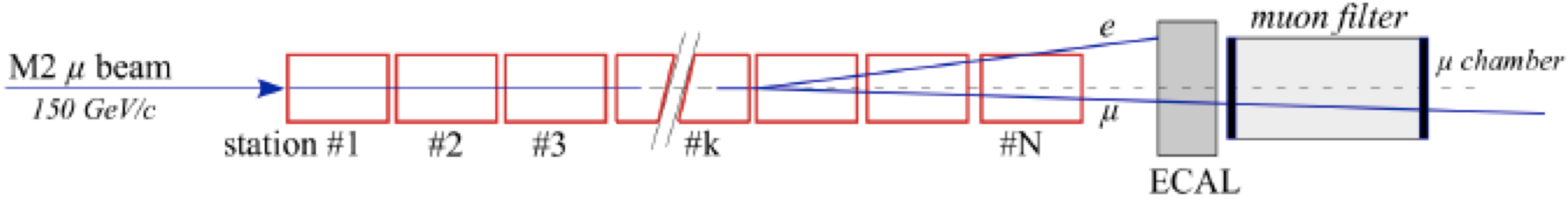
L’esperimento MUonE

G. Venanzoni,
INFN-Pisa
on behalf of the proponents



Discussione preventivi,
INFN-PI, 19 Giugno 2020

Outline

- Reminder sulla proposta MUonE
- Cosa abbiamo fatto negli ultimi anni
- Piani per il futuro
- Richieste in sezione

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad \text{(0.54 ppm)}$$

- Tantalizing ~3.5σ deviation with SM (persistent since ~20 years):

$$a_\mu^{SM} = 11659181.0(4.3)\times 10^{-10}$$

T. Aoyama, et al. 2006.04822
(new!)

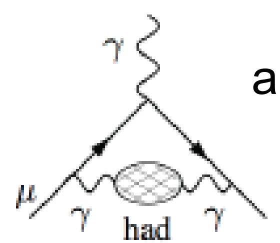
$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (27.9 \pm 7.6)\times 10^{-10}} \quad (3.7\sigma)$$

- Current discrepancy limited by:
  - Experimental uncertainty → New experiments at FNAL and J-PARC x4 accuracy
  - Theoretical uncertainty → limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Obtained with time-like data (integral on e+e- → hadrons cross sections)

Hadronic Vacuum polarization (HLO)



$a_\mu^{HLO} = (693.1 \pm 4.0)10^{-10}$

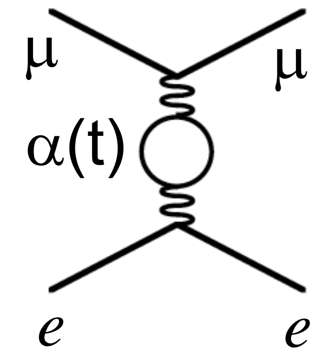
$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 0.6\%$

MUonE proposal: a_μ^{HLO} from space-like region

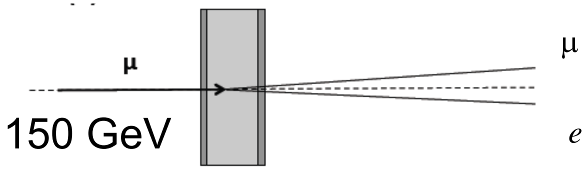
[C.M. C. Calame, M. Passera, L. Trentadue, GV, Phys. Lett. B 746 (2015) 325,
G. Abbiendi et al., Eur. Phys. J. C77 (2017) 139]

$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\cdot\Delta\alpha_{had}\left(-\frac{x^2 m_\mu^2}{1-x}\right)$$

$t=q^2<0$



Use of a 150 GeV μ beam on Be target at CERN (**elastic scattering μe →μ e**) to get $\Delta\alpha_{had}(t<0)$



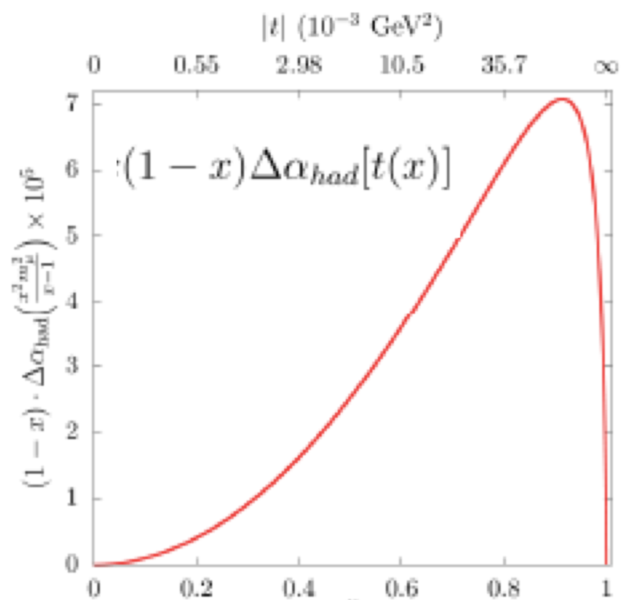
$$t = \frac{x^2 m_\mu^2}{x-1}$$

$$\frac{d\sigma^{\rm VP}}{dt} = \frac{d\sigma^{\rm no\ VP}}{dt}\,\frac{1}{|1-\Delta\alpha(t)|^2}$$

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

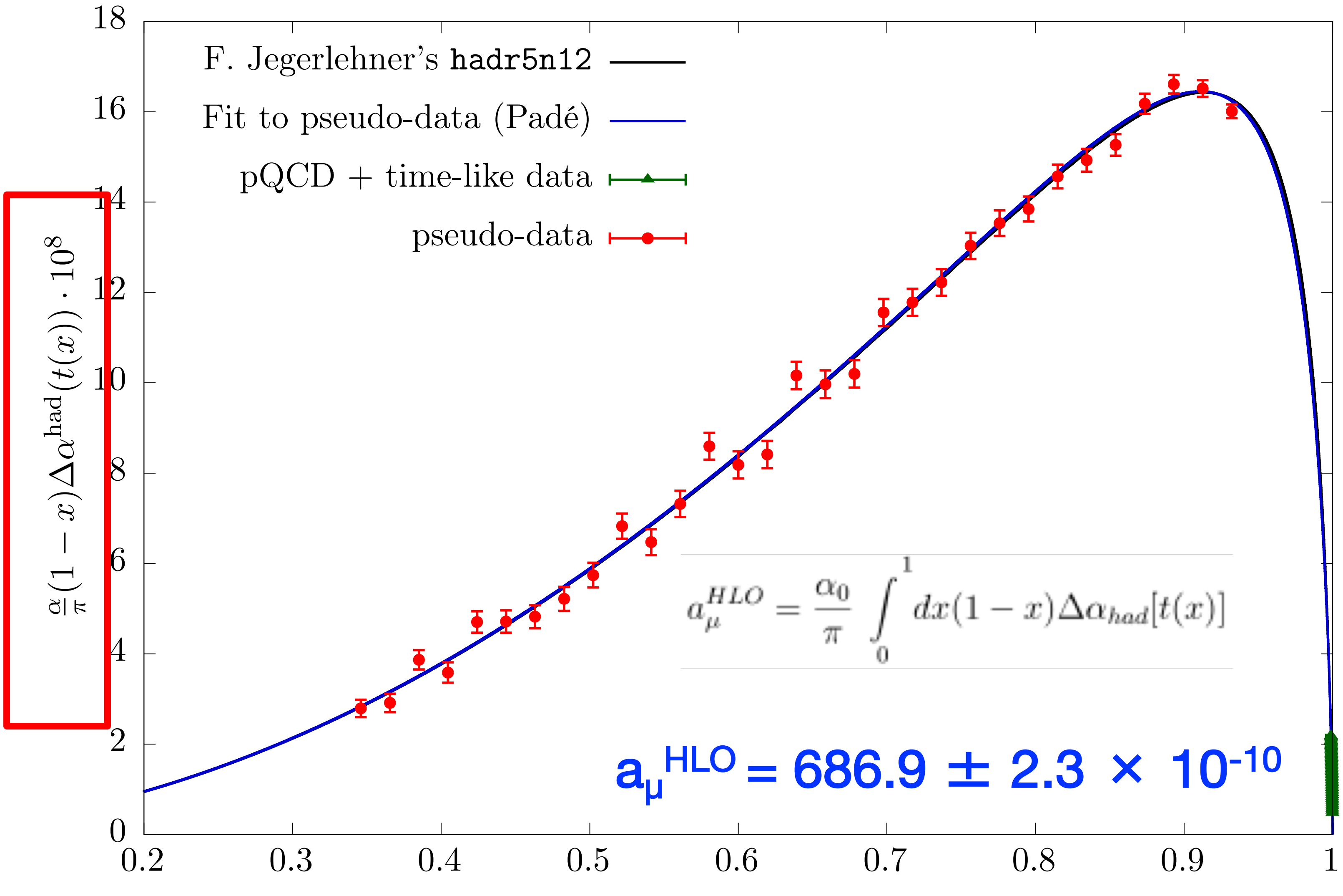
Known analytically from QED

Extracted from data



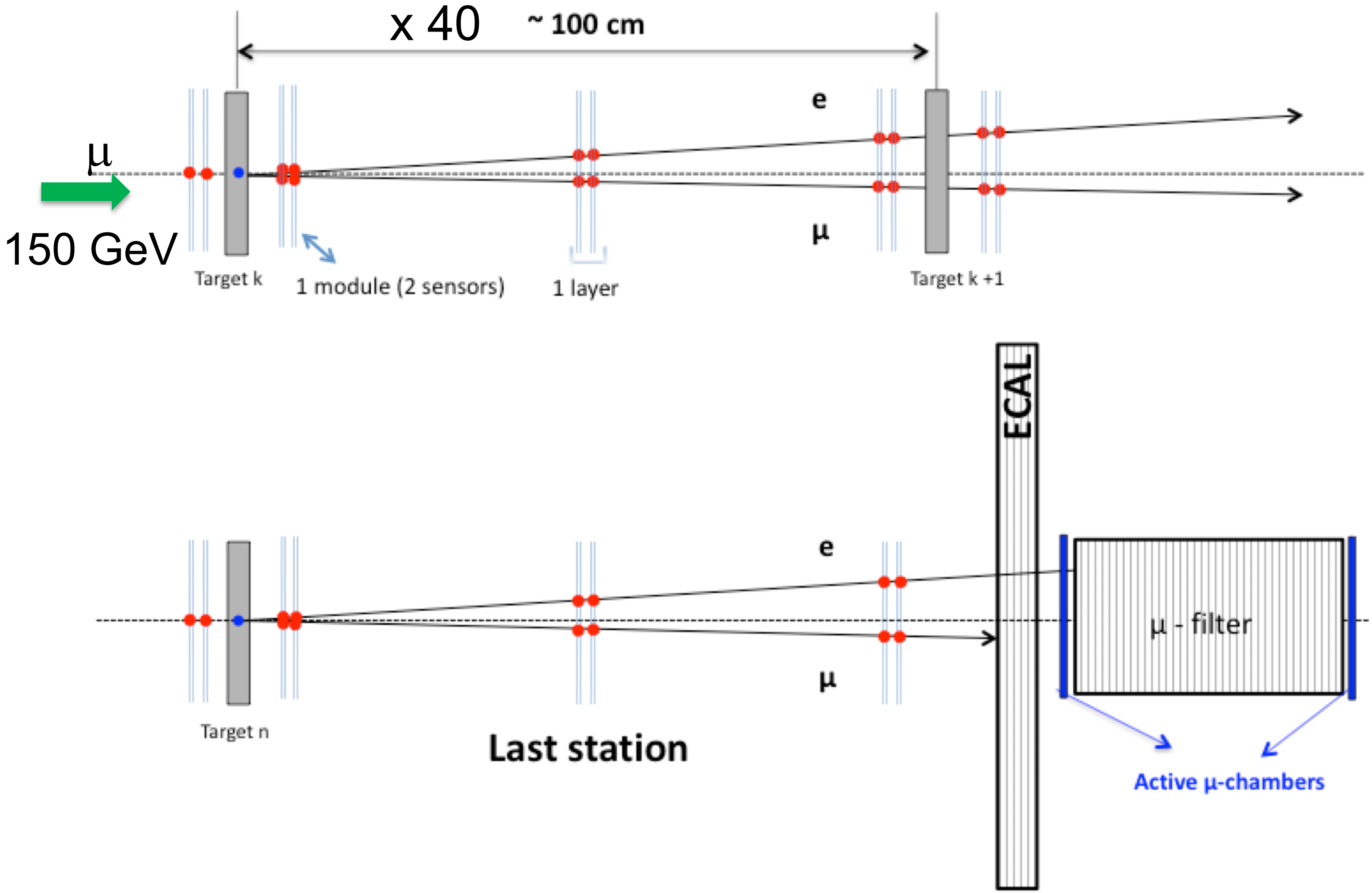
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx\,(1-x)\,\Delta\alpha_{had}[t(x)]$$

Statistical reach of MUonE on a_μ^{HLO}



A **0.3%** stat error can be achieved on a_μ^{HLO} in 3 years of data taking with 1.3×10^7 μ/s (4×10^{14} μ total)

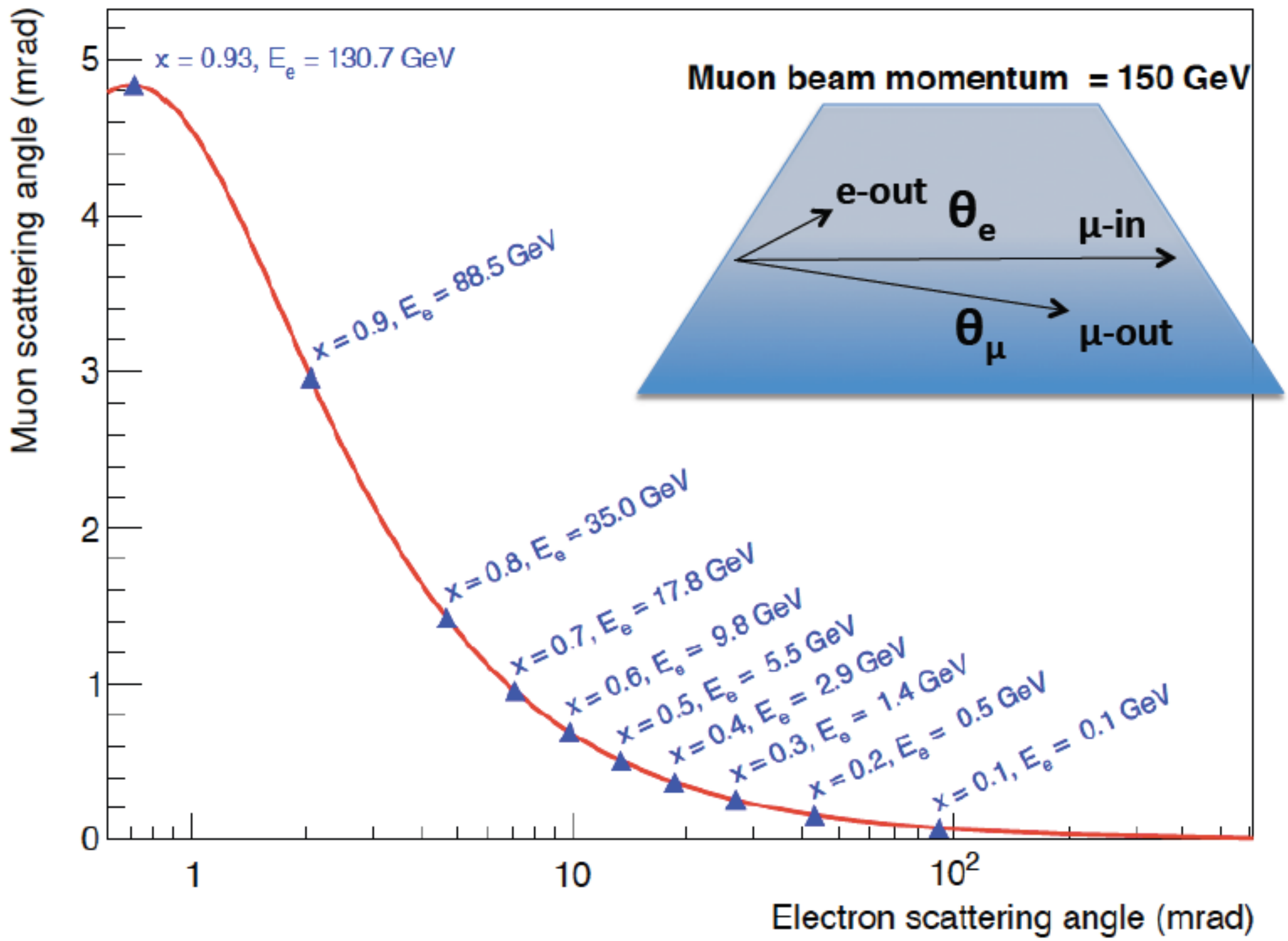
Detector concept



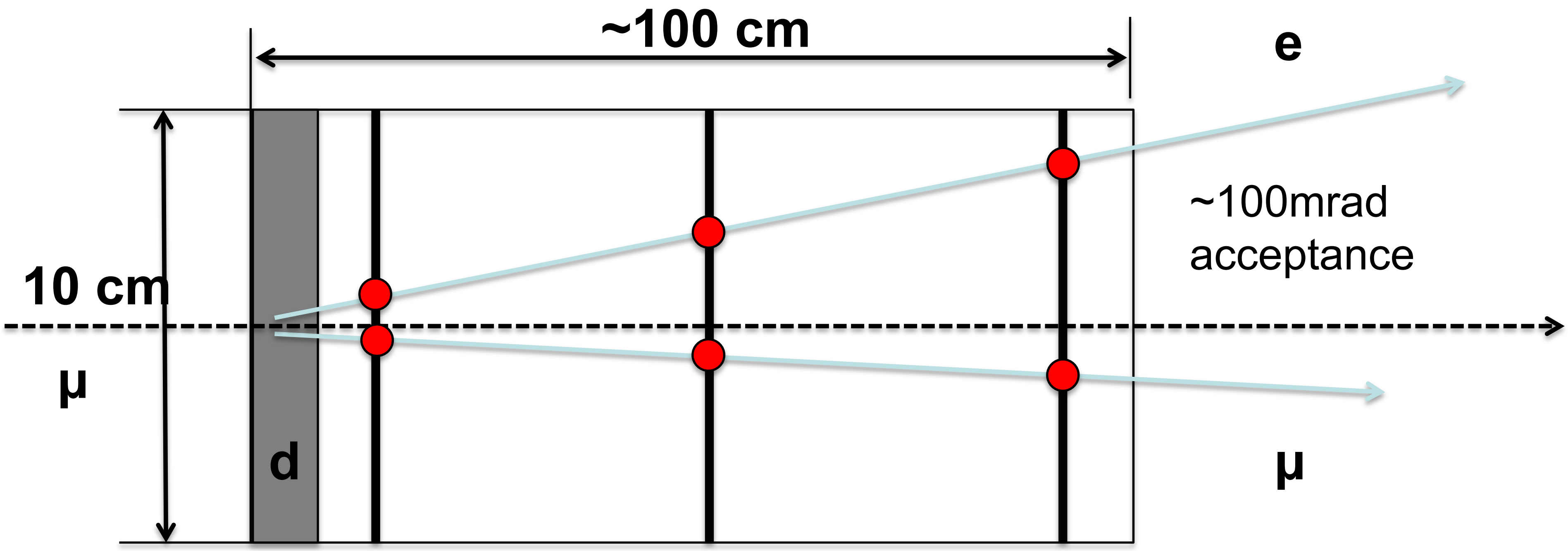
40 'independent' stations will provide 60 cm Be target material

Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint



Single Unit



~1.5 cm
Be Target

State-of-art Silicon detectors

hit resolution ~20 μm

Expected angular resolution ~ 20 μm / 1m = 20 μrad
At the end ECAL and Muon Filter for PID

Systematics

1. Multiple scattering
2. Tracking (alignment & misreconstruction)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the mu-e cross section (NNLO MC needed)
7. …

All the systematic effects must be known to ensure an error on the cross section < 10ppm

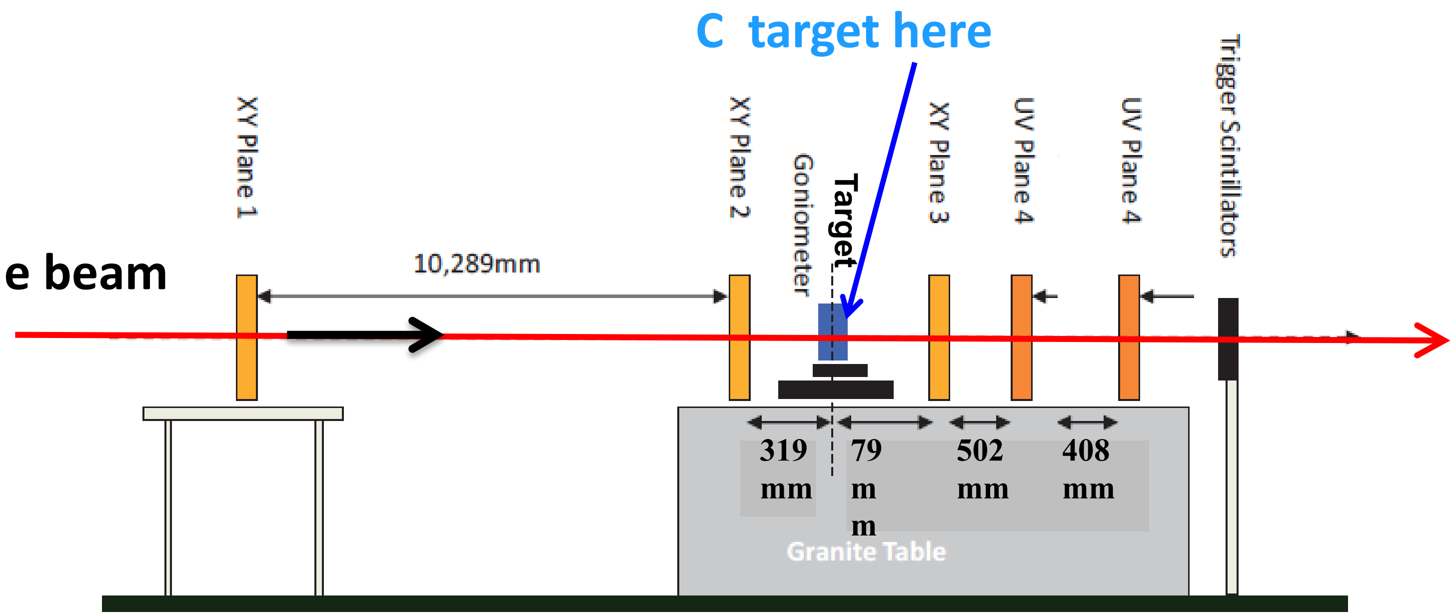
Last 3 years progress

1. Multiple scattering studies* (TB 2017)
2. Test beam at M2 in 2018
3. Baseline Si detector defined (moduli 2S CMS)
4. LO and NLO Studies
5. Location at EHN2
6. LOI submitted to CERN (June 2019)
   → 3 weeks Test Run approved at the end of 2021
7. Theory progress ("Theory for muon-electron scattering @ 10ppm: A report of the MUonE theory initiative", P. Banerjee et al, 2004.13663)

*R. Pilato "The MUonE experiment: a novel way to measure the hadronic contribution to the muon g-2" Tesi di LM, DF Unipi, 26/10/2019, https://etd.adm.unipi.it/theses/available/etd-09252019-114845/

Test Beam 2017at H8: the setup

- We used the UA9 tracking system to record scattering data
- Alignment, tracking, pattern recognition, comparison with Geant4 simulation.
- **The goal**: reach **~1%** in the **core** of the MS distributions and **few per cent on the tails**



Adapted UA9 apparatus

5 Si planes: 2 before and 3 after the target, 3.8x3.8 cm2 intrinsic angle resolution ~**100**μrad

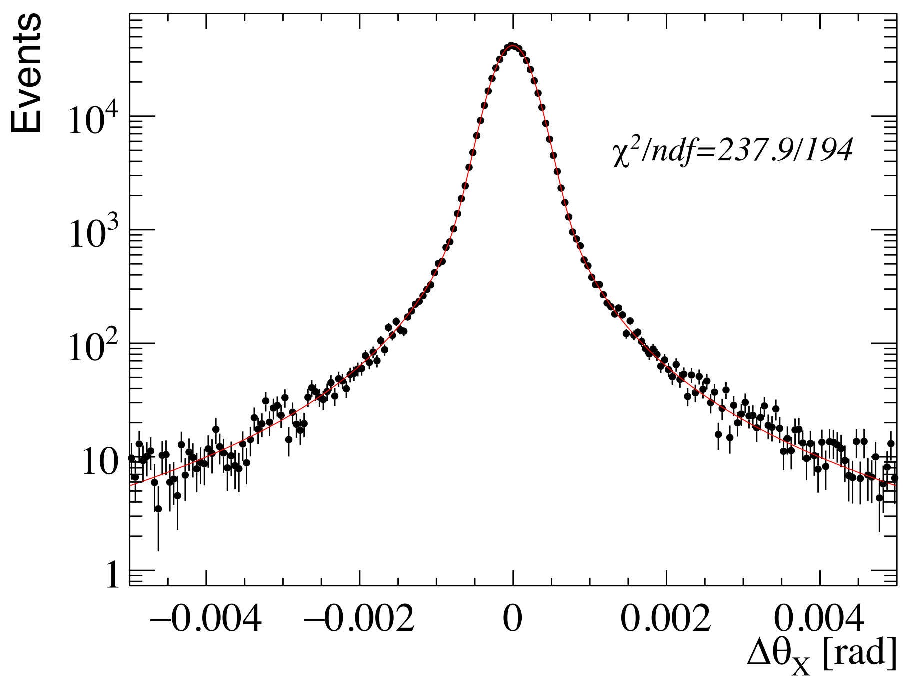
arXiv:1905.11677

Results on Multiple Coulomb Scattering from 12 and 20 GeV electrons on Carbon targets (8, 20 mm)

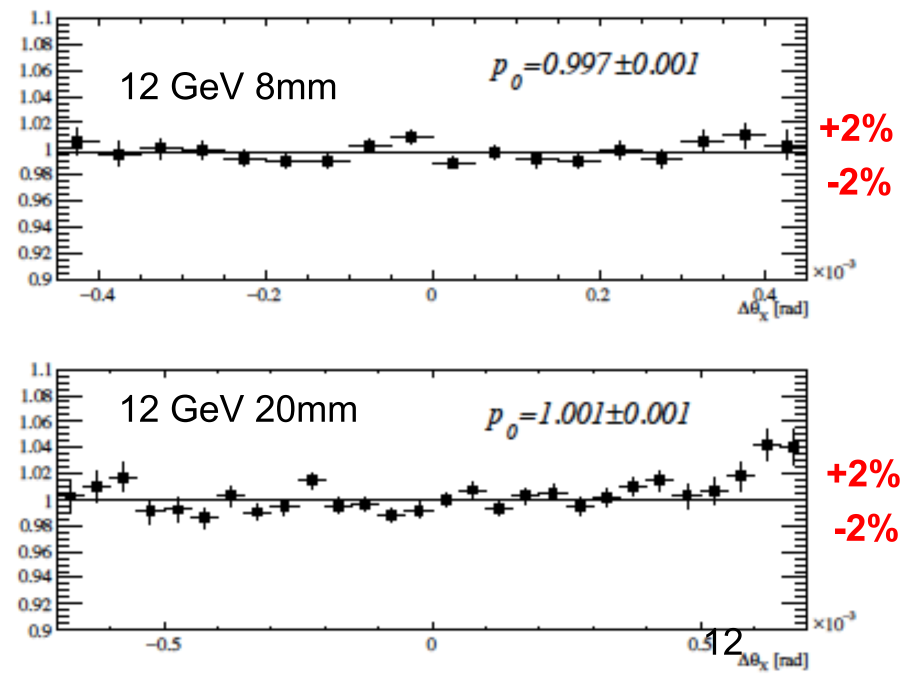
JINST 14 (2020) 01, 01

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]

12 GeV 8mm



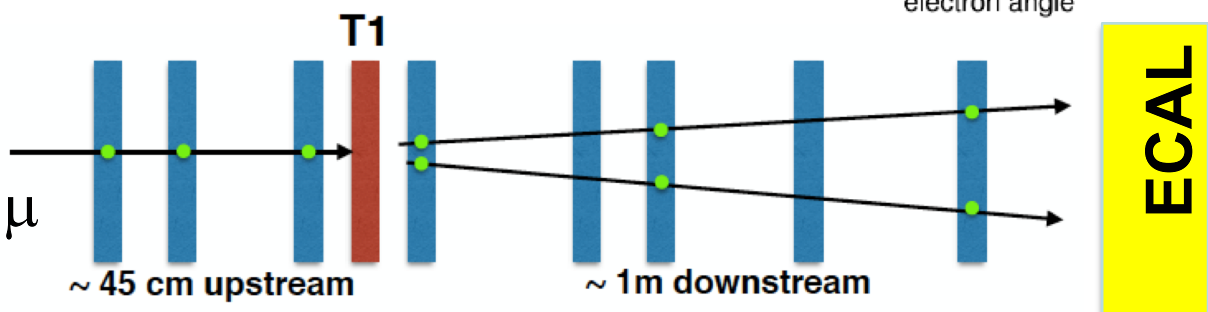
data/MC



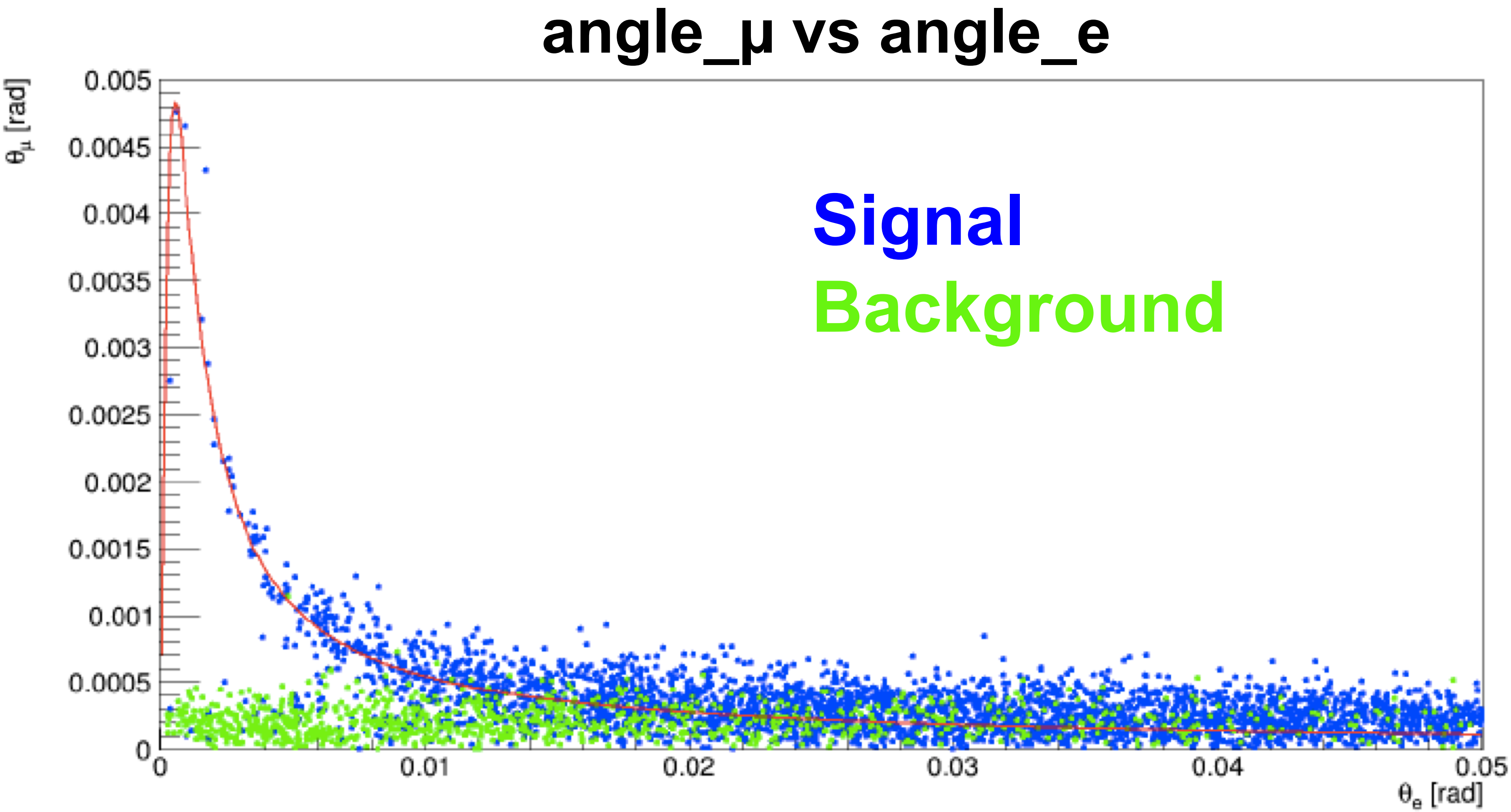
Test beam 2018

- A full scale prototype has been located downstream COMPASS, behind the Tungsten hadrons filter.
- Aim of the measurement campaign: muon – electron elastic scattering with high statistics
  - 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; use of the e- Energy
- The detector consists of:
  - Tracking system: AGILE silicon strip sensors: 400 μm thick, single sided, about 40 μm intrinsic hit resolution.
  - Electromagnetic calorimeter: 3x3 cell matrix.

Data analysis in progress

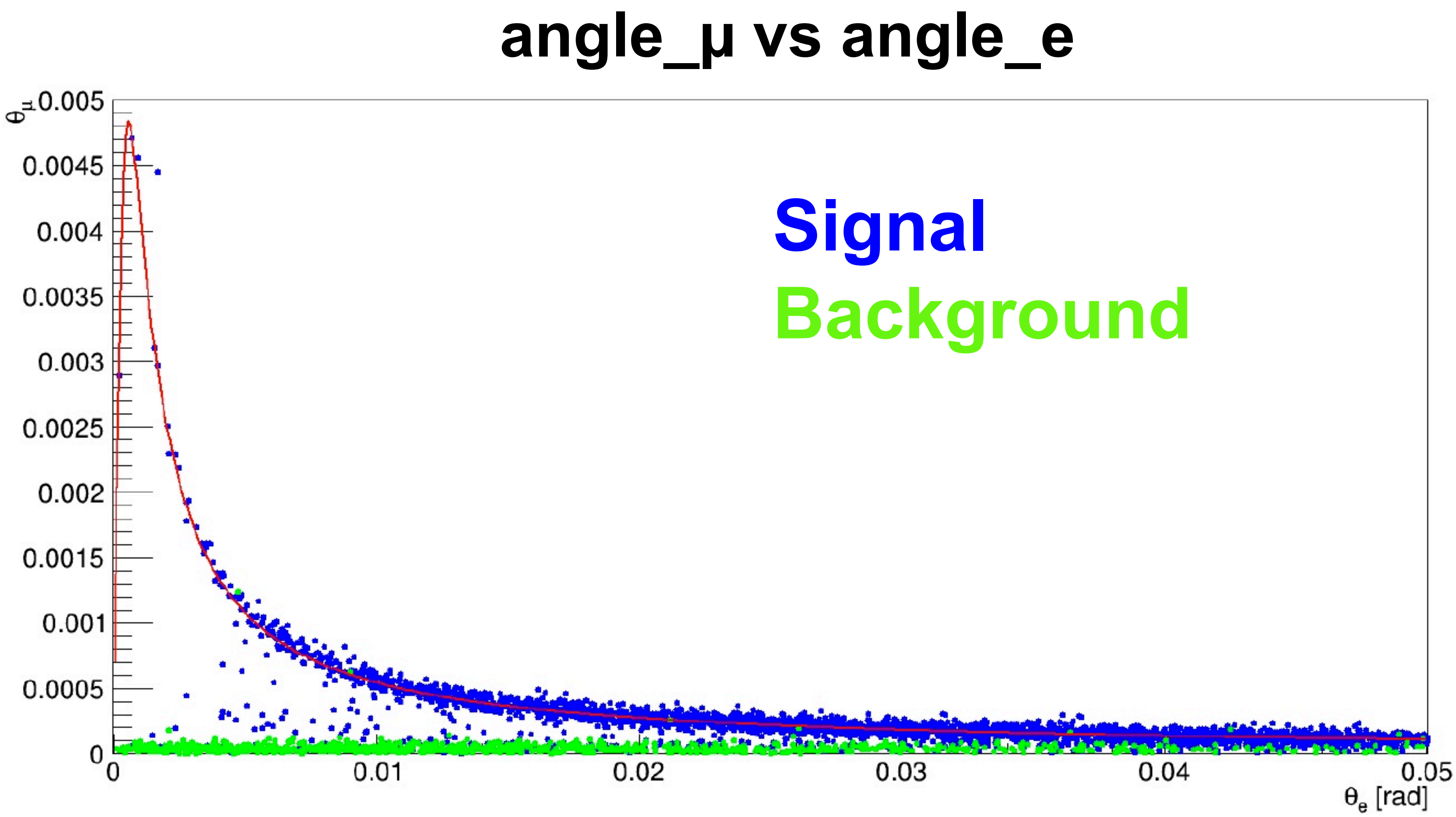


Effect of the resolution: GEANT4 (40μm hit resolution)



Pair production

Effect of the resolution: GEANT4 (10μm hit resolution)

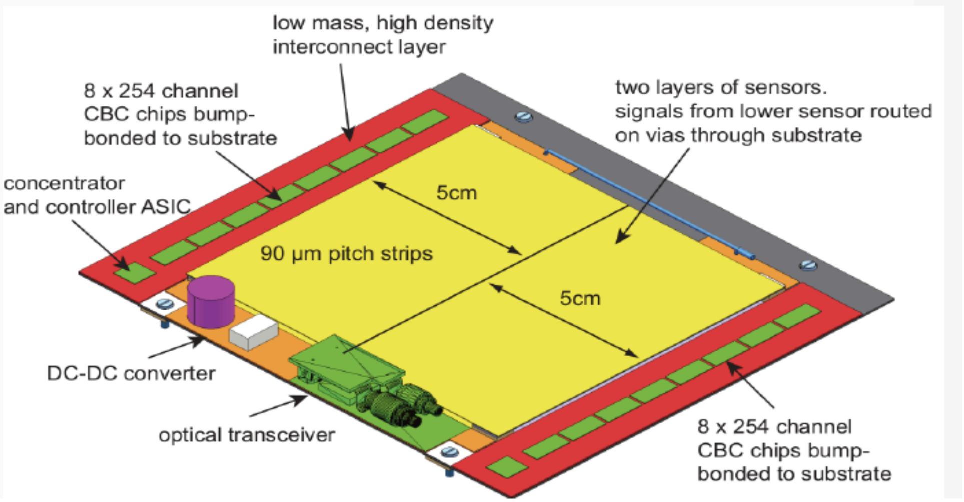


Pair production

Tracking system: CMS 2S Module

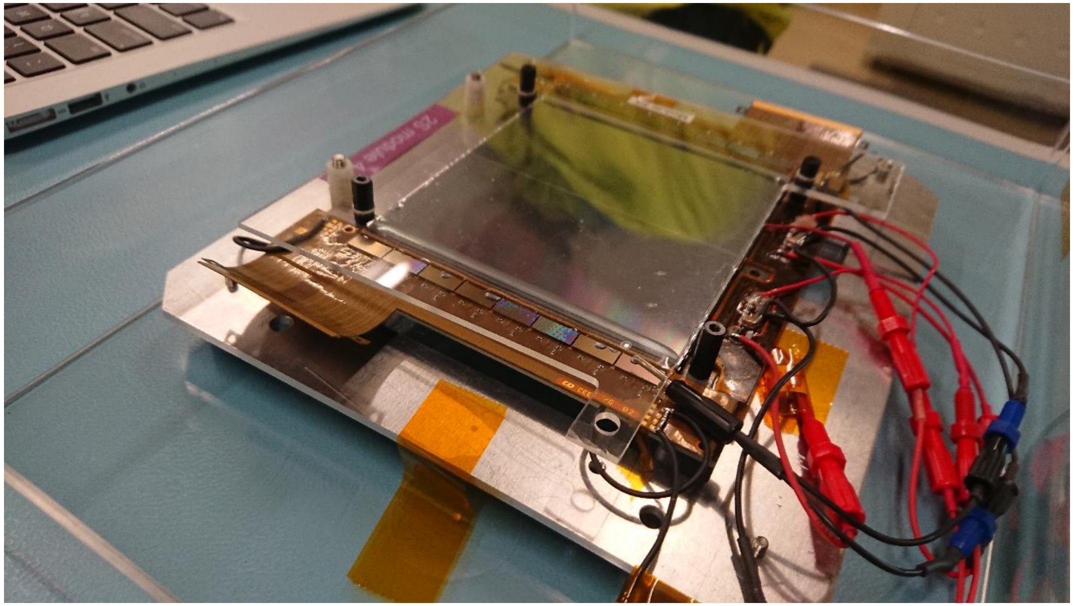
Requirements:

- Good resolution (~ 20 μm)
- High uniformity ($\varepsilon \gtrsim$ 99.99%)
- Capable to sustain high rate (50 MHz)
- Available technology (pilot run 2021)



Achievement: CMS 2S Module

- Thickness : 2 × 320 μm
- Pitch: 90 μm → σ_x = 26 μm
- Angular resolution: σ_θ ~ 30 μrad
- Readout rate: 40 MHz
- Area: 10 cm × 10 cm
- Efficiency= 99.988 ± 0.008



ECAL possible implementation

- **ECAL**: ~ 100 cm × 100 cm.
- Inner part (40 cm × 40 cm):$PbWO_4$ owned by CMS (14 cm x14 cm for Test Run 2021).
- Outer part: to be finalized: a possibility could be OPAL lead glass: rather a big cell size
- Front end electronics running at 40 MHz.

→ For Test Run 2021: 25 $PbWO_4$ crystals from CMS

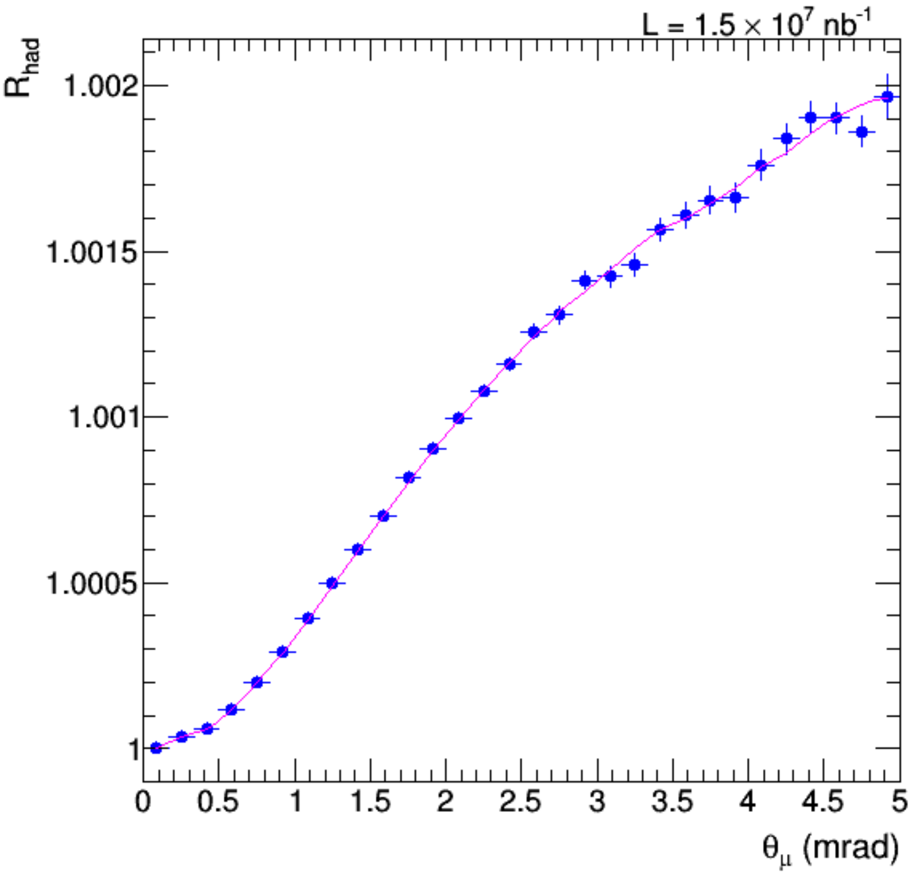
Template method for NLO studies

- Template method is used to measure the hadronic running $\Delta\alpha_{had}(t)$.
- 2D parameterization of the hadronic running tested by fitting the time-like model.
- Pseudo data samples generated varying the parameters in the 2D lattice.
- Convolution the angular distributions with the detector resolution function and M2 beam spread

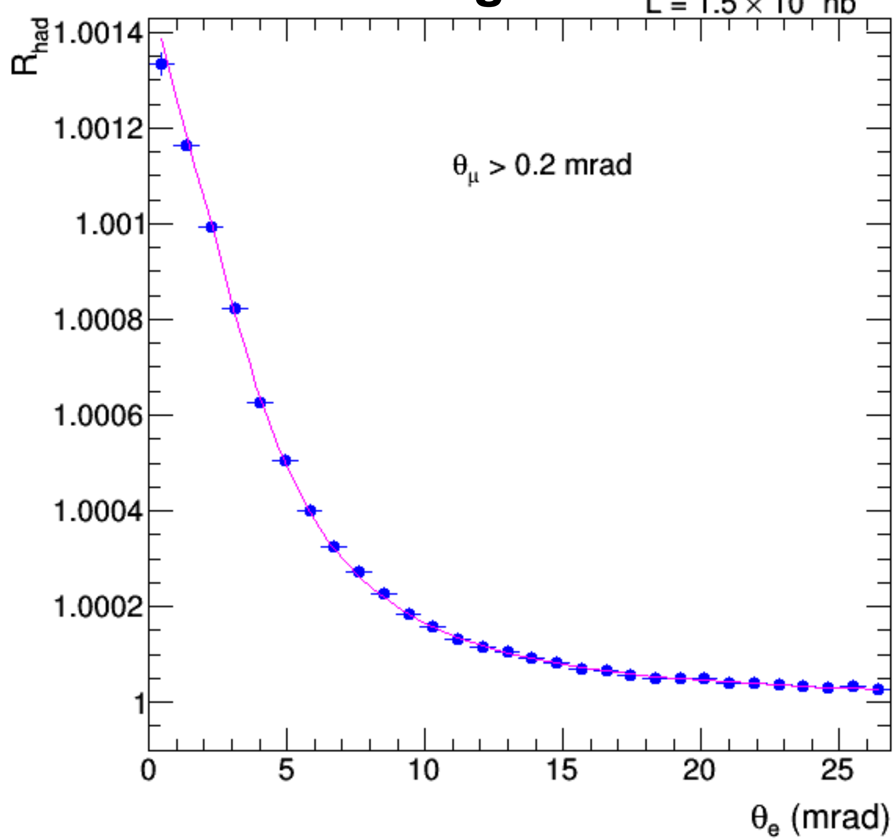
$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

Results (NLO)

Muon angle



Electron angle



From 3000 pseudo experiments we got $a_\mu^{HLO} = (689.8 \pm 2.3)10^{-10}$, to be compared with 688.6×10^{-10} (agreement within 1 sigma)

Location at CERN M2

- **Between BSM and COMPASS**

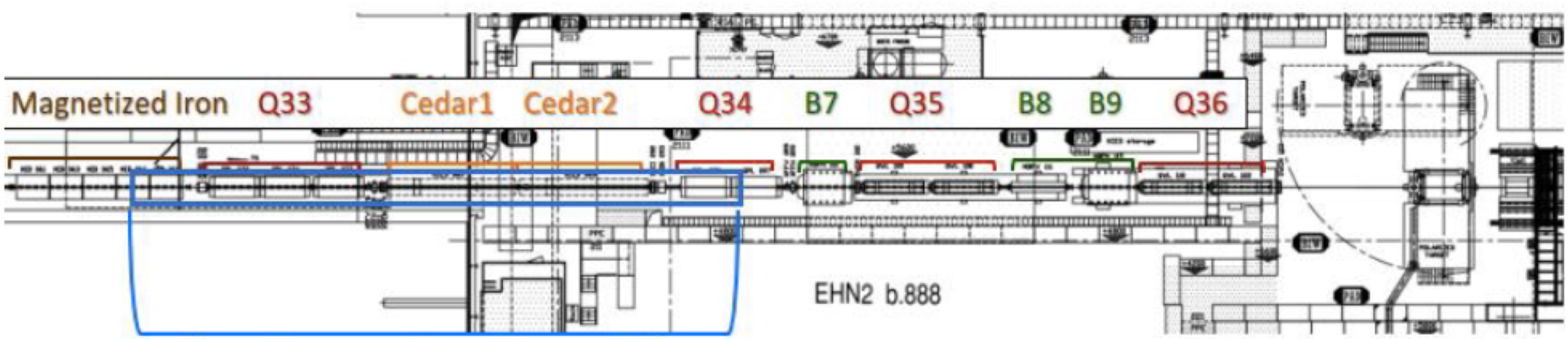
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

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

- Pro: Could allow running μ-e/μ-p_{Radius} in parallel.

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

- Beam(s) compatibility for μ-e & μ-p_{Radius} : <u>Optic's wise looks OK</u> (see Add. Sl.14 from D.B.)



μ-e Upstream (under-study) ~ 30 m

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

10

Space available : 40 m upstream COMPASS

Location at CERN M2

Status of MUonE

1. Letter of Intent submitted to the CERN's SPSC: https://cds.cern.ch/record/2677471?ln=it

2. First funding in 2019 from CSN1 INFN (~100kE) for the preparation of the Pilot Run 2021 and approval of sigla (PMUonE)

3. Test Run approved with two stations (3 weeks at the end of 2021)

Test Run 2021

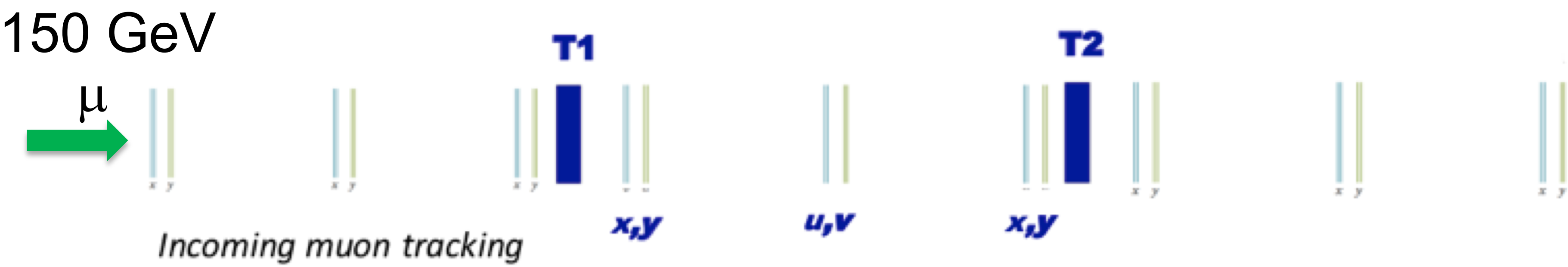
1. Confirm the system engineering, i.e. assembly, mounting and cooling.
2. Monitoring mechanical and thermal stability.
3. Assessing the detector FEE counting rate capability.
4. Checking of the DAQ system.
5. Test the procedure for the alignment of the sensors.
6. Validating the trigger strategy: FPGA real-time processing to identify and reconstruct μ−e events.

Test Run 2021

In the LoI, the MUonE requests the M2 beam:

3 weeks at the end of 2021

to run with 2 full stations in the configuration:



➡ at the end of the 2 stations, a calorimeter ~ 50x50 cm^2 under study

The test run should provide ~ 10^8 elastic events

Test Run 2021

- **Location:**
  upstream COMPASS after the BMS

- **Cooling system:**
  To operate the Si tracker electronics at ~ few (0-5) degrees
  CMS experts suggests **water**
  Need a thermalized volume around the setup

- **Mechanics:**
  needs support from EN-SMM-HPA for
  Initial survey for stations alignment
  Support in case of using the Universal Alignment Platforms

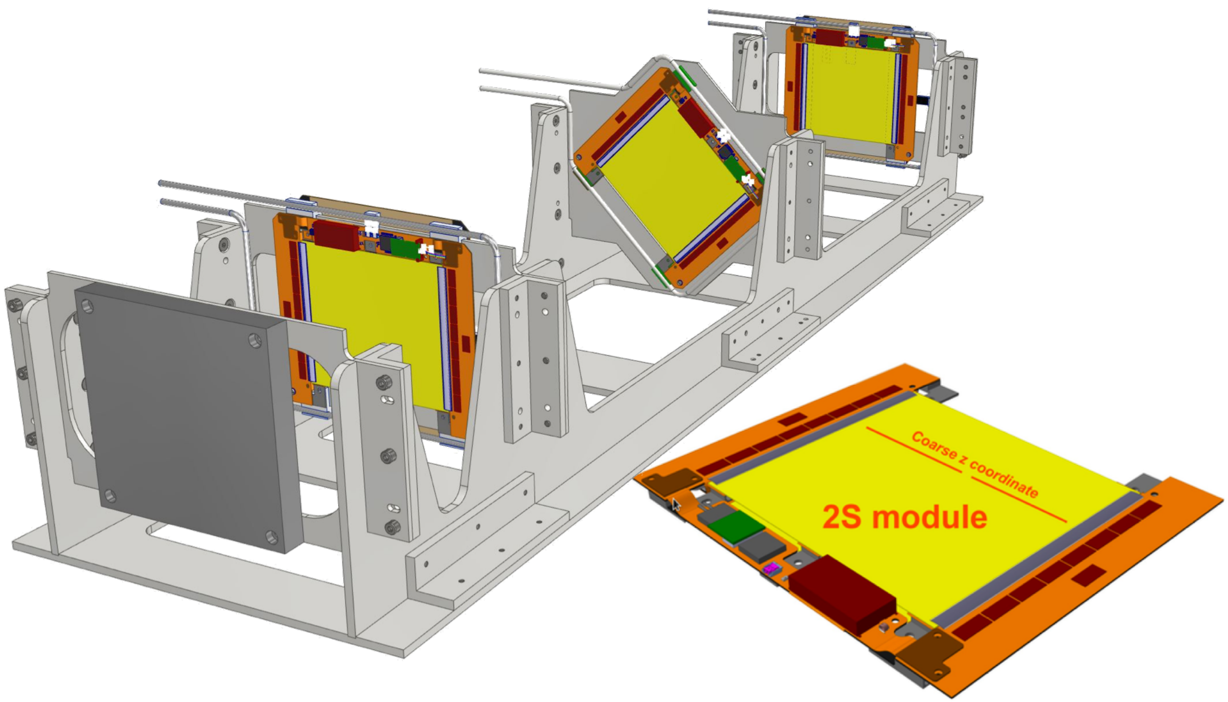
ATTIVITA’ e RICHIESTE MUONE 2021 a Pisa

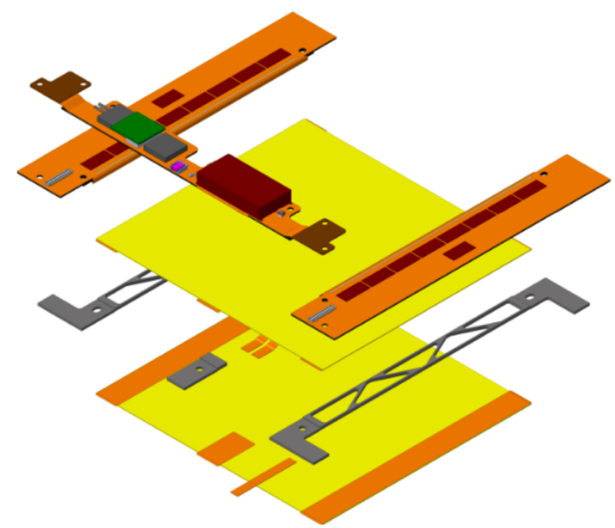
- Principalmente focalizzata alla realizzazione del TR 2021:
  - Meccanica tracker
  - Integrazione moduli 2S (a Pisa o al CERN)
  - Calibrazione EMC
  - Studi simulazione

- Forte collaborazione con CMS:
  - Possibilità di integrare i moduli 2S a Pisa
  - Firmware elettronica di lettura moduli PS/2S

The tracker station

- A tracker station is composed by a target and 3 tracker layers
- The target is Berillum (or maybe Carbon), 15mm thick
- Each tracker layer is made by 2 2s modules with strips at 90º ; layers 1 and 3 have modules in (x,y), layer 2 in (u,v)
- Each module is made by 2 sensors, 1.8mm apart



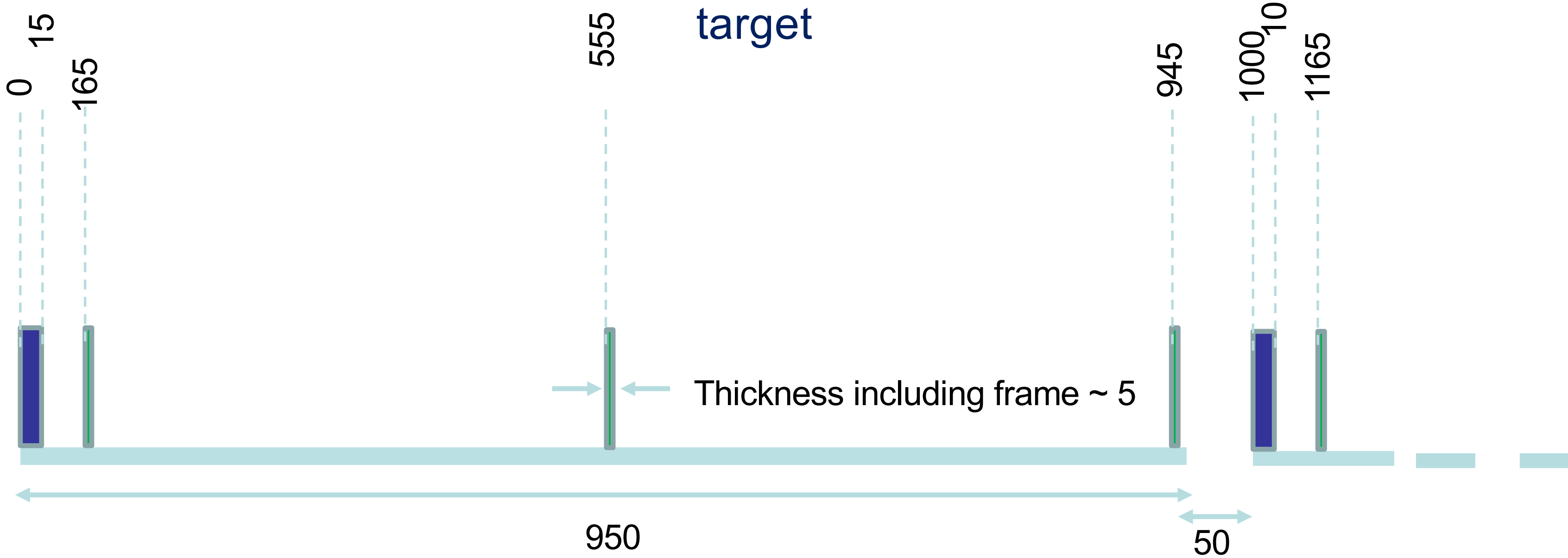


(M. Incagli, C. Ferrari, M. Massa, A. Moggi)

Scheme 1 of a *MUonE* station

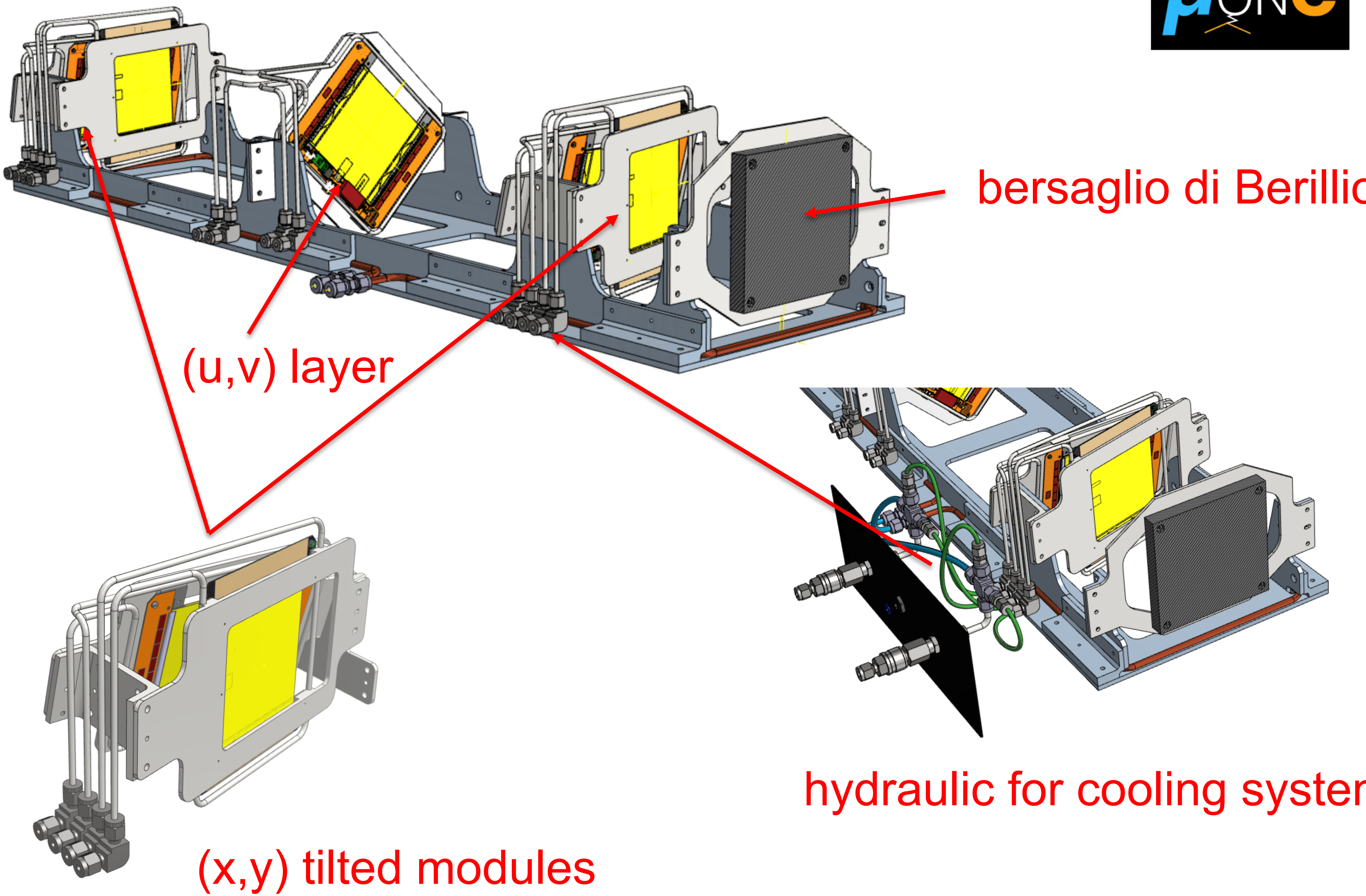
All units in mm
Carbon fiber support
Beryllium target
Silicon layers:
2 sensors per view (x,y)
2 mm apart 0.3 mm thick

This scheme is based on the following constraints:
- 1000 mm between targets
- equidistant Si layers within station
- 150 mm between target and first layer
- 50 mm between last layer and following target



(M. Incagli, C. Ferrari, M. Massa, A. Moggi)

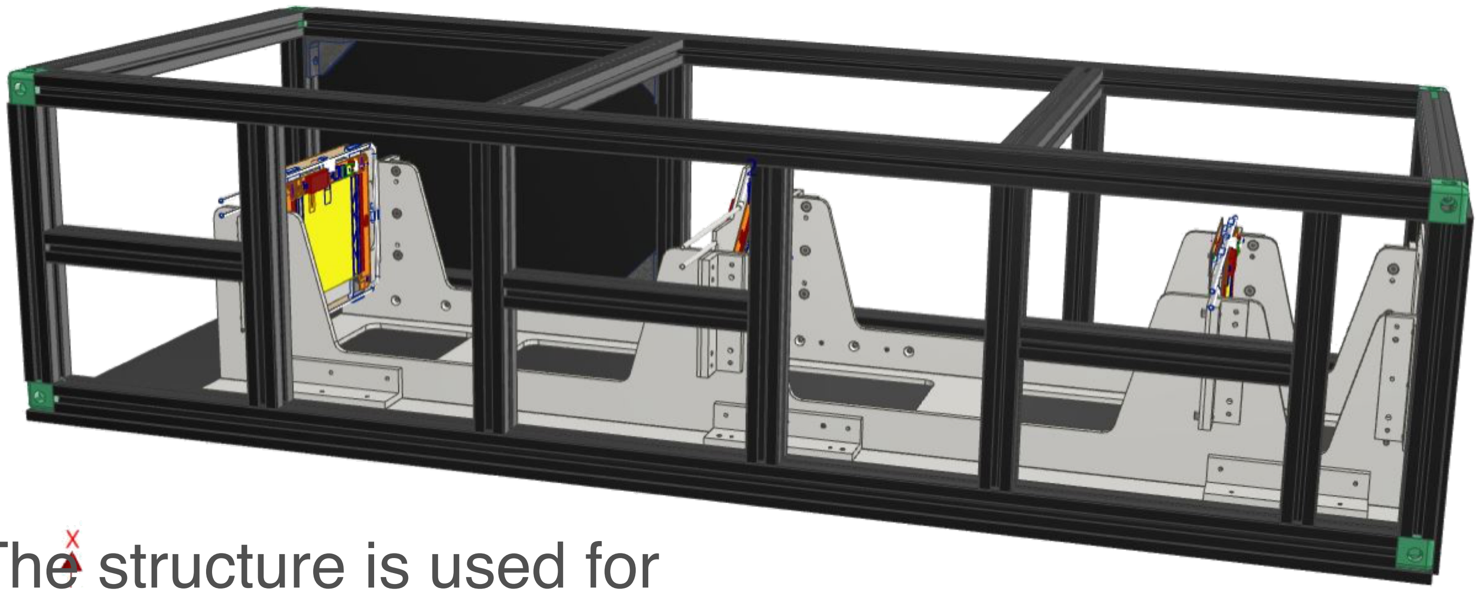
Disegno meccanico stazione



(M. Incagli, C. Ferrari, M. Massa, A. Moggi)

external structure

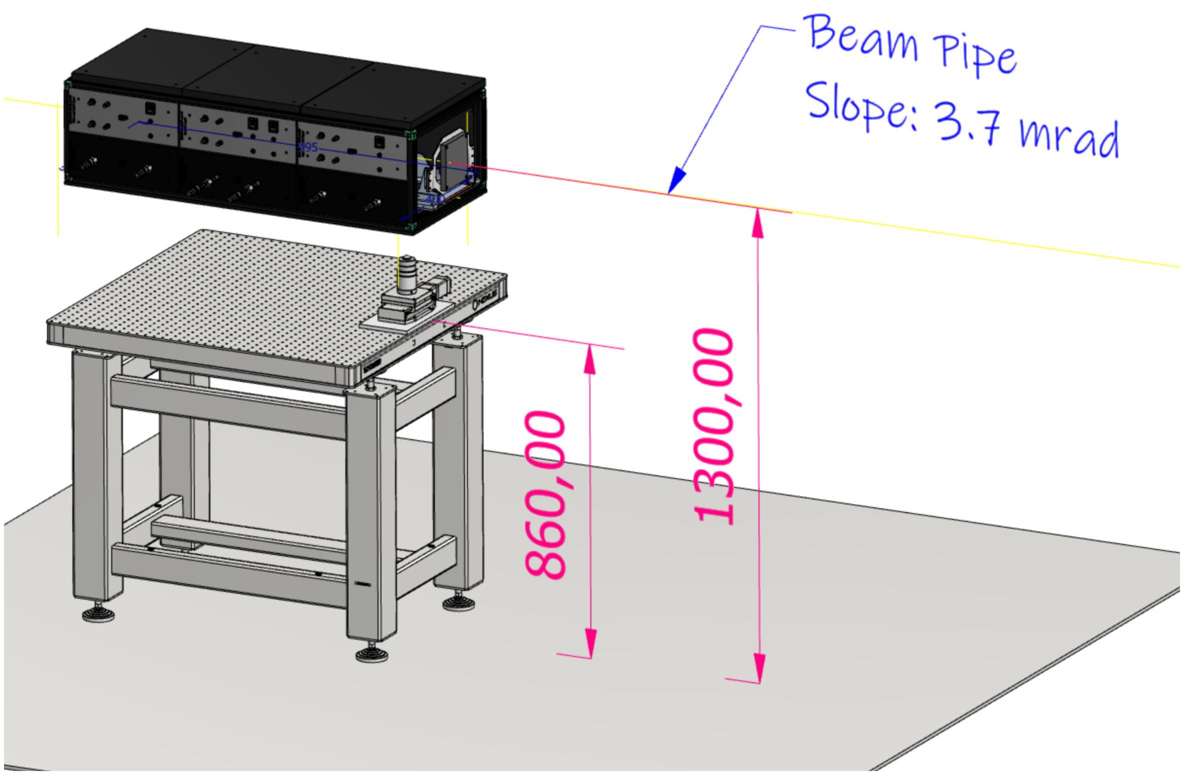
- The support is enclosed in an external structure with patch panels for electrical, optical and hydraulic connections



- The structure is used for light tightness and to keep the inner temperature constant at 18±1 degree

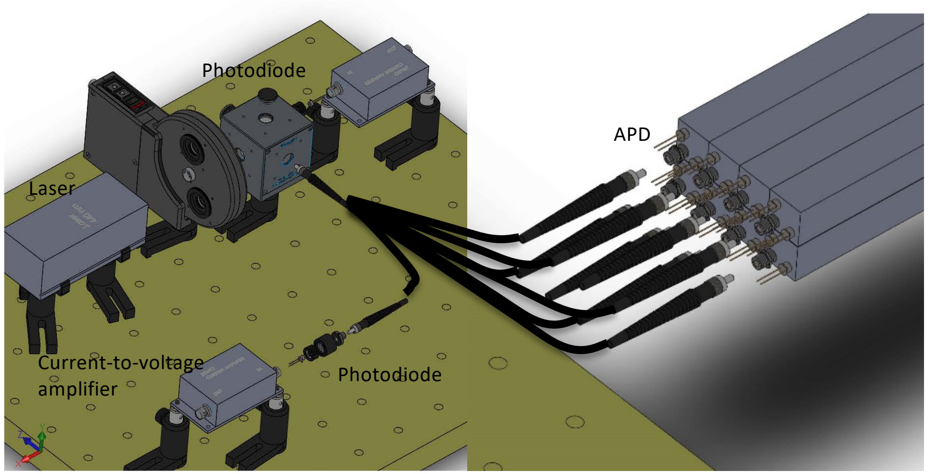
tavolo di supporto

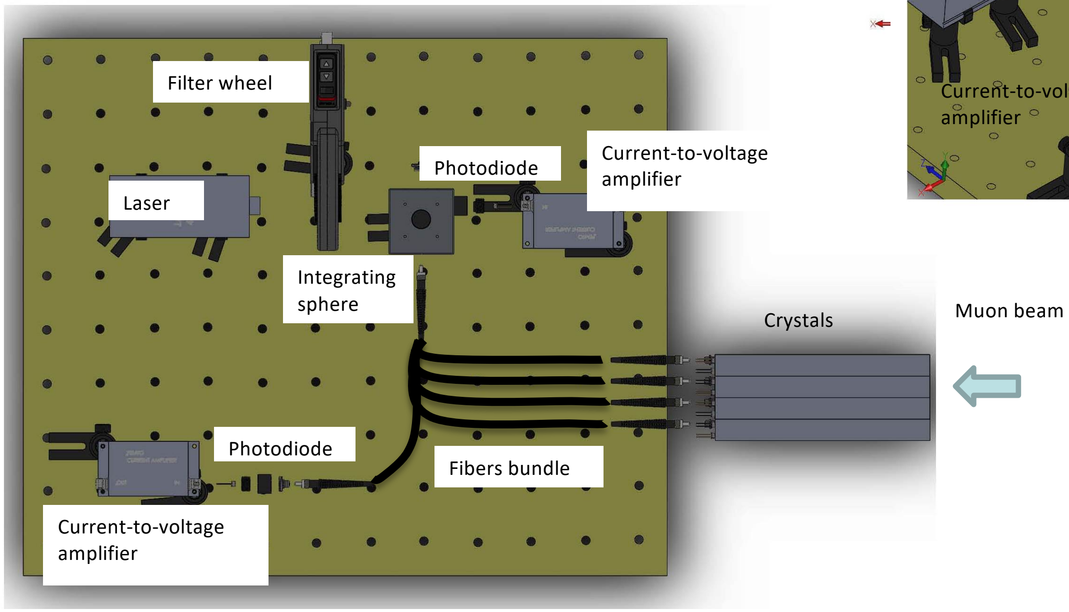
- il tracciatore si monta su un tavolo ottico dotato di sistema di movimentazione per allineamenti fini
- ancora da stabilire la altezza esatta del fascio



Laser calibration system

(Mutuato da g-2)





(C. Ferrari)

(F. Ligabue, R. Pilato)

MUonE simulation

Simulation software is developed in separate packages, to allow flexibility:

- **Geant4 simulation** → https://baltig.infn.it/muone/simula
- **Digitiser** → https://gitlab.cern.ch/muesli/digitiser
- Track Reconstruction
- Calo Reconstruction
- Analysis

Packages to be versioned in a set of CERN GitLab repositories dedicated for MUonE:

https://gitlab.cern.ch/muesli

Geant4 simulation

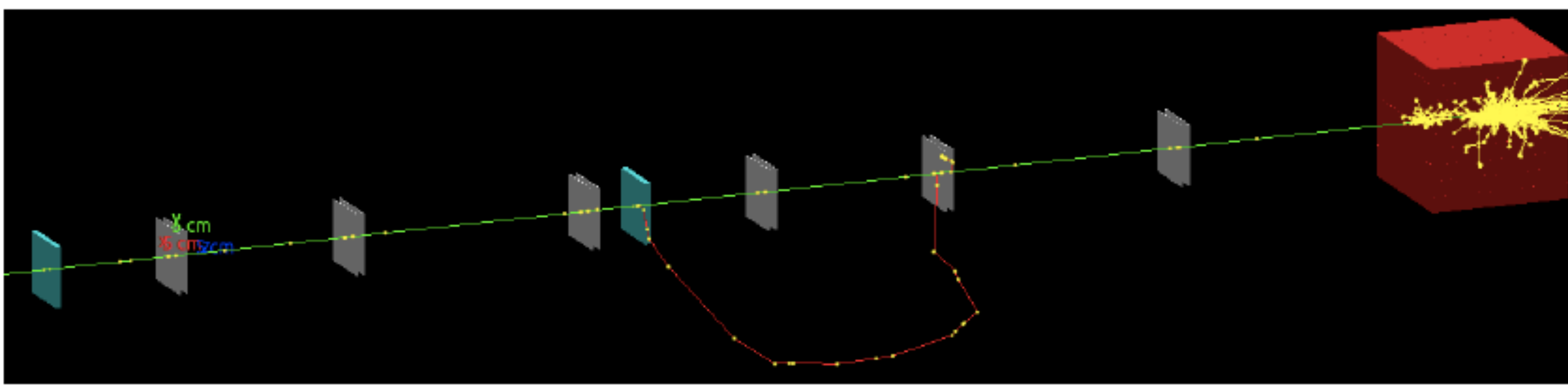
Several event generators are available, to study different aspects of the experiment:

- M2 muon beam
- Hand-made LO elastic interaction
- NLO elastic interaction

Digitiser

It gets the result of the Geant4 simulation as input. It is intended to carry out:

- Pileup effects.
- Hits digitisation, starting from the hits in the Si sensors and the corresponding energy deposited. (Transportation model adapted from CMSSW).
- Stub finding logic.



Richieste in sezione

- 10% Massa + 10% Moggi per progettazione struttura
- 6 settimane uomo in officina per la lavorazione delle 3 stazioni che devono essere prodotte per il test run di autunno 2021 (la prima, senza bersaglio, serve a misurare la direzione di ogni muone entrante)
- 4 settimane uomo da parte del servizio alte tecnologie per assemblaggio e misura di precisione, con tastatore della posizione dei frame che su cui si fissano i sensori di silicio

Personale coinvolto

- C. Ferrari 30%. (INO)
- M. Incagli 10%
- F. Ligabue 25%
- G. Venanzoni 25%
- R. Pilato (dottorando) 100%

- M. Massa (TECNOLOGO) 10%
- A. Moggi (TECNOLOGO) 10%

> 2 FTE (apertura sigla locale)

(altre persone interessate che devono confermare la loro partecipazione)

News about the collaboration

List of active experimental groups:

INFN : Bologna, Milano-Bicocca, Padova, Pisa, Trieste

Russia: Novosibirsk

Poland : Kracow, Institute of Nuclear Physics PAN

UK : Imperial College

USA : University of Virginia
Northwestern University

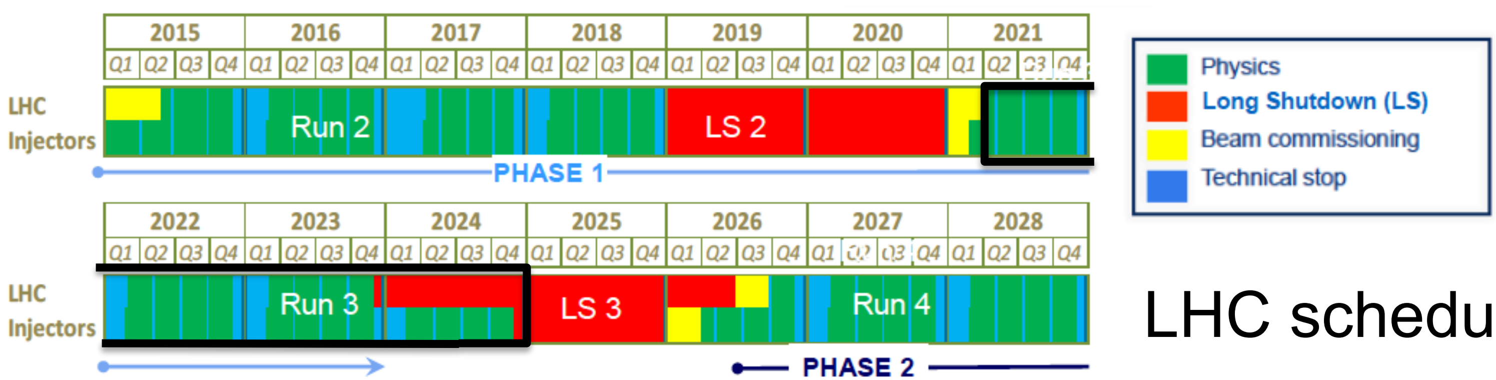
CHINA : University of Shanghai

new New member of the collaboration: Demokritos Institute, Athens
(involved in CMS Outer tracker, plan to work on DAQ, simulation, analysis in **MUonE** *)*

Info from the active theory groups: document dedicated to MUonE
P. Banerjee et al., **"Theory for muon-electron scattering @ 10ppm: A report of the MUonE theory initiative"**, arXiv:2004.13663 [hep-ph] (submitted to EPJC).

Plans*

- **2020-2021**
  - Detector construction and installation (test run in 2021)
- **2022–2024**
  - Analysis of TR data
  - TDR to SPSC
  - If approved: data taking to measure a_{μ}^{HLO} with increasing precision



LHC schedule

(*A meno di ritardi)

THE END

SPARE

$\Delta\alpha_{had}$ parameterization

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

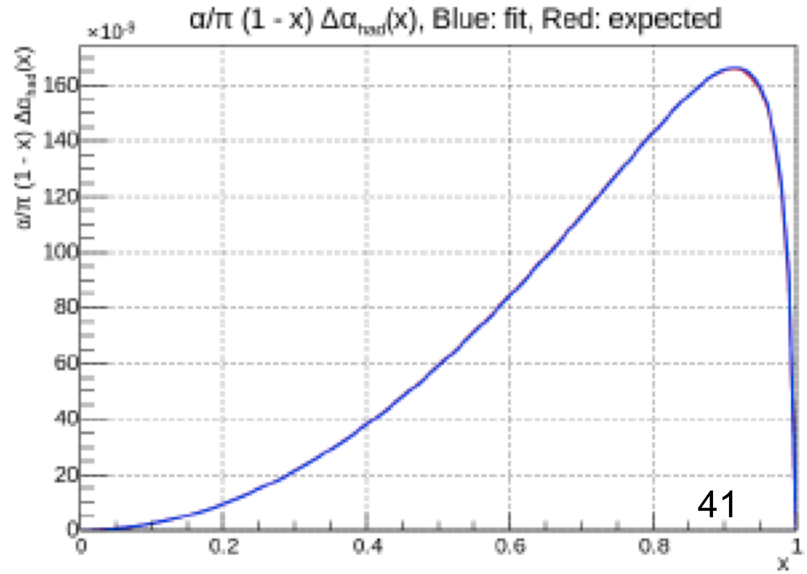
$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

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

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

2-parameters function (k, M)

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



Laser calibration system

The calorimeter PWO scintillators produce short light pulses (3 to 30 ns) and maximum emission around 440 nm. We expect maximum light pulses in the order of 10^7 photons (4.5 pJ/pulse @ 440 nm).

The most common way to perform gain calibration of the calorimeter is by laser pulses of known amplitude sent to the crystals (and then to the photodetectors), with amplitude and width close to the pulses produced by particles interaction.

The basic components of the laser system are:

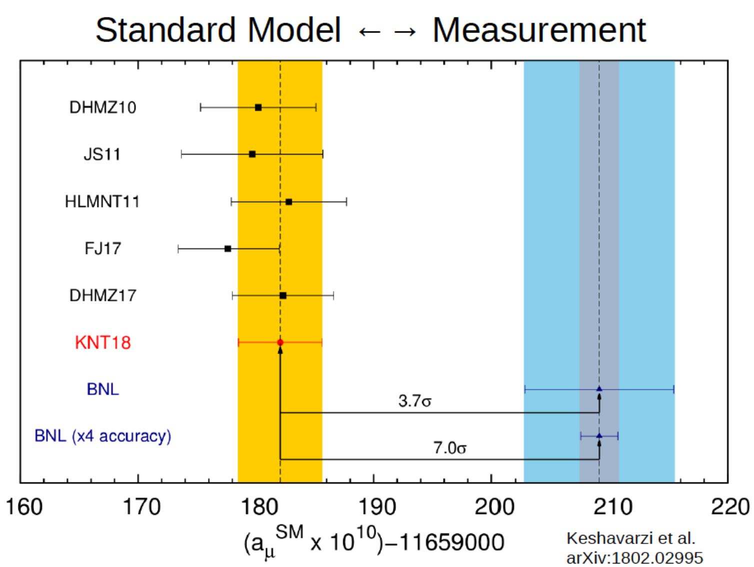
laser, filter wheel, integrating sphere, monitor system, optical fiber bundles, connection to the crystals, long term absolute monitor.

Laser calibration system

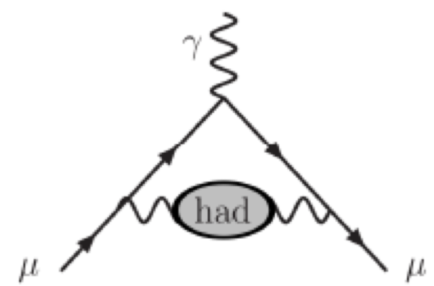
- The motorized filter wheel will be used to adjust the laser pulses amplitude, to assess the linearity of the photosensors and to perform calibration of the photosensors.
- The integration sphere will perform the fan-out, from the laser beam entering at one port to the optical fibers (grouped in bundles), connected to the others port of the sphere, one fiber for each crystal. Up to three bundles can be connected to one sphere. Up to 200 fibers per bundles (depending on the fibers diameter). The optical transmission of the integrating sphere depends on the fibers diameter and NA of the fibers.
- The short-term monitor system will be performed by silicon photodiode (es. Hamamatsu s1226-18BK) connected to the monitor port of the integrating sphere.
- Each optical fiber of the fibers bundle will be terminated with SMA connector and will be connected to the back of a crystal of the calorimeter: a SMA adapter should be glued at the back of each crystal (es. Thorlabs HASMA).
- The long term absolute monitor will not be used during the short pilot run.

$a_\mu=(g-2)/2$

- ~3.5σ discrepancy between exp and TH
- New $(g-2)_\mu$ experiments at Fermilab (E989) and JPARC (E34)
- If E989 confirms E821 (with full stat) → a_μ^{EXP}- a_μ^{SM} ~ 7σ → New Physics?
- Discrepancy limited by the uncertainty on the theory side (hadronic effects)



Different methods to control the theory very important !



HLO (HVP)