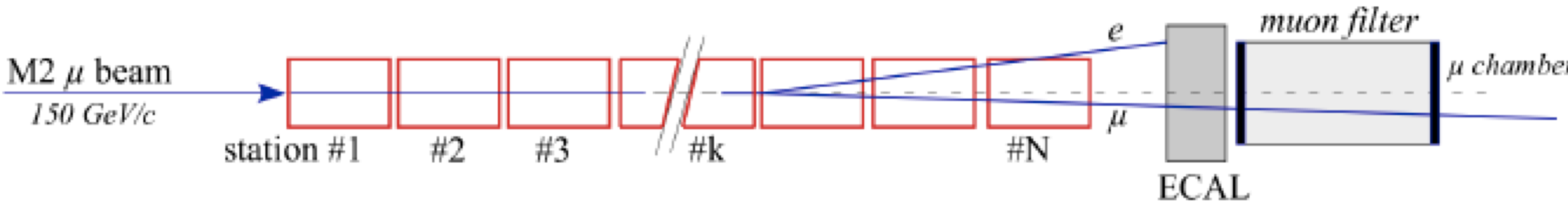
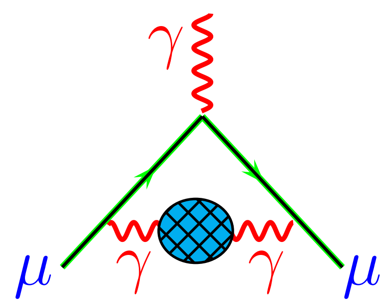
Status of MUonE

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





"The closer you look the more there is to see" (F. Jegerlehner)

PBC Workshop, CERN 5 November 2019

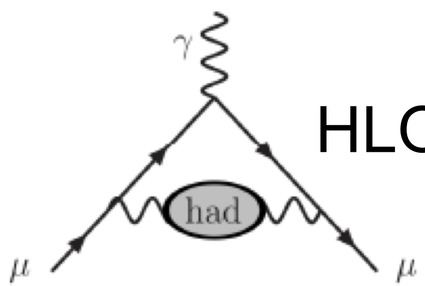
Outline

- A (brief) Reminder on MUonE proposal
- Some recent updates
- Plans
- Conclusions

Muon g-2: summary of the present status

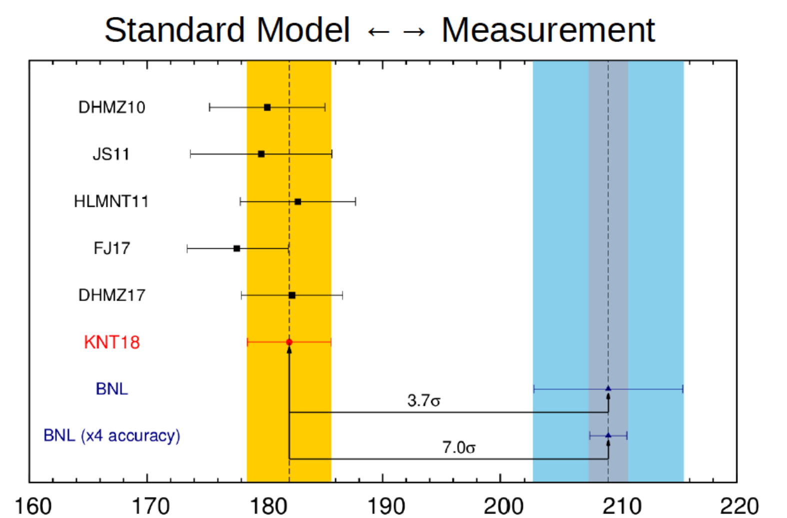
- ~3.5σ discrepancy between exp and TH
- New $(g\text{-}2)_\mu$ experiments at Fermilab (E989) and JPARC (E34)
- If E989 confirms E821 (with full stat)
  → $a_\mu^{EXP} - a_\mu^{SM} \sim 7\sigma$ → New Physics?
- Discrepancy limited by the uncertainty on the theory side (hadronic effects)

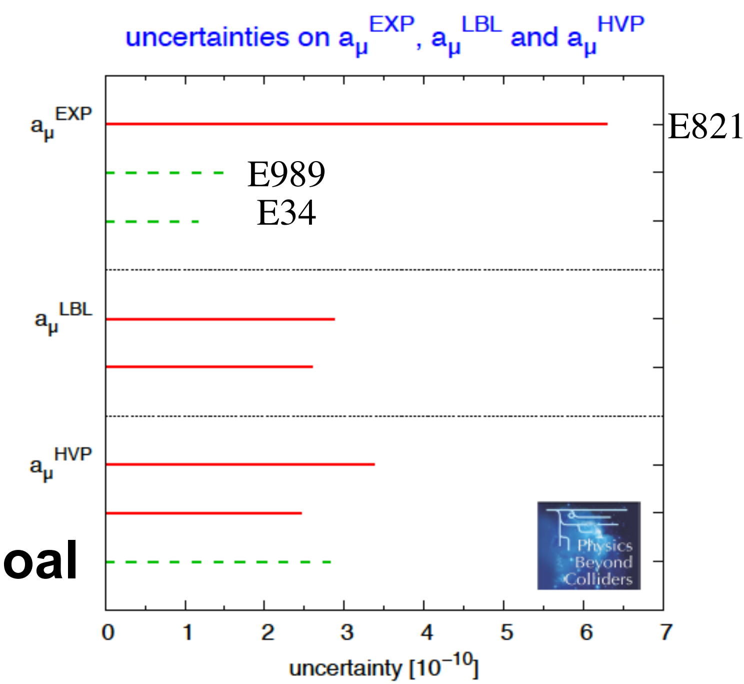
→ HLO (HVP)



Different methods to control the theory very important !

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





MUonE Goal

G. Venanzoni, PBC Workshop, CERN, 5 Nov 2019

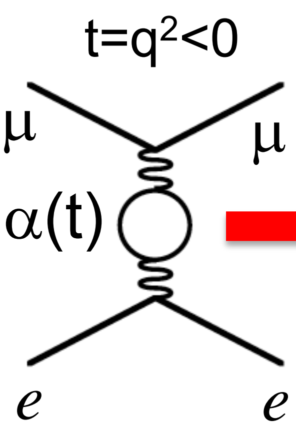
MUonE proposal: a_μ^{HLO} from space-like region

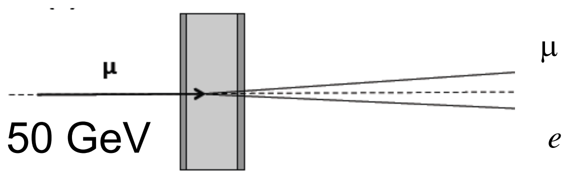
[C.M. C. Calame et al, Phys. Lett. B 746 (2015) 325,
G. Abbiendi et al., Eur. Phys. J. C77 (2017) 139]

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

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

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



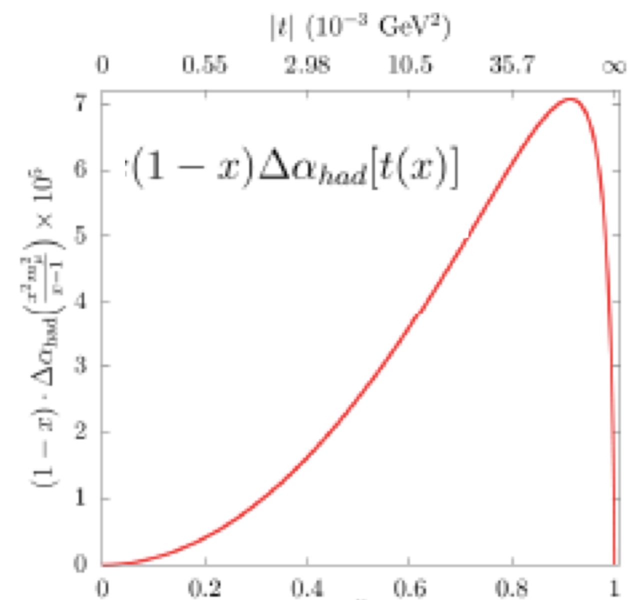


$$\frac{d\sigma^{VP}}{dt} = \frac{d\sigma^{\text{no VP}}}{dt}\,\frac{1}{|1-\Delta\alpha(t)|^2}$$

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

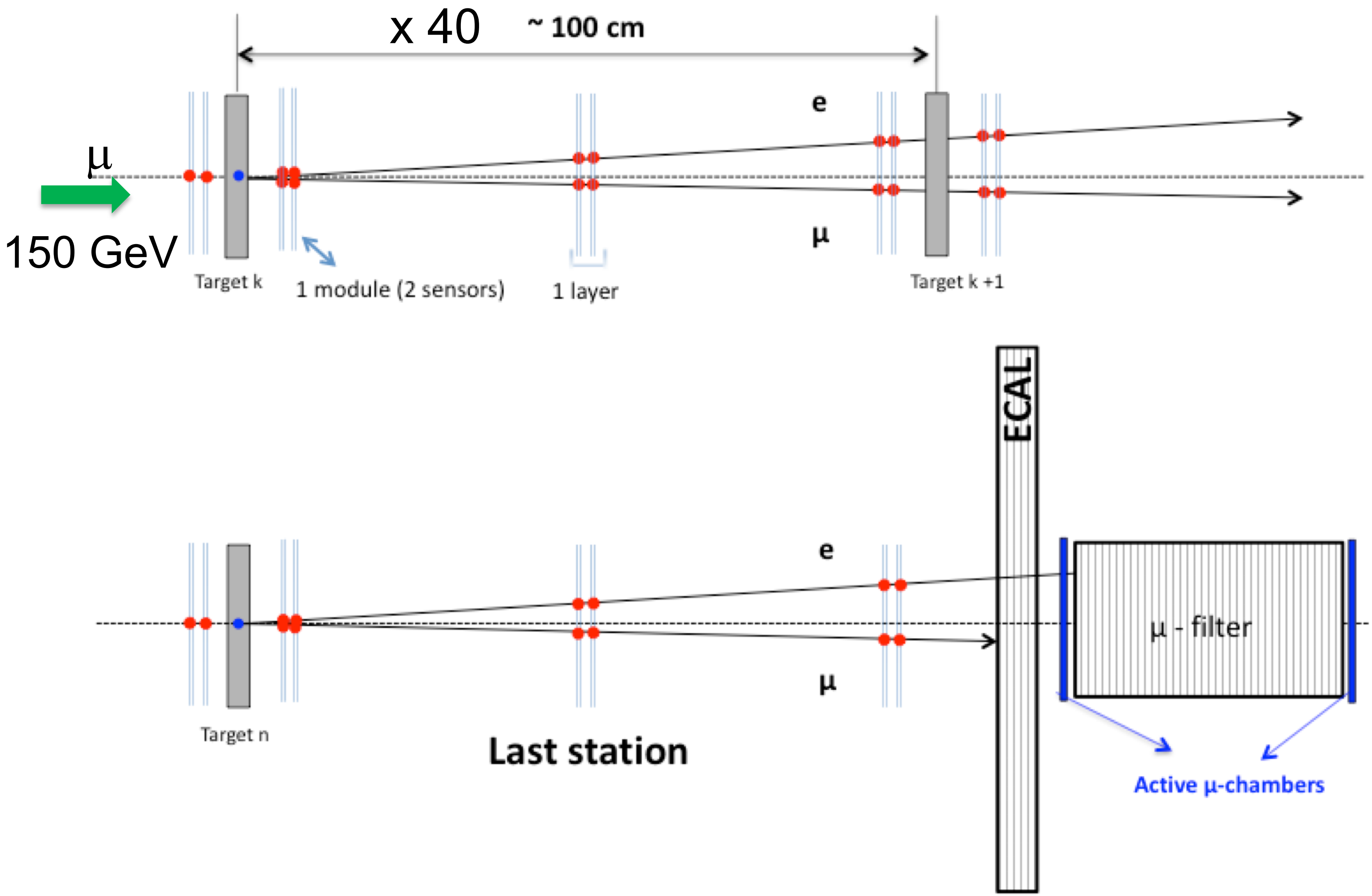
Known analytically from QED

Extracted from data



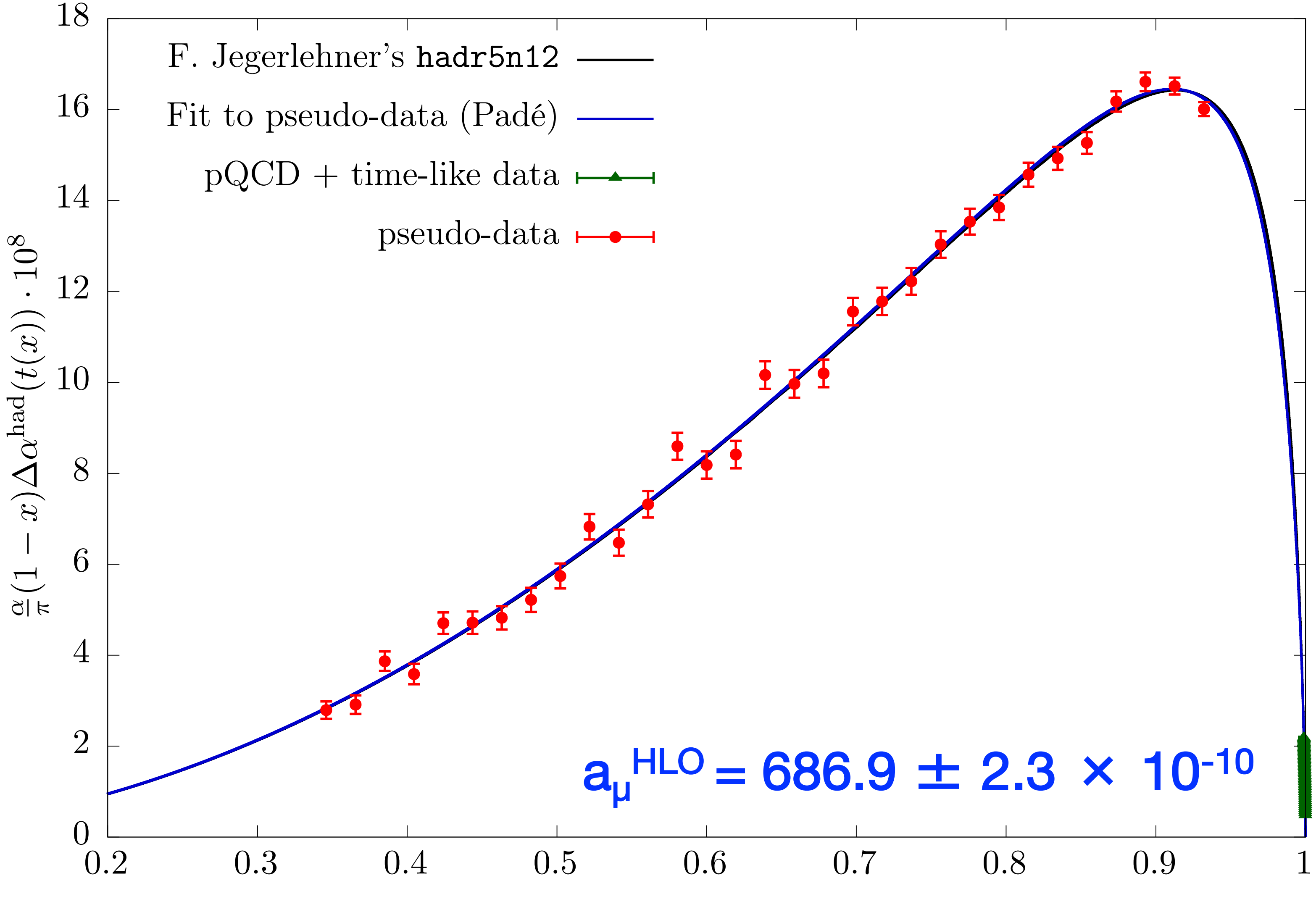
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

Detector concept



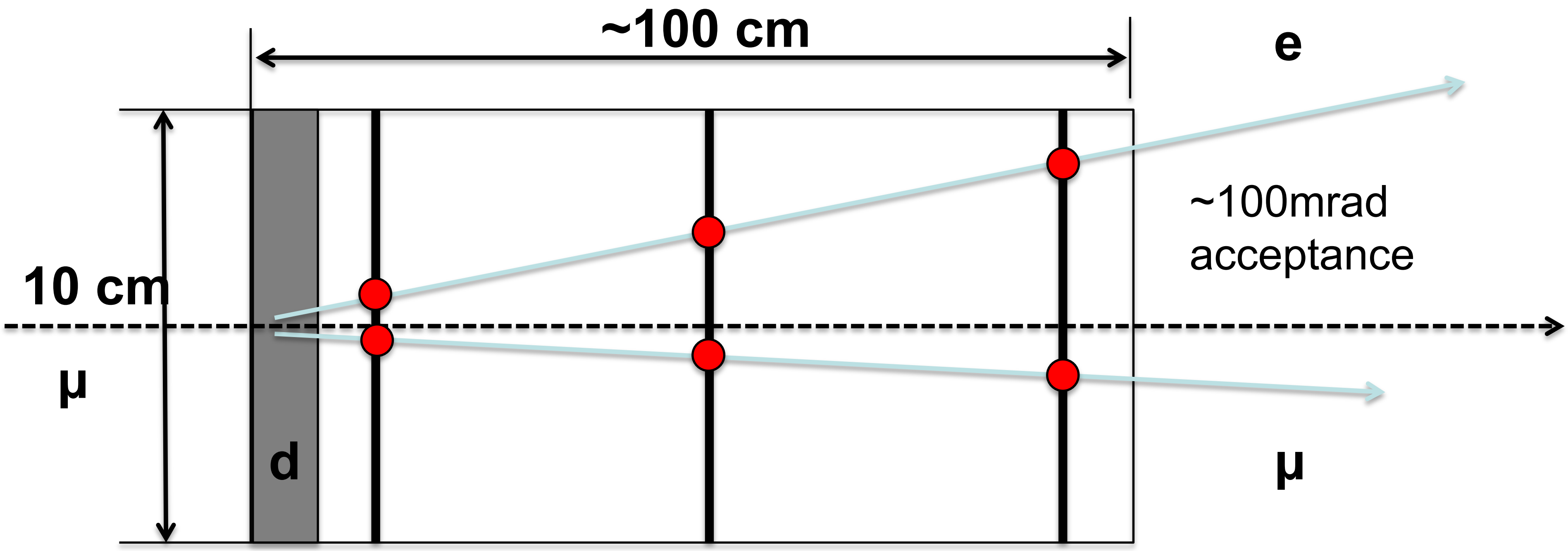
40 'independent' stations will provide 60 cm Be target material

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)

Single Unit



~1.5 cm
Be Target

State-of-art Silicon detectors

hit resolution ~20 μm

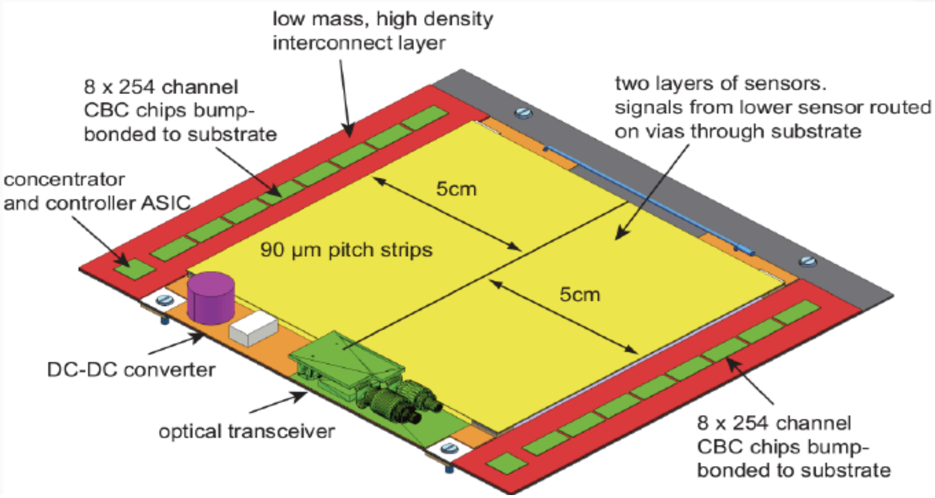
Expected angular resolution ~ 20 μm / 1m = 20 μrad

At the end ECAL and Muon Filter for PID

Tracking system

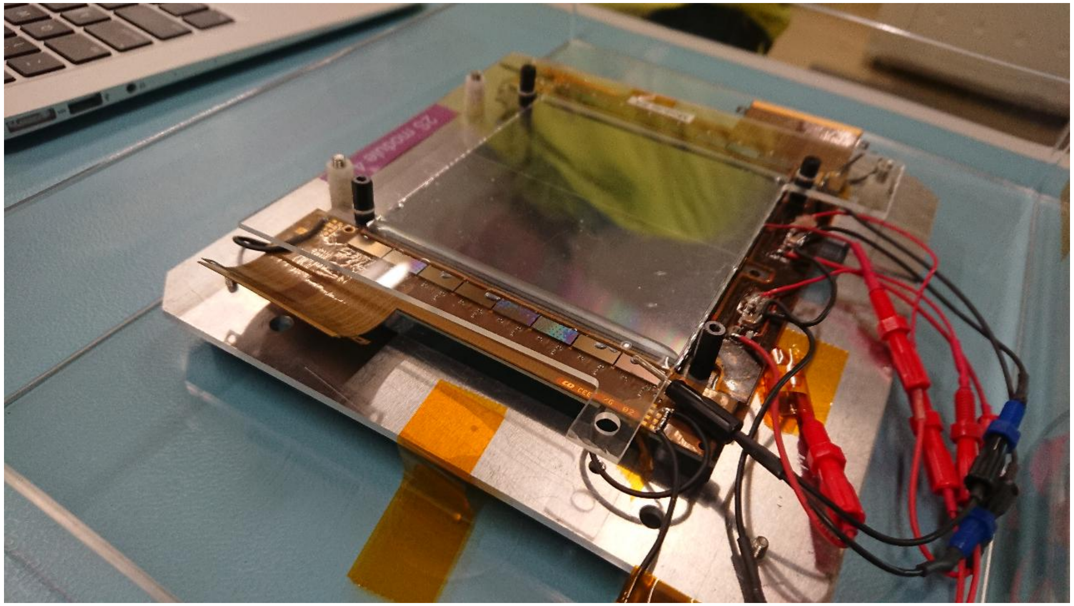
Requirements:

- Good resolution (~ 20 μm)
- High uniformity (ε ≳ 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



Location at CERN M2

- **Between BSM and COMPASS**

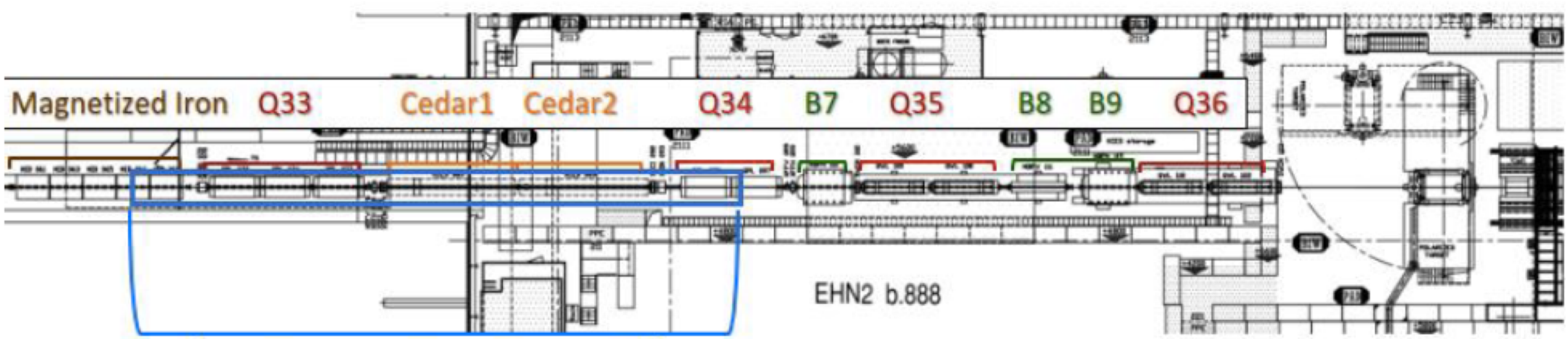
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- 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} : Optic's wise looks OK (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) ~ 39 m

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 meeting with the SPSC's referees (Arnaud Ferrari and Urs Wiedemann) took place on October 14

3. First funding from INFN (~100kE) for the preparation of the Pilot Run 2021

4. Pilot Run requested in LoI with two stations (3 weeks at the end of 2021)

Pilot 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.

Pilot Run 2021

In the LoI, the MUonE requests the M2 beam:

3 weeks at the end of 2021 *(due to the Si planes availability)*
to run with 2 full stations in the configuration:

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

The pilot run should provide ~ 10^8 elastic events

Pilot Run 2021

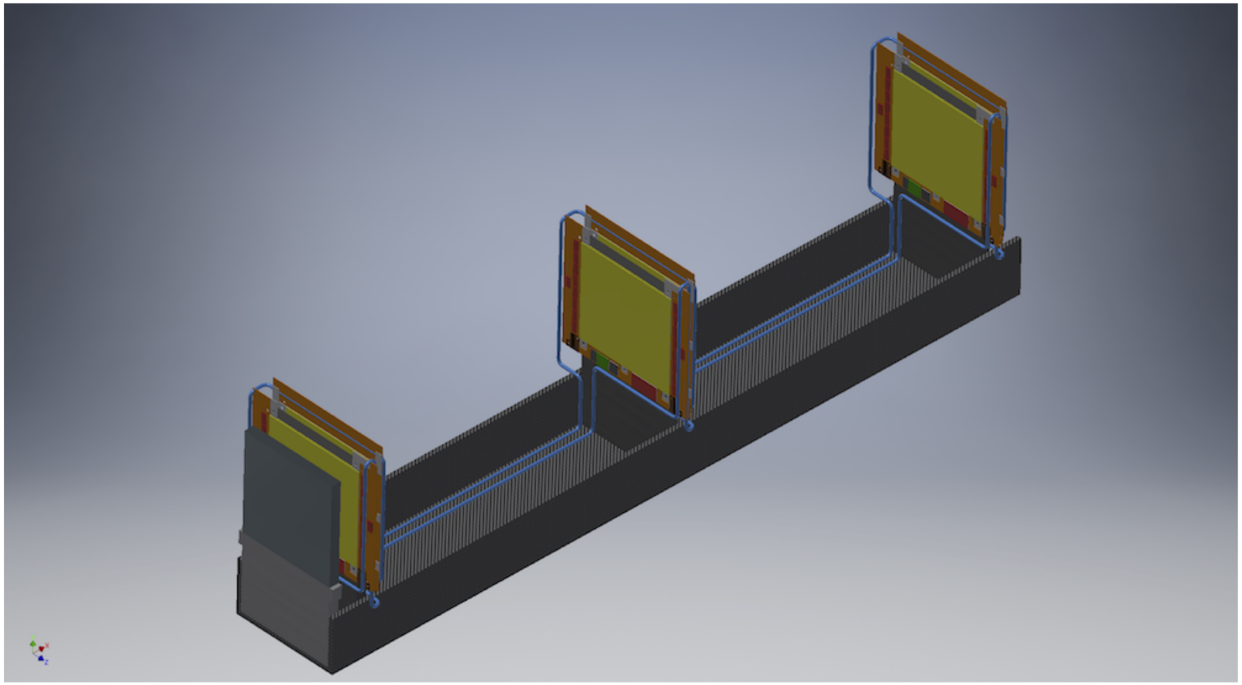
- **Location:**
  upstream COMPASS after the BMS

- **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

Mechanics and cooling

A station 1m long requires a CTE of the order of 10^{-6} K^{-1} to keep the z position stable within 10 μm for temperature variations of $\Delta T < 1^{\circ}$



- The tracker mechanics is based on a Carbon Fiber structure with inserts supporting the Beryllium target and the Silicon modules.
- Sensor relative positions continuously monitored by laser holography

$\Delta\alpha_{had}$ NLO fit results (LoI)

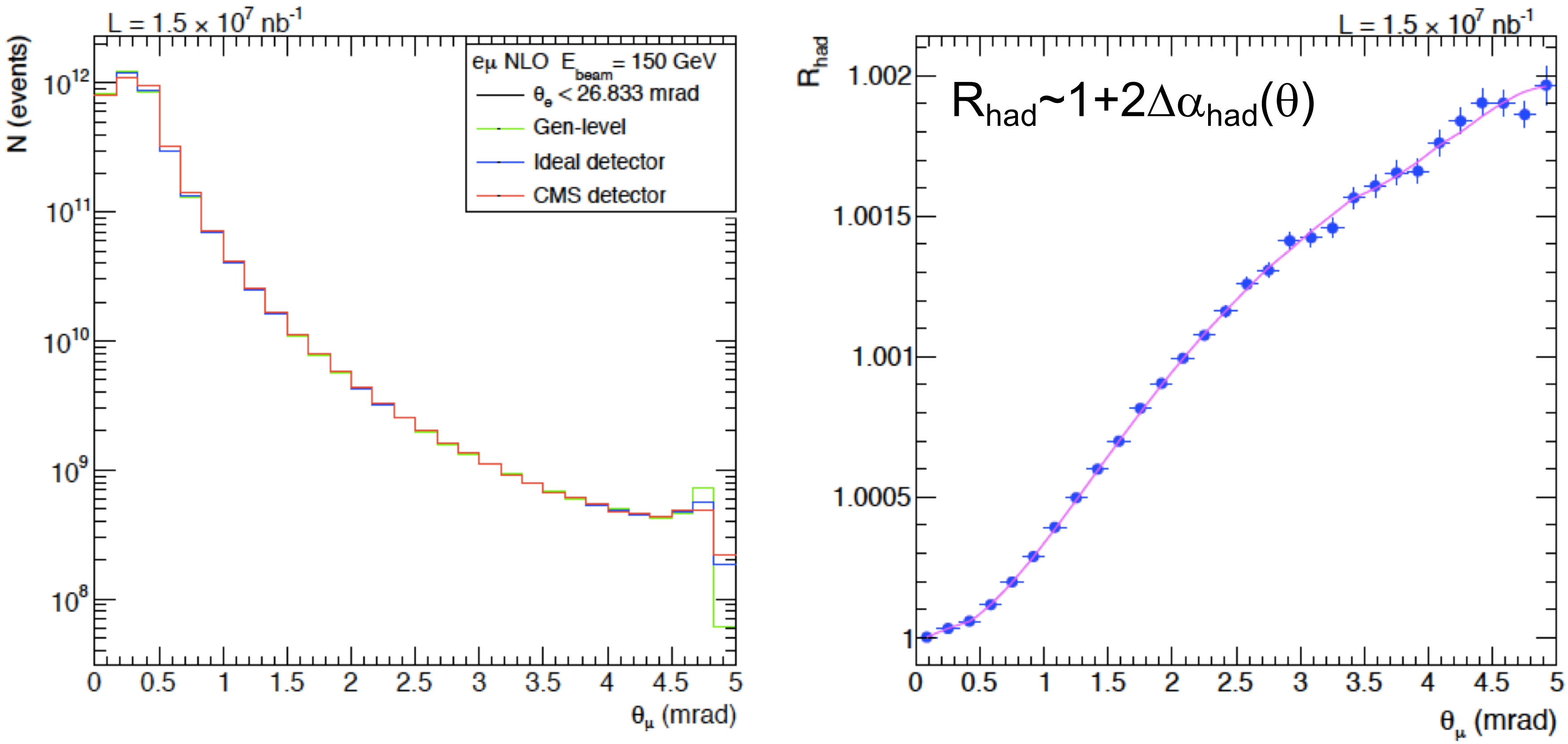


Fig. 29: Left: muon angular distribution (after the acceptance cut $\theta_e < 26.833$ mrad). In comparison: the pure generator level from NLO MC with fixed beam energy of 150 GeV and simulations for an ideal detector and for the MUonE tracker, including a beam energy spread of 3.75%. Right: observable ratio $R_{had}(\theta_\mu)$ for pseudodata showing the hadronic contribution to the running of α with the result of the template fit superimposed. Entries and error bars correspond to the nominal MUonE integrated luminosity of 1.5×10^7 nb^{-1}.

$\Delta\alpha_{had}$ parameterization

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

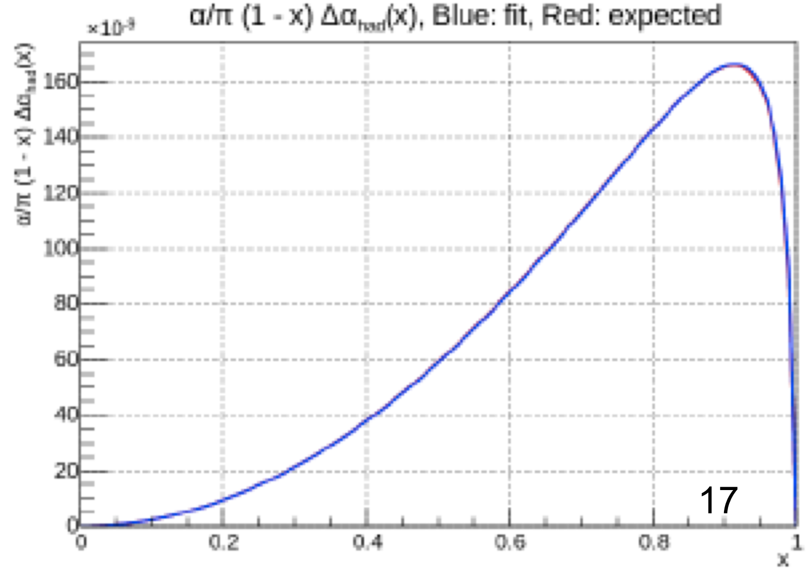
$$\Delta\alpha_{had}(t) = k\left\{-\frac{5}{9} - \frac{4M}{3t} + \left(\frac{4M^2}{3t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

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.

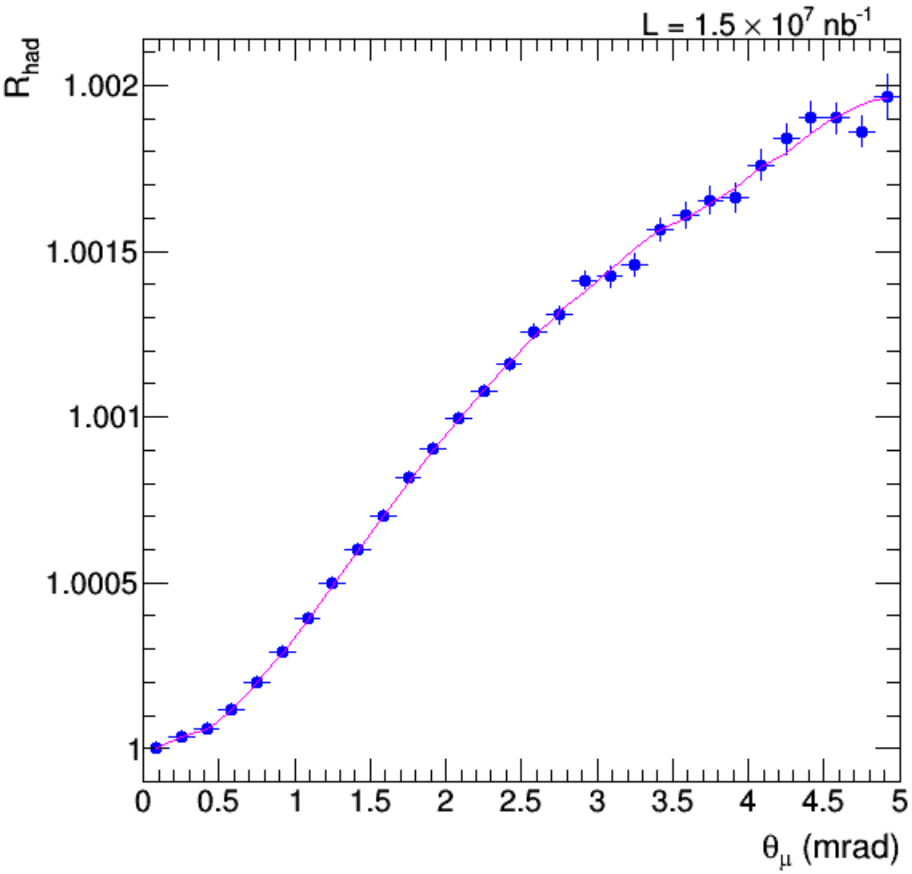


Template method for NLO studies

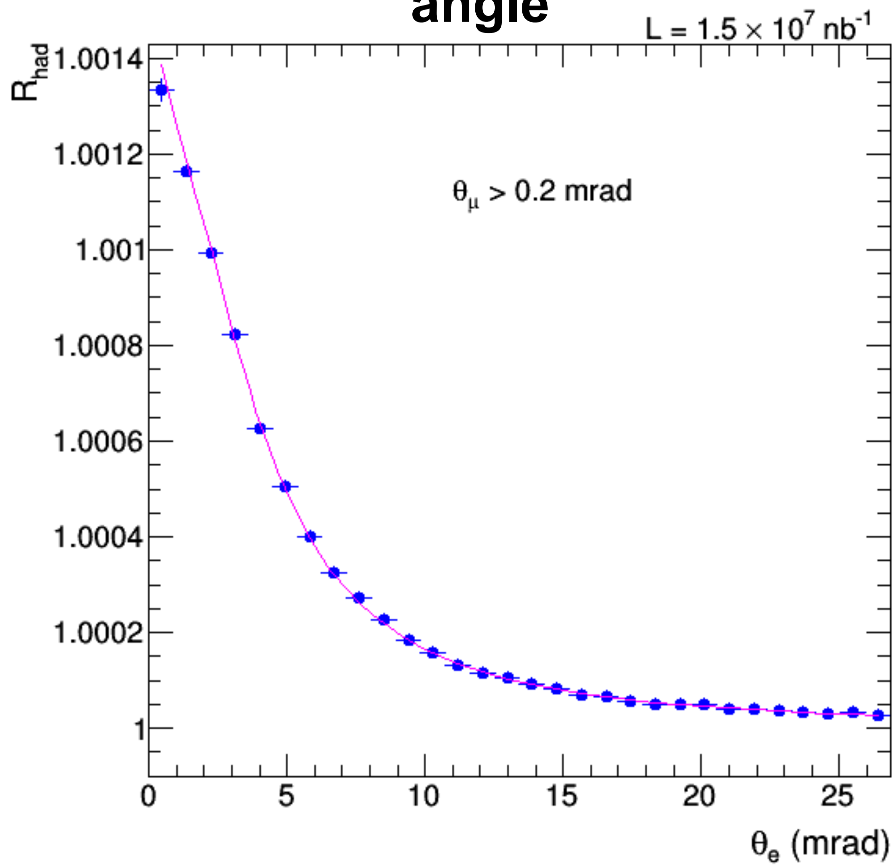
- Template method is used to measure the hadronic running $\Delta\alpha_{had}(t)$.
- 2D parameterization of the hadronic running tested by fitting the time-like model.
- Pseudo data samples generated varying the parameters in the 2D lattice.
- Convolution the angular distributions with the detector resolution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

Results

Muon angle



Electron angle

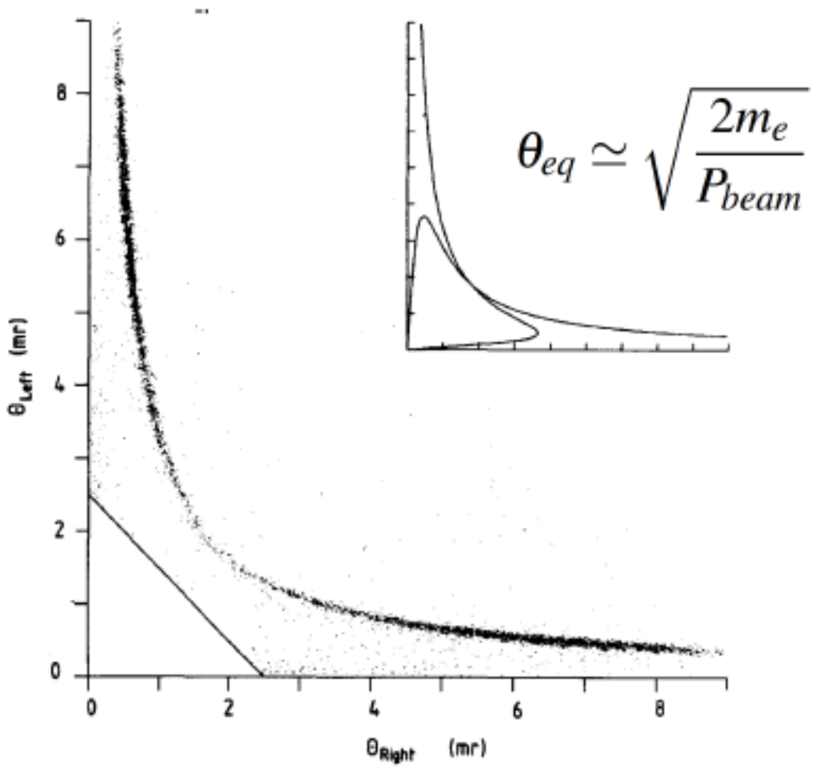


From 3000 pseudo experiments we got $a_\mu^{HLO} = (689.8 \pm 2.3)10^{-10}$, to be compared with 688.6×10^{-10} (agreement within 1 sigma)

Momentum scale

S.R.Amendolia et al, Phys.Lett.B146(1984)116 / Nucl.Phys.B277(1986)168

πe Elastic scattering in the (θ_R,θ_L) plane

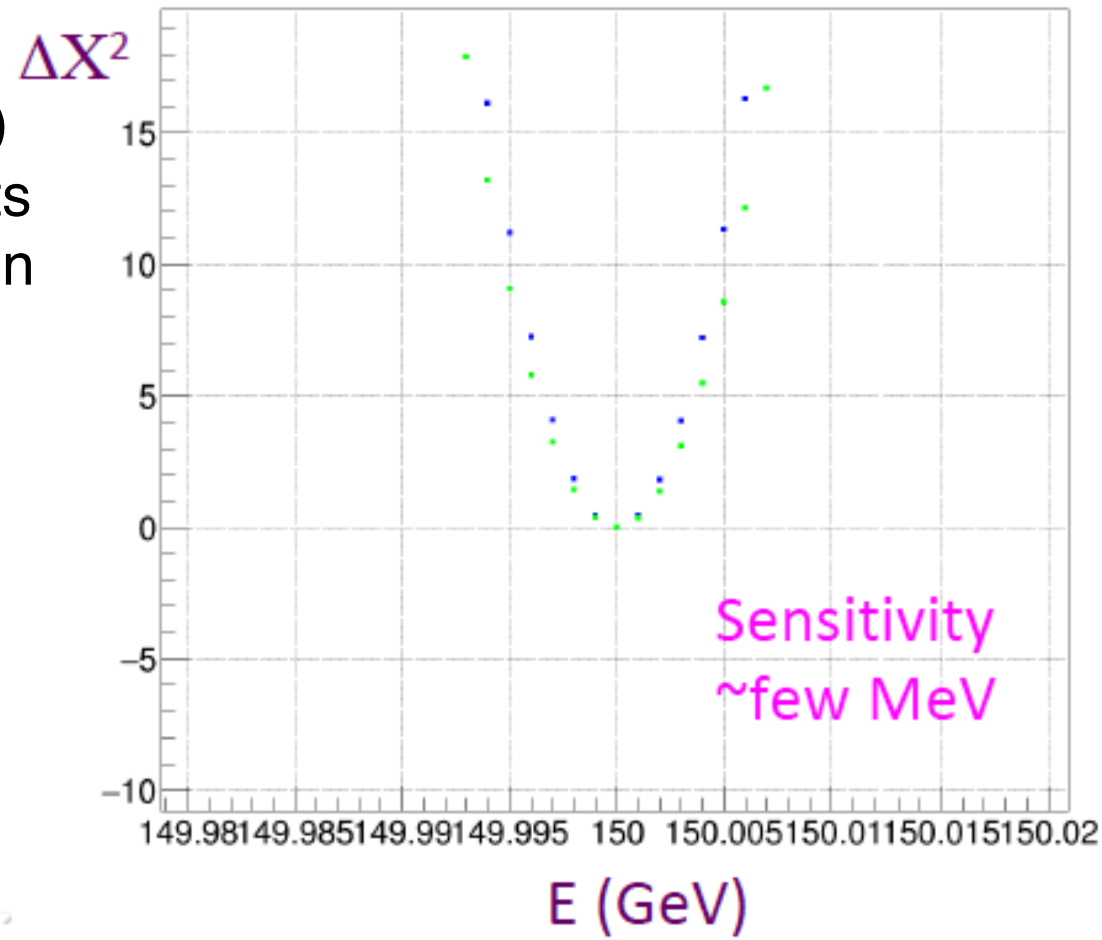


- Beam energy determined by kinematics by measuring the angles of the two outgoing particles. Method previously used by NA7
- Selection of events ~ 2.5 mrad (E~75 GeV) Distribution of the angle sum (or the average angle) for the selected events.
- This technique is robust against transverse misalignments (null effect to the first order).
- Longitudinal misalignments should be limited to O(10) microns.

Momentum scale

Template method: χ^2 comparison of pseudodata with distributions for the average angle

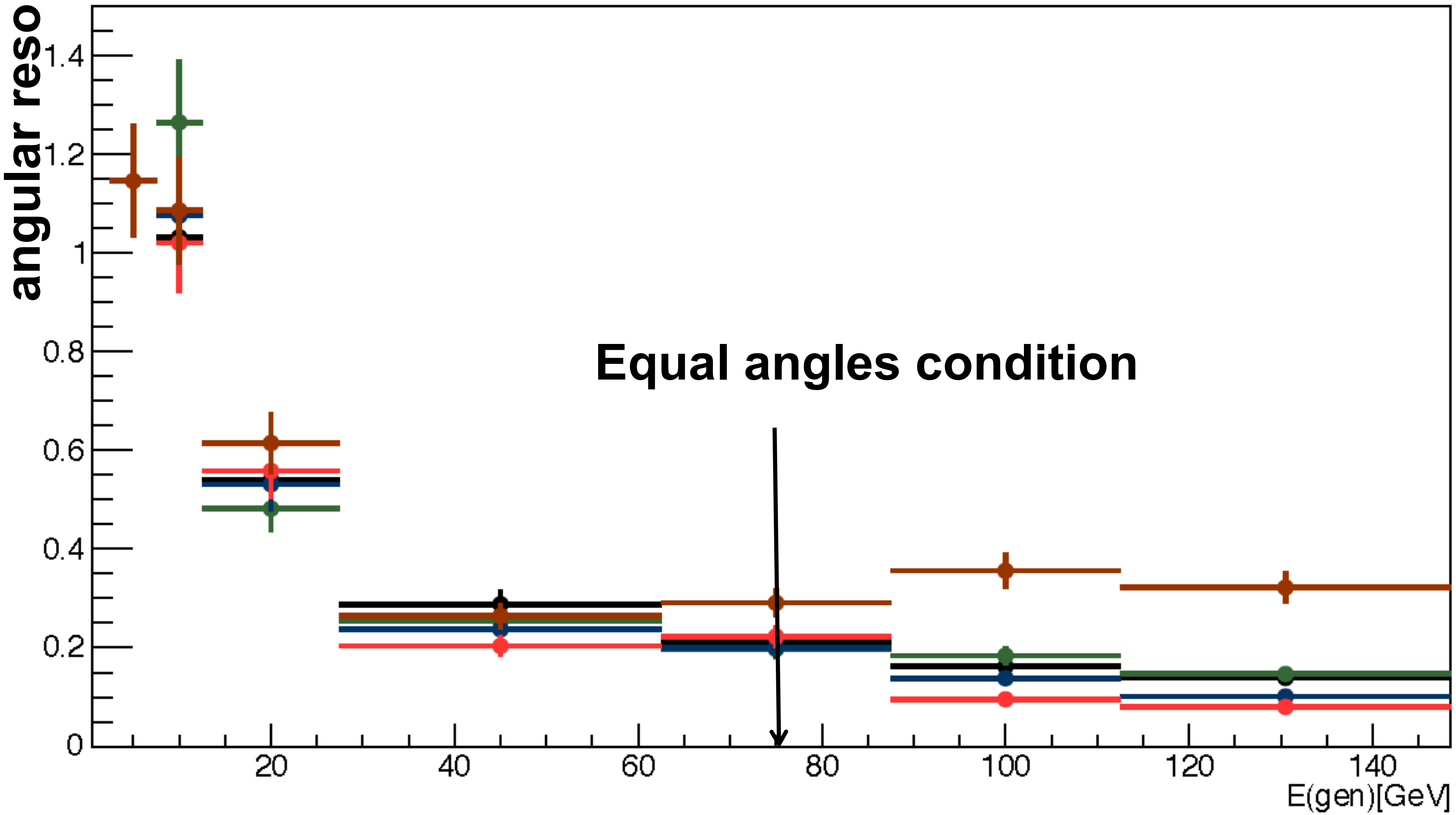
- Ebeam = 150 GeV with 1% spread (spectrometer)
- Generation of 10^7 events selecting an angular region around θ~2.5 mrad and realistic angular spread
- Accuracy ~ 1 MeV
- Systematic error ~MeV
- Statistics in few days



Calorimeter

- PID based on ECAL is important when both the angles are below 5 mrad, where $\theta_\mu \sim \theta_e$
- Measuring the electron energy would enable:
  - Triggering on the 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.

ECAL angular resolution



ECAL possible implementation

- **Inner ECAL**: 40 cm × 40 cm.
- Recycle existing $PbWO_4$ owned by CMS
- New crystals PbF_2 or new $PbWO_4$
- **Outer ECAL**: ~ 100 cm × 100 cm.
- OPAL lead glass: rather a big cell size.
- L3 BGO: we are waiting for an answer.
- Front end electronics running at 40 MHz.

The two options ($PbWO_4$ vs PbF_2) are under study

Theory

- 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;** **r**esummation (effects beyond fixed-order perturbation theory) and "massification" (massless matrix elements → differential cross section) (A. Signer, Y. Ulrich, PSI Group)

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)
→ **International** efforts!

(Tentative) Time schedule

- In agreement with the CMS we plan for the final detector to have ~250 2S modules with the following time profile:
  - 50% of stations delivered by spring 2022 (20 stations)
  - 50% by end of 2022 (20 stations)

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 (ultimate goal of a statical error on a_{μ}^{HLO}~$2x10^{-10}$)

Conclusion

- MUonE: a novel way (space-like region) to measure a_μ^{HLO} at per mille accuracy
- Many progress in the last year(s) !
- Growing interest from both experiment and theory community
- LoI submitted to SPSC in June 2019; referees assigned; if approved a few-weeks pilot run in 2021 to assess the detector performance and validate the design; then ~3 years run (2022-2024) for ultimate precision

Thanks !

THE END

(Thanks to J. Berhnard, L. Gatignon and A. Magnon for many useful discussions and work)

SPARE

Two options under study

- The CMS $PbW0_4$ crystals transverse dimensions: 2.86cm × 2.86cm front and 3.00cm × 3.00cm back side.
  - How good they are? How many available?
- PbF_2 Cherenkov crystals with PMT readout
- 64 elements of 2.5cm × 2.5cm × **L**cm.
  - Studying effects of the length on the ΔE/E with L = 17, 20, 23 cm ($25X_0$)
- Used for the $(g\text{-}2)_\mu$ calorimeter with L=14cm, coupled to SiPMT.
- FEE has to be developed, possibly adapting existing boards by CMS.

ECAL's PID

- PID requires the ECAL's area of 40 cm × 40 cm.
- Homogenous calorimeter with small cells size and small R_M~1 cm, with 25 X_0 to contain the shower.
  - PID based on the minimal distance between tracks' impact points to the electromagnetic cluster centroid.
  - Highly efficient within the available statistics with 2.5 cm × 2.5 cm × 25 cm $PbWO_4$
- High counting rate, high radiation dose, due to the muon beam.
  - Event rate ~500 kHz: it is not a problem.
  - Beam rate ~ 50 MHz: it implies the need of fast response sensors, with τ ~ 10ns
  - Dose ~ 20 μGy/s. In the run lifetime 400 Gy

Suitable sensors and ASICs

- **Requirements:**
  - **Dimensions: 10 cm × 10 cm**
  - **Single hit resolution: r ≤ 10 μm**
  - **Fast timing (25 ns).**
  - **Minimal thickness: d ≤ 300 μm**
- **Possible implementation:**
  - **strip pitch p ≤ 50μm and floating electrodes charge sharing to get a resolution better than the geometrical σ=p/sqrt(12), depending on S/N**
  - **1028 channel hybrid per sensor single sided**

Letter of Intent

(submitted to SPSC in June)

70 authors; 16 Institutions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

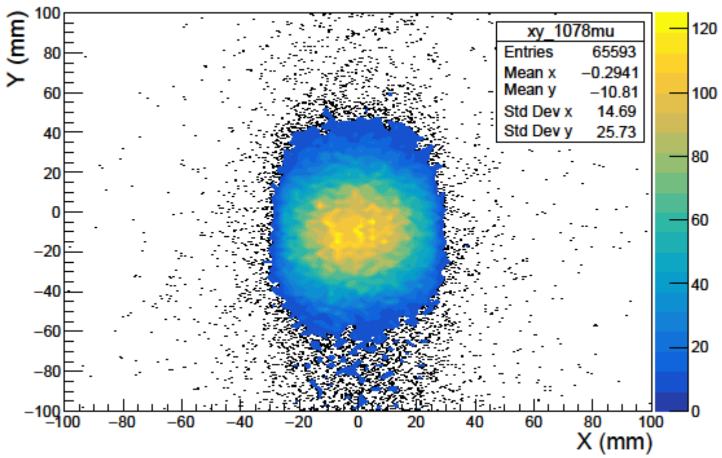
To be specified

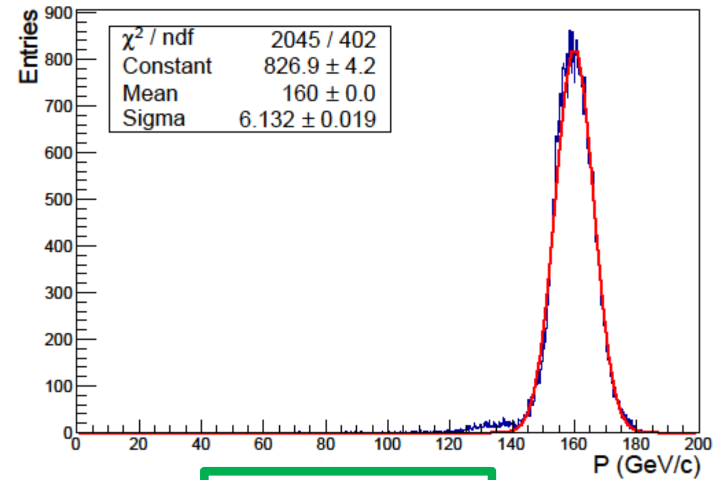
Letter of Intent: The MUonE Project

MUonE Collaboration

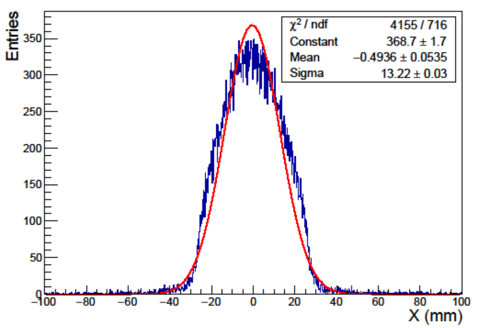
Contents

Beam parameters for MUonE *(from Dipanwita B., sep*





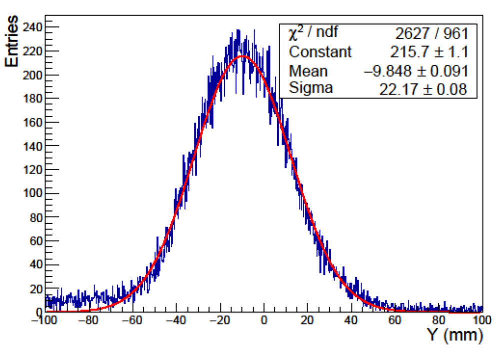
$E\mu$ = 160 GeV

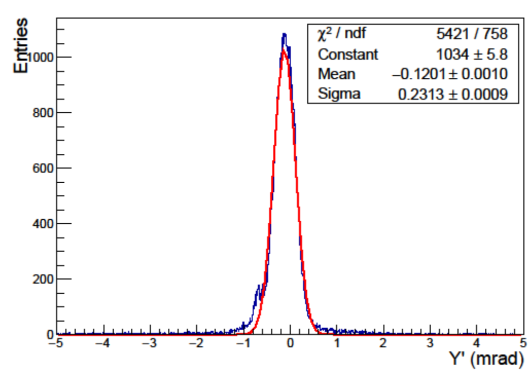


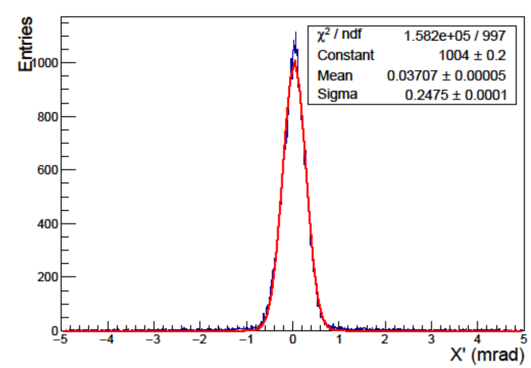
Very low divergence

0.23 mrad

0.24 mrad



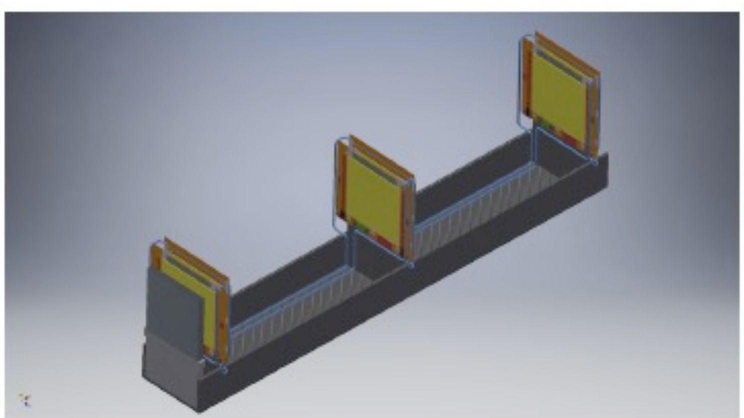


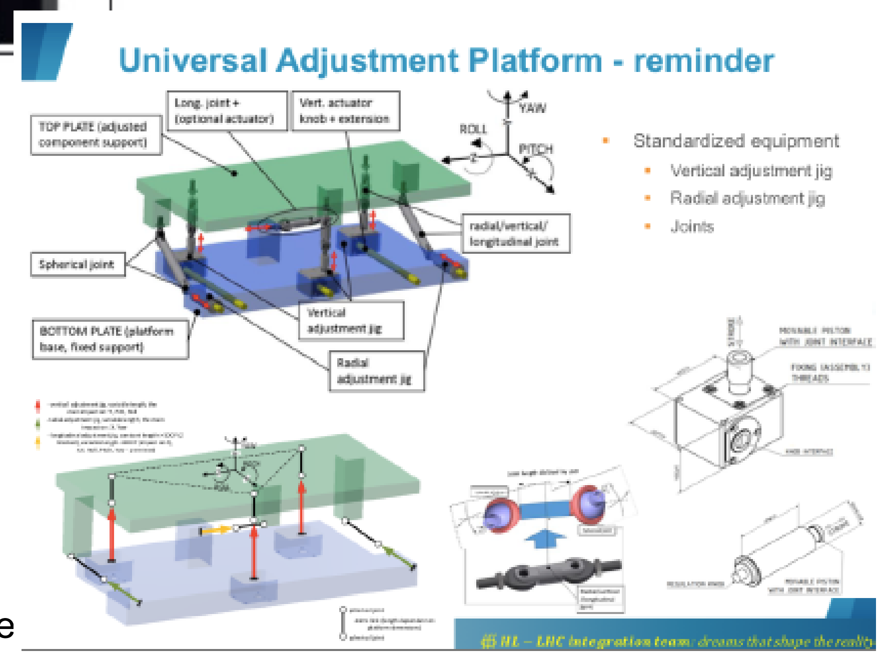


Study and test for the mechanics

PFR6090-7
High rigid frame

Nexus Breadboard

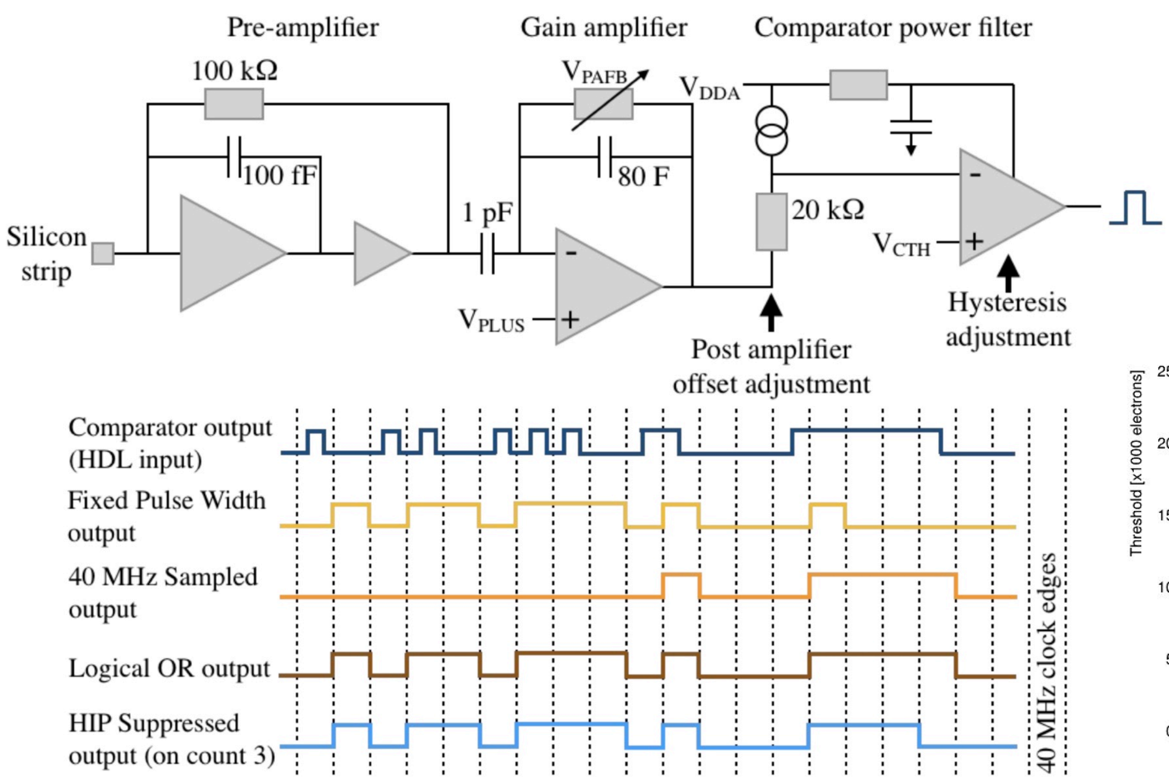


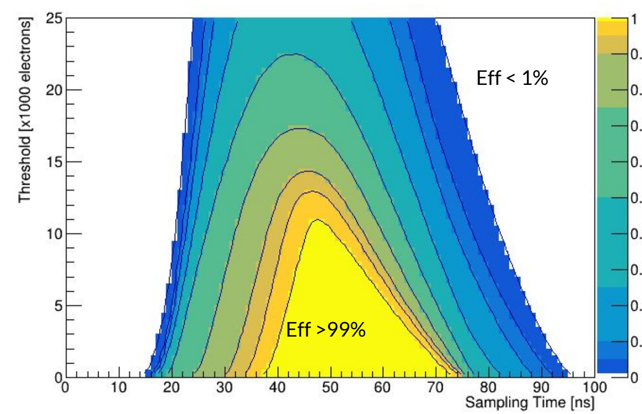


Clara Matte

Signals generation

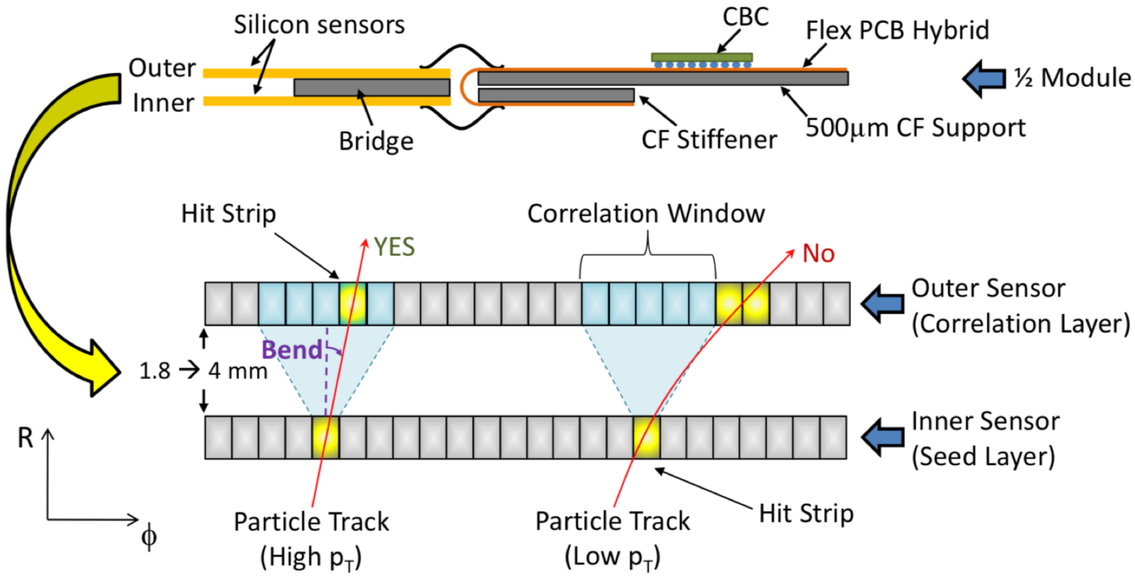
- Muons (average intensity ~50 MHz) have a random phase with respect to the reference clock at 40 MHz.
- CBC has several options for selecting the duration of the comparator output, which can be studied for optimized performance.

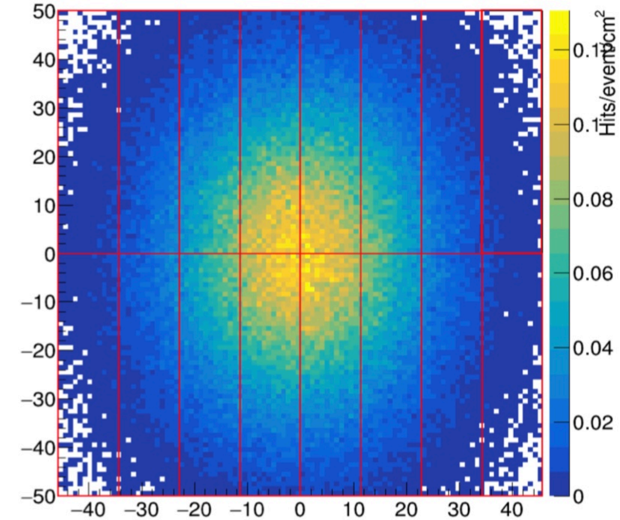




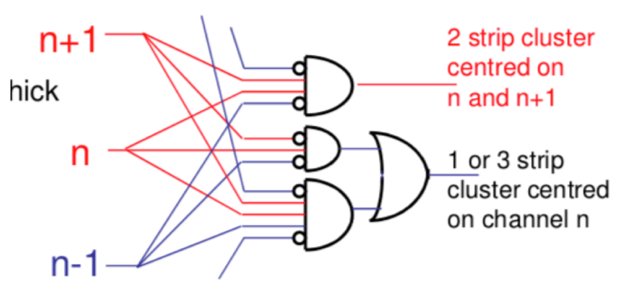
Simulated efficiency for the CBC to detect a minimum ionising particle signal as a function of comparator threshold and sampling time.

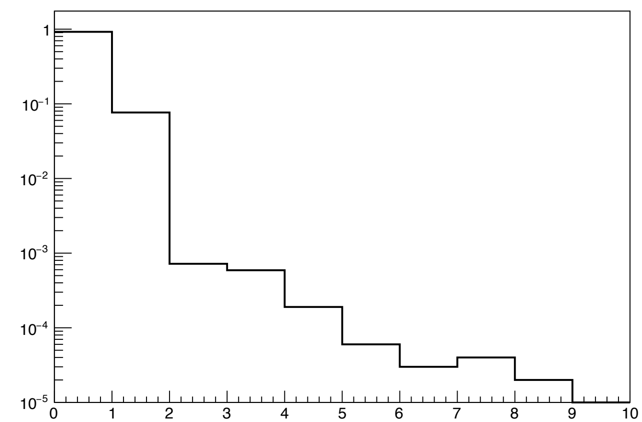
CBC3 stubs



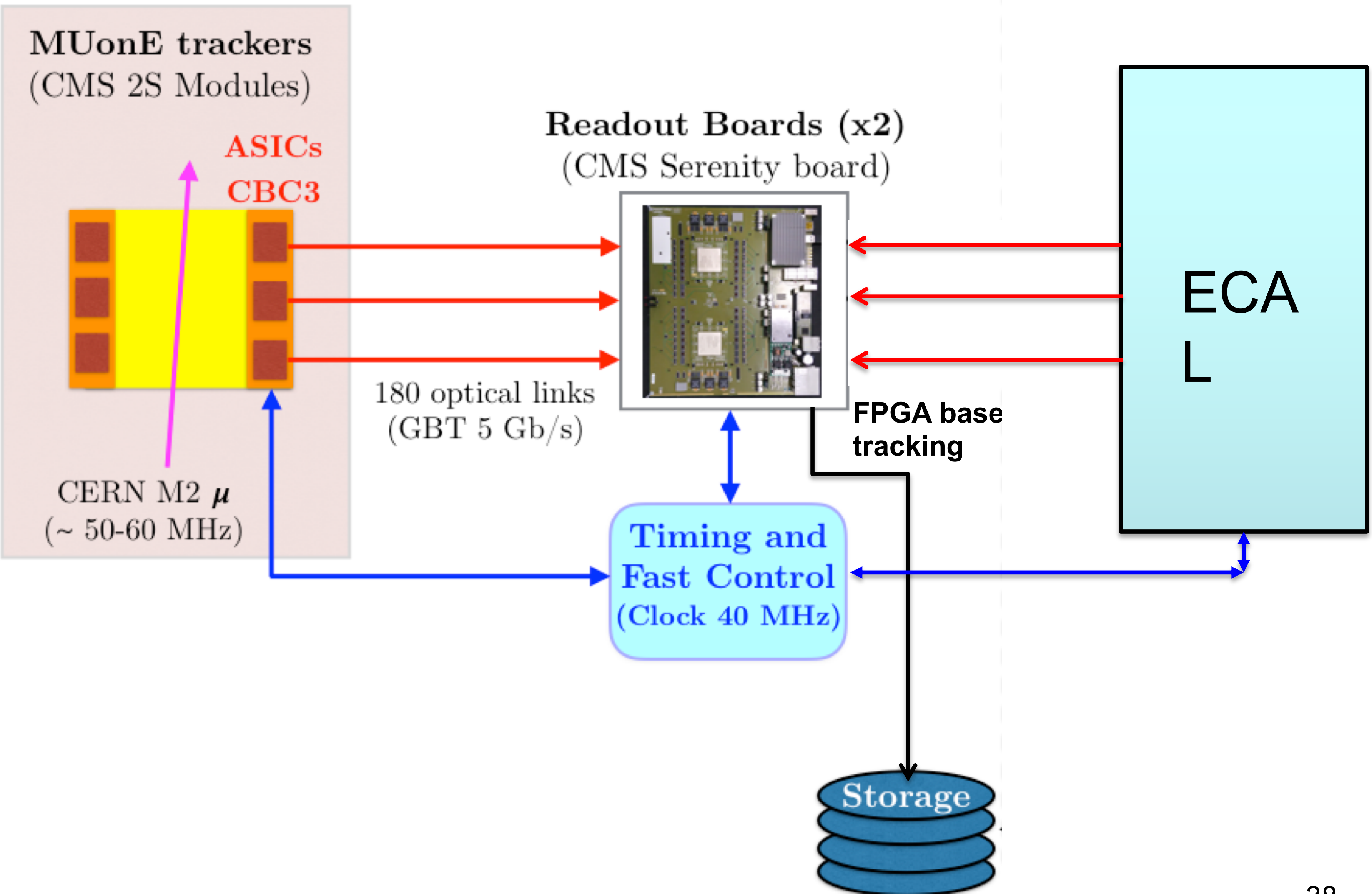


- High-PT tracks (**Stubs**) can be identified if cluster centre in top layer lies within a correlation window in R-Φ (rows)
- p_T cut given by: module radius (z), sensor separation and correlation window





The DAQ and trigger system



: 400kHz ×