Status of the MUonE experiment

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for the MUonE Collaboration

ICHEP 2022
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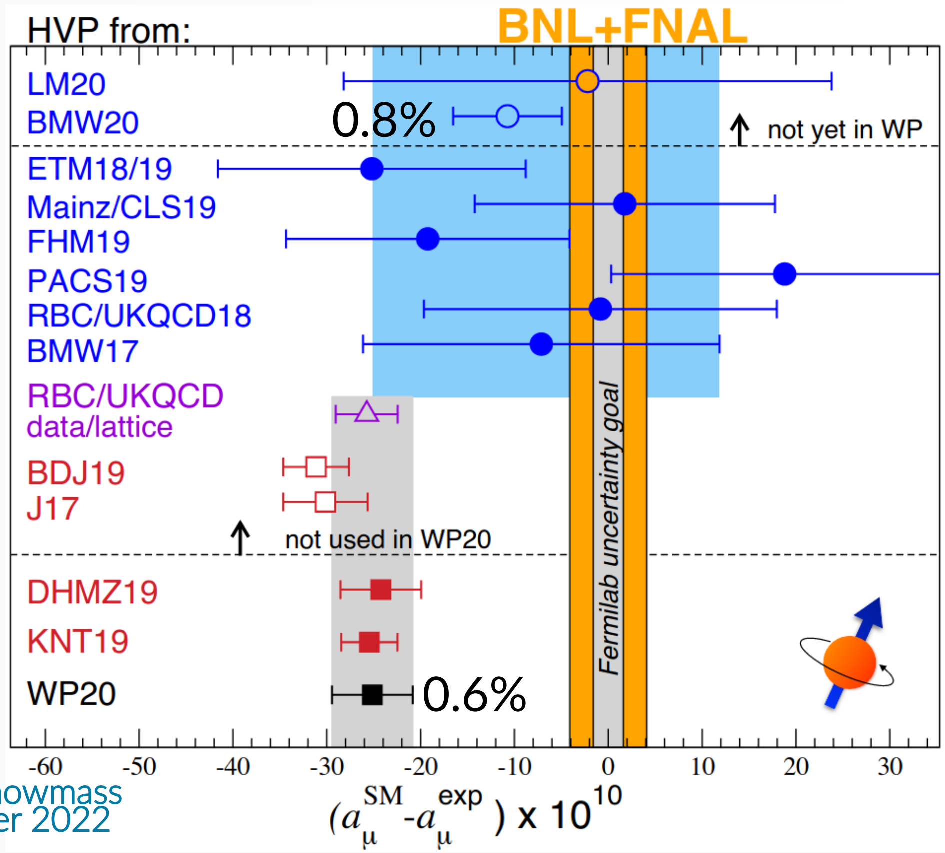
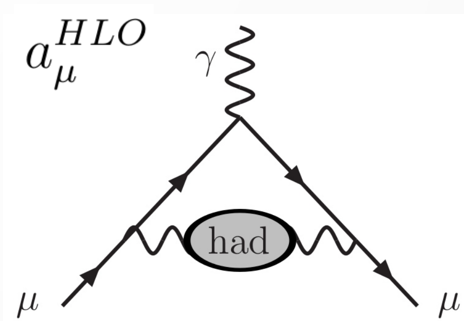
a_μ^{HLO} : present status



TI Snowmass paper 2022

Hadronic contribution a_μ^{HLO}: main limitation to the precision of a_μ Standard Model prediction



Discrepancy between recent lattice (BMW20) and e^+e^- evaluations (WP20)

"Further insights into these connections will be provided by another complementary method for HVP, which is expected to become available over the next years at the MUonE experiment". (TI Snowmass paper 2022)

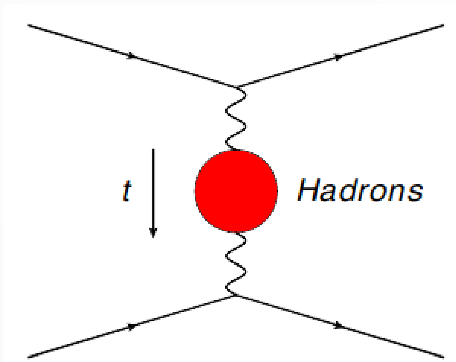
a_μ^{HLO} : space-like approach

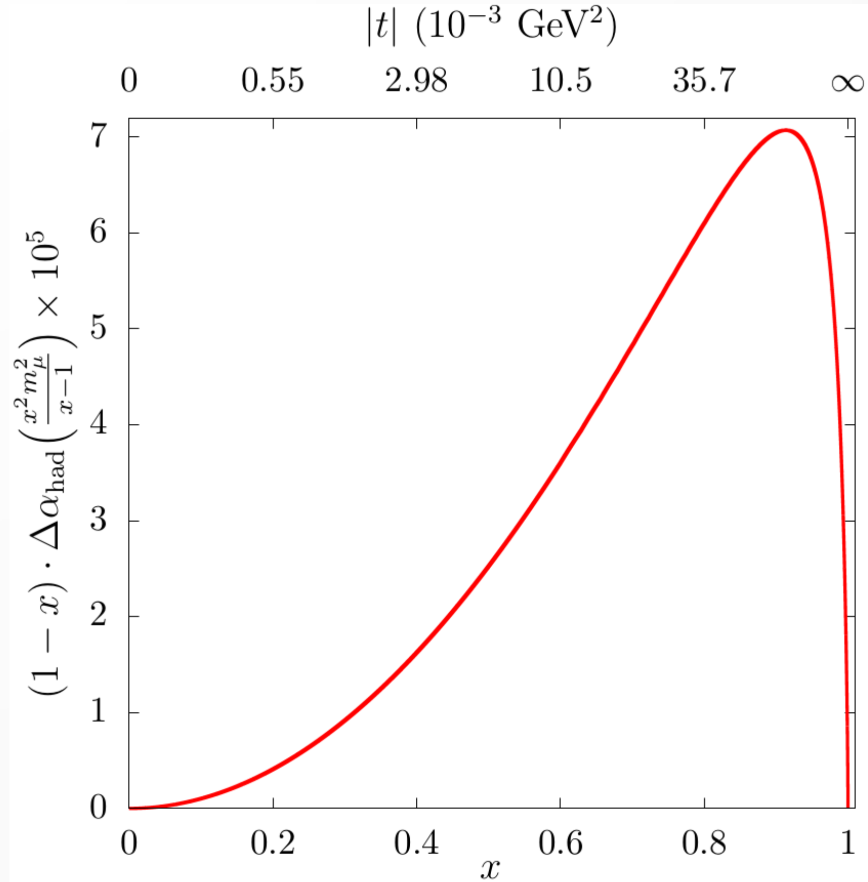
MUonE: a new independent evaluation of a_μ^{HLO}

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

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

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



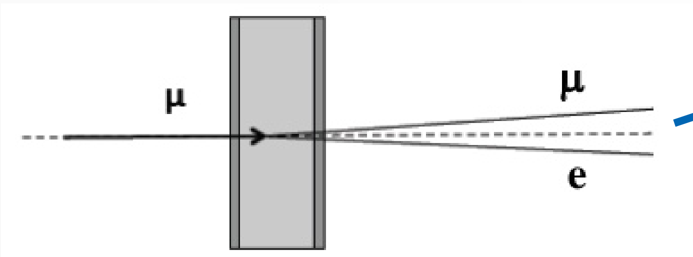


Carloni Calame, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015), 325

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

The MUonE experiment

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

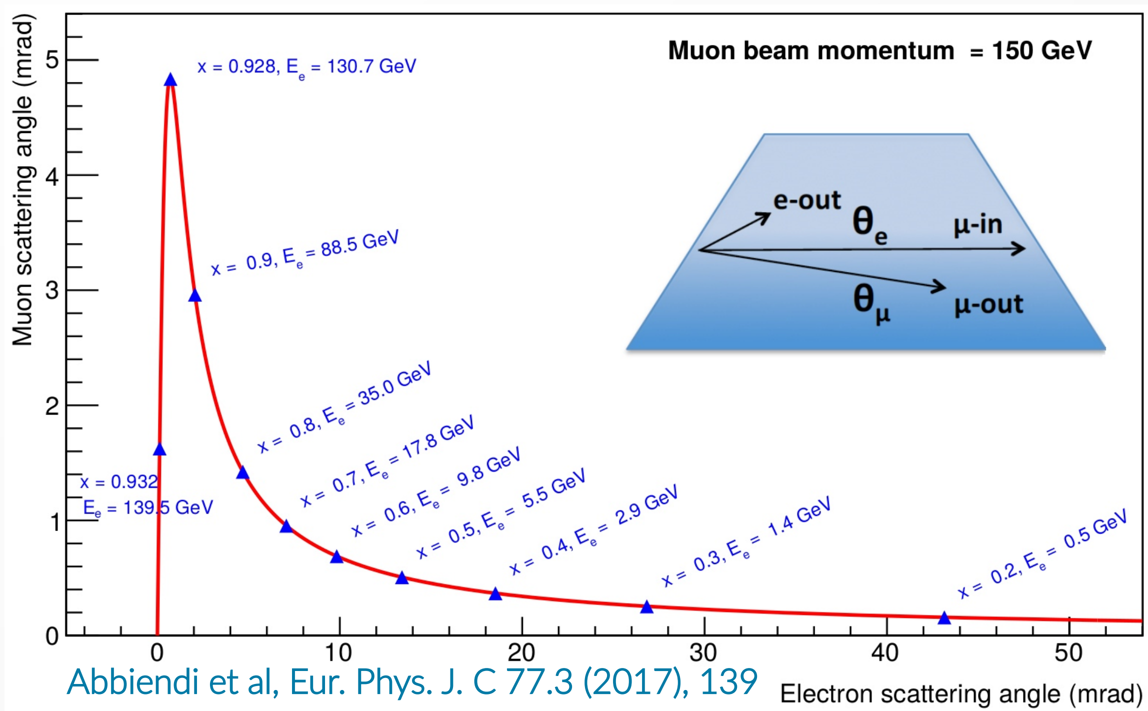


$$\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$

From theoretical calculation

To be measured

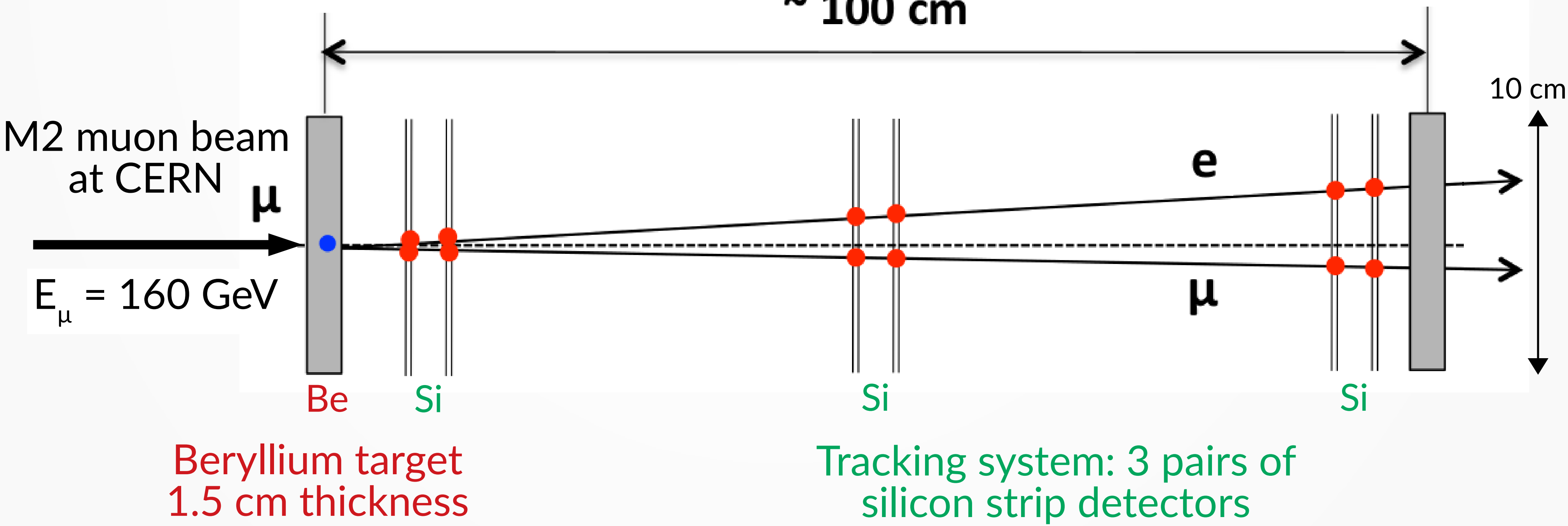
- A beam of 160 GeV muons allows to cover the 87% of a_μ^{HLO}.
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production).
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.

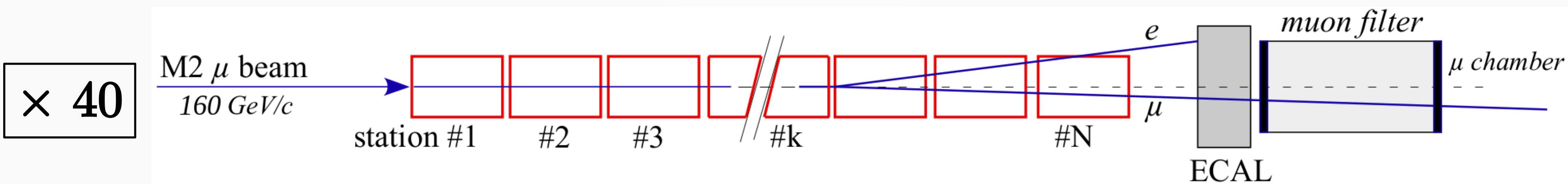


Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

The experimental apparatus

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





Achievable accuracy

40 stations + 3 years of data taking ($I_\mu \sim 10^7\ \mu^+/s$) = ~0.3% statistical accuracy on a_μ^{HLO}

→ 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 %)

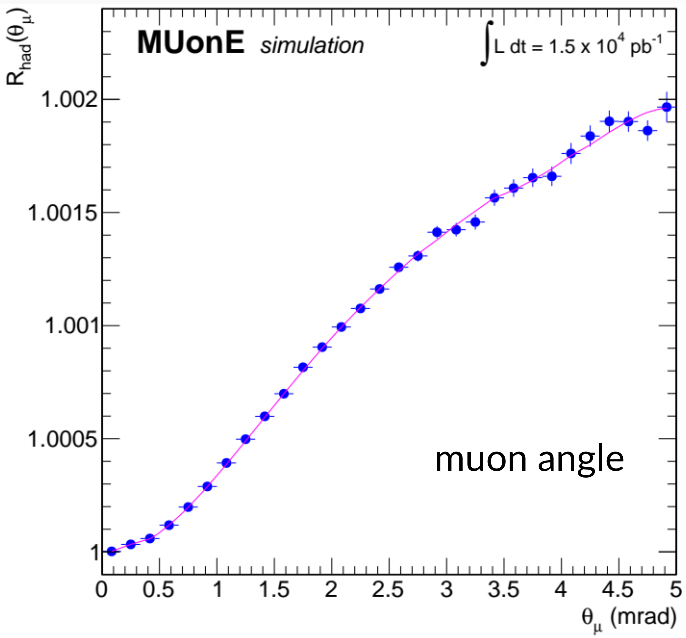
Extraction of a_μ^{HLO}

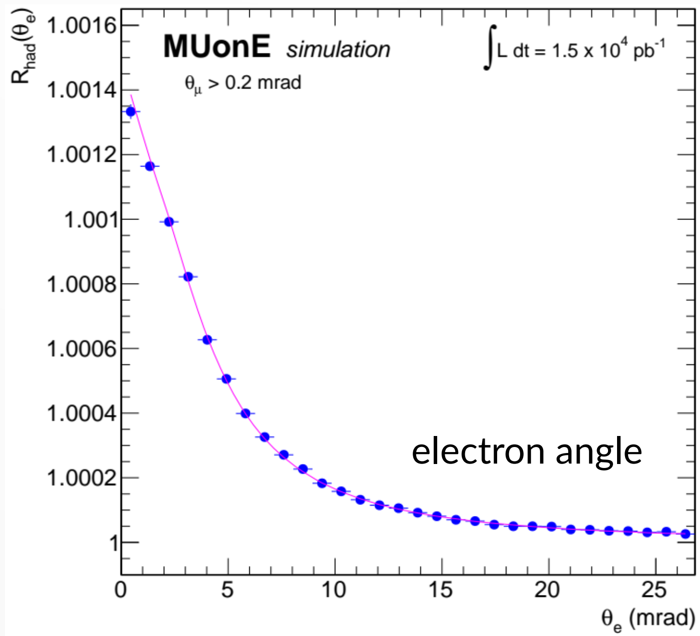
$\Delta\alpha_{had}(t)$ parameterization: inspired from the 1 loop QED contribution of lepton pairs and top quark at $t < 0$

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

2 parameters: K, M

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





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

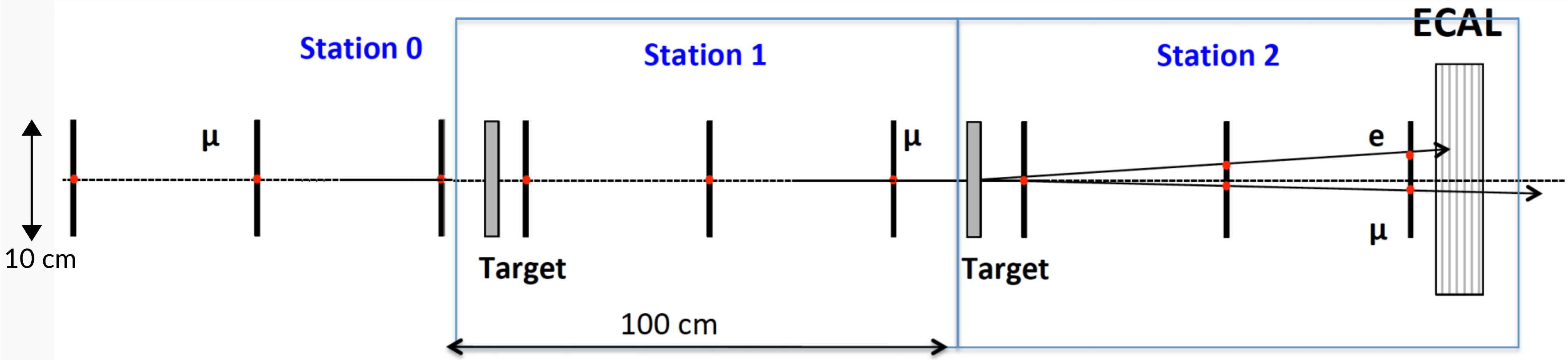
$a_\mu^{HLO} = (688.8 \pm 2.4)\ 10^{-10}$

Input value:

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

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

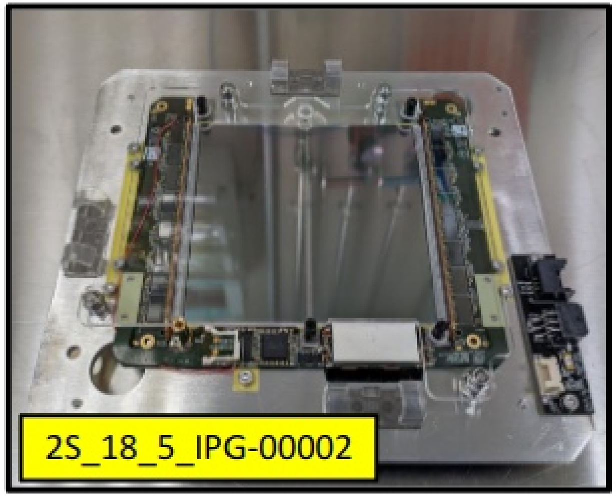
- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Assess the systematic errors.
- Initial sensitivity to $\Delta\alpha_{had}(t)$.
- Possible measurement of $\Delta\alpha_{lep}(t)$.

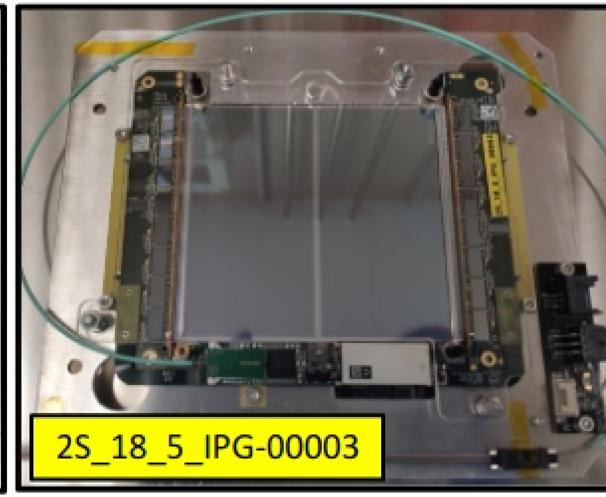
Tracker: CMS 2S modules

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.



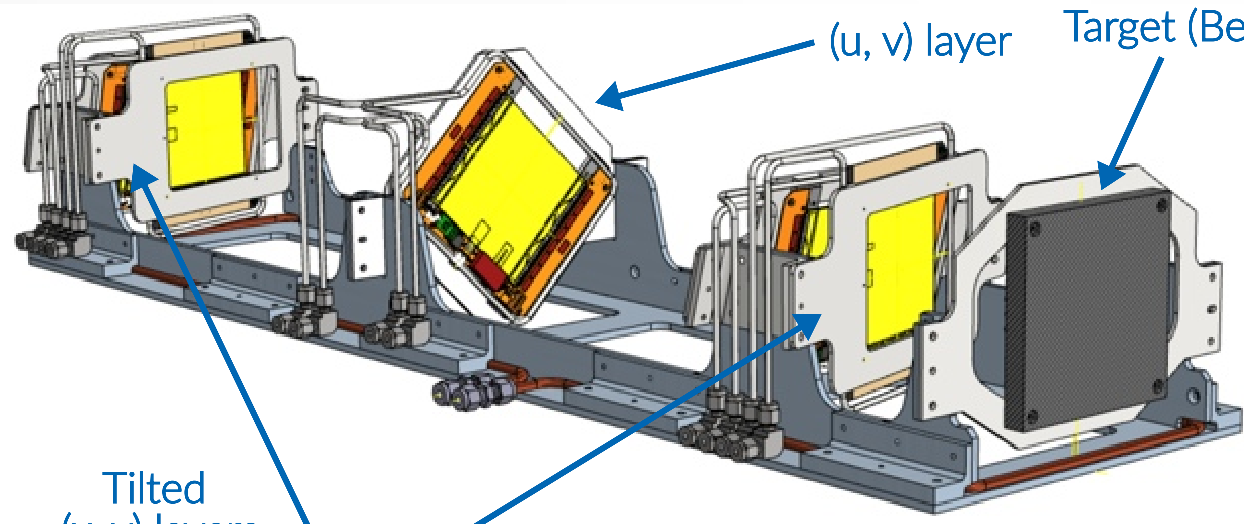


Four 2S modules assembled by CMS Perugia assembly center for MUonE. 5^{th} module foreseen in the next weeks.

- 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.

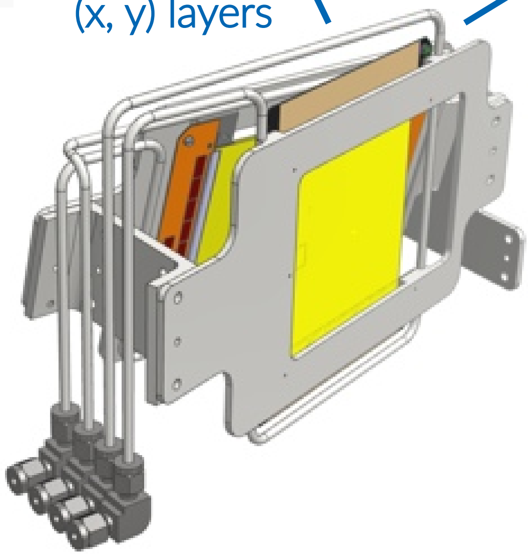
Tracking station



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

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

Laser holographic system to monitor stability.

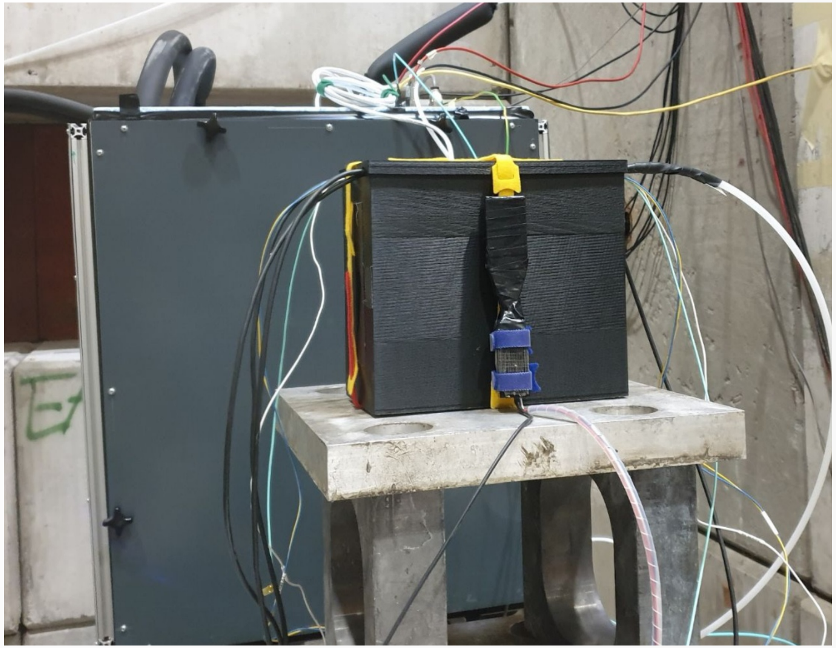


- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

Beam Test 2021

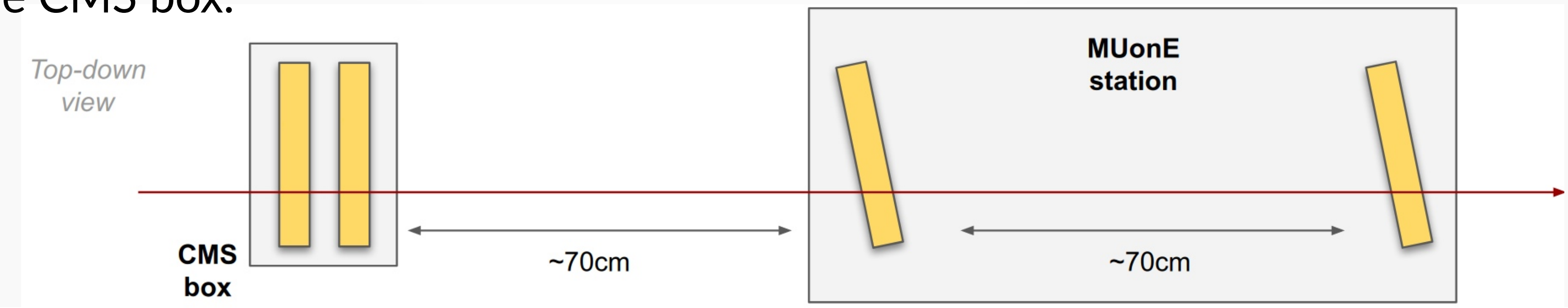
Parasitic beam test at M2 beam line, 3 weeks in October/November 2021

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



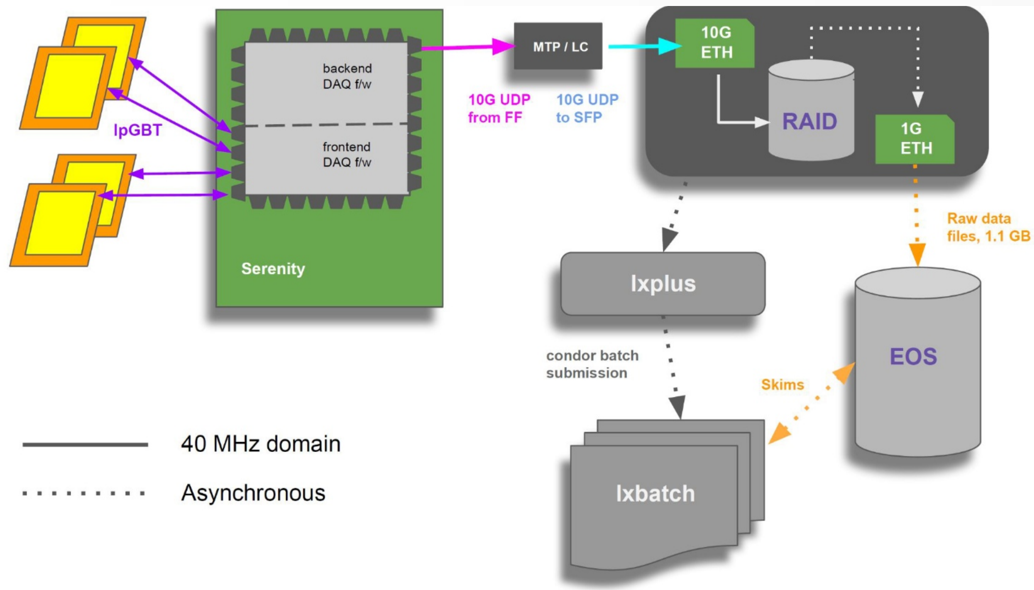
Four 2S modules tested in beam:

- 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



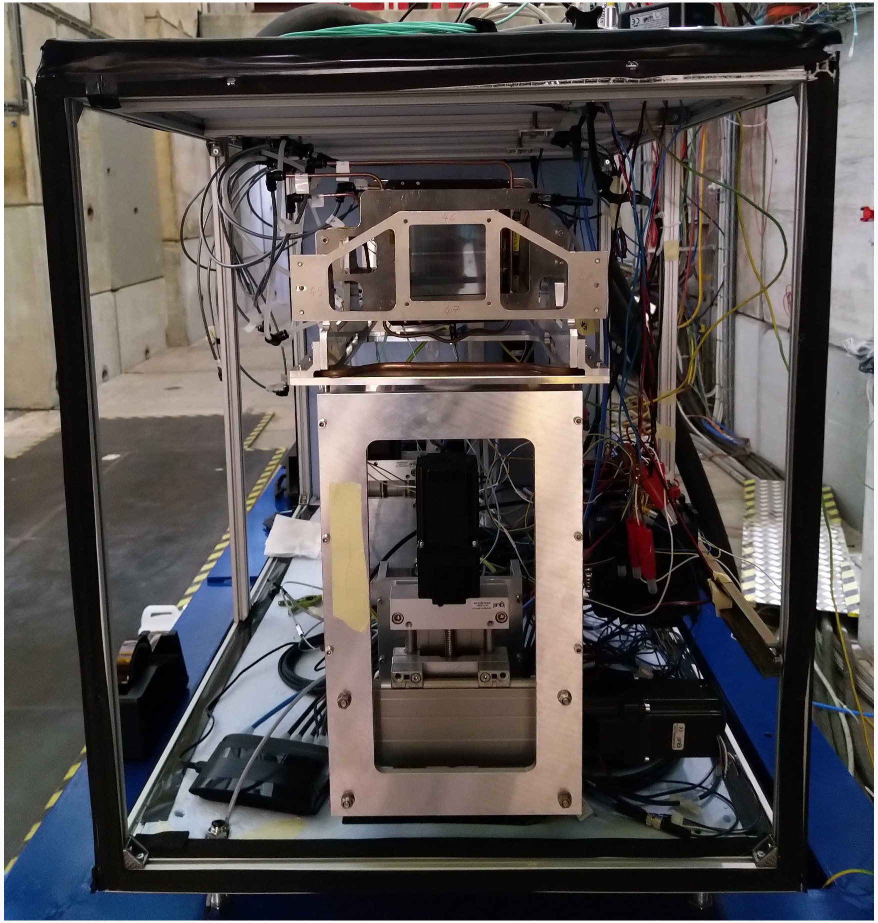
- Continuous stream of 40 MHz data from 2S modules captured to disk.
- Reliable readout over >6h runs.
- 30 TB of raw data collected to disk, ~1 TB after empty packets removal (low beam rate).
- Offline analysis ongoing: check data integrity and modules synchronization, beam behaviour, track reconstruction...

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 repolarizing its target.
- Trolley installed to insert/remove our station from beam.
- ~1 week as main users at October/November (TBD).

Beam Test 2022

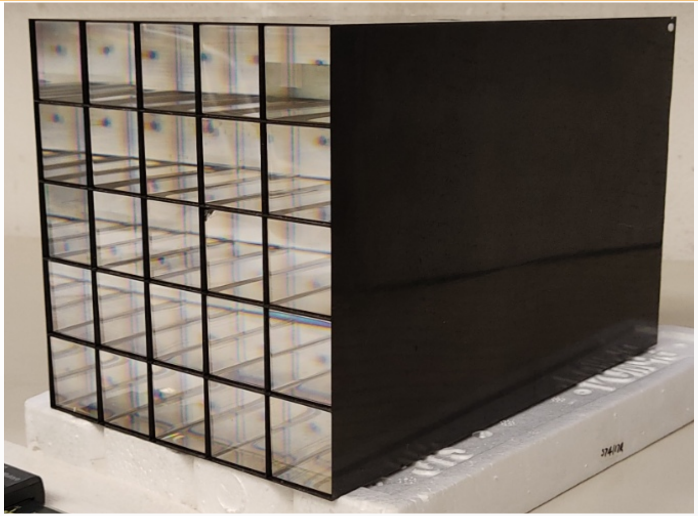
- Continue commissioning of the first tracking station with high rate beam:
  - Study performances of 2S modules and DAQ stability.
- Add a second station in September, equipped with 4 modules, to track the incoming muons:
  - Demonstrate DAQ scalability.
  - Offline track reconstruction and selection of elastic events. Validation of the Geant4 simulation.
  - First tests for software alignment.



Current status: 4 2S modules in the MUonE station.
June 29th: first run with beam.

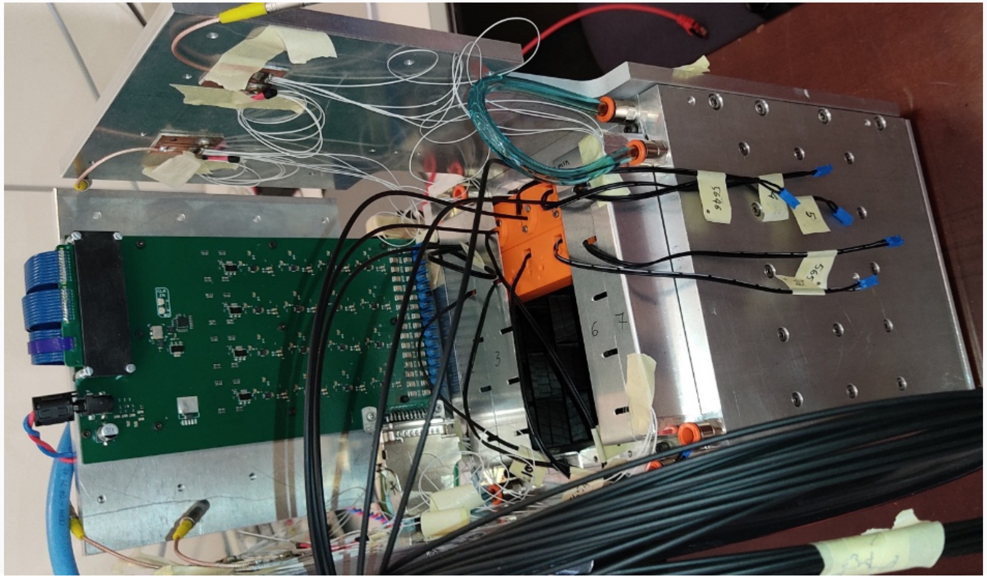
Calorimeter

- 5x5 $PbWO_4$ crystals:
  area: 2.85x2.85 cm^2, length: 22cm (~25 X_0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors.



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

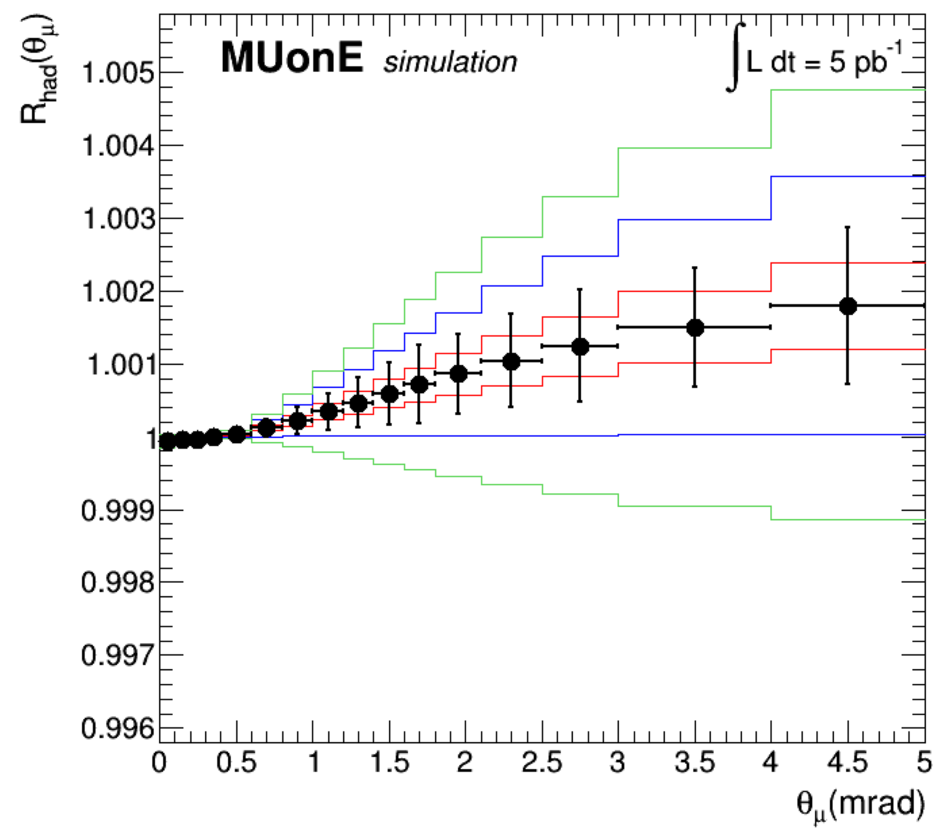
- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter installed downstream the tracking station at M2 beam line in September.



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)

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



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

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

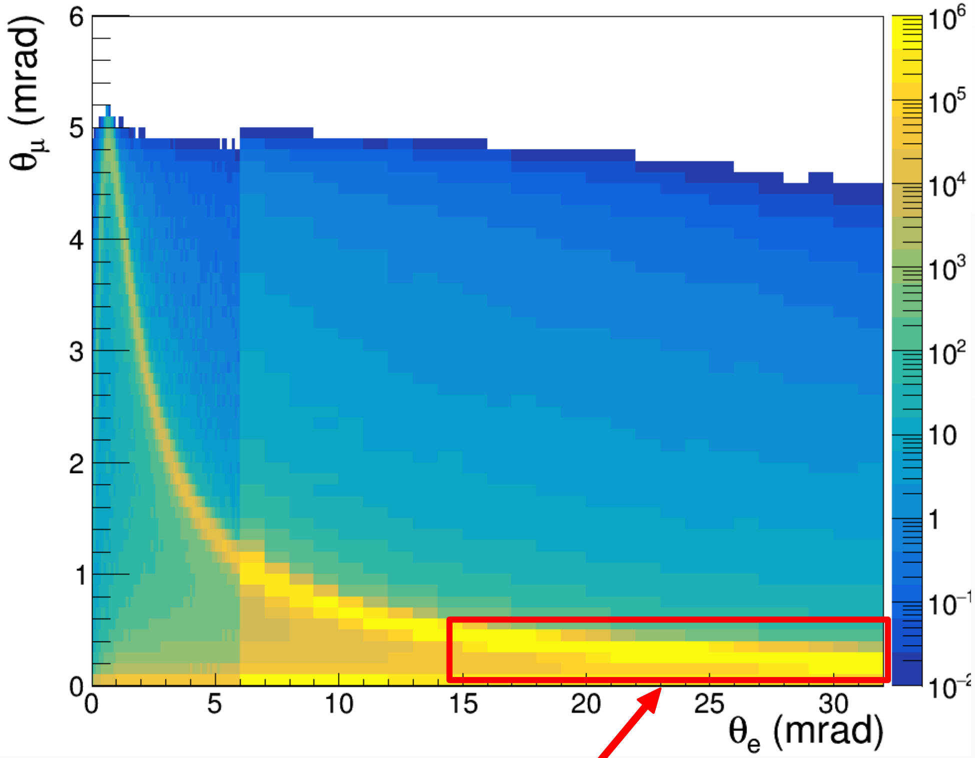
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$

K = 0.136 ± 0.026

(20% stat error)

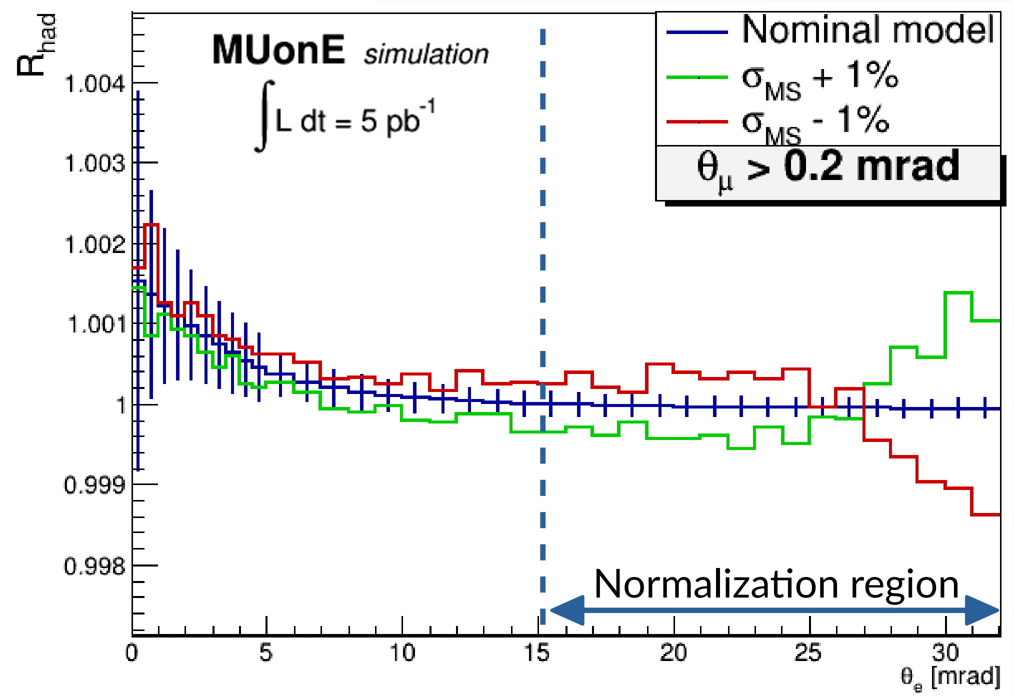
Strategy for the systematic effects

Large effects in the normalization region.
(no sensitivity to $\Delta\alpha_{had}$ here)



Normalization region

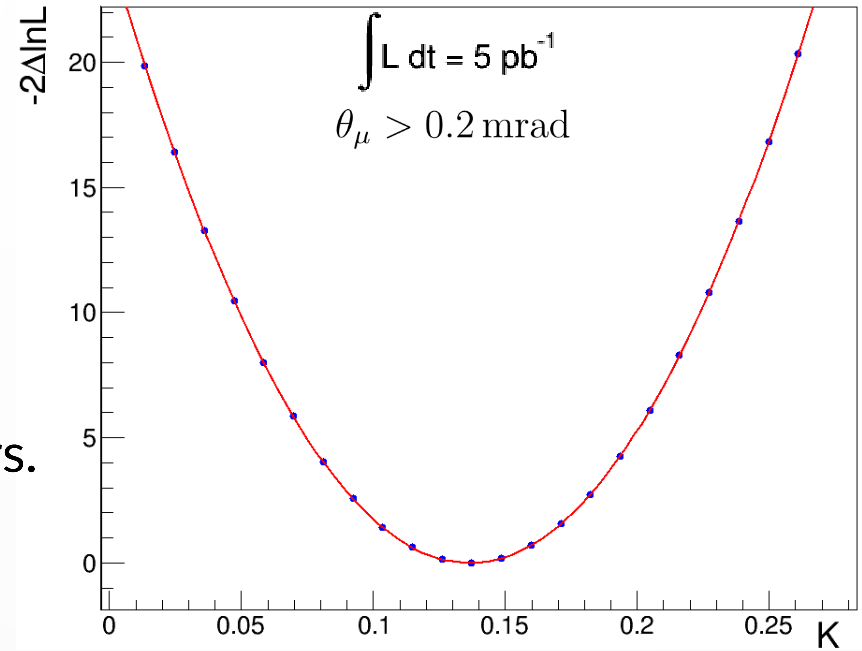
Effect of a ±1% error on the multiple scattering core width:



Strategy for the systematic effects

Promising strategy:

- Use normalization region to calibrate these effects.
- Include residual systematics as nuisance parameters in a combined fit with signal.
- MESMER MC for template fit @NLO
  + Combine tool to fit the nuisance parameters.



K : signal parameter

μ_{MS} : nuisance parameter for multiple scattering systematics

Input shift:
$\sigma_{MS} \rightarrow +0.5\%$

Fit results ($\theta_\mu > 0.2\,\mathrm{mrad}$)
$K = 0.136 \pm 0.028$
$\mu_{MS} = (0.508 \pm 0.013)\%$

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

Similar results introducing different systematics at the same time.
Work in progress to improve the procedure.

Conclusions

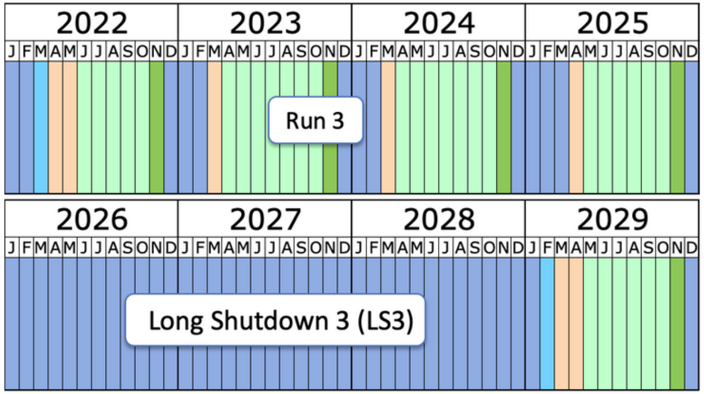
MUonE web site

- Alternative determinations of a_μ^{HLO} are essential.
  The new method proposed by MUonE is independent and competitive with the latest evaluations.

- 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.

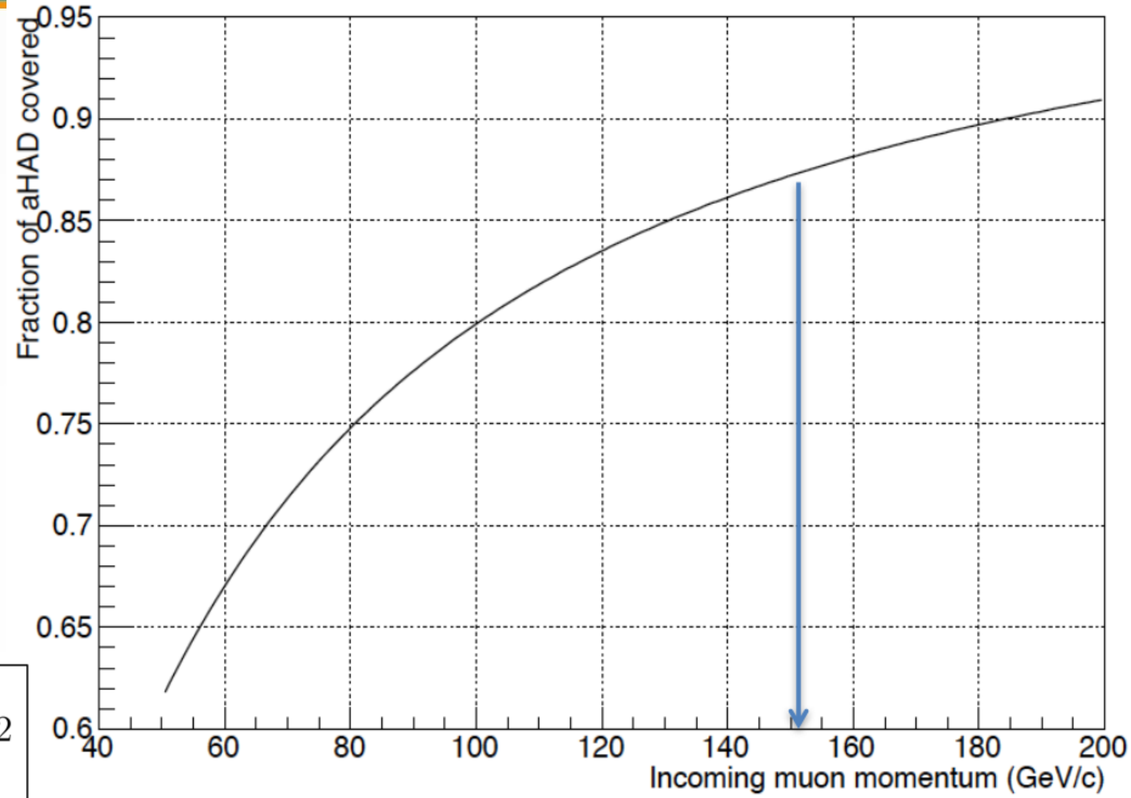
- Towards the full experiment: 10 stations before LS3 (2026).
  Four months data taking:
  ~2% (stat) measurement of a_μ^{HLO}.

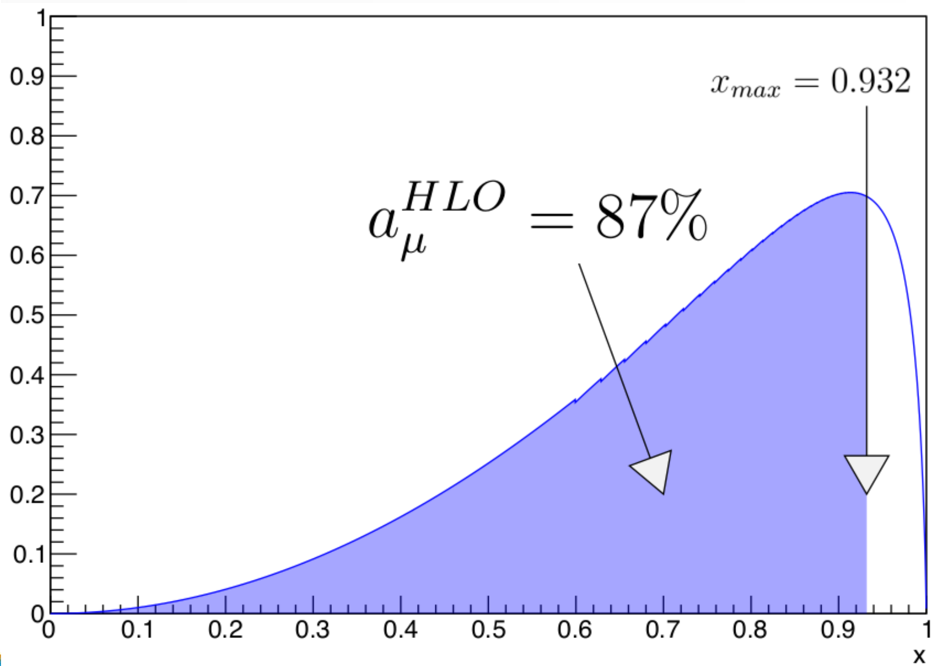


- Progress on the MUonE Geant4 simulation:
  more details in the poster
  by Patrick Asenov.

BACKUP

$$x \lesssim 0.93$$



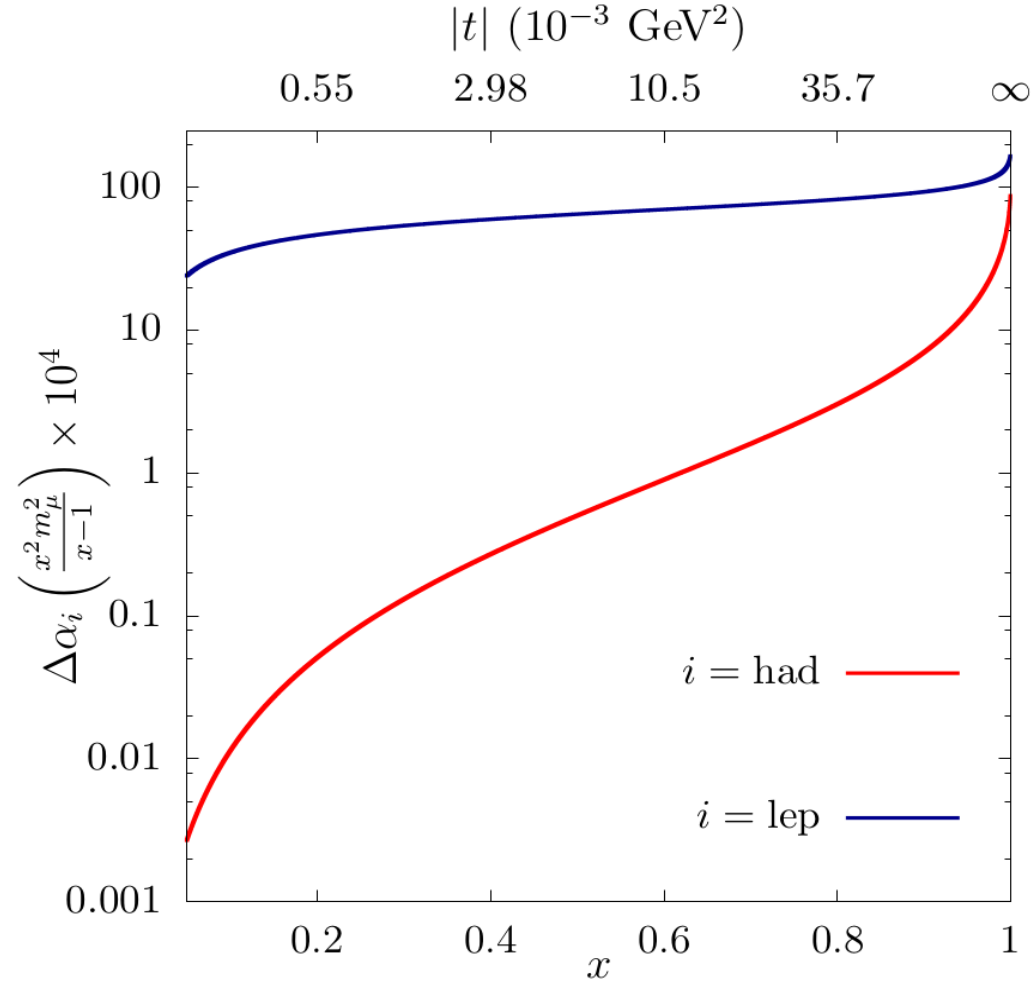


- 160 GeV muon beam on atomic electrons.

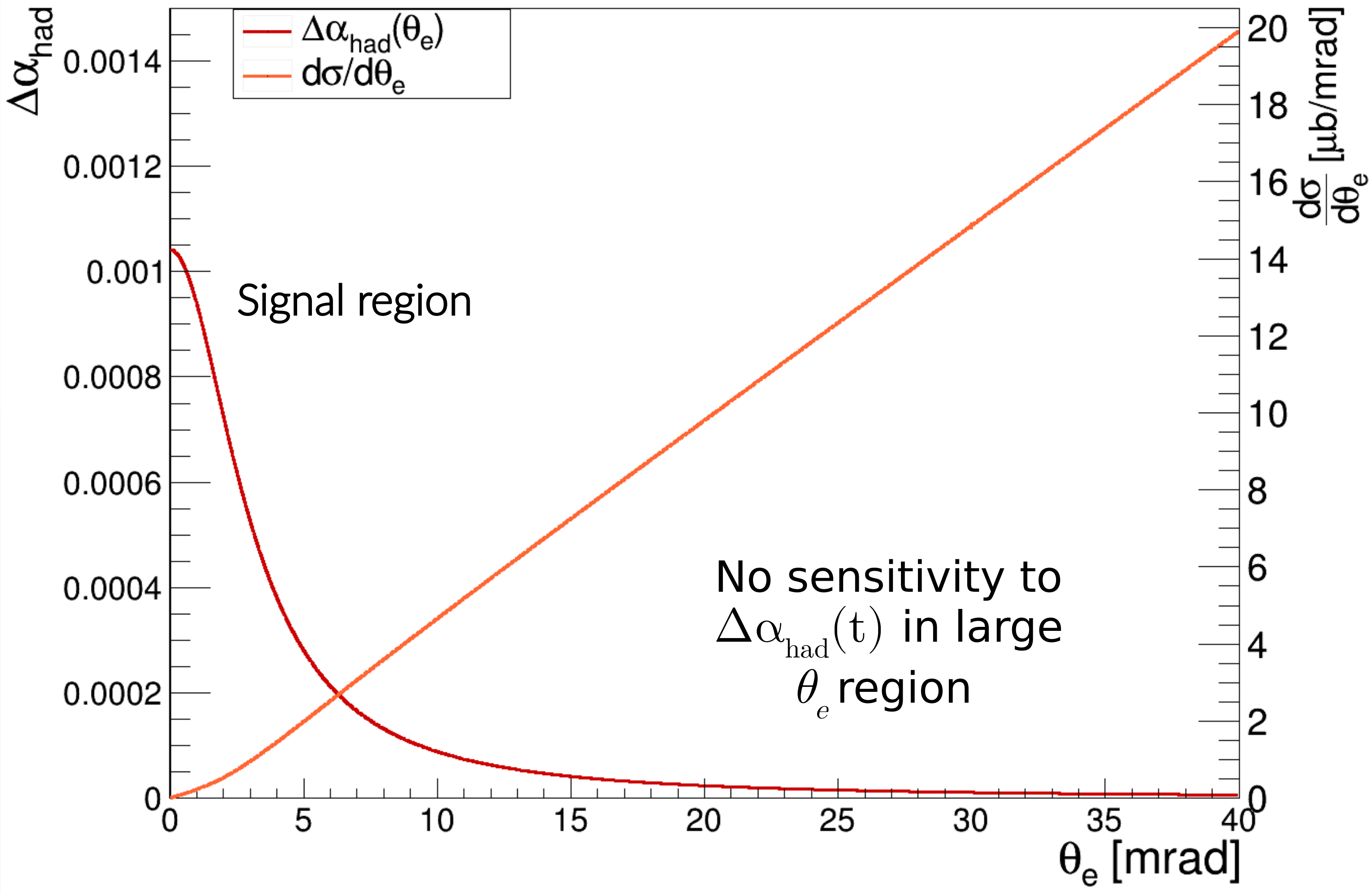
$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

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

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

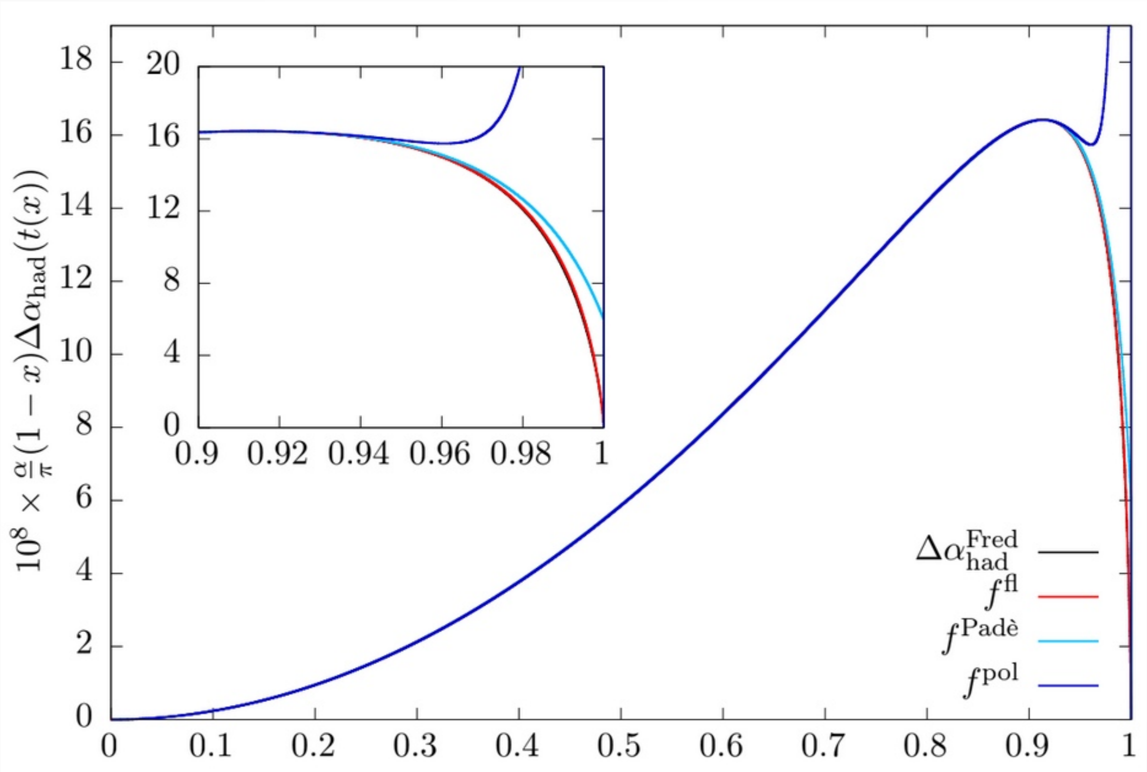


Extraction of $\Delta\alpha_{had}(t)$



"Lepton-like" parameterization

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



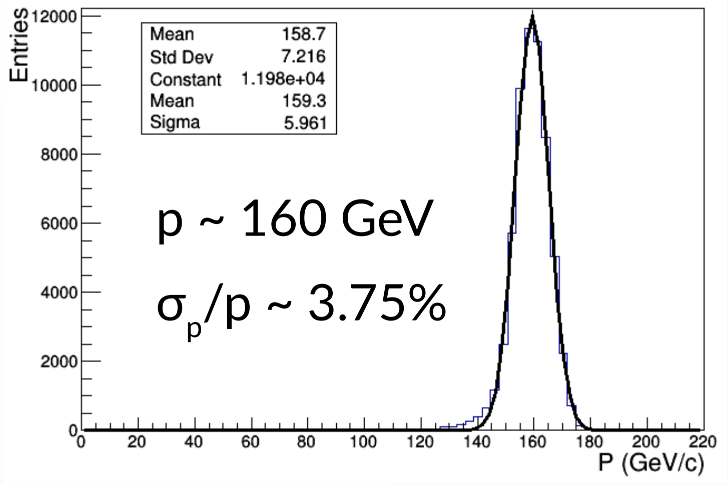
K = related to α_0 and the electric charge of the lepton in the loop (and also colour charge for quarks)

M = related to the squared mass of the particle in the loop

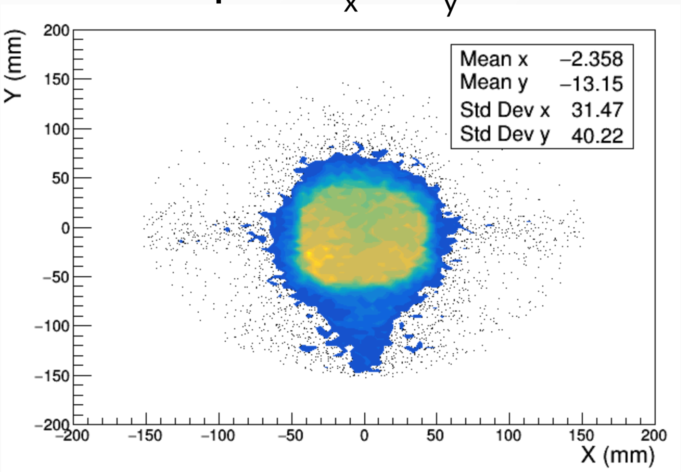
It allows to extrapolate $\Delta\alpha_{had}(t)$ also in the region which is not accessible by kinematics (x > 0.93).

Location: M2 beam line at CERN

Beam momentum



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

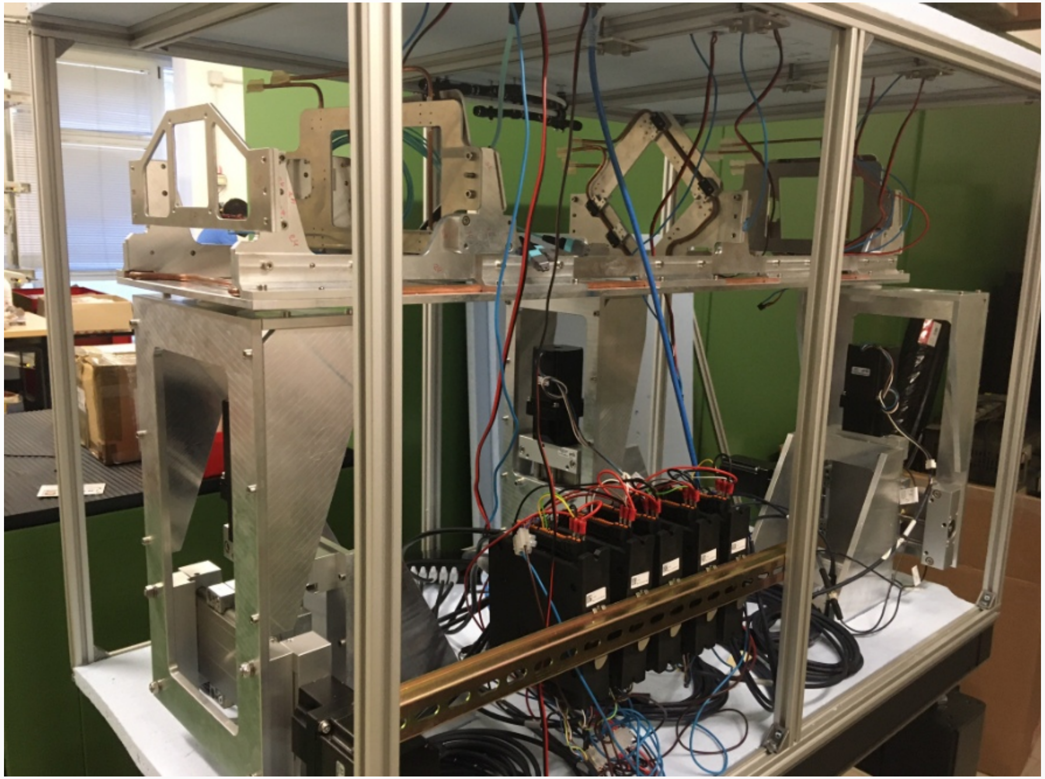


- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 3×10^8 μ^+/spill).

Tracking station: status readiness

- 2 complete stations in Aluminum are ready. 1 at CERN, being used in the Beam Tests. The second one is in Trieste, to test the holographic system.

- 2 complete INVAR stations being assembled in Pisa. To be shipped to CERN in the next weeks.



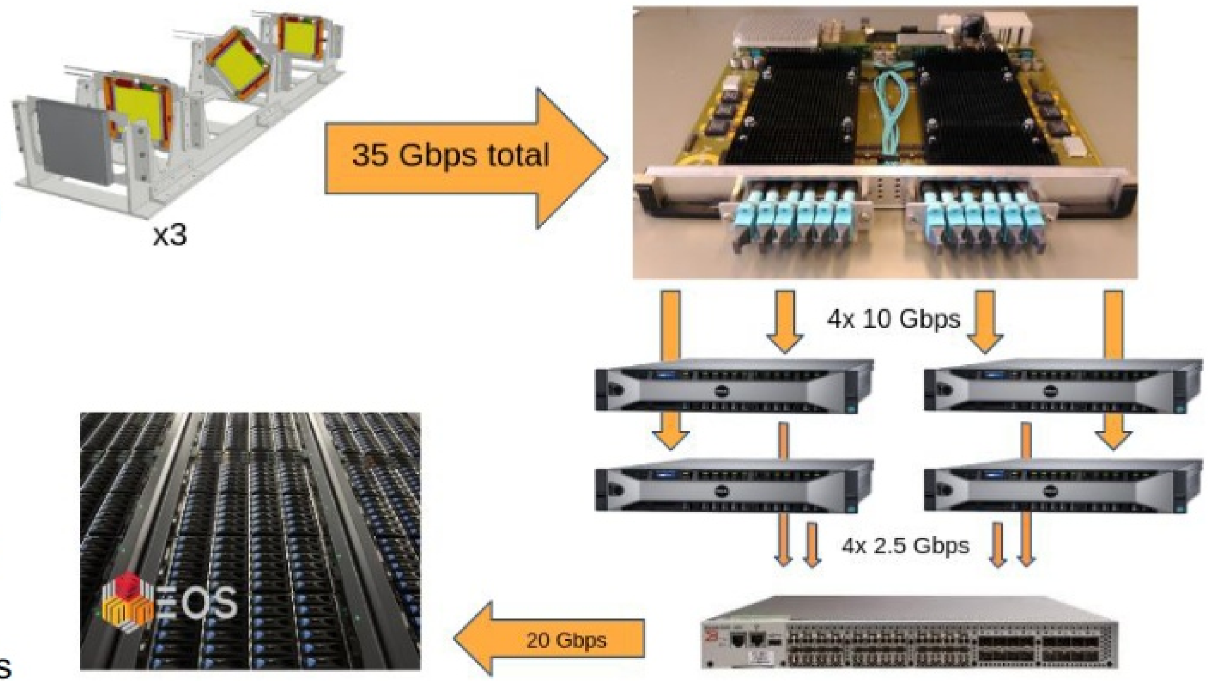
BE-DAQ architecture

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

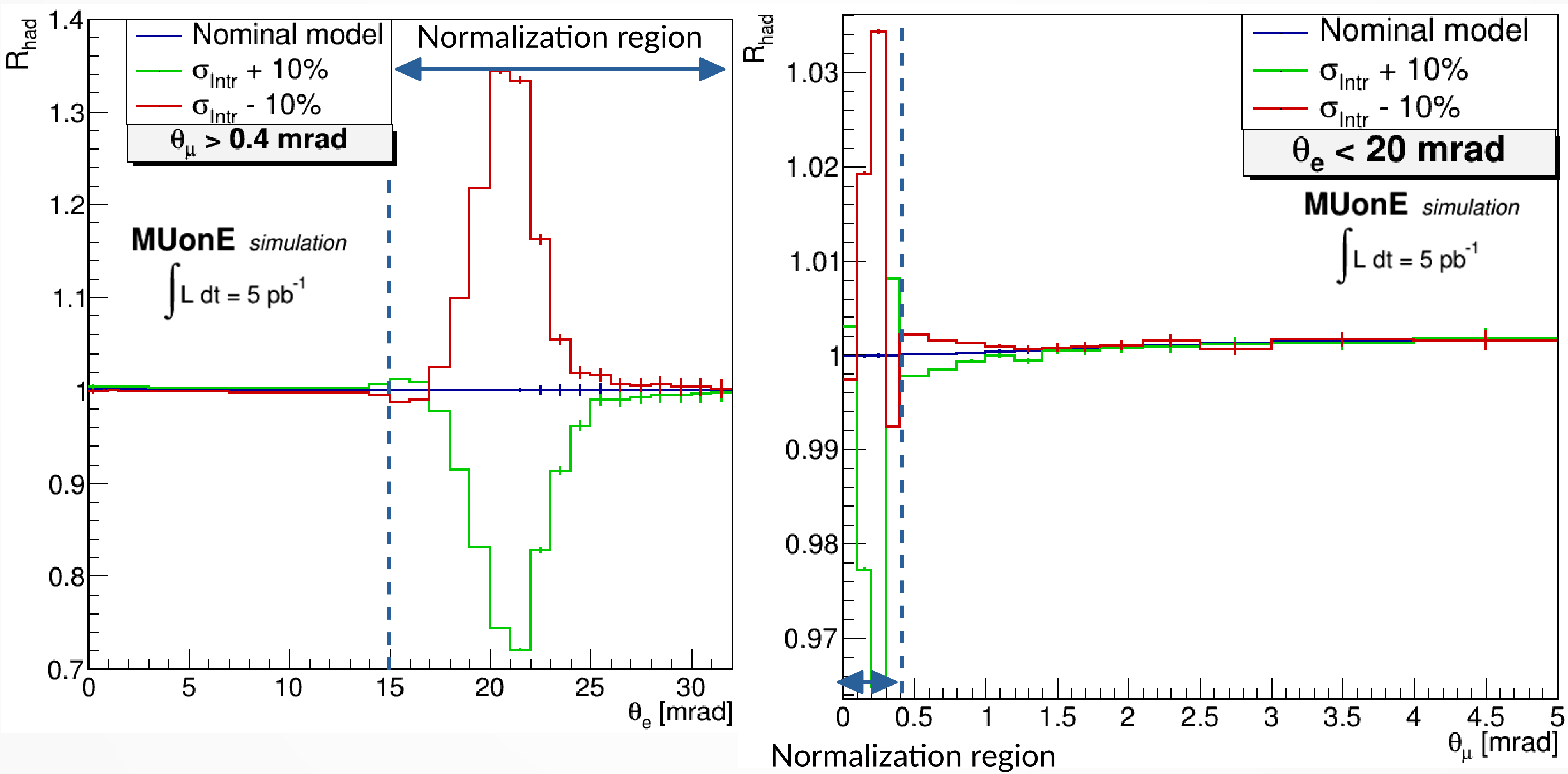
Reduced data rate from servers

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



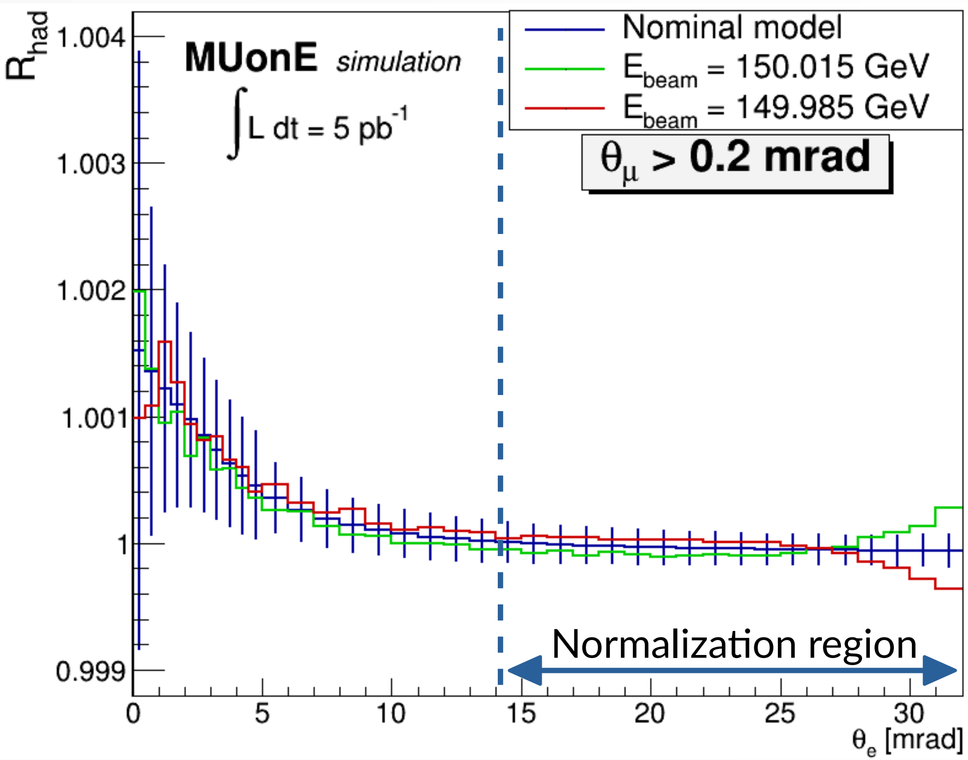
- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

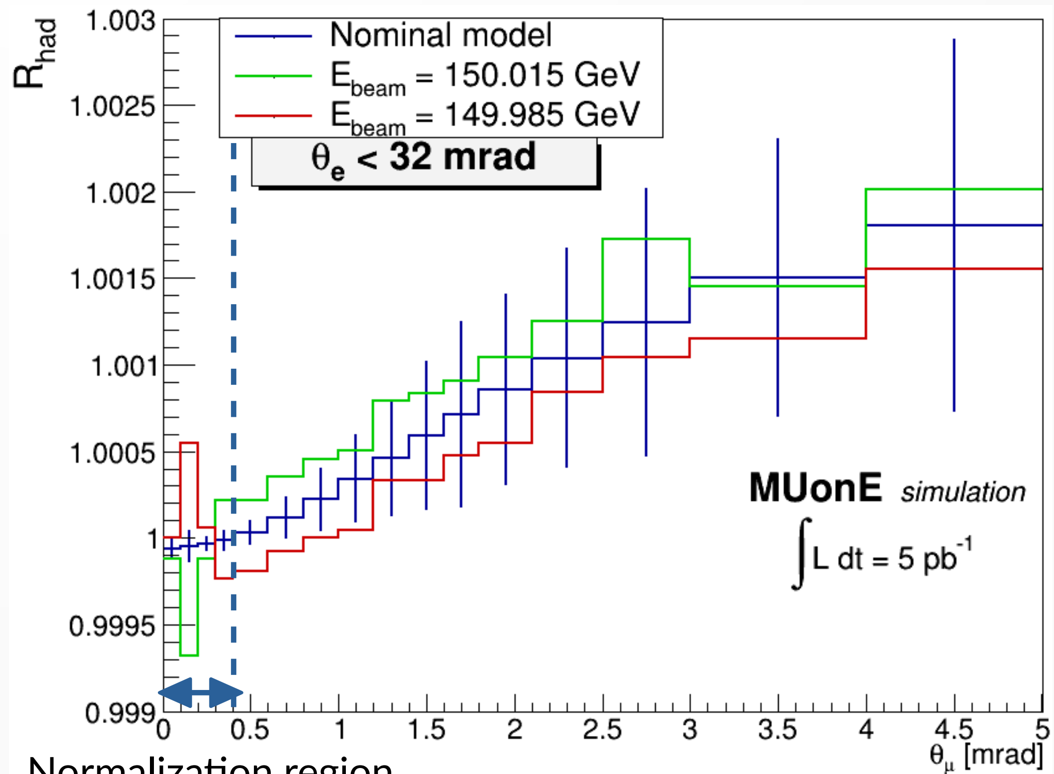
Effect of a ±10% error on the angular intrinsic resolution:



Systematic error on the beam energy scale

Effect of a ± 15 MeV shift

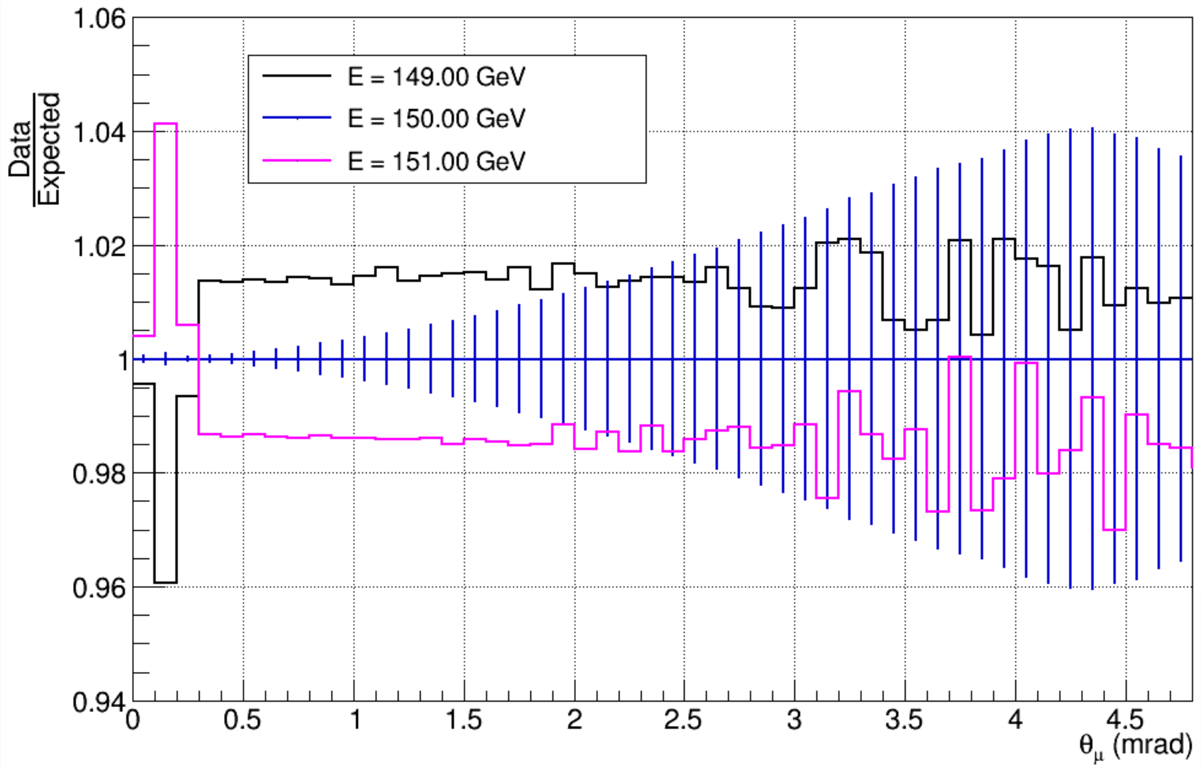




Normalization region

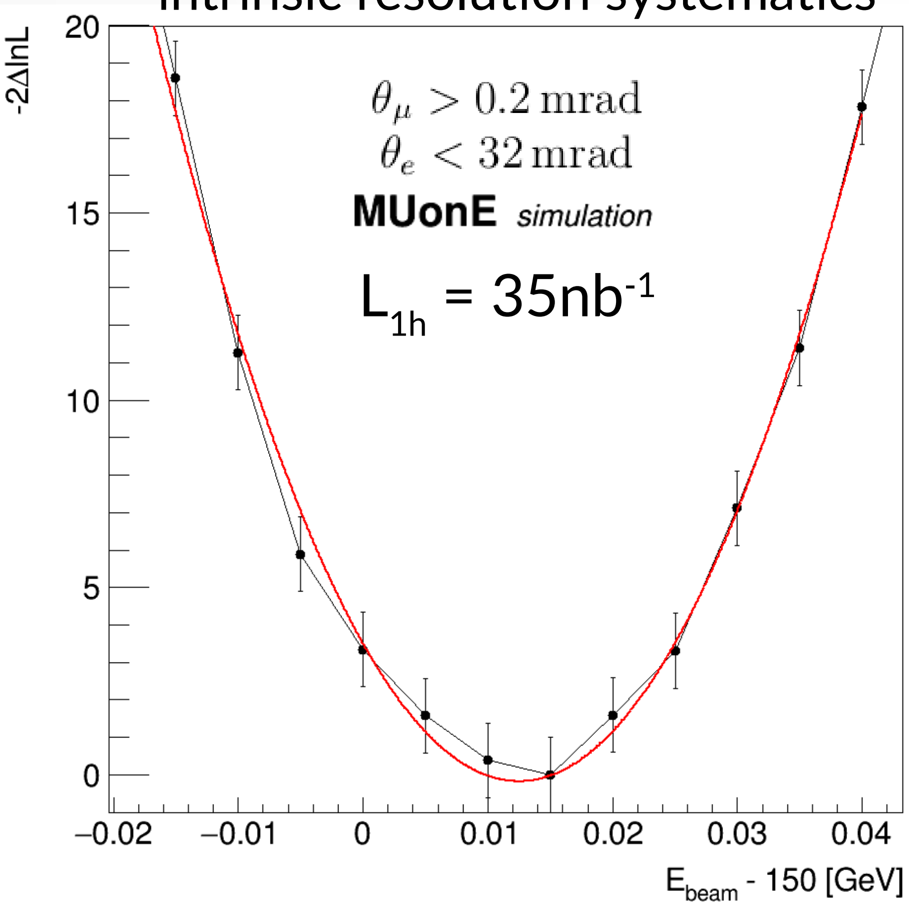
Calibration of the beam energy scale

Data/MC, L = 35 nb^{-1} (1h, 1station)



Template fit + systematics: the beam energy

E_{beam}: template fit parameter
μ_{Intr}: nuisance parameter for intrinsic resolution systematics



Data sample:

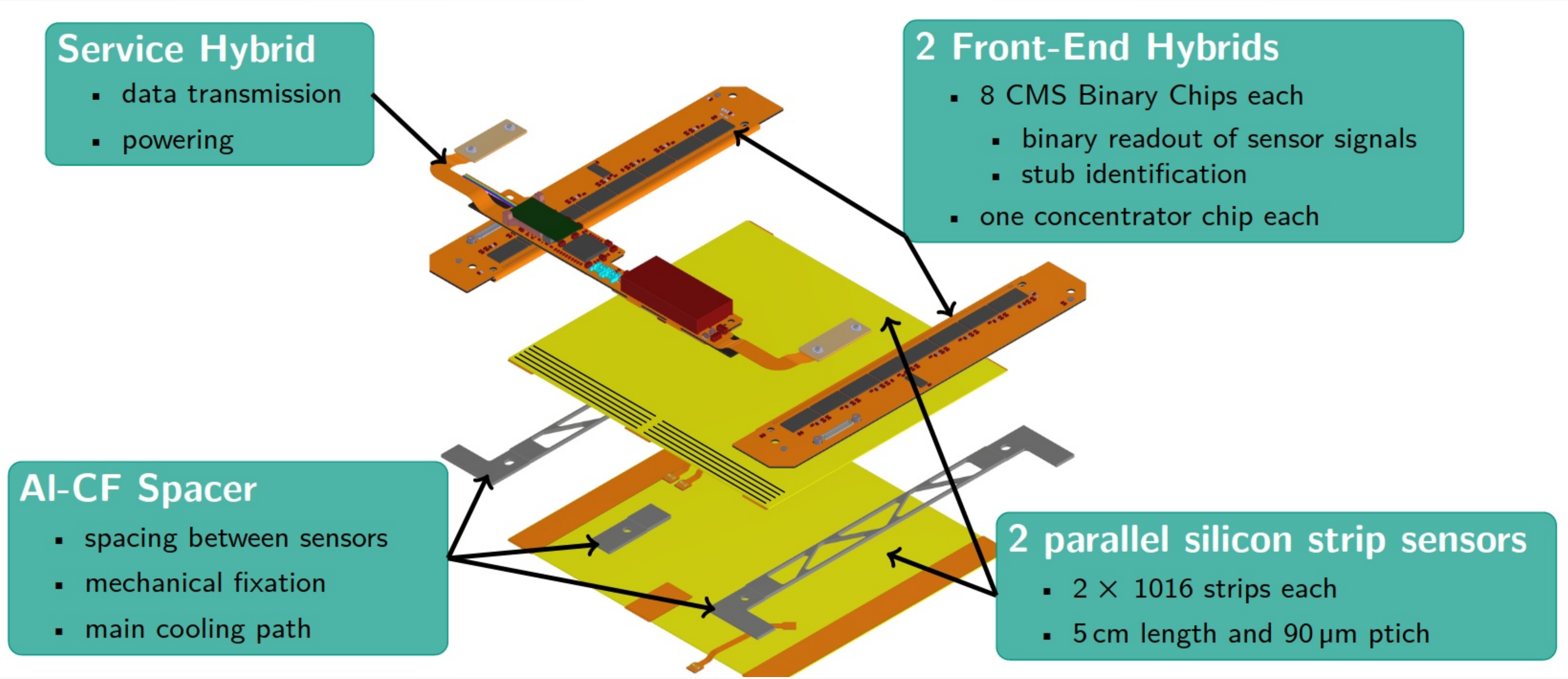
- E_{beam} = 150.012 GeV
- σ_{Intr} → σ_{Intr} + 5%

Selection cuts	Fit results
$\theta_\mu > 0.2\,\mathrm{mrad}$ $\theta_e < 32\,\mathrm{mrad}$	$E_{beam} = (150.012 \pm 0.007)$ GeV $\nu = 0.06 \pm 0.32$ $\mu_{Intr} = (5.2 \pm 0.1)\%$

Similar results also for distributions with no PID.

Perfect agreement with the input shifts!

CMS 2S modules

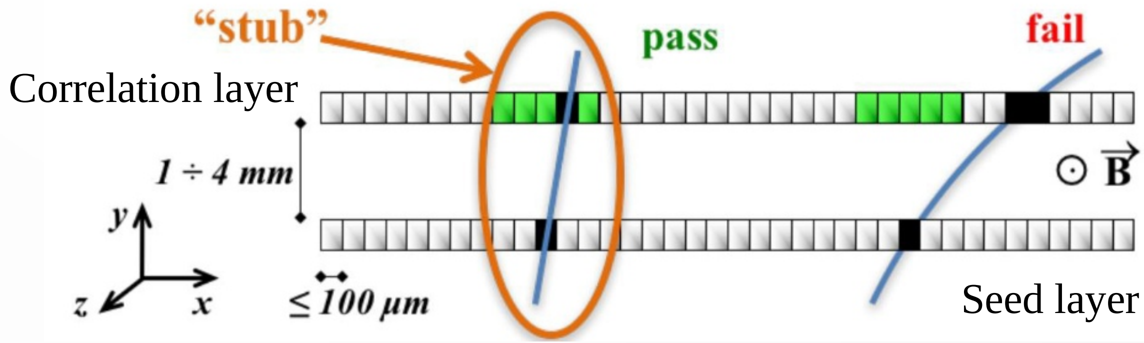


Picture from: Florian Wittig et al, iWoRiD 2022

CMS 2S modules: general concepts

CMS Tracker Phase2 Upgrade - TDR

The aim is to select only particles above a certain transverse momentum p_t for the 40 MHz readout.

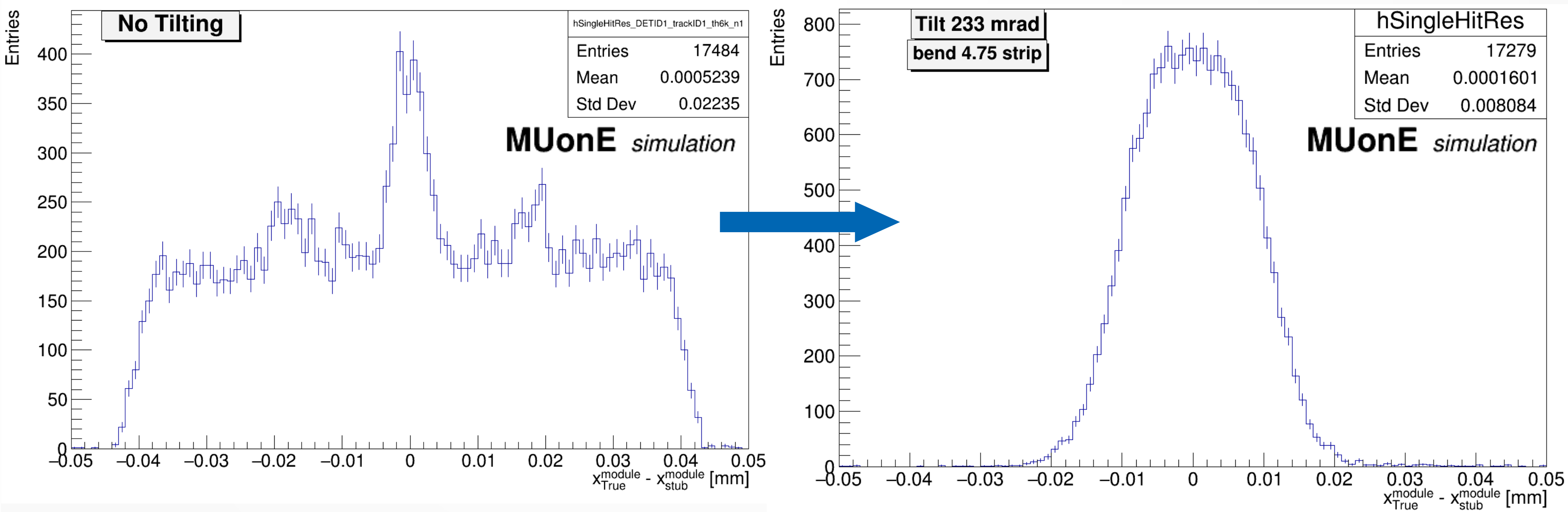


Free parameters which can be tuned in the front-end ASIC:

- Correlation window.
- Window offset.
- Max cluster width.

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

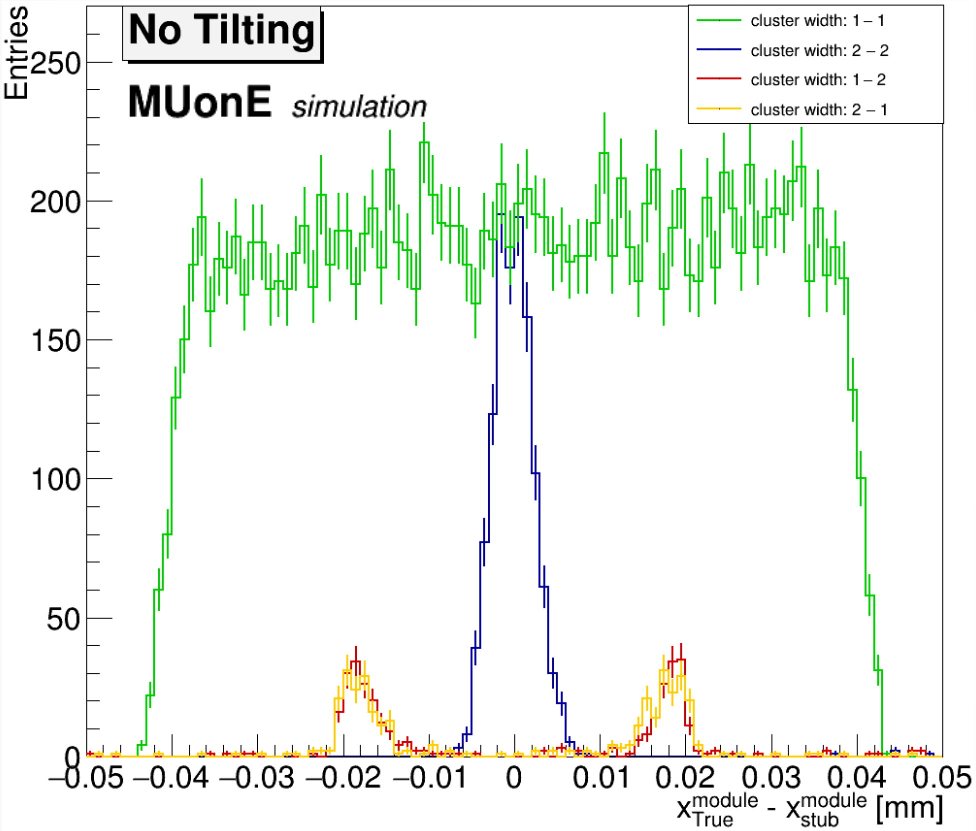


Improvement due to:

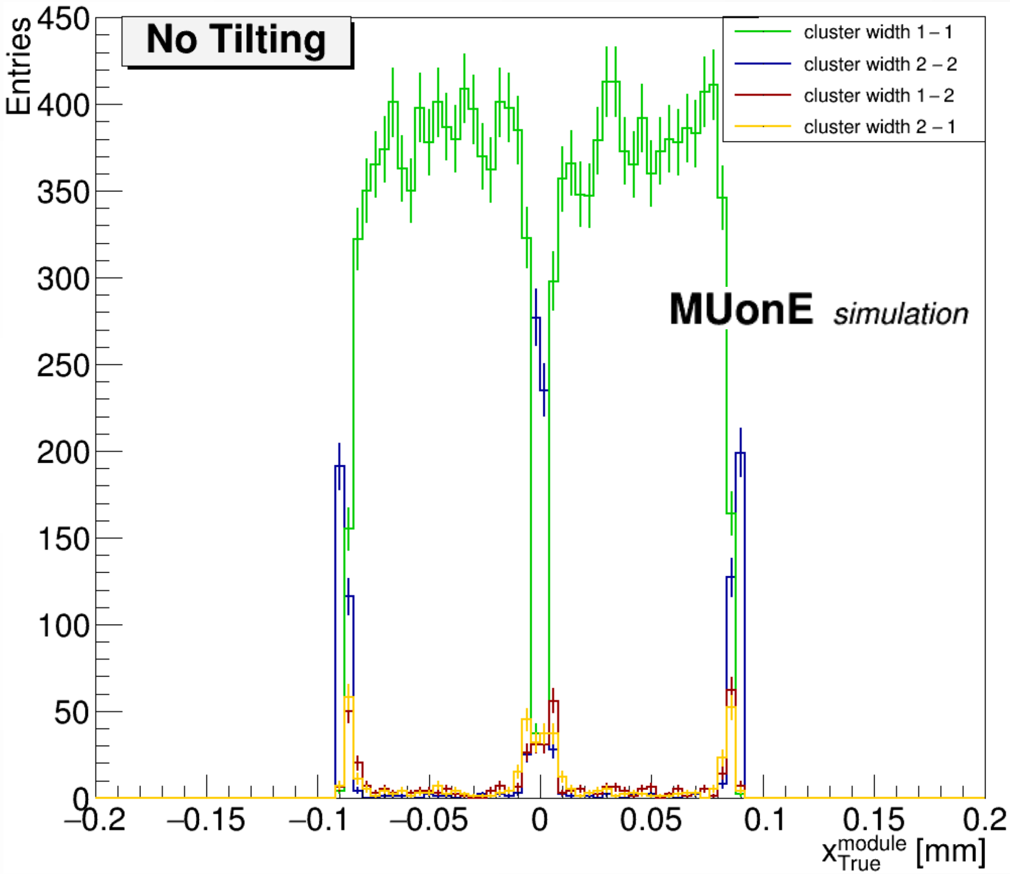
- charge sharing between adjacent strips
- effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

Final resolution

22 µm → 8-11 µm

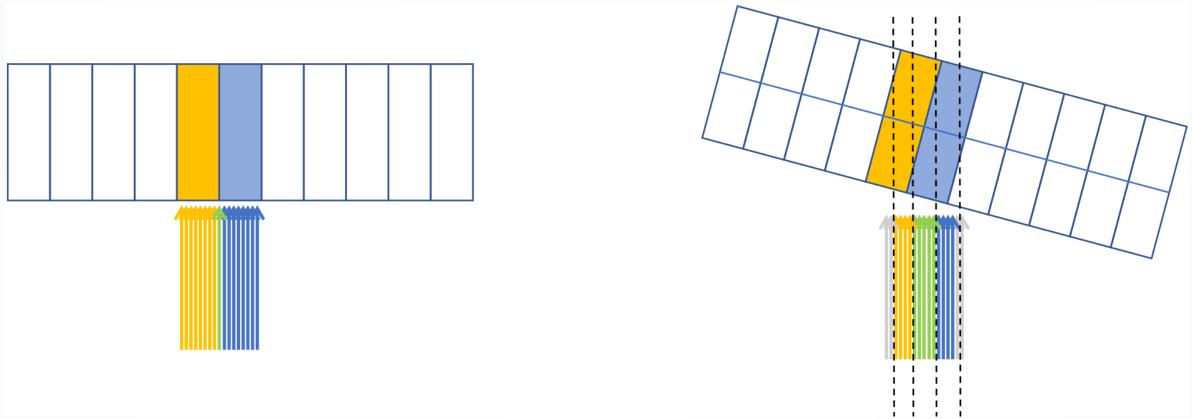


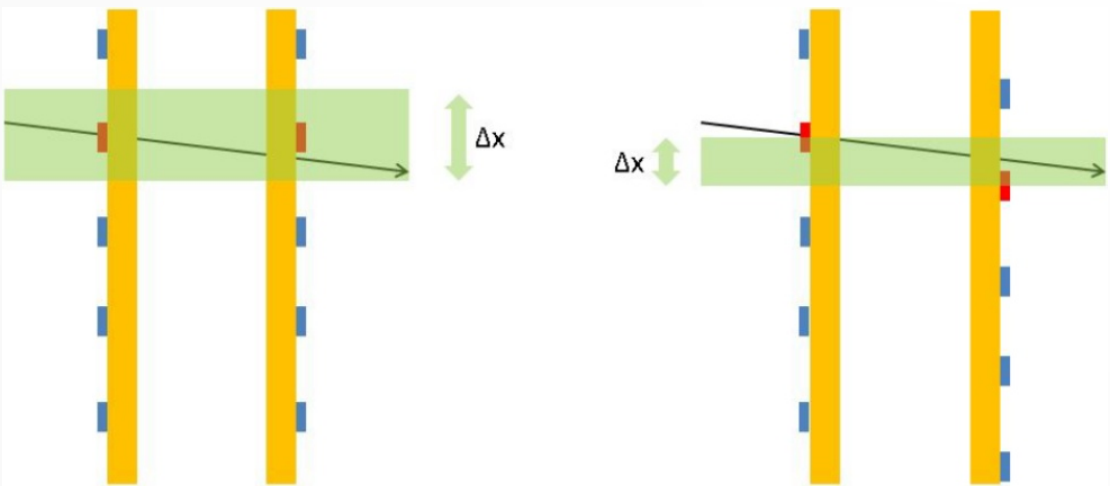
No Tilting
MUonE simulation
cluster width: 1 – 1
cluster width: 2 – 2
cluster width: 1 – 2
cluster width: 2 – 1
Entries
x_{True}^{module} - x_{stub}^{module} [mm]



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]

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





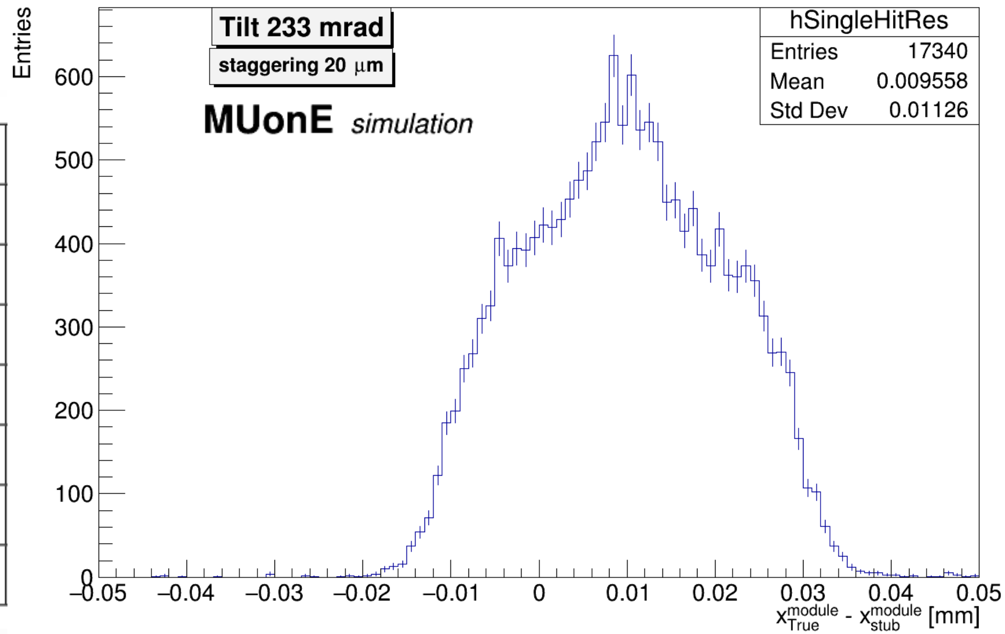
2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch

MUonE simulations:
Improving resolution - tilted geometry

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

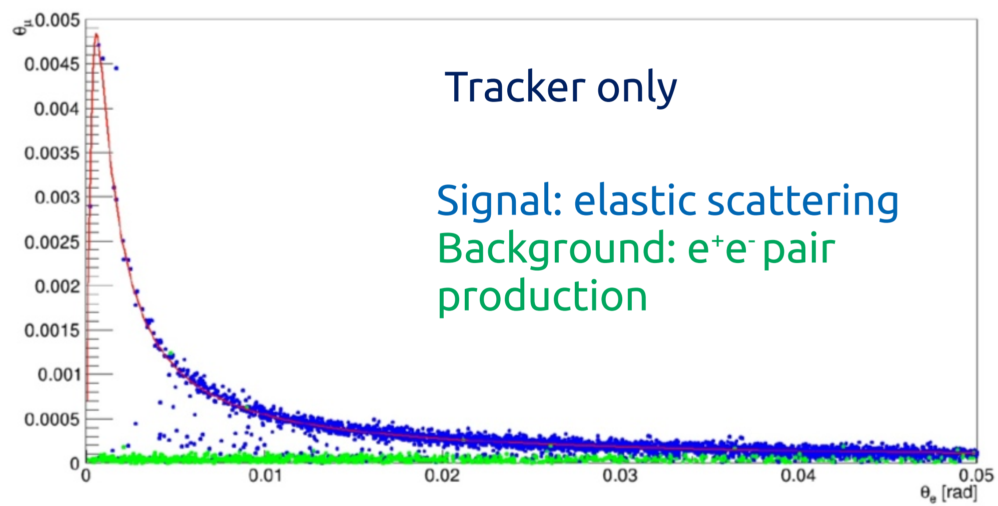
Effect of a staggering between the two sensors

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

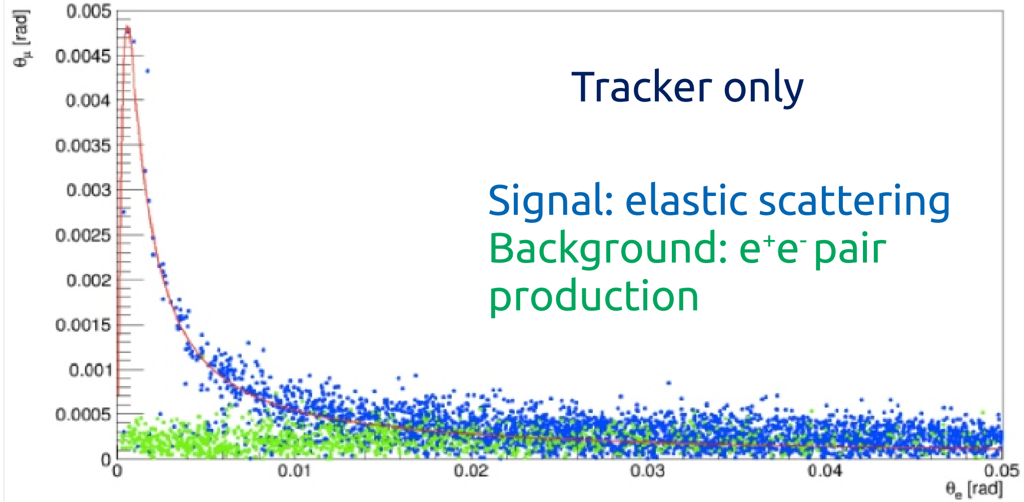


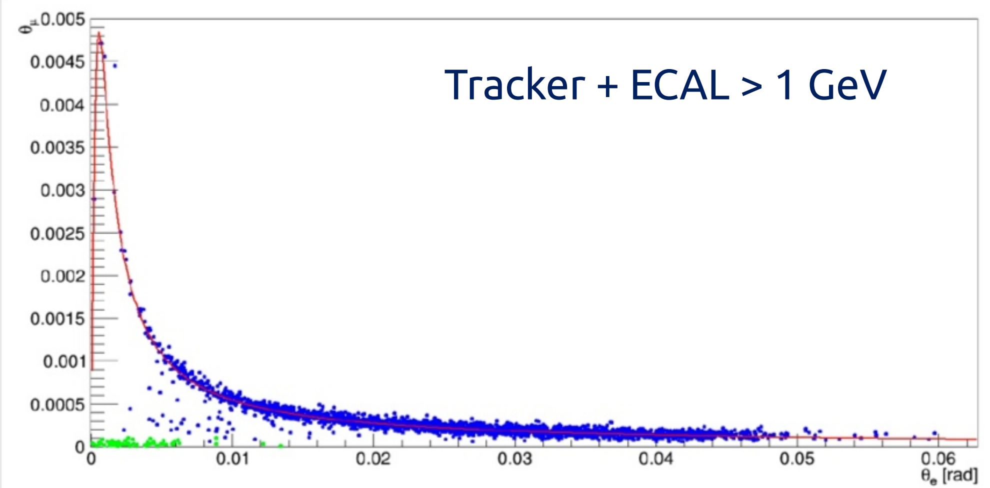
GEANT4 simulations

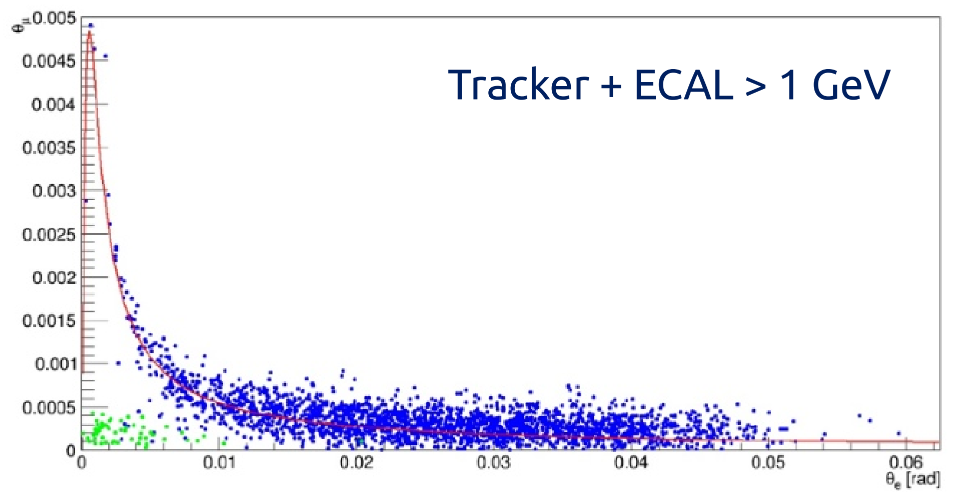
TB2017 (resolution ~7μm)



TB2018 (resolution ~40μm)





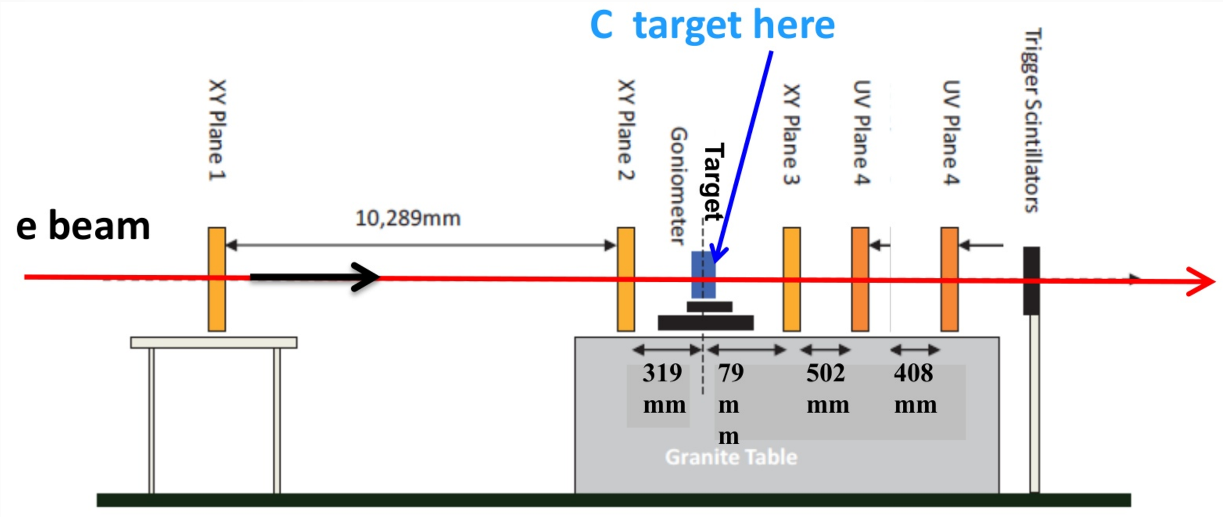


Multiple scattering: results from TB2017

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

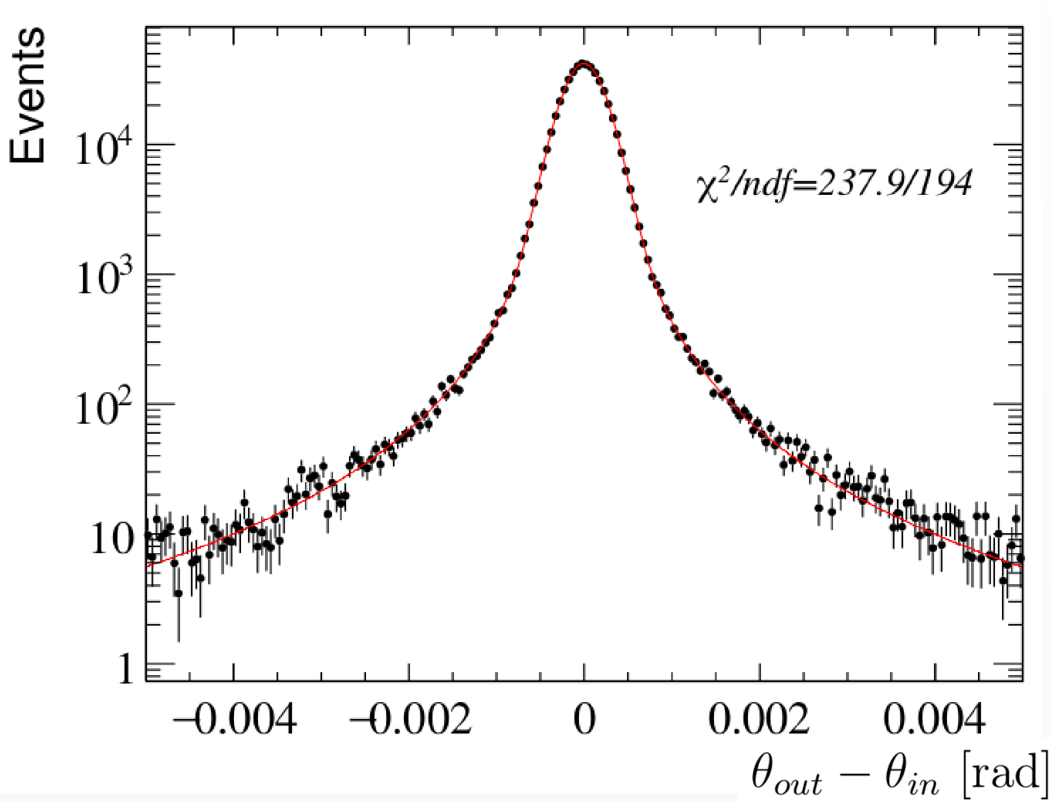
Main goals:

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



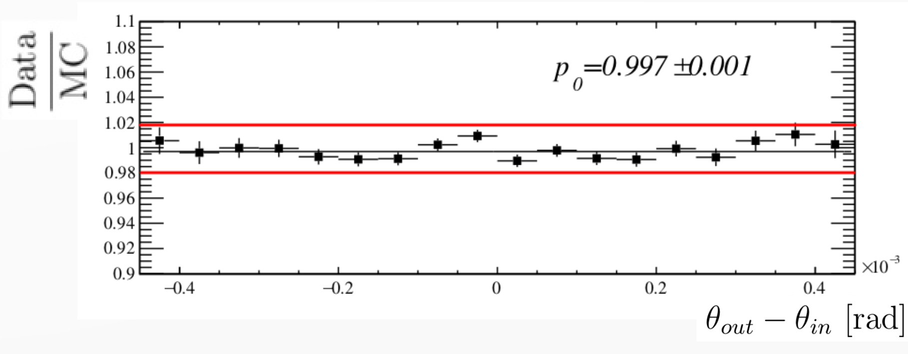
Multiple scattering: results from TB2017

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



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

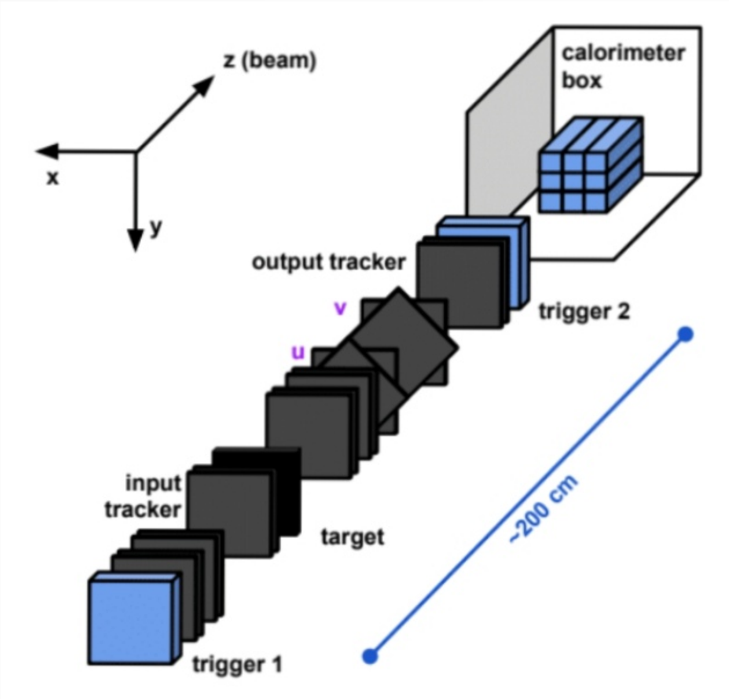
Results show a ~1% agreement between data and MC for the Gaussian core

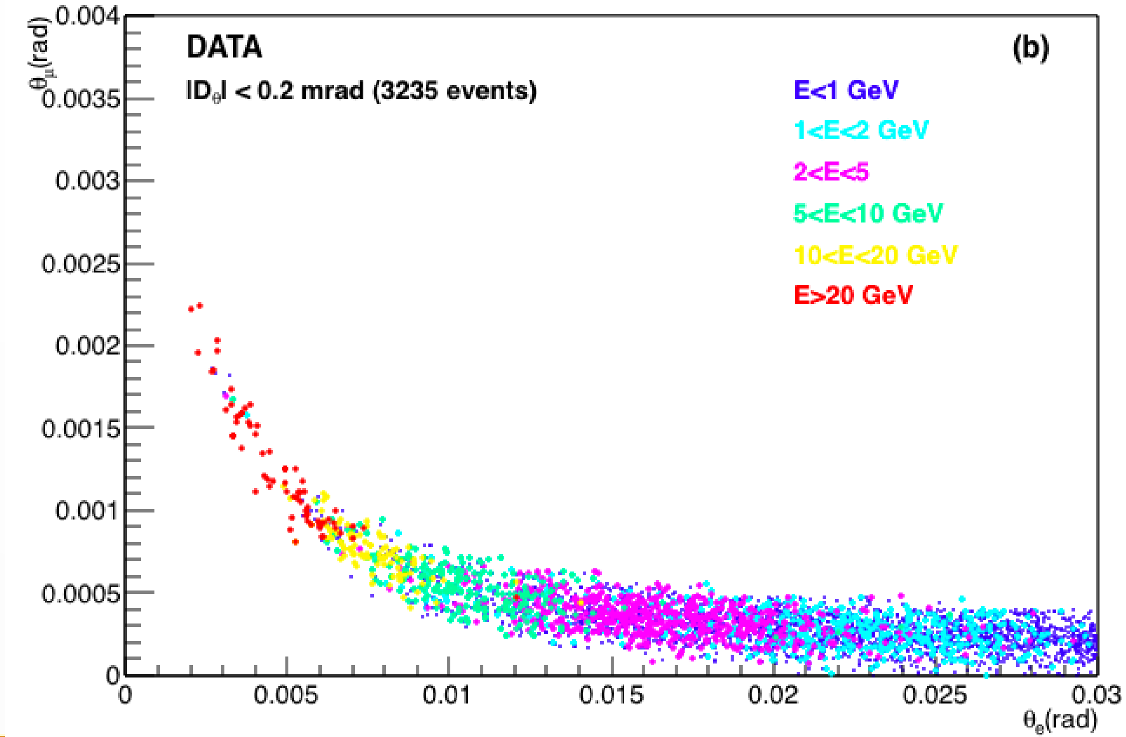


Test Beam 2018

Abbiendi et al, JINST 16 (2021) P06005

- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. $2.1 \times 2.1 cm^2$, 23 cm length





First evidence of elastic scattering.