Status of the MUonE experiment

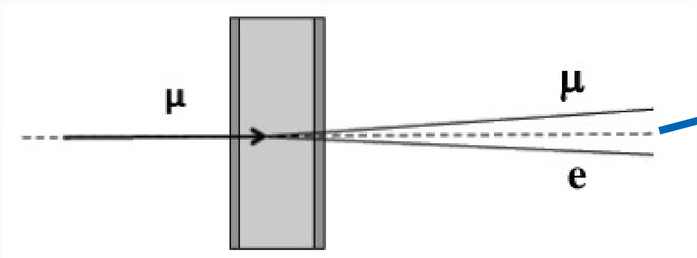
Riccardo Nunzio Pilato
University and INFN Pisa

for the MUonE Collaboration

The 5th Plenary Workshop of the Muon g-2 Theory Initiative
University of Edinburgh, September 9, 2022

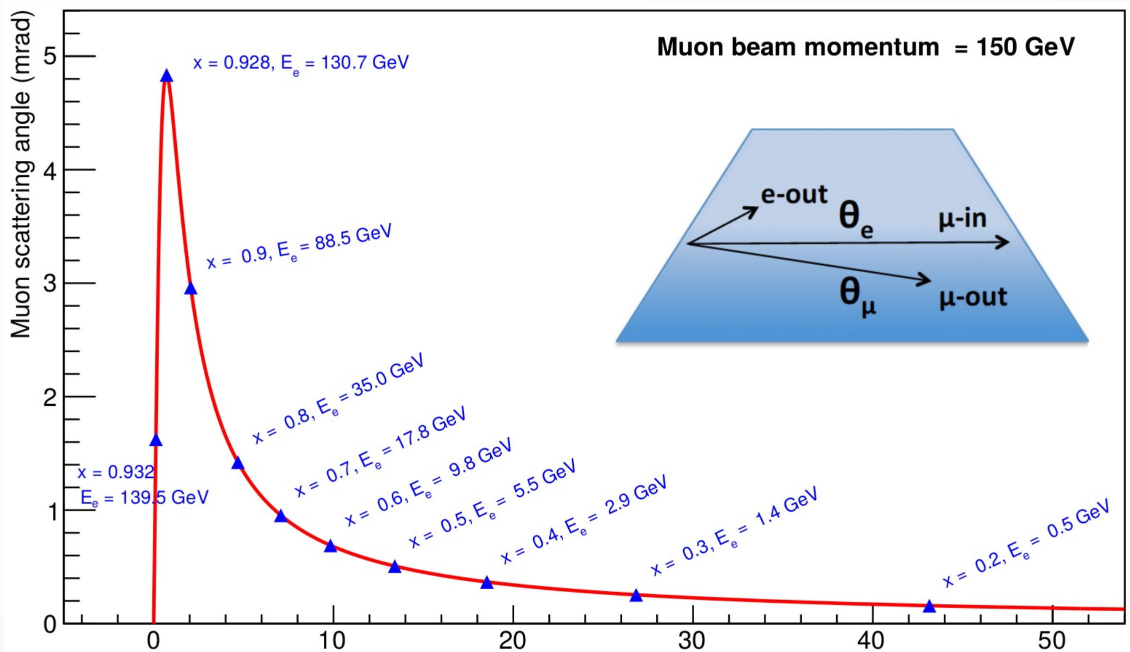
The MUonE experiment

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



$$\underbrace{\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)}}_{\text{From theoretical calculation}} \sim 1 + \underbrace{2\Delta\alpha_{\rm had}(t)}_{\text{To be measured}}$$

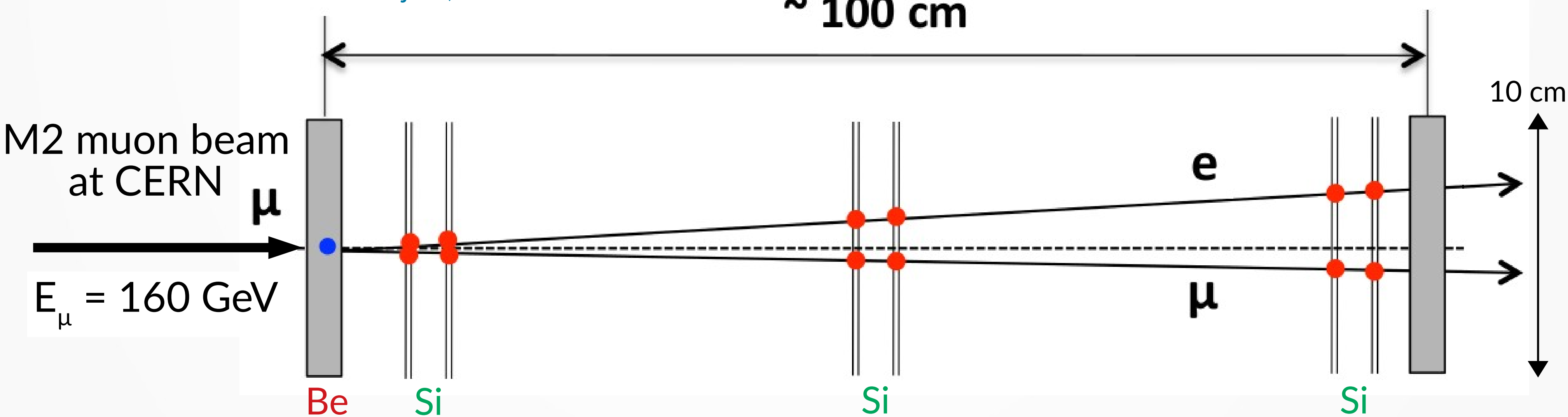
- A beam of 160 GeV muons allows to get the whole $a_\mu^{\rm HVP}$ (88% directly measured + 12% extrapolated).
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics:
  $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



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

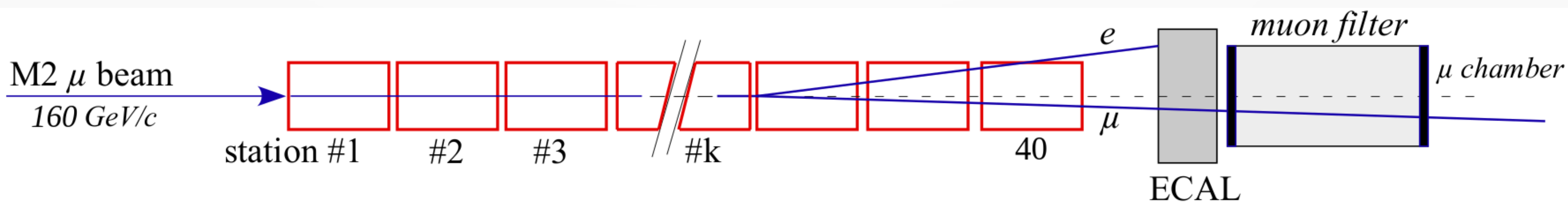
The experimental apparatus

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



Beryllium target
1.5 cm thickness

Tracking system: 3 pairs of
silicon strip detectors



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking ($\sim 4\times10^7$ s) ($I_\mu \sim 10^7\ \mu^+/s$) $\sim 4\times10^{12}$ events with $E_e > 1$ GeV = $\boxed{\sim 0.3\%\text{ statistical accuracy on } a_\mu^{HVP}}$

Competitive with the latest theoretical predictions.

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

Systematic uncertainty of 10 ppm at the peak of the integrand function (low θ_e, large θ_μ)

Main systematic effects:

- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (~1%)
- Angular intrinsic resolution (few %)

$\Delta\alpha_{had}$ parameterization

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

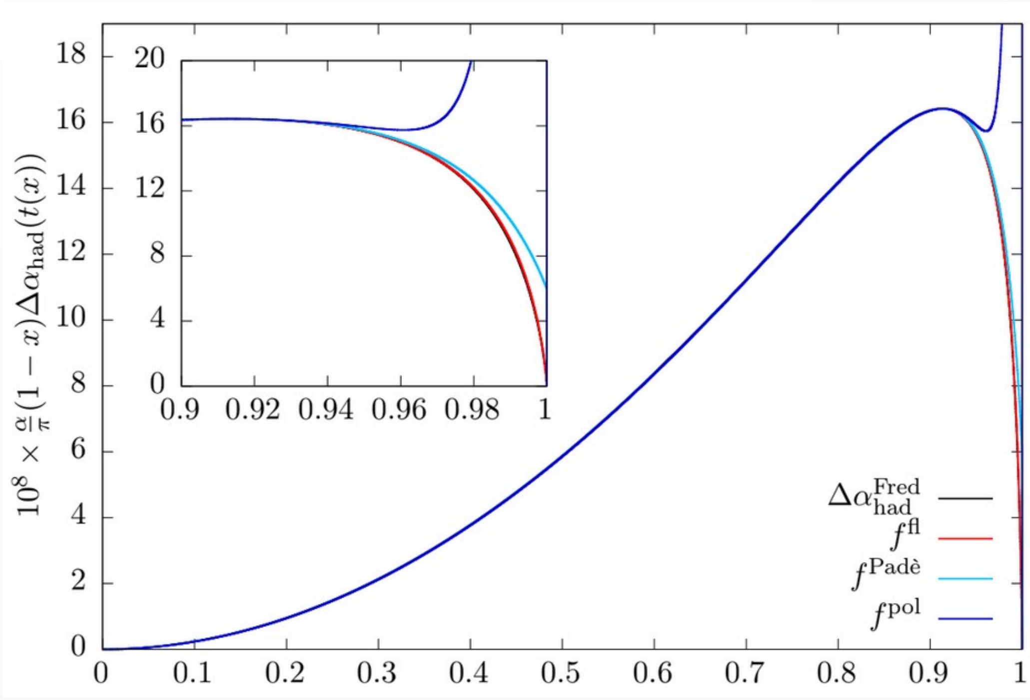
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters:
K, M

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

Dominant behaviour in the
MUonE kinematic region:

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



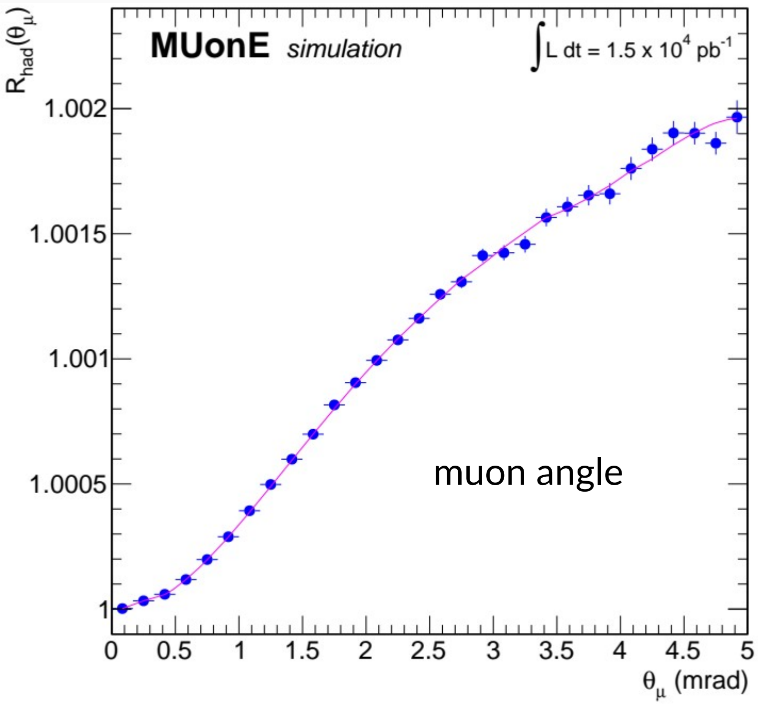
Extraction of a_μ^{HVP}

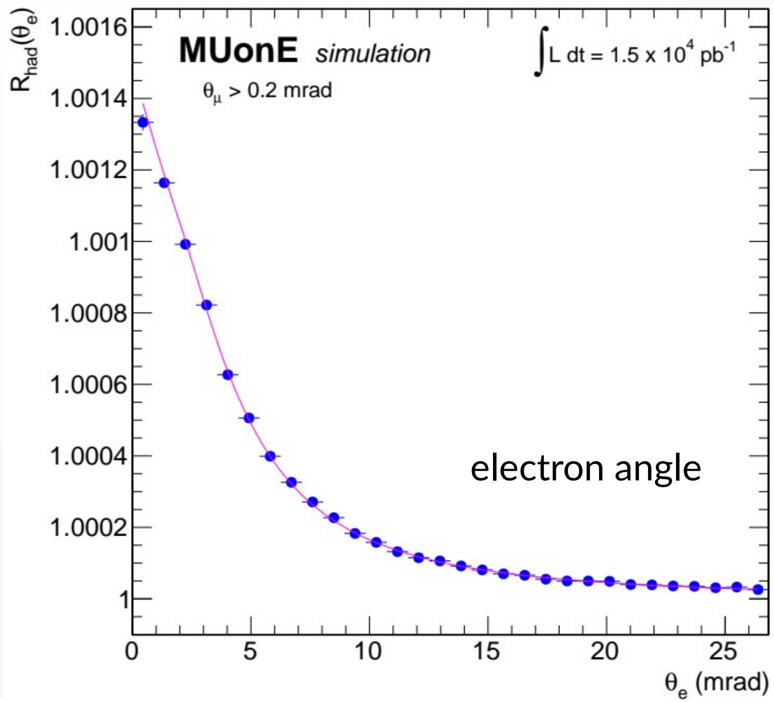
Extraction of $\Delta\alpha_{\mathrm{had}}(t)$ through a template fit to the 2D (θ_e, θ_μ) distribution

Results from simulation: $a_\mu^{\mathrm{HVP}} = (688.8 \pm 2.4) \times 10^{-10}$

Input value (FJ): $a_\mu^{\mathrm{HVP}} = 688.6 \times 10^{-10}$

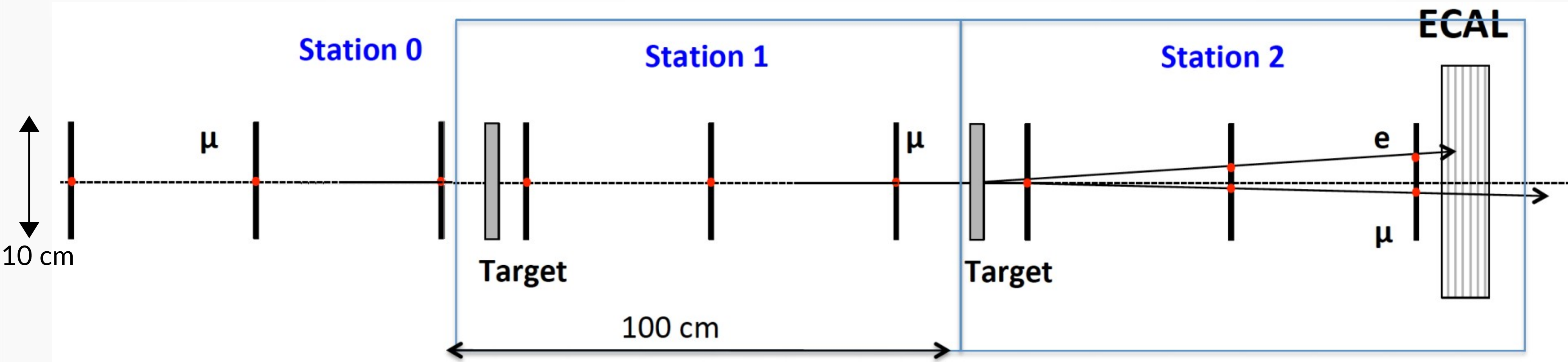
$$R_{had} = \frac{d\sigma(\Delta\alpha_{had})}{d\sigma(\Delta\alpha_{had} = 0)}$$





Test Run

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



Main goals:

- Pretracker +
- 2 MUonE stations +
- ECAL

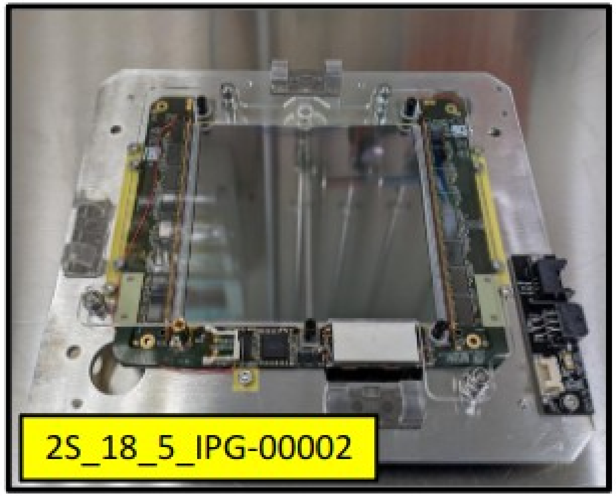
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the systematic errors.
- Initial sensitivity to $\Delta\alpha_{\mathrm{had}}(t)$.
- Possible measurement of $\Delta\alpha_{\mathrm{lep}}(t)$.

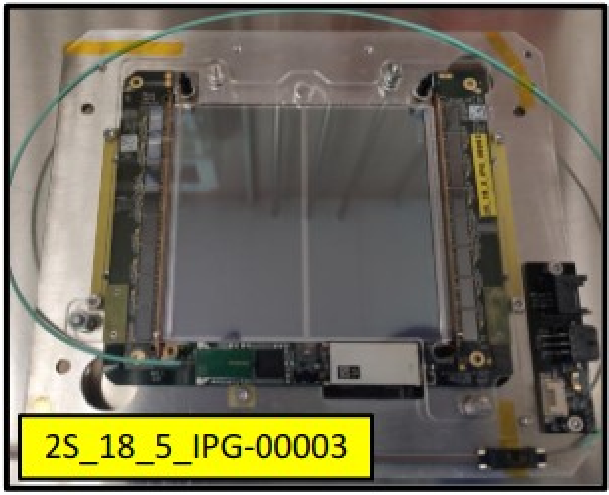
Tracker: CMS 2S modules

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

Two close-by strip sensors reading the same coordinate:

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



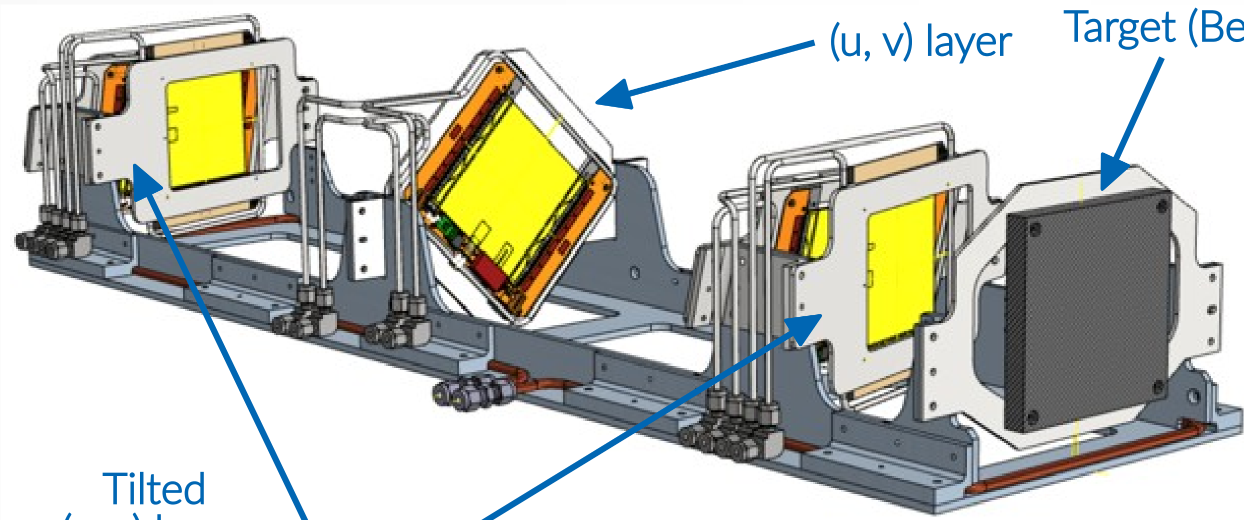


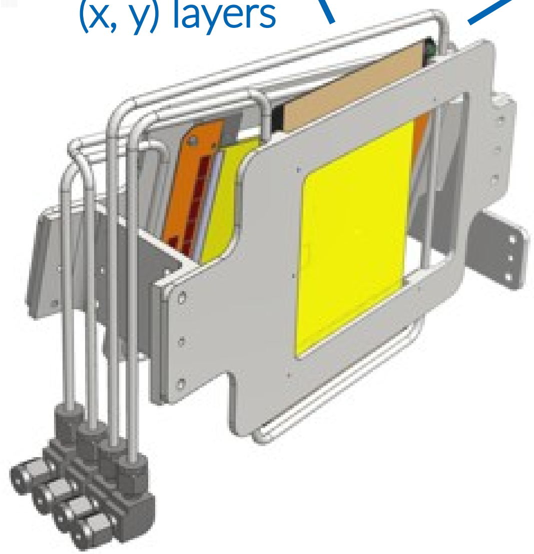
Four 2S modules assembled by CMS Perugia assembly center for MUonE.

- Thickness: 2 × 320 μm
- Pitch: 90 μm (σ_x ~ 26 μm)
- Readout rate: 40 MHz
- Sensitive area: 10×10 cm^2

Modules performance to be tested in real beam conditions during Beam Test 2022 campaign.

Tracking station





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

Low CTE material:
INVAR (CTE ~ $1.2\times10^{-6}\ K^{-1}$)

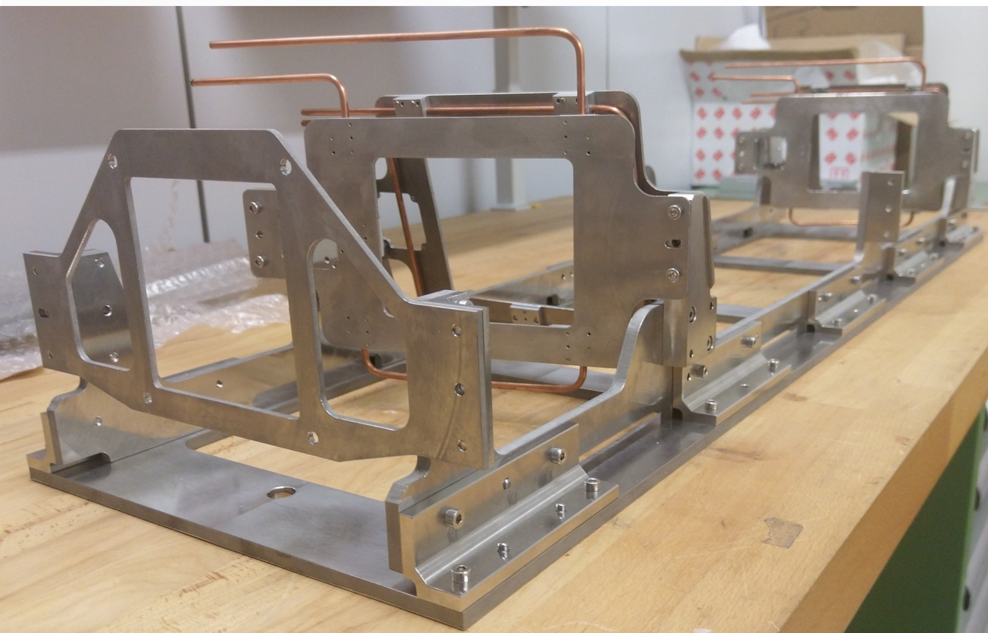
Laser holographic system to monitor stability.

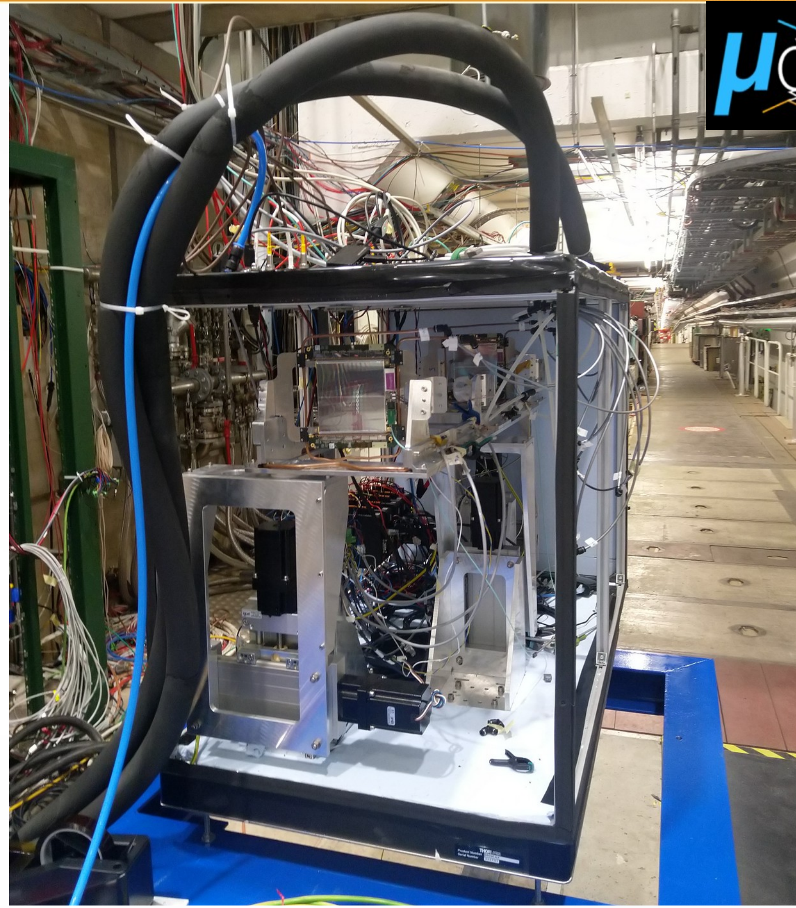
- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
    - Simulation studies show a resolution of ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

Tracking station: status readiness

2 Aluminum stations assembled:

- One at CERN, currently in use at the Beam Test.
- One at INFN Trieste, to test the holographic system.



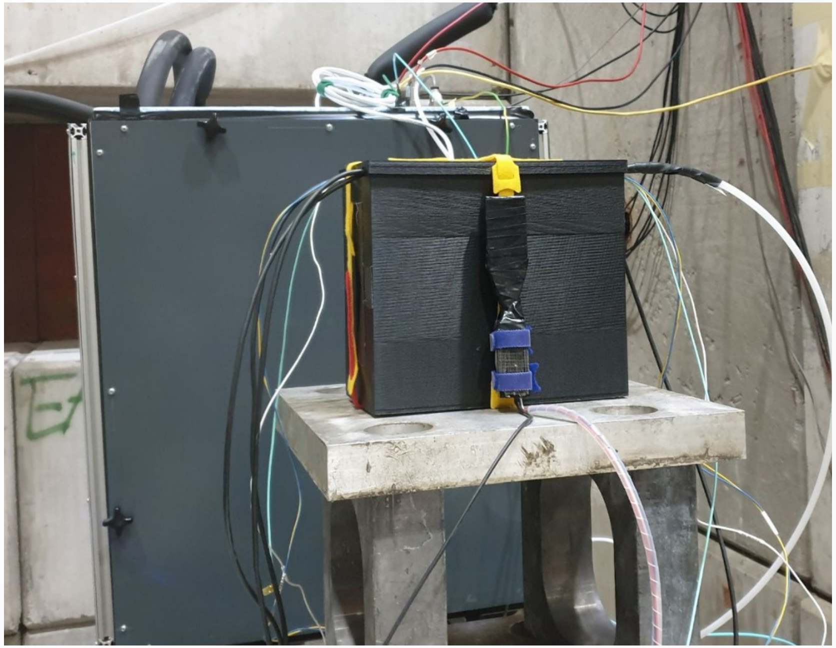


2 INVAR stations completed. Will be shipped to CERN next week.

Beam Test 2021

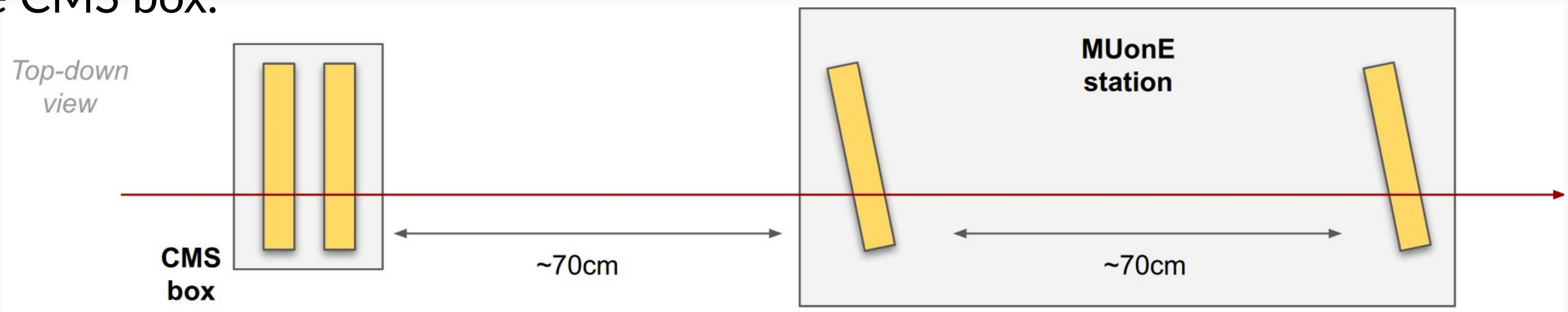
Parasitic beam test at M2 beam line,
3 weeks in October/November 2021

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



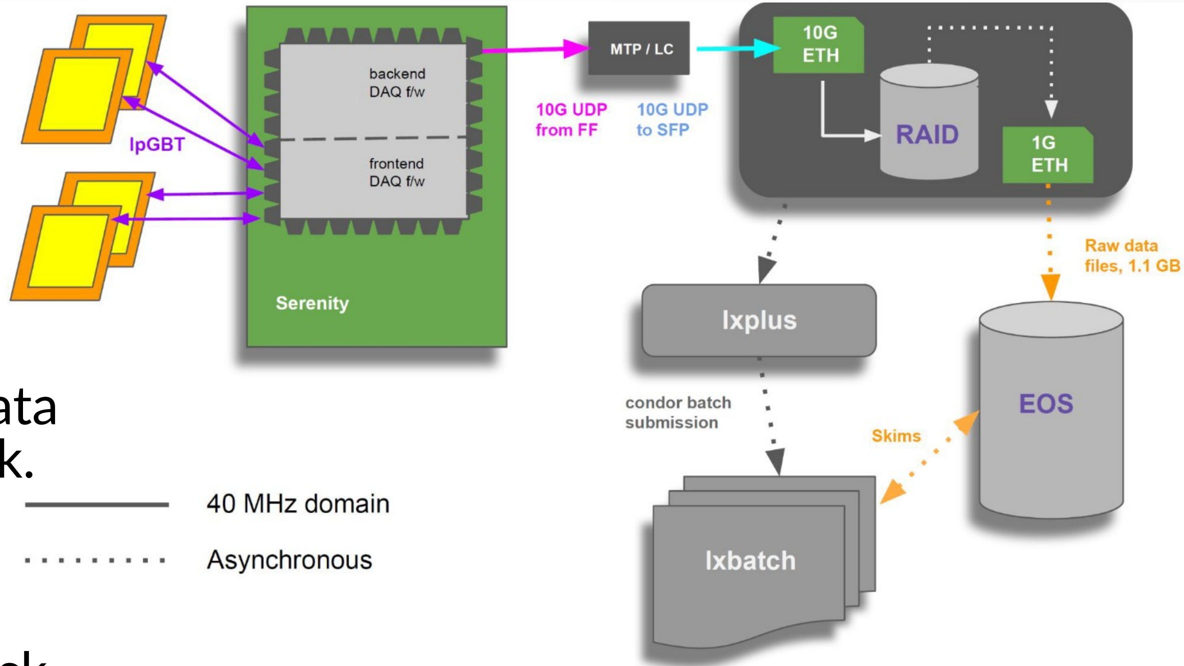
Four 2S modules tested in beam:

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

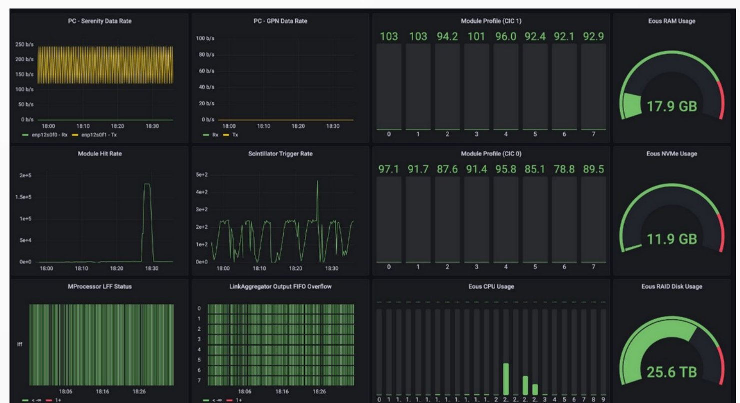


Beam Test 2021

First demonstration of the full DAQ chain with the M2 asynchronous beam



- Continuous stream of 40 MHz data from 2S modules captured to disk.
- Reliable readout over >6h runs.
- 30 TB of raw data collected to disk, ~1 TB after empty packets removal (low beam rate).
- Offline analysis ongoing: check data integrity and modules synchronization, beam behaviour, track reconstruction...

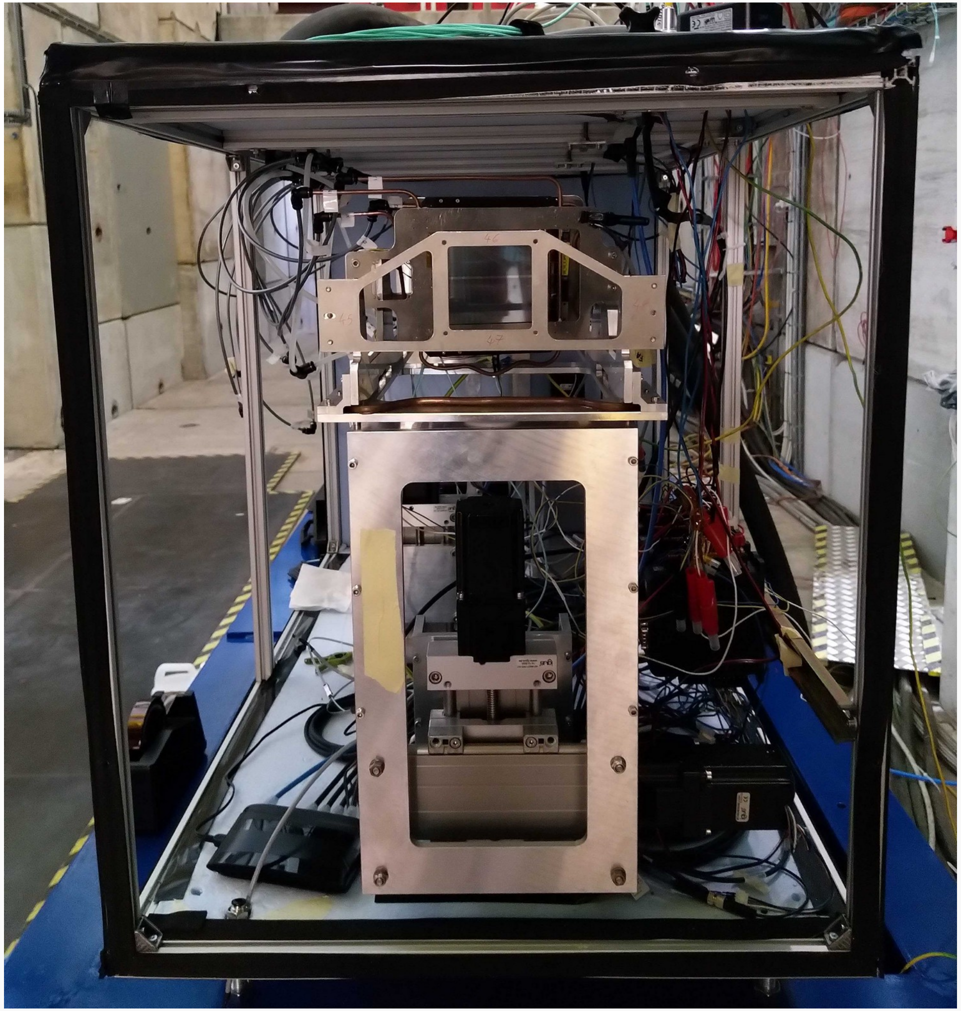


Beam Test 2022

- Joint test with CMS Tracker.
- M2 beam line upstream of Compass (final MUonE location).
- June/October: Opportunity to run for ~48h while Compass (main user) is not using the beam.
- Trolley installed to insert/remove our station from beam.
- 1 week as main users in October.

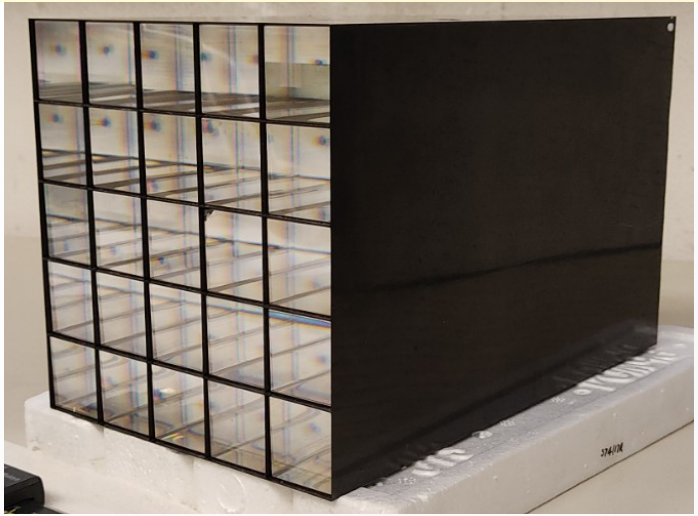
Beam Test 2022

- Continue commissioning of the first tracking station with high rate beam:
  - Study performances of 2S modules and DAQ stability.
- Add a second station in October, to track the incoming muons:
  - Demonstrate DAQ scalability.
  - Offline track reconstruction and selection of elastic events. Validation of the Geant4 simulation.
  - First tests for software alignment.



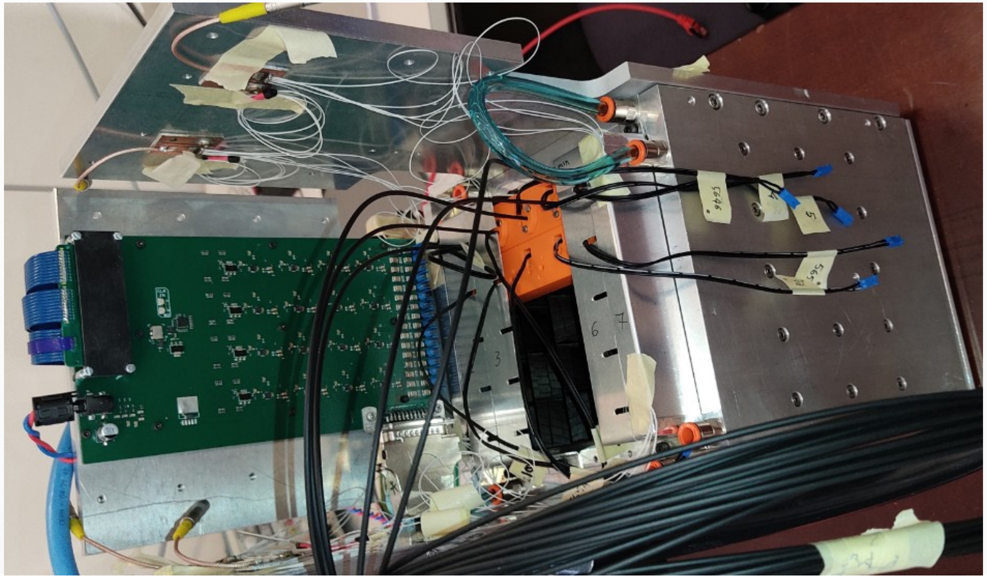
Calorimeter

- 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.



Beam Test: 20-27 July 2022, CERN East Area.

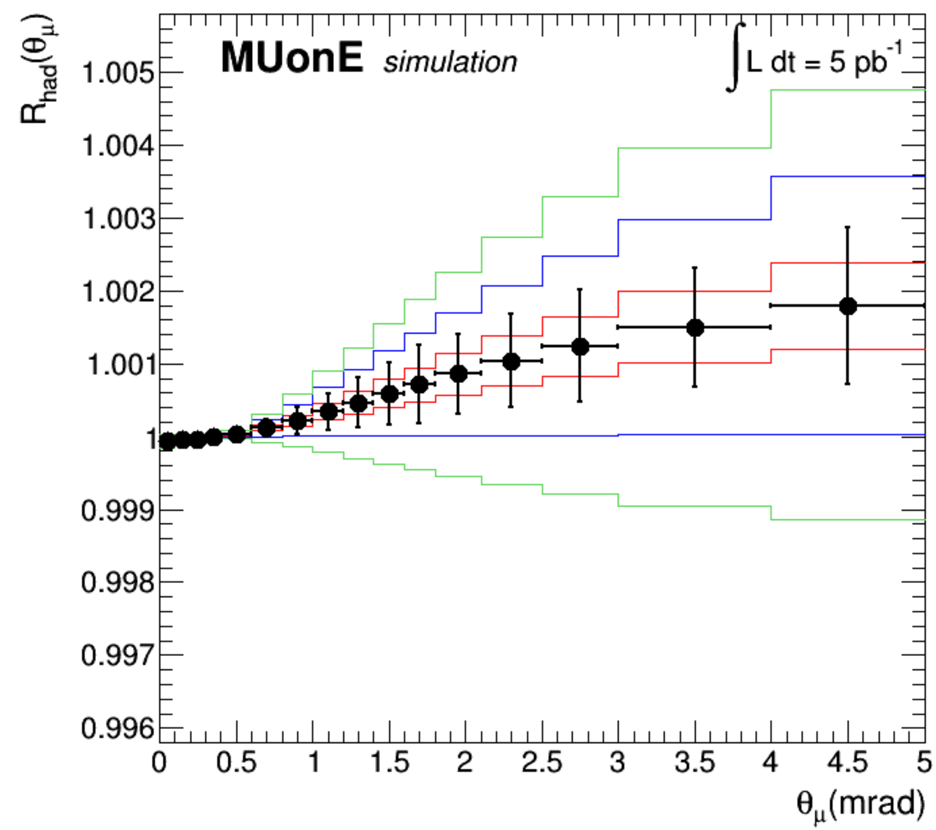
- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter being installed downstream of the tracking station at the M2 beam line.



Test Run: expected sensitivity on $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: L_{TR} = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 32 mrad)

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



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

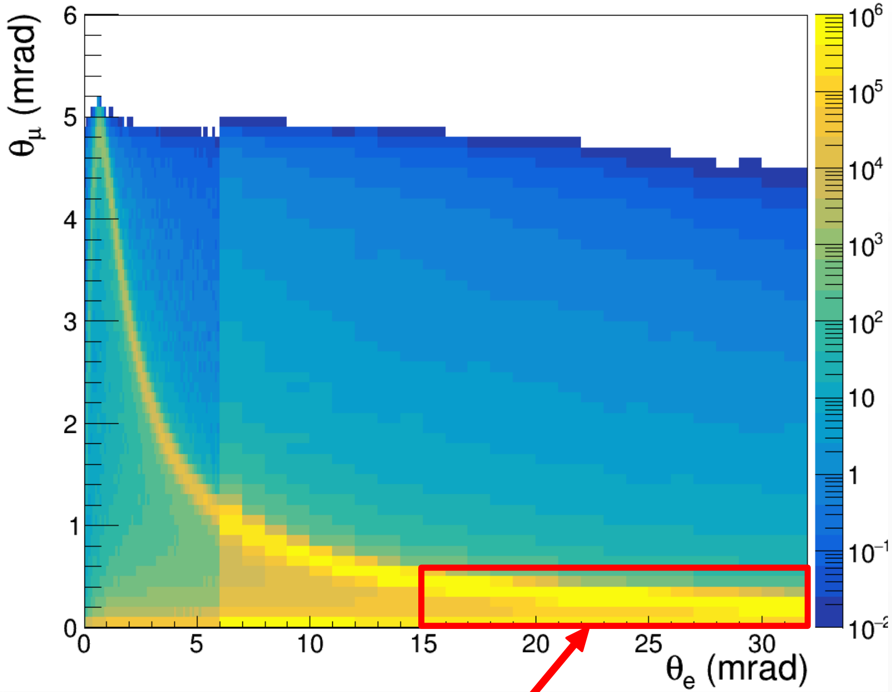
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$

K = 0.136 ± 0.026
(20% stat error)

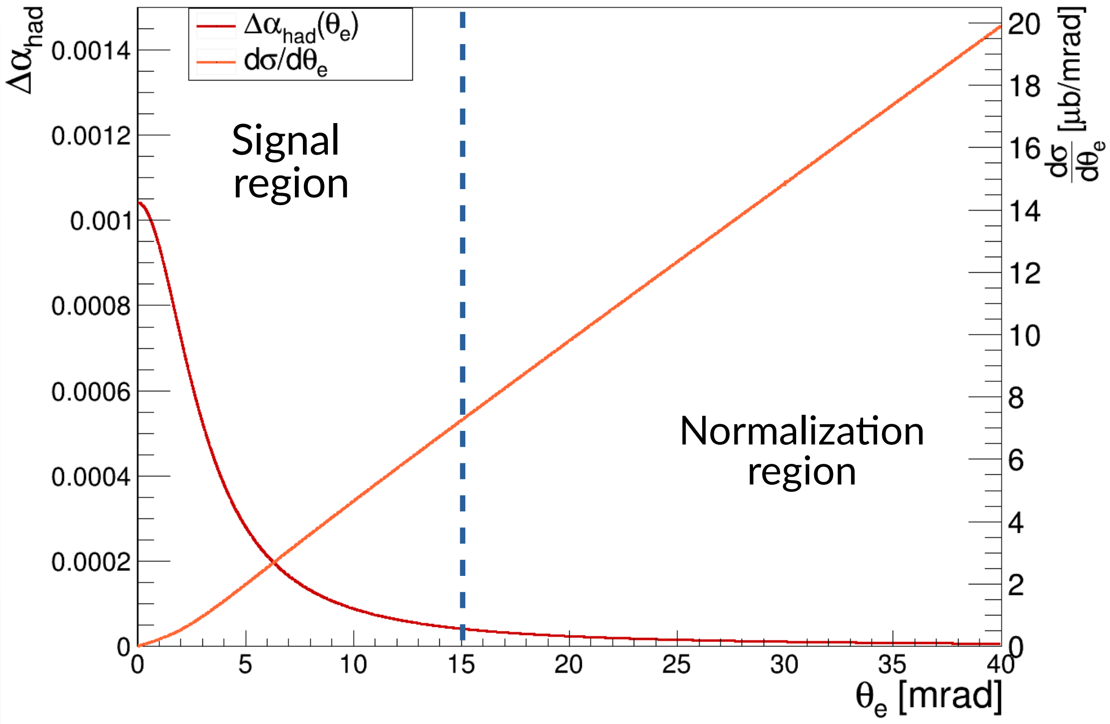
We will be sensitive to the leptonic running ($\Delta\alpha_{lep}(t) < 10^{-2}$)

Strategy for the systematic effects

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



Normalization region
Lots of events here!



Strategy for the systematic effects

Promising strategy: 2 steps workflow

1. Use normalization region to calibrate the larger systematic effects (beam energy, angular intrinsic resolution).

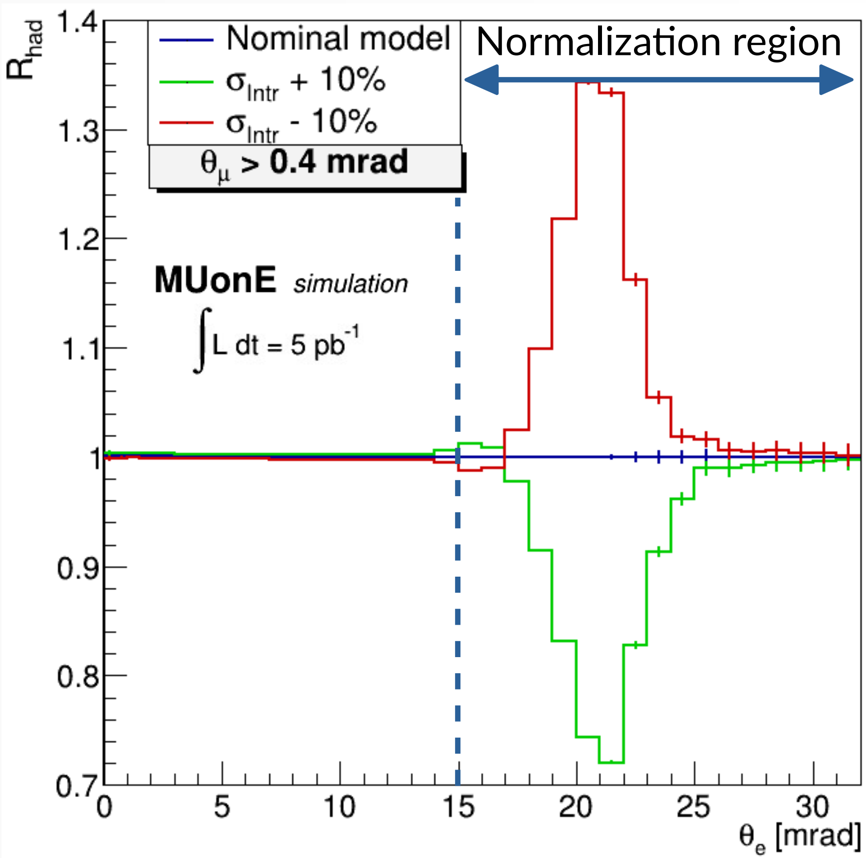
2. Include residual systematics as nuisance parameters in a combined fit with signal.

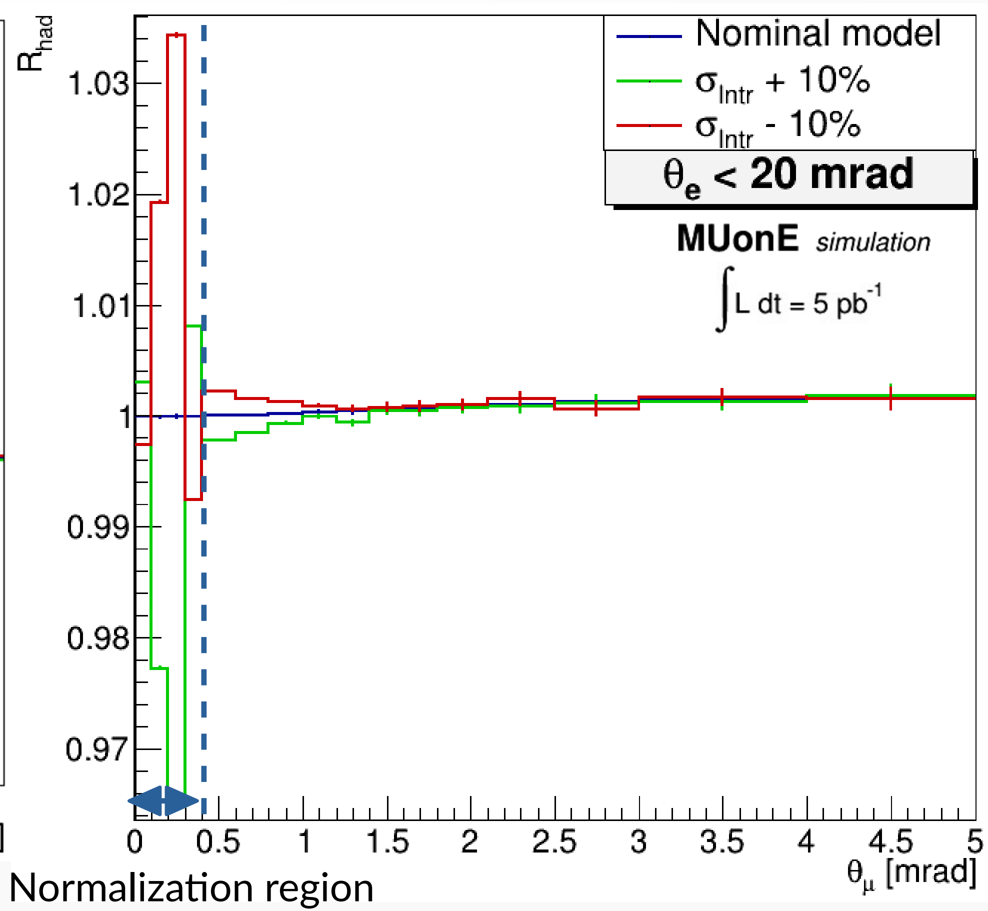
- MESMER MC + fast detector simulation to generate template distributions.
- Combine analysis tool to perform the combined likelihood fit to the signal + systematics.

https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/

Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution: huge effect.

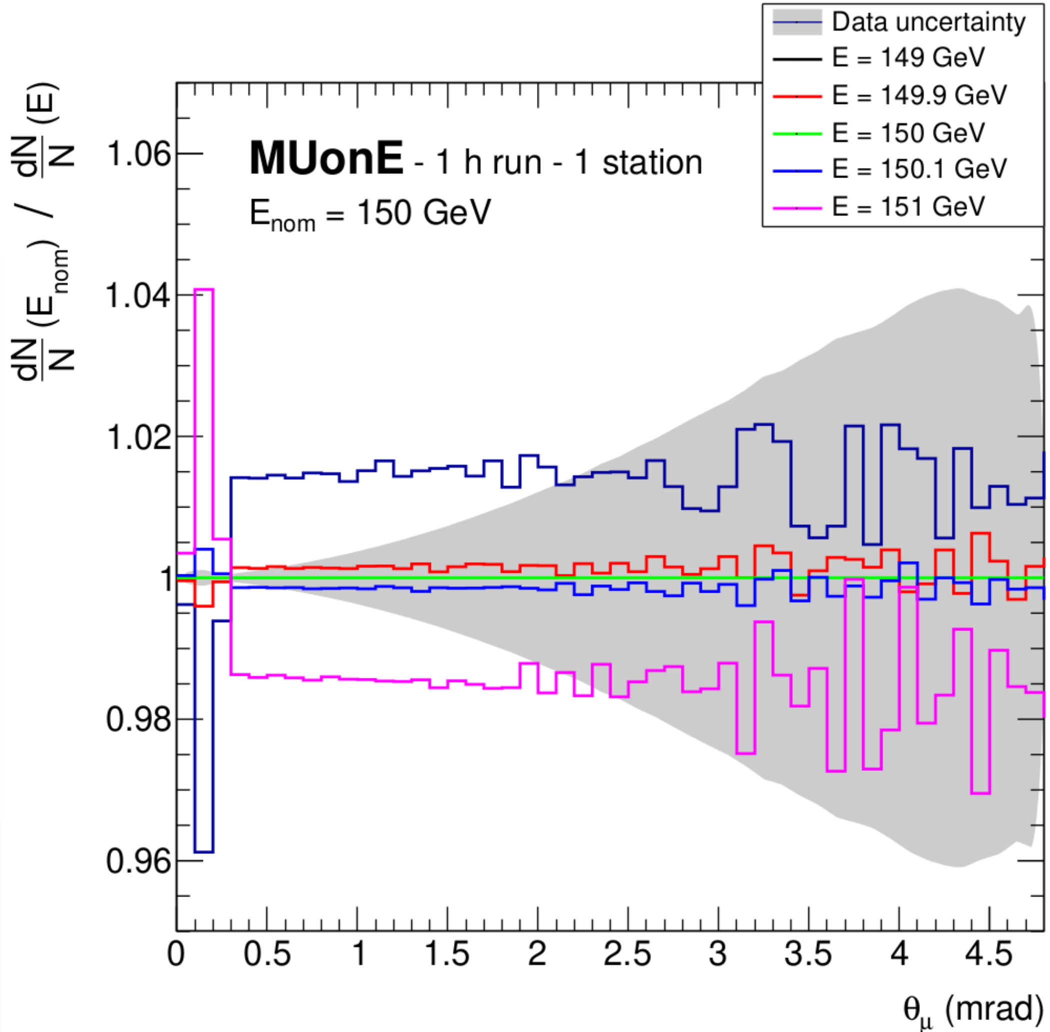




Systematic error on the muon beam energy

Accelerator division provides E_{beam} with O(1%) precision (~ 1 GeV).
It must be controlled by a physical process.

Effects of such shift on E_{beam} can be seen in our data in 1h of data taking per station.

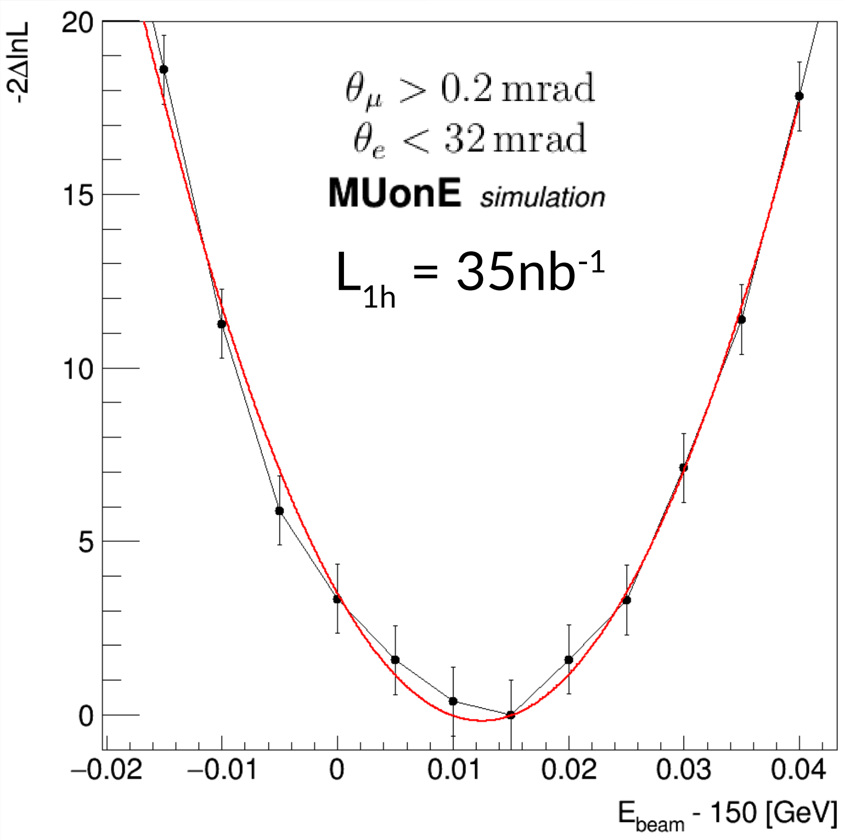


G Abbiendi Phys. Scr. (2022) 97 054007

Step 1: tuning larger systematic effects

Pseudo-data sample:

- E_{beam} = 150.012 GeV
- $\sigma_{Intr} \rightarrow$ + 5%



1h data taking per station to tune the main systematics

(assuming a fixed model for $\Delta\alpha_{had}$)

E_{beam}: template fit parameter

μ_{Intr}: nuisance parameter for intrinsic resolution systematics

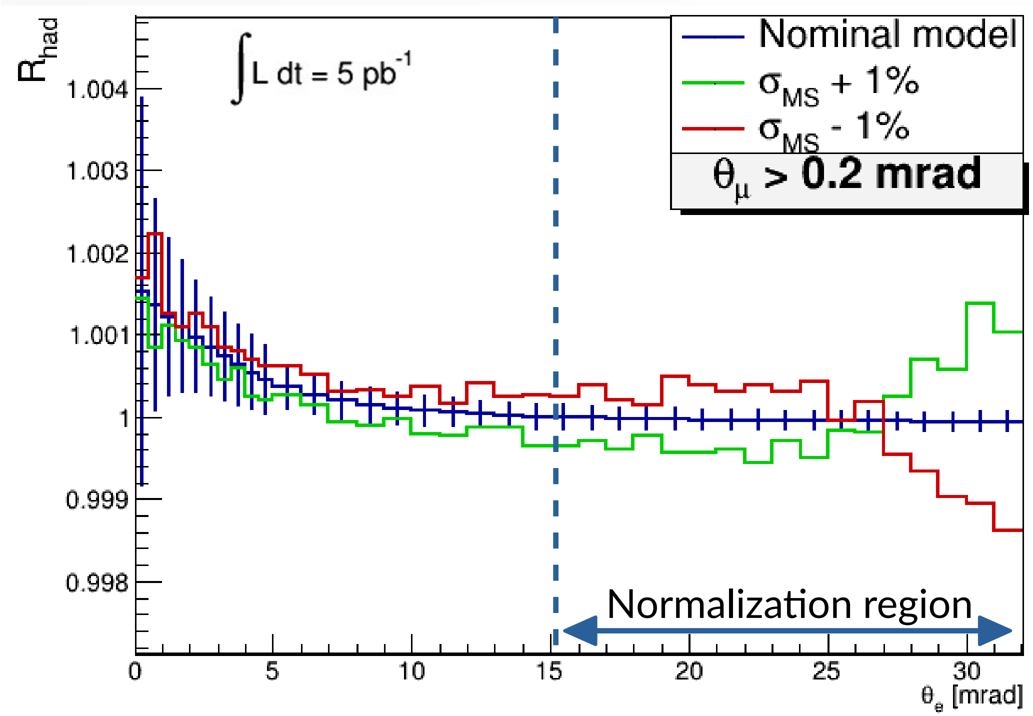
Selection cuts	Fit results
$\theta_\mu > 0.2\,\mathrm{mrad}$	$E_{Beam} = (150.012 \pm 0.007)$ GeV
$\theta_e < 32\,\mathrm{mrad}$	$\mu_{Intr} = (5.2 \pm 0.1)\%$

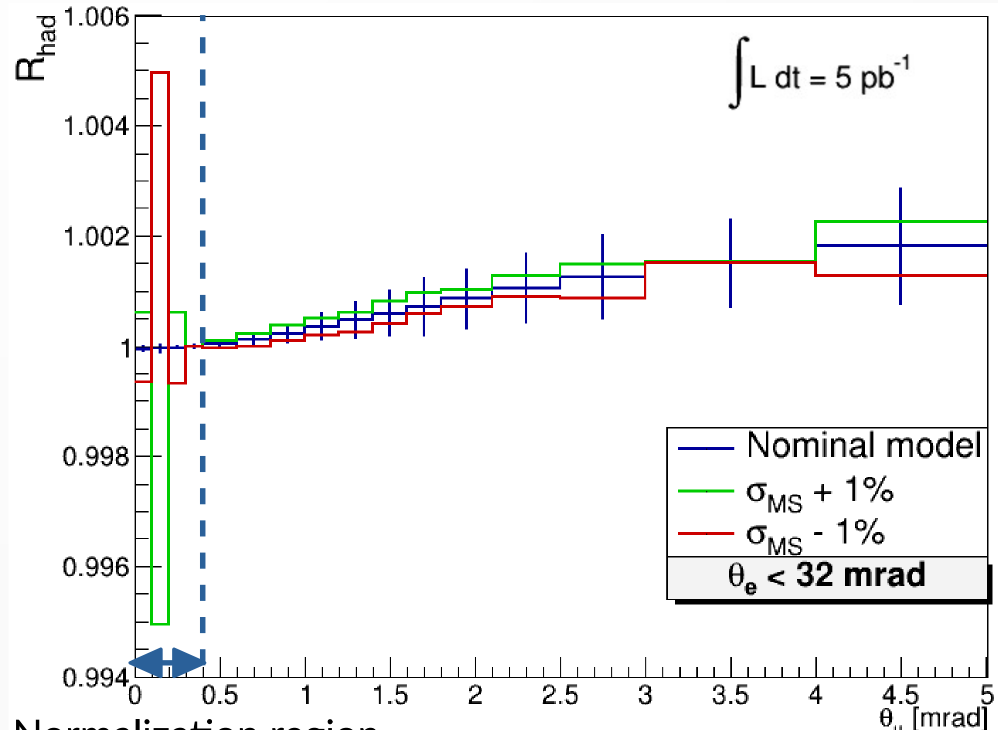
Similar results also for distributions with no PID.

Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

G. Abbiendi et al JINST (2020) 15 P01017





Normalization region

Step 2: combined fit signal + systematics

Pseudo-data sample:

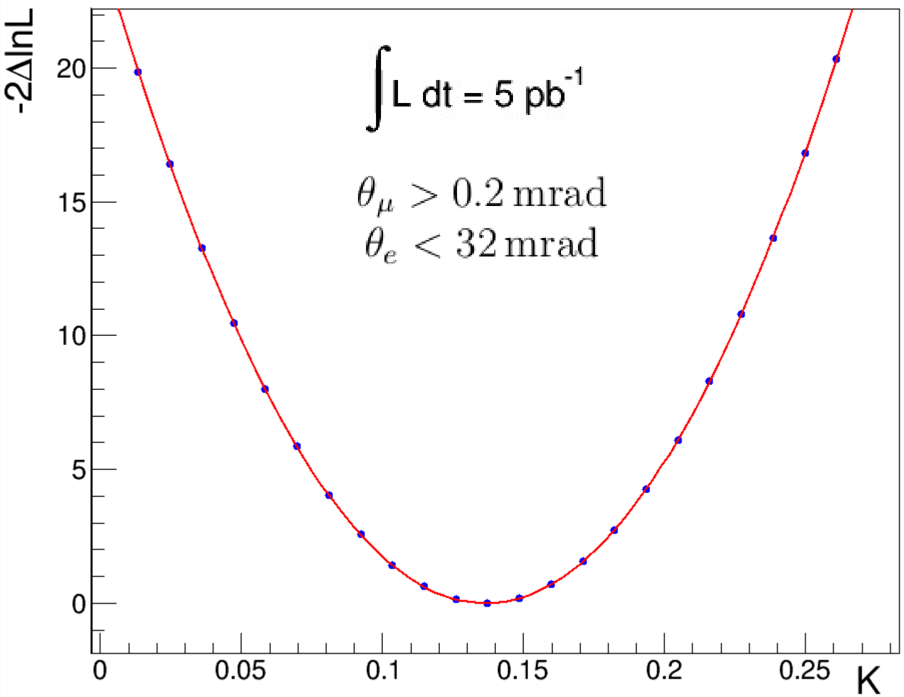
- $E_{beam} \rightarrow + 6$ MeV
- $\sigma_{Intr} \rightarrow + 5\%$
- $\sigma_{MS} \rightarrow + 0.5\%$

K : signal parameter

μ_{Ebeam} : nuisance parameter for beam energy

μ_{Intr} : nuisance parameter for intrinsic resolution

μ_{MS} : nuisance parameter for multiple scattering



Selection cuts	Fit results
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 32\,\mathrm{mrad}$	$K = 0.135 \pm 0.026$ $\mu_{E_{Beam}} = (5.9 \pm 0.5)$ MeV $\mu_{Intr} = (4.99 \pm 0.02)\%$ $\mu_{MS} = (0.51 \pm 0.03)\%$

Systematic effects identified with good precision.
No degradation on the signal parameter.

Work in progress to optimize the procedure.

Conclusions and future plans

Staged approach towards the full experiment:

- 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 3 tracking stations + calorimeter.
- Possibly 10 stations before LS3 (2026):
  ~2% (stat) measurement of a_μ^{HVP}
  in 4 months of data taking.

being formed, still growing up

CERN
Exp

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

Imperial College (London)
Liverpool U.
Exp-Th

Krakow IFJ Pan
Exp

Northwestern U.,
Virginia U.
Regis U.
Exp

Budker Inst. (Novosibirsk)
Exp

The MUonE Collaboration

Demokritos INPP (Athens)
Exp

Shanghai Jiao Tong U.
Exp

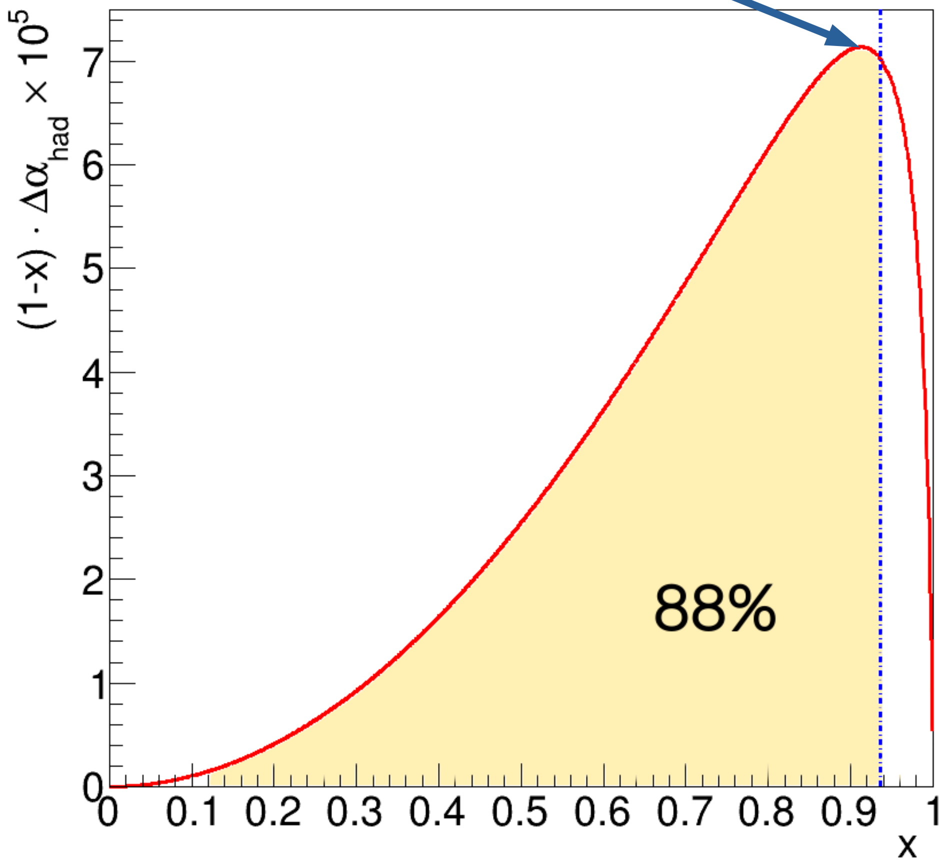
PSI (Villigen), ETH and U.Zürich
Th

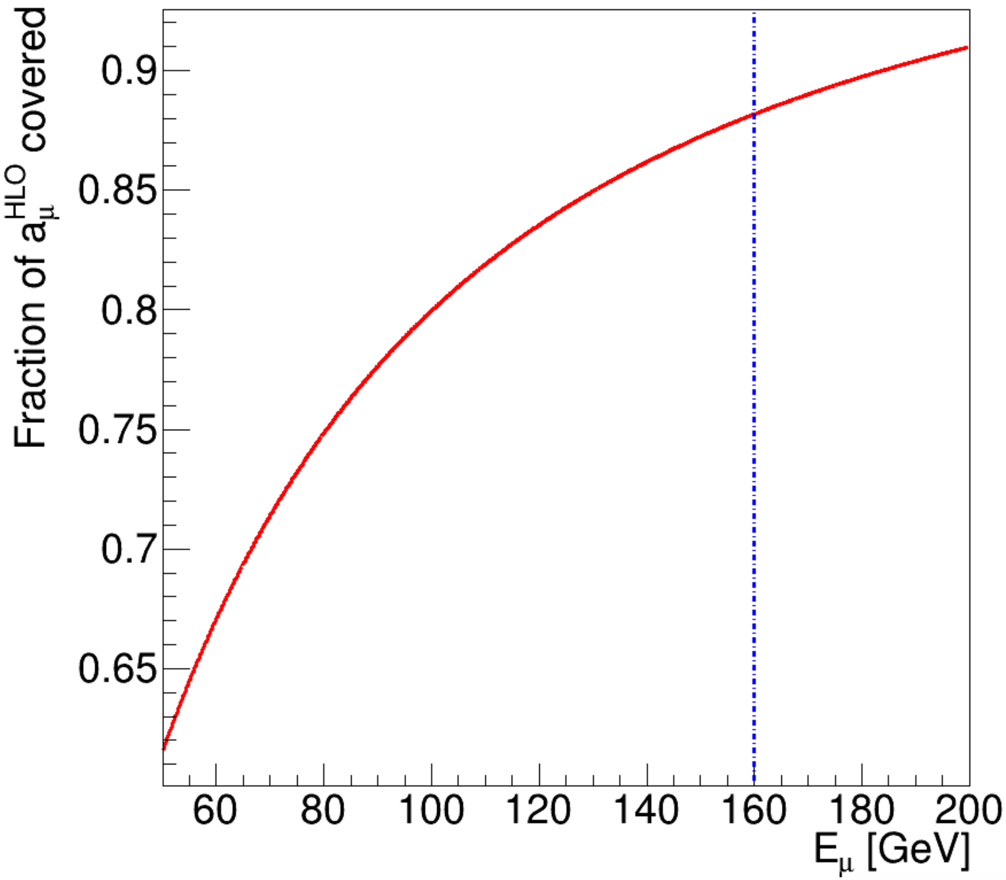
+ other involved theorists from: U.Valencia (E), KIT/Karlsruhe, Munich MPI (D), Durham U. (UK), New York City Tech (USA)

BACKUP

$x < 0.936$

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



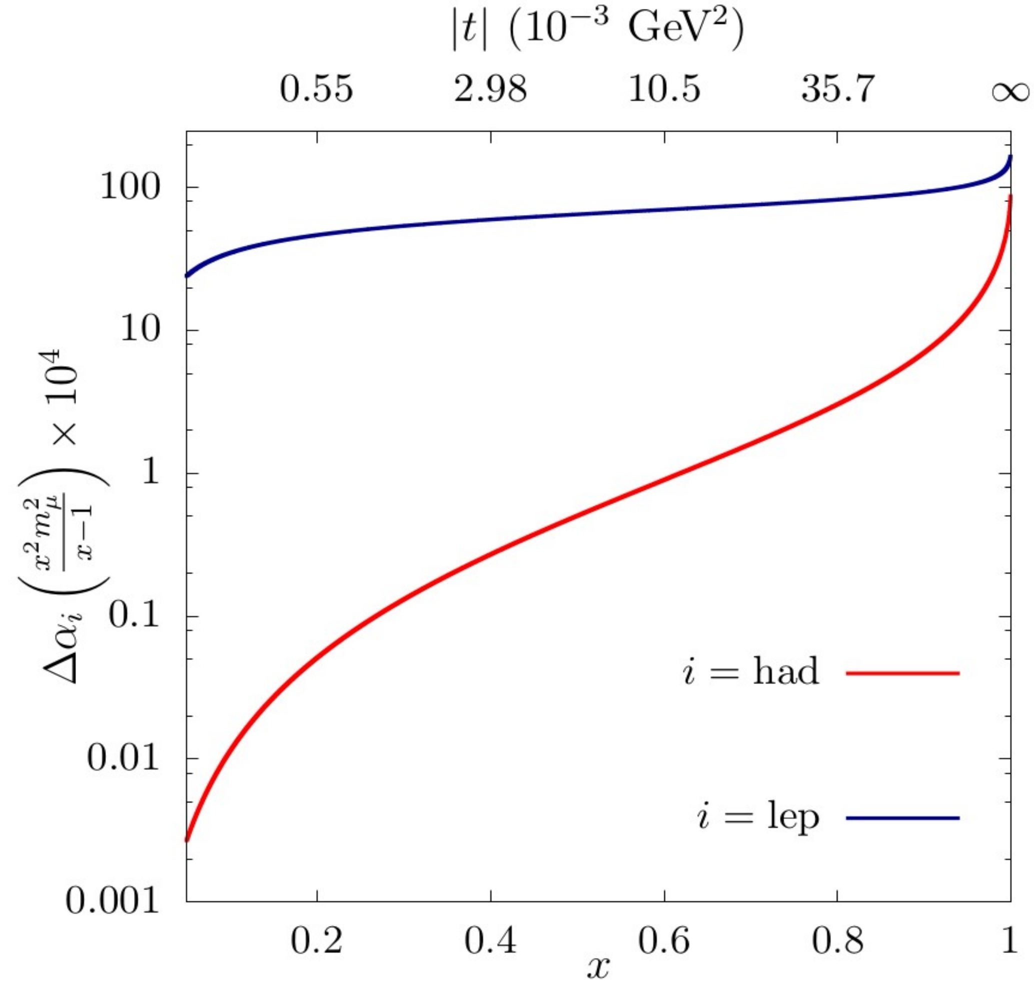


- 160 GeV muon beam on atomic electrons.

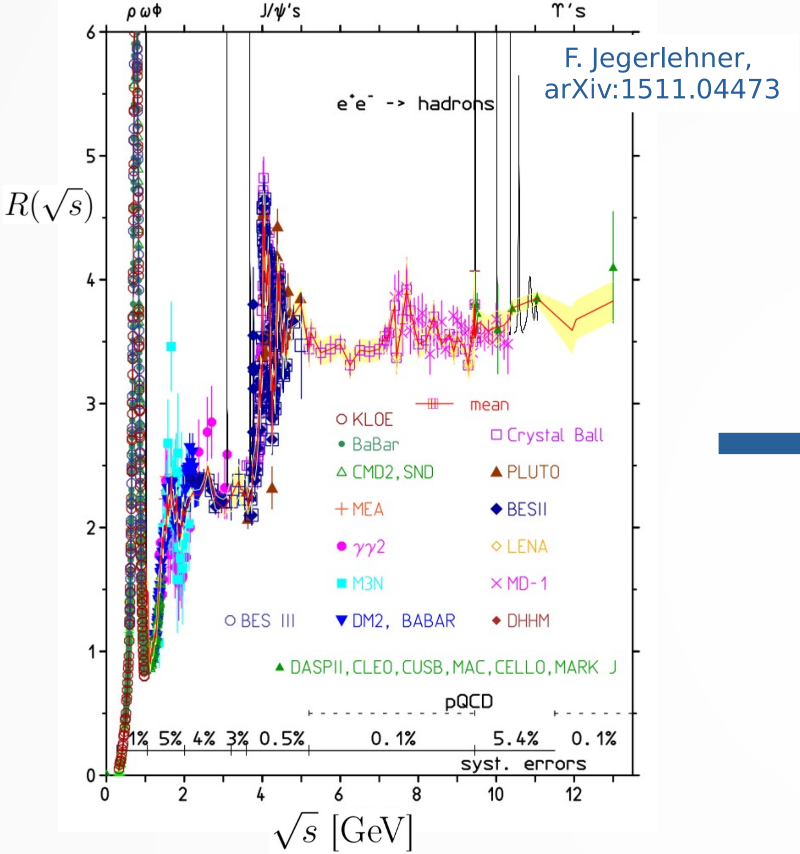
$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

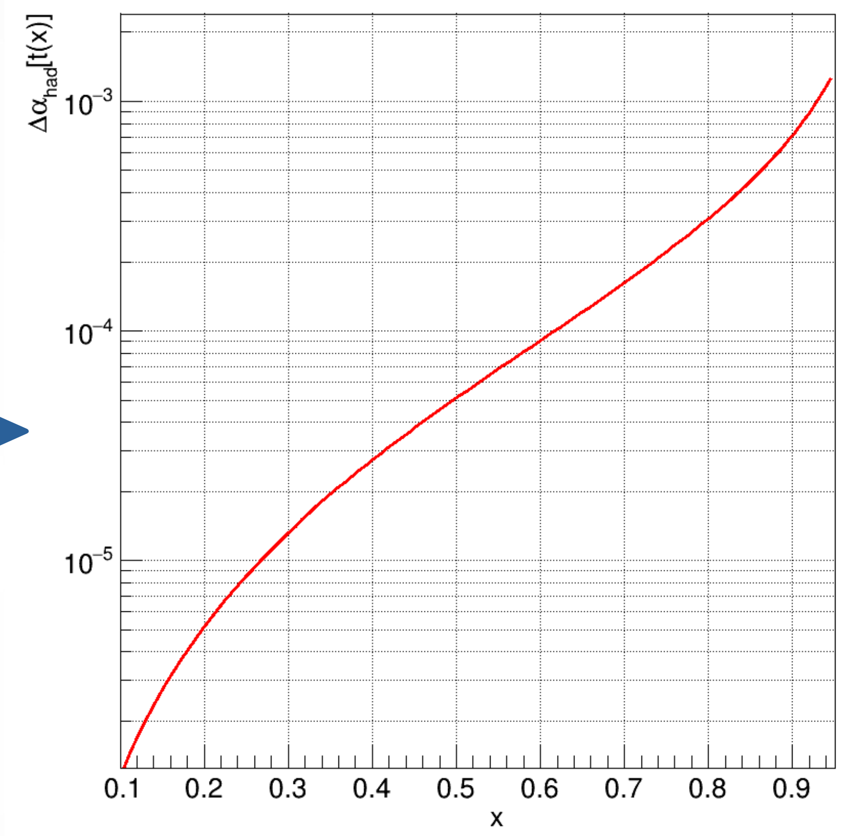
$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

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



From time-like to space-like



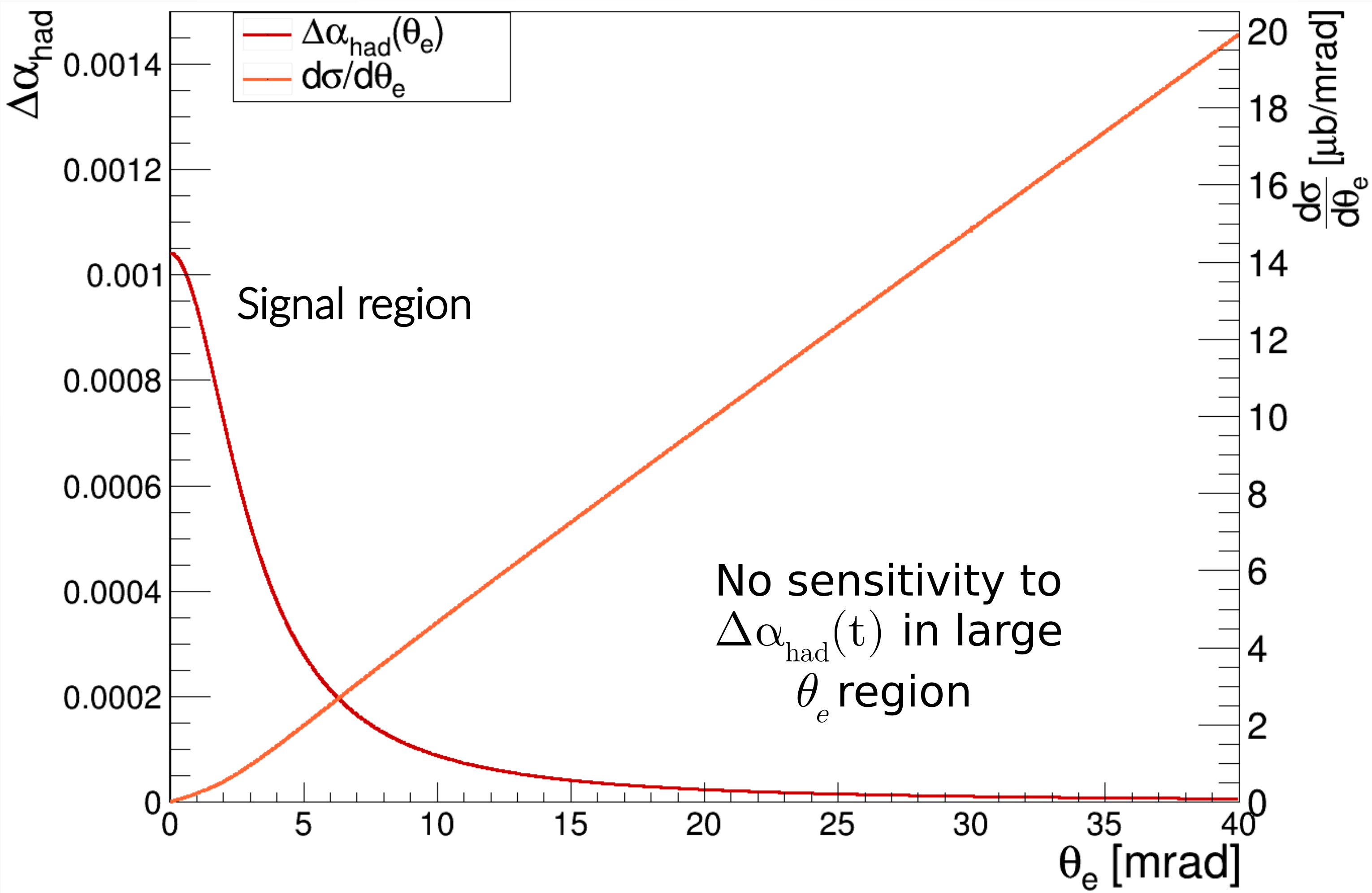


$$a_\mu^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

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

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

Extraction of $\Delta\alpha_{had}(t)$

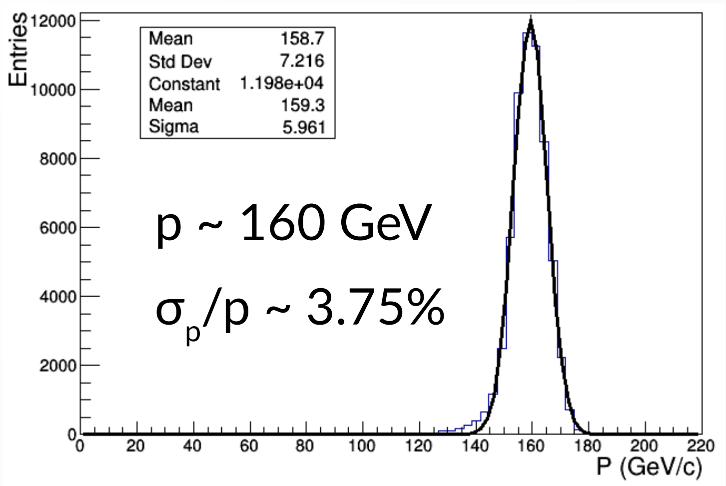


Last years progress

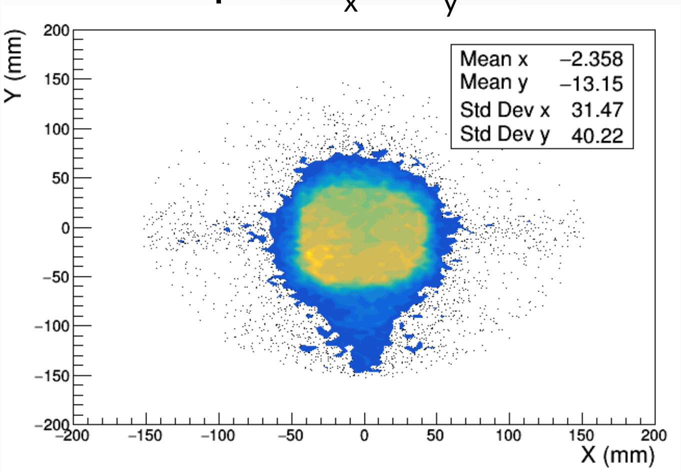
- Multiple scattering studies (TB 2017).
- Beam Test at M2 beamline in 2018:
  the first elastic scattering events.
- LOI submitted at SPSC in 2019, and 3 weeks Test Run approved.
- Detector optimization and assembly.
- Defining the analysis strategy.
- Intense Beam Test activities in 2021-2022:
  first experience with detector in real beam conditions.

Location: M2 beam line at CERN

Beam momentum



Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm



- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 3×10^8 μ^+/spill).

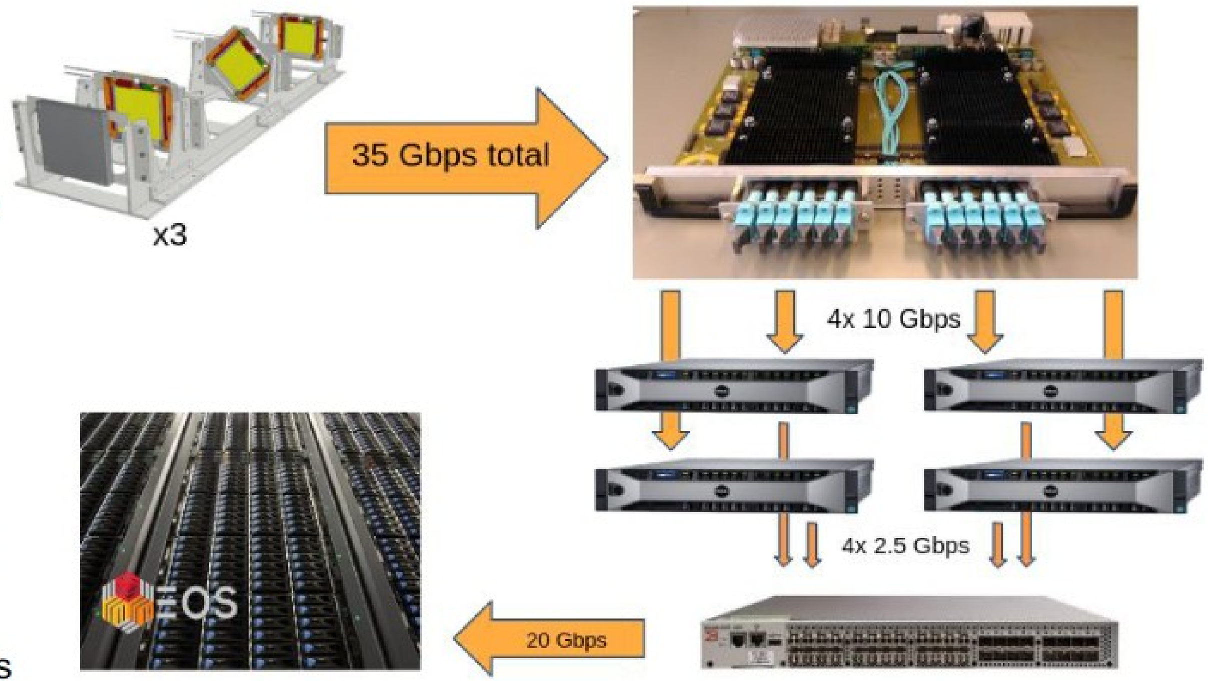
BE-DAQ architecture

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

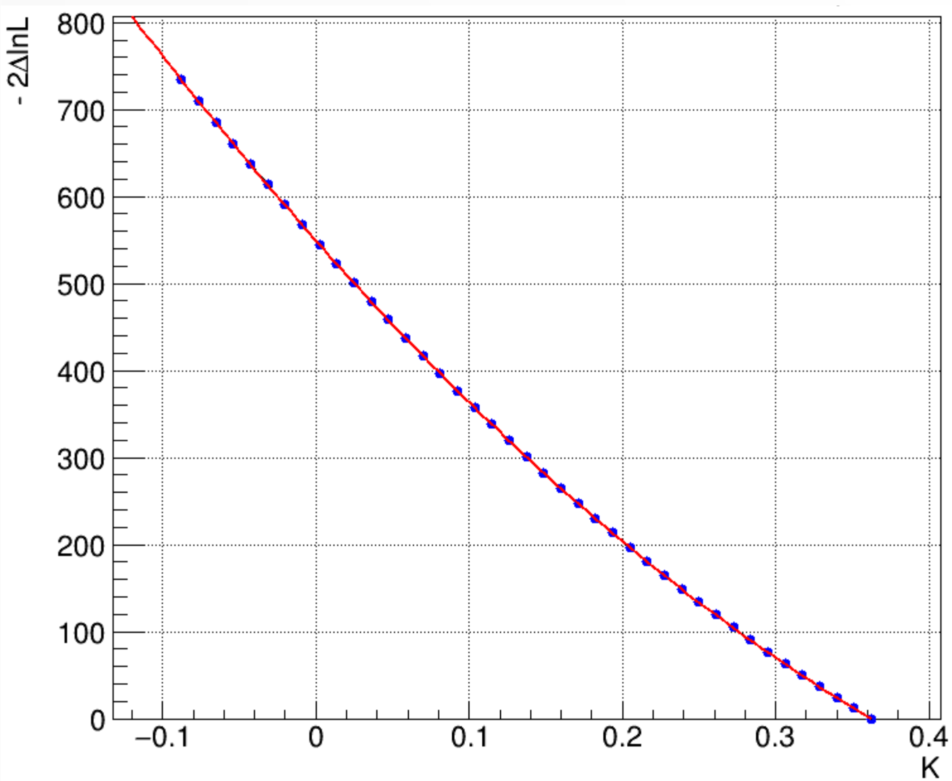
- Book-keep empty frames but do not forward to switch
- From switch to EOS/CTA with 20 Gbps



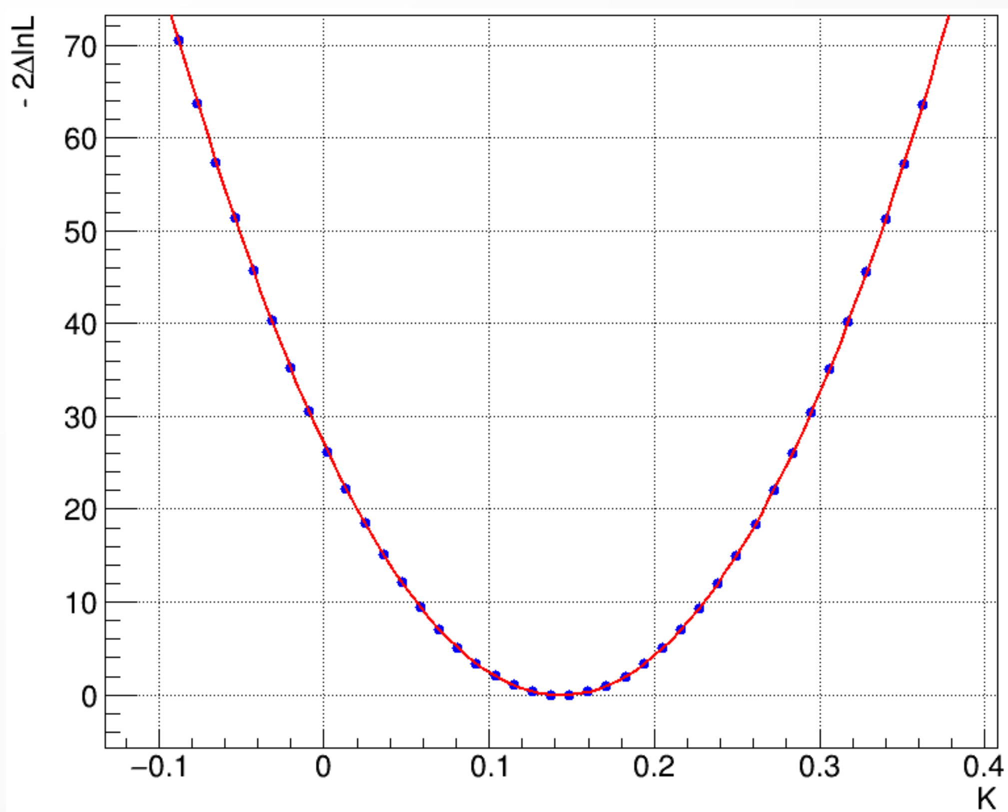
- Commissioning phase: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the future runs.

Simultaneous fit signal + nuisance parameters @L_{TR}

If the systematics are not taken into account in the fit...

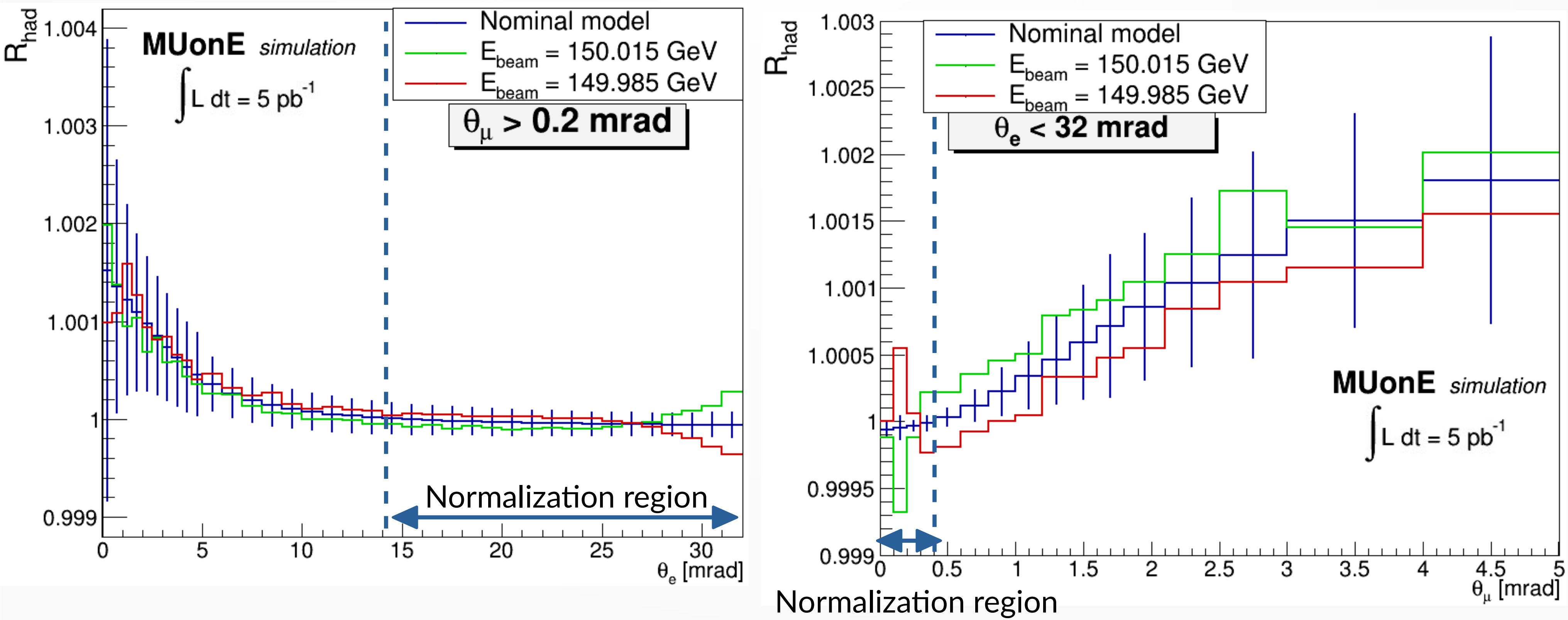


If the nuisance parameters are introduced in the fit procedure...



Systematic error on the beam energy scale

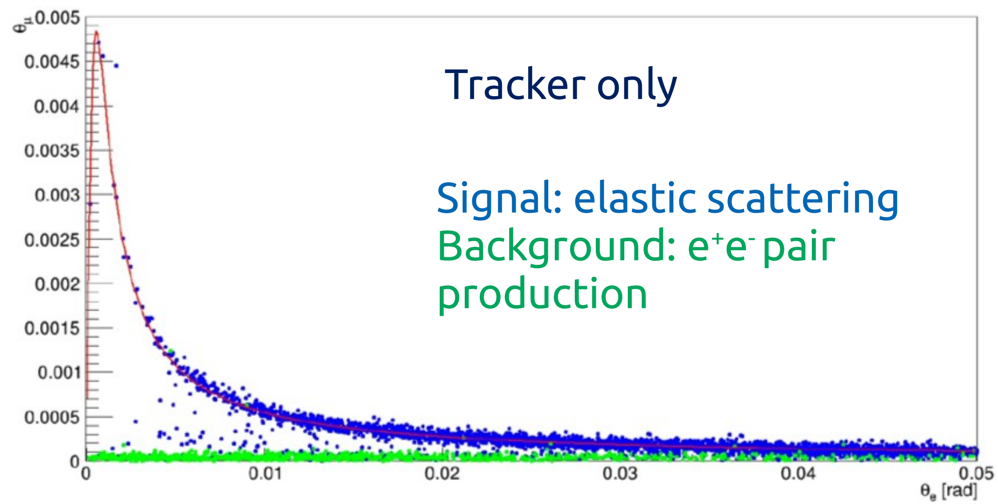
Effect of a ± 15 MeV shift

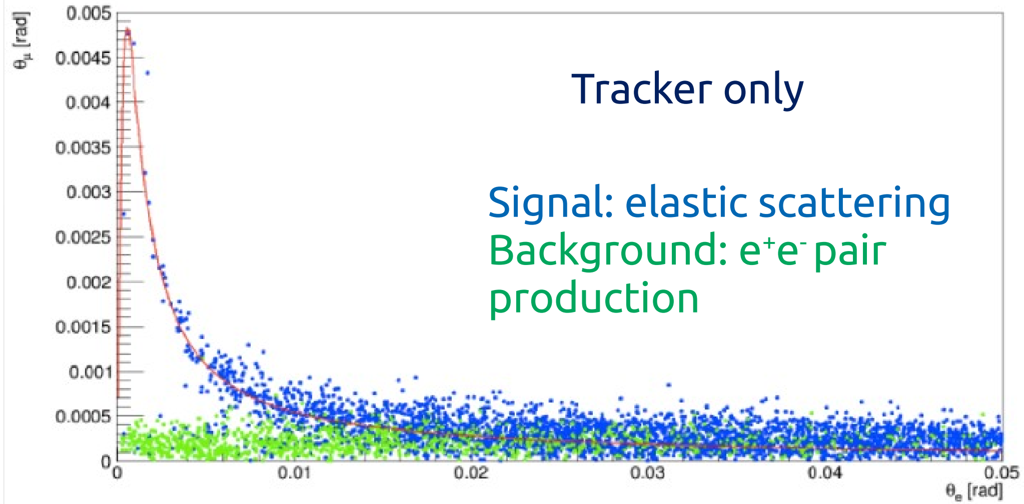


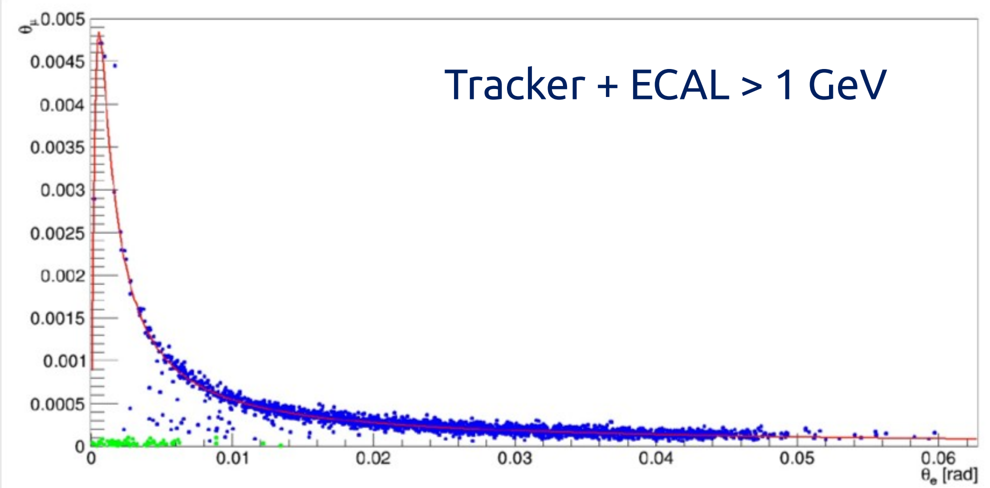
GEANT4 simulations

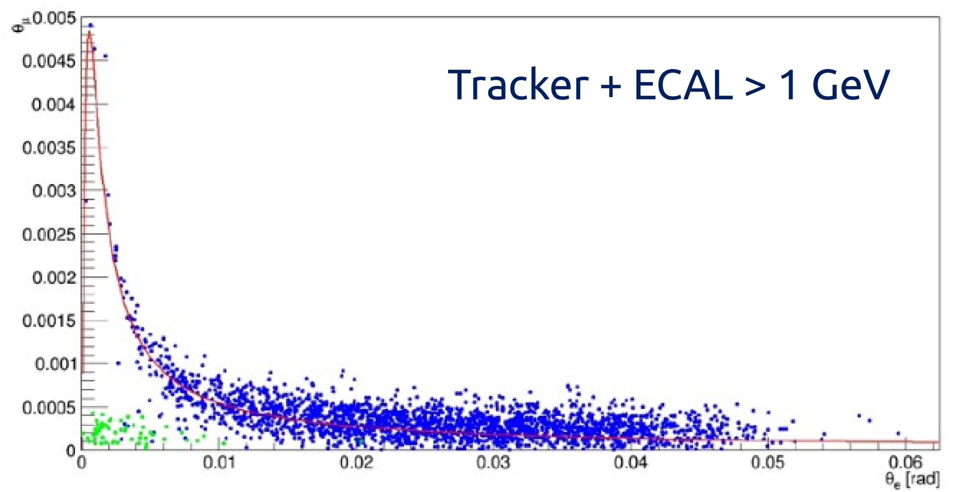
TB2017 (resolution ~7μm)

TB2018 (resolution ~40μm)

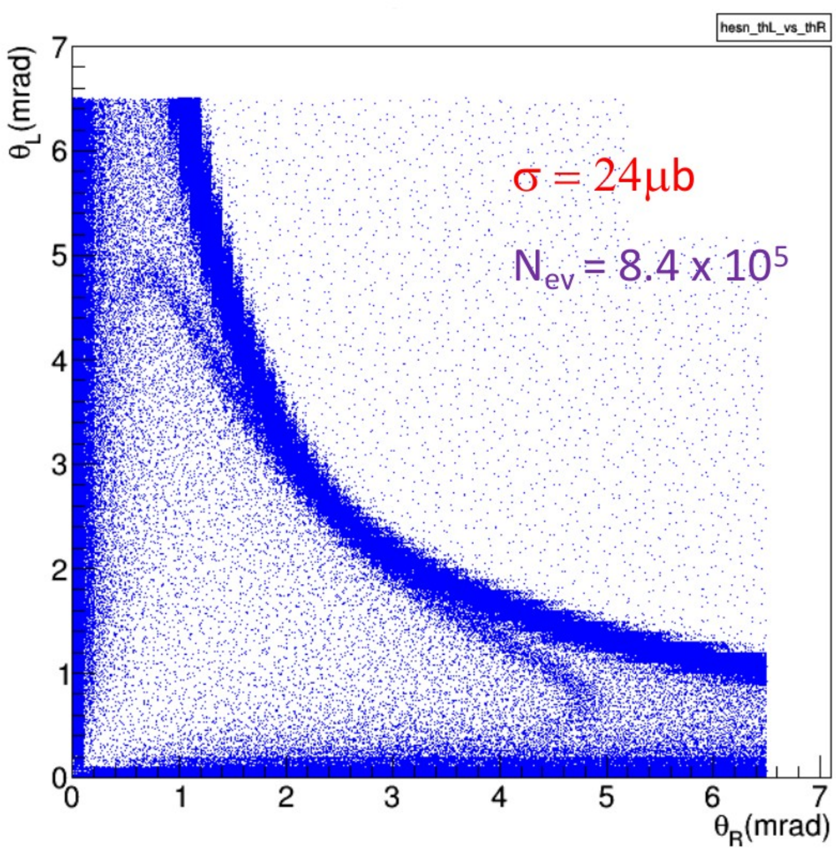


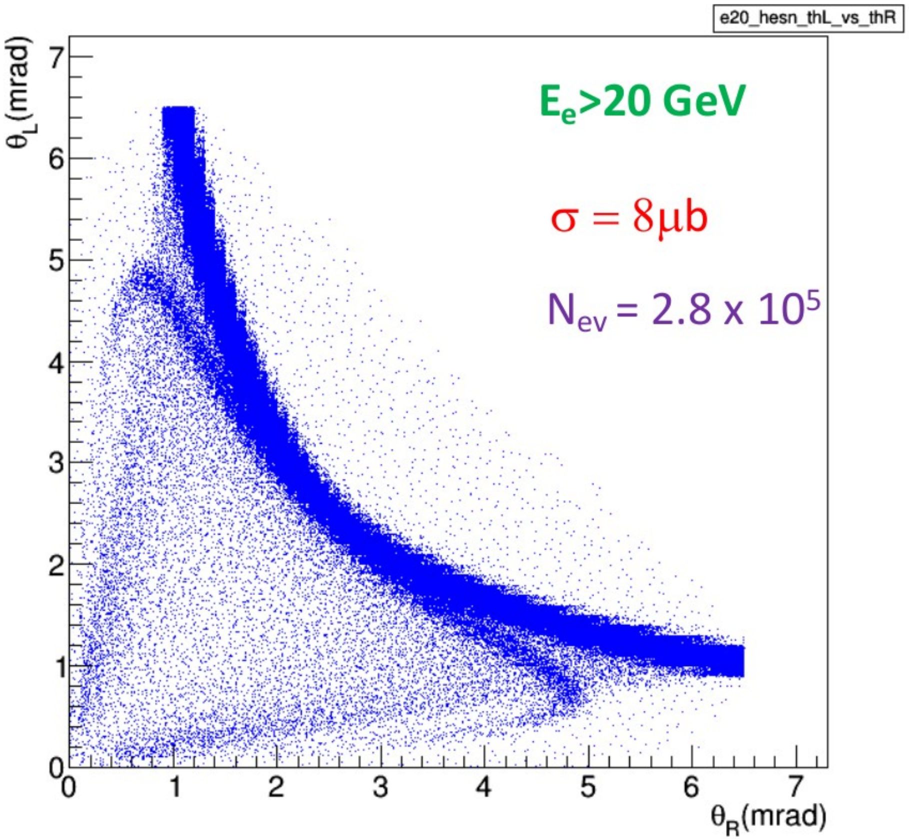






Effect of energy selection using the calorimeter





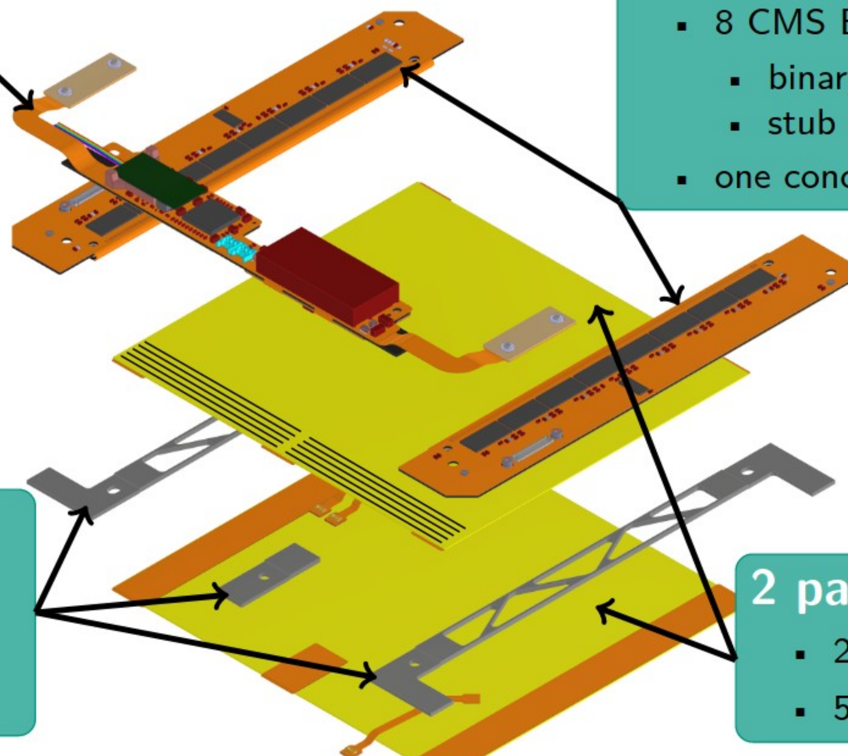
Tracker: CMS 2S modules

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

Service Hybrid
- data transmission
- powering

2 Front-End Hybrids
- 8 CMS Binary Chips each
  - binary readout of sensor signals
  - stub identification
- one concentrator chip each

Readout rate: 40 MHz



Al-CF Spacer
- spacing between sensors
- mechanical fixation
- main cooling path

2 parallel silicon strip sensors
- 2 × 1016 strips each
- 5 cm length and 90 µm ptich

Thickness: 2 × 320 µm

Sensitive area: 10×10 cm²

Picture from: Florian Wittig et al, iWoRiD 2022

Tracker: CMS 2S modules

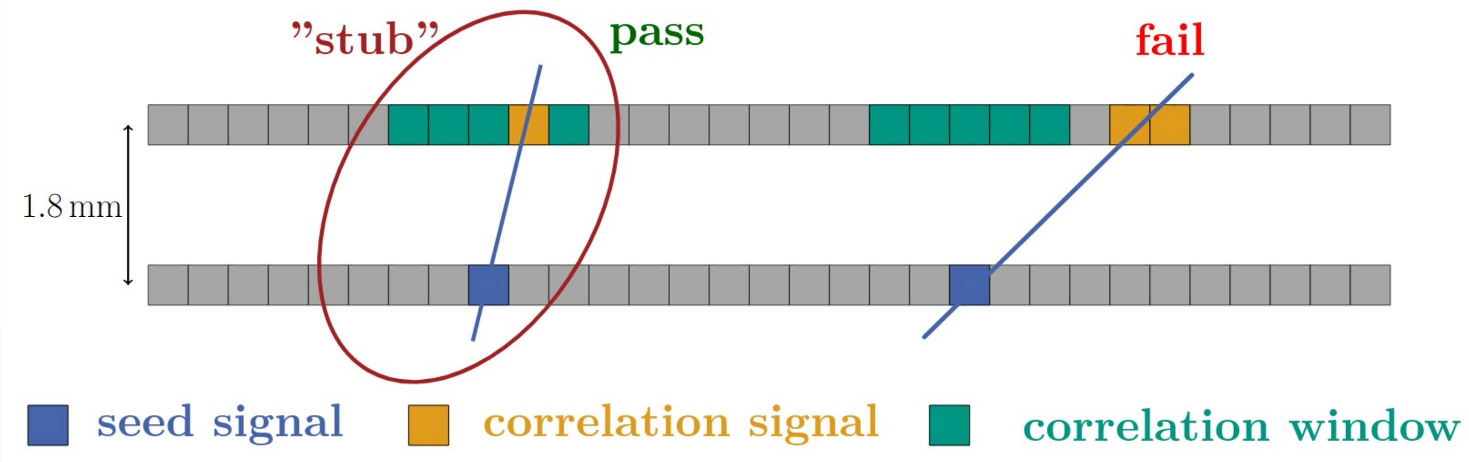
CMS Tracker Phase2 Upgrade - TDR

Two sensors reading the same coordinate:

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

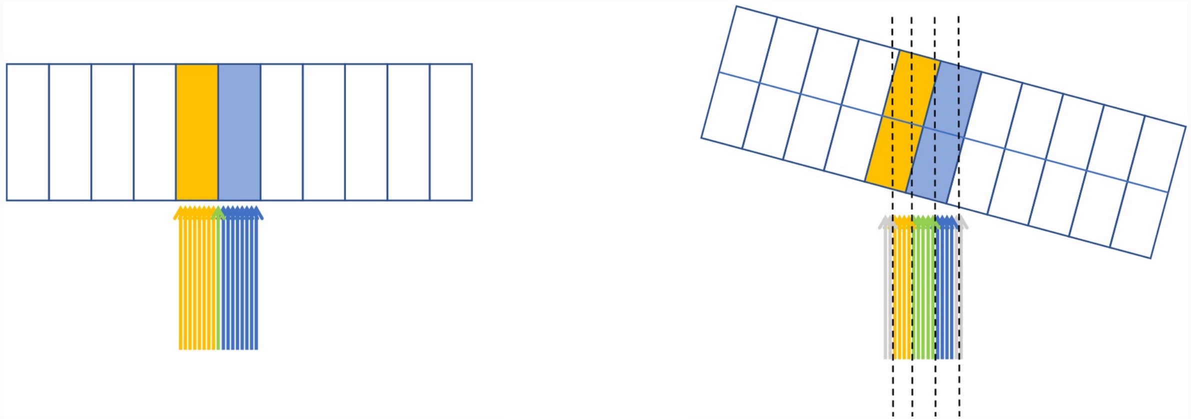
- x_{seed}
- bend = x_{corr} - x_{seed}

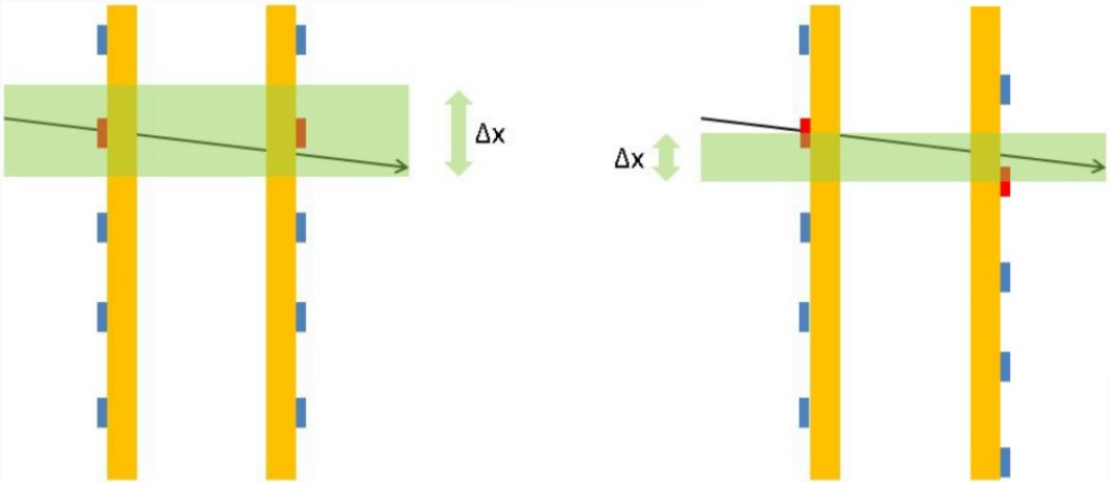
$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$



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

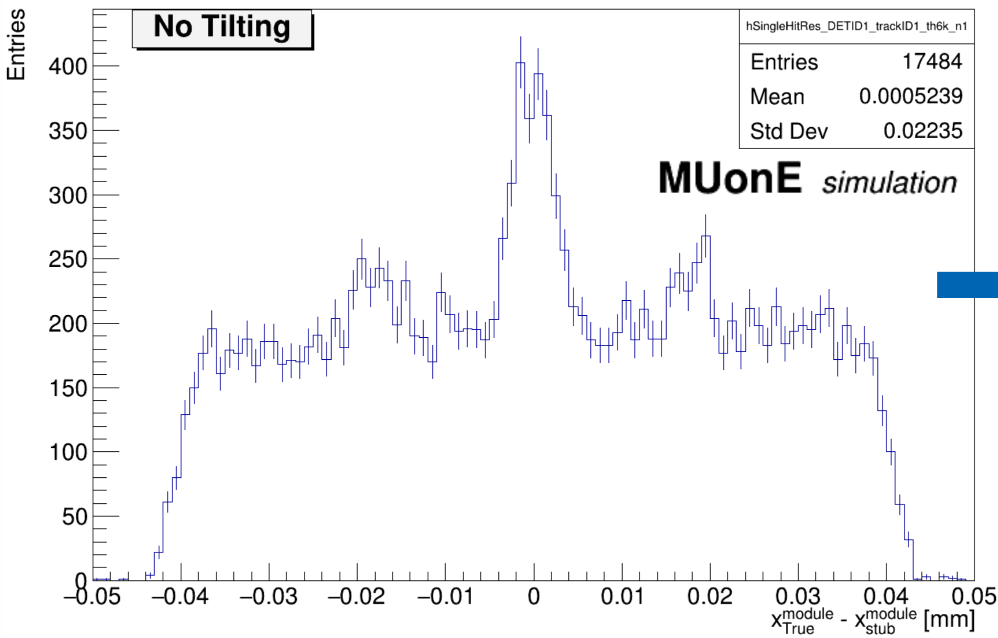
1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips

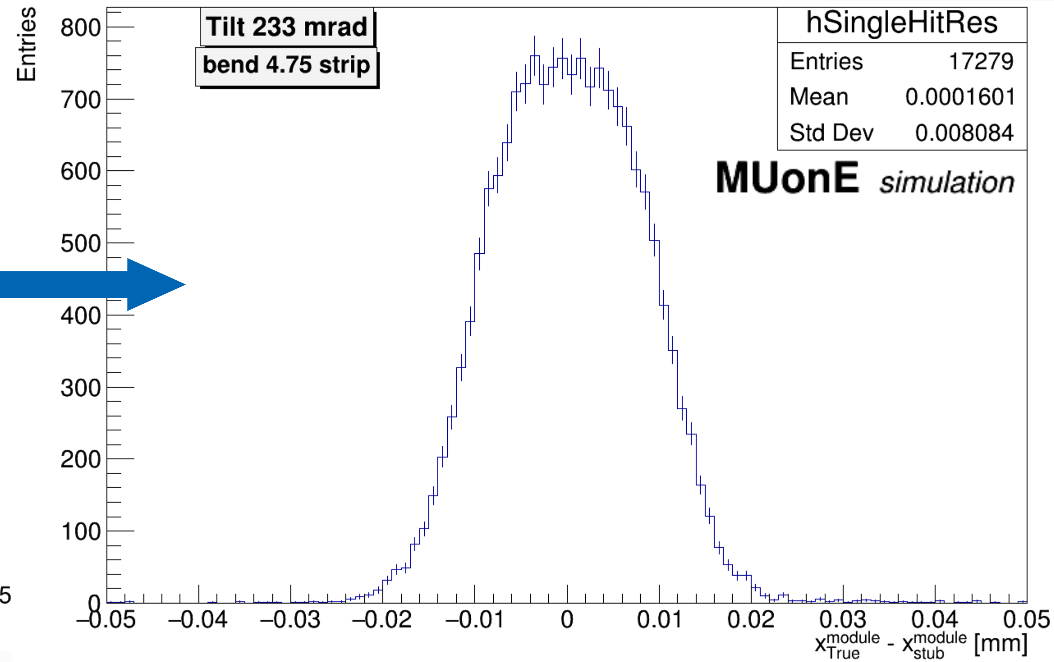




2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

MUonE simulations: Improving resolution - tilted geometry



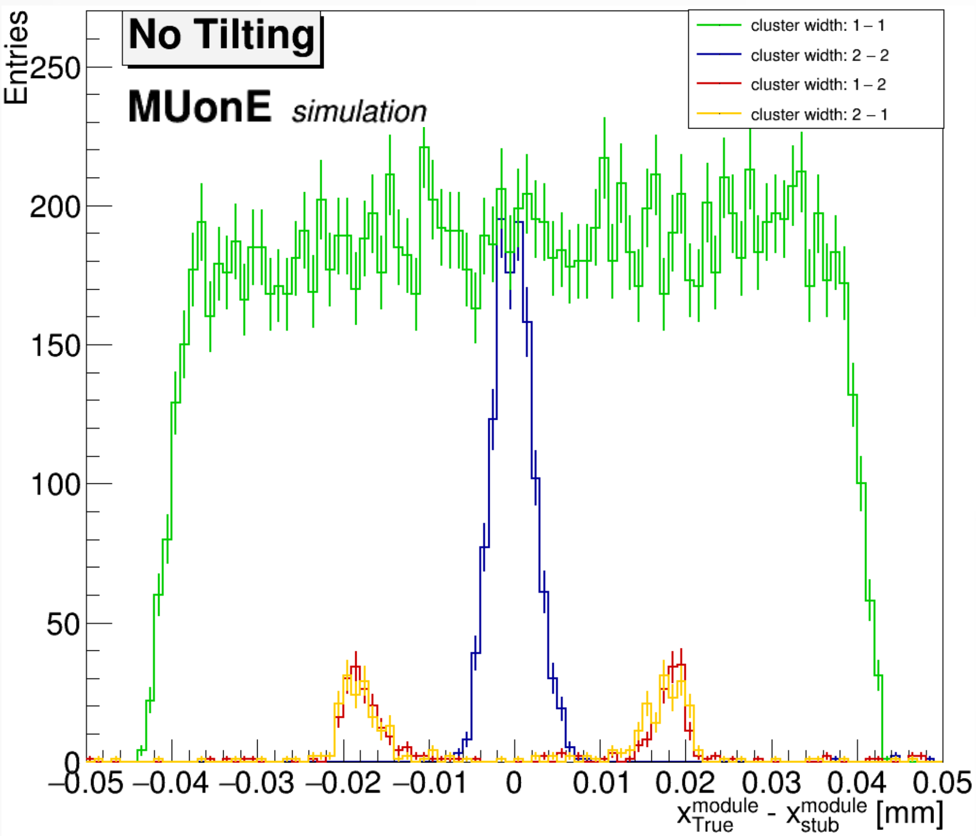


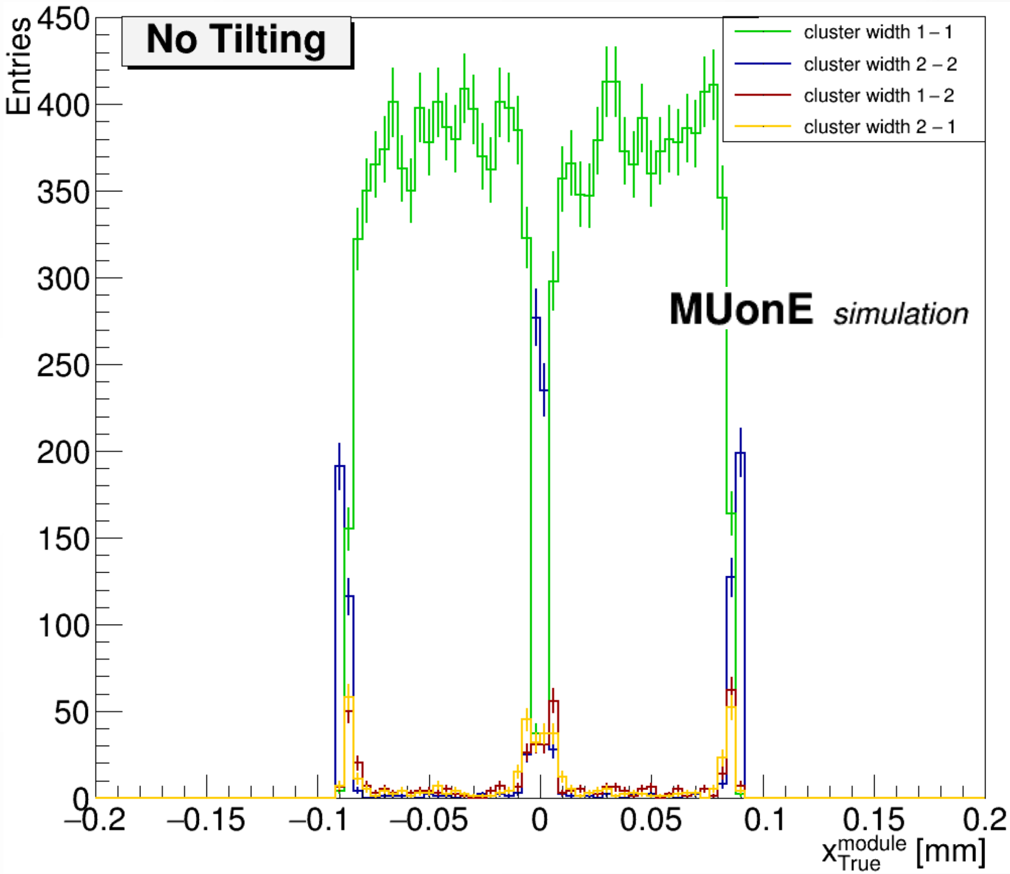
Improvement due to:

- charge sharing between adjacent strips
- effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

Final resolution

22 μm → 8-11 μm


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]

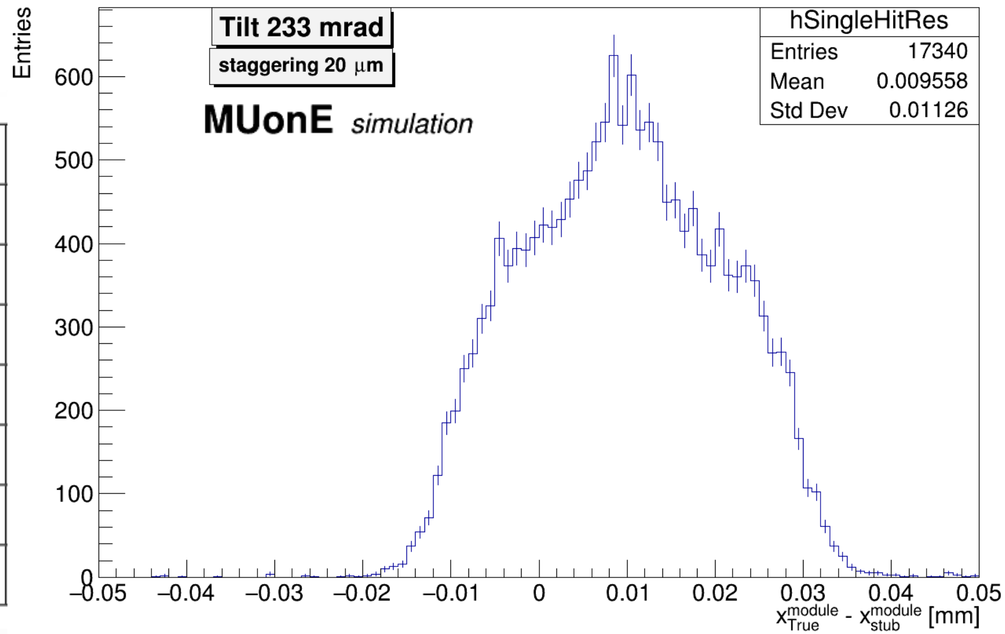

No Tilting
MUonE simulation
cluster width 1 – 1
cluster width 2 – 2
cluster width 1 – 2
cluster width 2 – 1
Entries
x_{True}^{module} [mm]

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

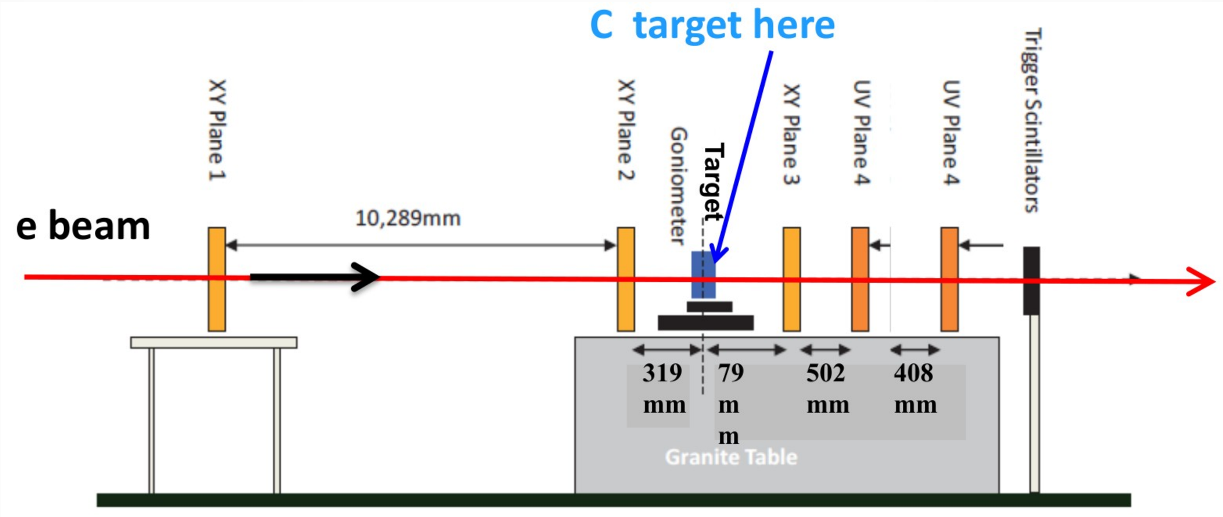


Multiple scattering: results from TB2017

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

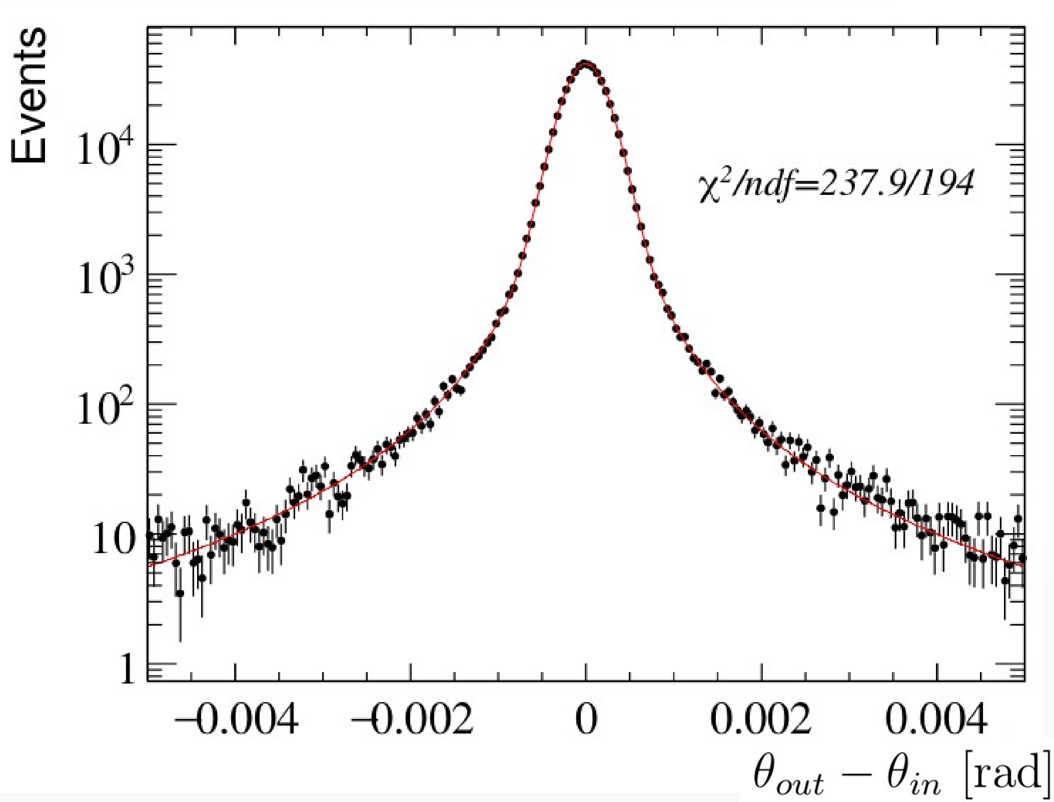
Main goals:

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



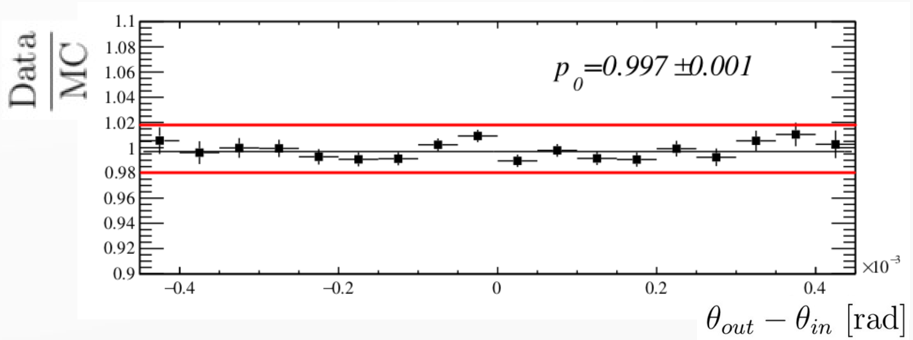
Multiple scattering: results from TB2017

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



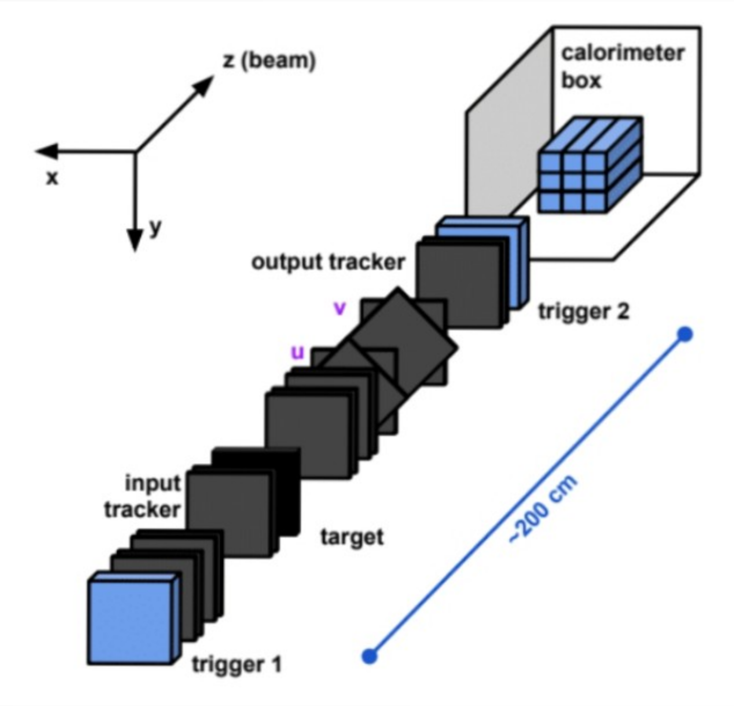
$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

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