UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

Status of the MUonE experiment

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on behalf of the MUonE Collaboration

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μONe

6th Plenary Workshop of the Muon g-2 Theory Initiative
September 8th 2023

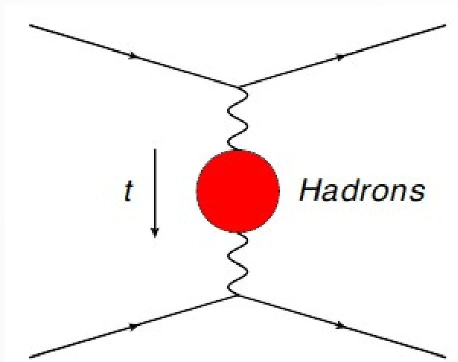
a_μ^{HLO} : space-like approach

MUonE: a new independent evaluation of a_μ^{HLO}

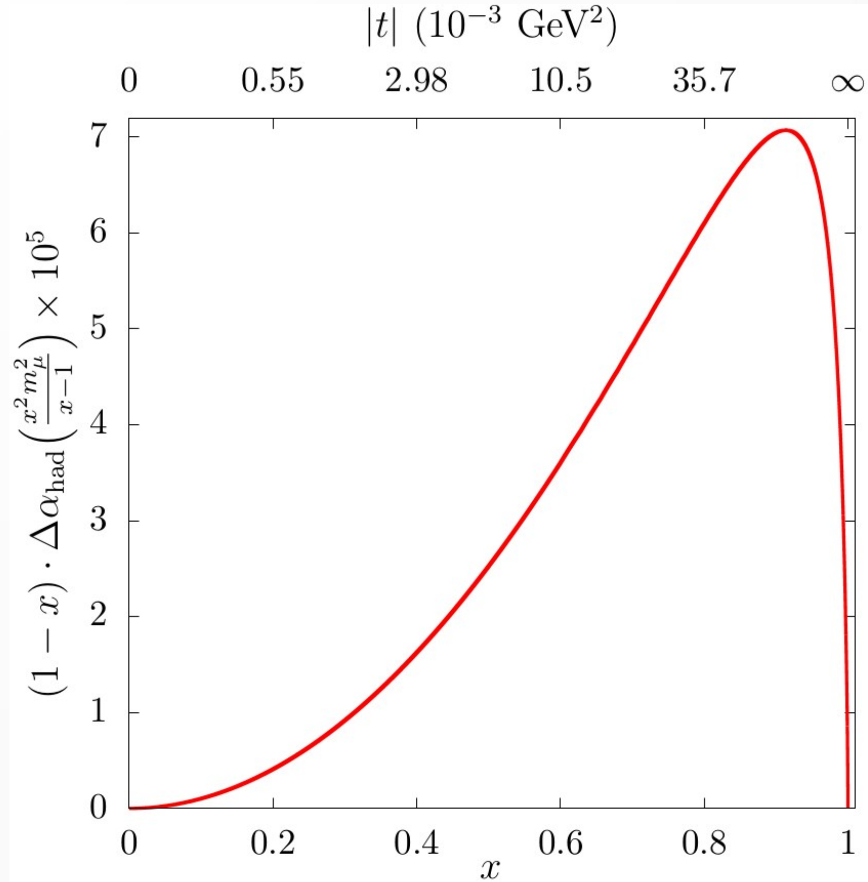
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)]$$

Lautrup, Peterman, De Rafael, Phys. Rep. C3 (1972), 193

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



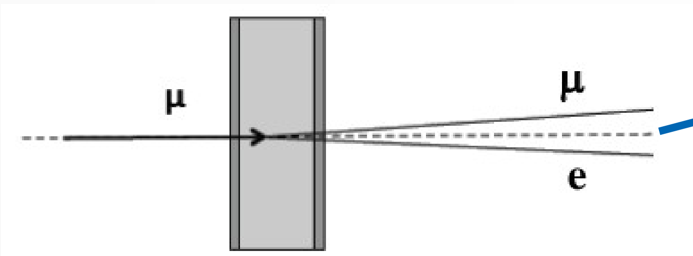
Based on the measurement of $\Delta\alpha_{\mathrm{had}}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.



Carloni Calame, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015), 325

The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the ***shape*** of the $\mu e \to \mu e$ differential cross section

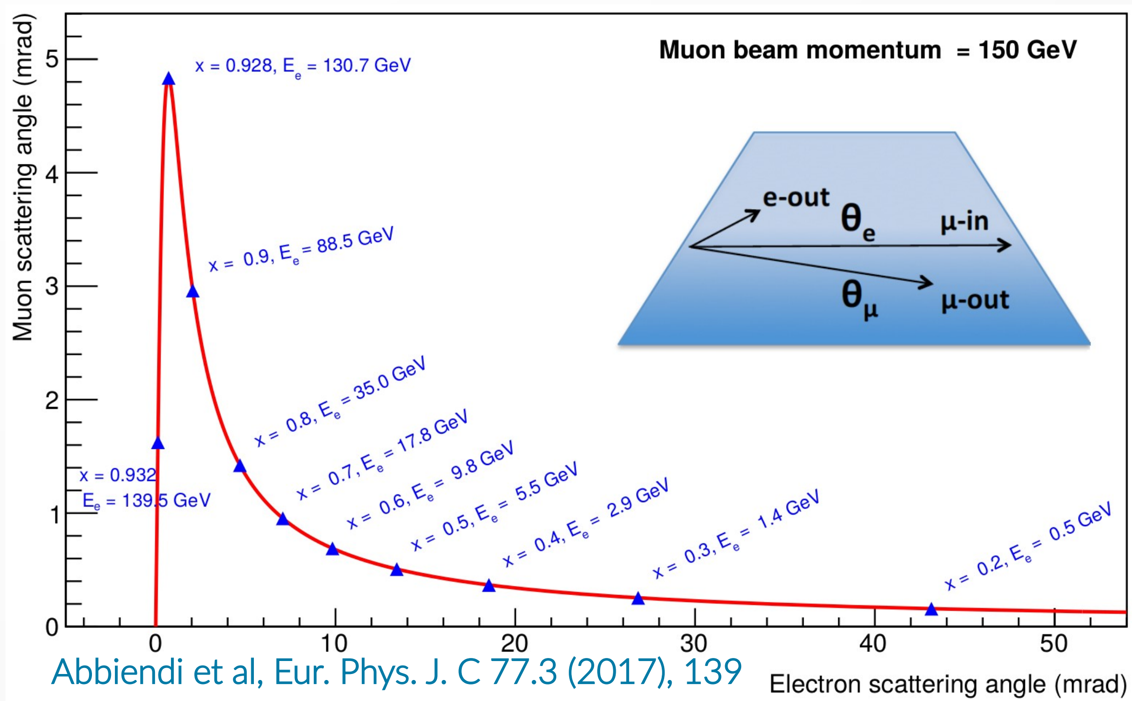


$$\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$

From theoretical calculation

To be measured

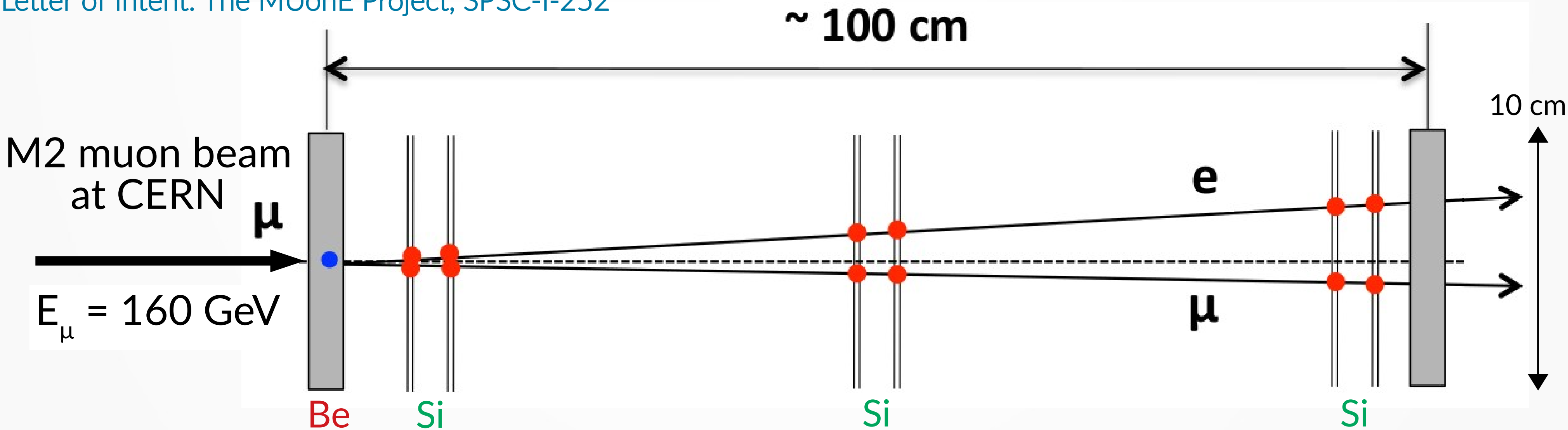
- Compute a_μ^{HLO} using data from one single experiment.
- Correlation between muon and electron angles allows to select elastic events and reject background (μ N → μ N e^+e^-).
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad.



Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

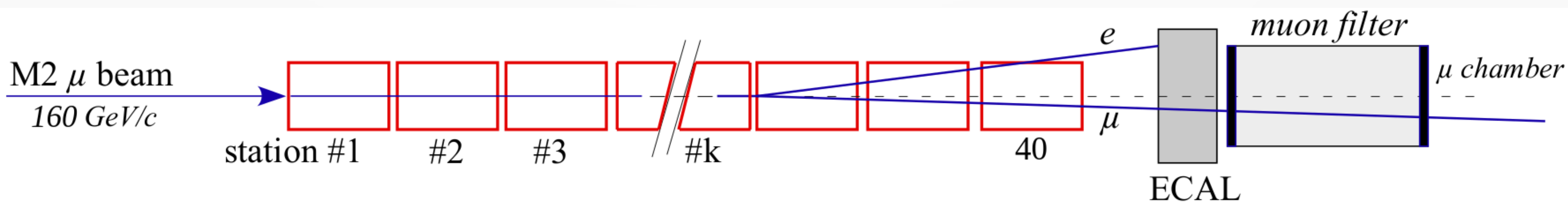
The experimental apparatus

Letter of Intent: The MUonE Project, SPSC-I-252



Be (or C) target
1.5 cm thickness

Tracking system:
3 pairs of silicon strip detectors (CMS 2S modules)



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking = ~0.3% statistical accuracy on a_μ^{HLO}

(~4x10^{12} events $E_e > 1$ GeV)

Competitive with the latest theoretical predictions.

Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm in the signal region.

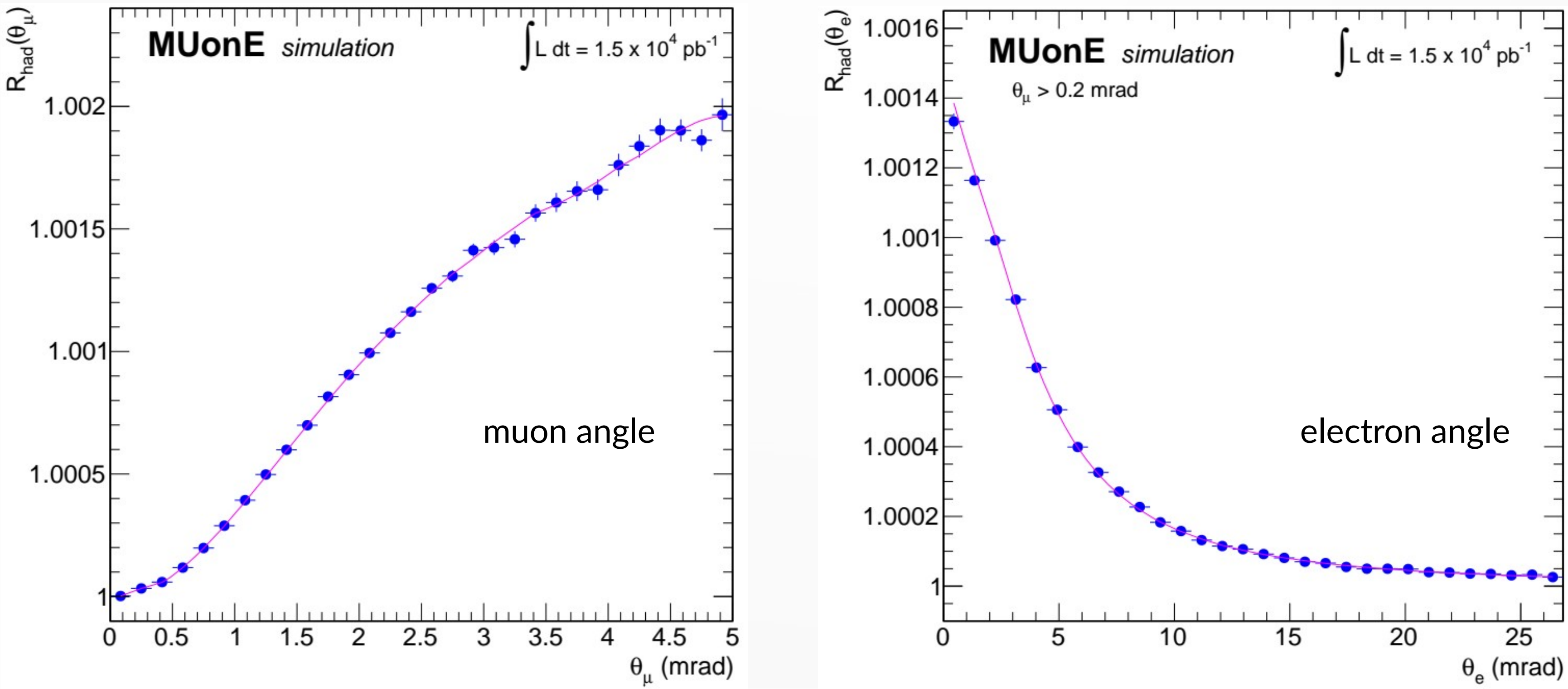
Main systematic effects:

- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering
- Angular intrinsic resolution
- Non-uniform detector response

Sensitivity to $\Delta\alpha_{had}(t)$

$$R_{had} = \frac{d\sigma(\Delta\alpha_{had}(t) \neq 0)}{d\sigma(\Delta\alpha_{had}(t) = 0)} \sim 1 + 2\Delta\alpha_{had}(t)$$

$\Delta\alpha_{had}(t) < 10^{-3}$



$\Delta\alpha_{had}$ parameterization

Inspired from the 1 loop QED contribution of lepton pairs and top quark at $t < 0$

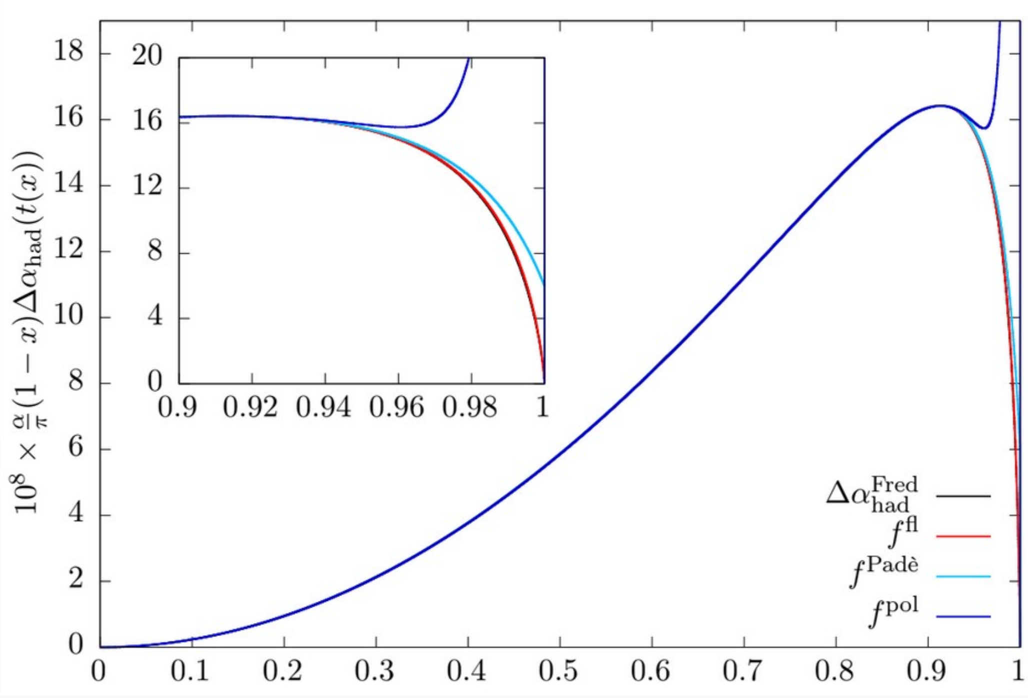
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

Allows to calculate the full value of a_μ^{HLO}

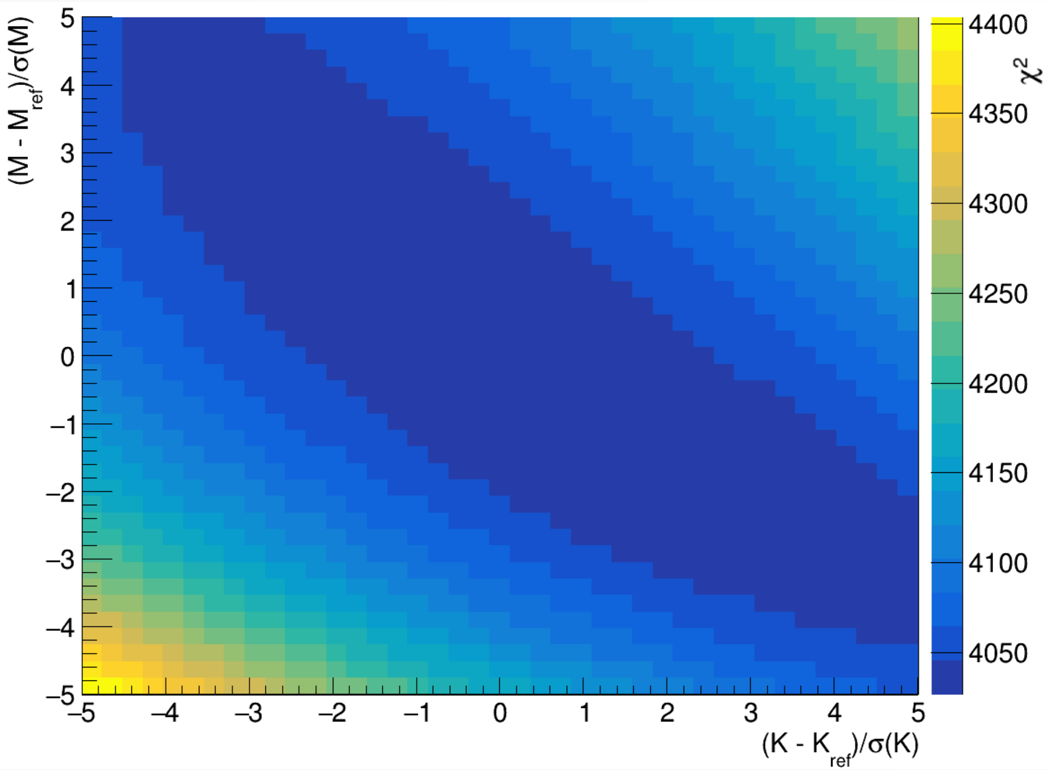
Dominant behaviour in the MUonE kinematic region:

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



Calculation of a_μ^{HLO}

Extraction of $\Delta\alpha_{\text{had}}(t)$ through a template fit to the 2D (θ_e, θ_μ) distribution



Simulation
@ final luminosity: $1.5\text{x}10^4$ pb^{-1}

4×10^{12} elastic events
with E_e > 1 GeV (θ_e < 32 mrad)

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

(0.35% stat error)

Input value:

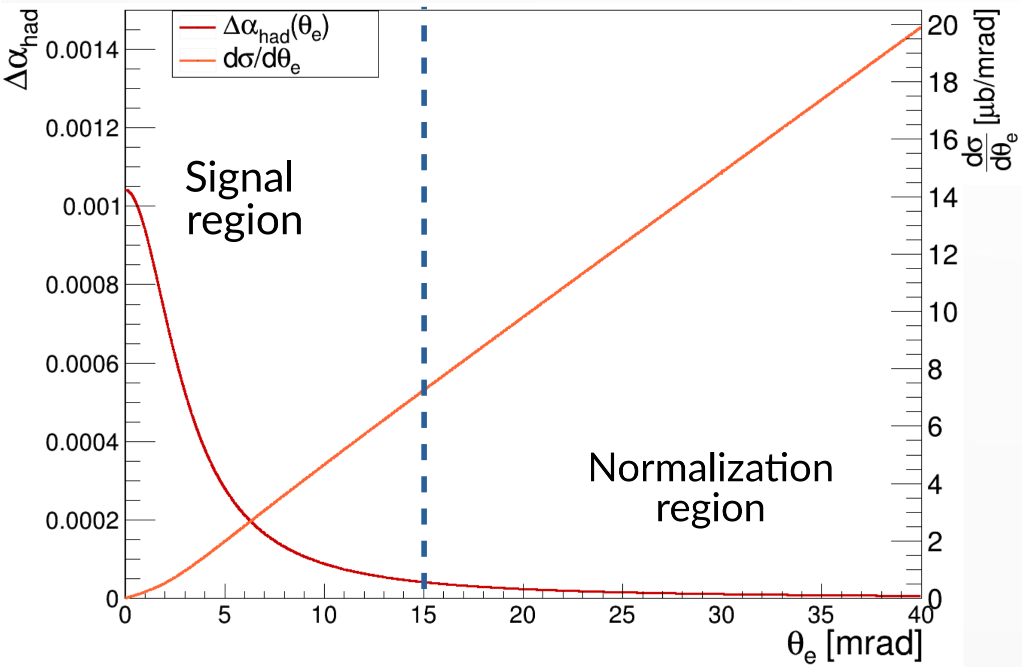
$$a_\mu^{\text{HLO}} = 688.6 \times 10^{-10}$$

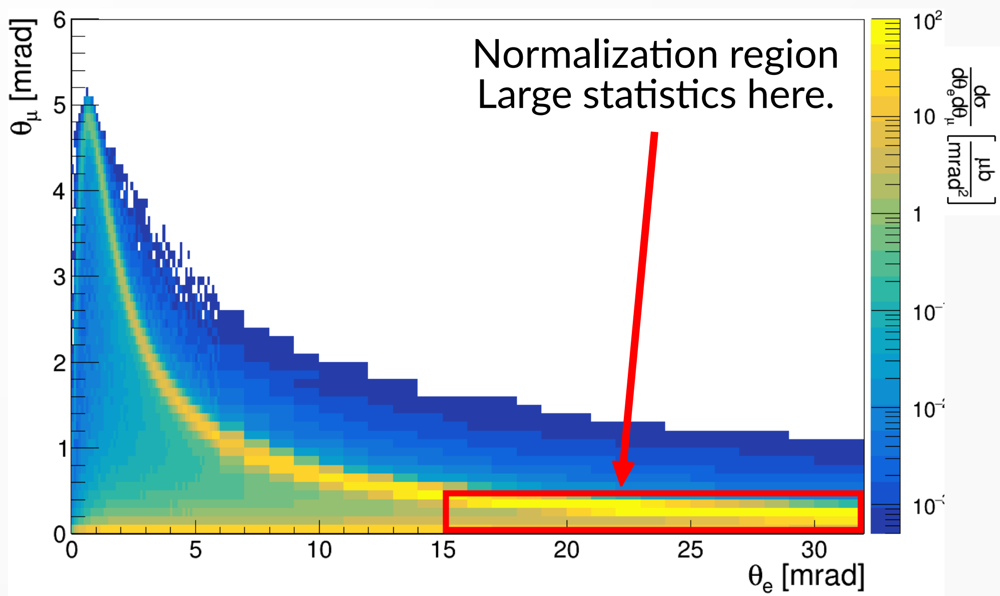
Strategy for the systematic effects

Main systematics have large effects in the normalization region.
(no sensitivity to $\Delta\alpha_{\text{had}}$ here)

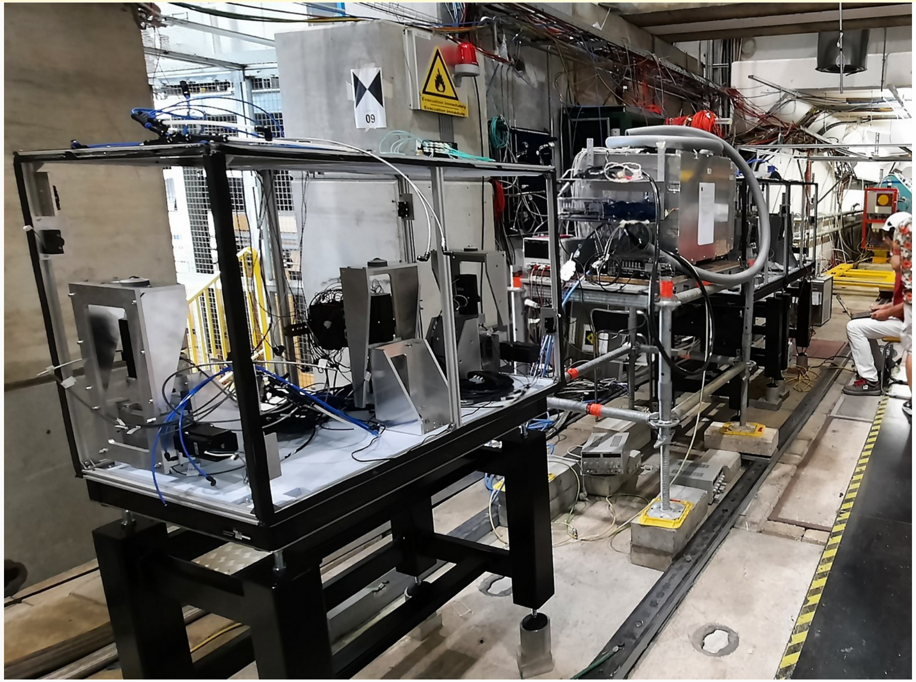
Promising strategy:

- Study the main systematics in the normalization region.
- Include residual systematics as nuisance parameters in a combined fit with signal.

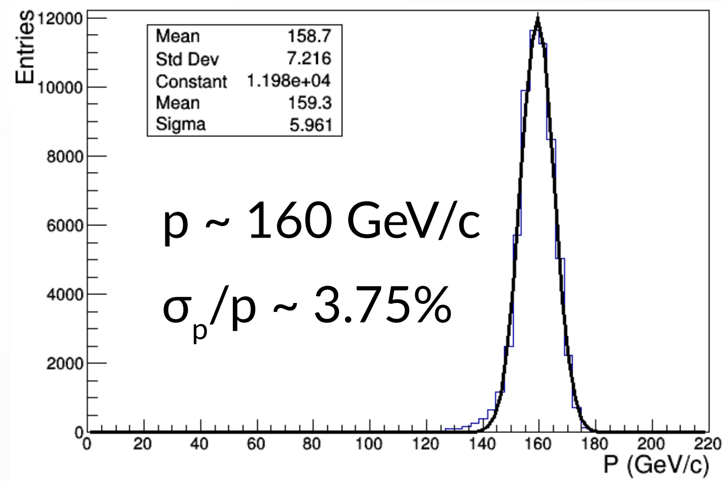




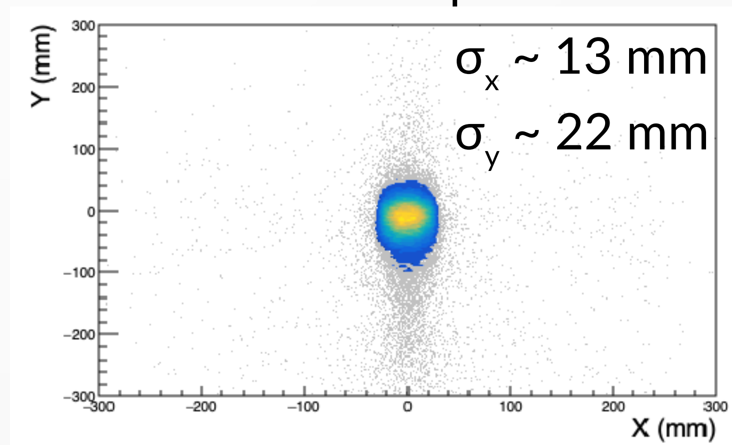
Location: M2 beamline at CERN



Beam momentum



Beam spot



- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.2$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 2-3x10^8 μ^+/spill).

Tracker: CMS 2S modules

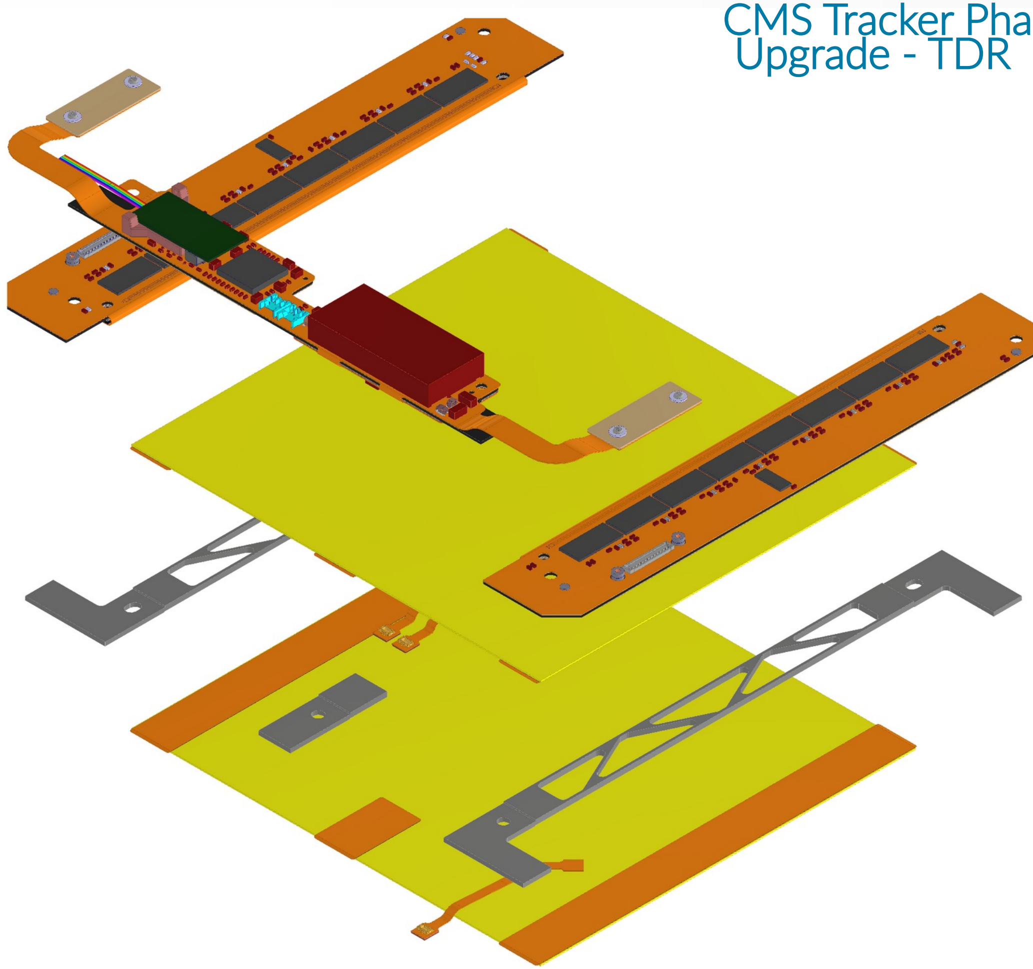
Silicon strip sensors currently in production for the CMS-Phase2 upgrade.

Two close-by strip sensors reading the same coordinate:

- Suppress background of single sensor hits.
- Reject large angle tracks.

- Pitch: 90 µm
- Digital readout
- Readout rate: 40 MHz
- Area: 10×10 cm^2 (~90 cm^2 active)
- Thickness: 2 × 320 µm

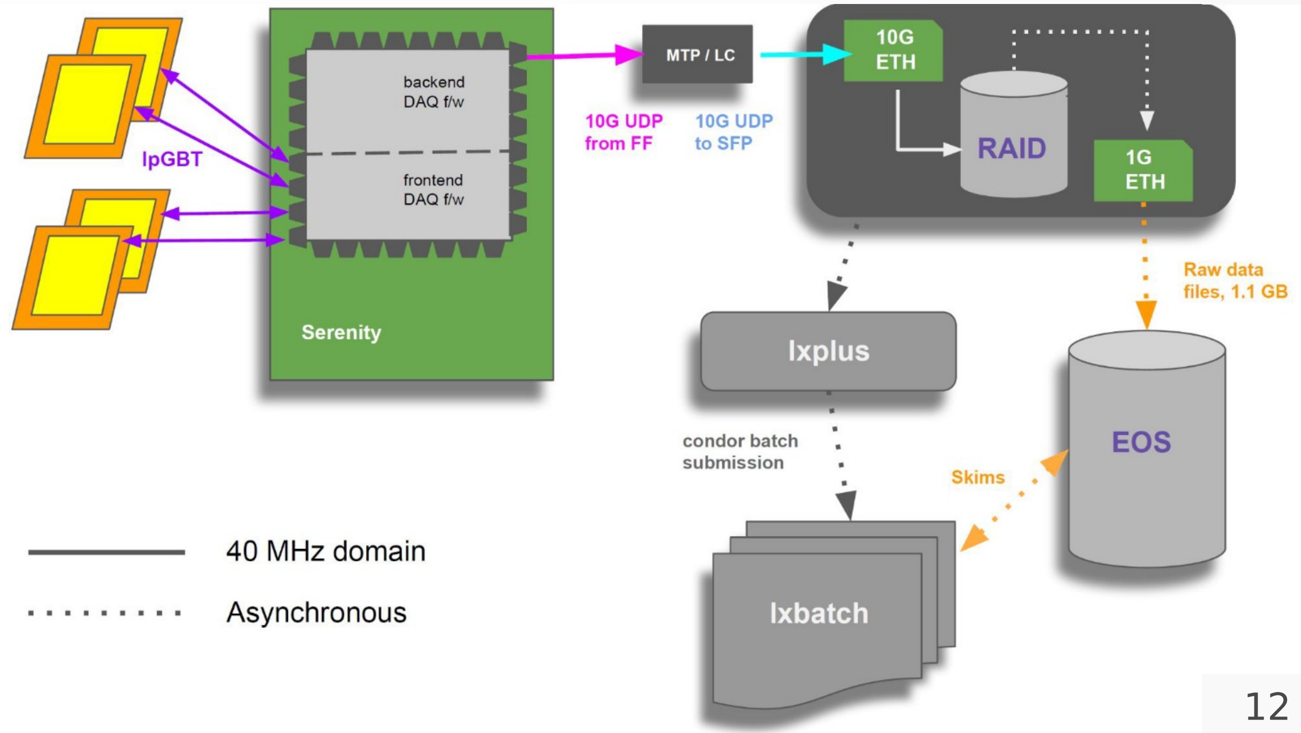
CMS Tracker Phase2 Upgrade - TDR



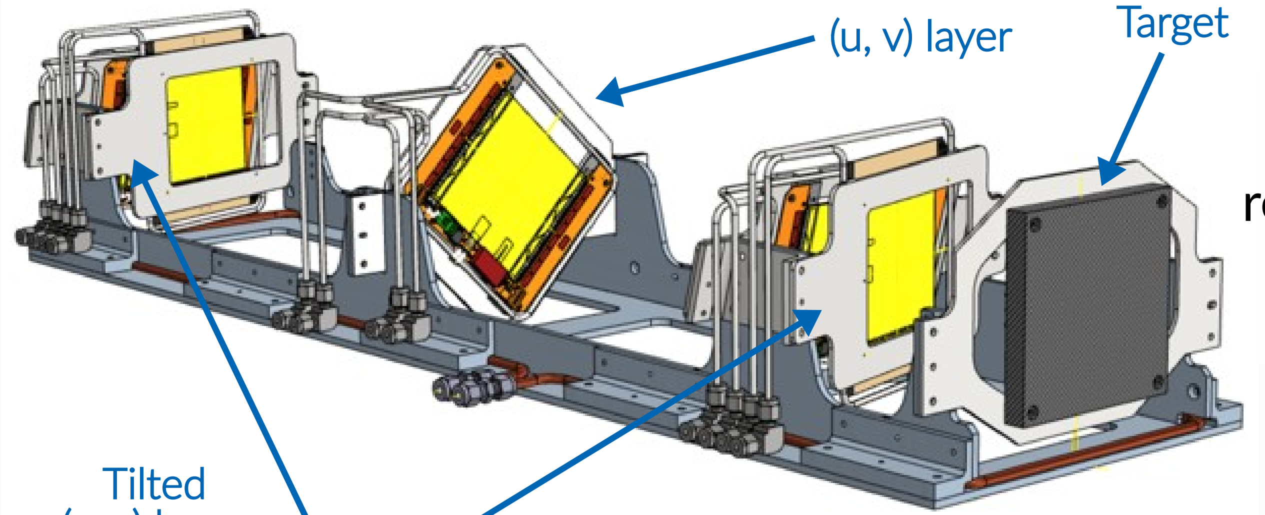
DAQ system

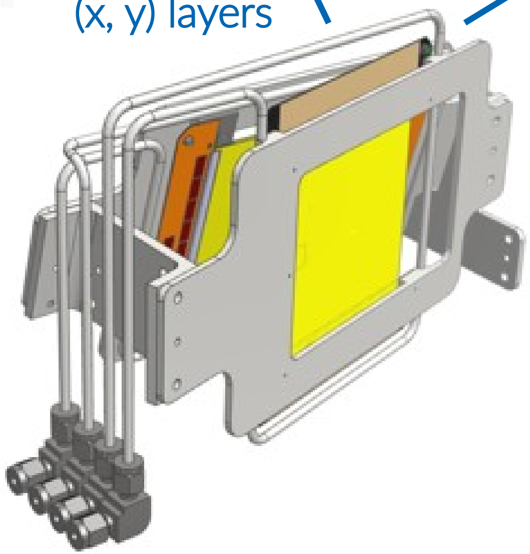
Frontend control and readout via Serenity board
(to be used in the CMS-Phase2 upgrade).

- Asynchronous beam: triggerless readout of the 2S modules @40MHz.
- Event aggregator on FPGA.
- Further data aggregation on the PC.
- Transmission to EOS into ~1GB files.



Tracking station





Stringent request:
relative position within a station must be stable at 10 μm.

↓

Low CTE material:
INVAR (CTE ~ $1.2 \times 10^{-6}\ K^{-1}$)

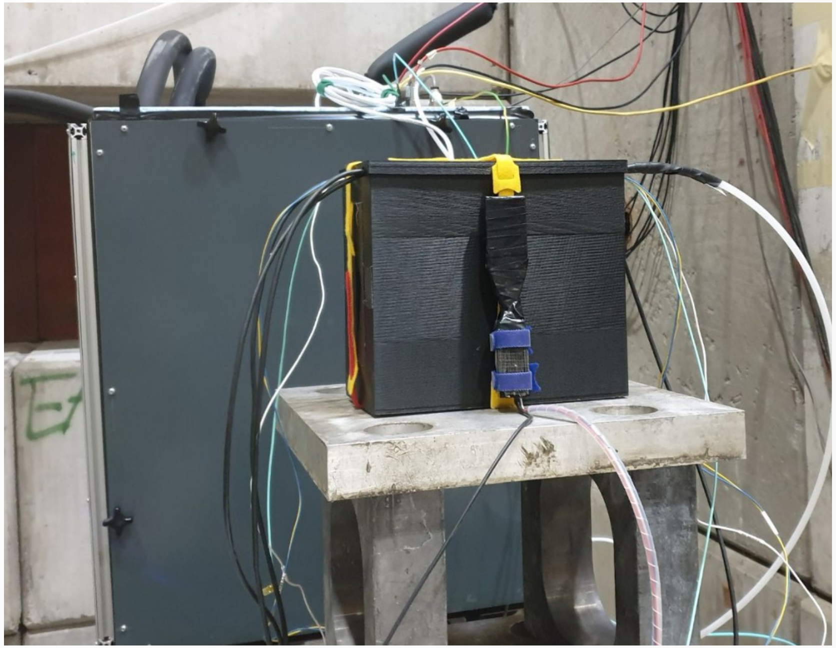
Laser holographic system to monitor stability.

- (x, y) layers tilted by 233 mrad:
  reduce the effective pitch and improve spatial resolution.
  - Simulations: ~22μm → ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

Beam Test 2021

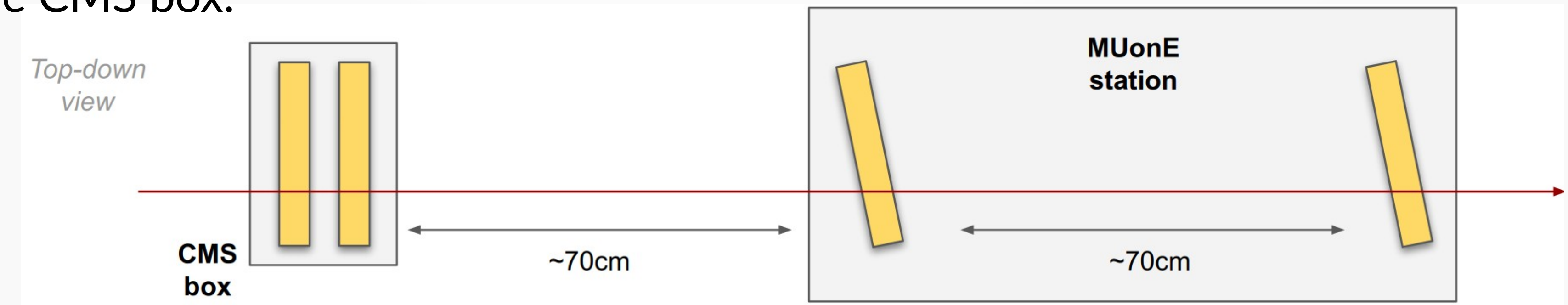
Parasitic beam test at M2 beam line,
3 weeks in October/November 2021

- Joint test with CMS Tracker.
- Apparatus located downstream of NA64.
- 160 GeV muons, ~16 kHz rate.



Four 2S modules tested in beam:

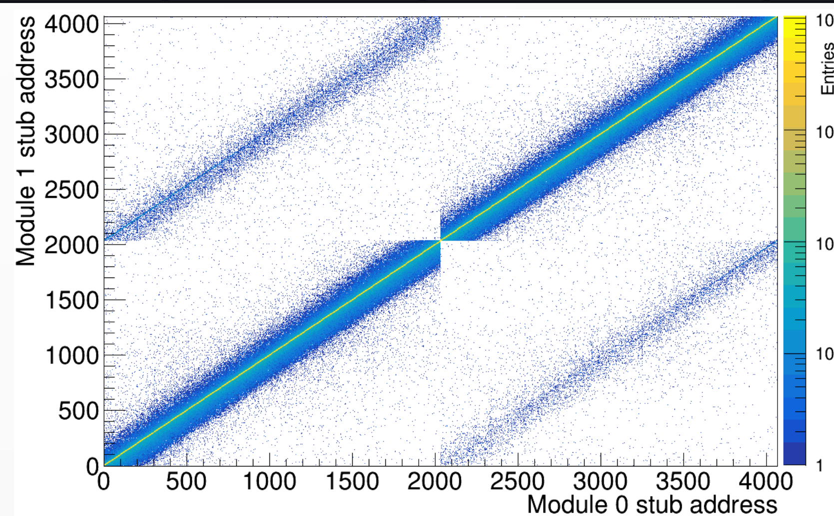
- 2 modules built for MUonE in the MUonE station.
- 2 modules built for CMS Tracker in the CMS box.



Beam Test 2021

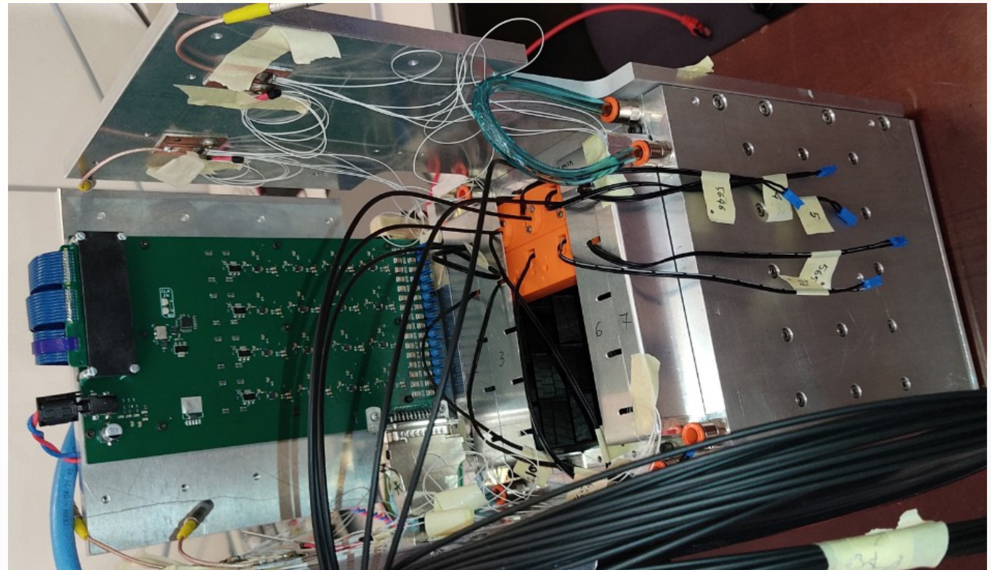
First demonstration
of the full DAQ chain
with an asynchronous beam

- Reliable readout over >6h runs.
- 30 TB of raw data collected to disk, ~1 TB after empty packets removal (low beam rate).
- Offline analysis:
  check data integrity,
  beam behaviour,
  simple 2S modules
  synchronization and correlations.



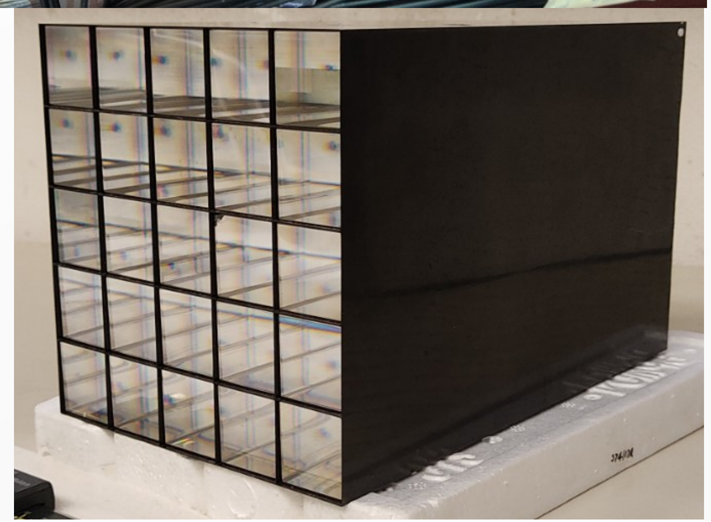
Calorimeter

- 5x5 $PbWO_4$ crystals:
  area: 2.85×2.85 cm^2,
  length: 22cm (~25 X_0).
- Total area: ~14×14 cm^2.
- Readout: APD sensors.



Dedicated beam tests:

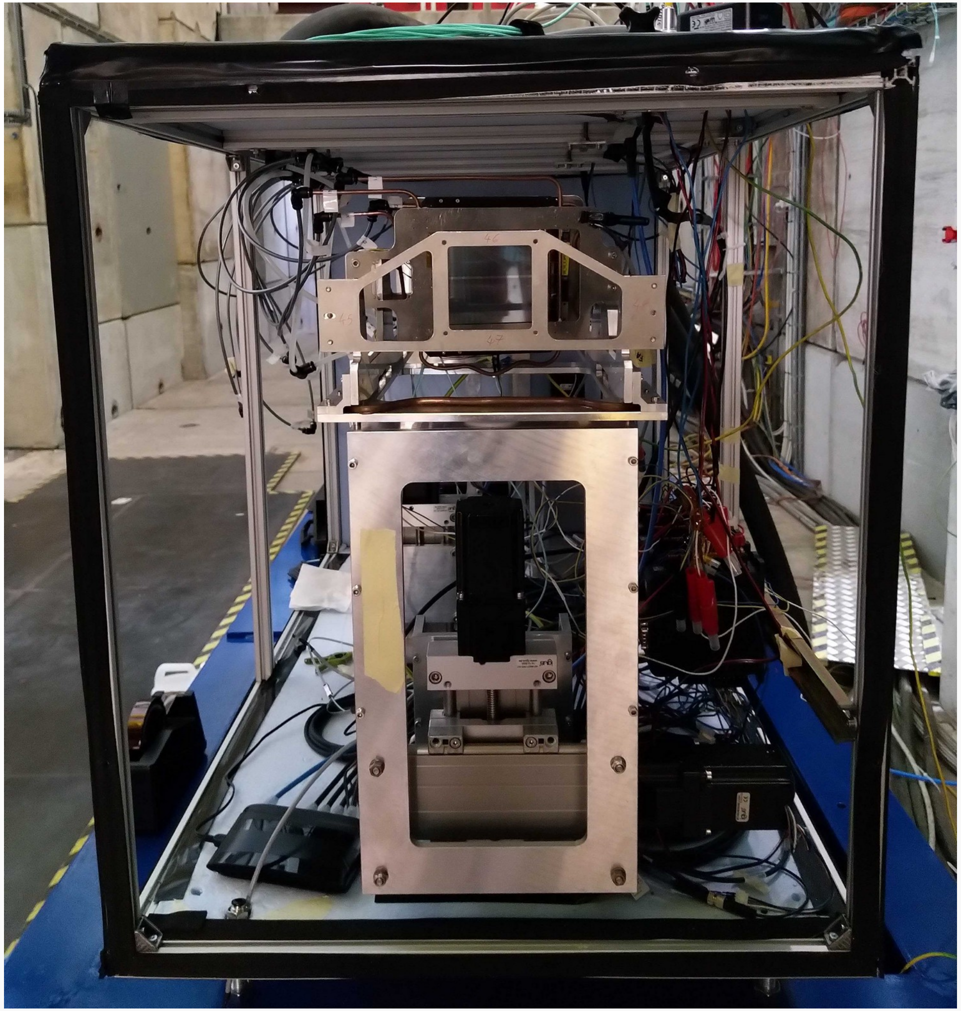
- July 2022: 1-4 GeV.
  Overall detector & DAQ debug.
  Absolute energy calibration.
- 31/05–10/06 2023: 20–150 GeV e^-.
- 21-26/06 2023: 1-10 GeV e^-.
- Energy resolution studies ongoing.



Beam Test 2022

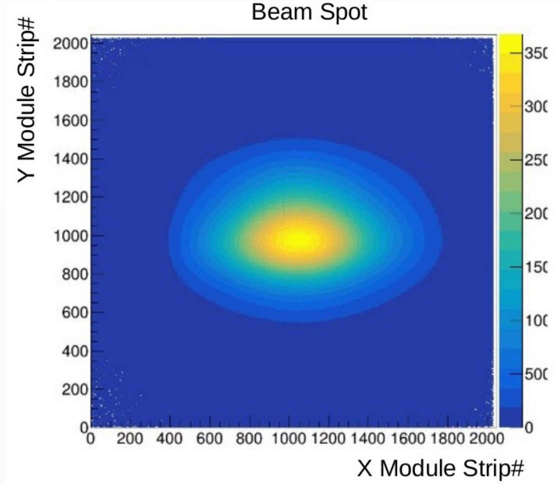
One week as
main users in October

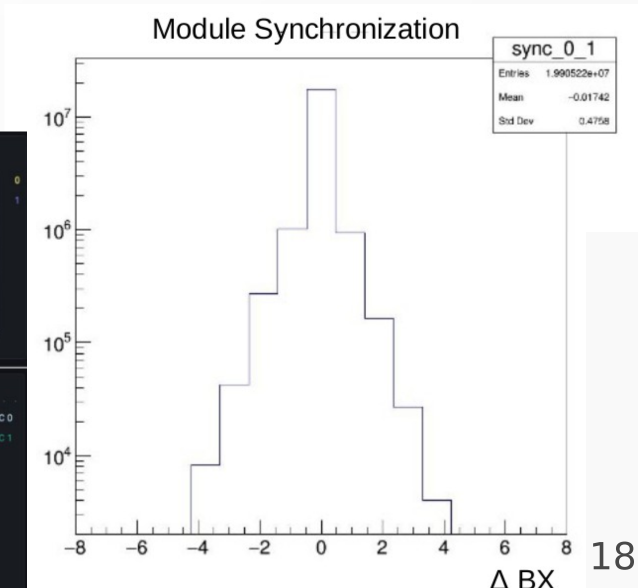
- Joint test with CMS Tracker.
- Apparatus in the final location of MUonE on the beamline.
- 1 fully equipped tracking station (6 modules)+ ECAL.
- Scale up DAQ system.
- High intensity 160 GeV muon beam + 40 GeV electrons (low intensity).

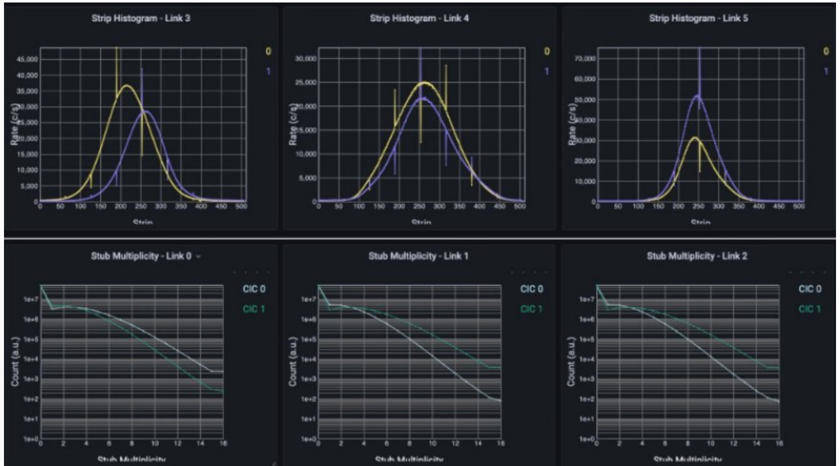


Beam Test 2022

- A more extensive DQM framework: many 2021 analyses incorporated as detector monitoring.
- Achieved tracker synchronization < 0.5 ns (exploiting fine delays in the 2S modules electronics).
- Positive response on the thermal stability of the apparatus.
- First track fitting.



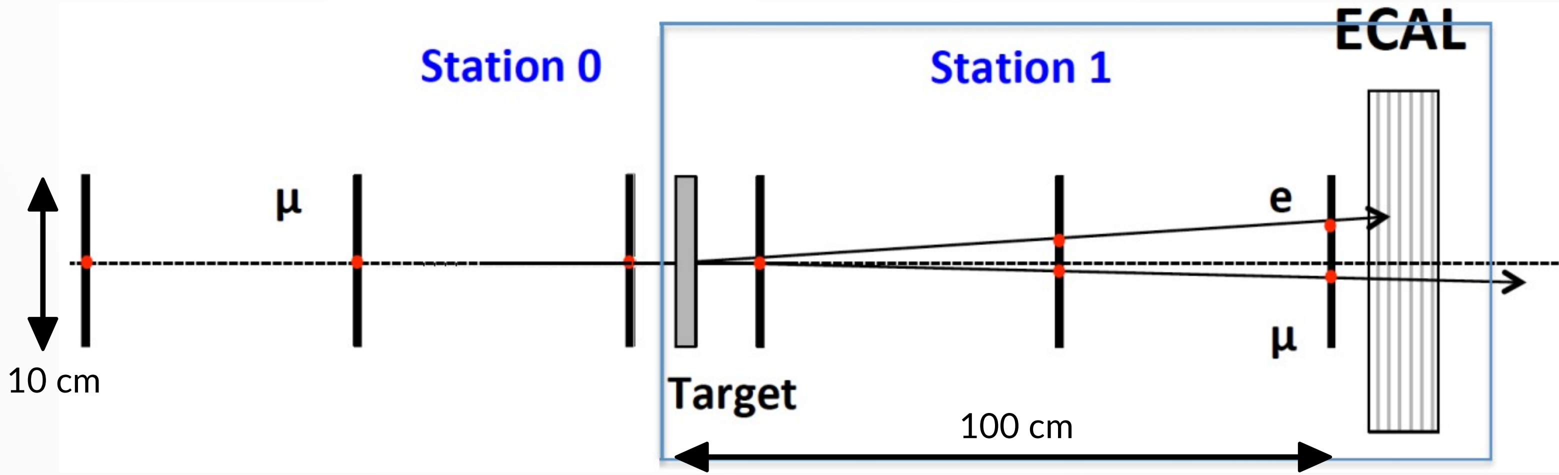




Test Run 2023 (21 Aug – 10 Sept)

A 3 weeks Test Run with a reduced detector
has been approved by SPSC, to validate our proposal.

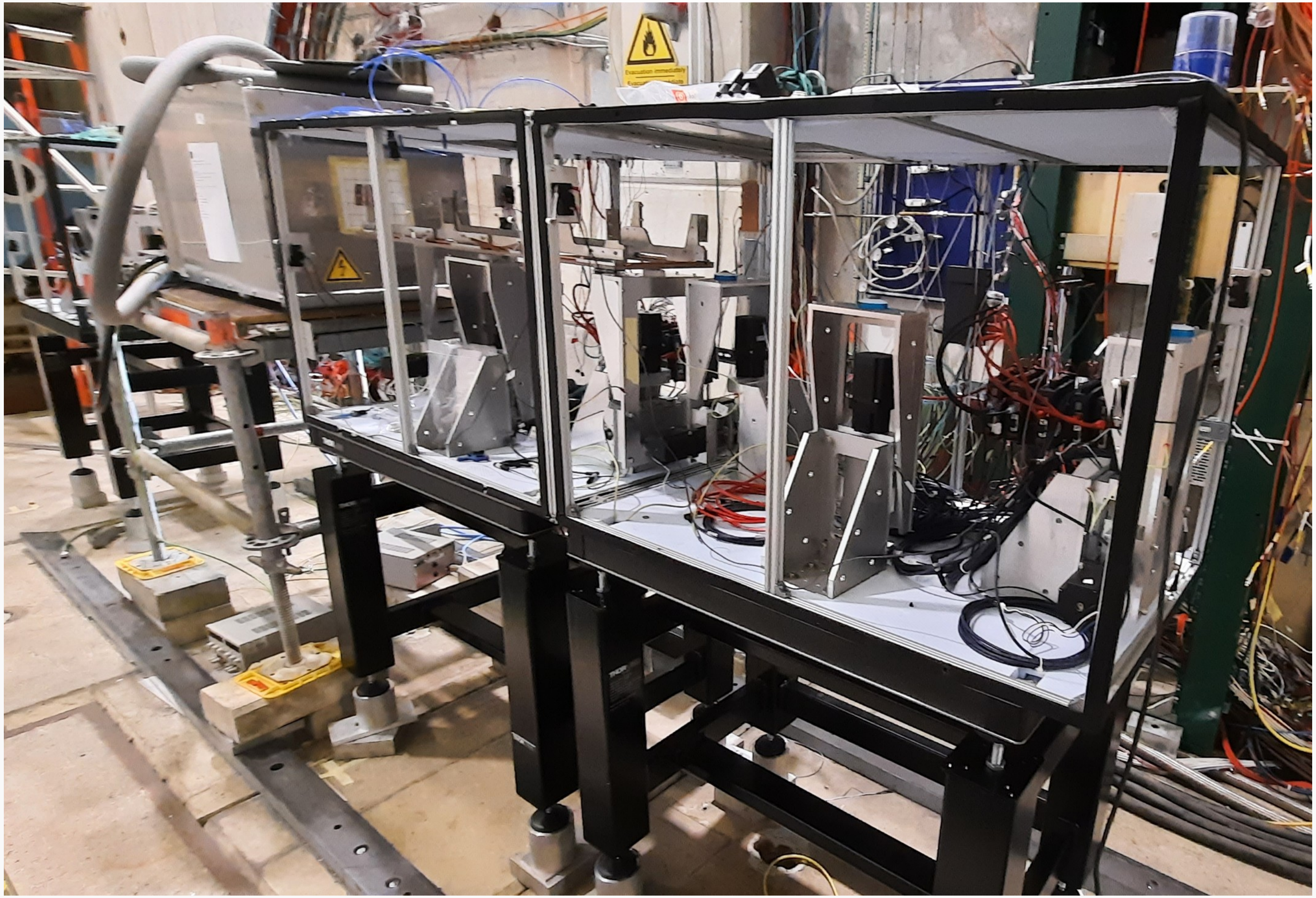
- Pretracker +
- 1 station +
- ECAL

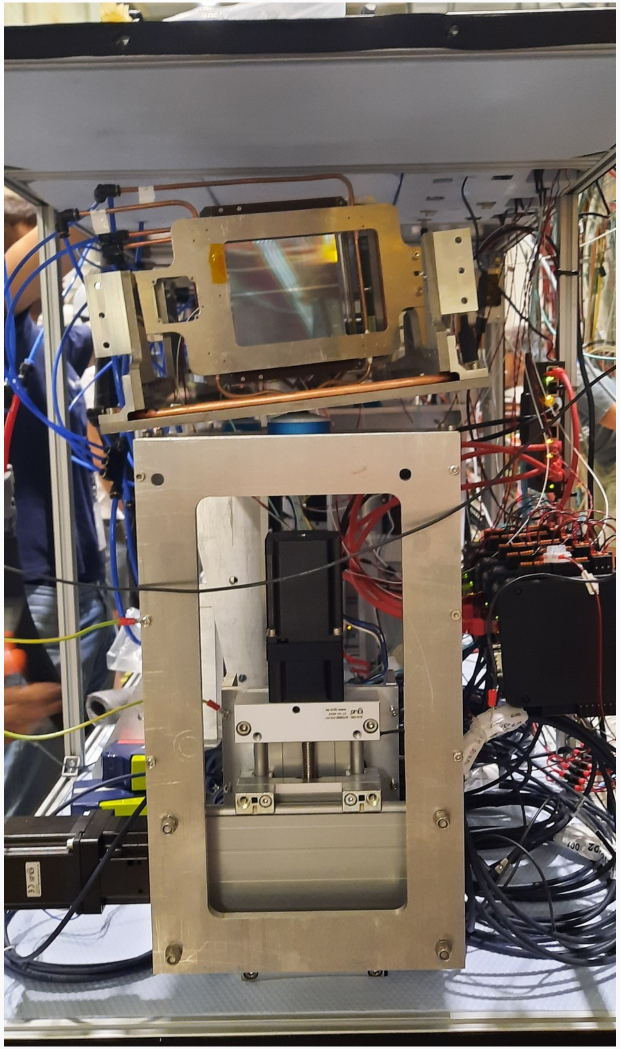


Main goals:

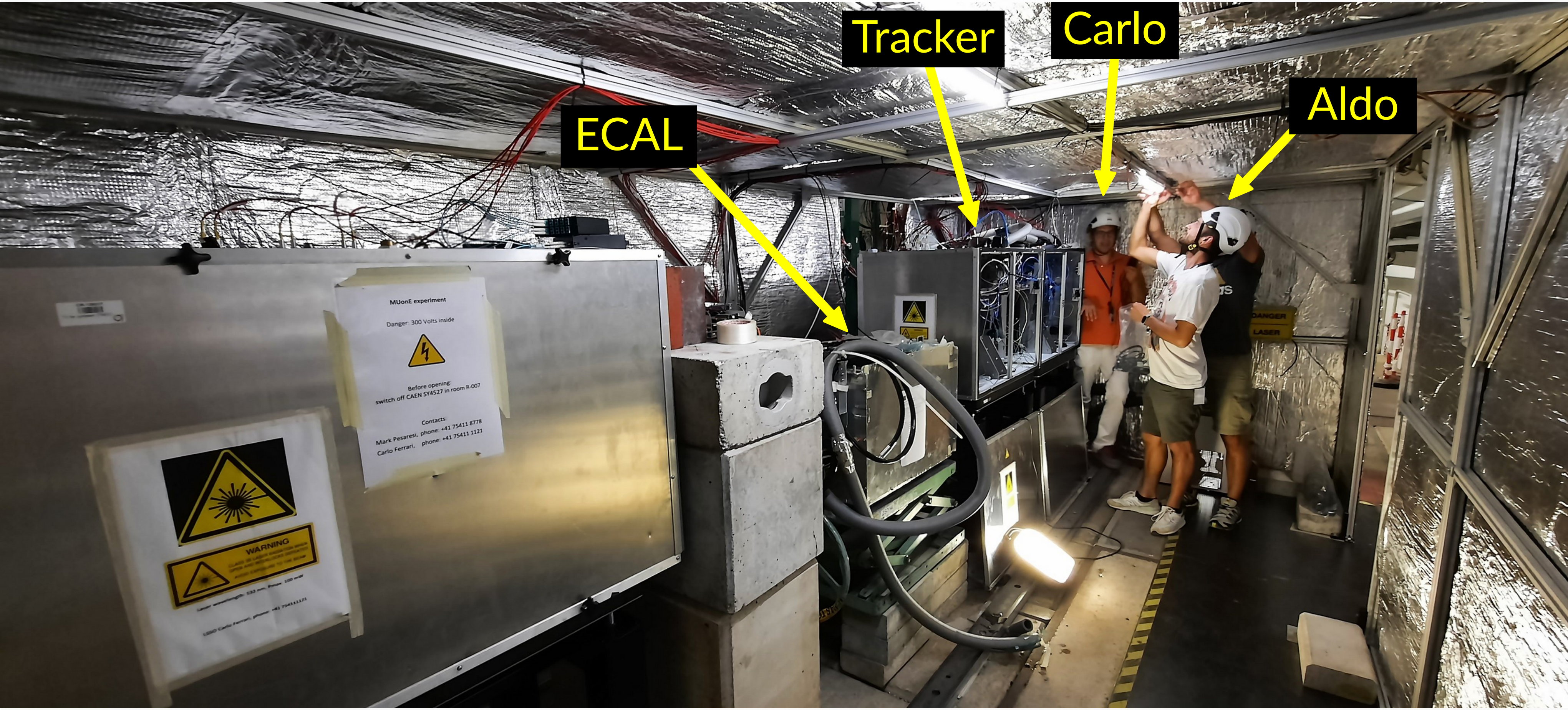
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Test the detector performance.
- Test the reconstruction algorithms.
- Study the background processes and the sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{lep}(t)$ with a few % precision.

Installing the detector...



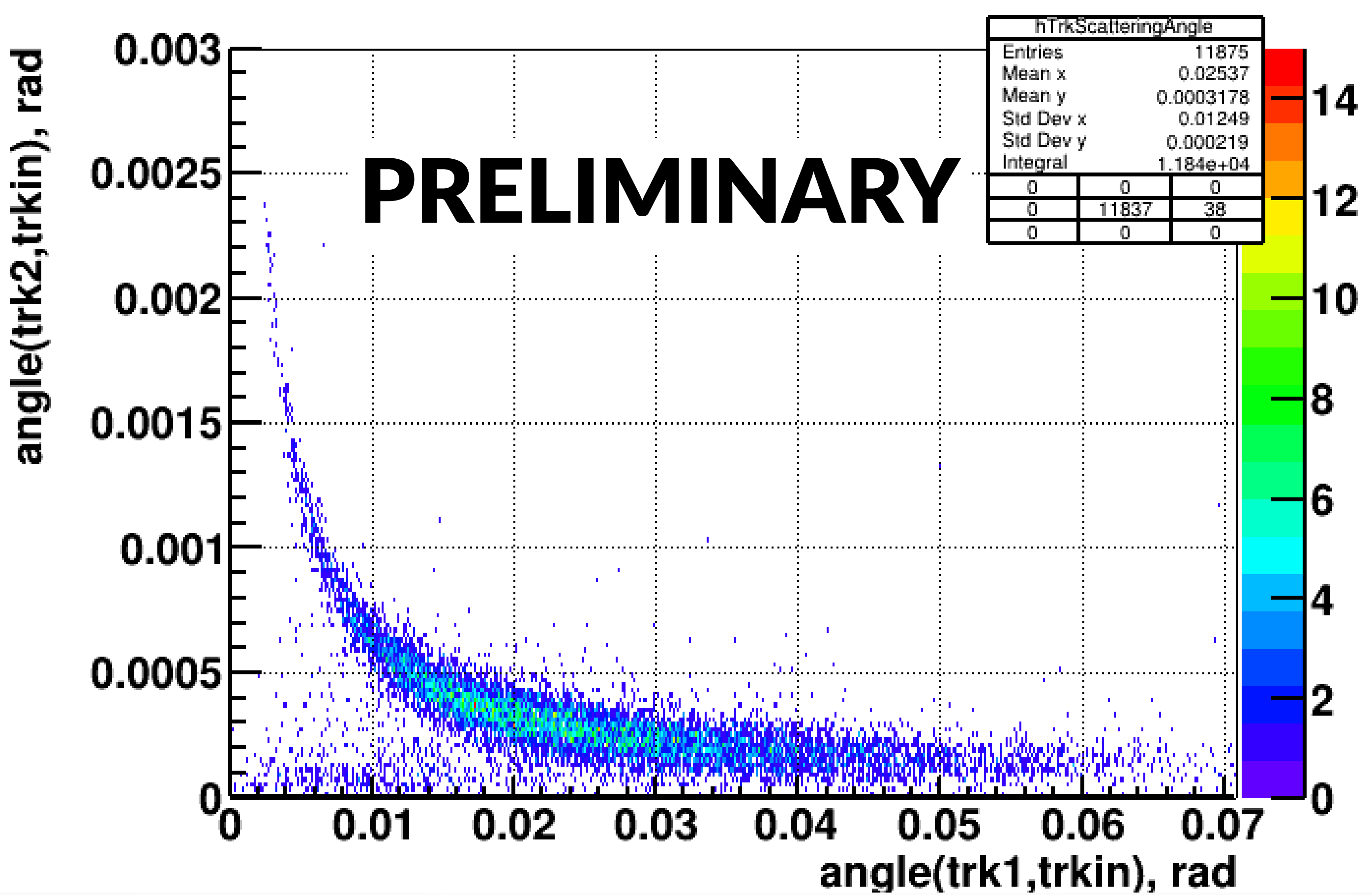


Installing the detector...



Ready for data taking!

The first elastic events @ 40 MHz

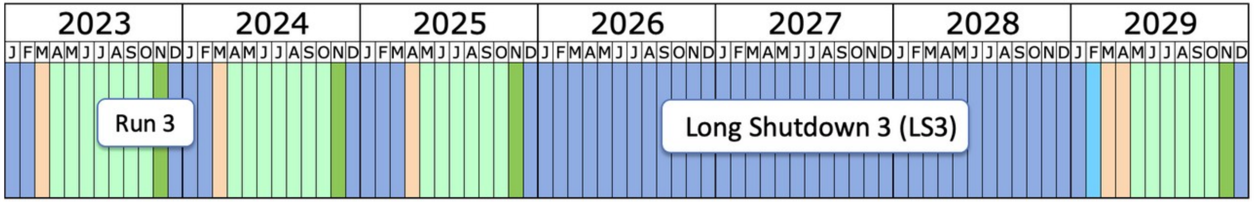


Conclusions and future plans

MUonE web site

- Intense Beam Test activities in 2021-2022:
  first experience with detector in real beam conditions.
- 3 weeks Test Run in 2023:
  proof of concept of the experimental proposal
  using 2 tracking stations (pretracker + 1 station with target) and ECAL.
- Technical proposal in 2024 based on the results of the Test Run.
- Towards the full experiment: 5-10 stations before LS3 (2026).
  2-4 months data taking: first measurement (few % precision) of a_μ^{HLO}.
- Full apparatus (40 stations) after LS3 to achieve the target precision
  (~0.3% stat and similar syst).

The MUonE Collaboration gratefully
acknowledges the contributions
of the CMS Collaboration.



New collaborators are welcome!

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

CERN
Exp-Th

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

Krakow IFJ Pan
Exp

The MUonE Collaboration

Cornell U., Northwestern U., Regis U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) *Exp-Th*

Shanghai Jiao Tong U.
Exp

PSI (Villigen), U.Zürich, ETH Zürich
Th

Mainz U., Max-Planck Inst.
Exp-Th

+ other involved theorists from: New York City Tech (USA), Vienna U. (A)

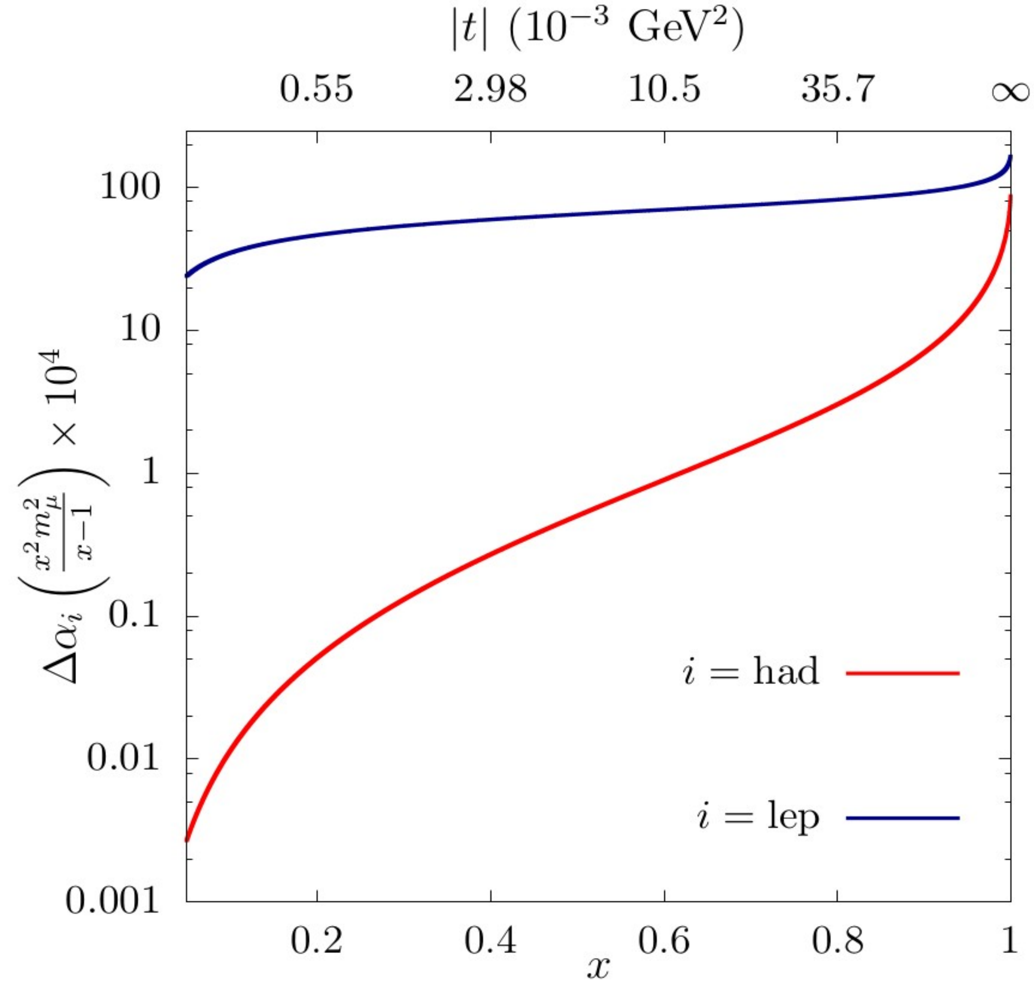
BACKUP

- 160 GeV muon beam on atomic electrons.

$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

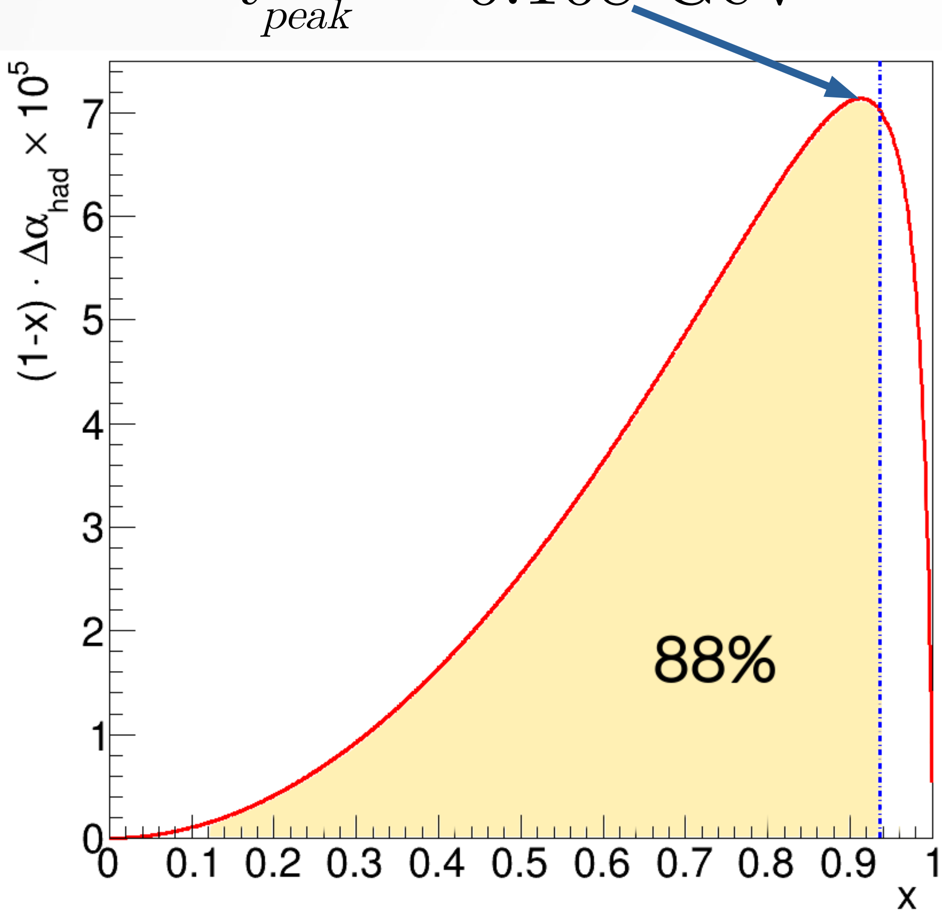
$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

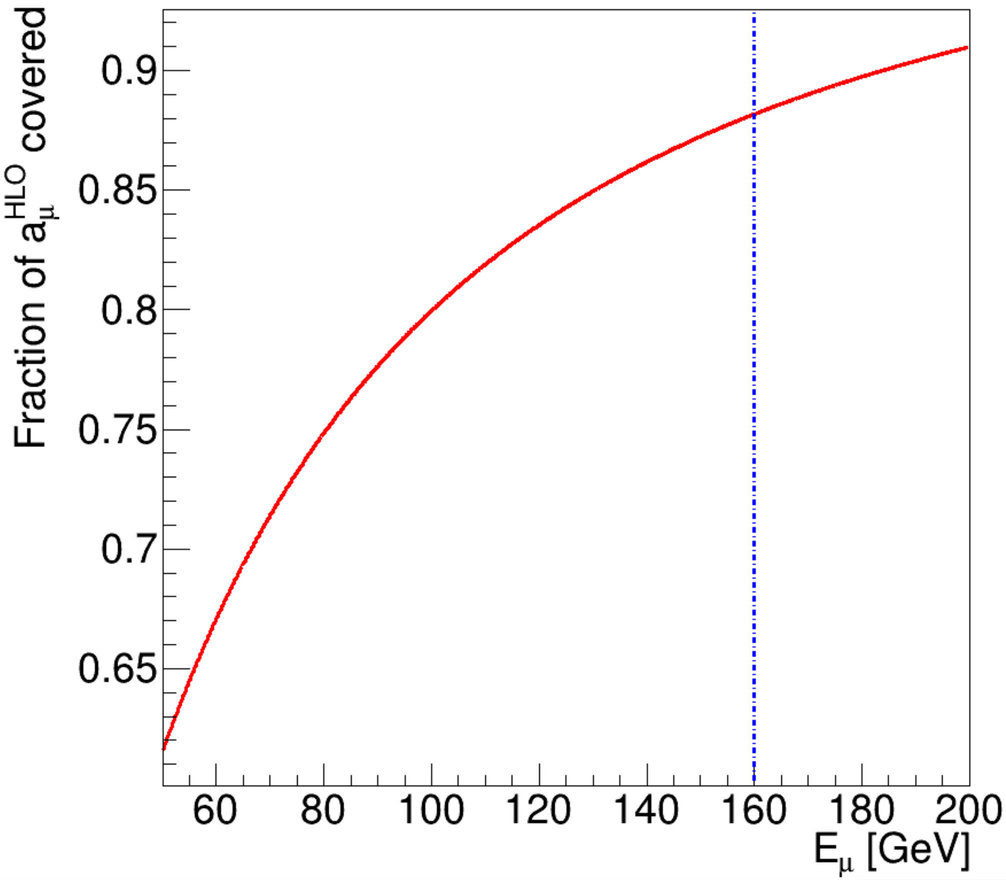
$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



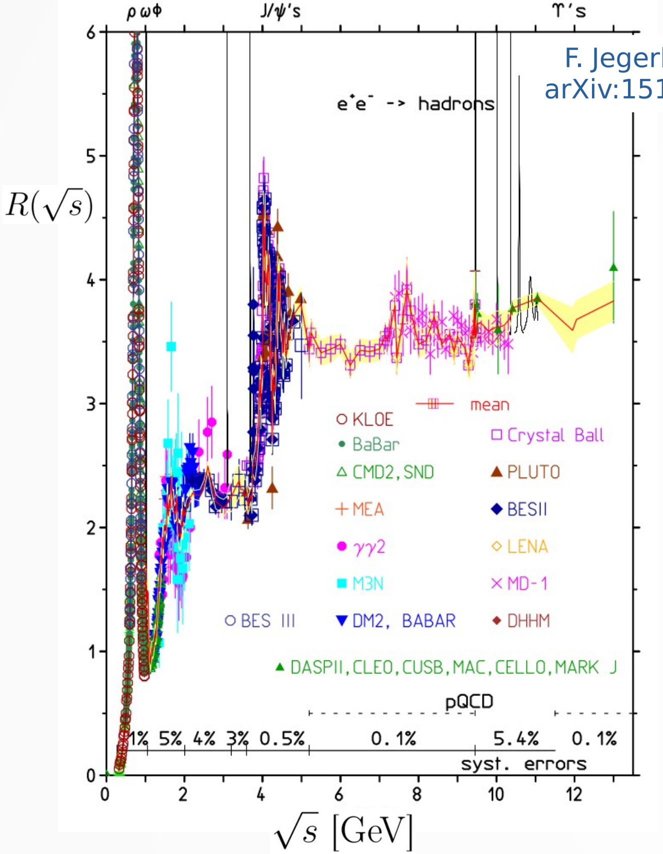
$x < 0.936$

$t_{peak} \sim -0.108\ \mathrm{GeV}^2$ $x_{peak} \sim 0.92$

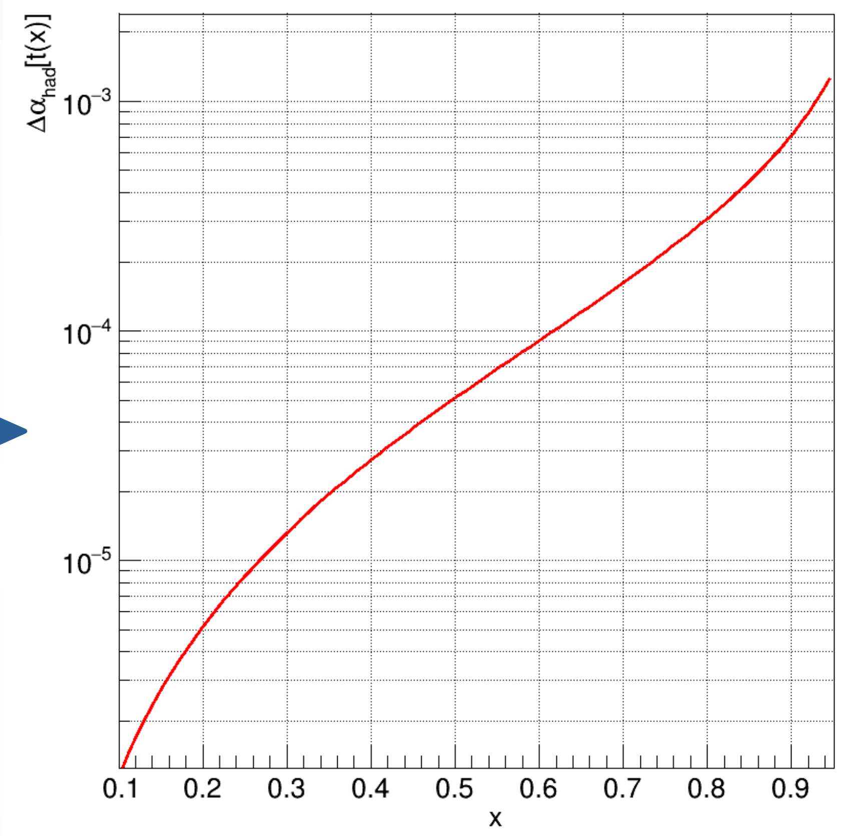




From time-like to space-like



F. Jegerlehner, arXiv:1511.04473

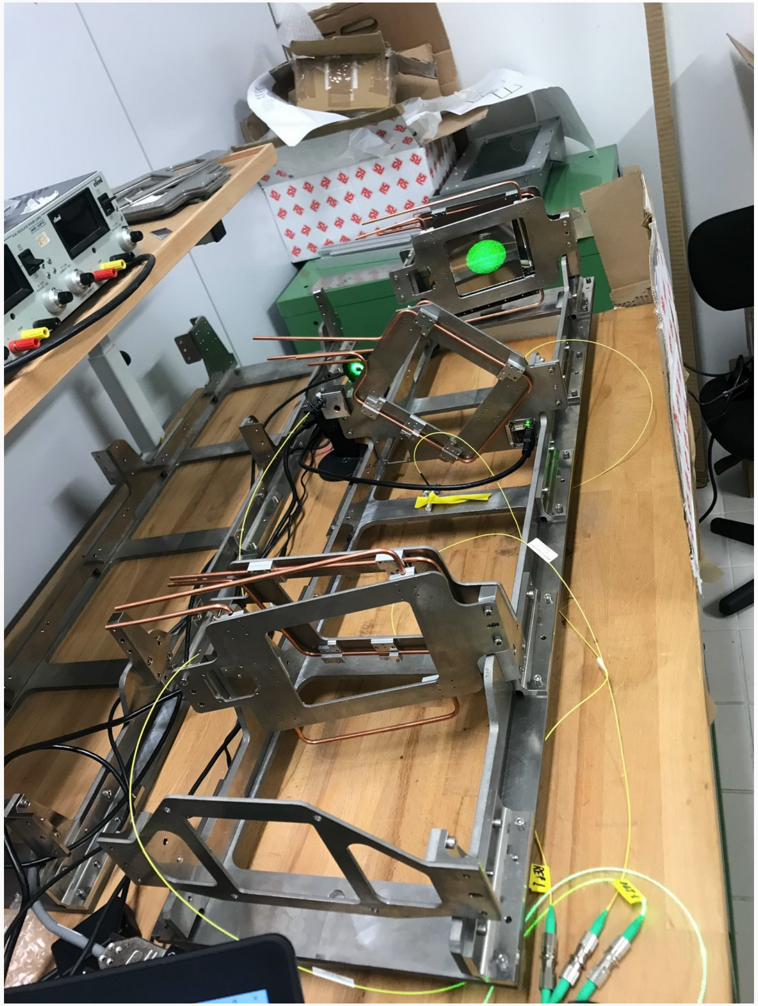


$$a_\mu^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

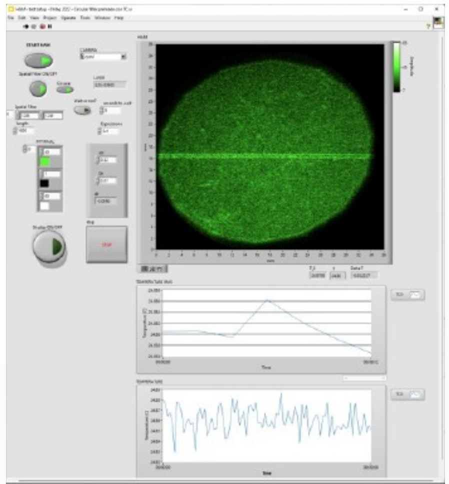
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)s/m_\mu^2}$$

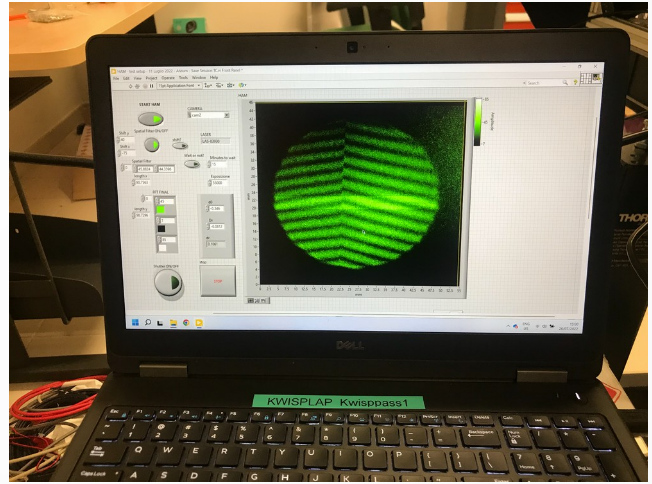
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

Laser holographic system



Initial state

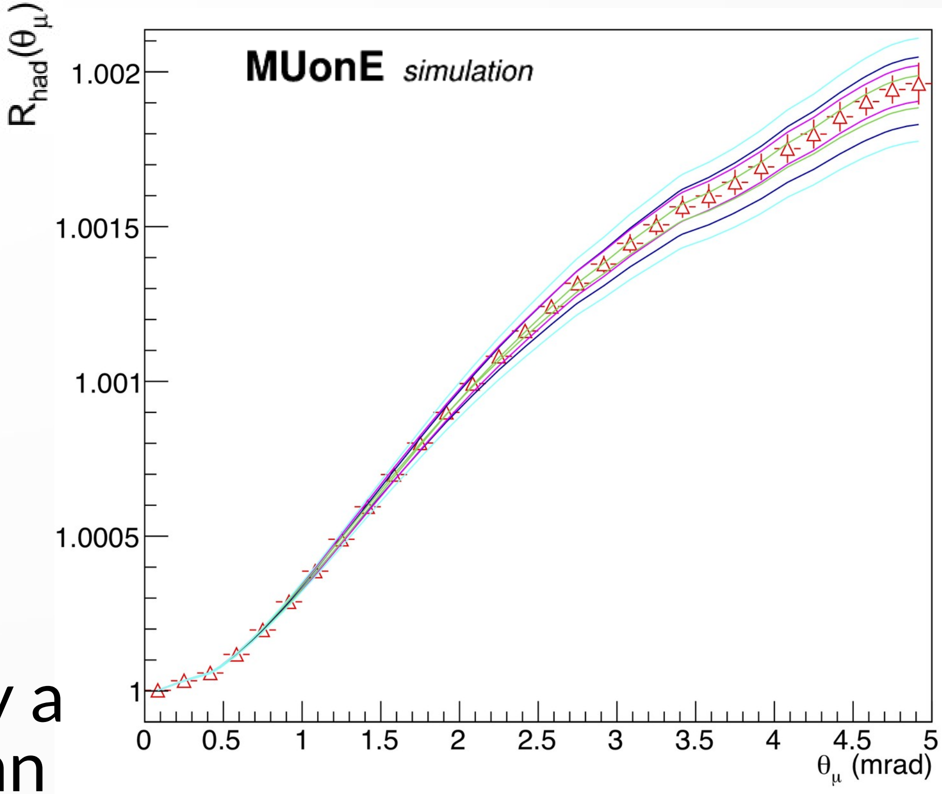




- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.
- Developed at INFN Trieste, tested in 2022 at CERN.

Template fit

1. Define a grid of points (K, M) in the parameters space, in order to cover a region ±5σ around the expected values (σ = expected uncertainty). Step size: σ/4 or σ/2.



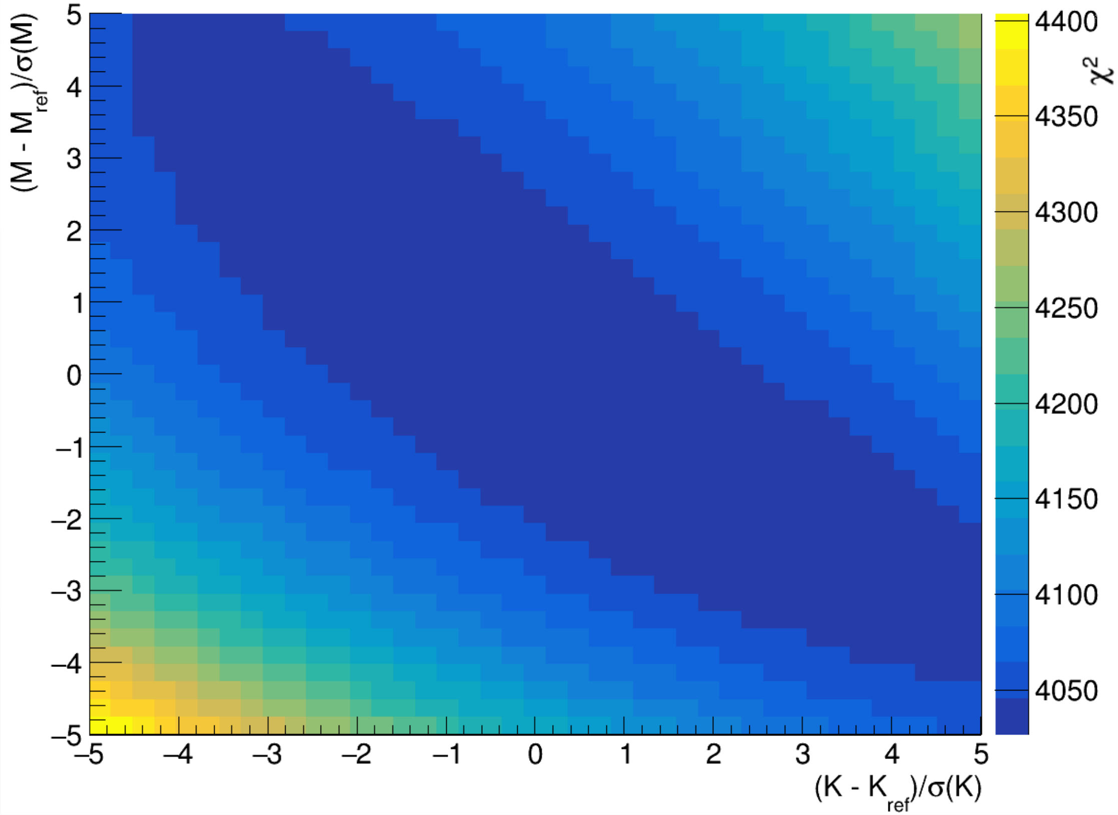
2. Generate a MC sample and apply a reweighting procedure to make an ensemble of template distributions. Each template distribution corresponds to a (K, M) point in the grid.

Template fit

3. Make a χ^2 (or likelihood) comparison between the data and each template distribution.

4. Perform a parabolic interpolation across the grid points to get the best fit parameters (K, M).

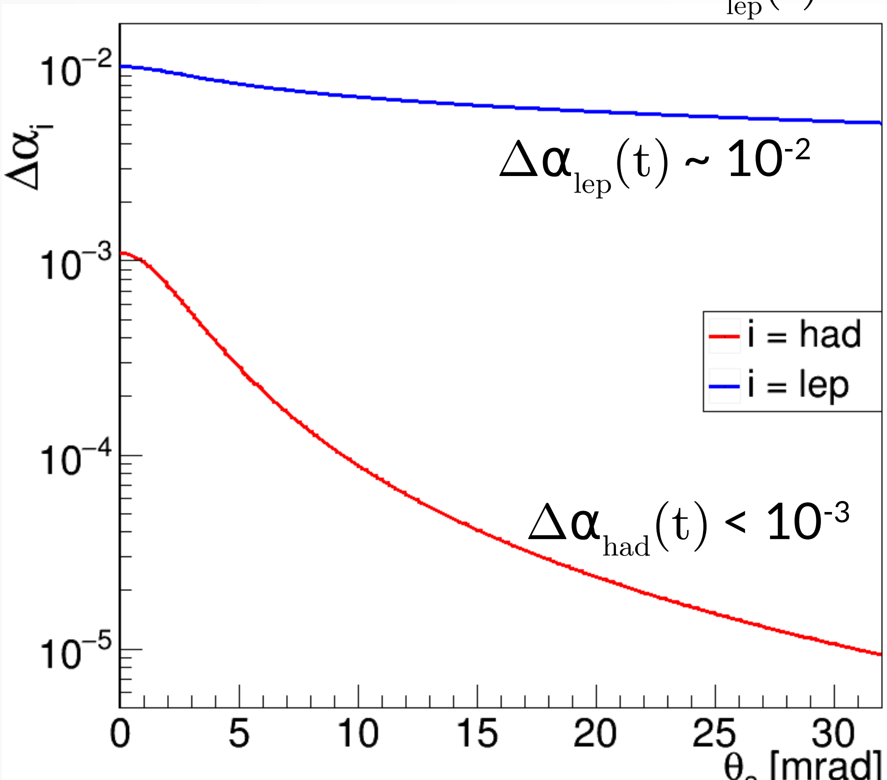
$$\chi^2 = \sum_i^{\text{bins}} \left(\frac{\text{data}_i - \text{templ}(K, M)_i}{\sigma_i^{\text{data}}} \right)^2$$



Test Run 2023: extraction of $\Delta\alpha_{lep}(t)$

Expected ~10^{12} μ on target, ~2.5×10^{8} elastic events E_e > 1 GeV
(Expected luminosity: ~ $1 pb^{-1}$)

Not enough for $\Delta\alpha_{had}(t)$,
but we can measure $\Delta\alpha_{lep}(t)$



1 loop QED contribution of lepton pairs:

$$\Delta\alpha_{lep}(t) = k\left[f(m_e) + f(m_\mu) + f(m_\tau)\right]$$

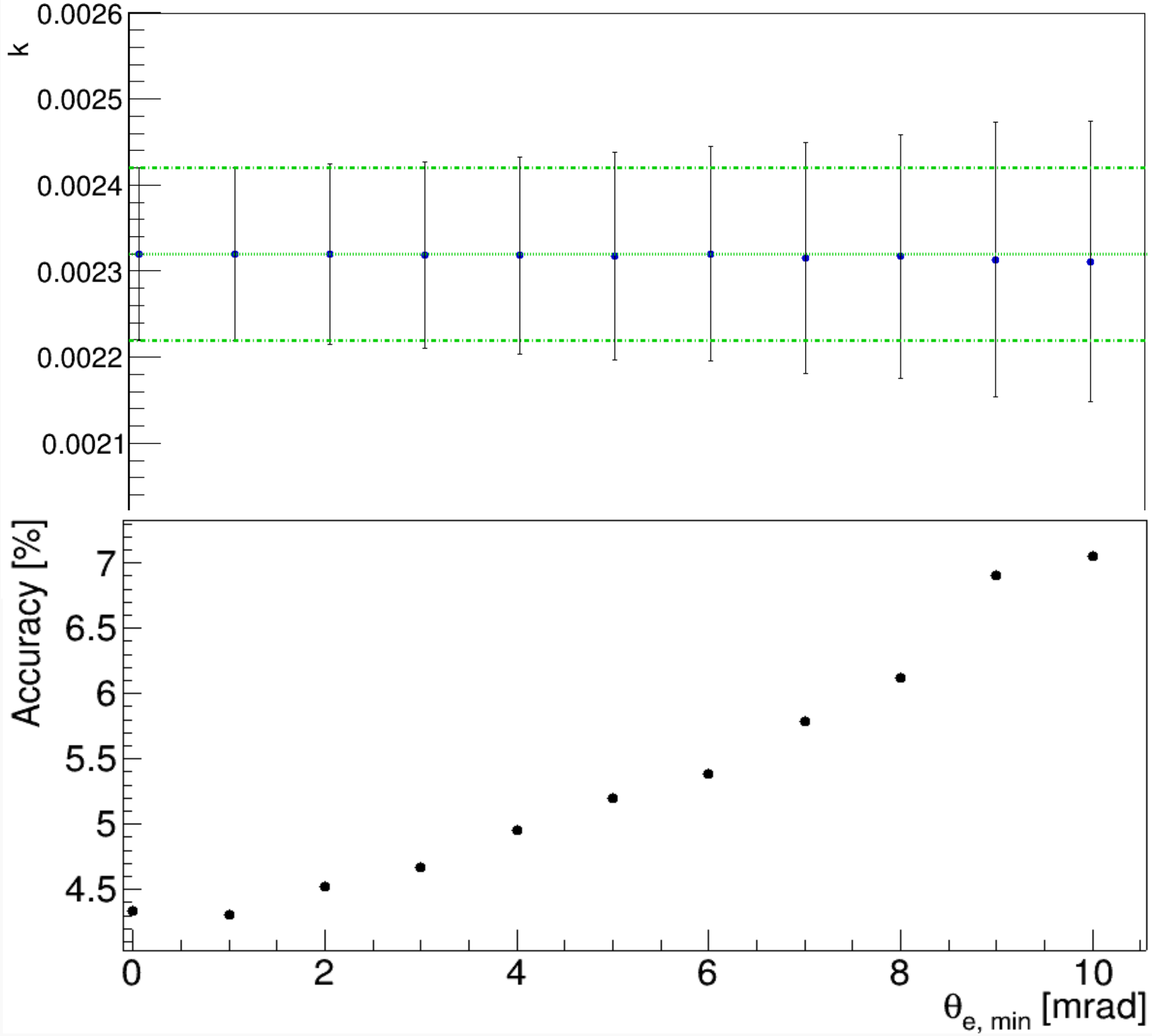
$$f(m) = -\frac{5}{9} - \frac{4}{3}\frac{m^2}{t} + \left(\frac{4}{3}\frac{m^4}{t^2} + \frac{m^2}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4m^2}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4m^2}{t}}}{1+\sqrt{1-\frac{4m^2}{t}}}\right|$$

1 parameter template fit:
Fix lepton masses and fit k

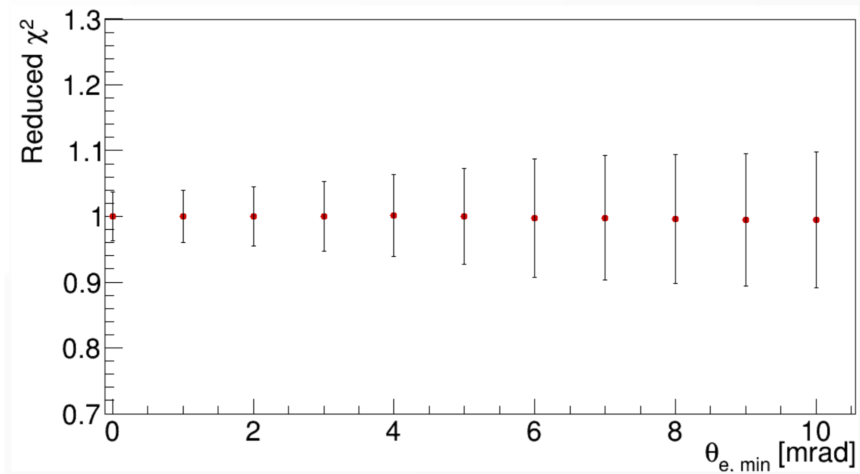
$$k = \frac{\alpha}{\pi}$$

Expected precision: ~5%

Template fit without PID
Stability for different angular cuts



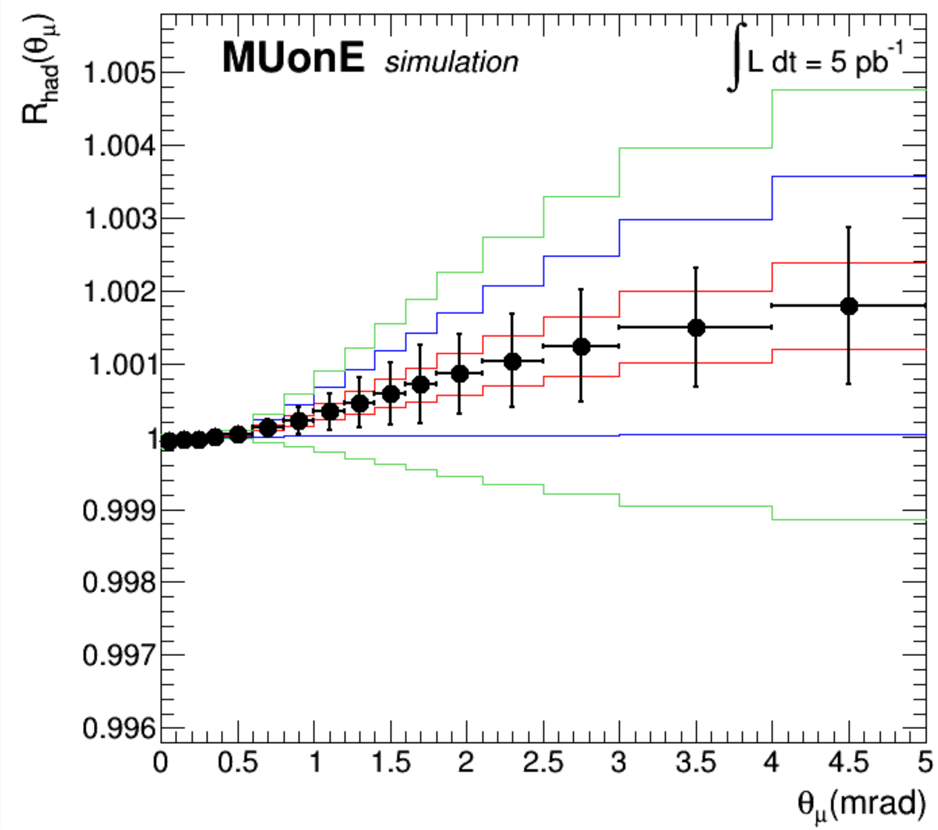
$\theta_\mu > 0.2$ mrad
$\theta_e \in [\theta_{e\ min}, 32\text{mrad}]$



Sensitivity 2025

Assuming: L_{TR} = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 32 mrad)

$$R_{\rm had} = \frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$



We will be sensitive to the leptonic running ($\Delta\alpha_{\rm lep}(t)$ < 10^{-2})

Low sensitivity to the hadronic running ($\Delta\alpha_{\rm had}(t)$ < 10^{-3})

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

K = 0.136 ± 0.026
(20% stat error)

Systematic error on the multiple scattering model

Expected precision on the gaussian core: ± 1%

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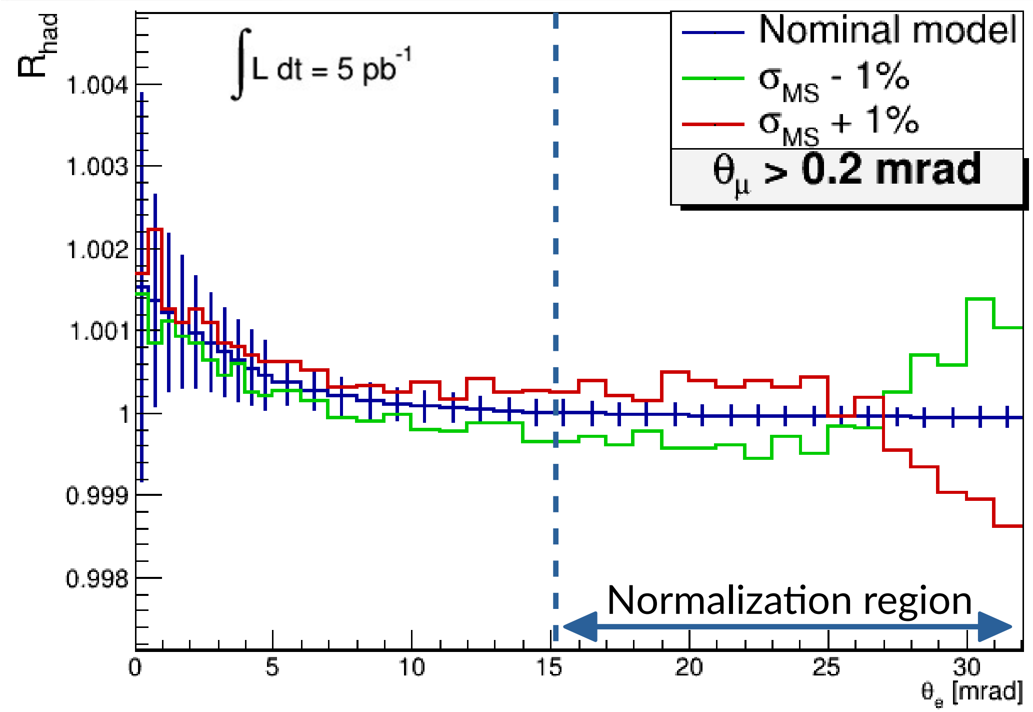
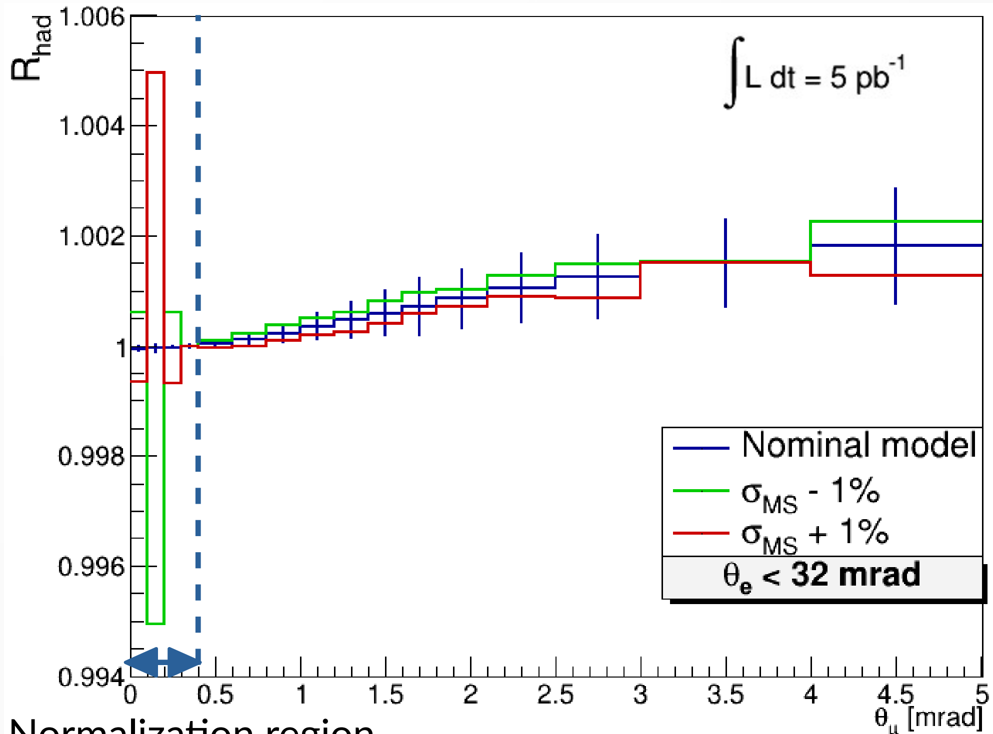
PDG modelization:

$$\sigma_{MS} \propto \sqrt{\frac{x}{X_0}}$$

x = target thickness



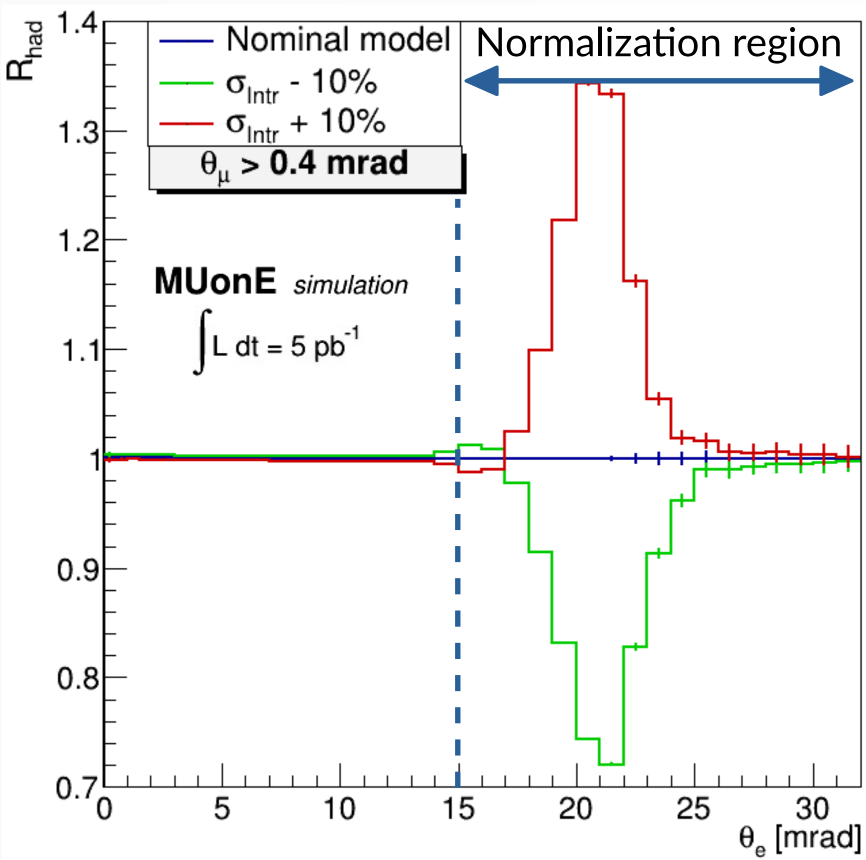


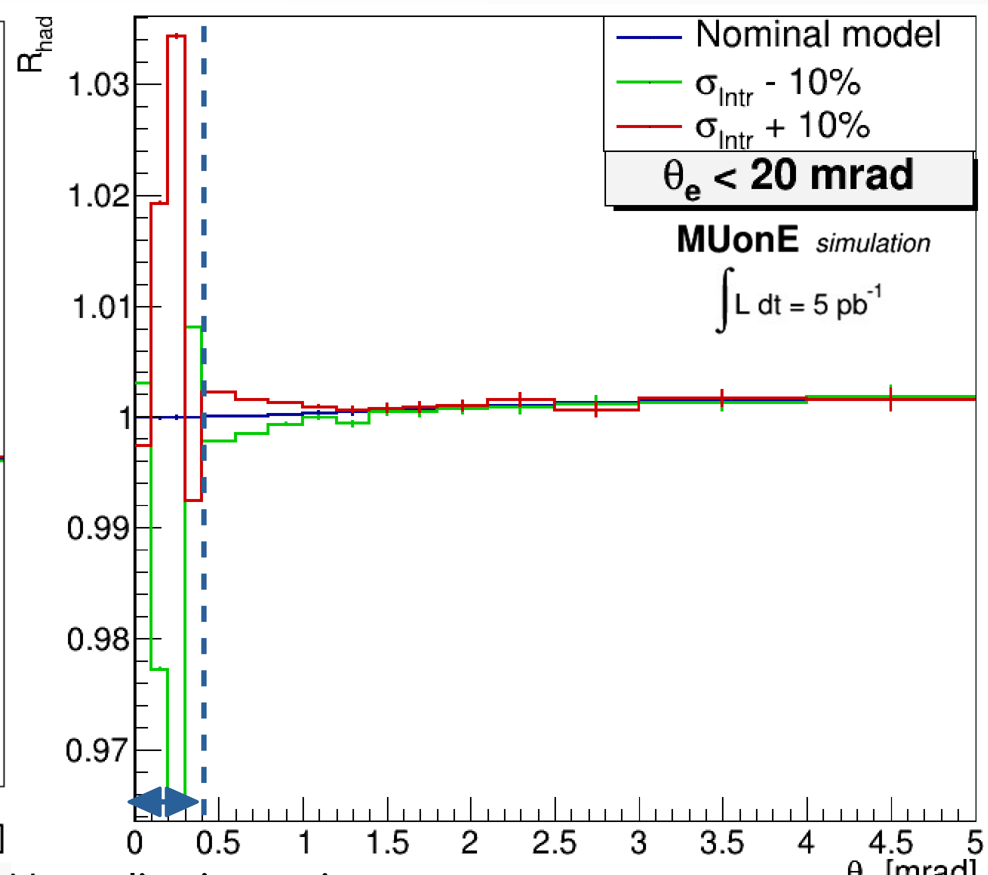
Normalization region

Systematic error on the detector angular resolution

2S modules resolution: 8-11μm

±10% error on the detector angular resolution.



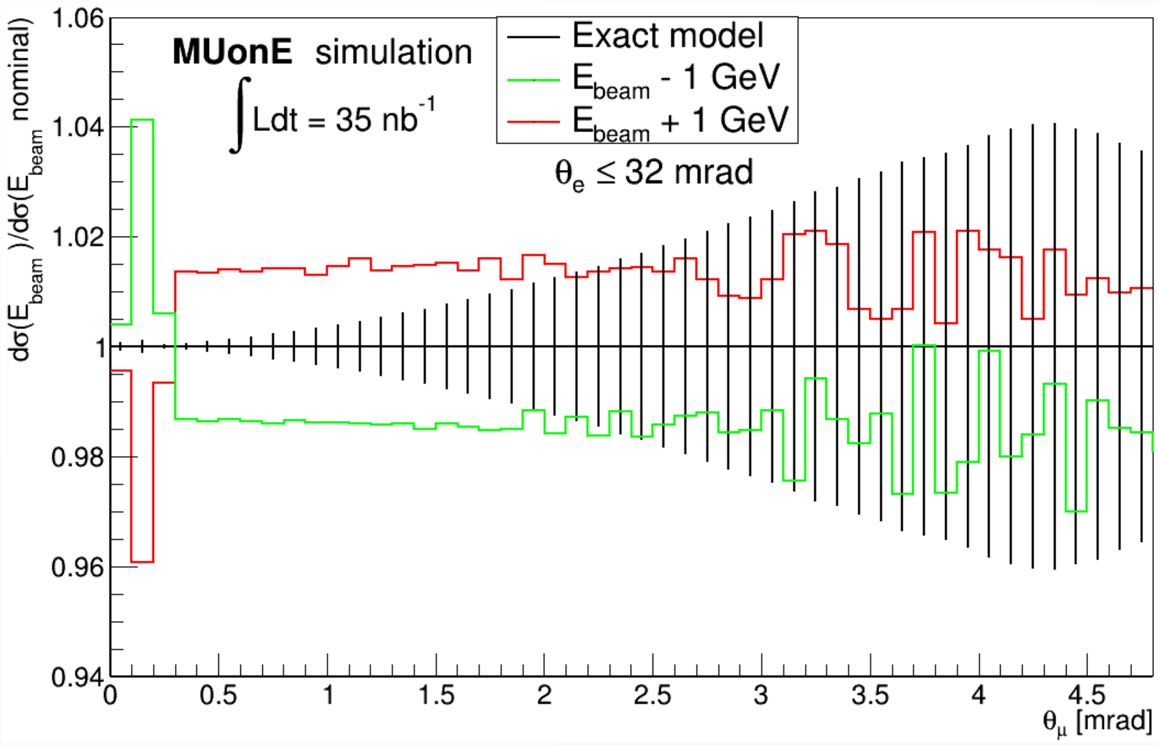


Normalization region

Systematic error on the muon beam energy

Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV).

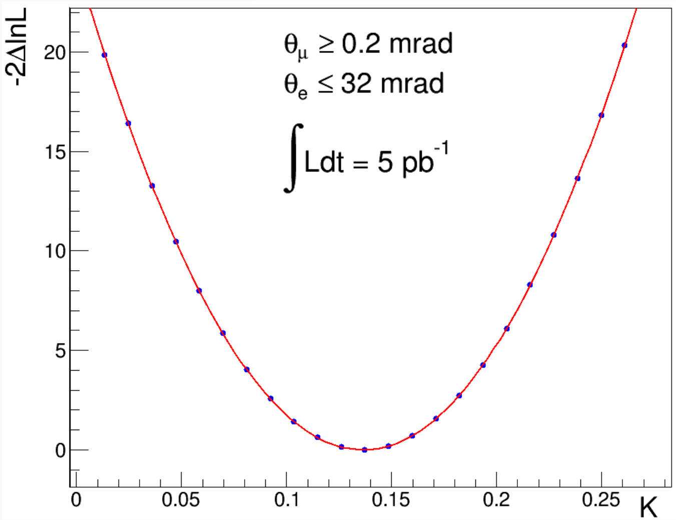
This effect can be seen from our data in 1h of data taking per station.



Strategy for the systematic effects

Promising strategy:

- Study the main systematics in the normalization region.
- Include residual systematics as nuisance parameters in a combined fit with signal.
- MESMER MC for the template fit + Combine tool to fit the nuisance parameters.



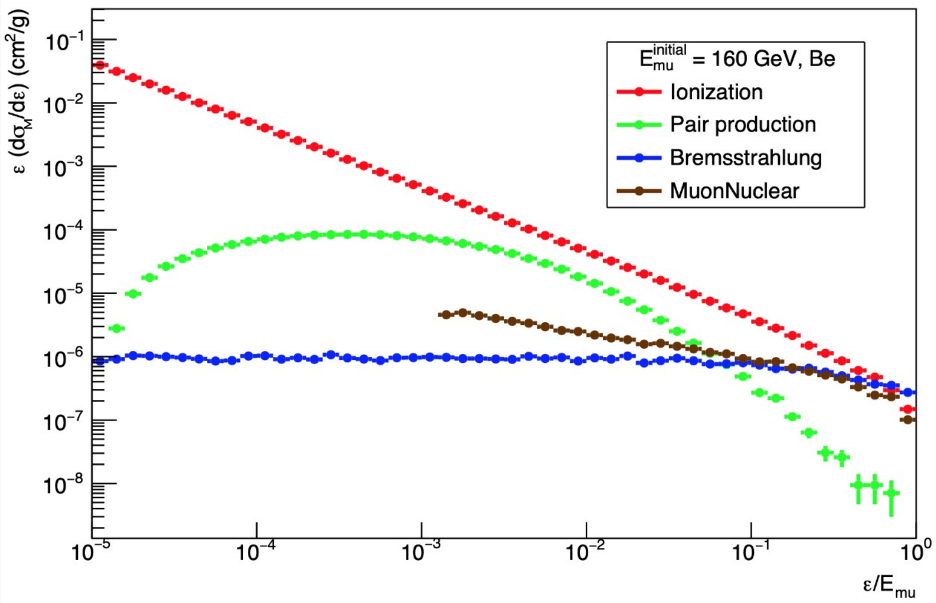
Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$, $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\mathrm{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\mathrm{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\mathrm{E_{Beam}}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$

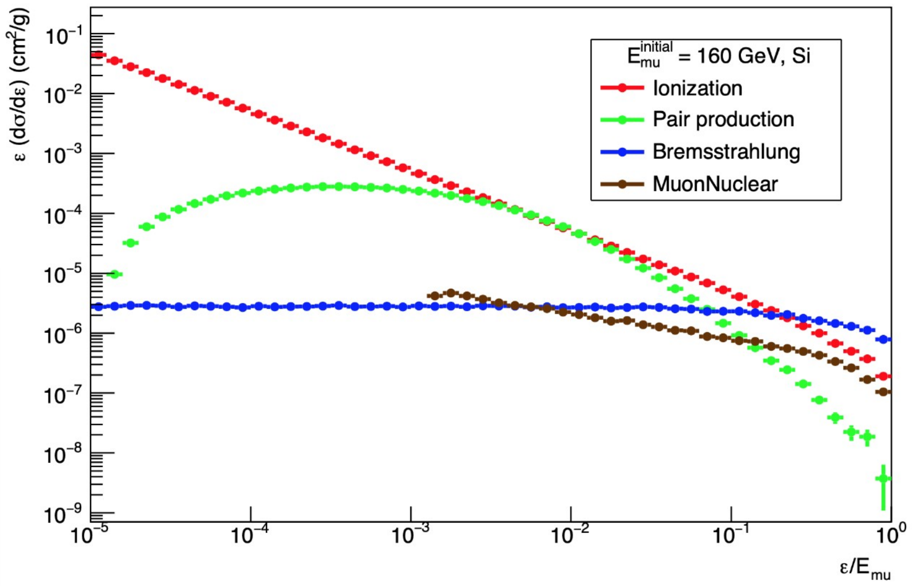
- K_{ref} = 0.137
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

Next steps:

- Test the procedure for the MuonE design statistics.
- Improve the modelization of systematic effects.

Backgrounds





MESMER

- $\mu e^- \to \mu e^- \gamma$
- $\mu e^- \to \mu e^- e^+ e^-$

Soon complete implementation in MESMER

GEANT4

- $\mu N \to \mu N \gamma$
- $\mu N \to \mu N e^+ e^-$
- $\mu N \to \mu X$

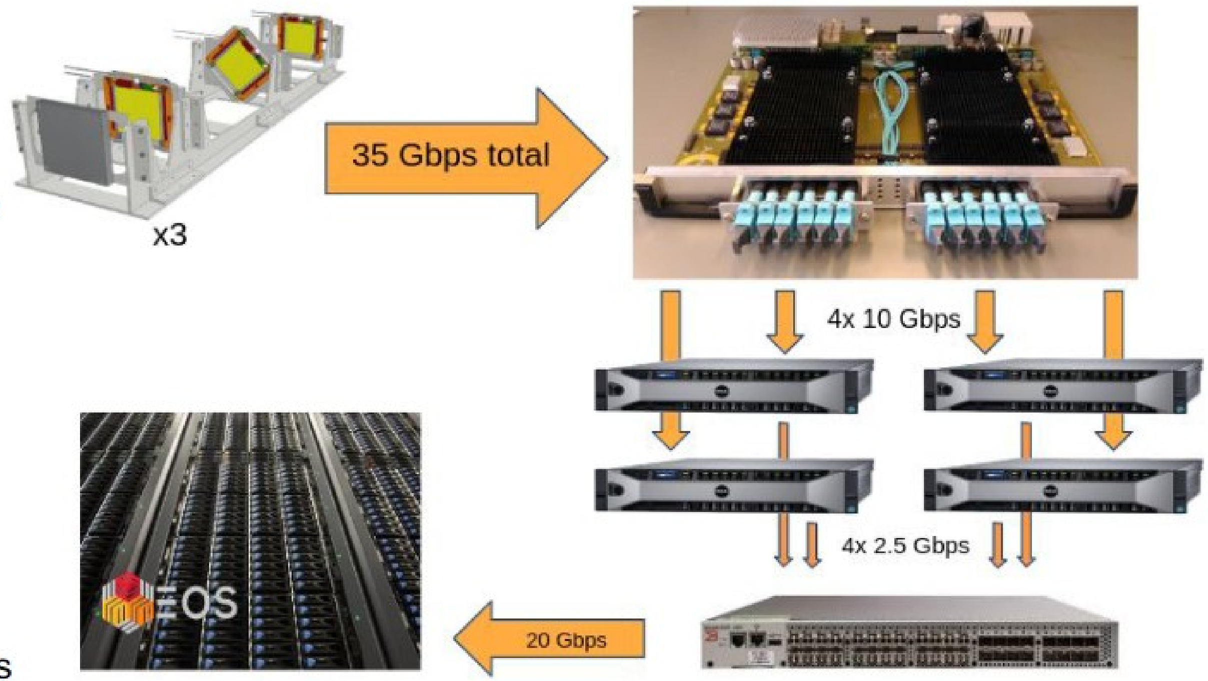
BE-DAQ architecture

Single Serenity communicates with frontends in the Test Run

- Expected event size : 1 Kb (Tk)
- Output data split across 4 servers via 10 Gbps Ethernet (UDP)
- Empty frames from beam gap forwarded in addition to in-spill data

Reduced data rate from servers

- Book-keep empty frames but do not forward to switch
- From switch to EOS/CTA with 20 Gbps



- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

Tracker: CMS 2S modules

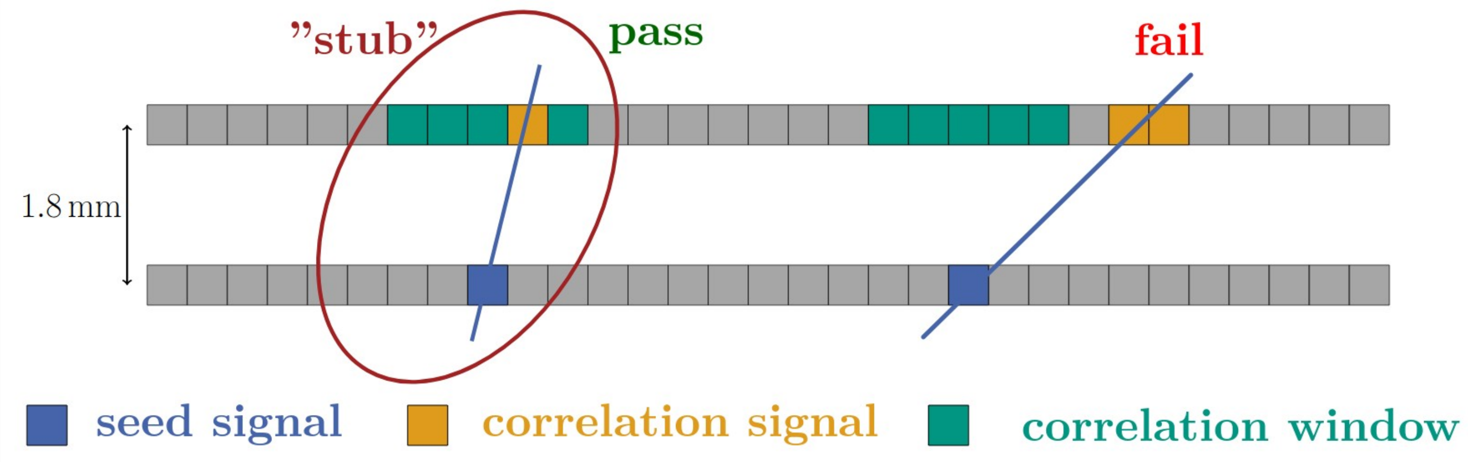
CMS Tracker Phase2 Upgrade - TDR

Two sensors reading the same coordinate:

- Background suppression from single-sensor hits.
  - Rejection of large angle tracks.

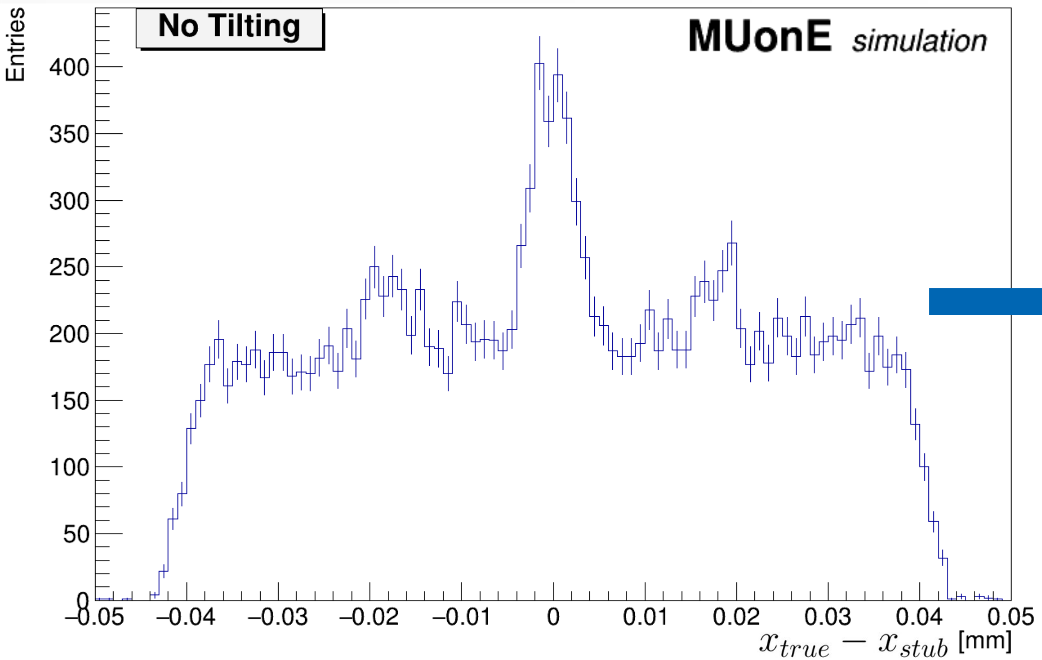
- x_{seed}
- bend = $x_{corr} - x_{seed}$

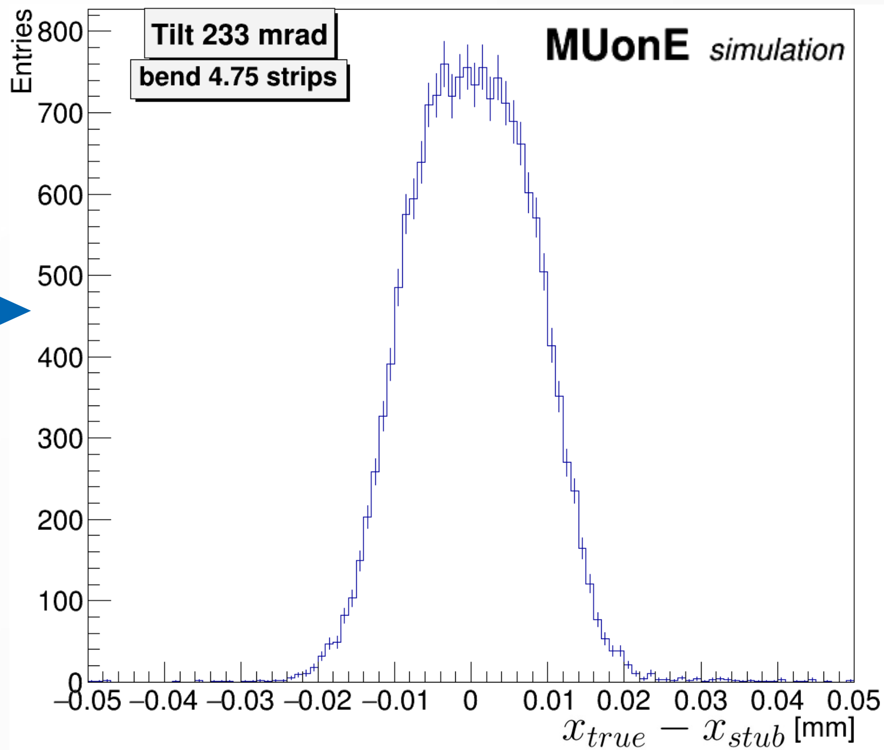
$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$



Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)

MUonE simulations: Improving resolution - tilted geometry



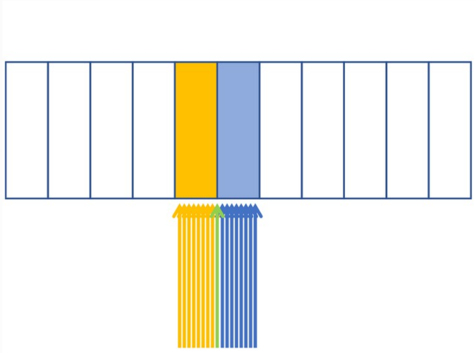


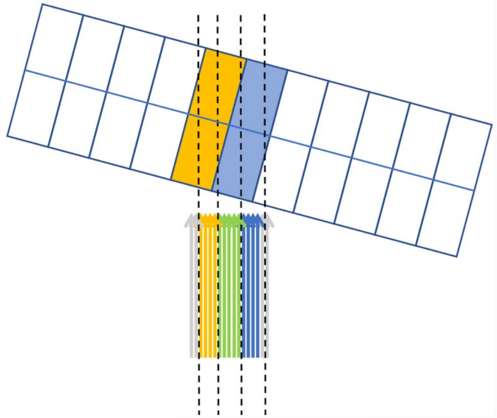
- Improvement mainly due to charge sharing between adjacent strips
- Tune the tilt angle and the digitization threshold to equalize the number of hits composed of 1 or 2 strips.

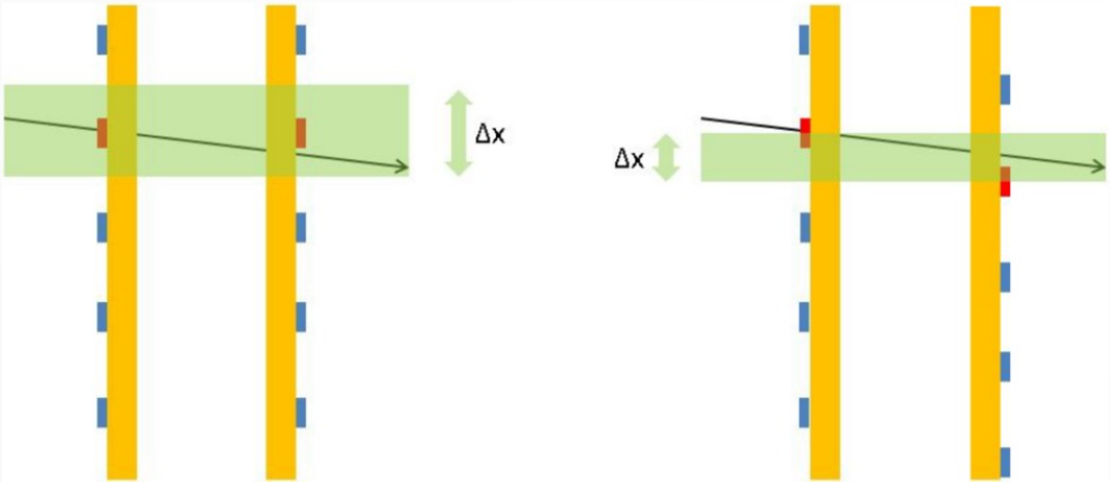
Final resolution

22 µm → ~10 µm

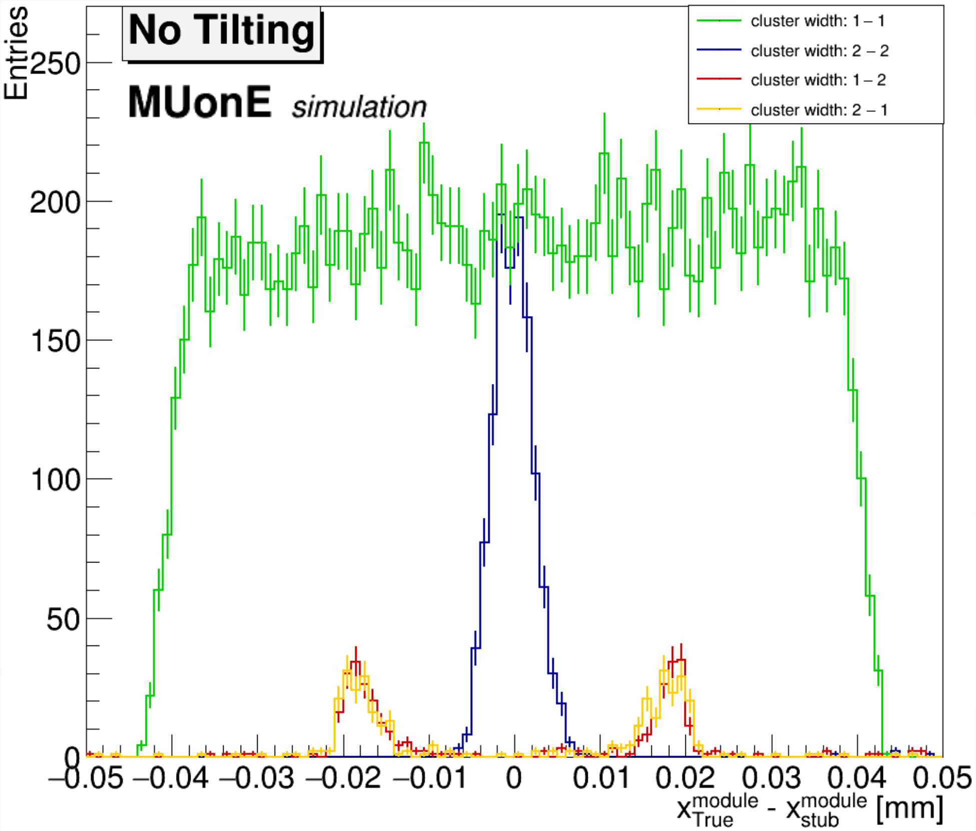
1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips

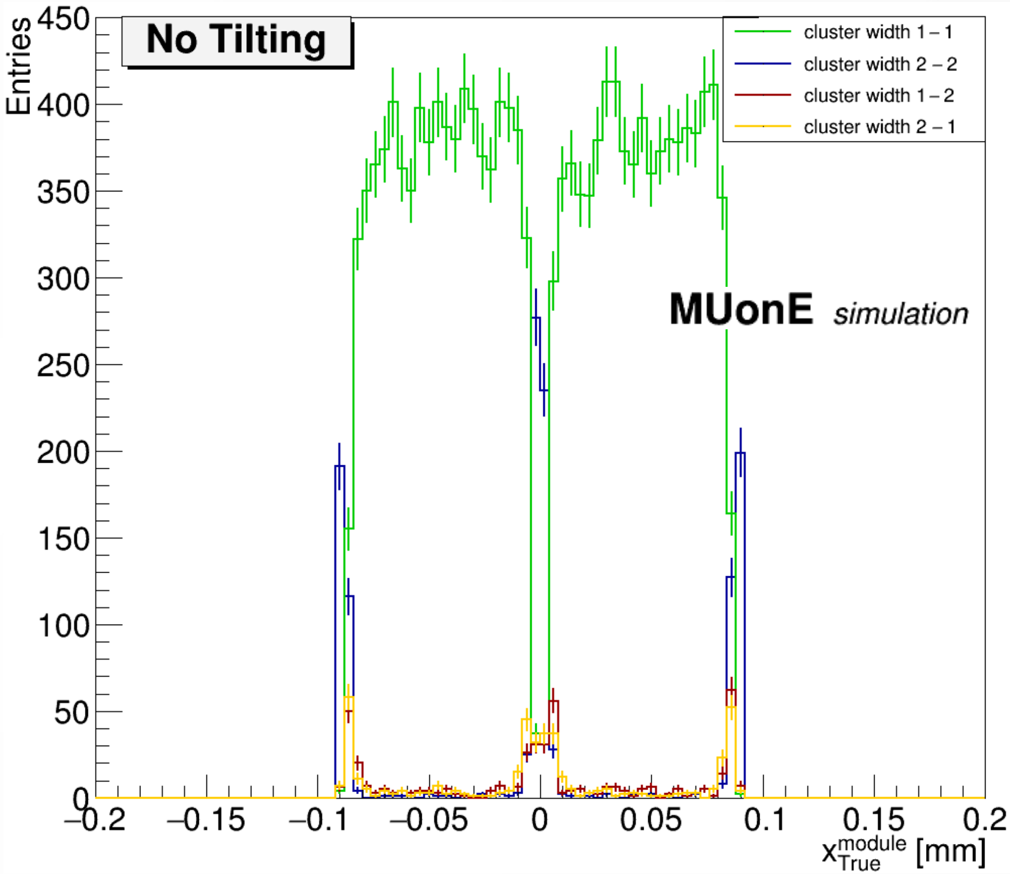






2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch


No Tilting
MUonE simulation
cluster width: 1 – 1
cluster width: 2 – 2
cluster width: 1 – 2
cluster width: 2 – 1
Entries
x_{True}^{module} - x_{stub}^{module} [mm]

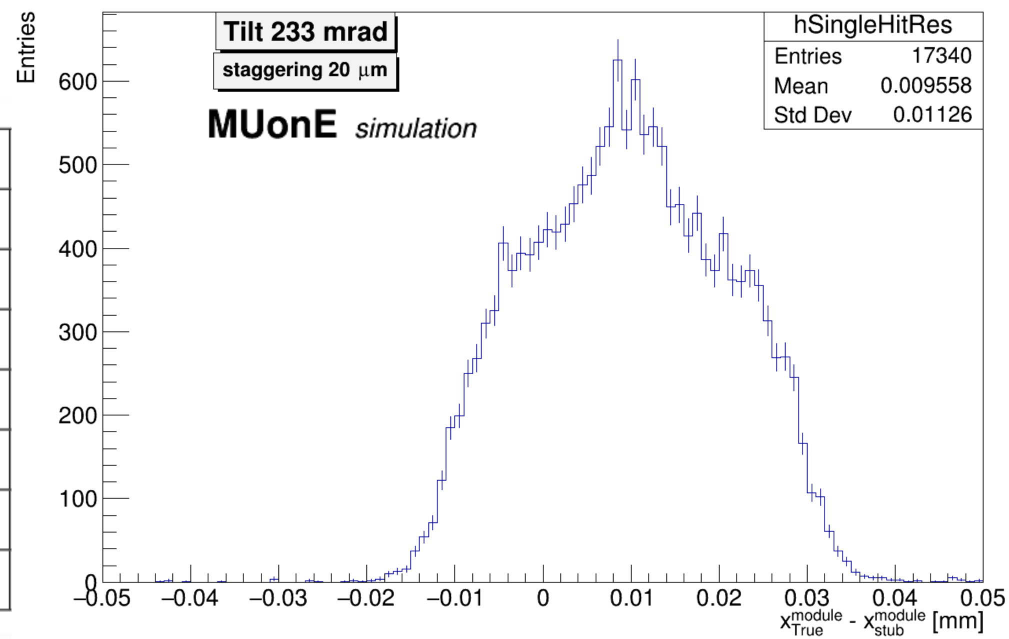

No Tilting
MUonE simulation
cluster width 1 – 1
cluster width 2 – 2
cluster width 1 – 2
cluster width 2 – 1
Entries
x_{True}^{module} [mm]

MUonE simulations: Improving resolution - tilted geometry

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

Effect of a staggering between the two sensors

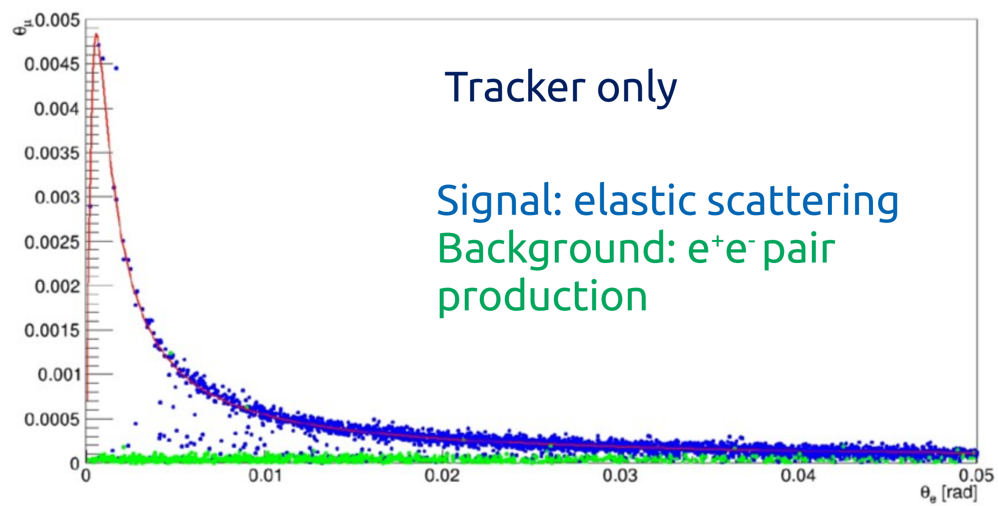
Staggering [μm]	resolution [μm]	bias [μm]
0	8.0	0
5	8.4	2.4
10	9.4	4.9
15	10.4	7.3
20	11.3	9.6
25	11.2	12.1
30	10.4	14.5

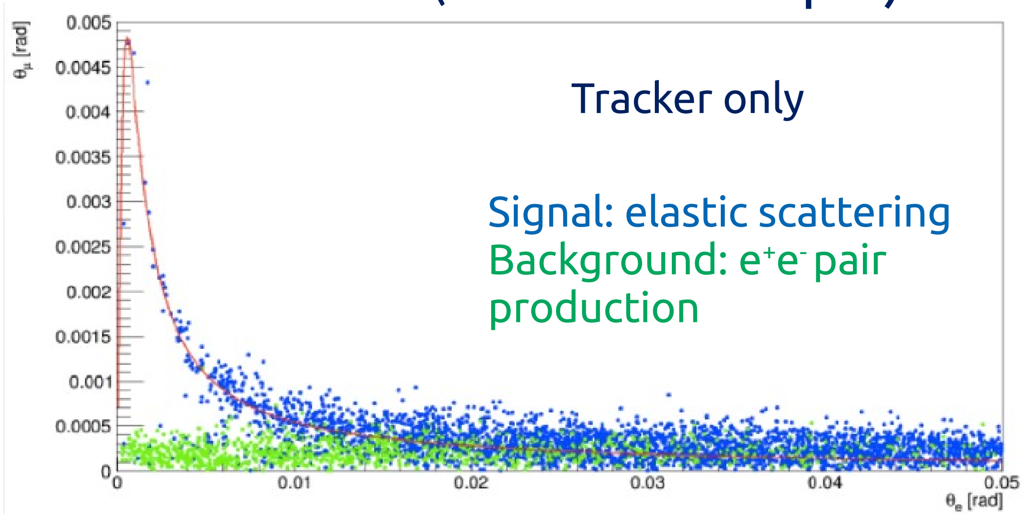


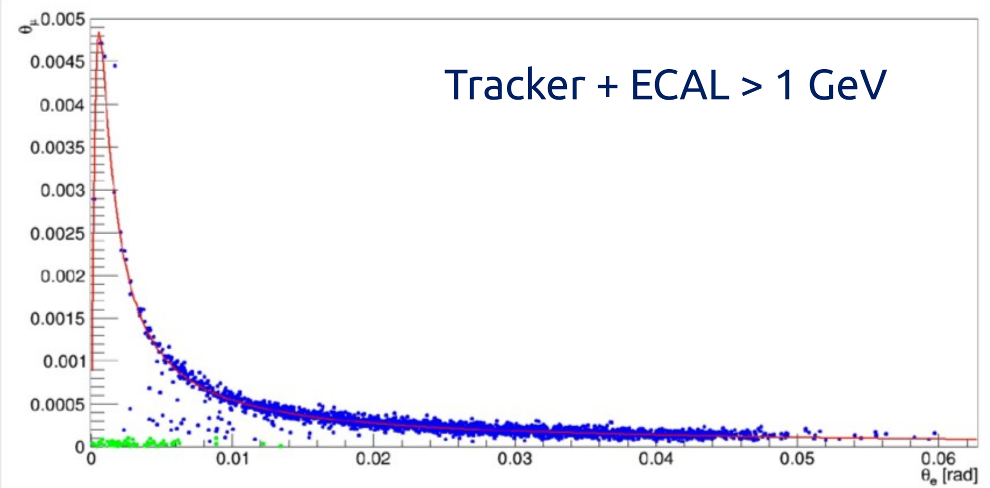
GEANT4 simulations

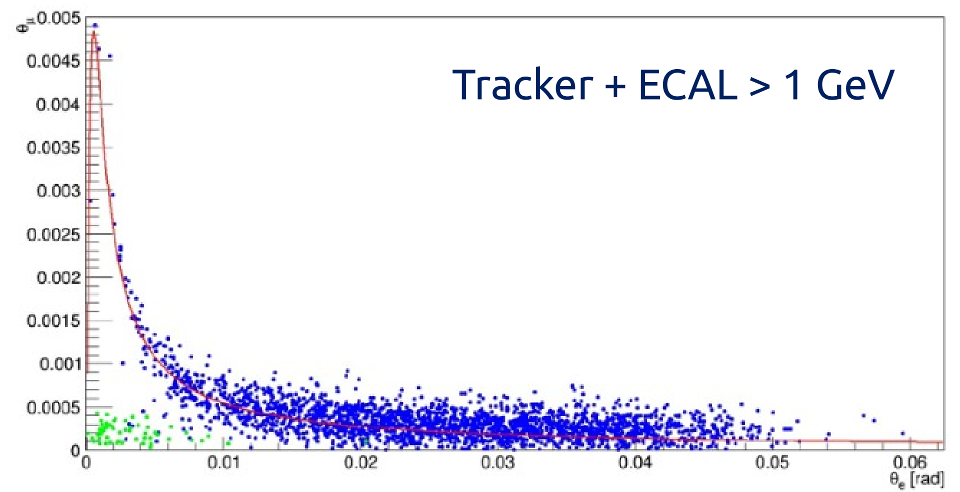
TB2017 (resolution ~7µm)

TB2018 (resolution ~40µm)

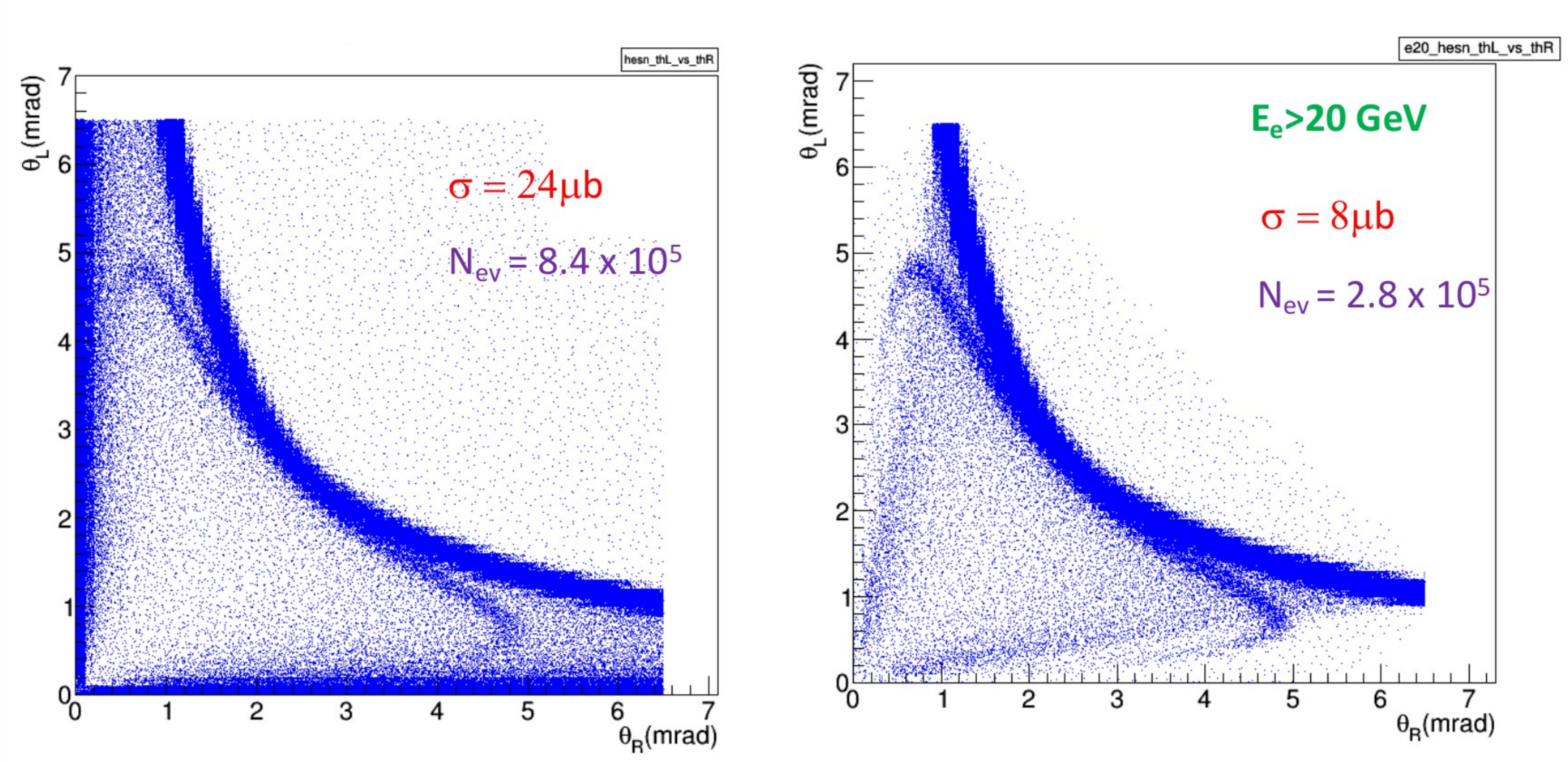








Effect of energy selection using the calorimeter

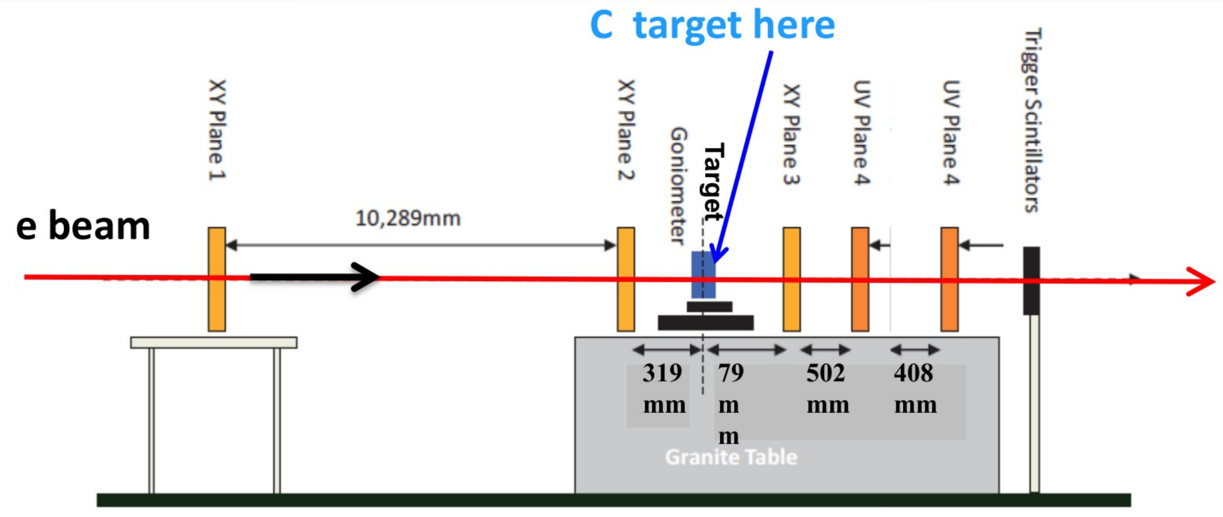


Multiple scattering: results from TB2017

Multiple scattering effects of electrons with 12 and 20 GeV on Carbon targets (8 and 20 mm)

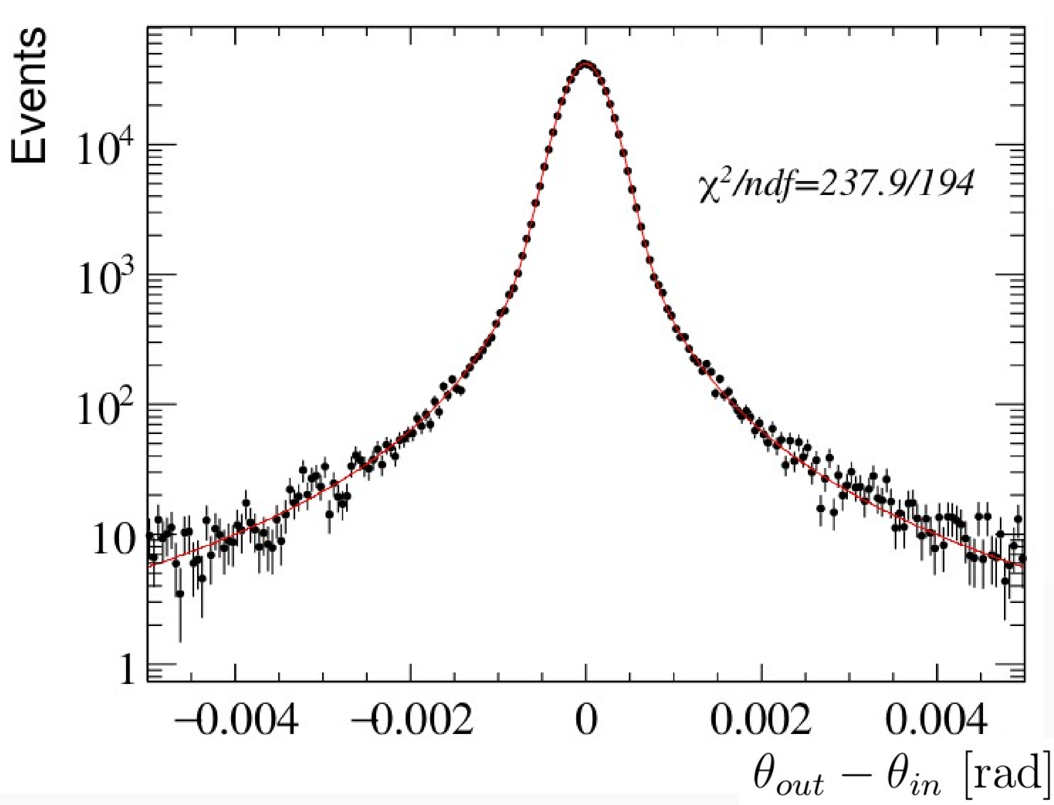
Main goals:

- to determine a parameterization able to describe also non Gaussian tails
- to compare data with a GEANT4 simulation of the apparatus



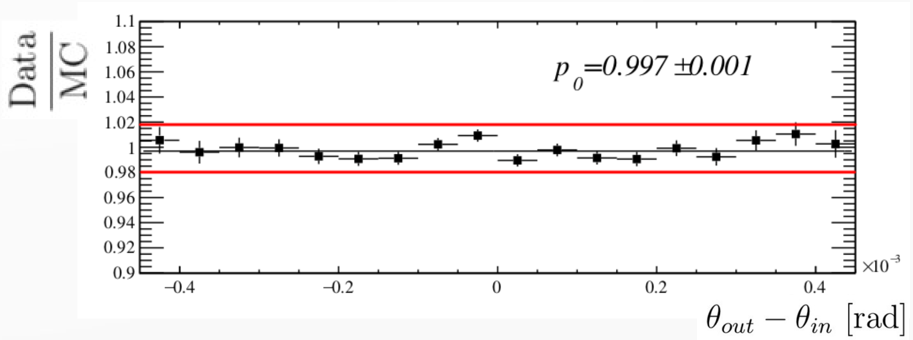
Multiple scattering: results from TB2017

$$f_e(\delta\theta_e^x) = N\left[(1-a)\frac{1}{\sqrt{2\pi}\sigma_G}e^{-\frac{(\delta\theta_e^x-\mu)^2}{2\sigma_G^2}} + a\frac{\Gamma(\frac{\nu+1}{2})}{\sqrt{\nu\pi}\sigma_T\Gamma(\frac{\nu}{2})}\left(1+\frac{(\delta\theta_e^x-\mu)^2}{\nu\sigma_T^2}\right)^{-\frac{\nu+1}{2}}\right]$$



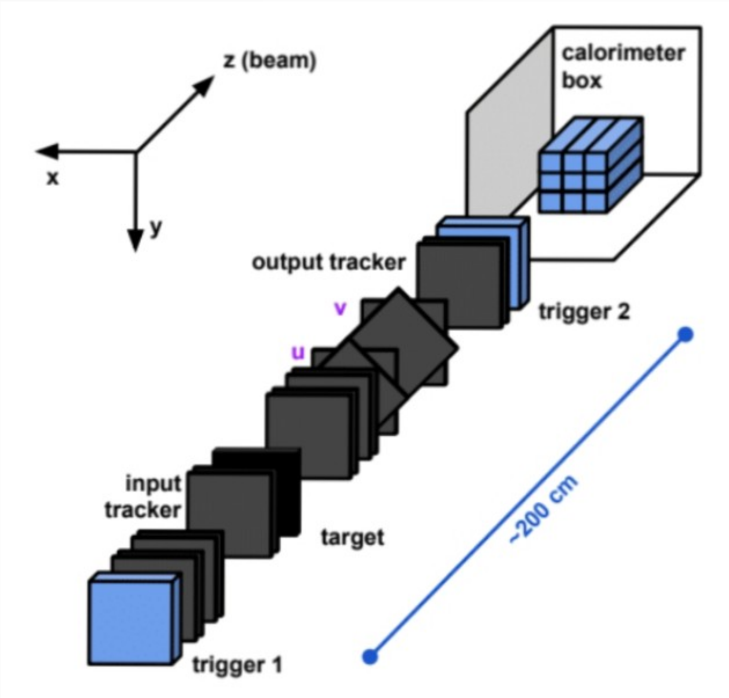
$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

Results show a ~1% agreement between data and MC for the Gaussian core



Test Beam 2018

Abbiendi et al, JINST 16 (2021) P06005



First evidence of elastic scattering.

- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. 2.1x2.1cm², 23 cm length