The **MUonE project:**

Measuring the running of α(t) in the space-like region

A proposal for measuring a_μ^{HLO} contribution from

$\mu + e \longrightarrow \mu + e$ elastic scattering

Clara Matteuzzi
SPSC 21/01/2020

On behalf of the MUonE Collaboration

Outline

- ★ **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:

G. Abbiendi et al., Eur. Phys. J. C (2017) 77:139. doi :10.1140/epjc/s10052-017-4633-z.

Physics motivations

1. Will measure the running of α_{em} in the space-like region, accessing the leptonic and hadronic contributions

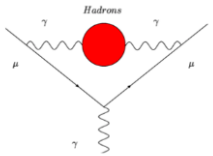
$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\text{lept}}(t) - \Delta\alpha_{\text{had}}(t)}$$

testing QED at unprecedented precision *(collaboration with theoretists is fundamental)*

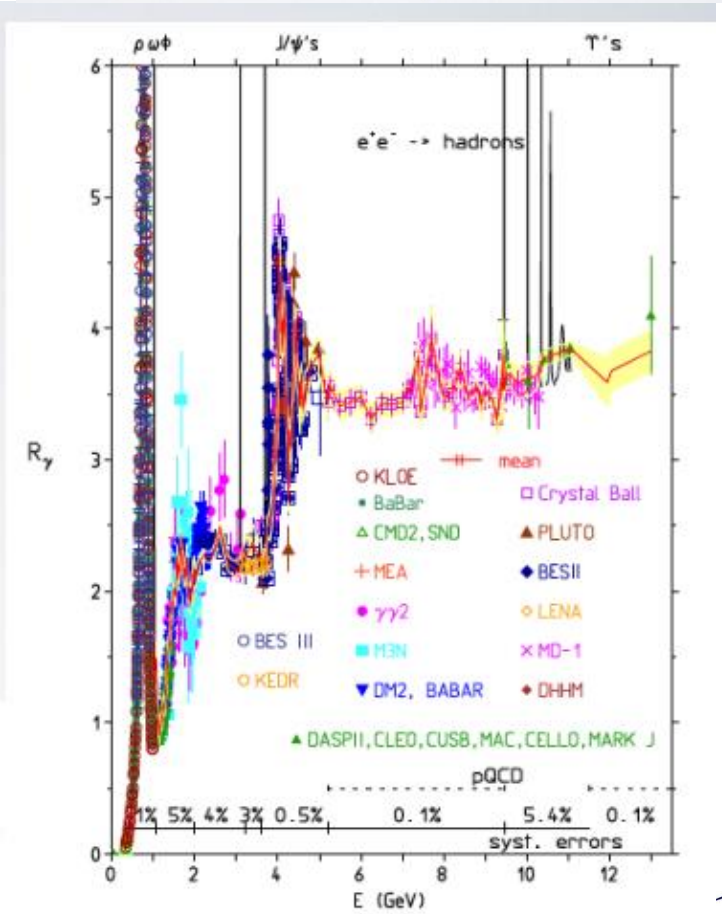
2. In the context of $(g\text{-}2)_\mu$, the measurement of the hadronic contribution to the running of α with MUonE is completely independent and complementary to the time-like method, and will make the theoretical expectation more precise

Physics motivations *(the running of α)*

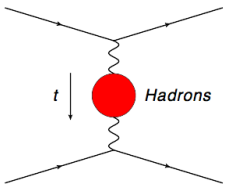
Time-like evaluation



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

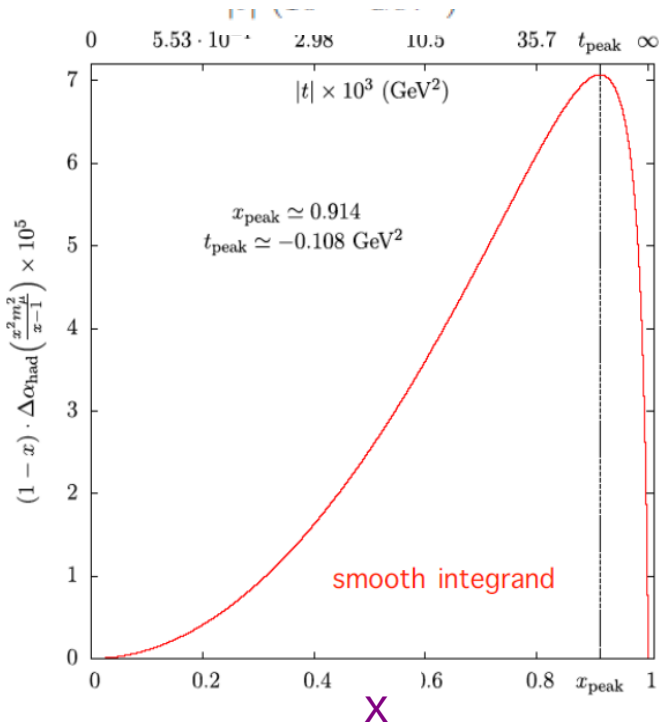


Space-like approach



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

$|t|$ (10^{-3} GeV^2)



$a_\mu^{\rm HLO}$ is the total area under this curve

Physics motivations *(g-2 SM prediction)*

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

The *muon g-2* is measured with high precision:

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

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

New expt result from FNAL in 2020

It shows a long standing ≈ 4σ deviations from the Standard Model prediction:

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

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

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

- 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 $g-2$

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

constitutes the main uncertainty of the SM predictions

Why μ + e → μ + e ?

μ 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 α and in particular to the hadronic component α_μ^{HLO}

- A high intensity (~1.3×10^7 μ/s) muon beam is available in the North Area at CERN with **E_{beam} ~ 150 GeV**

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

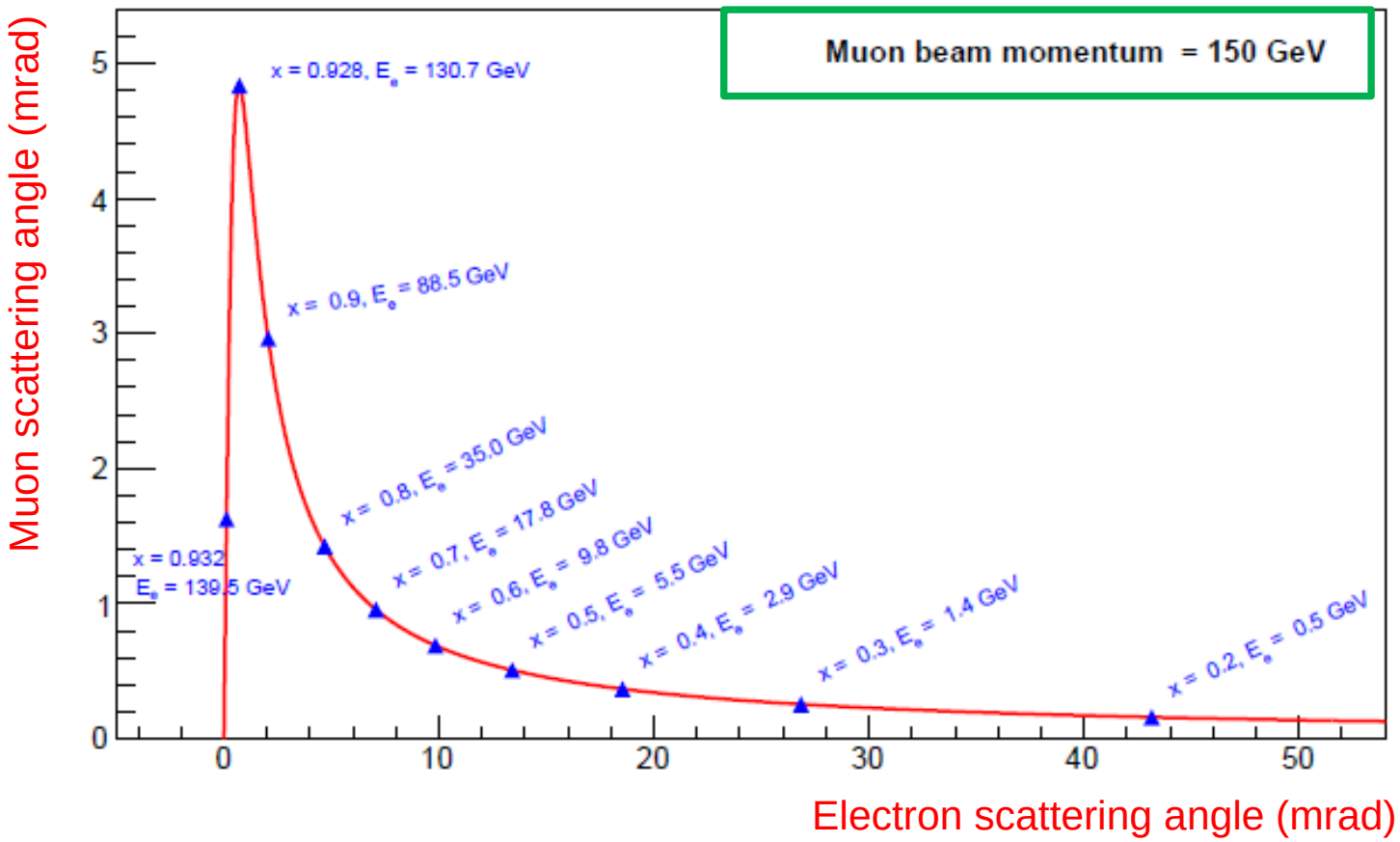
$$-0.143 \lesssim t < 0 \text{ GeV}^2 \qquad 0 < x \lesssim 0.93$$

➡ *(it spans the peak)*

- The same detector can cover **signal (x > 0.4 – 0.5)** and **normalization (x $\leq$ 0.3)** regions

The kinematics: *correlation curve*

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



The constraint is useful to select elastic events, reject background and reduce systematics in *t* determination around 2-3 mrad *μ* and *e* overlap, to be resolved by *μ/e* identification
Multiple scattering breaks the correlation: simulation and data will help to optimize the detector and reduce the systematics

Tools to do the measurement

A high energy muon beam *(must cover the **t** range needed)*

the beam **M2 at CERN** has the characteristics **($E_\mu \approx 150$ GeV, $\sim 1.3 \times 10^7$ μ/s)** adequate for such a measurement.

The target : atomic electrons must be provided by a light material,

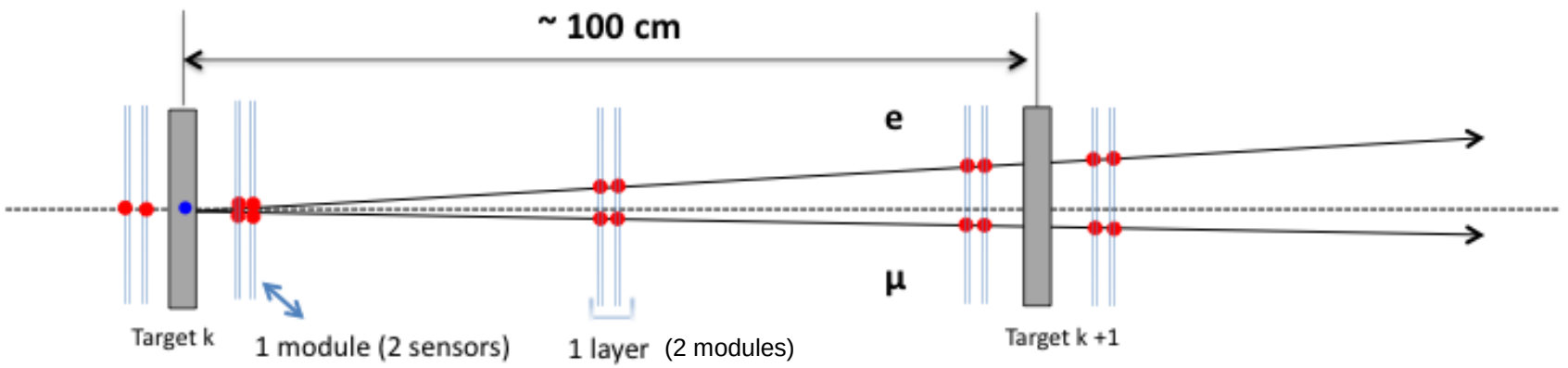
to minimize the e.m. interactions inside the target, but at the same time must provide a high enough number of target electrons
Berillium (or eventually **Carbon**)

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 μ-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):*

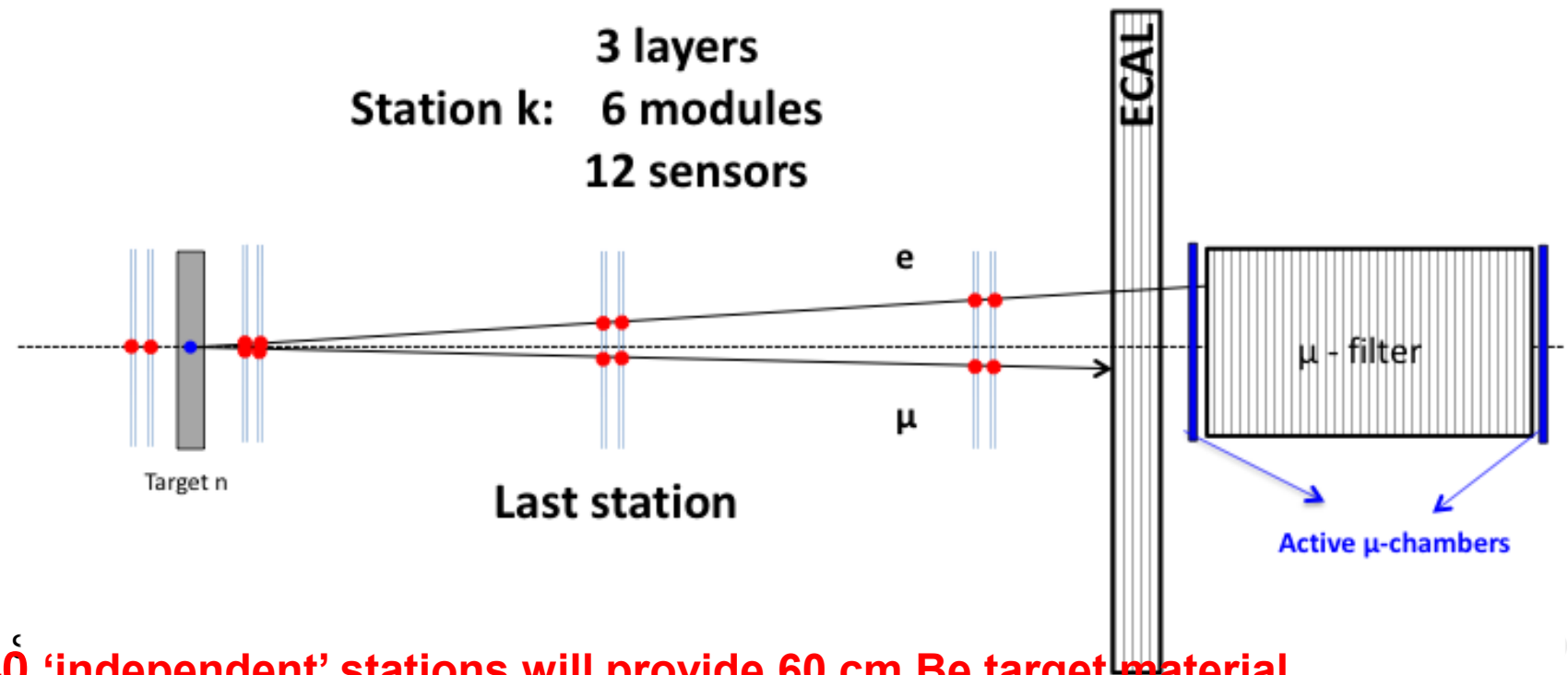
Trasversal size is 10 × 10 cm²



3 layers

Station k: 6 modules

12 sensors



40 'independent' stations will provide 60 cm Be target material

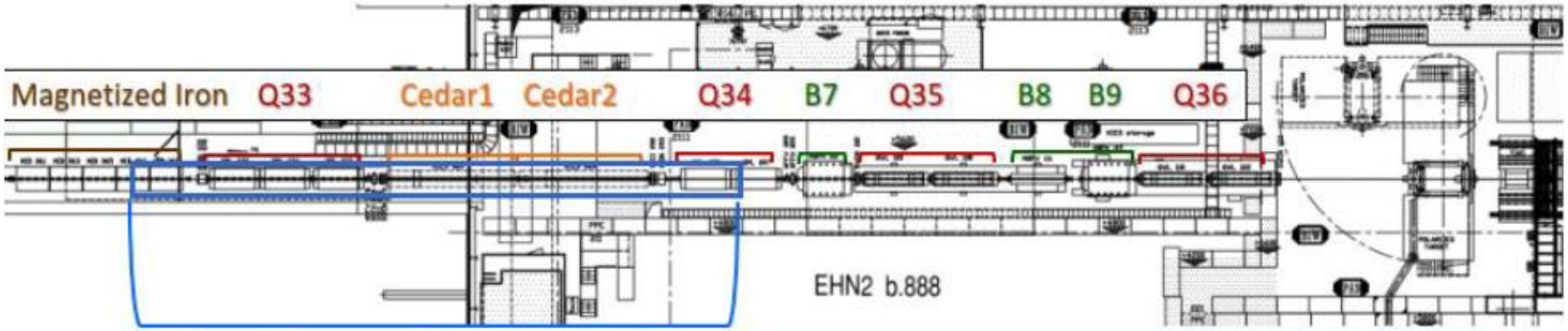
Possible location of μONe at CERN M2

- ***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.



μ-e Upstream (under-study) ~ 30 m

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m

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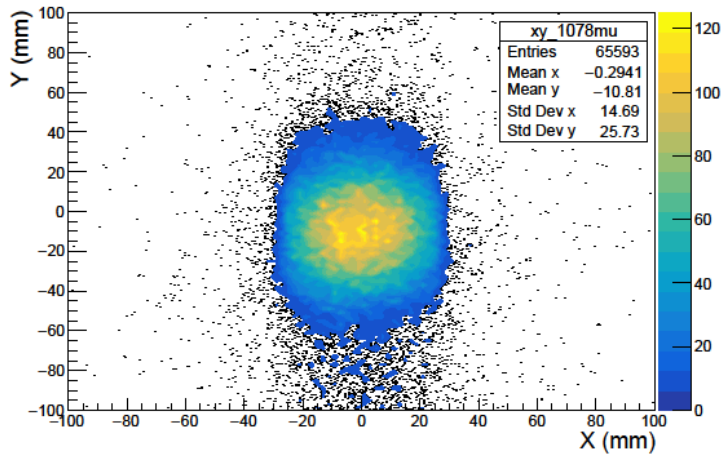
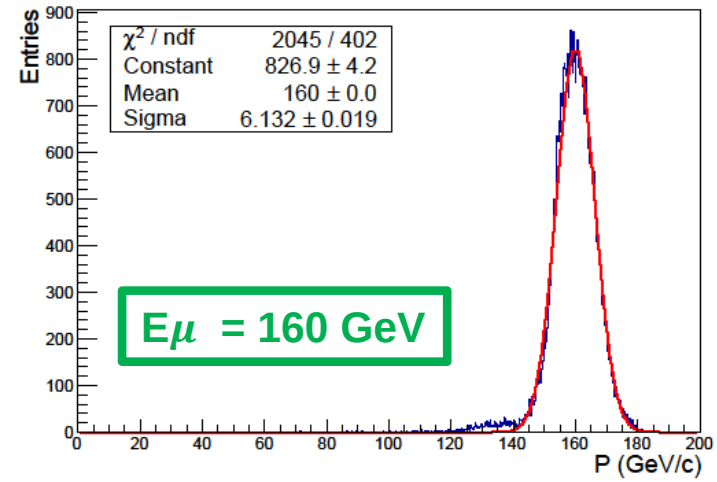
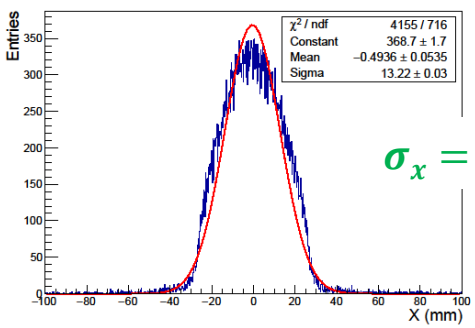
M2 Beam parameters for MUonE *(from Dipanwita B., sept 2019)*

Need a 'large' and 'parallel'(=small divergence) beam

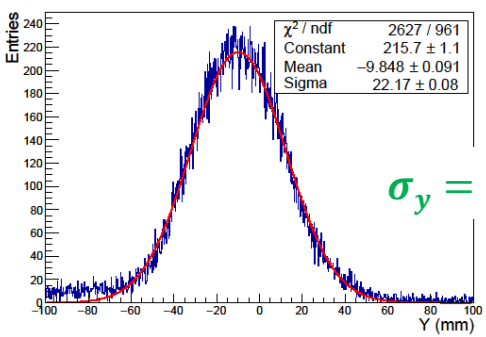




Eμ = 160 GeV



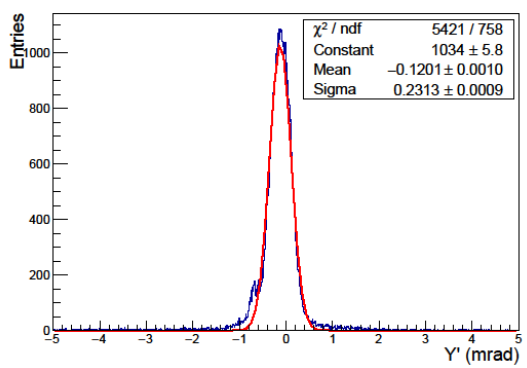
$\sigma_x = 1.3$ cm



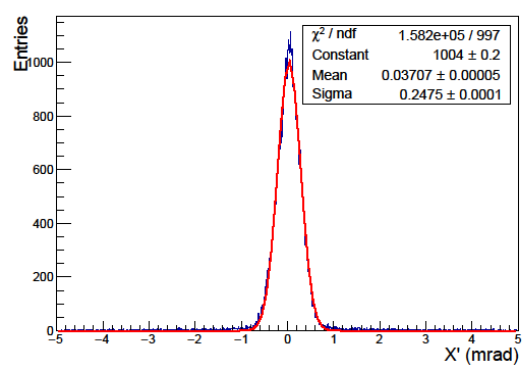
$\sigma_y = 2.2$ cm

Very low divergence

0.23 mrad



0.24 mrad



Clara Matteuzzi

Tracking system

★ **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

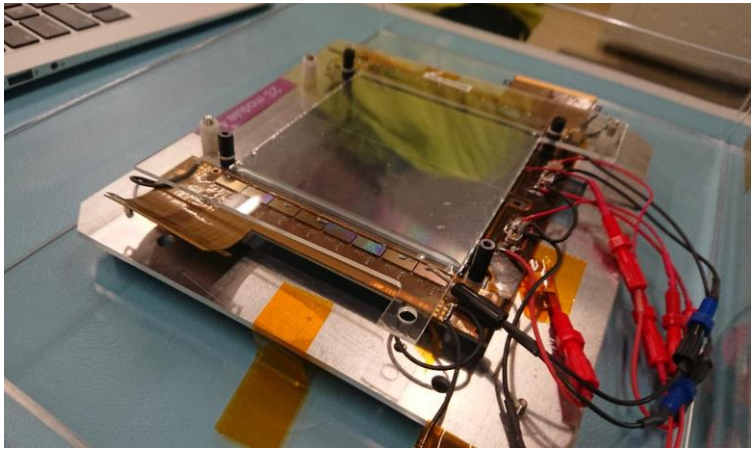
Pitch: 90 μm → σ_x = 26 μm

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)



The calorimeter

- **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 ~ 40 cm × 40 cm of $PbWO_4$ crystals
- an Outer ECAL extending up to ~ 100 cm × 100 cm *with same/other crystals*

  with ex-OPAL lead glass (rather large size 9.5x9.5 cm) or

  new $PbW0_4$ new crystals ***(GEANT4 simulation study under way)***

Testbeam performed

★ **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 μ-e -> μ-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)*

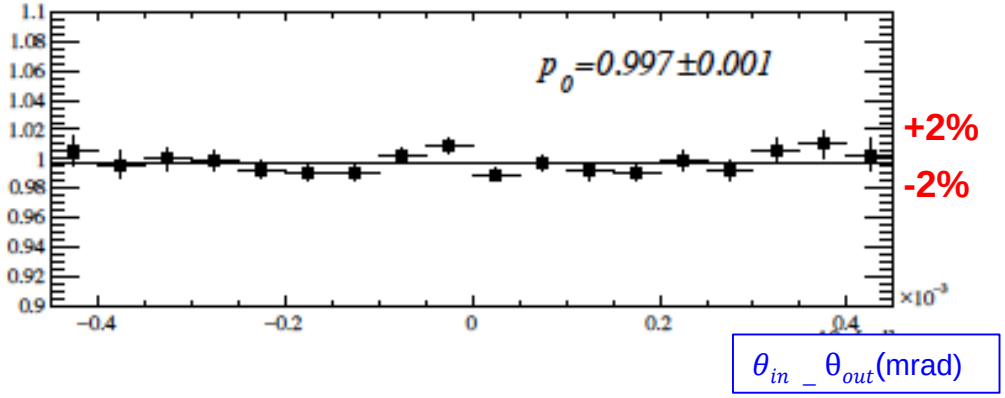
Dedicated test in H8 with electron beams and UA9 apparatus (7 μm intrinsic resolution)

JINST 15 (2020) P01017

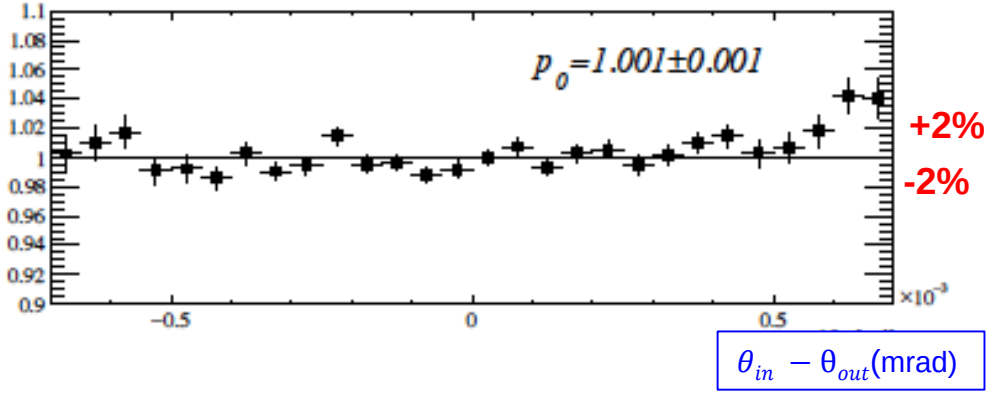
Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets

G. Abbiendi[a], J. Bernhard[b], F. Betti[a,c], M. Bonanomi[d], C. M. Carloni Calame[e], M. Garattini[b,g], Y. Gavrikov[f], G. Hall[g], F. Iacoangeli[h], F. Ignatov[i], M. Incagli[j], V. Ivanchenko[b,k], F. Ligabue[j,l], T. O. James[g], U. Marconi[a], C. Matteuzzi[d], M. Passera[m], M. Pesaresi[g], F. Piccinini[e], R. N. Pilato[j,n], F. Pisani[a,b,c], A. Principe[a,c], W. Scandale[b], R. Tenchini[j], and G. Venanzoni[j,1]

data/MC



12 GeV electrons, 8 mm graphite
Comparison DATA/GEANT



12 GeV electrons, 20 mm graphite
DATA/GEANT

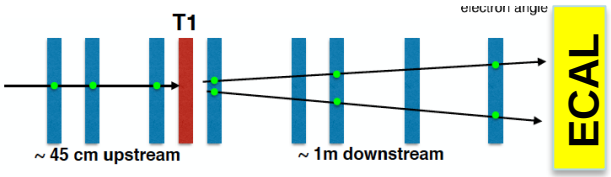
Testbeam in 2018 *(μ-e elastic scattering study)*

- **The setup was located downstream COMPASS**

  (behind the Tungsten hadrons filter)

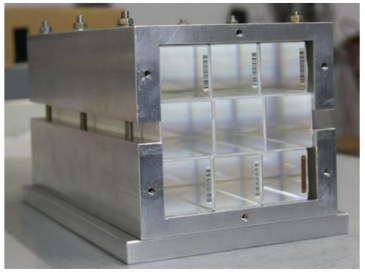
- **Aim to measure μ – e elastic scattering**
  - *Using muons from pions decays (hadron beam) with an estimated beam momentum p = (187±7) GeV*
  - *To measure the correlation between the scattering angles: muon angle vs the electron angle;*
  - *Electron energy vs the electron angle correlation and PID.*

- **The detector consists of:**
  - Tracking system: stations equipped with the **AGILE** silicon strip sensors: 400 micron thick, single sided about 40 μm intrinsic hit resolution.



  - Electromagnetic calorimeter: 3x3 crystals matrix (CMS PbWO4)

    $25X_o$, 9.9 cm^2

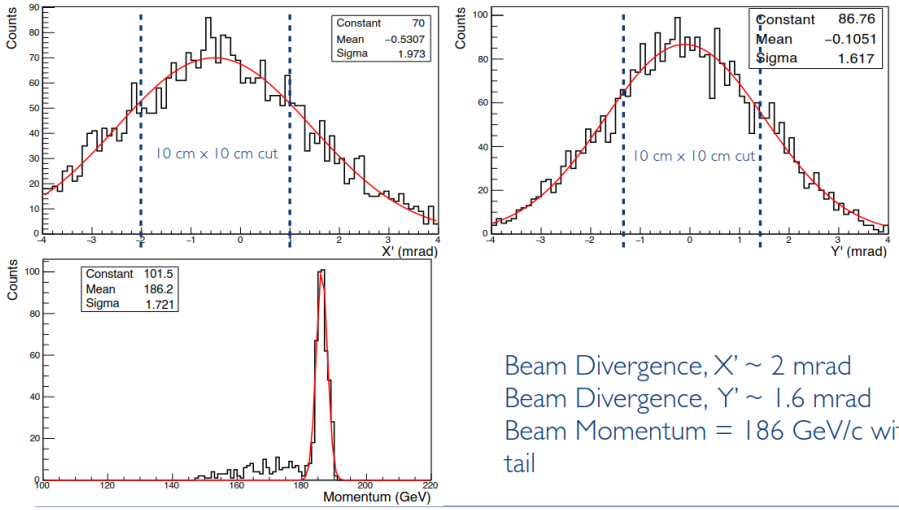


Testbeam in 2018

Setup located in the North Area behind the COMPASS detector

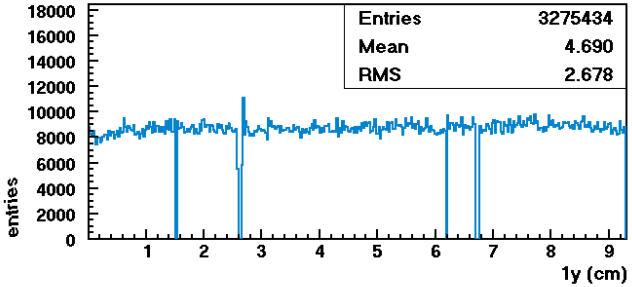
Muon Distribution Downstream (D)

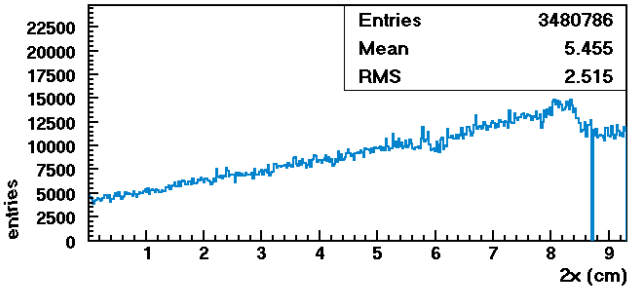
- Muon Momentum



Beam Divergence, X' ~ 2 mrad
Beam Divergence, Y' ~ 1.6 mrad
Beam Momentum = 186 GeV/c with tail

(Courtesy from D. Banerjee)





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

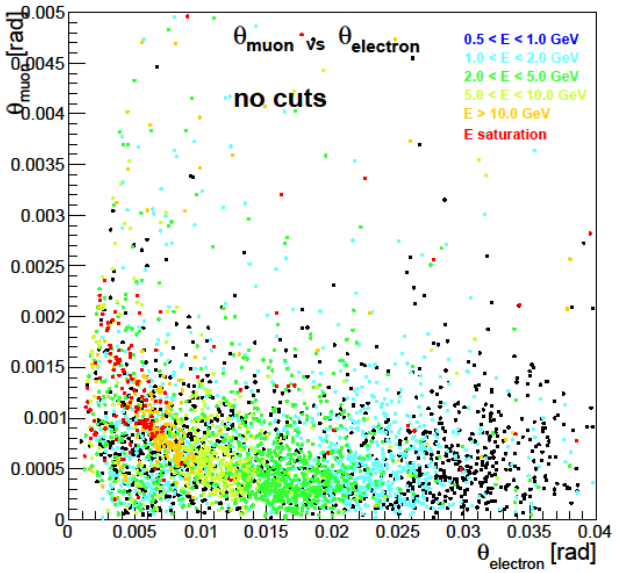
Testbeam in 2018

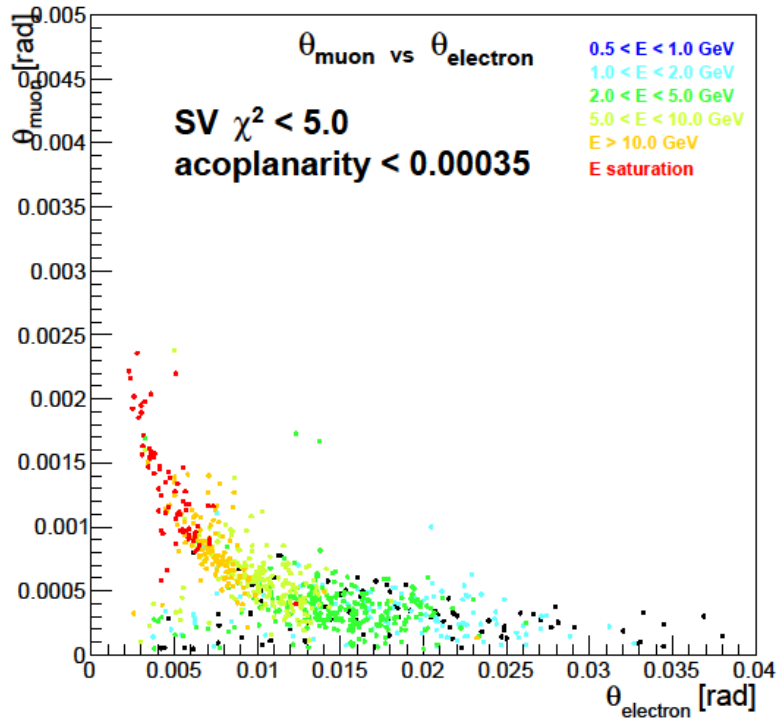
θ_μ *vs* θ_e

40µm hit resolution
~0.100 mrad angular

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





Tools to do the measurement

Strategy:

- measure $\Delta\alpha_{\rm had}(t)$ *in the reachable experimental kinematic range determined by* E_μ

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

- get the integrand function and the value of $a_\mu^{\rm HLO}$

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

(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 bremstrhalung)

Uncertainty in the location of interaction vertices *(will be inside the target but also in the Si planes)*

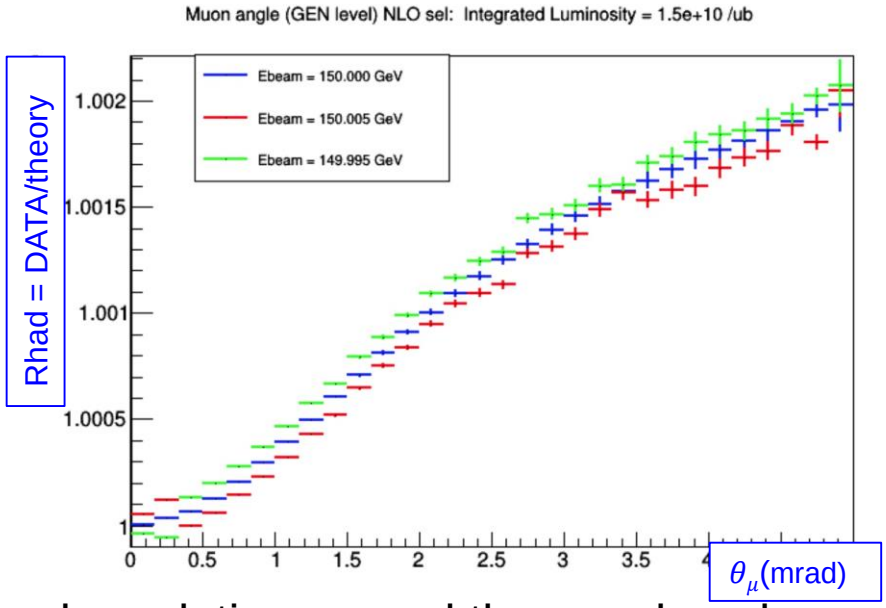
Uncertainty in the muon beam momentum scale *(see next slide)*

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 $<E_\mu>_{in}$ mean energy for the full integrated luminosity.

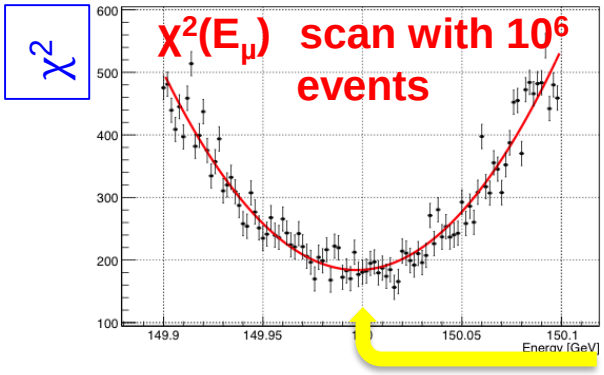


- Determine the $<E_\mu>_{in}$ from the energy-angles relation around the equal angle condition

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

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

- χ^2 test comparing θ distribution of simulated data samples *(templates)* to the measurement



~ 40 hours needed to collect 10^6 events with a single MUonE's station

minimum at 150.000±0.002 GeV

The theory: status

QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group)

M. Alacevich, *et al* **arXiv:1811.06743**.

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

P. Mastrolia, *et al*, **JHEP 1711 (2017) 198**;
S. Di Vita, *et al.* **JHEP 1809 (2018) 016**;
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 μ-e scattering (10^{-5} accuracy) → **International efforts under way, a report is in preparation**

The MUonE Pilot Run

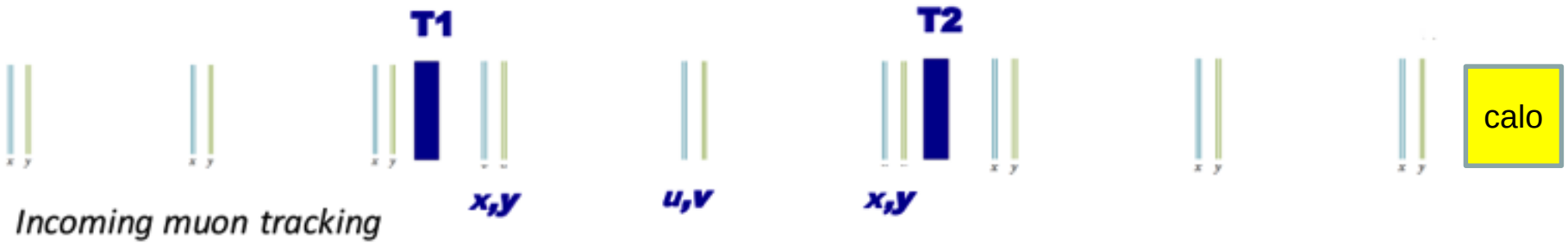
In the LoI, the MUonE requests the M2 beam

- **Location:**

  upstream COMPASS after the B*eam* M*omentum* S*tation* (BMS)

- **3 weeks at the end of 2021** *(due to the Si planes availability)*

  ➡ to run with 2 full stations in the configuration:



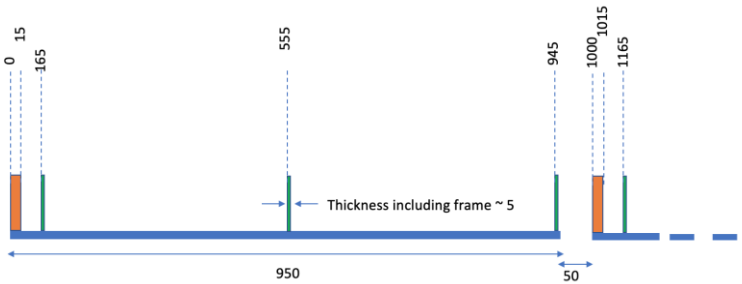
➡ the apparatus will be in a thermalized volume

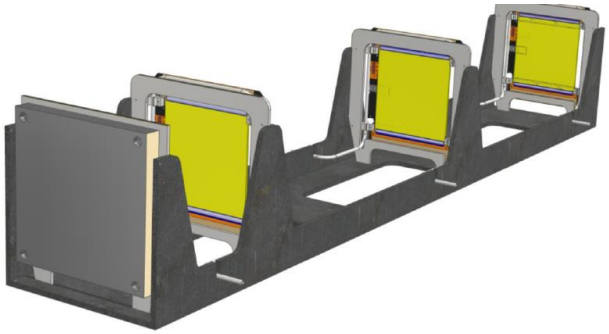
at the end of the 2 stations, a calorimeter ~ 20x20 cm^2 under study

The pilot run should provide ~ 10^8 elastic events

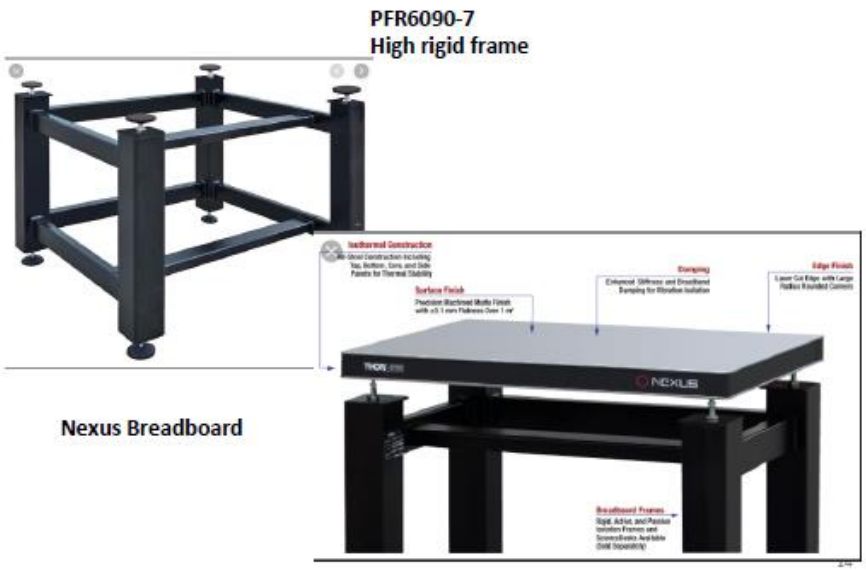
Ongoing studies and test for the mechanics

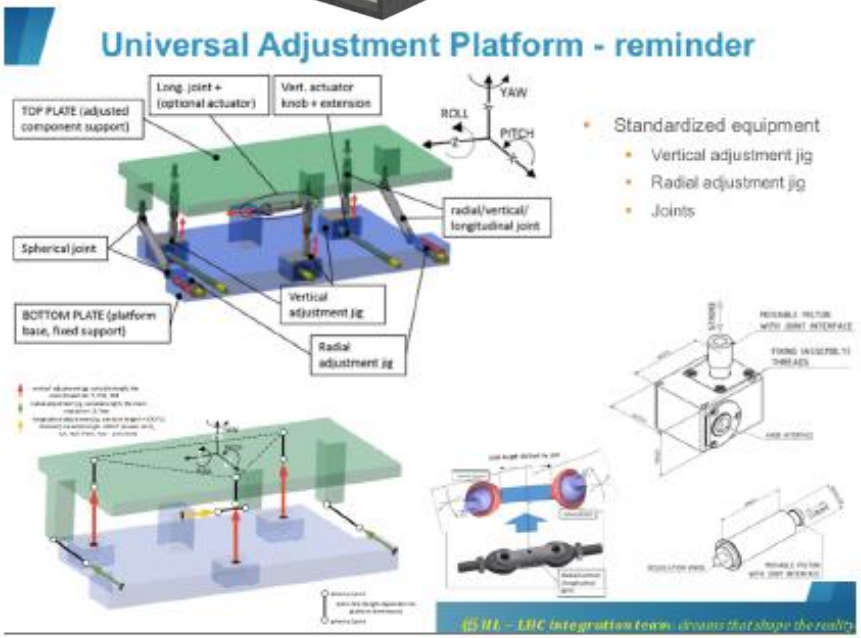
In September 2019
105 keuro were granted for 2020 by the INFN committee *(mainly for mechanics study and test)* for the preparation of a Pilot Run in 2021.





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:

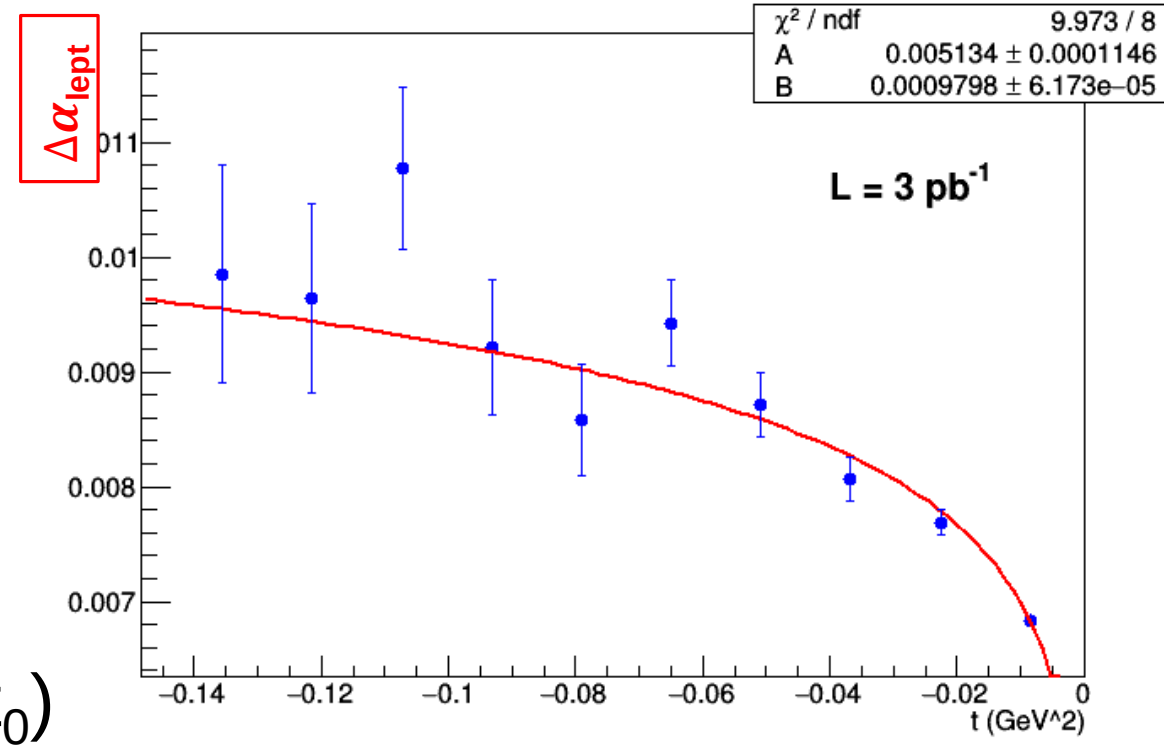
- Confirm the system engineering, i.e. assembly, mounting and cooling;
- Assessing the detector counting rate capability;
- Checking the signal integrity in the process of data transfer for the DAQ;
- Proving the validity of the trigger-less operation mode;
- Evaluate the FPGA real-time processing, to 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 ($O(10^8)$ elastic events) ***they will be used to perform a test measurement of the leptonic contribution $\Delta\alpha_{lept}$ to the running of α.***
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 $\Delta\alpha_{lept}$ with the pilot run data

Very preliminary!

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



Fit with

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

(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 $\sim 10^{7}$ 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 6th June 2019 :
https://cds.cern.ch/record/267747?ln=it

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

On the 30th 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).*

(from LoI:)

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

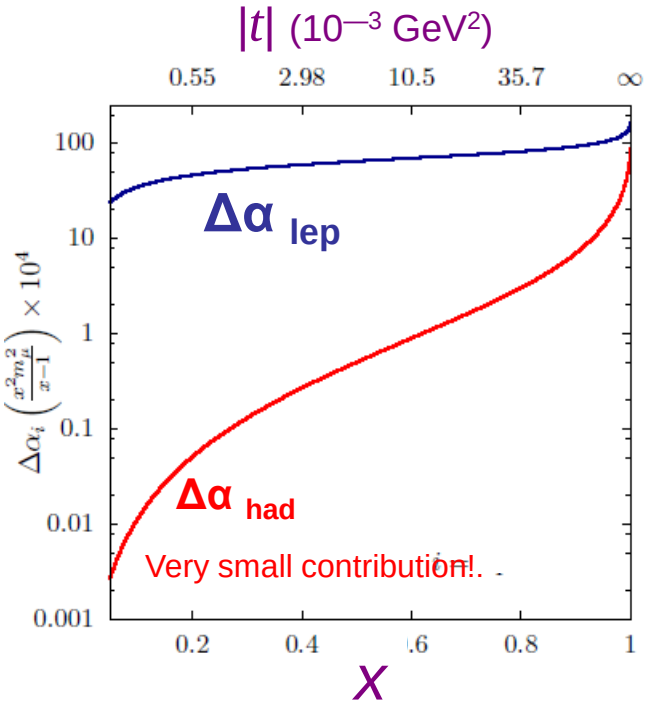
We propose to measure $\mu\, e \rightarrow \mu\, e$ scattering in the space-like region with the existing CERN North Area μ beam and a detector which should not require R&D for new technologies

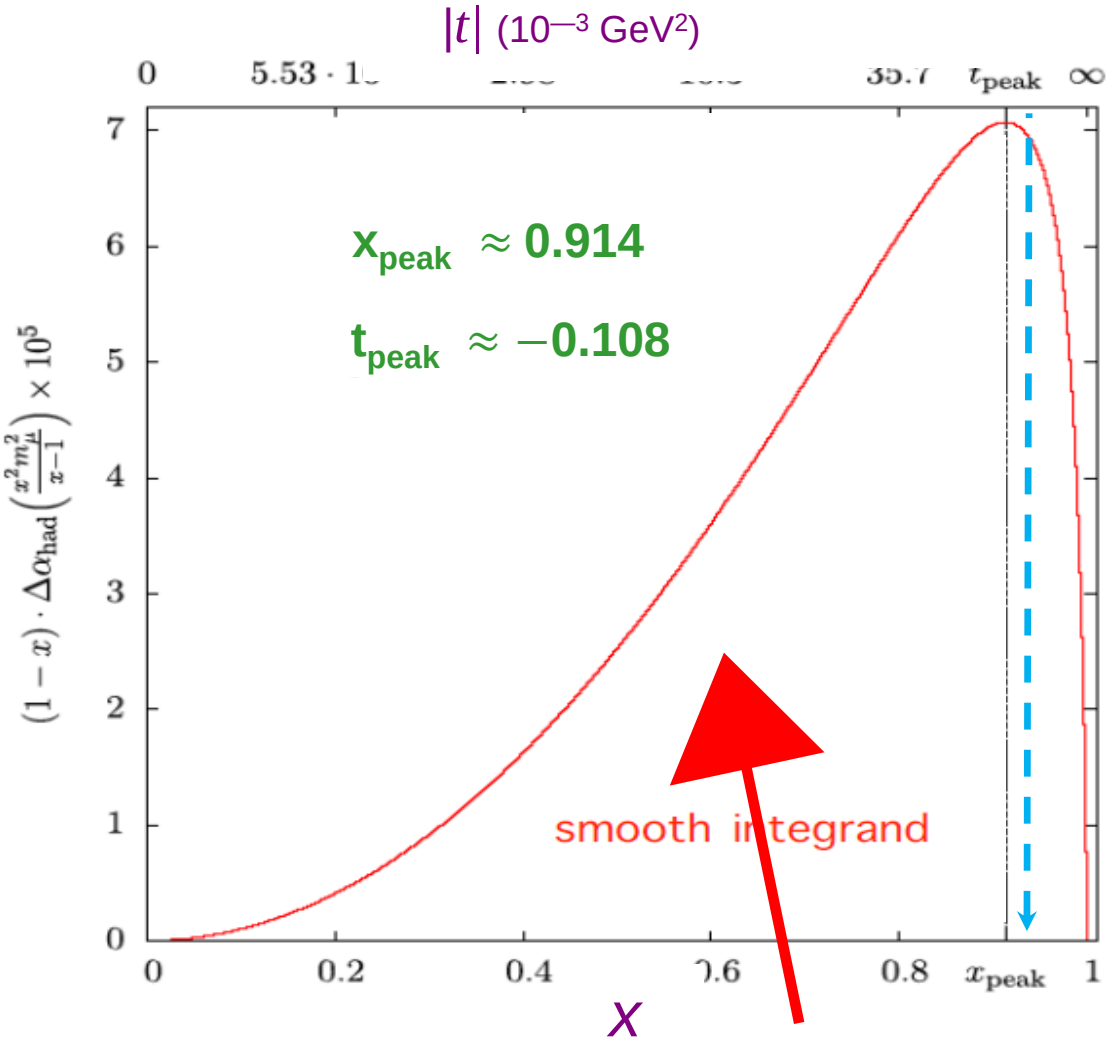
The experiment is very challenging from the experimental point of view considering the systematic uncertainty which must be achieved.

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.*

Spares

Approach: space-like evaluation





$$\Delta\alpha_{\rm had}(t_{peak}) = \mathcal{O}(10^{-3})$$

integrand function $(1-x)\Delta\alpha_{\rm had}(t(x))$

$a_\mu^{\rm HLO}$ is the total area under this curve

Approach: space-like evaluation

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha}{\pi}\int_0^1 dx(x-1)\bar{\Pi}_{\mathrm{had}}(t(x)) = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\mathrm{had}}(t(x))$$

$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad t = \begin{cases} 0^- & \text{for } x \to 0^+ \\ -\infty & \text{for } x \to 1^- \end{cases}$$

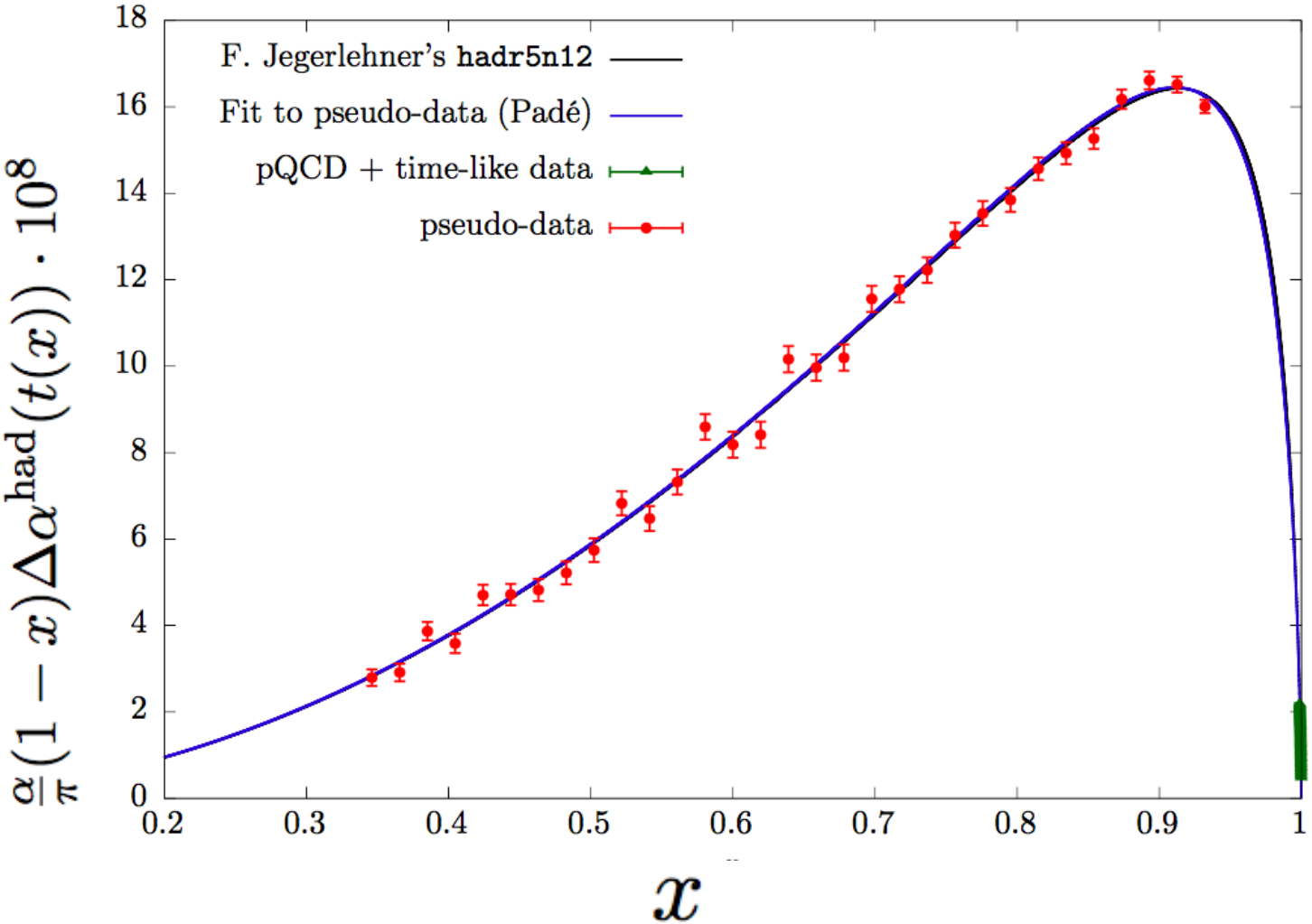
$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\text{lept}}(t) - \Delta\alpha_{\mathrm{had}}(t)}$$

★ **Strategy:**

- measure $\Delta\alpha_{\mathrm{had}}(t)$ *in the reachable experimental kinematic range determined by* E_μ
- get large *x* values from theory (pQCD, lattice)
- get the integrand function and the value of a_μ^{HLO}

★ Fit $\Delta\alpha_{had}(t)$ from :

(From C. Carloni-Calame)

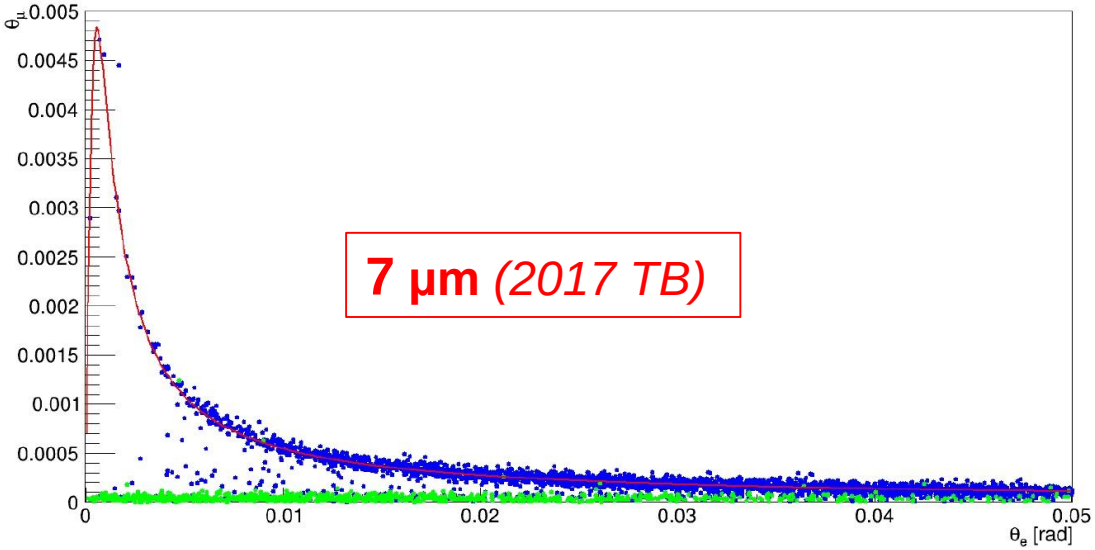


To be competitive with the current evaluations, *$\Delta\alpha_{had}(t)$* needs to be measured at the % level

Testbeam in 2018

θ_μ *vs* θ_e correlation

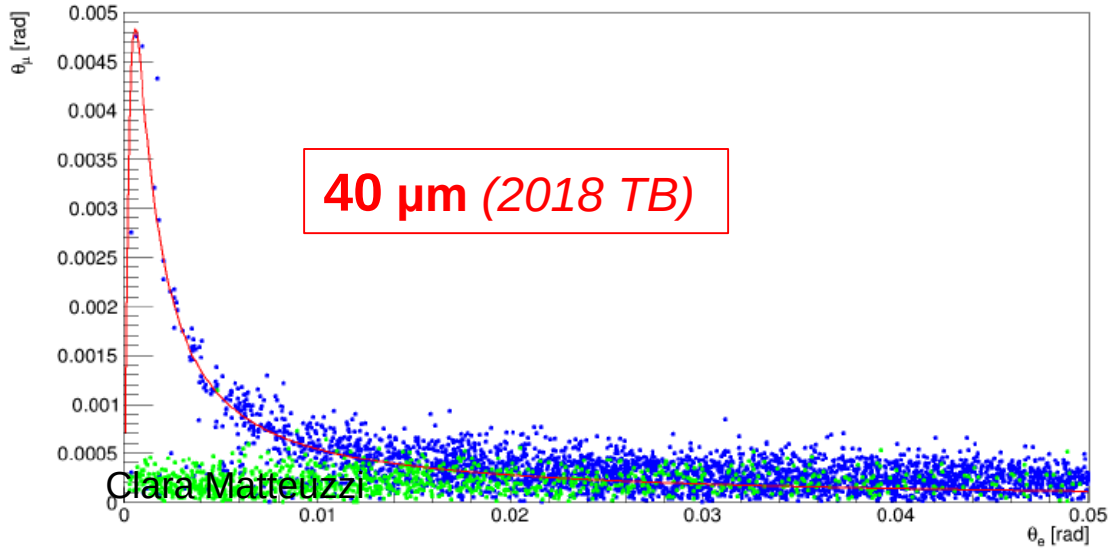
Effect of the resolution with GEANT4



Signal *(elastic)*

Background

(pair production)



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

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