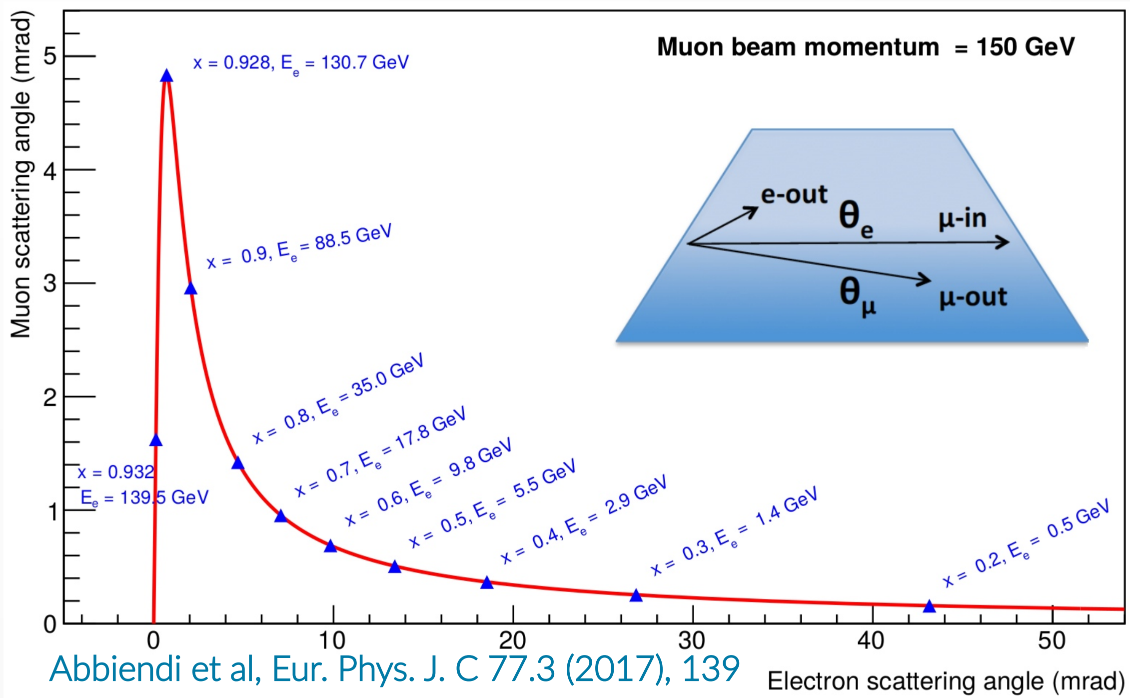


$$\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$

From theoretical calculation

To be measured

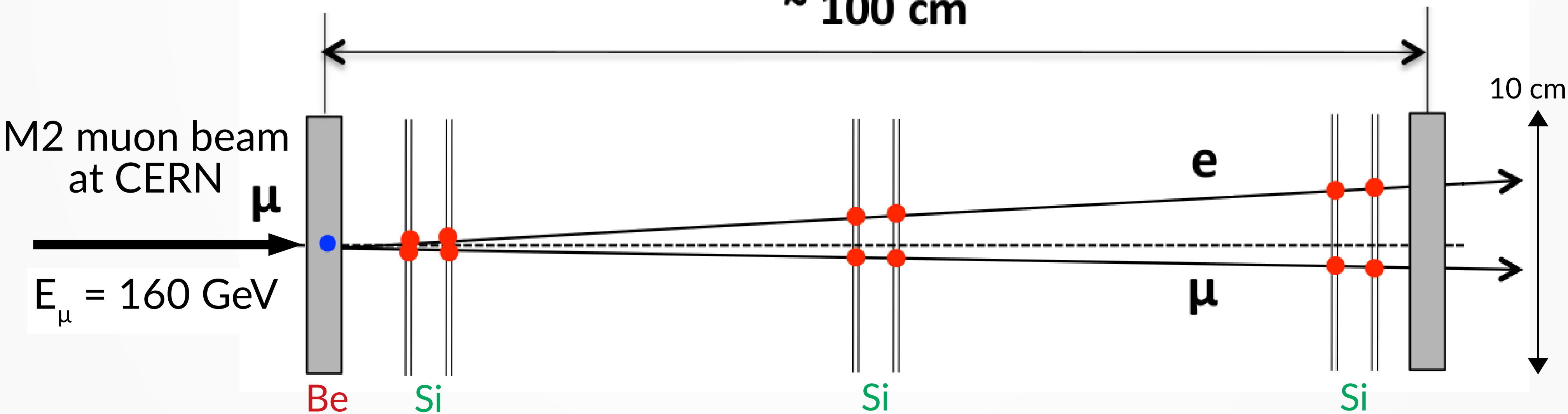
- A beam of 160 GeV muons allows to get the whole a_μ^{HLO} (87% directly measured + 13% extrapolated).
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics:
  $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

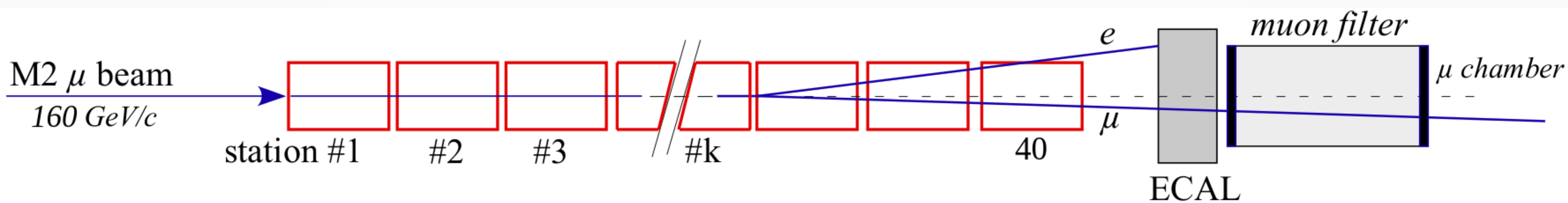
The experimental apparatus

Letter of Intent: The MUonE Project, SPSC-I-252



Beryllium target
1.5 cm thickness

Tracking system: 3 pairs of silicon strip detectors



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking ($\sim 4\text{x}10^7$ s) ($I_\mu \sim 10^7\ \mu^+$/s) $\sim 4\text{x}10^{12}$ events with $E_e > 1$ GeV = $\boxed{\sim 0.3\%\ \text{statistical accuracy on } a_\mu^{HLO}}$

Competitive with the latest theoretical predictions.

Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm at the peak of the integrand function (low θ_e, large θ_μ)

Main systematic effects:

- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)
- Angular intrinsic resolution (few %)

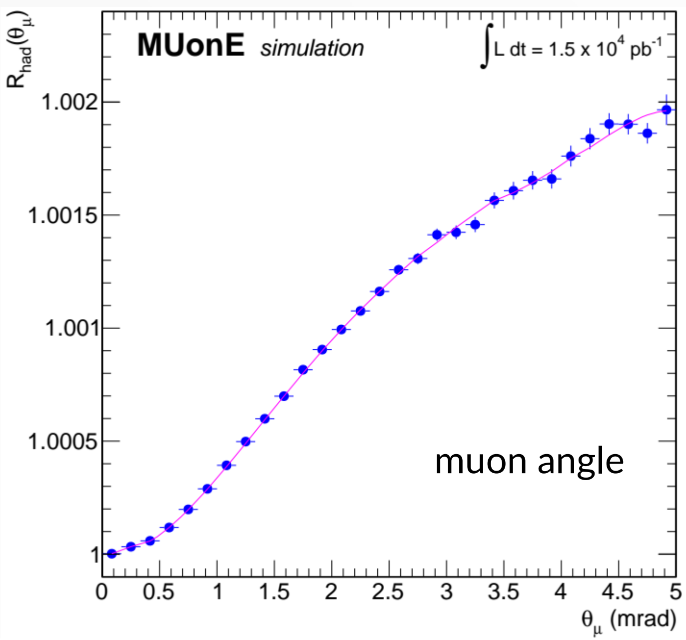
Extraction of a_μ^{HLO}

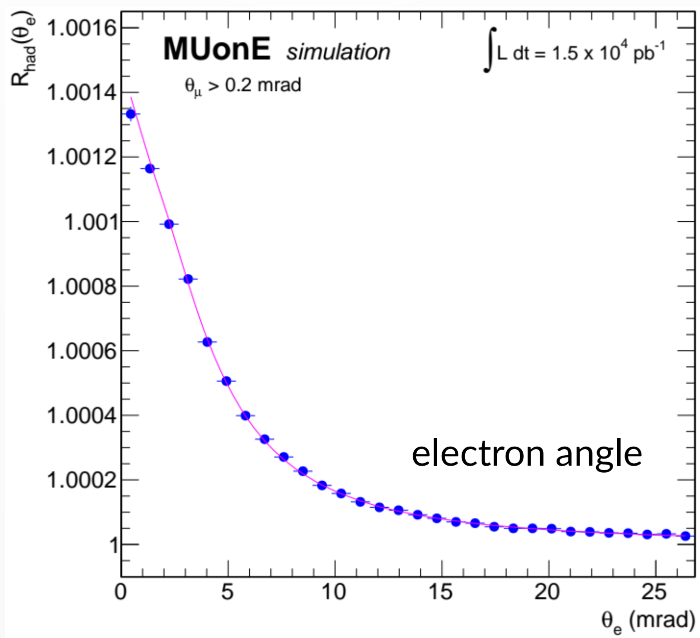
$\Delta\alpha_{\text{had}}(t)$ parameterization: inspired from the 1 loop QED contribution of lepton pairs and top quark at t < 0

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

2 parameters:
K, M

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





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

Results from simulation:

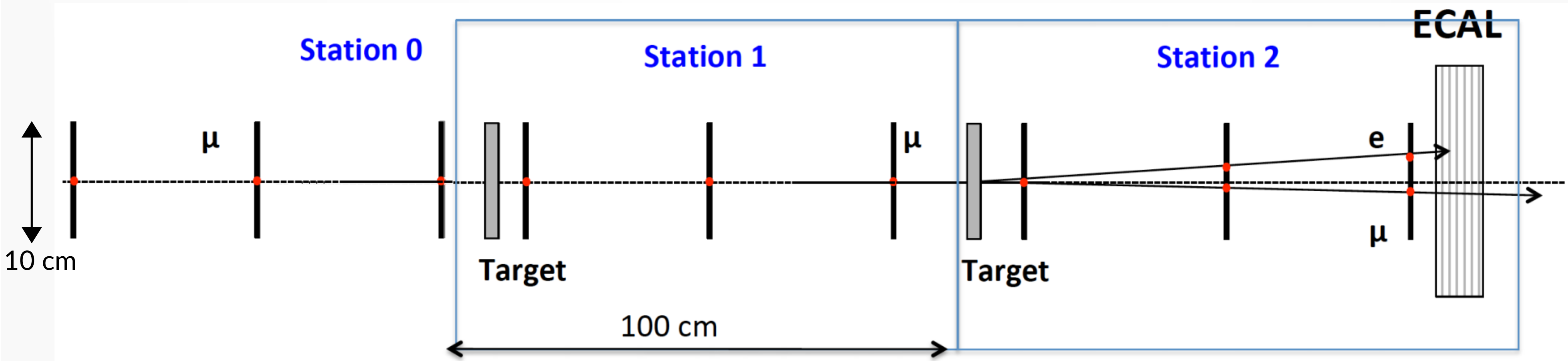
$a_\mu^{HLO} = (688.8 \pm 2.4)\ 10^{-10}$

Input value:

$a_\mu^{HLO} = 688.6\ 10^{-10}$

Test Run

A 3 weeks Test Run with a reduced detector
has been approved by SPSC, to validate our proposal.



Main goals:

- Pretracker +
- 2 MUonE stations +
- ECAL

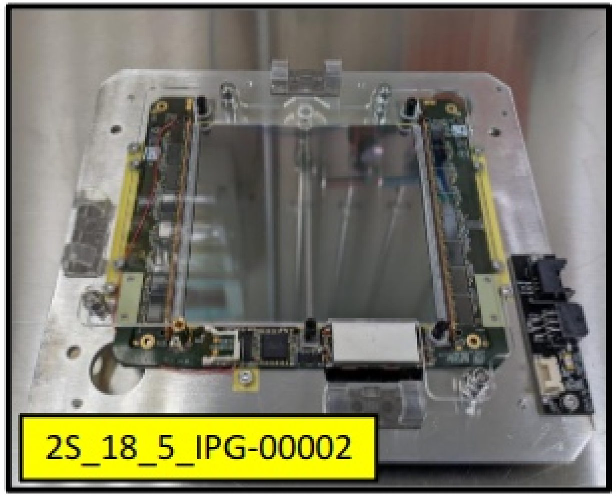
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the systematic errors.
- Initial sensitivity to $\Delta\alpha_{had}(t)$.
- Possible measurement of $\Delta\alpha_{lep}(t)$.

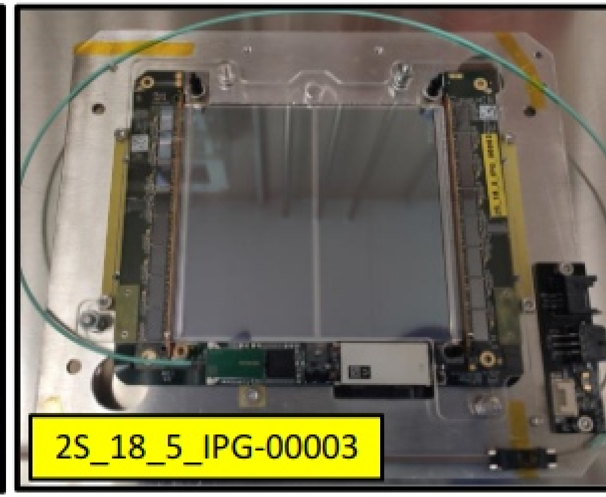
Tracker: CMS 2S modules

Silicon strip sensors currently in production for the CMS-Phase2 upgrade.

Two close-by strip sensors reading the same coordinate:

- Background suppression from single-sensor hits.
  - Rejection of large angle tracks.



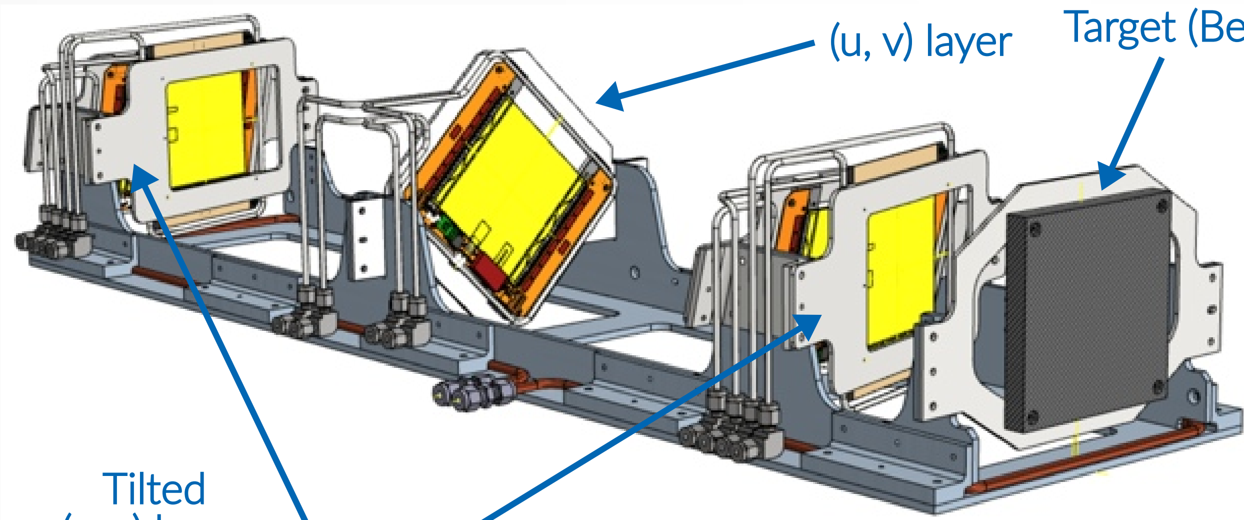


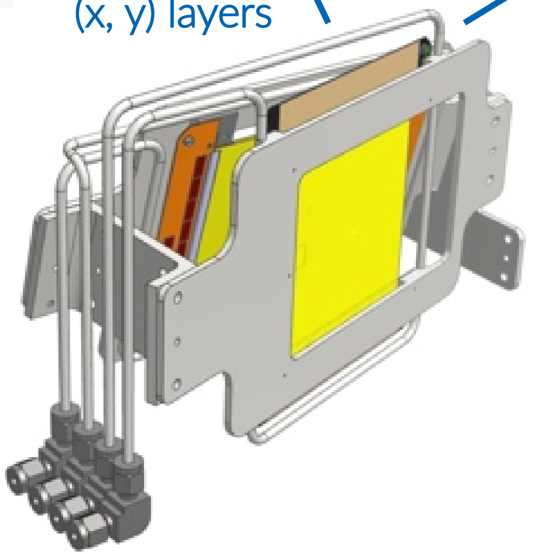
Four 2S modules assembled by CMS Perugia assembly center for MUonE. 5th module foreseen in the next weeks.

- Thickness: 2 × 320 μm
- Pitch: 90 μm (σ_x ~ 26 μm)
- Readout rate: 40 MHz
- Sensitive area: 10×10 cm^2

Modules performance to be tested in real beam conditions during Beam Test 2022 campaign.

Tracking station





Stringent request:
relative position within a station
must be stable at 10 μm.

Low CTE material:
INVAR (CTE ~ 1.2x10^{-6} K^{-1})

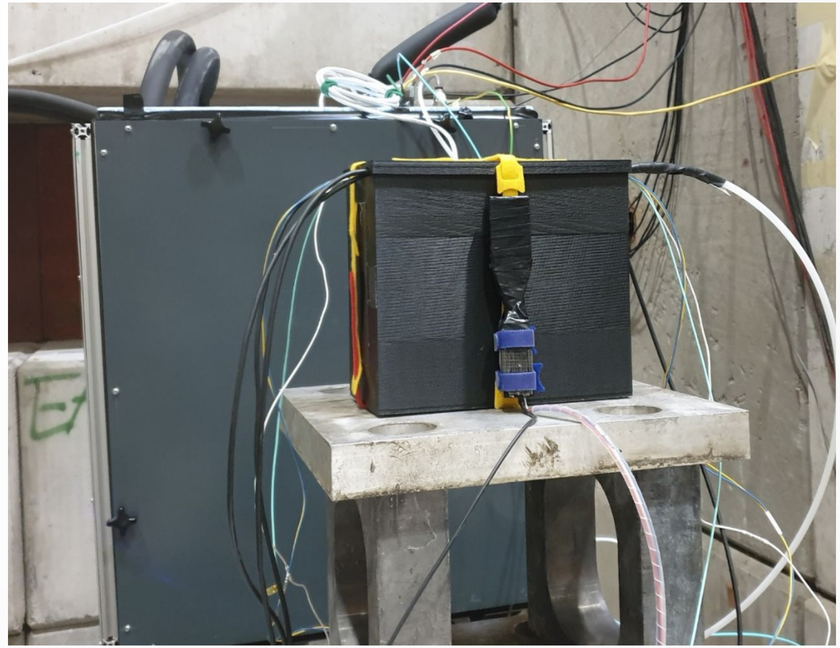
Laser holographic system
to monitor stability.

- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
    - Simulation studies show a resolution of ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

Beam Test 2021

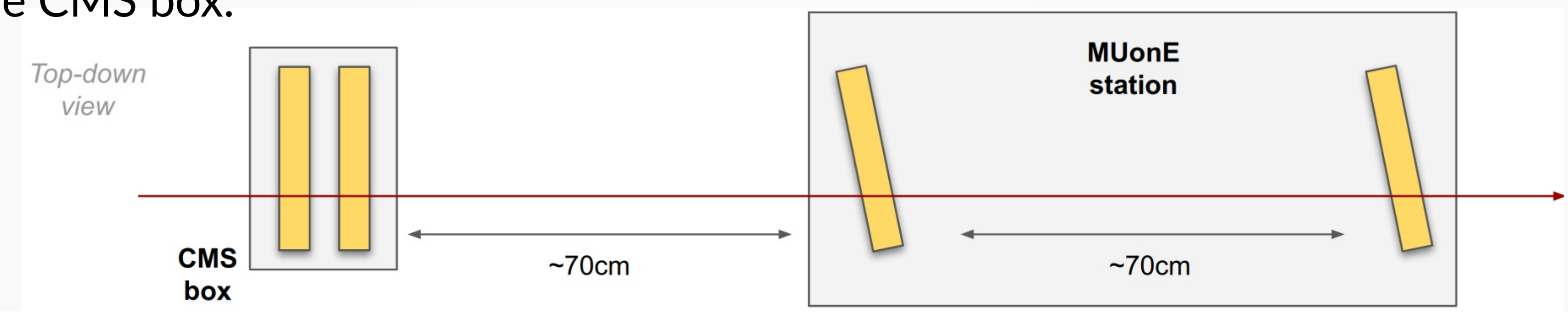
Parasitic beam test at M2 beam line, 3 weeks in October/November 2021

- Joint test with CMS Tracker.
- Apparatus located downstream of NA64.
- 160 GeV muons, asynchronous rate of ~16 kHz.



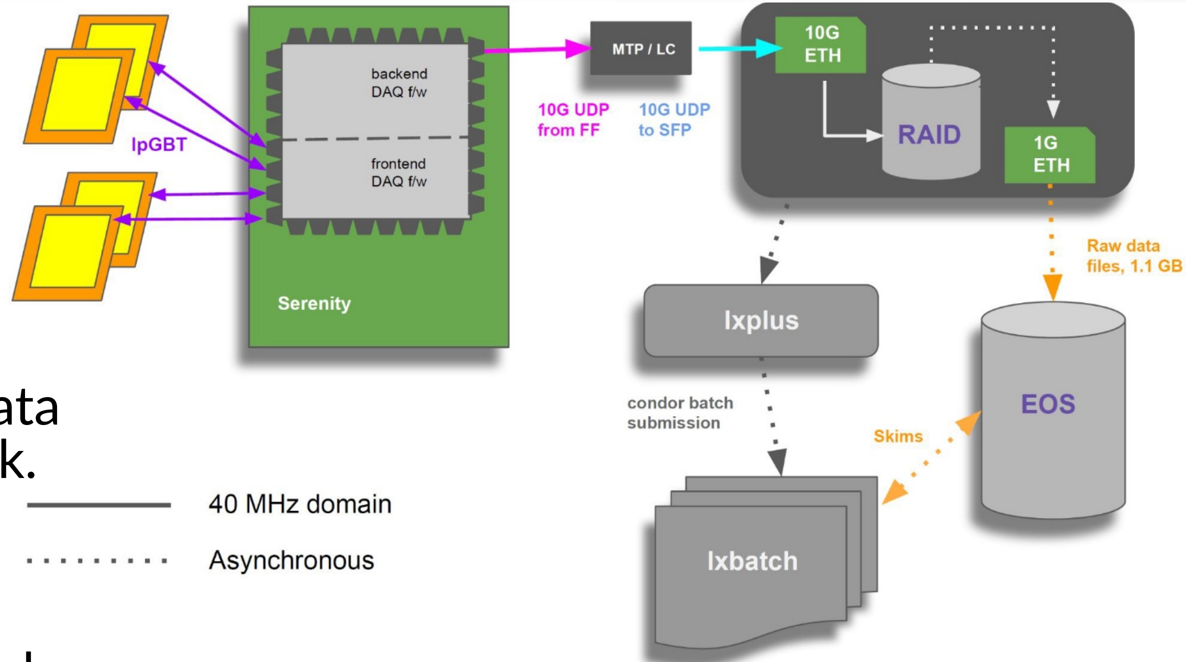
Four 2S modules tested in beam:

- 2 modules built for MUonE in the MUonE station.
- 2 modules built for CMS Tracker in the CMS box.

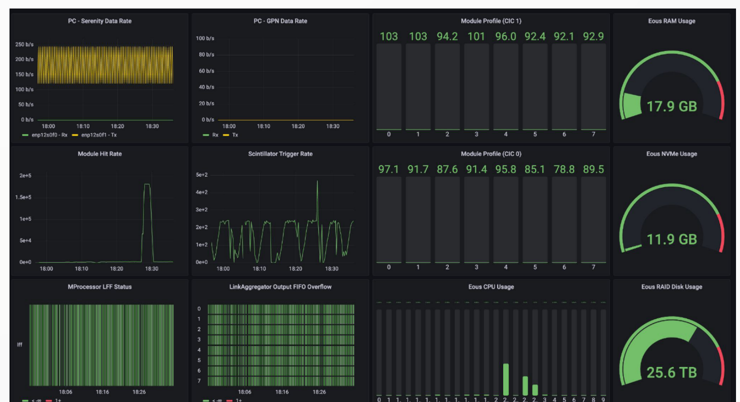


Beam Test 2021

First demonstration
of the full DAQ chain
with the M2
asynchronous beam



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



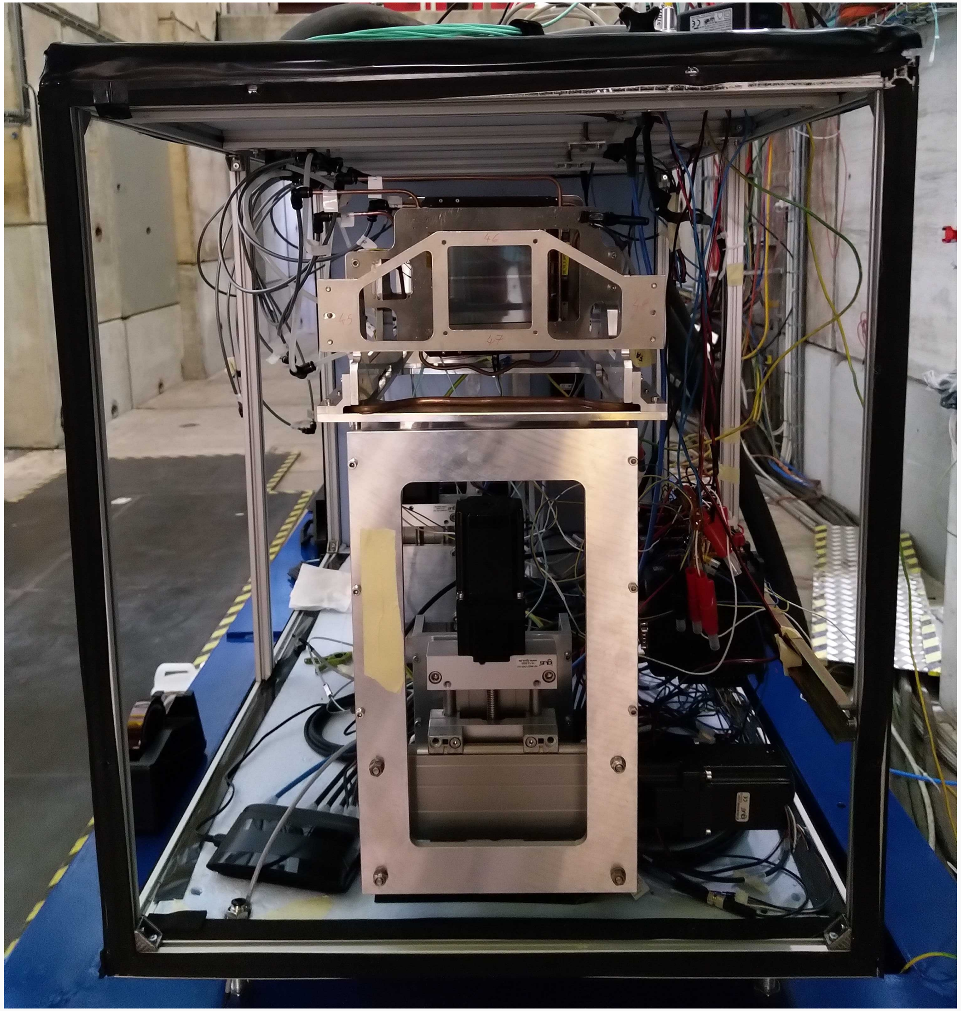
Beam Test 2022

- Joint test with CMS Tracker.
- M2 beam line upstream of Compass (final MUonE location).
- June/October: Opportunity to run for ~48h while Compass (main user) is not using the beam.
- Trolley installed to insert/remove our station from beam.
- ~1 week as main users in October.

Beam Test 2022

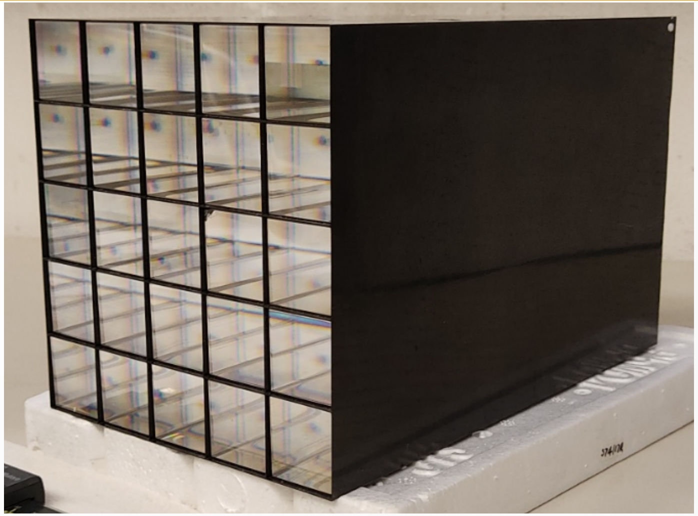
- Continue commissioning of the first tracking station with high rate beam:
  - Study performances of 2S modules and DAQ stability.

- Add a second station in September, equipped with 4 modules, to track the incoming muons:
  - Demonstrate DAQ scalability.
  - Offline track reconstruction and selection of elastic events. Validation of the Geant4 simulation.
  - First tests for software alignment.



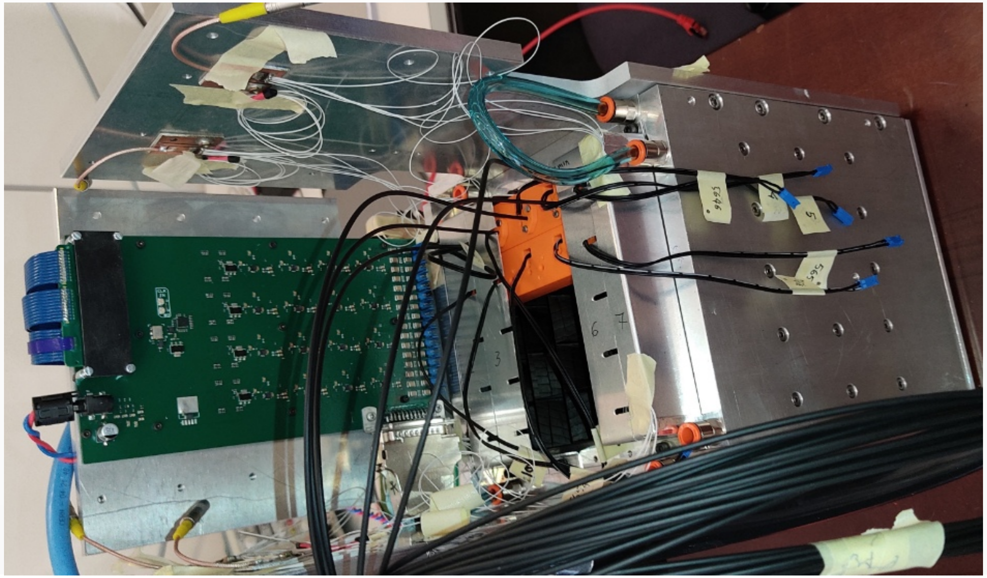
Calorimeter

- 5x5 $PbWO_4$ crystals:
  area: 2.85x2.85 cm^2, length: 22cm (~25 X_0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors.



Beam Test: 20-27 July 2022,
CERN East Area.

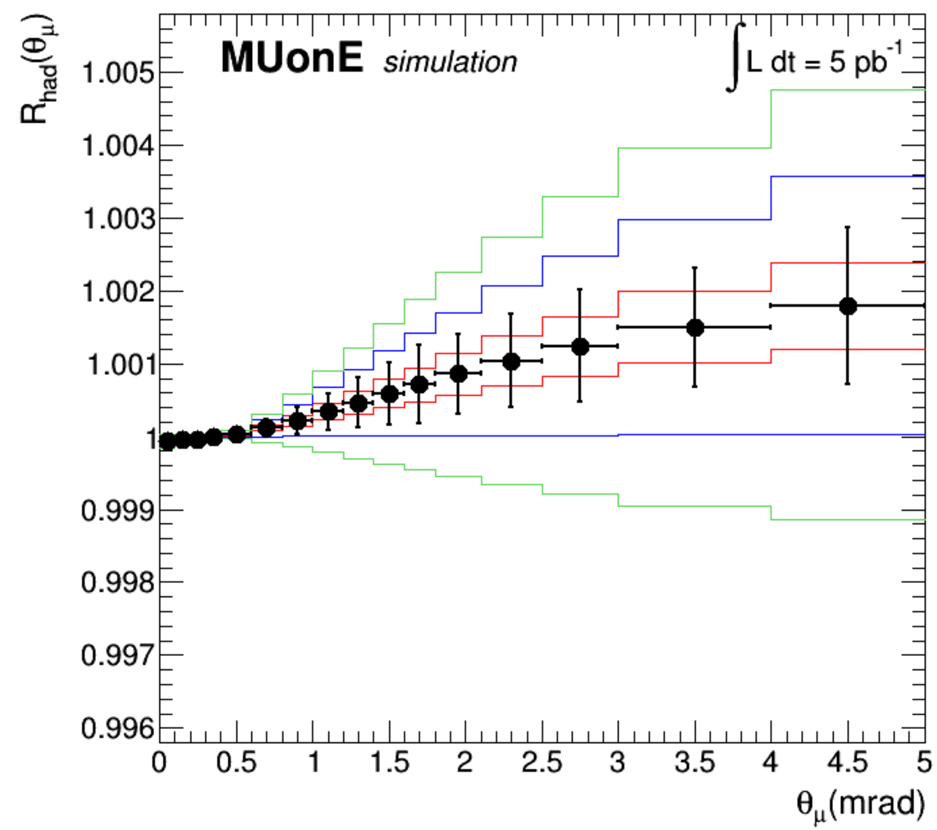
- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter installed downstream the tracking station at M2 beam line in September.



Test Run: expected sensitivity on $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: L_{TR} = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 32 mrad)

$$R_{\rm had} = \frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$



We will be sensitive to the leptonic running ($\Delta\alpha_{lep}(t)$ < 10^{-2})

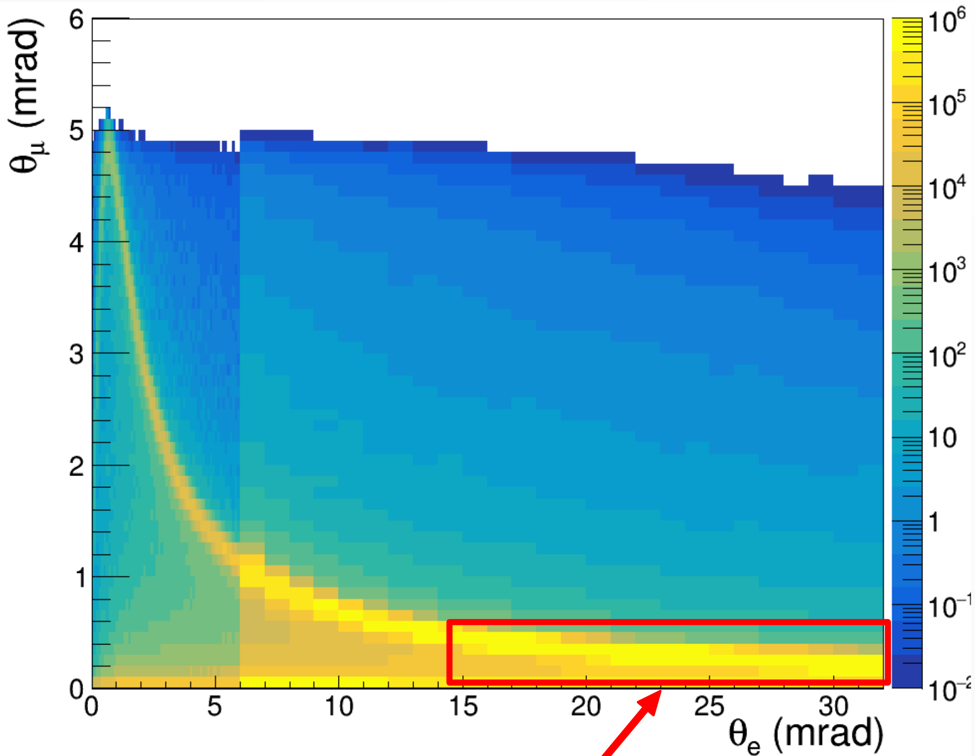
Low sensitivity to the hadronic running ($\Delta\alpha_{had}(t)$ < 10^{-3})

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

K = 0.136 ± 0.026
(20% stat error)

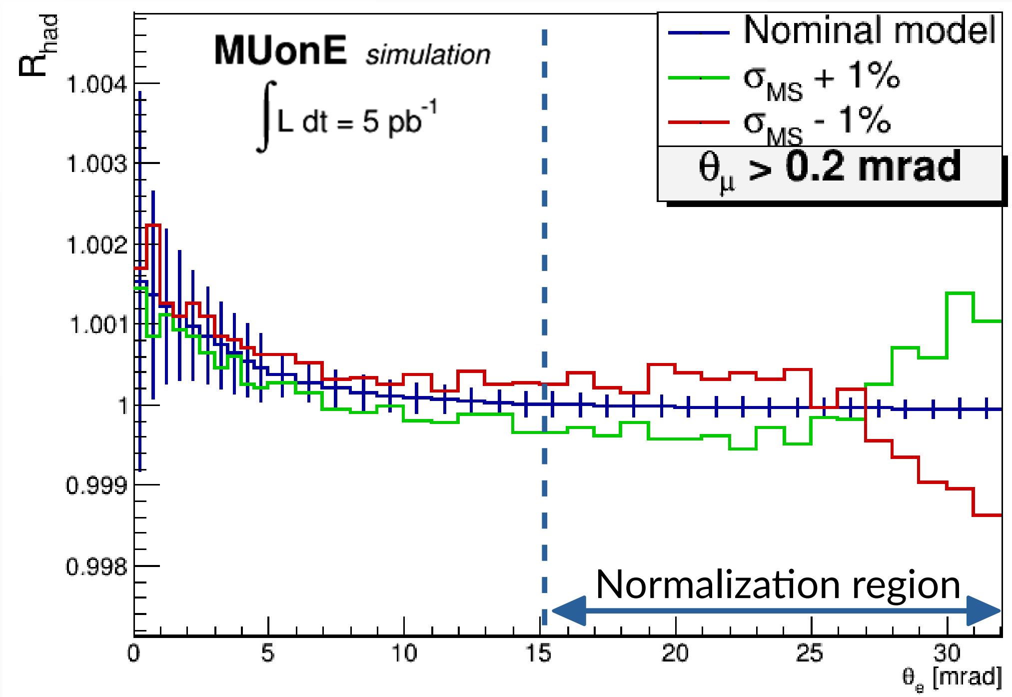
Strategy for the systematic effects

Large effects in the normalization region.
(no sensitivity to $\Delta\alpha_{had}$ here)



Normalization region

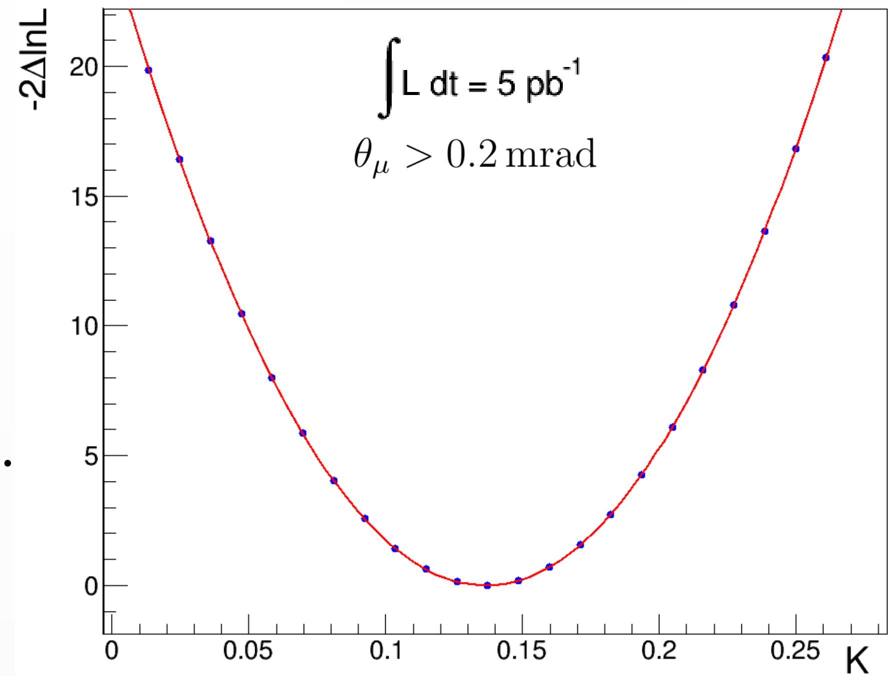
Effect of a ±1% error on the multiple scattering core width:



Strategy for the systematic effects

Promising strategy:

- Use normalization region to calibrate these effects.
- Include residual systematics as nuisance parameters in a combined fit with signal.
- MESMER MC for template fit @NLO
  + Combine tool to fit the nuisance parameters.



K : signal parameter

μ_{MS} : nuisance parameter for multiple scattering systematics

Input shift:
$\sigma_{MS} \to +0.5\%$

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

Similar results introducing different systematics at the same time.
Work in progress to improve the procedure.

Conclusions

MUonE web site

- The new method proposed by MUonE to measure a_μ^{HLO} is independent and competitive with the latest evaluations.
- Intense Beam Test activities in 2021-2022: first experience with detector in real beam conditions.
- 3 weeks Test Run in 2023: proof of concept of the experimental proposal using 3 tracking stations + calorimeter.
- Towards the full experiment: 10 stations before LS3 (2026). Four months data taking: ~2% (stat) measurement of a_μ^{HLO}.