Status of the MUonE project

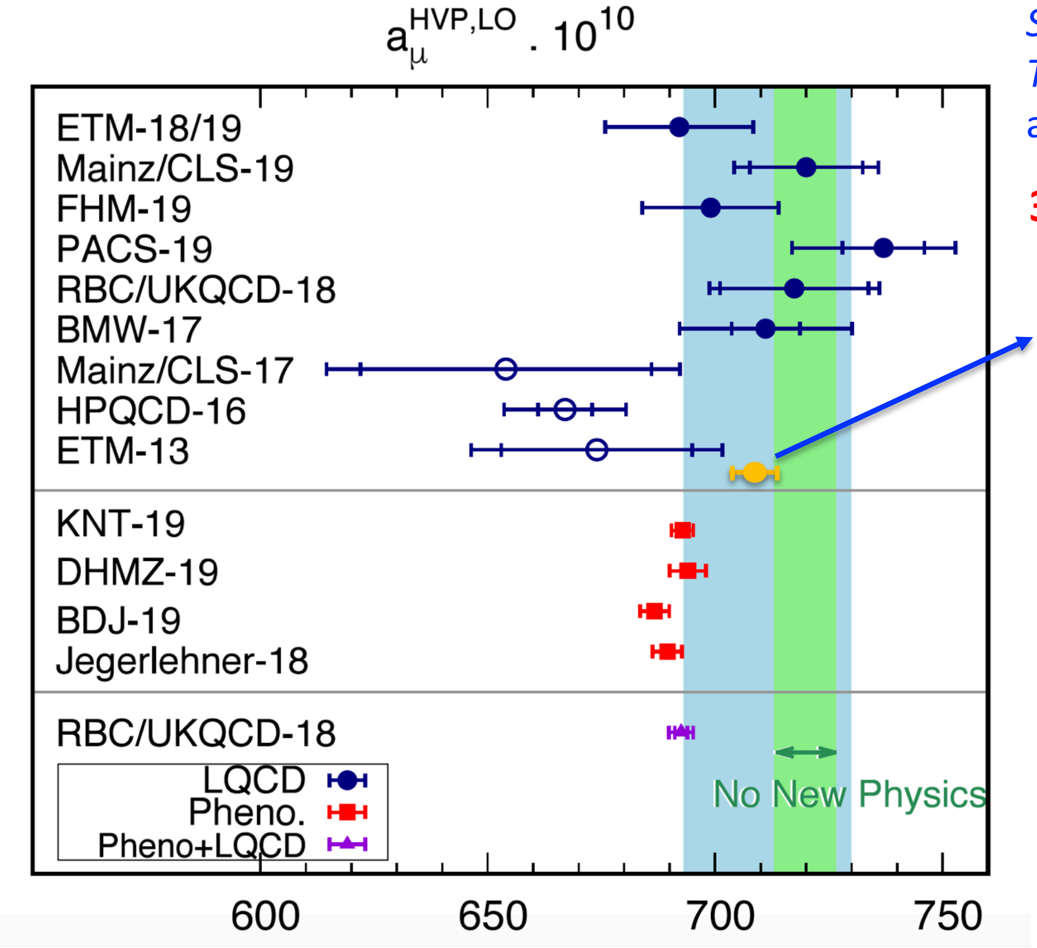
Giovanni Abbiendi

(INFN Bologna)

on behalf of the proponents

Physics Beyond Colliders Annual Workshop, *CERN, 1-4 March 2021*

a_μ measurement versus SM



Status report:
T. Aoyama et al., Phys.Rept.887(2020)1
$a_\mu^{HVP,LO} = 693.1(4.0) \times 10^{-10}$

3.7 σ discrepancy: *new physics ?*

Recent lattice (still unpublished)
BMW20 arXiv:2002.12347
$a_\mu^{HVP,LO} = 708.7(5.3) \times 10^{-10}$

New g-2 experiment on-going at Fermilab aims at **a reduction of the experimental error by a factor of 4**

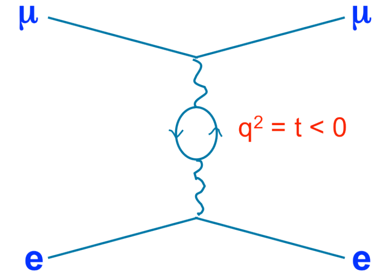
Theory error dominated by the **LO Hadronic contribution to the Vacuum Polarization: 0.6%**

should be improved

MUonE experiment proposal: independent method, competitive precision

MUonE experiment idea Eur.Phys.J.C77(2017)139

Very precise measurement of the running of α_{QED} from the shape of the differential cross section of elastic scattering of μ(150-160GeV) on atomic electrons of a fixed target with low Z (Be or C) at the CERN SPS



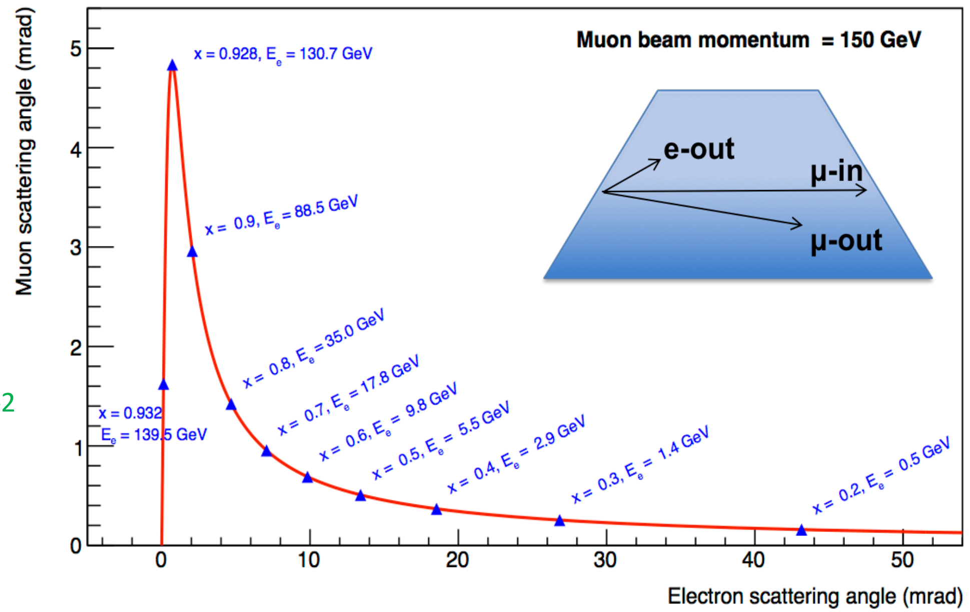
$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \underbrace{\frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2}_{\text{running of }\alpha} \Rightarrow \Delta\alpha(t) = \underbrace{\Delta\alpha_{lep}(t)}_{\text{known from QED}} + \underbrace{\Delta\alpha_{had}(t)}_{\text{to be measured}}$$

From $\Delta\alpha_{had}(t)$ determine a_μ^{HLO} by the space-like approach: Phys.Lett.B746(2015)325

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

Observable effect ~ 10^{-3}/wanted accuracy ~10^{-2}

→ required challenging precision ~10^{-5}



- **Elastic scattering: simple kinematics.**
- Scattering angles θ_e and θ_μ correlated (helps selection: rejection of radiative/inelastic events)
- For E(beam)=150 GeV the phase space covers 87% of the a_μ^{HLO} integral.
    - ❖ Smooth extrapolation to the full integral with a proper fit model

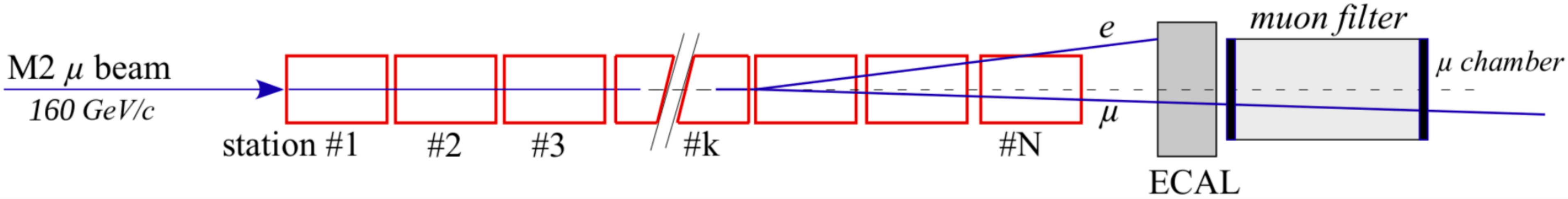
MUonE Detector Layout

Letter-Of-Intent SPSC-I-252

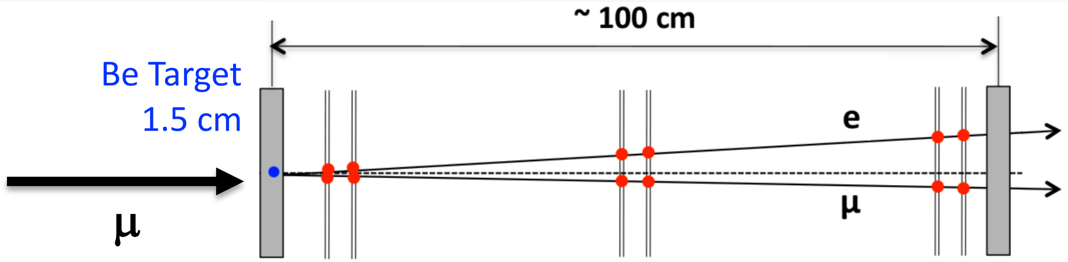
The detector concept is simple, the challenge is to keep the systematics at the same level as the statistical error .

- Large statistics to reach the necessary sensitivity
- Minimal distortions of the outgoing e/μ trajectories within the target material and small rate of radiative events

- ➢ Modular structure of 40 independent and precise tracking stations, with split light targets equivalent to 60cm Be
- ➢ ECAL and Muon filter after the last station, to help the ID and background rejection



incoming μ direction measured by the previous module

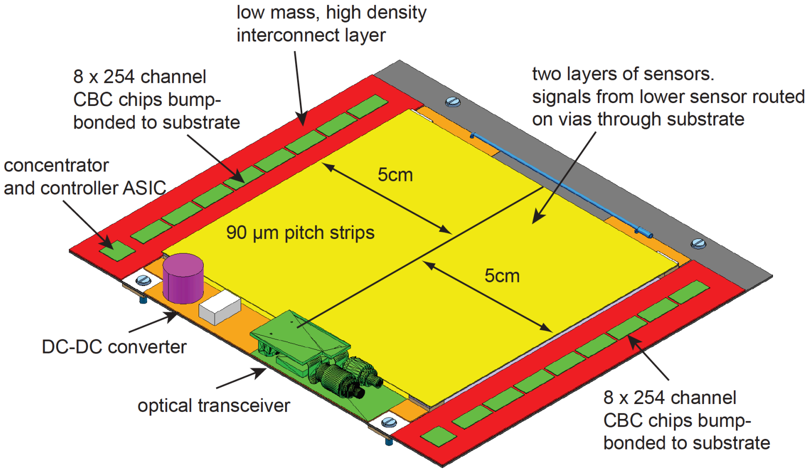


Tracking: 3 pairs of Si layers with orthogonal strips

Boosted kinematics: $\theta_e<32$mrad (for $E_e>1$ GeV), $\theta_\mu<5$mrad: the whole acceptance can be covered with a 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

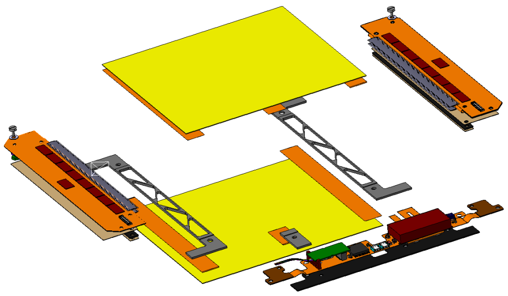
Detector choice: CMS-upgrade Outer Tracker 2S

MUonE Letter-Of-Intent SPSC-I-252 Details: see CMS Tracker Upgrade TDR



Two close-by planes of strips reading the same coordinate, providing track elements (**stubs)**

suppression of background from single-layer hits or large-angle tracks



- Large active area 10x10 cm^2
  -> complete/uniform angular coverage with a single sensor

- Good position resolution ~20µm
  -> further improvable with a 15^o-20^o tilt around the strip axis and/or with effective staggering of the planes (with a microrotation)

MAIN Difference w.r.t. LHC operation: signal is asynchronous while sampling has fixed clock at 40MHz -> can be overcome with a specific configuration of the FE

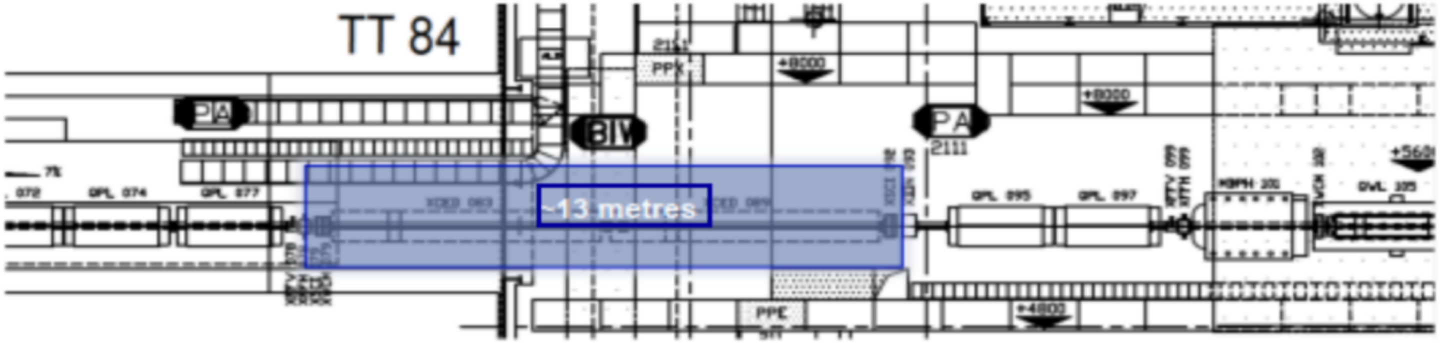
MUonE proposal

June 2019: Letter-Of-Intent at the SPSC LOI SPSC-I-252

January 2020: SPSC acknowledges the interest of the MUonE proposal and approves a Test Run to be held in 2021

MUonE has been allocated 3 weeks beam time at the end of the proton running in the North Area (Oct-Nov 2021), unless SPS schedule changes

It will be installed upstream of COMPASS in the region presently occupied by CEDARS



The MUonE Collaboration

still growing up

CERN
Exp

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

Imperial College (London), Liverpool U. *Exp-Th*

Krakow INP Pan
Exp

Northwestern U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) *Exp-Th*

Shanghai Jiao Tong U.
Exp

LMU München
Th

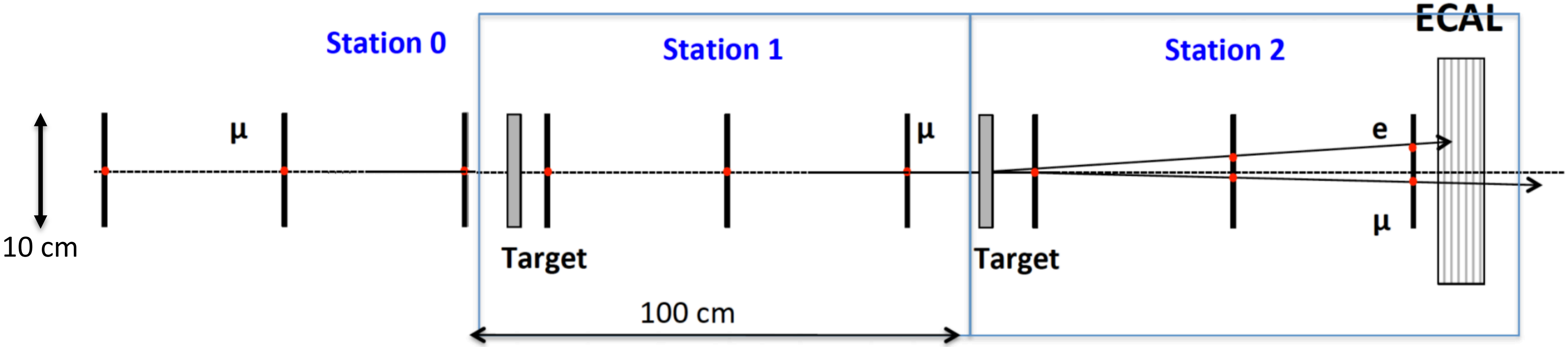
PSI (Villigen), U.Zürich
Th

+ other involved theorists from: LAPTH/Annecy (F), U.Valencia (E), KIT/Karlsruhe (D), New York City Tech (USA)

Test Run setup

To be held at CERN in Fall 2021: 3 weeks allocated with full intensity μ beam

Location: M2 beam line, upstream of the COMPASS detector, after its BMS (available ~40 m)

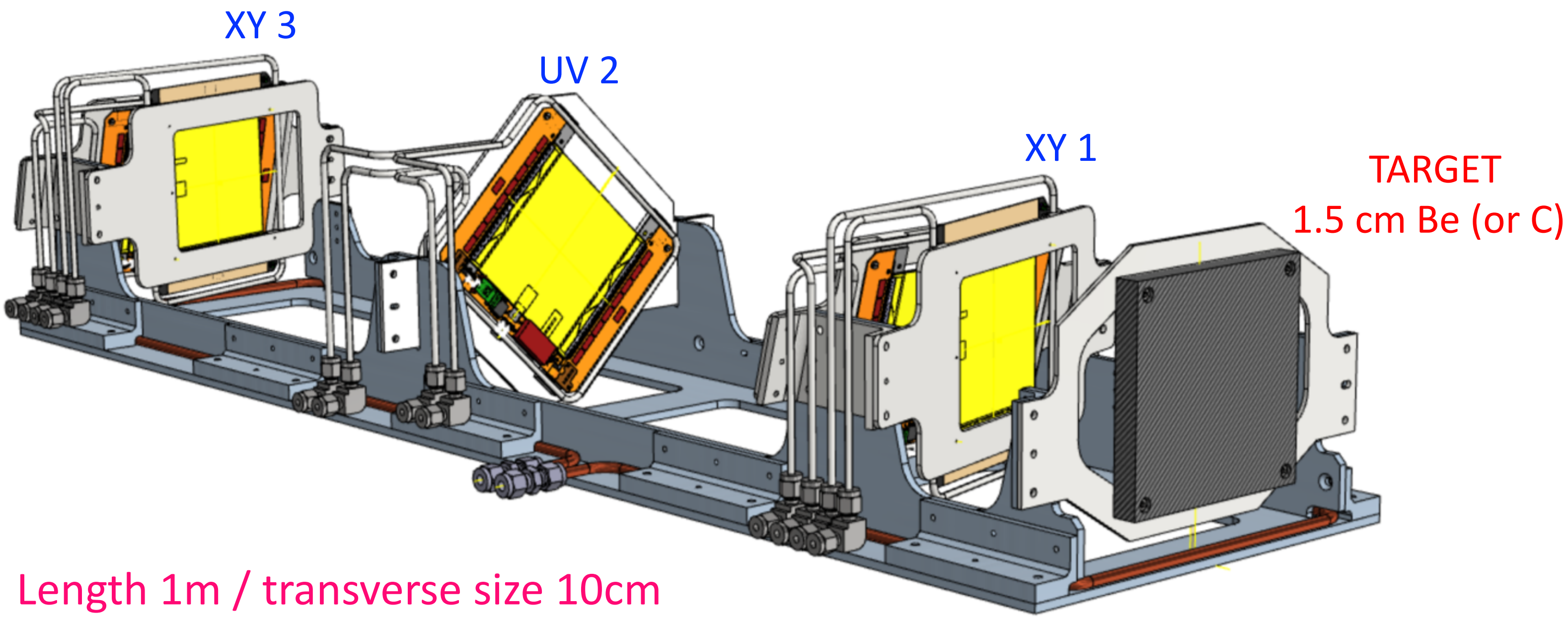


Main objectives:

- Confirm the system engineering
- Check mechanical and thermal stability.
- Test the alignment procedure
- Assess the detector counting rate capability.
- Check the DAQ system.
- Validate the trigger strategy (FPGA real-time processing to identify and reconstruct μ−e events).
- Assess the systematic errors
- After commissioning, take data to measure the leptonic contribution to the running of $\alpha(q^2)$.

If the results are satisfactory proceed to full-scale experiment to be deployed during LHC Run3

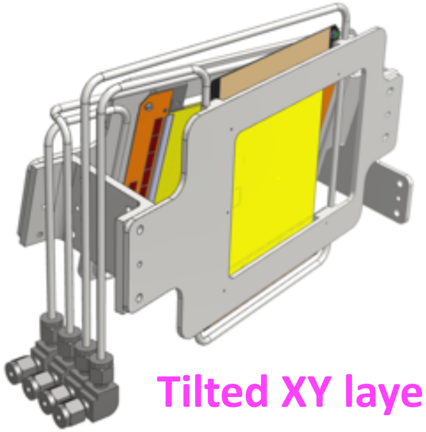
MUonE tracking station



Length 1m / transverse size 10cm
Target followed by 3 tracking layers:
each one is a pair of close-by 2S modules
with orthogonal strips, tilted by 233mrad

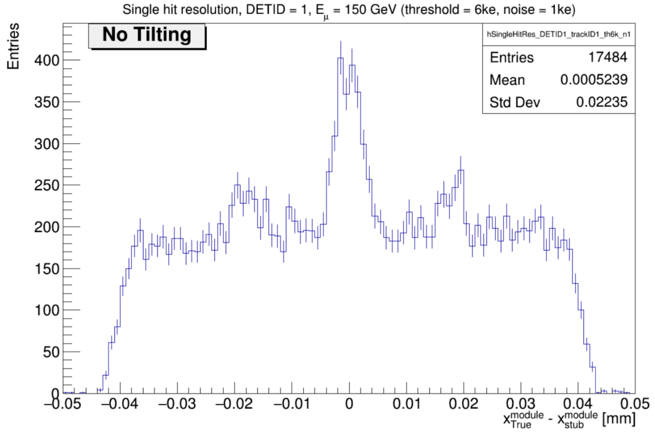
Stringent request: relative positions within the station stable to better than 10μm

Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni)
Cooling system, tracker enclosure, Room temperature stabilized within 1-2 °C



Tilted XY layers

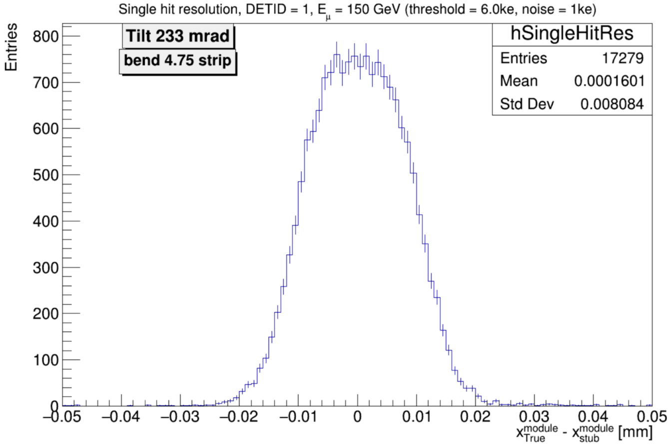
Simulation: Intrinsic Resolution – Tilted geometry



Strip digital readout: with 90μm pitch the expected resolution is 90/sqrt(12)≅26μm on a single sensor layer for single-strip clusters

Tilting a sensor around an axis parallel to the strips →
Charge sharing between adjacent strips, improving the resolution

The best is obtained when <cluster width>~1.5 (same number of clusters made of 1 or 2 strips) for a tilt angle ~15 degrees

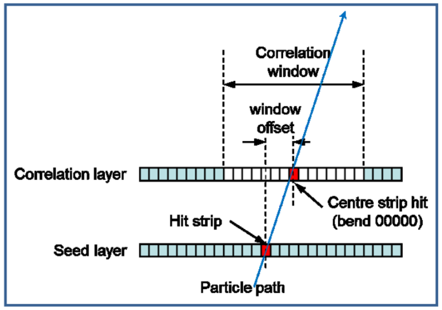


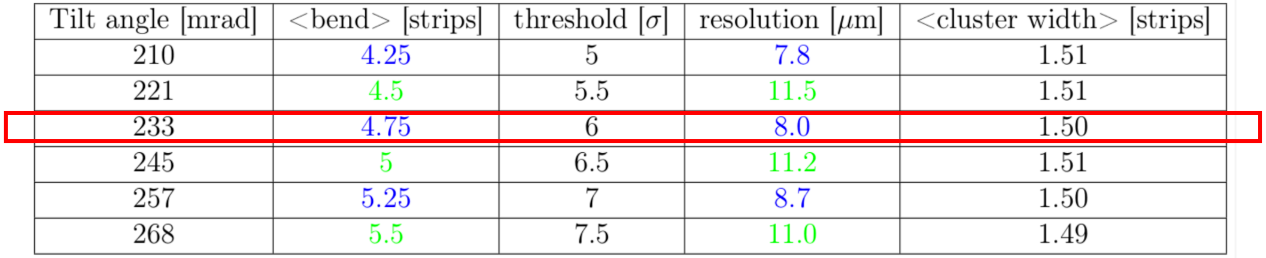
Further improvement: a small tilt of 25mrad is equivalent to an half-strip staggering of the two sensor layers of a 2S module

Final resolution:

22 μm → 8-11 μm

measured coordinate (x) determined by hit position on one layer and direction of the track stub



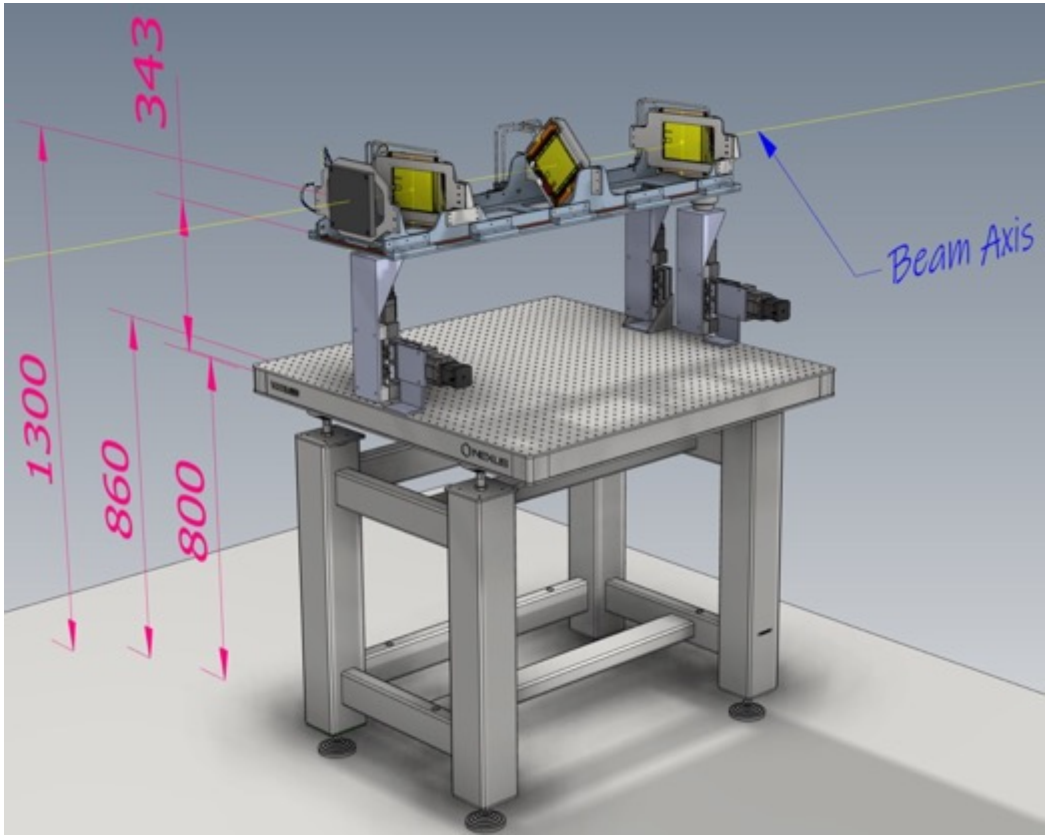


Tilt angle [mrad]	<bend> [strips]	threshold [σ]	resolution [μm]	<cluster width> [strips]
210	4.25	5	7.8	1.51
221	4.5	5.5	11.5	1.51
233	4.75	6	8.0	1.50
245	5	6.5	11.2	1.51
257	5.25	7	8.7	1.50
268	5.5	7.5	11.0	1.49

Tracker mechanics

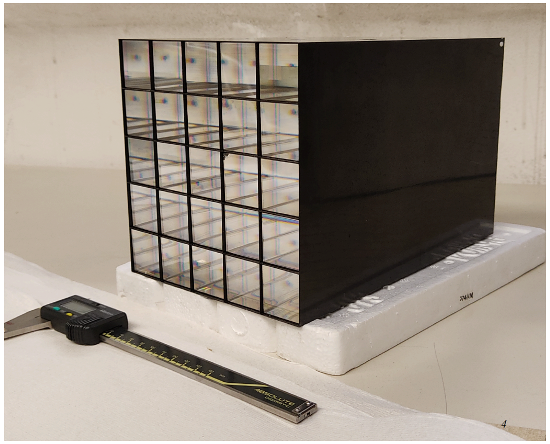
Two aluminium mockups have been built: test mounting of dummy stations, planarity, alignment, cooling system, precision movement system and holographic system

Each station's position/orientation will be precisely adjustable with 3 motorized linear stages allowing to shift on X, Y axes by up to 3cm in steps of 5 μm (by kinematic coupling)



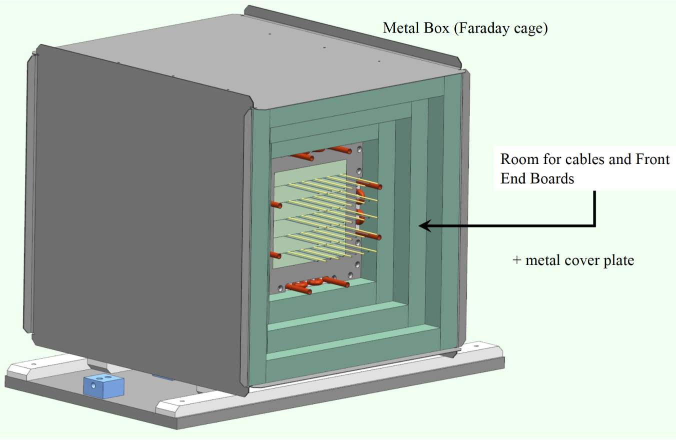
Calorimeter

PbWO4 crystals used by the CMS ECAL
Small 5x5 array, size 14x14 cm^2, length 22cm (24.7 X_0)



Mechanics: Carbon fiber alveolar structure with

- cooling system
- thermal insulation by polyurethane rigid foam panels and temperature control ($\Delta T <\sim 0.1\ ^\circ C$)
  - ➢ Both crystal light yield and APD gain depend on temperature: ($\approx -2\%/^\circ C$ for the crystals, and $\approx -4\%/^\circ C$ for the APDs)
- all cables and fibers on the back face
- movable with mm precision in the two axes perpendicular to beam

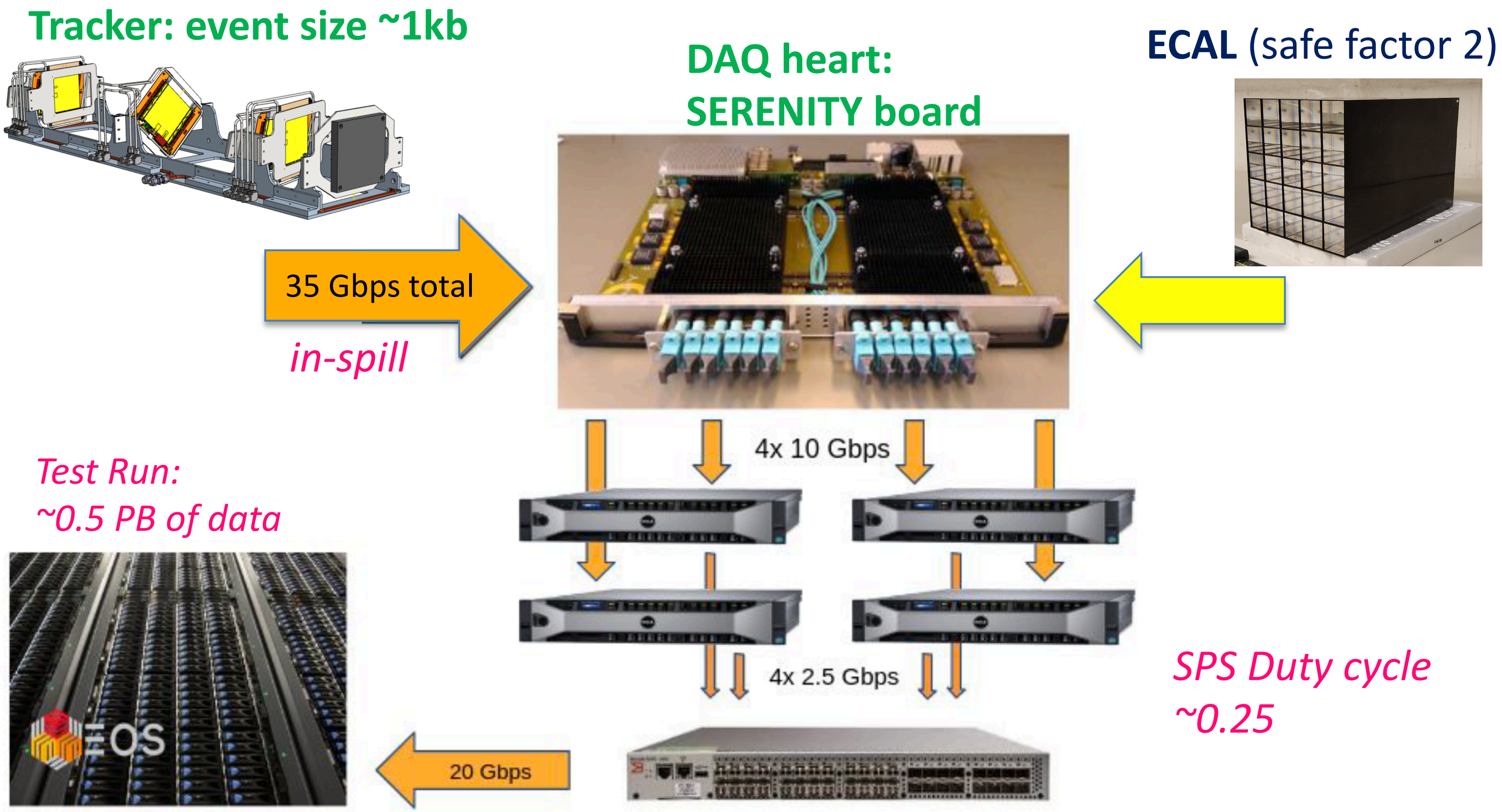


Hamamatsu APD sensor (1 cm^2)

FE electronics linking with Serenity board for DAQ

Laser calibration /monitoring system for APD and FEE gain

DAQ



Tracker: event size ~1kb

DAQ heart: SERENITY board

ECAL (safe factor 2)

35 Gbps total

in-spill

4x 10 Gbps

Test Run:
~0.5 PB of data

4x 2.5 Gbps

SPS Duty cycle
~0.25

20 Gbps

Plan for the Test Run: **NO online selection, read out all data (3 stations)**

FPGA algos will be run online just to tag events and replayed offline for detailed studies

Data taking for ~two weeks, SPS efficiency ~2/3 → **~0.5 PB of data**

The Test Run will be a proof of concept for the MUonE DAQ

Status / plans for the Test Run

- **Tracker:** delays (few months) in the procurement of the 2S modules (bottleneck: hybrids' production) due to Covid-19
  - Unlikely to have more than one MUonE tracking station fully integrated and ready for beam test in Fall 2021
  - Situation still subject to unpredictable changes
- **Calorimeter**: tight schedule but original plan still feasible
- **DAQ**: good progress, but partly related to the availability of tracker modules

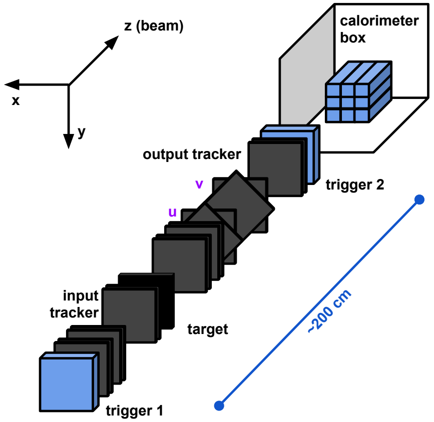
MUonE plans to have the Test Run at the end of 2021 even with a partial setup

- *In this case with reduced objectives, mainly detector commissioning in real conditions of beam and environment*
- *If so we will consider the request of some time in early 2022, according to which conditions will have been realized in 2021.*

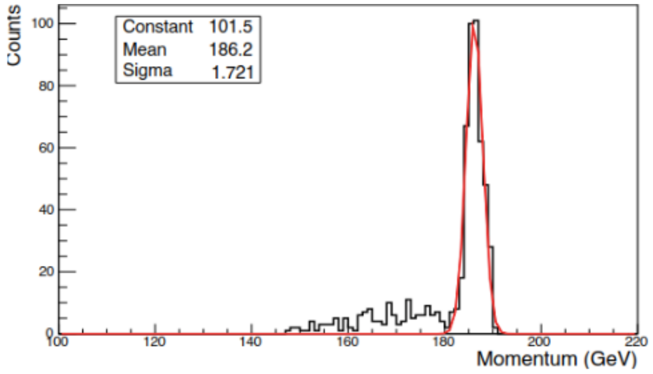
2018 Beam Test: μe elastic scattering

arXiv:2102.11111

CERN North Area, downstream COMPASS
8mm C target
Si strip tracking (sensors from AGILE, with worse resolution than MUonE)
Small BGO ECAL

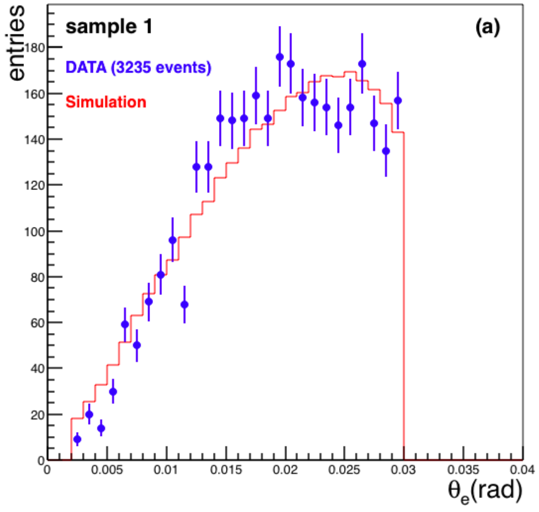


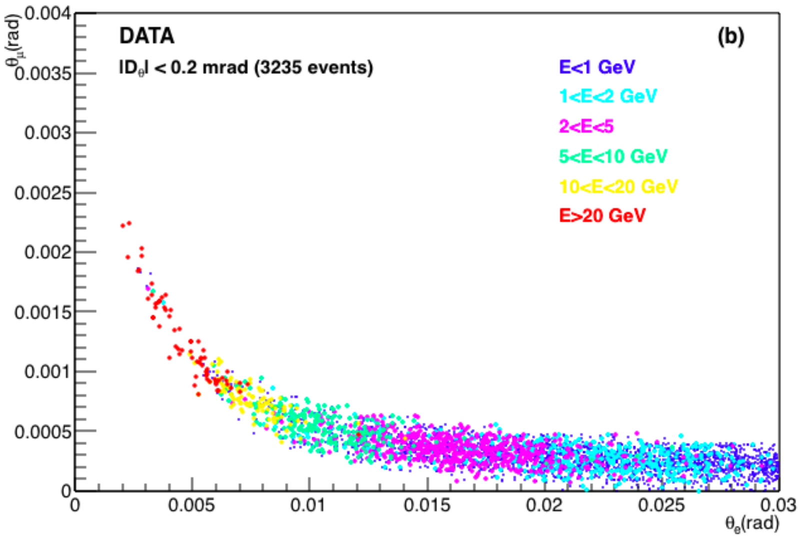
μ spectrum peaked at 187 GeV
From decays of 190 GeV beam π
1m W dump absorbing all surviving π



Setup with lower performance than MUonE (σ_X~35μm)

Selection of a clean sample of elastic events





Important: Simulation of Background processes in part. e^+e^- pair production

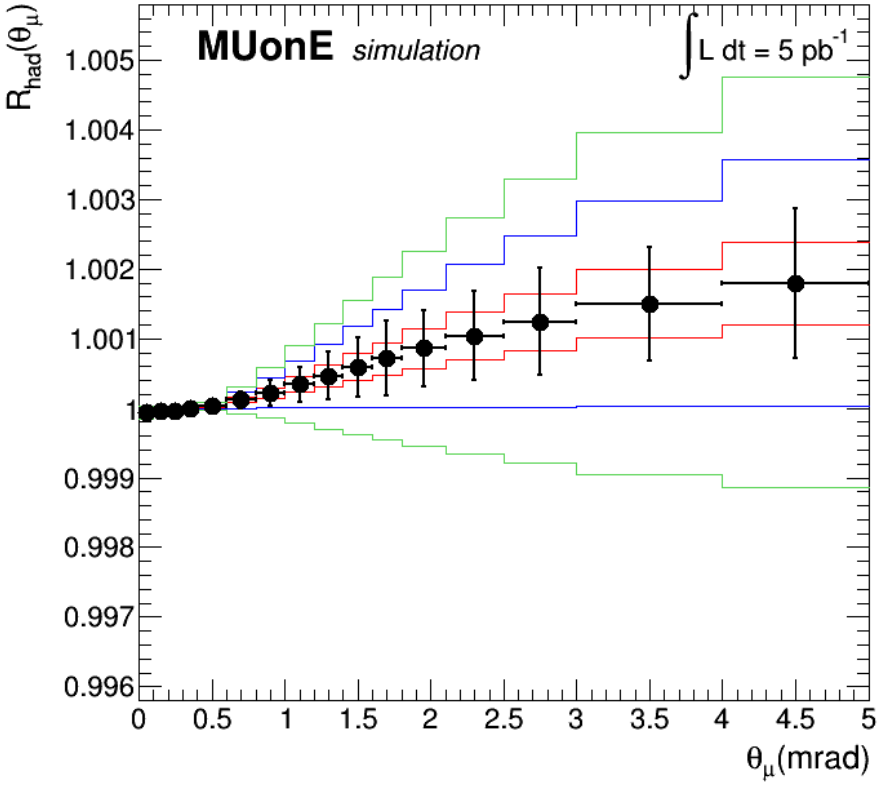
New GEANT4 version 10.7 (validation ongoing)

Expected sensitivity of a First Physics Run

Expected integrated Luminosity with the Test Run setup with full beam intensity & detector efficiency ~ $1 pb^{-1}$/day

In one week ~$5pb^{-1}$ → ~10^9 μe scattering events with $E_e > 1$ GeV ($\theta_e < 30$ mrad)

arXiv:2012.07016



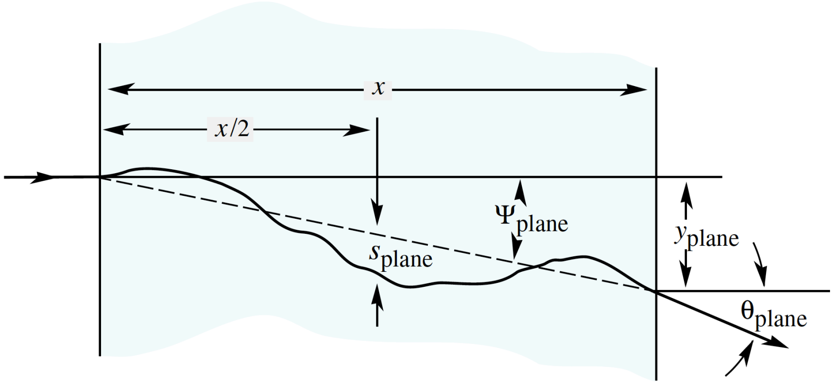
Initial sensitivity to the hadronic running of α.

Pure statistical level: 5.2σ
2D (θ_μ,θ_e) K=0.136 ± 0.026

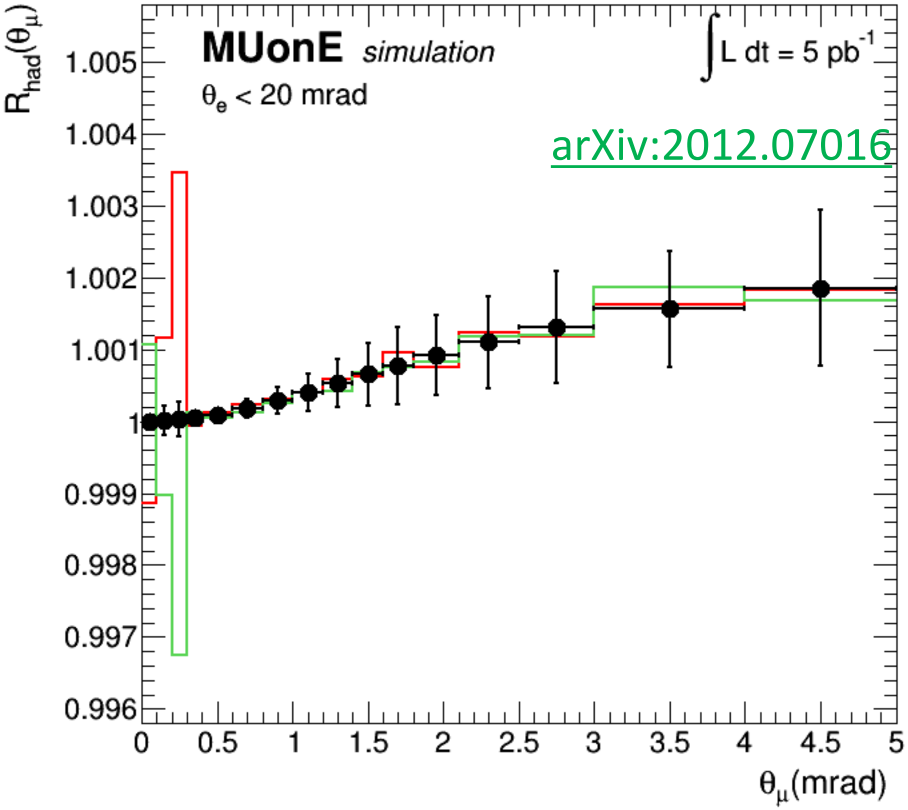
Definitely we will have sensitivity to the leptonic running (ten times larger)

Template fit with just one fit parameter K= k/M in the $\Delta\alpha_{had}$ parameterization.
The other parameter fixed at its expected value: M = 0.0525 GeV^2

Systematic Effects: Multiple Coulomb Scattering



Particle trajectories disturbed: especially low-energy electrons



arXiv:2012.07016

Effects of a flat error of ±1% on the core width of multiple scattering

Multiple scattering previously studied in a Beam Test in 2017: JINST 15 (2020) P01017 with 12–20 GeV electrons on 8-20 mm C targets

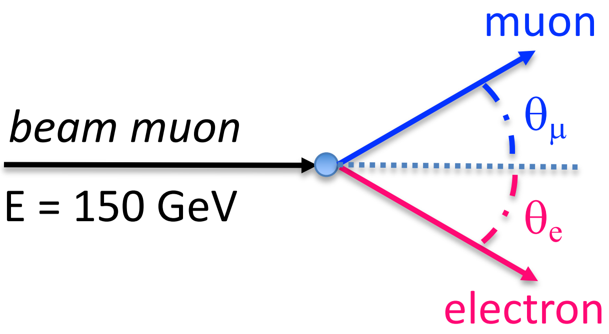
Systematic Effects: Beam Energy scale

Time dependency of the beam energy profile has to be continuously monitored during the run:

- SPS monitor
- COMPASS BMS

} needed external infos

However, the absolute beam energy scale has to be calibrated by a physics process: kinematical method on elastic μe events



For equal angles:

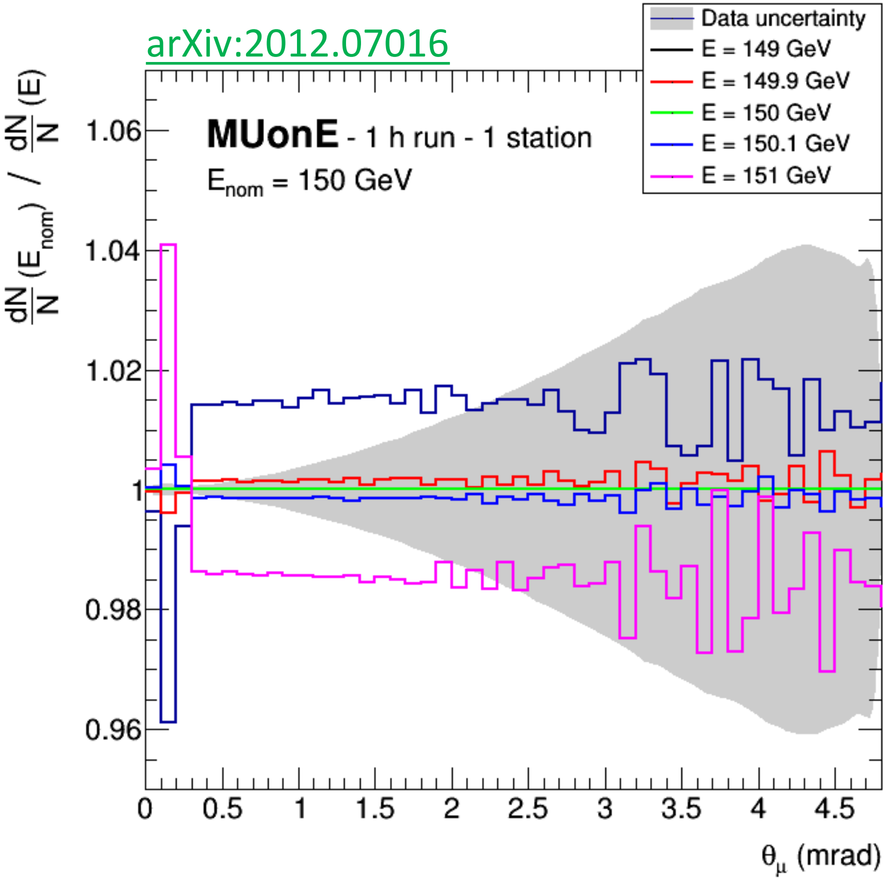
$\theta_\mu = \theta_e \equiv \theta$

$$\theta \simeq \sqrt{\frac{2m_e}{E}}$$

Can reach <3 MeV uncertainty in a single station in less than one week

From SPS E scale ~1% : 1.5 GeV

arXiv:2012.07016



Effect of a syst shift of the average beam energy on the θ_μ distribution: 1h run / 1 station

Theory

Impressive progress

STATUS: report of the **MUonE theory initiative**

"Theory for muon-electron scattering @ 10ppm", P.Banerjee et al, Eur.Phys.J.C80(2020)591

NLO exact calculation including masses (m_μ, m_e) and EWK corrections in a fully differential MC code
M.Alacevich et al, JHEP02(2019)155 cross-checked with independent calculation by Fael & Passera

Full NNLO not yet available

- Two-loop master integrals ($m_e=0$, $m_\mu \neq 0$)
  planar P.Mastrolia et al, JHEP11(2017)198 and non-planar S.Di Vita et al, JHEP09(2018)016
- NNLO hadronic corrections: M.Fael,M.Passera, Phys.Rev.Lett.122(2019)192001; M.Fael, JHEP02(2019)027
- Framework to recover leading m_e terms at NNLO from amplitudes calculated with massless electrons:
  T.Engel et al., JHEP02(2019)118, JHEP01(2020)085
- Two independent fully exclusive NNLO MC codes, featuring the exact NNLO photonic corrections on the leptonic legs, including all mass terms: C.Carloni Calame et al., arXiv:2007.01586; P.Banerjee et al, arXiv:2007.01654

➡ **VERY GOOD AGREEMENT between the two codes**

Resummations (Parton shower and YFS) matched to (N)NLO fixed order under way

Study of possible contaminations from NEW physics on MUonE:

A.Masiero, P.Paradisi and M.Passera, arXiv:2002.05418
P.S.Bhupal Dev et al., JHEP05(2020)53

→ **MUonE is NOT vulnerable !**

Summary

- **Long-standing puzzle of muon g-2:**
  - Experiment-Theory(SM) discrepancy 3-4σ
  - sensitive to BSM physics
  - Ongoing/future experiments will reduce the exp.error by a factor of 4
  - Theory error dominated by the Leading Hadronic contribution a_μ^{HLO}
- **MUonE** experiment proposal: measuring the running of α_{QED} from the shape of the differential cross section for elastic scattering of μ(150GeV) on atomic electrons at the CERN SPS Eur.Phys.J.C77(2017)139
  - Getting a_μ^{HLO} with a novel method integrating over the space-like region
  - Independent and complementary to the standard method integrating over the time-like region and to lattice QCD calculations
  - Competitive precision ~0.35-0.5% on a_μ^{HLO} allowing to better constrain the theory prediction , will help to solve the puzzle
- Letter-Of-Intent SPSC-I-252 submitted to CERN in June 2019
- **CERN has recognized the fundamental interest** and **approved a Test Run to be carried out at the end of 2021, which should verify the detector design and assess the potential to achieve a competitive measurement, as a condition to move on towards the full-scale experiment.**
  - Main challenge: control of systematic effects at the level of the statistical precision
- Full-scale experiment foreseen during LHC Run3 (2022-2024) if results of the Test Run are satisfactory
- Delays in the Test Run preparation related to the Covid-19 pandemic, need to follow up the evolving situation

BACKUP

Muon anomalous magnetic moment

$$\vec{M}_l = g_l \frac{e}{2m_l} \vec{S}$$

Dirac eq : $g_l = 2$

Quantum corrections → the anomaly

$$\boxed{a_l \equiv \frac{g_l - 2}{2}}$$

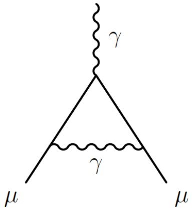
This observable can be both precisely measured experimentally and predicted in the Standard Model, providing a stringent test of the SM.

E821 experiment at BNL :
[Phys.Rev.D73 (2006) 072003]

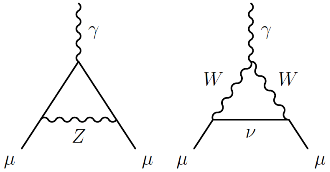
$$a_\mu^{E821} = 11659209.1(5.4)(3.3) \times 10^{-10}$$

0.54 ppm
Dominated by statistics

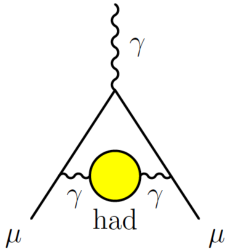
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had}$$



QED corrections known up to 5 loops, rel. precision ~7×10^{-10}
LO term (Schwinger) = $\alpha/2\pi$ ~ 0.00116



EWK corrections ~ 10^{-9}
rel. uncertainty <1%



Hadronic contribution ~ 7×10^{-8}

-not calculable by pQCD-

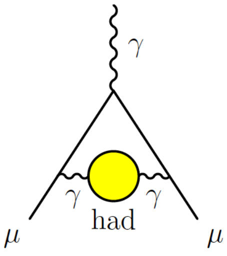
Main contribution: LO Vacuum Polarization

estimated rel. uncertainty 0.6%

Dominant Theoretical uncertainty

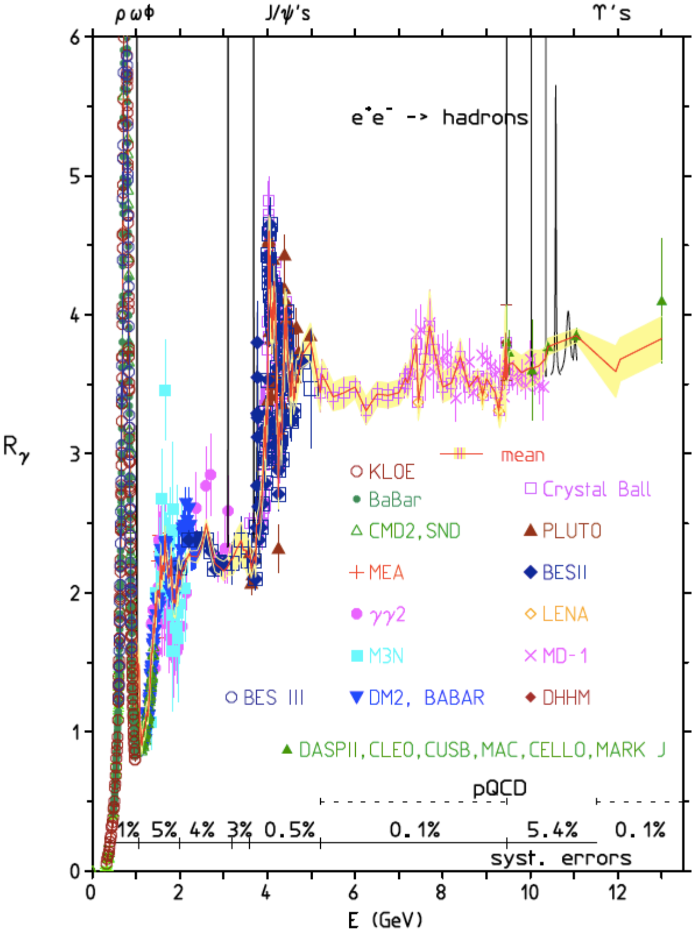
a_μ^{HLO}: standard data-driven approach (time-like)

Dispersion relations, optical theorem:



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

F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016



$R_{had}(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

K smooth function

Traditionally the integral is calculated by using the experimental measurements up to an energy cutoff, beyond which perturbative QCD can be applied.

Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

Alternative: **Lattice QCD calculations**

continuously progressing, expected to become more and more competitive in the near future

a_μ^{HLO}: the MUonE approach (space-like data)

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, Phys.Lett.B746(2015)325

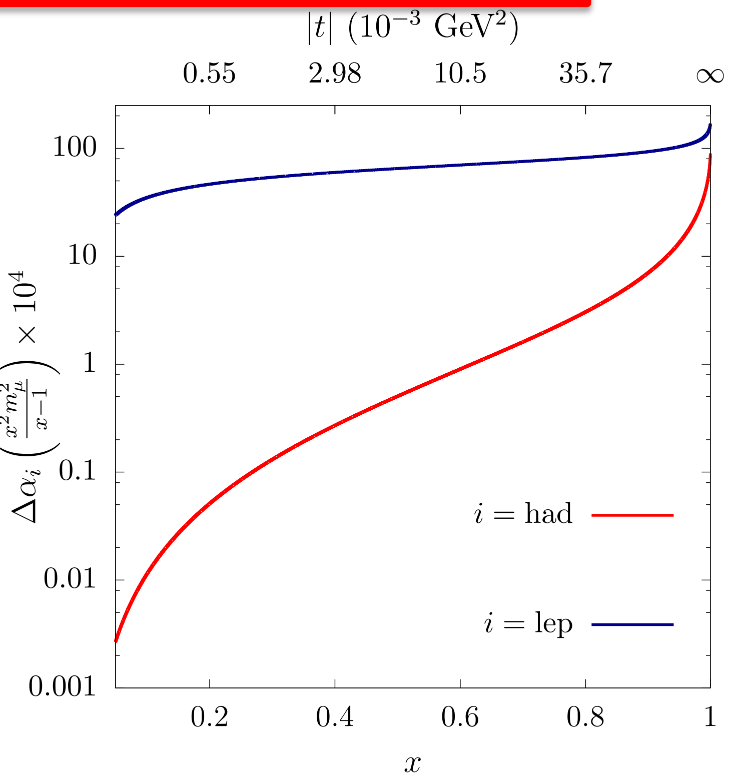
$$\boxed{a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]}$$

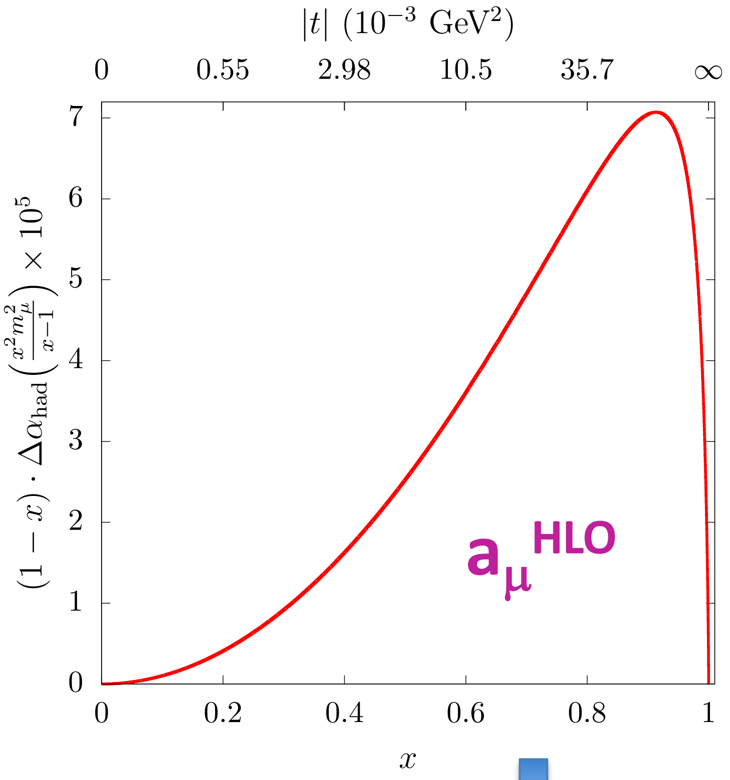
$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad \begin{array}{l} 0 \le -t < \infty \\ 0 \le x < 1 \end{array}$$

$\Delta\alpha_{had}$ is the hadronic contribution to the running of α in the space-like region ($t<0$)

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$



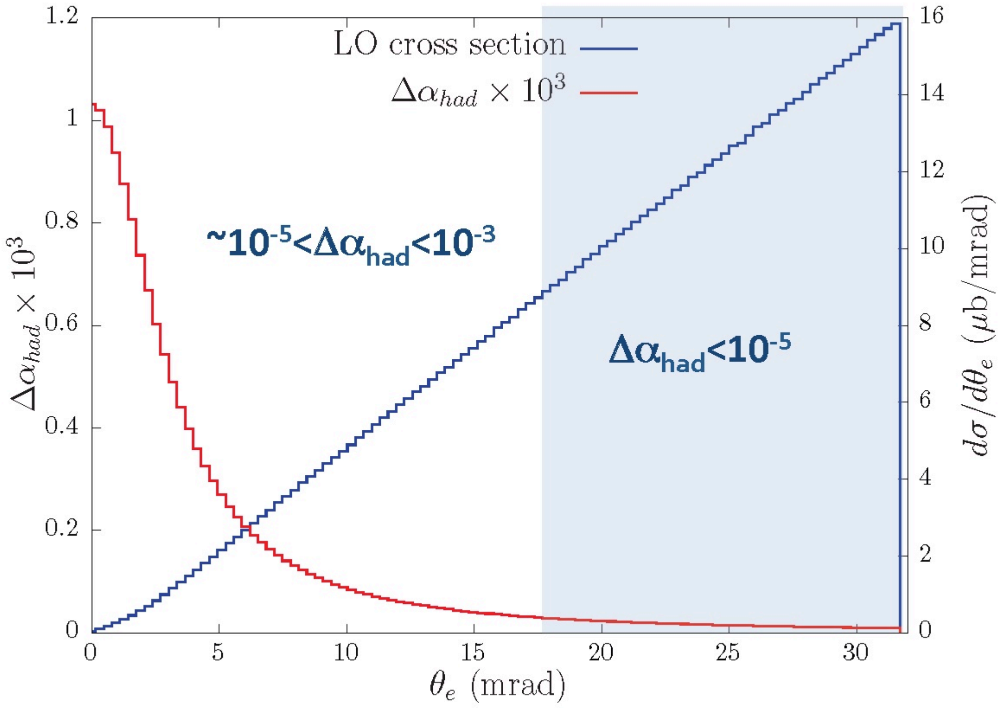


Integrand function smooth: no resonances

Low-energy enhancement:

peak of the integrand at $x \cong 0.9$ → $t = -0.11$ GeV^2 → $\Delta\alpha_{had} \sim 10^{-3}$

LO μ-e elastic scattering



$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{\lambda(s, m_e^2, m_\mu^2)}\left[\frac{(s - m_e^2 - m_\mu^2)^2}{t^2} + \frac{s}{t} + \frac{1}{2}\right]$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)} \qquad \Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

Simple kinematics: $t \cong -2\, m_e\, E_e$

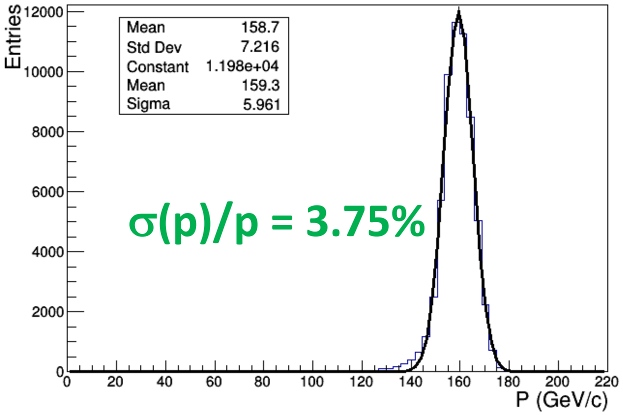
E_e can be determined from the scattering angle θ_e and the beam energy

Location @ CERN & M2 beam parameters

MUonE Letter-Of-Intent SPSC-I-252

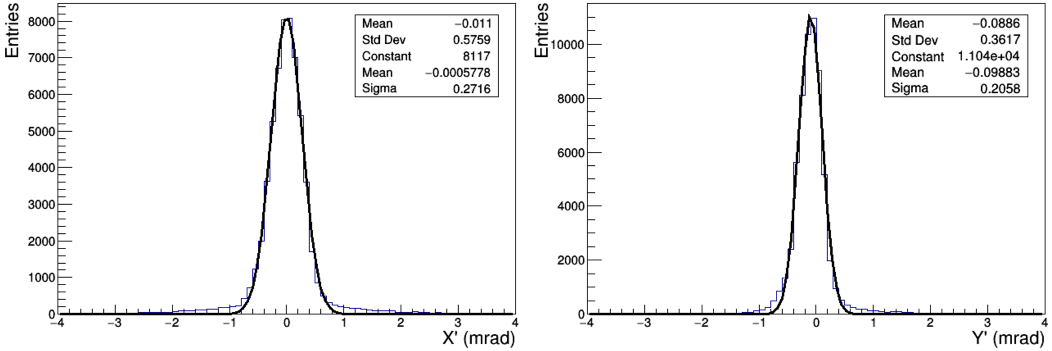
Upstream of the COMPASS detector, after its Beam Momentum Station (BMS), on the M2 beam line : available ~ 40 m

Beam Momentum

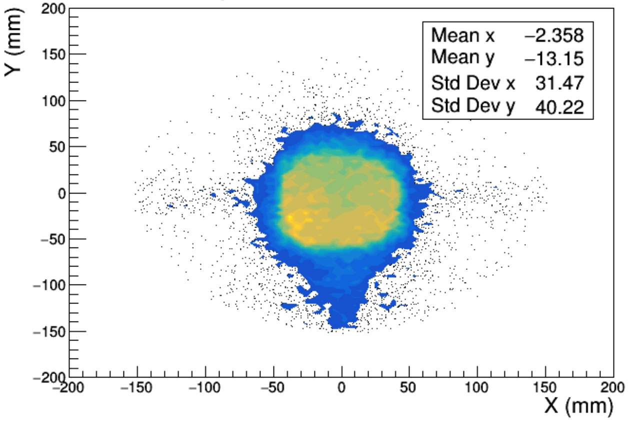


$\sigma(p)/p = 3.75\%$

Very small divergence ~0.2-0.3 mrad



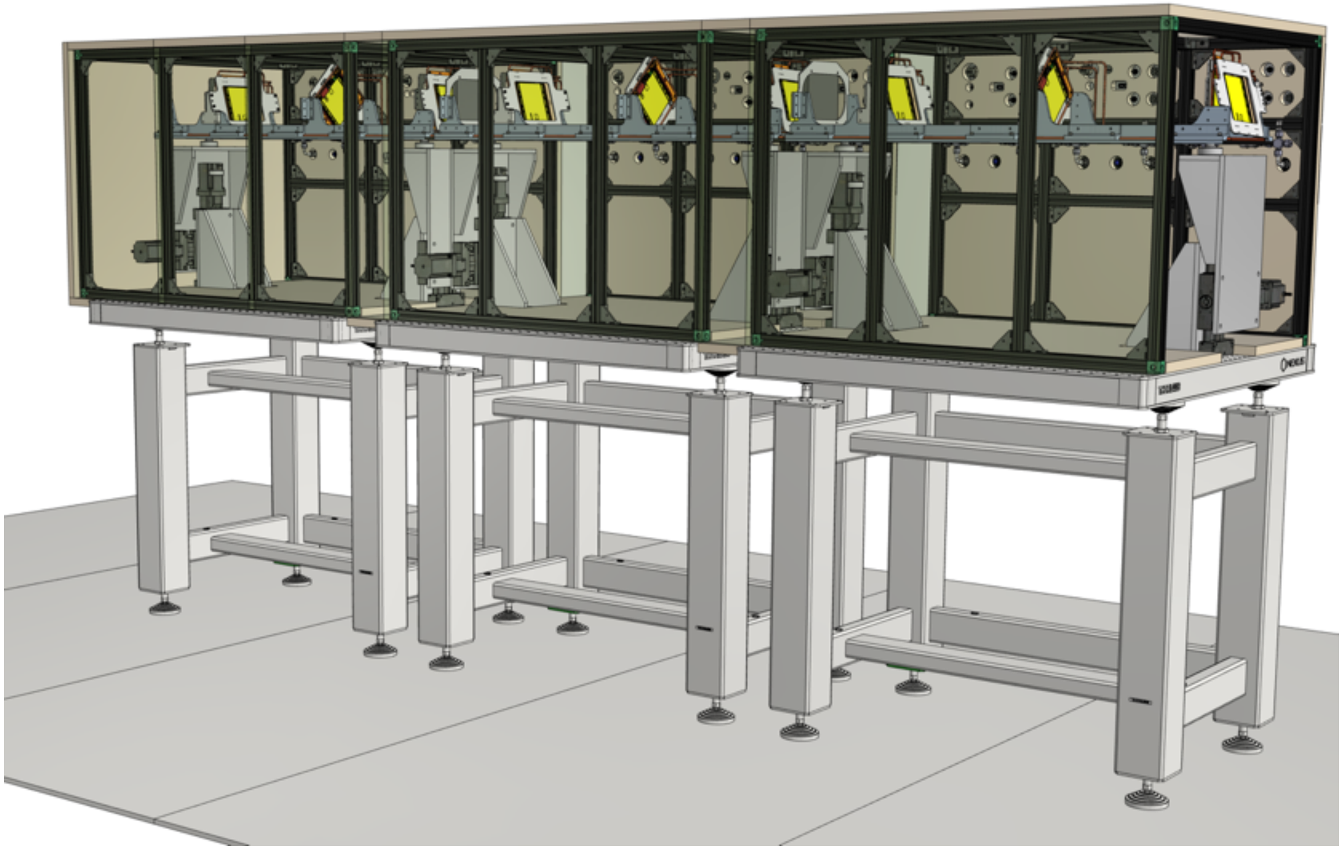
Beam spot size $\sigma_X \sim \sigma_Y \sim 3$cm



M2 beam typical max intensity: 5×10^7 μ/s

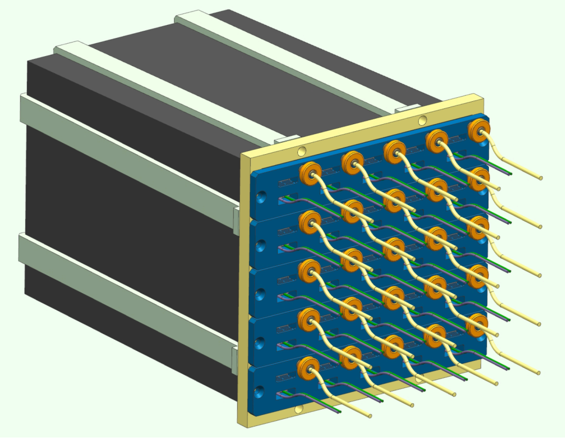
SPS Fixed Target cycle ~15-20 s / Spill duration ~ 5s

Tracker mechanics (2)

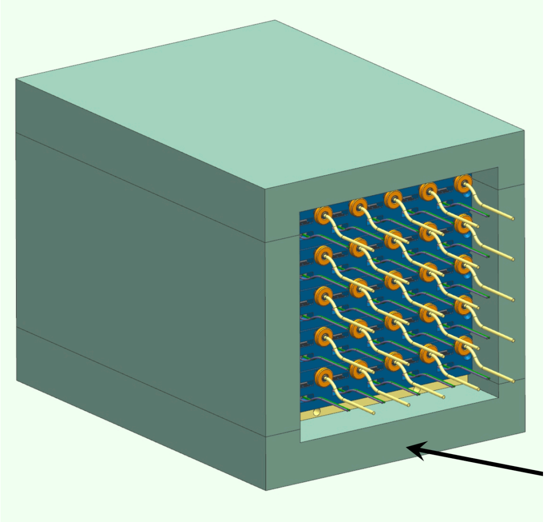


- Tracker enclosure shielding from light and to stabilise thermally
- Electrical, optical and hydraulic connections on the top, removable side panels
- Further complemented by a surrounding tent containing also the calorimeter, with chiller stabilising the room temperature

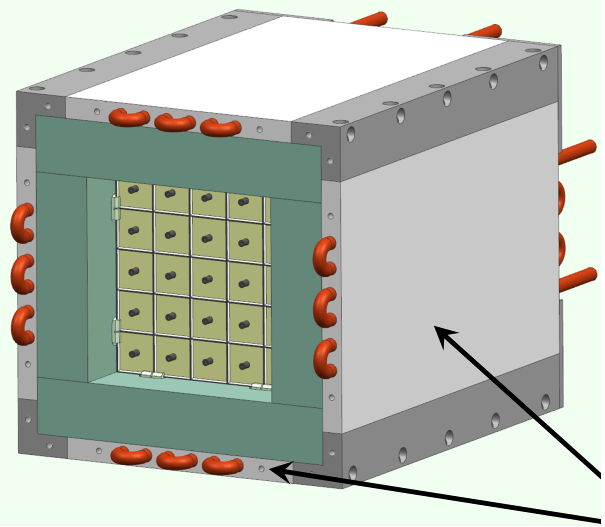
Calorimeter (2)



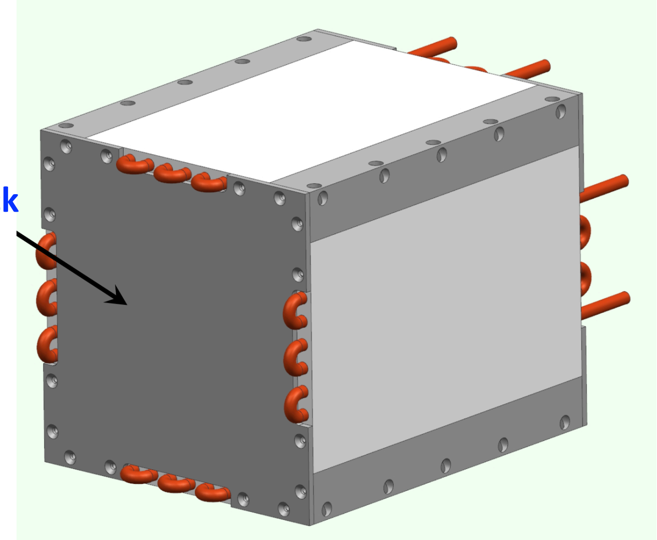
BACK Side



Thermal insulator



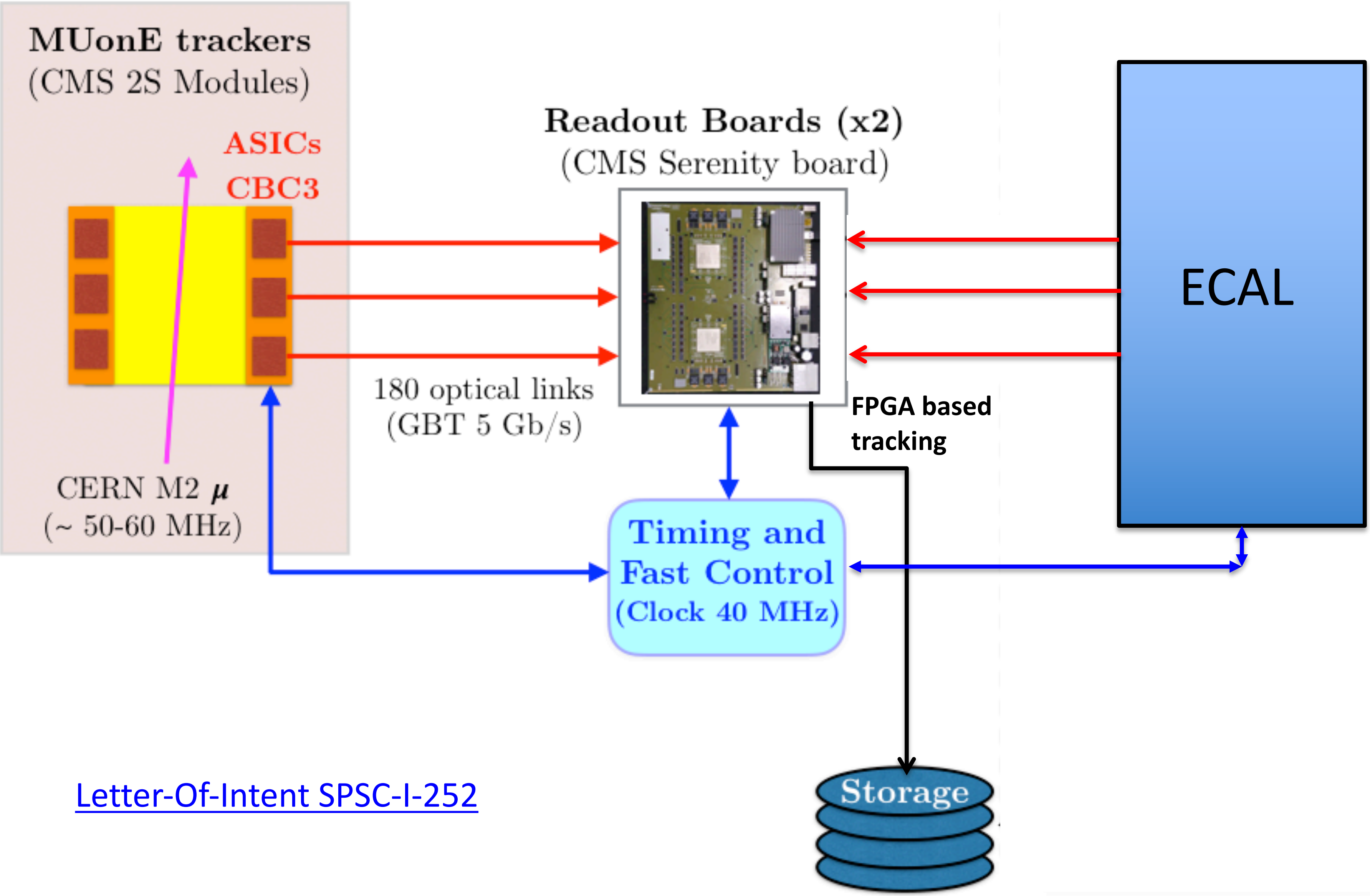
FRONT Side



5mm thick
Al foil

Aluminum plates
with embedded
cooling pipes

The DAQ and trigger system



Letter-Of-Intent SPSC-I-252

$\Delta\alpha_{had}$ parameterization

Physics-inspired from the calculable contribution of lepton-pairs and top quarks at t<0

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

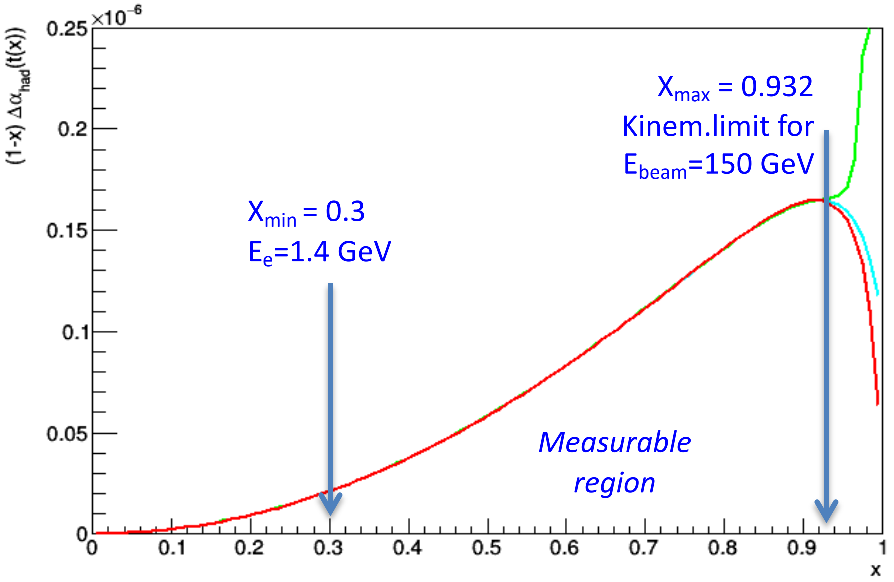
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

Low-|t| behavior dominant in the MUonE kinematical range:

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

a_μ^{HLO} calculable from the master integral in the FULL phase space with this parameterization.

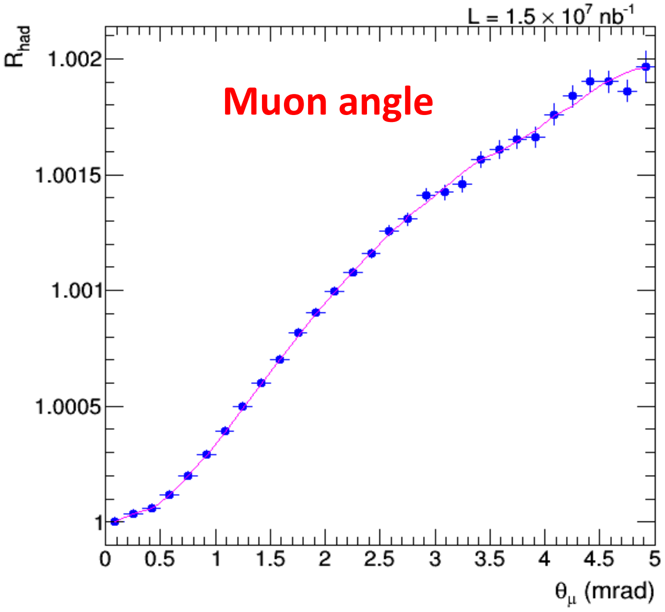
Instead simple polinomials diverge for x->1 (green is a cubic polinomial in t)

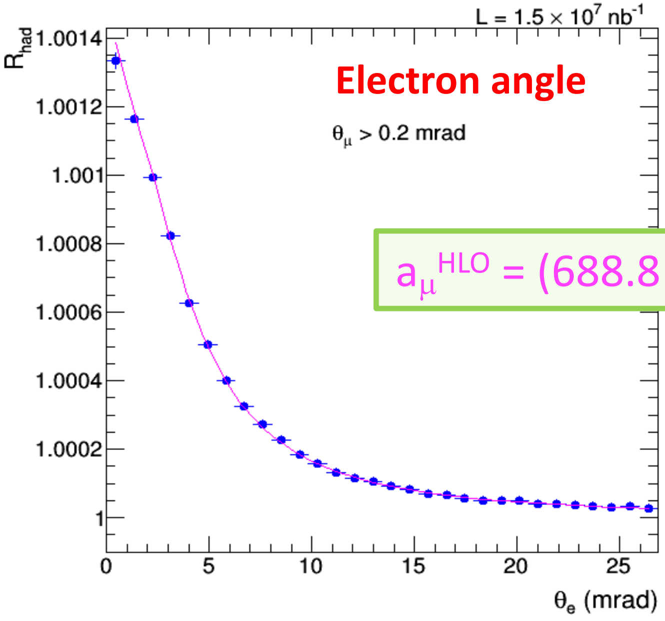


Extraction of the hadronic running of α

Most easily displayed by taking ratios of the observed angular distributions and the theory predictions evaluated for $\alpha(t)$ corresponding to only the leptonic running.
Observable effect ~ 10^{-3} / wanted precision ~10^{-2} → required precision ~10^{-5}

Example toy experiment shown with statistics corresponding to the nominal integrated Luminosity L = 1.5×10^{7} nb^{-1} (corresponding to 3-year run)



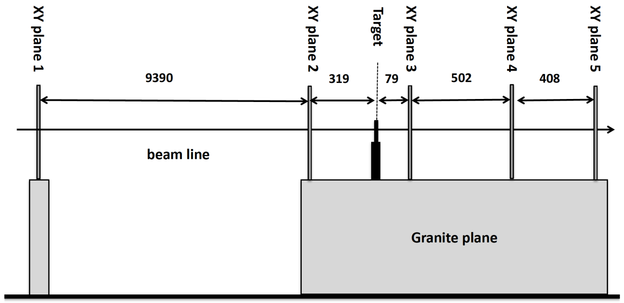


$a_{\mu}^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$

Template fit to the 2D angular distribution from NLO MC generator with parameterised detector resolution.
$\Delta\alpha_{had}(t)$ parameterised according to the "Lepton-Like" form. Shape-only χ^2 fit.

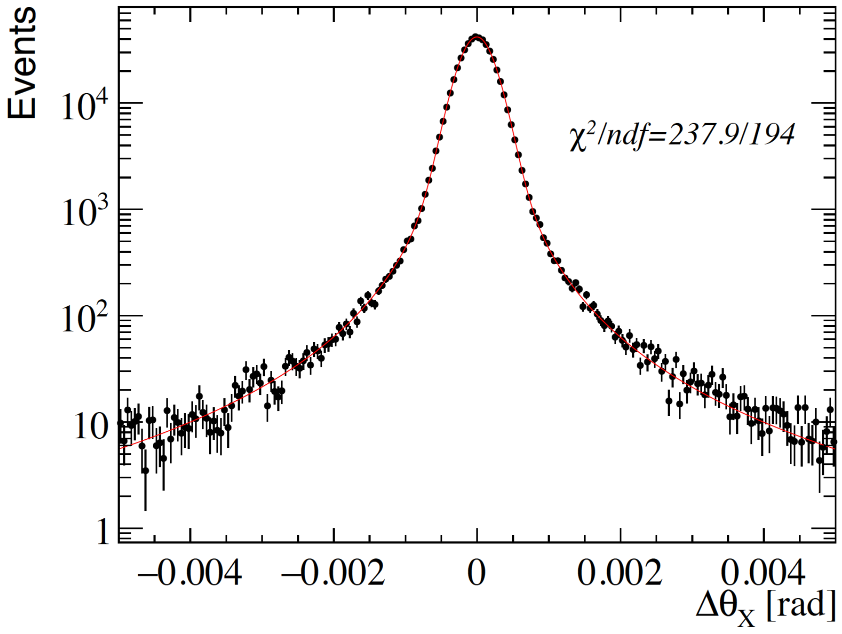
Multiple Coulomb scattering

Studied in a Beam Test in 2017:
JINST 15 (2020) P01017
12–20 GeV electrons
on 8-20 mm C targets

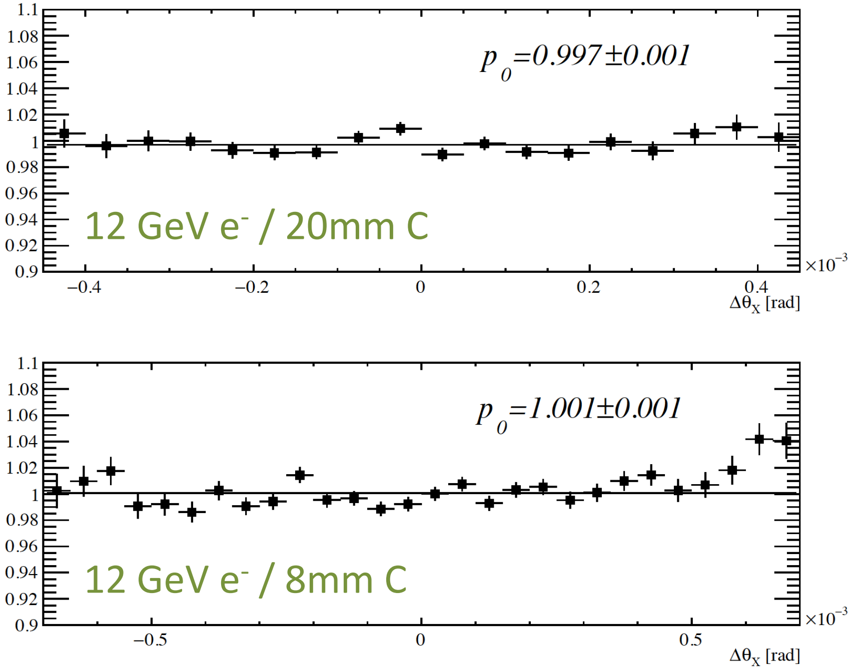


Adapted UA9
detector at CERN
H8 Beam Line

DATA 12 GeV e- / 8mm C



DATA/MC (Geant4) comparison



- Good description of data with a fit.
- Distribution core within 1-few % from GEANT.

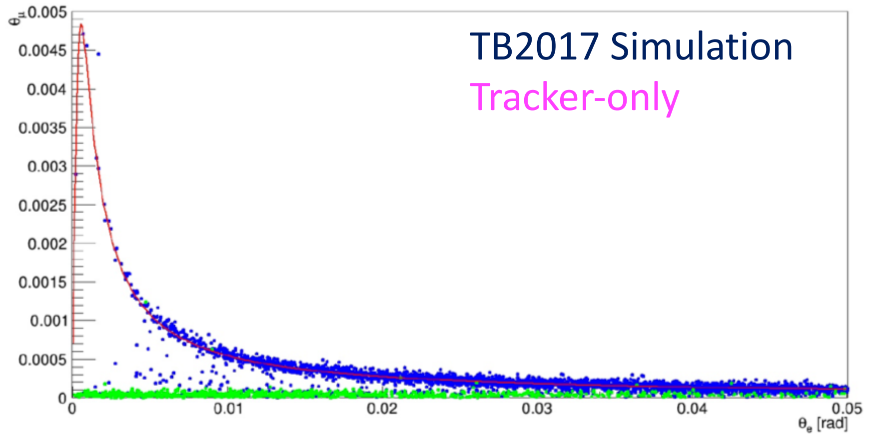
GEANT4 simulations

Effect of the tracker position resolution on θ_μ vs θ_e distribution:

(Left) TB2017: UA9 resolution $7\mu m$; (Right) TB2018: resolution ~35-40μm

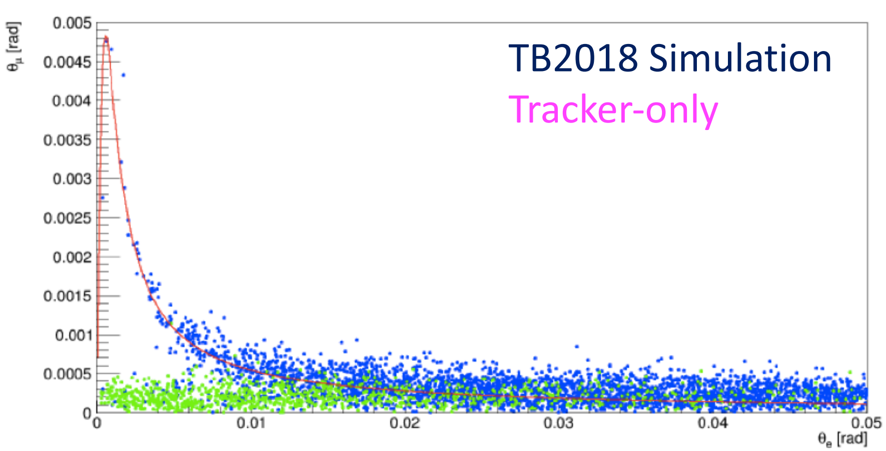
Signal: elastic μe

Background: e^+e^- pair production



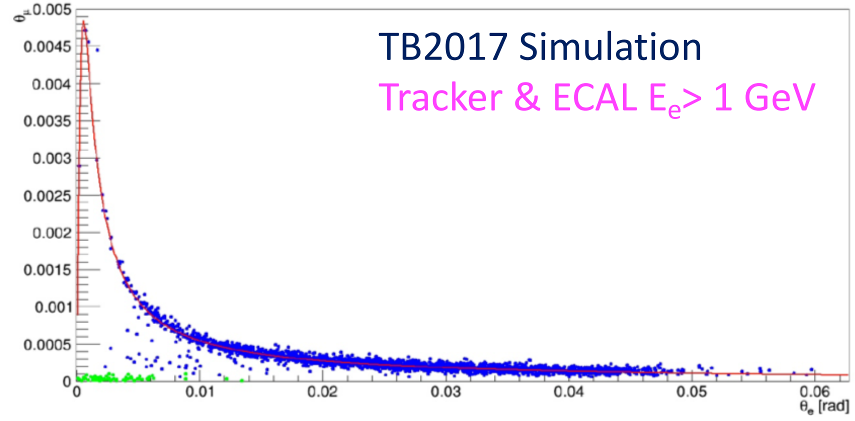
TB2017 Simulation

Tracker-only



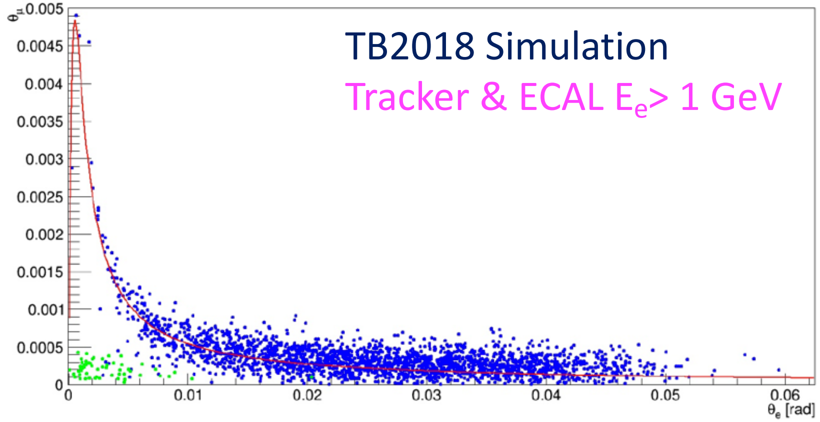
TB2018 Simulation

Tracker-only



TB2017 Simulation

Tracker & ECAL E_e> 1 GeV



TB2018 Simulation

Tracker & ECAL E_e> 1 GeV