MUonE experiment at SPS

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XIV International Conference on Beauty, Charm and Hyperon Hadrons (BEACH 2022) 5-11 June 2022, Kraków

Outline

- a_μ: Standard Model vs experiment
- How to measure hadronic contribution to a_μ
- Proposal of the MUonE experiment
- MUonE detector
- Test-beams & plans
- Subsystems status

Anomalous magnetic moment of the muon

$$\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{S}$$ *g - gyromagnetic ratio*

Landé *g*-factor is predicted from the Dirac equation to be qual to 2
in reality: $g > 2$ $\rightarrow$ anomalous magnetic moment

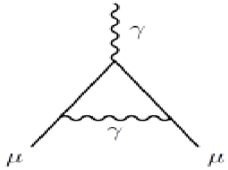
$$a_\mu = \frac{g-2}{2}$$

- one of the most precisely measured quantities
- most precisely determined in Standard Model

$\Rightarrow$ stringent test of theory

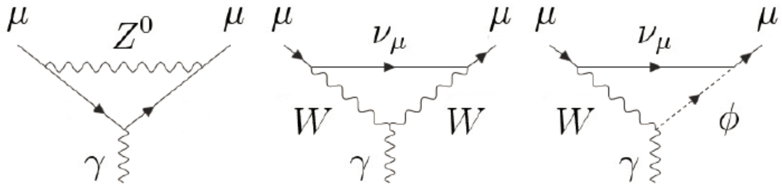
Additional effects from QED, electroweak theory and hadronic factors

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}$$



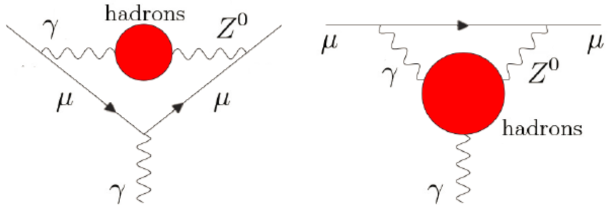
QED corrections known up to 5 loops
~ 0.001% of $\sigma(a_\mu{}^{SM})$

$$a_\mu^{\text{QED}} = 116\,584\,718.95(0.08) \times 10^{-11}$$



EW known up to 2 loops
~ 0.2% of $\sigma(a_\mu{}^{SM})$

$$a_\mu^{\text{EW}} = 153.6(1.0) \times 10^{-11}$$



Hadronic - not calculable with pQCD
~ 99.8% of $\sigma(a_\mu{}^{SM})$
dominant: leading-order vacuum polarization

Hadronic vacuum polarization contribution

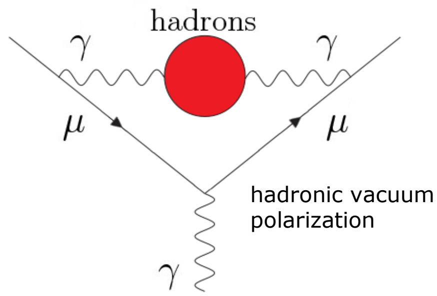
Hadronic vacuum polarization contribution determined from $e^+e^- \to$ *hadrons* x-section measurements at BESIII, CMD3, BaBar, KLOE, VEPP-2000

Dispersion relation, optical theorem (time-like)

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha_0^2}{3\pi^2}\int_{4m_\pi^2 c^4}^{\infty} ds K(s)\sigma^{(0)}(s)$$

$\sigma^{(0)}$ - total x-section $e^+e^- \to$ *hadrons*

$K(s) \sim 1/s$



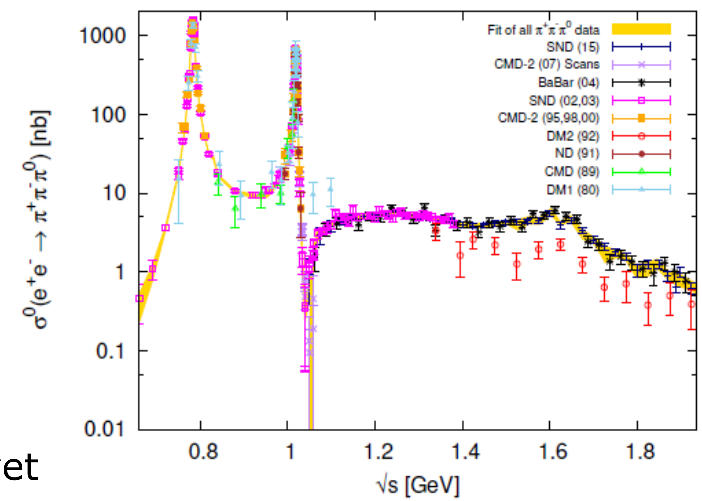
- $\sigma^{(0)}$ from experiments & subtracted from ISR and vacuum polarization corrections
- improved by integrating e^+e^- data with spectra of hadronic τ decays

$$a_\mu^{\mathrm{had,LO}} = \begin{cases} 6963(62)(36)\times 10^{-11} & e^+e^- \\ 7110(50)(8)(28)\times 10^{-11} & \tau \end{cases}$$

Data-driven dispersive approach (accuracy ~0.6%)

- low-energy region highly fluctuating
- hadron resonances and thresholds effects

$\pi^+\pi^-\pi^0$ [arXiv:1802.02995]



Lattice QCD also tried → progressing, not conclusive yet

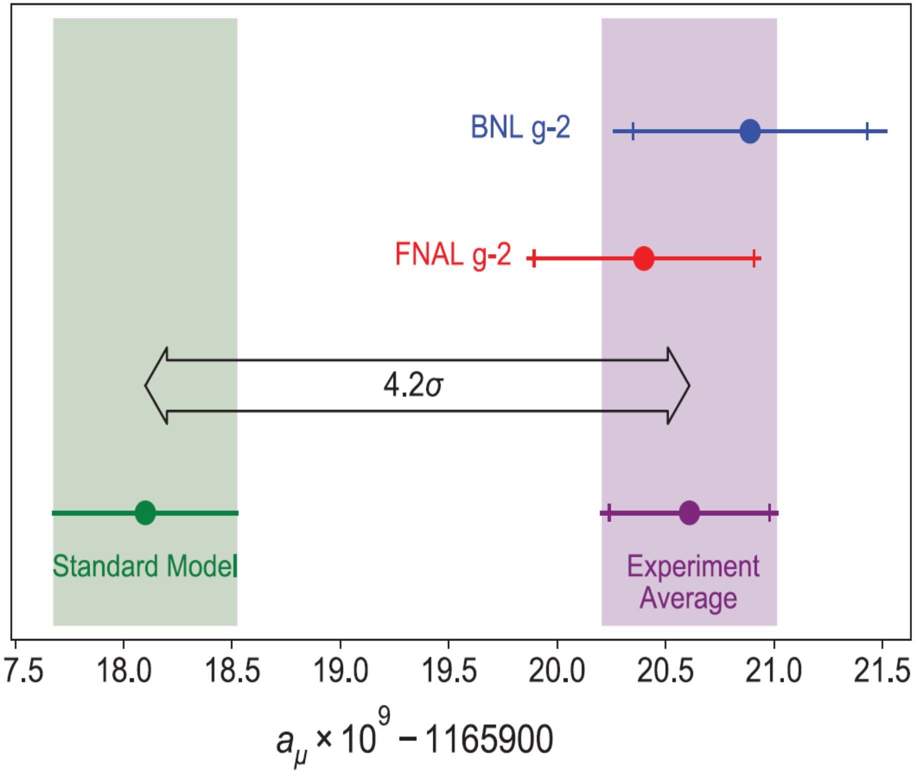
Experiment vs SM predictions

Adding predictions and combining errors in quadrature → overall SM prediction

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (251 \pm 59) \times 10^{-11}$$

[Phys. Rev. Lett. 126 (2021) 141801]

- This gives **4.2σ** discrepancy
- SM: LO-HVP determined with time-like data
- Prediction model- and dataset-dependent



In next years Fermilab experiment will increase the precision by factor of ~4

Forthcoming experiment at J-PARC should reach similar precision

Appropriate improvement in theoretical precision should be also reached

⇒ **proposal of new experiment - MUonE**

Lattice QCD based calculations reduces discrepancy with measurement, and is in tension with data-driven estimates *Nature 593 (2021) 51–55*

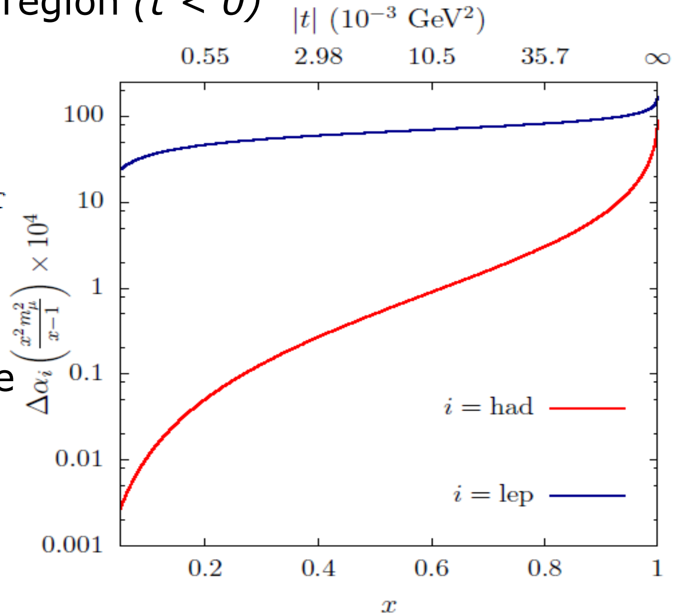
LO-HVP: space-like approach

[Phys. Lett. B746 (2015) 325]

Hadronic contribution to the running of α in the space-like region *(t < 0)*

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

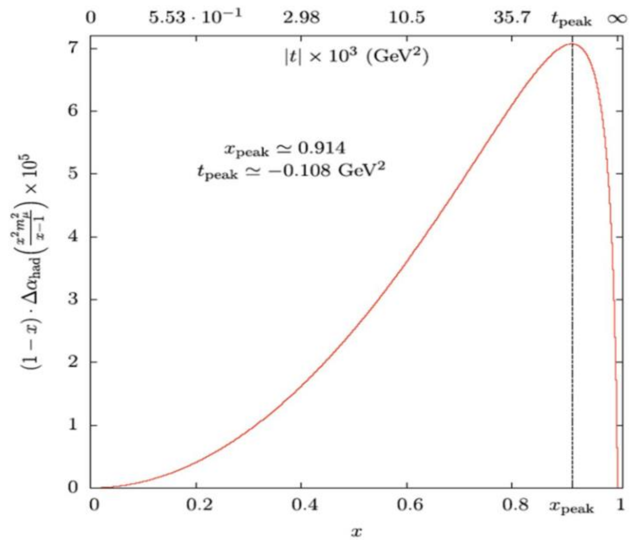
$t(x) = q^2(x) = x^2 m_\mu^2 c^4/(x-1)$ is the squared 4-momentum transfer
$\Delta\alpha_{\rm had}(t)$ is the hadronic contribution to the running of $\alpha(t)$
$\alpha_0 = e^2/\hbar c$ is the fine structure (or Sommerfeld's) constant



Hadronic and leptonic contribution to running fine-structure constant

$$\alpha(t) = \frac{\alpha_0}{1-(\Delta\alpha_{\rm lep}(t)+\Delta\alpha_{\rm had}(t))}$$

- integrand of a_μ^{HLO} smooth and free of resonances
- low-energy enhancement
  - → peak of the integrand at $x \sim 0.9$, $t = -0.11$ GeV^2
  - → $\Delta\alpha_{had}(t_{max}) \sim 10^{-3}$
- experimental data on *t*-channel processes needed:
  - → space-like contribution to Bhabha scattering
  - → fully space-like *μ-e* elastic scattering

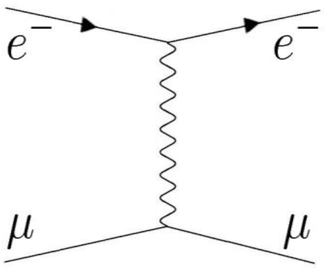


Measure differential cross-section as a function of *t* on a range which spans the t_{peak} value

Proposal of the MUonE experiment

A novel method exploits space-like processes

- determination of a_μ^{HLO} from scattering μ-e data
- elastic scattering of high-energy muons on the atomic electrons in a low-Z target
- $\Delta\alpha_{had}(t_{max})$ can be extracted from differential x-section for μ-e elastic scattering, and then aμHLO by the space-like approach



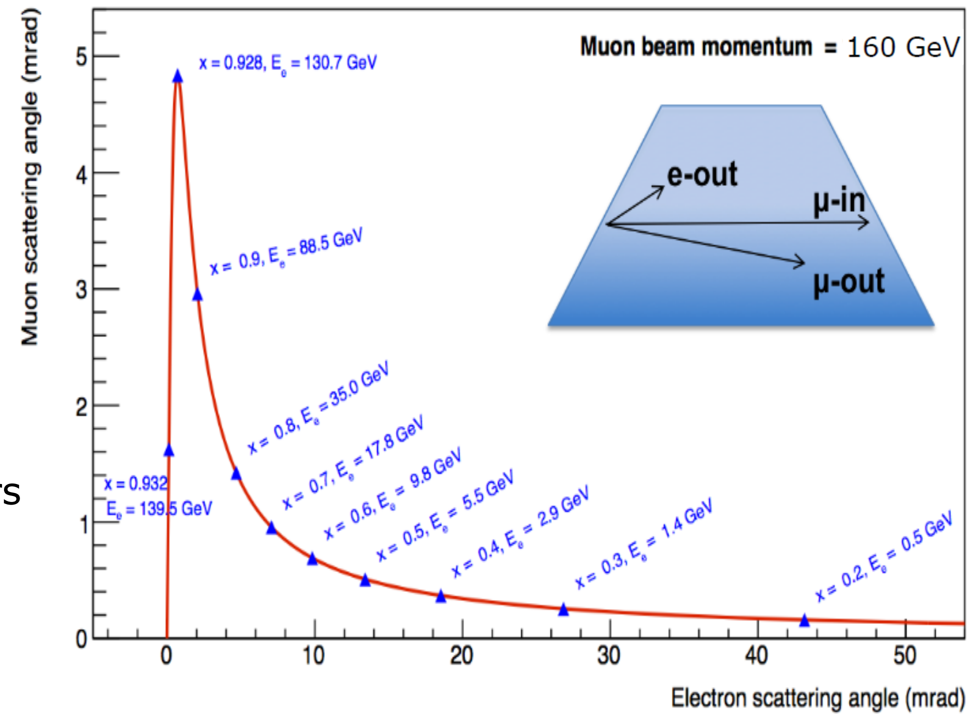
running of α

$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

- higly boosted final states produced in collisions: $0<-t<0.161\ \mathrm{GeV}^2$, $0<x<0.93$
- for E_μ = 160 GeV the phase space covers 87% of the integral
- smooth extrapolation to the full integral with a proper fit model

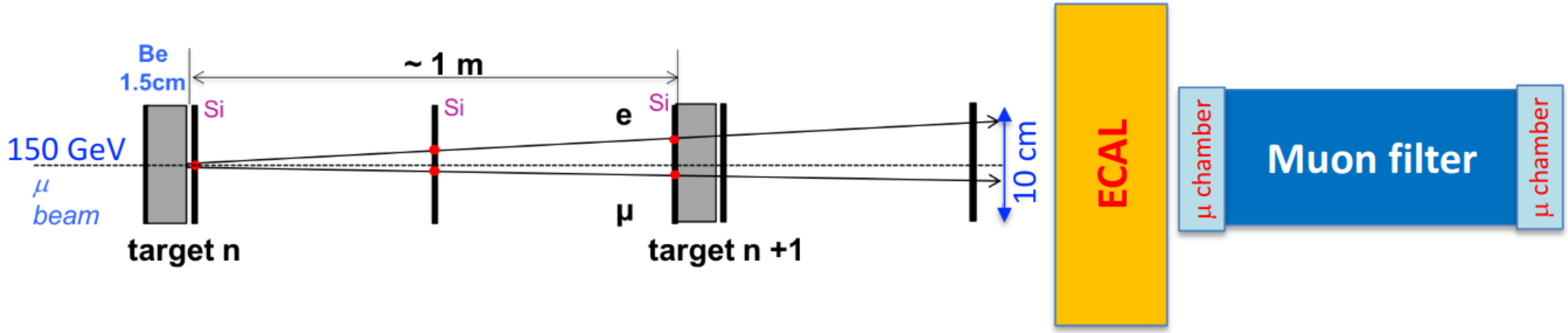
[Eur. Phys. J. C77 (2017) 139]



MUonE detector

Letter of Intent
SPSC-I-252 (2019)

- CERN SPS ~160 GeV muon beam M2 (1.3×10^7 μ/s)
- boosted kinematics: $\theta_e < 32$mrad (for $E_e > 1$ GeV), $\theta_\mu < 5$mrad
  - → whole acceptance covered by 10x10cm2 silicon sensor at 1m distance from the target
  - → reduce systematics
- minimize distortions of the outgoing e/μ trajectories
  - → target material
  - → low rate of radiative events
- modular structure made by up to 40 layers of Beryllium 1.5 cm thick
  - → interleaved with 6 layers of Si tracking planes
  - → expected angular resolution ~10 μm / 0.5 m = 0.02 mrad
- need to measure direction (and energy) of the incoming muon → a la COMPASS
- PID crucial for low angle particles & background rejection
  - → ECAL and Muon Filter after the last station



Main issue is to control the systematic error at the same level as the statistical one

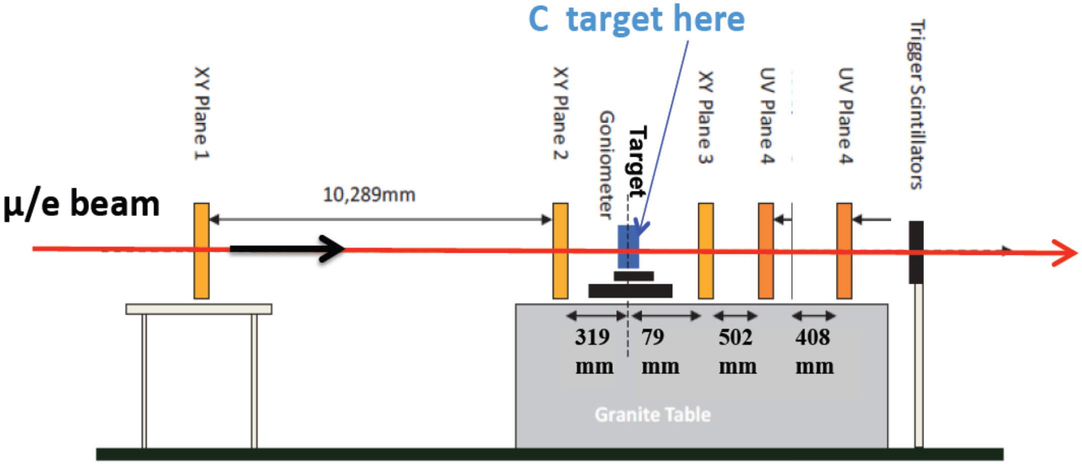
Test-beam 2017

[JINST 15 (2020) P01017]

- used existing UA9 setup in H8-128
  - → 5 *Si* strip planes: 2 before *(upstream)* and 3 after the target, 3.8×3.8 cm^2
- data taken with electron and muon beams
  - → beam energy: *e-* of 12/20 GeV; *μ* of 160 GeV
  - → 10^7 events with *C* targets of different thickness *(2,4,8,20mm)*

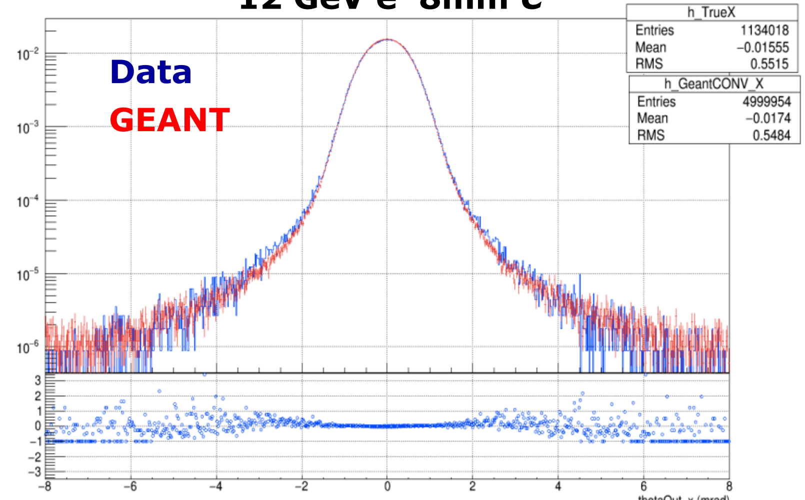
Goal: measure multiple scattering tails for *e* → *e* through material to compare with GEANT 4 model

- with muon data
  - → identify *μ* and *e* from elastic scattering in the final state
  - → measure multiplicity of particles from the target to evaluate background



Adapted UA9 apparatus

12 GeV e$^-$ 8mm *C*



Output angle [mrad]

Test-beam 2018

- Setup located downstream COMPASS
- Aim of the measurement campaign

  → muon-electron elastic scattering with high statistics
- Using muons from pions decays *(hadron beam)*

  → estimated beam momentum p_{beam} = (187±7) GeV
- Measure correlation between the scattering angles

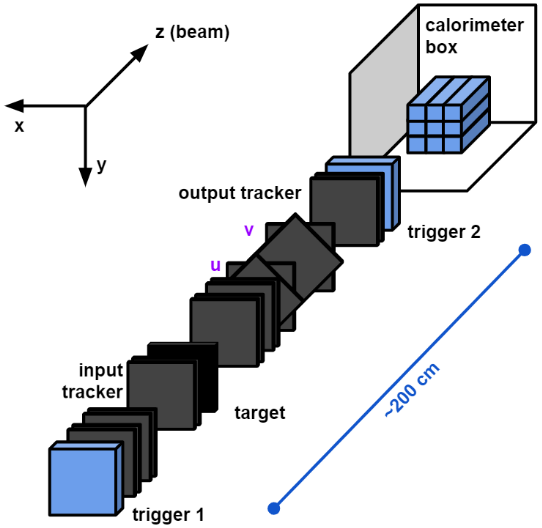
  → muon angle vs the electron angle
- Electron energy vs electron angle correlation and PID
- Detector

  → tracking system:

  16 stations equipped with AGILE silicon strip sensors

  400 micron thick, single sided, about 40 micron intrinsic hit resolution

  → electromagnetic calorimeter: 3x3 cell matrix, BGO-PMT crystals, ~8×8 cm^2



Test-beam 2018 - results

Published in JINST 16 (2021) P06005

- Aimed mainly to explore the ability to select a clean sample of elastic scattering events in view of desi-gning the final experiment

  → able to select clean sample even if the resolution worse than the one planned to be used in MUonE

  → first results of this kind

- Importance of an adequate calorimeter

  → understand the electrons emitted in the range of a few GeV

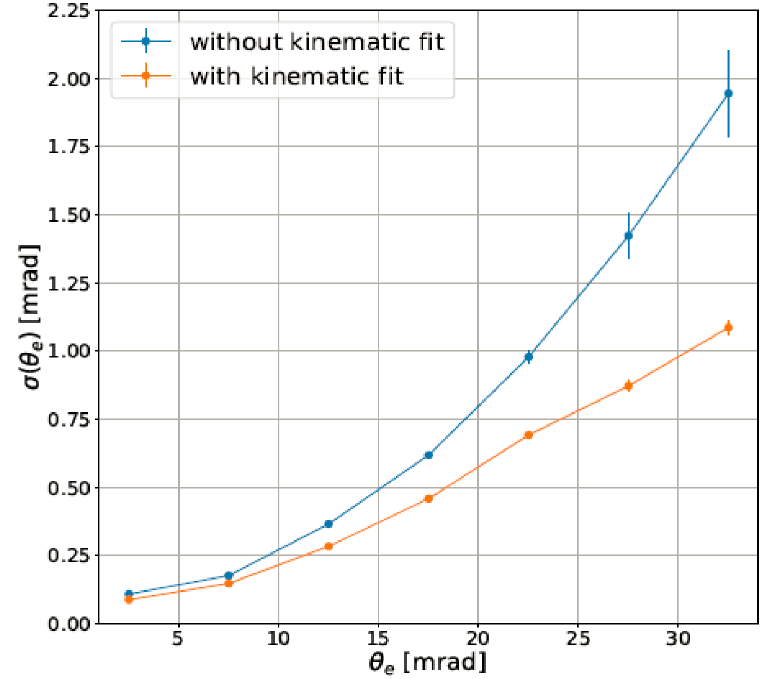
  → determine the behaviour of the background

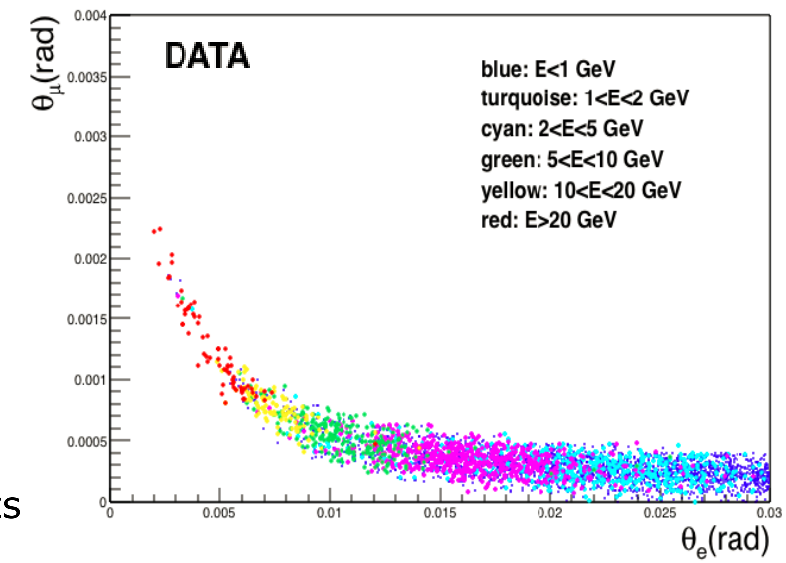
- Important upgrade of Geant4

  → accurate angular distribution of the electrons of the pair implemented

  → Geant4 version 10.7
  (already implemented in MUonE software)

Conclusion: able to select a clean sample of elastic events



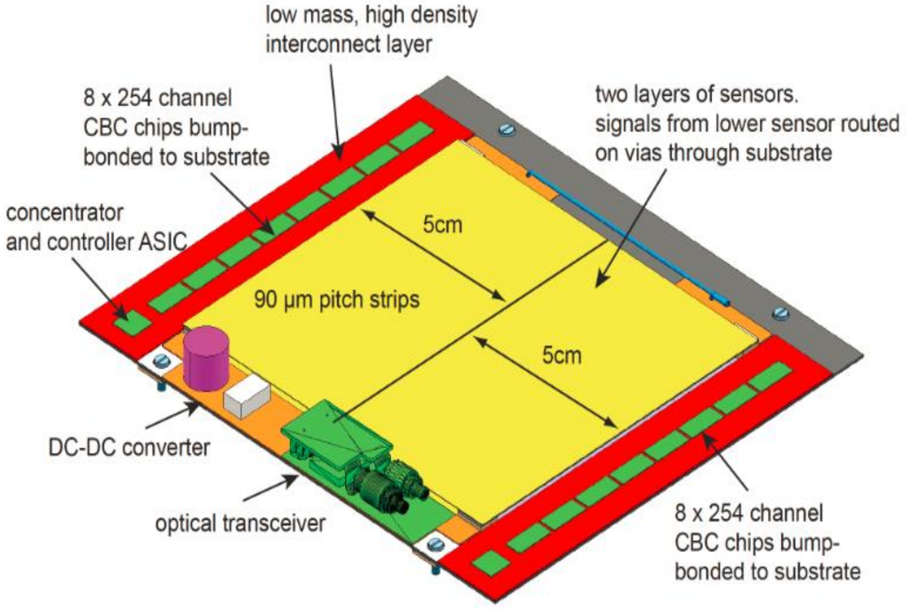


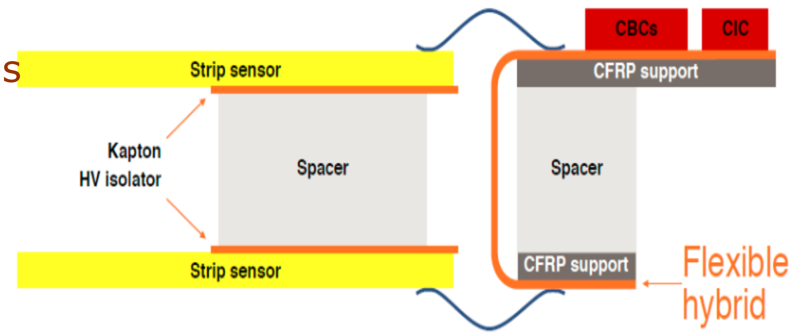
Muone detector: CMS 2S sensors

Letter of Intent
SPSC-I-252 (2019)

Developed for CMS Outer Tracker upgrade

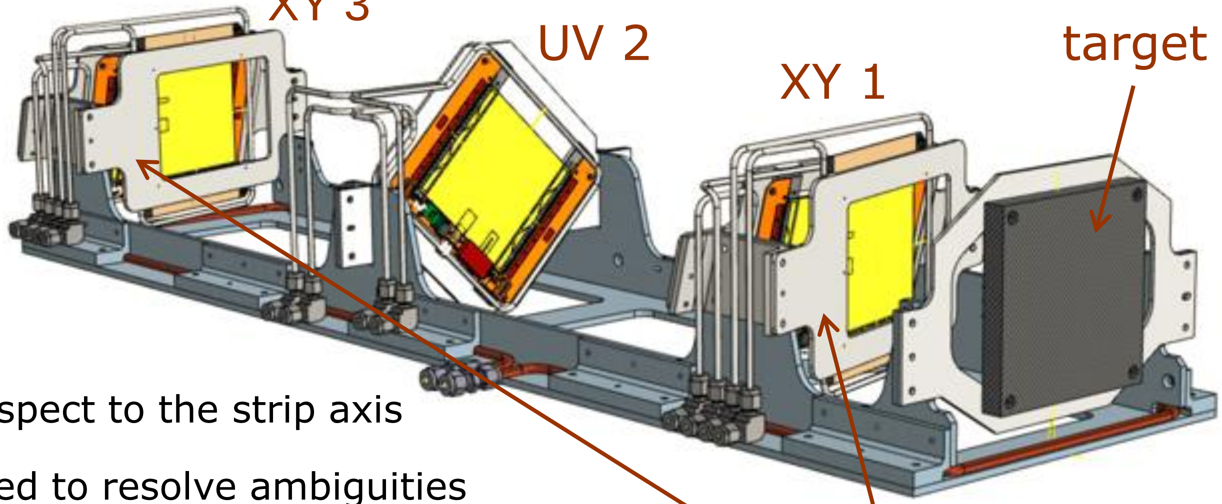
- under production now
- module consists of paired sensors
  - → pitch is 90μm, thickness 2 x 320μm
  - → large active area 10x10 cm^2
- two close-by planes of strips
  - → provide track elements (stubs)
  - → suppression of background
- distance bewteen sensors 1.8mm
- 16 CBC chips each reading 254 strips
  - → 127 from top and 127 bottom sensor
  - → binary strip readout
- tilting a sensor around an axis parallel to the strips
  - → induce charge sharing between adjacent strips
  - → good position resolution ~20μm
- modules provide stubs at 40MHz

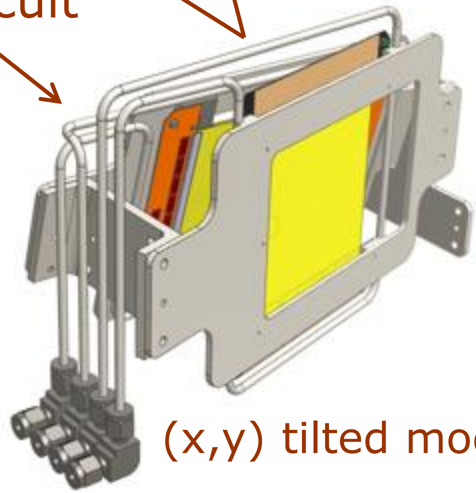




Muone detector: Tracking station

- station length ~1m
- target + 3 tracking layers
- layer:
  pair of close-by 2S modules
  with orthogonal strips
- (x,y) modules tilted with respect to the strip axis
- (u,v) central modules rotated to resolve ambiguities
- required high precision of mounting and mechanical stability
  → stringent request: relative positions within station better than 10μm
- structure with low thermal expansion coefficient material
  Invar, CTE = $1.2 \times 10^{-6}\ K^{-1}$
- cooling circuit foreseen to control temperature while removing the heat produced by modules
  (stabilized within 1-2 ^{o}C)





ECAL prototype

$PbWO_4$ 5 x 5 channels prototype

- 16 channels digitizer boards
- laser system used to pulse crystals
- DAQ for test and calibration ongoing
- integration of calorimeter into DAQ
  - → requires high speed optical data links
  - → optical mezzanine boards exists
  - → firmware to be developed

Test of electronics chains ongoing

Requested beam time in T9 East Area → end of July 2022

Preliminary test beam in 2021 with M2

Parasitic beam test, ran over 3 weeks in Oct/Nov 2021

→ M2 muon beam in the CERN North Area

→ apparatus located downstream of NA64

→ 160 GeV muons, asynchronous rate of ~16 kHz

Goal: test DAQ system thoroughly for the first time

- Module readout via Serenity FC7 prototype with KU15P FPGA
- Ryzen 9 5900X server PC to receive data
- MUonE power provided by CAEN SY4527 + A2519/A1542
- 40MHz continuous readout of 2S modules (stubs)
- Grafana monitoring of DAQ and module status

Test Run in 2022/2023

Requests: 2 weeks of M2 beam - end of 2022, 3 weeks - beginnig of 2023

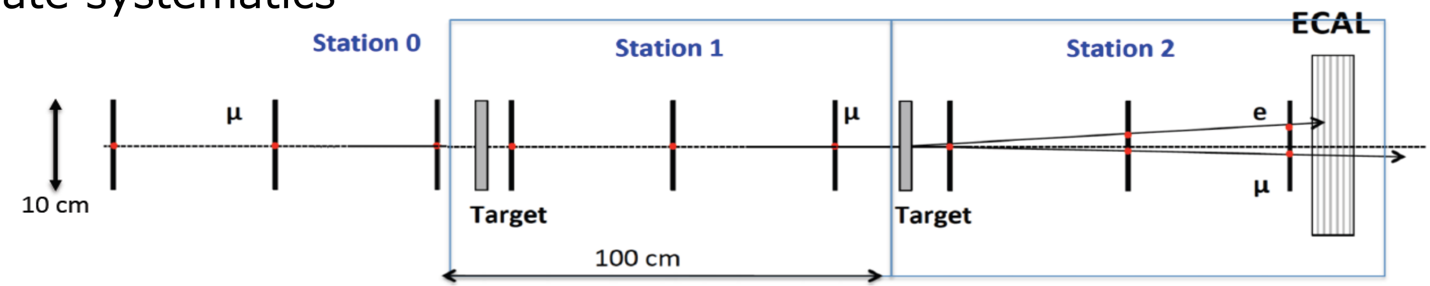
- upstream COMPASS

Prototype of the final setup

- 2 stations, each consists of a thin Be target and 6 CMS tracking layers
- 6 other tracking layers upstream detector for tracking the incoming muons

Goal

- confirm the system engineering, i.e. assembly, mounting and cooling
- assess the detector counting rate capability
- check the signal integrity in the process of data transfer for DAQ
- prove the validity of the trigger-less operation mode
- evaluate the FPGA real-time processing
- test the procedure for the alignment of the sensors
- investigate systematics



Test Run: expected sensitivity

[Phys. Scr. 97 (2022) 054007]

Test Run setup

- expected integrated lumi with full beam intensity and detector efficiency

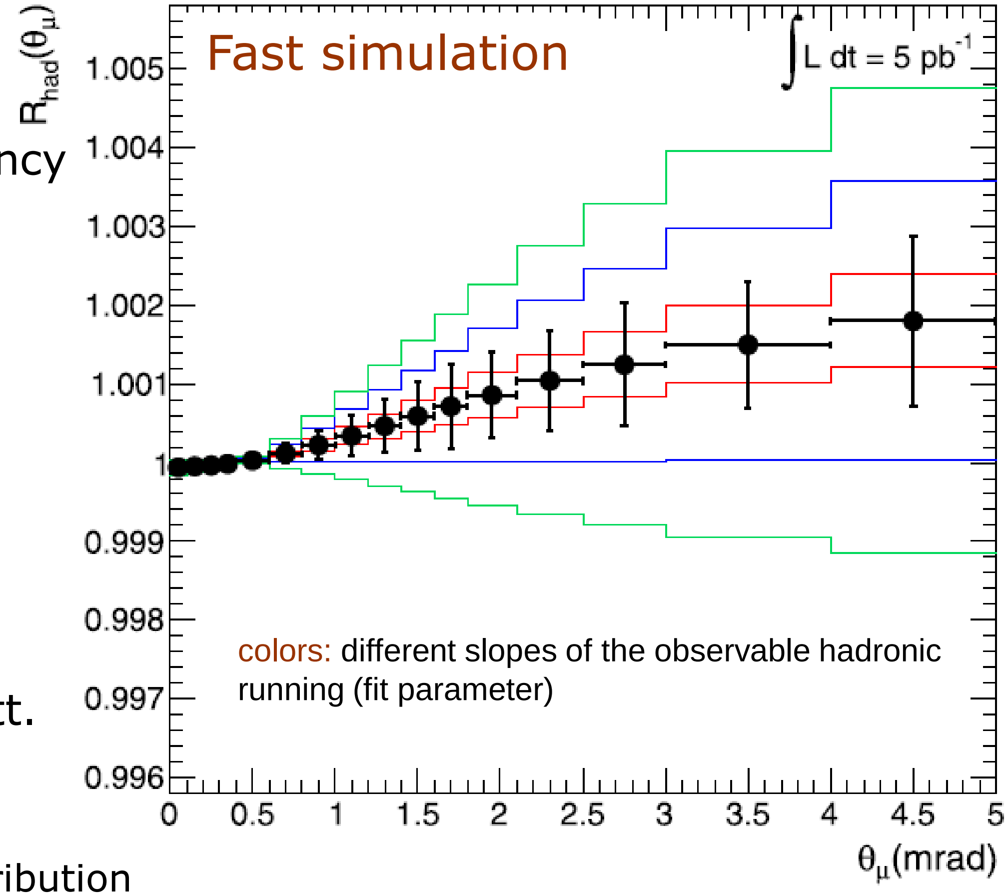
  ~1pb^{-1} / day

  ~5pb^{-1} / one week

  ~10^{9} μe scattering events
  (E_e > 1 GeV, θ_e < 30 mrad)

Sensitivity (template fit)

- NLO MC generator
- fast sim. for multiple Coulomb scatt.
- detector intrinsic resolution



template fit to the 2D($\theta\mu$,θe) angular distribution

$\Delta\alpha_{had}(t)$ parametrized according to the *'lepton-like'* form

R_{had} ratio of a cross section including the full running of α and the same x-section with no hadronic running

Will have sensitivity to leptonic running (10× larger)

MuonE collaboration

1st MUonE Collaboration Meeting 25-26 Mar 2019, CERN

18 institutes from 9 countries, ~40 people

Deep Machine Learning for MUonE online

- Idea: SPEED UP PATTERN RECOGNITION

  → output is 3D regardless of 2D (x-z, y-z) inputs

- Input: all hits concatenated, no distinction between X, Y and stereo layers

- Ground truth: MC track slope parameters

- Model

  → PyTorch

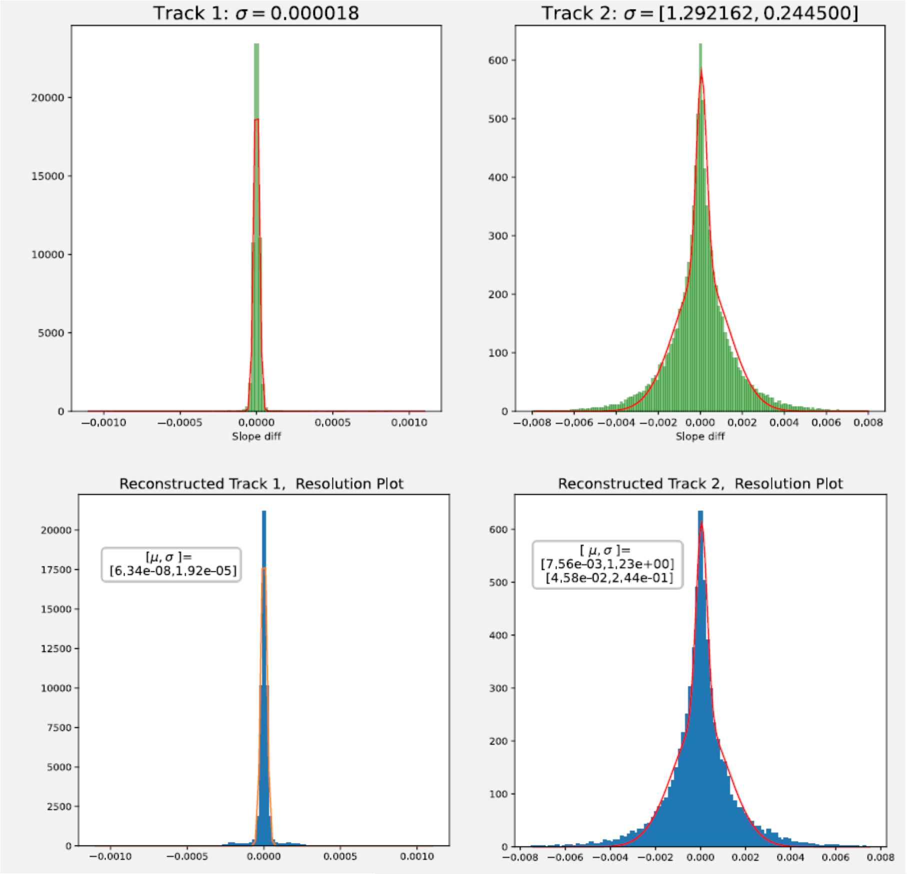
  → 6 linear layers

  → up to 2000 neurons per layer

- Loss function

  → MSELoss from PyTorch – uses difference between predicted slope parameters and ground truth

[Computer Science 20(4) (2019) 477-493]
[DCAI 2021 Lecture Notes, vol. 2, p 202-205]



- Track 1: muon, Track 2: electron
- Upper: DNN based algorithm
- Lower: „conventional" reconstruction

Conclusions

Exciting times for the muon *g*-2

- precise determination of a_μ at Fermilab and JPARC

LO-HVP corrections are essential

- space-like approach (MUonE) allows to reach the precision below 5 ppm

Successful test beams at CERN in 2017 and 2018

Letter of intent accepted by SPSC in 2019

Valuable solutions for the tracker exist *(not require R&D for new technologies)*

- final detector prototype will be tested in Test Run in 2022-2023
- data taking with final detector in 2023-2026.

Theoretical calculations

- MC at NLO available, and NNLO progressing successfully