UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

The MUonE experiment

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University of Liverpool

MUonE

Meeting of the Muon Group
1st June 2023

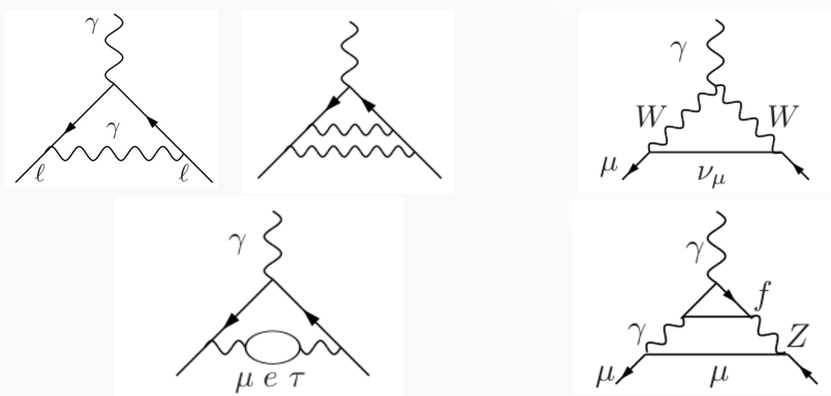
The muon g-2: Standard Model calculation

$$a_\mu^{\mathrm{SM}} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HAD}}$$

High precision calculations using perturbation theory

$$a_\mu^{\mathrm{QED}} = 116\ 584\ 71.8931(104) \times 10^{-10}$$

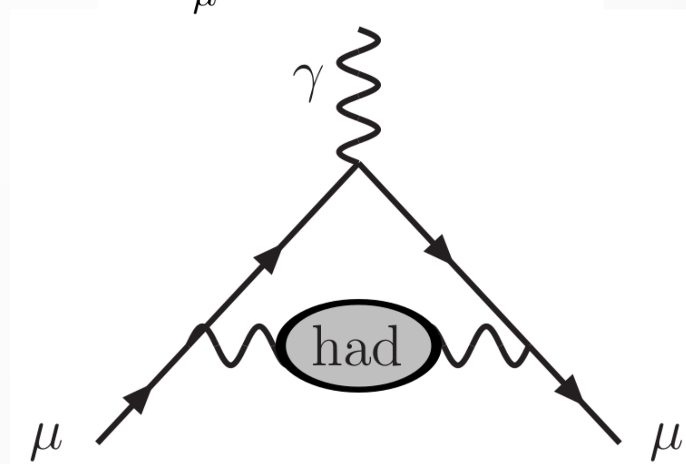
$$a_\mu^{\mathrm{EW}} = (15.36 \pm 0.10) \times 10^{-10}$$



a_μ^{HLO} is the leading order term

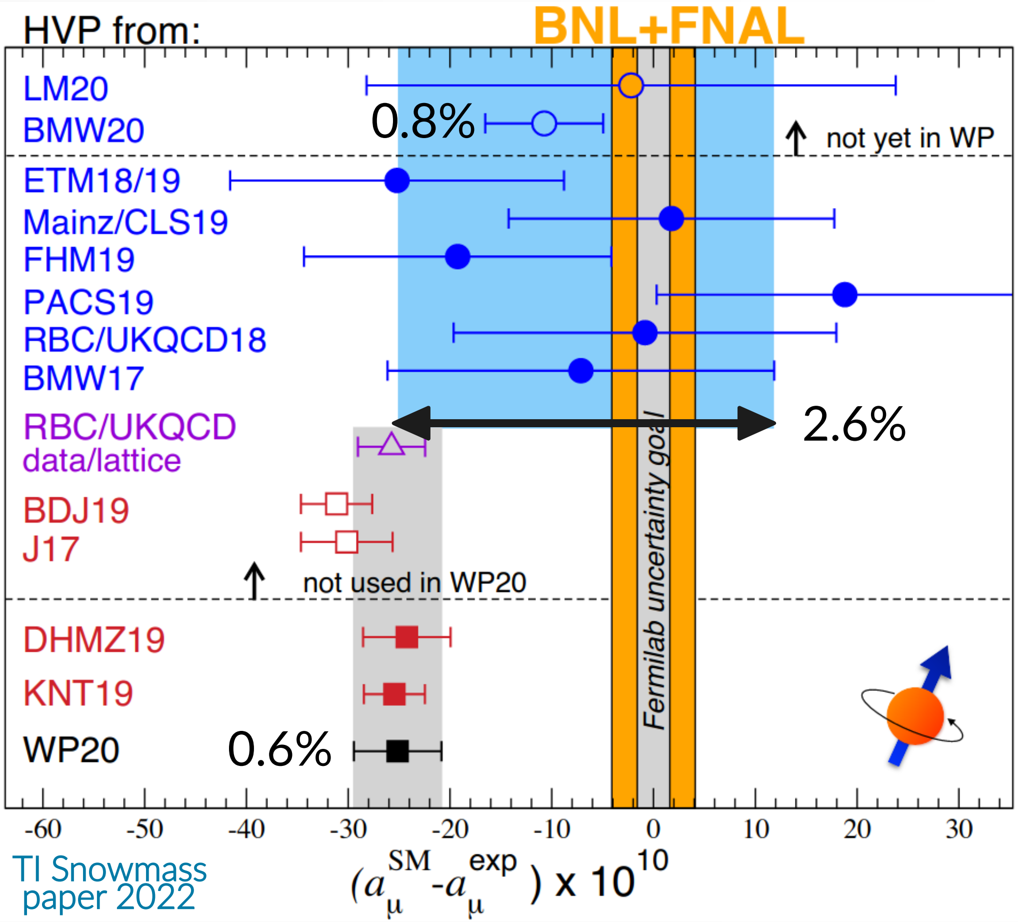
$$a_\mu^{\mathrm{HLO}} \sim 690 \times 10^{-10}$$

$$\Delta a_\mu^{\mathrm{HLO}} \sim 4 \times 10^{-10}$$



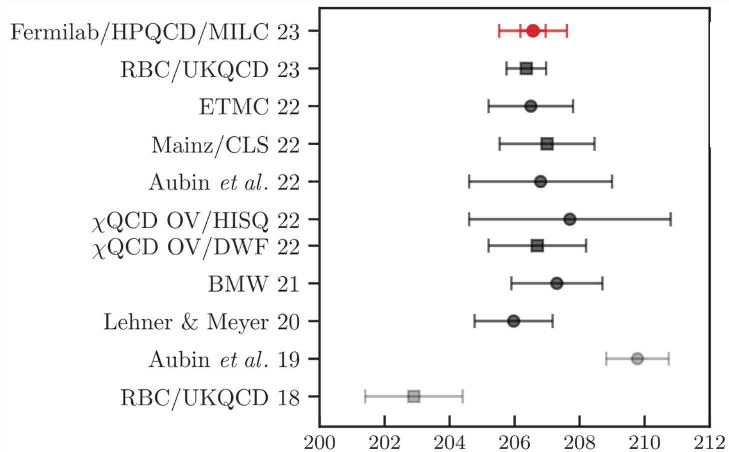
Perturbation theory cannot be used for this contribution

a_μ^{HLO} : present status



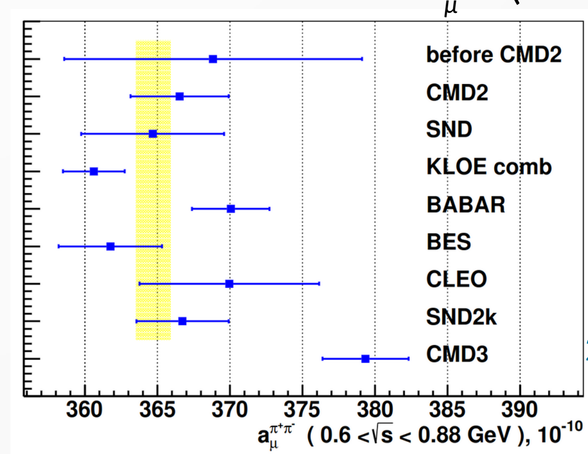
TI Snowmass paper 2022

New lattice results in the intermediate window (~30% a_μ^{HLO}):



Fermilab/HPQCD/MILC 2301.08274

New CMD3 result for $a_\mu^{HLO}(\pi^+\pi^-)$



2302.08834

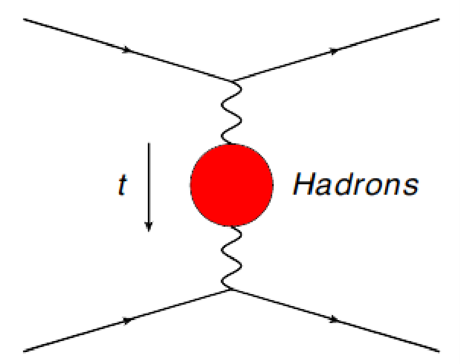
a_μ^{HLO} : space-like approach

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

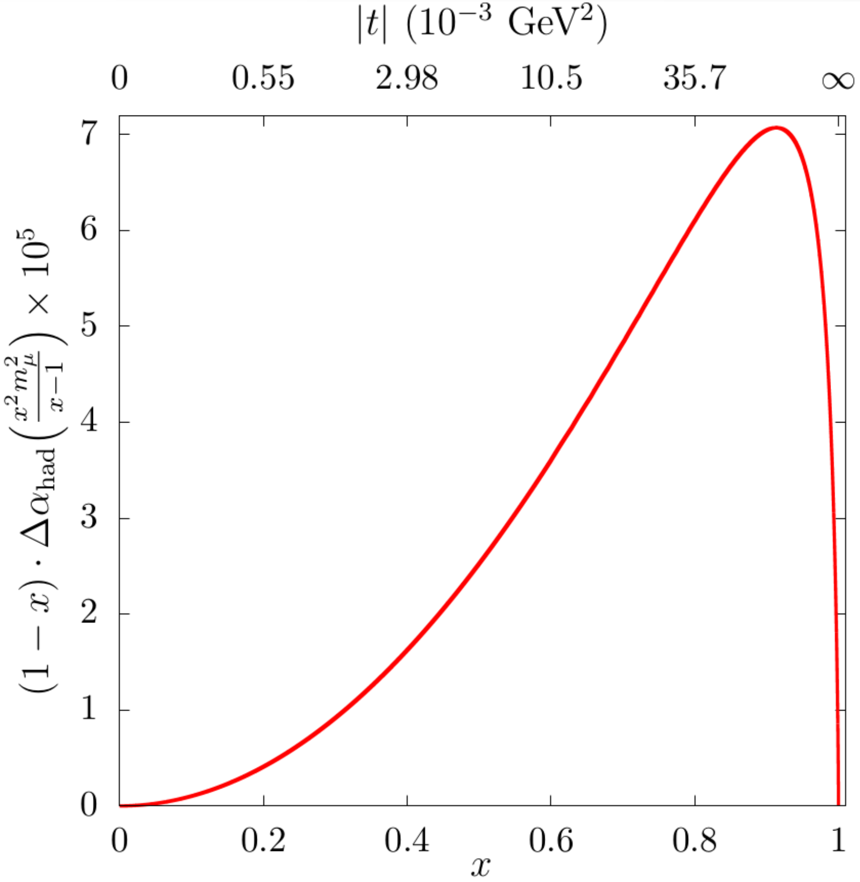
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

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

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



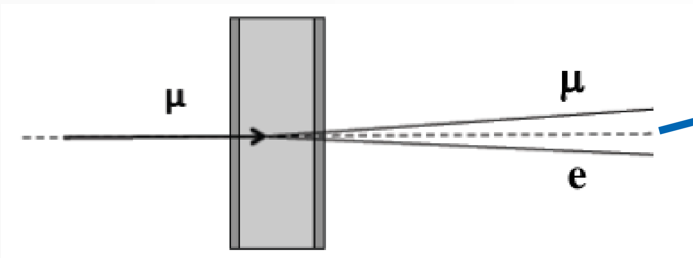
Based on the measurement of $\Delta\alpha_{\rm had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.



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

The MUonE experiment

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

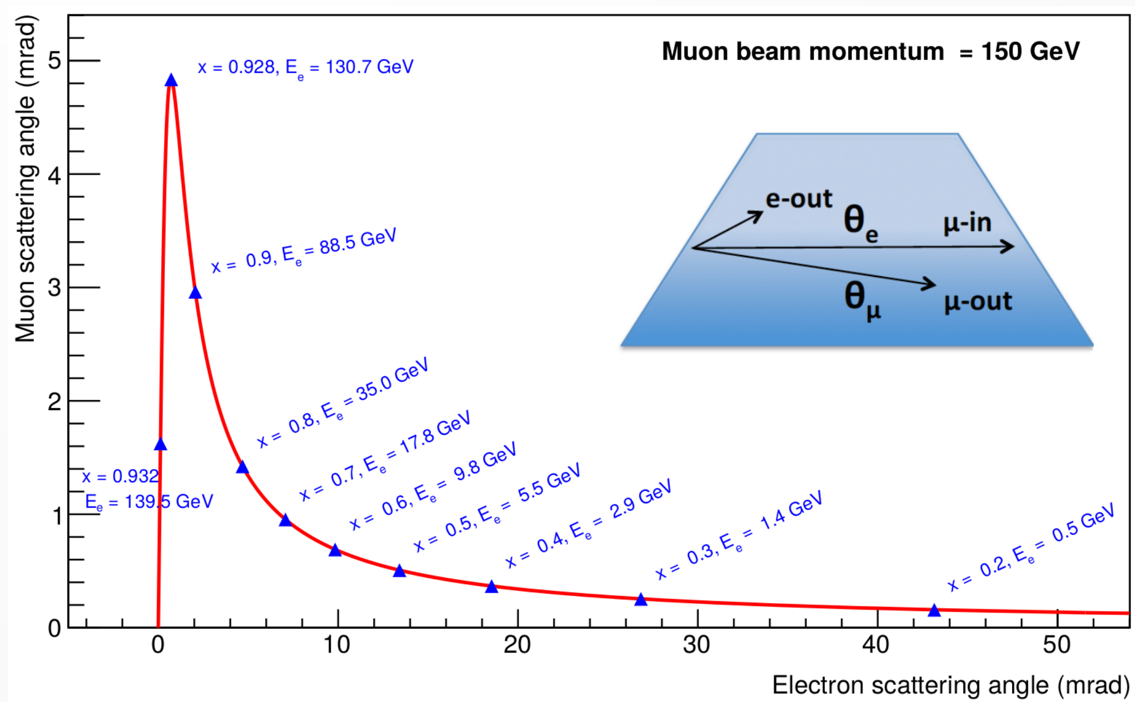


$$\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

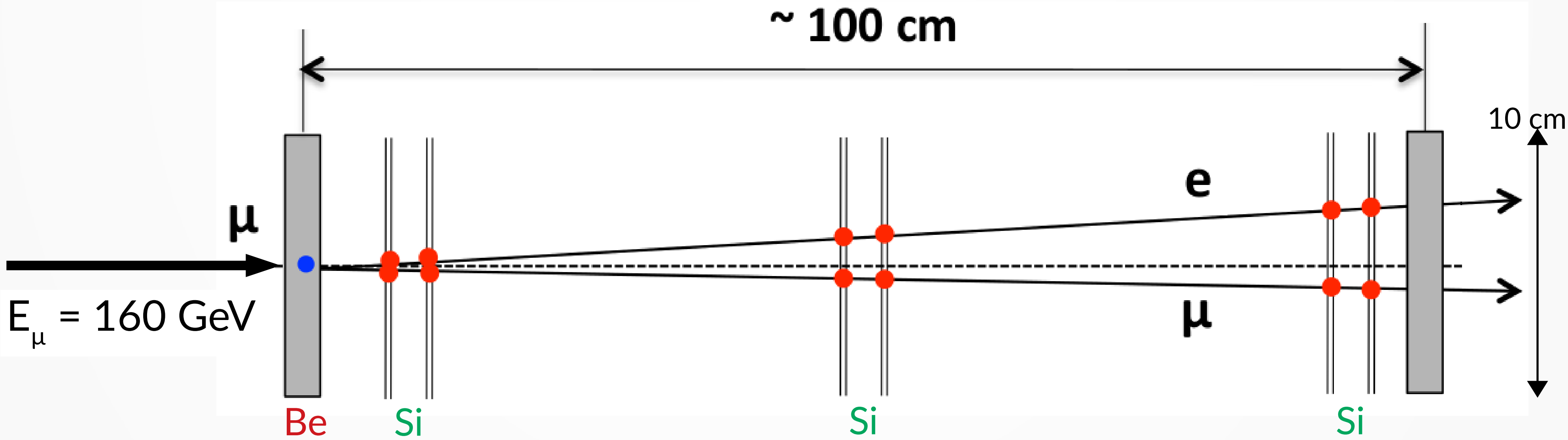
From theoretical calculation

To be measured

- A beam of 160 GeV muons allows to get the whole $a_\mu^{\rm HLO}$ (88% directly measured + 13% 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.

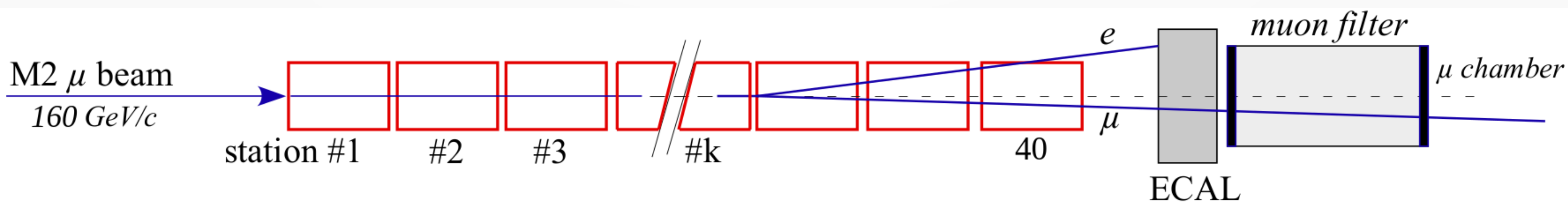


The experimental apparatus



Beryllium target
1.5 cm thickness

Tracking system:
6 silicon strip detectors



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking (~4×10^{12} events $E_e > 1$ GeV) =

~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

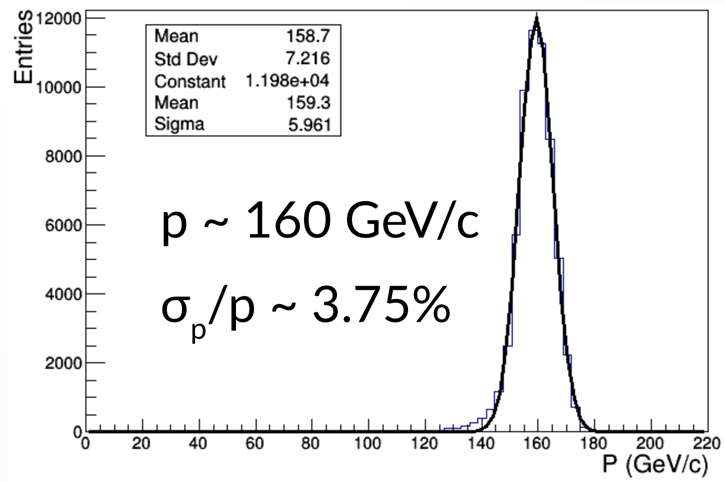
Systematic uncertainty of 10 ppm in the signal region.

Systematic effects, some examples:

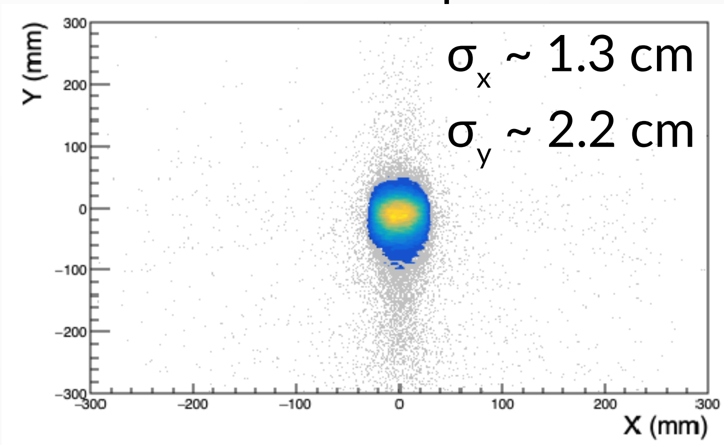
- Longitudinal alignment (~10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering
- Angular intrinsic resolution
- Theory: MC @NNLO

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).

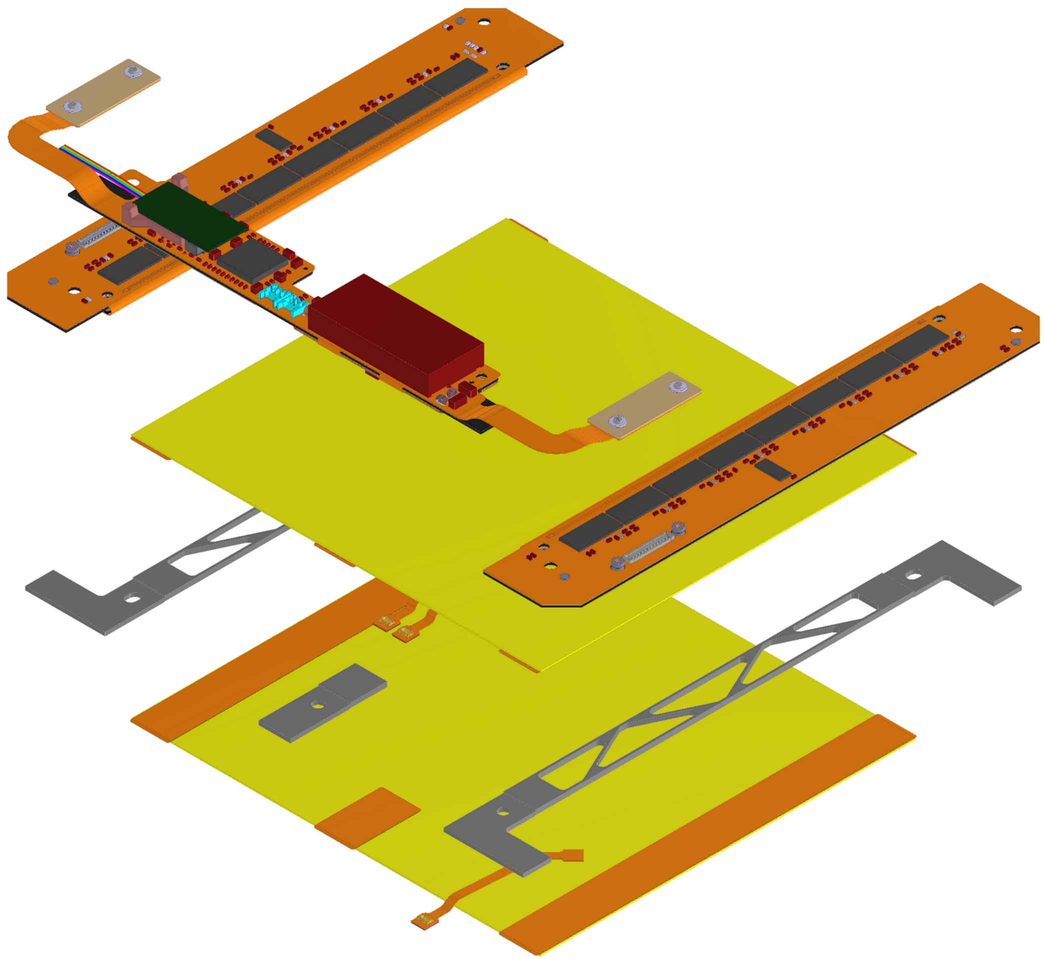
Tracker: CMS 2S modules

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

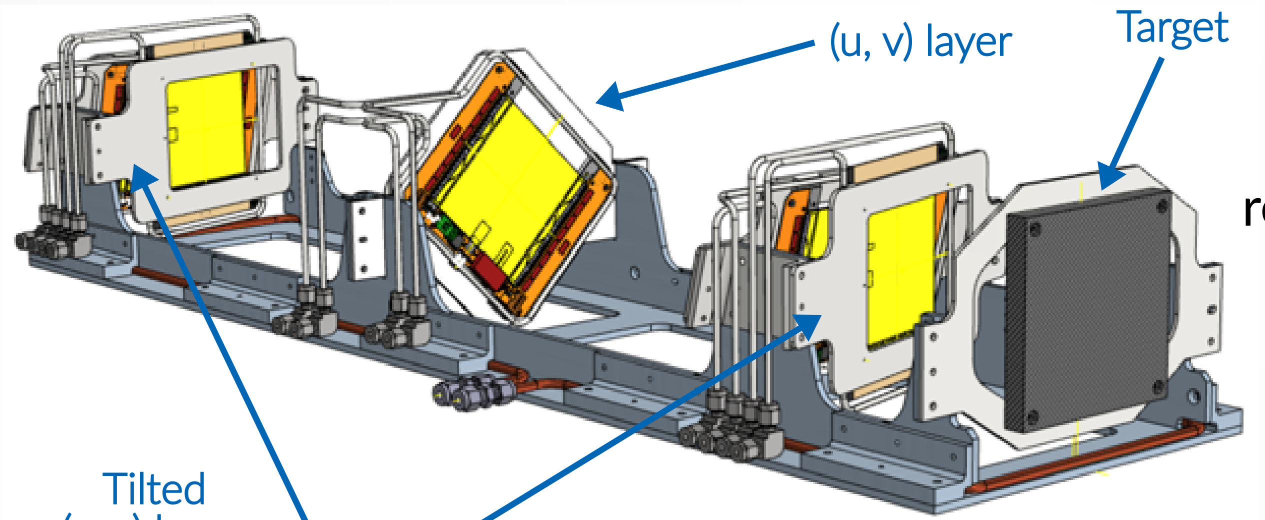
Two close-by strip sensors reading the same coordinate:

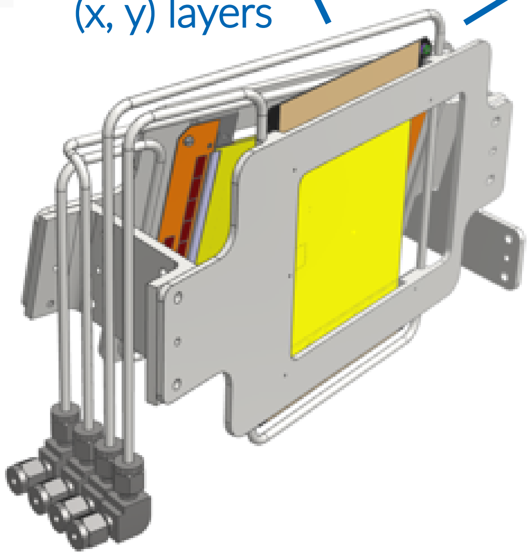
- Suppress background of single sensor hits.
- Reject large angle tracks.

  - Pitch: 90 µm
  - Digital readout
  - Readout rate: 40 MHz
  - Sensitive area: 10×10 cm^2
  - Thickness: 2 × 320 µm



Tracking station





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

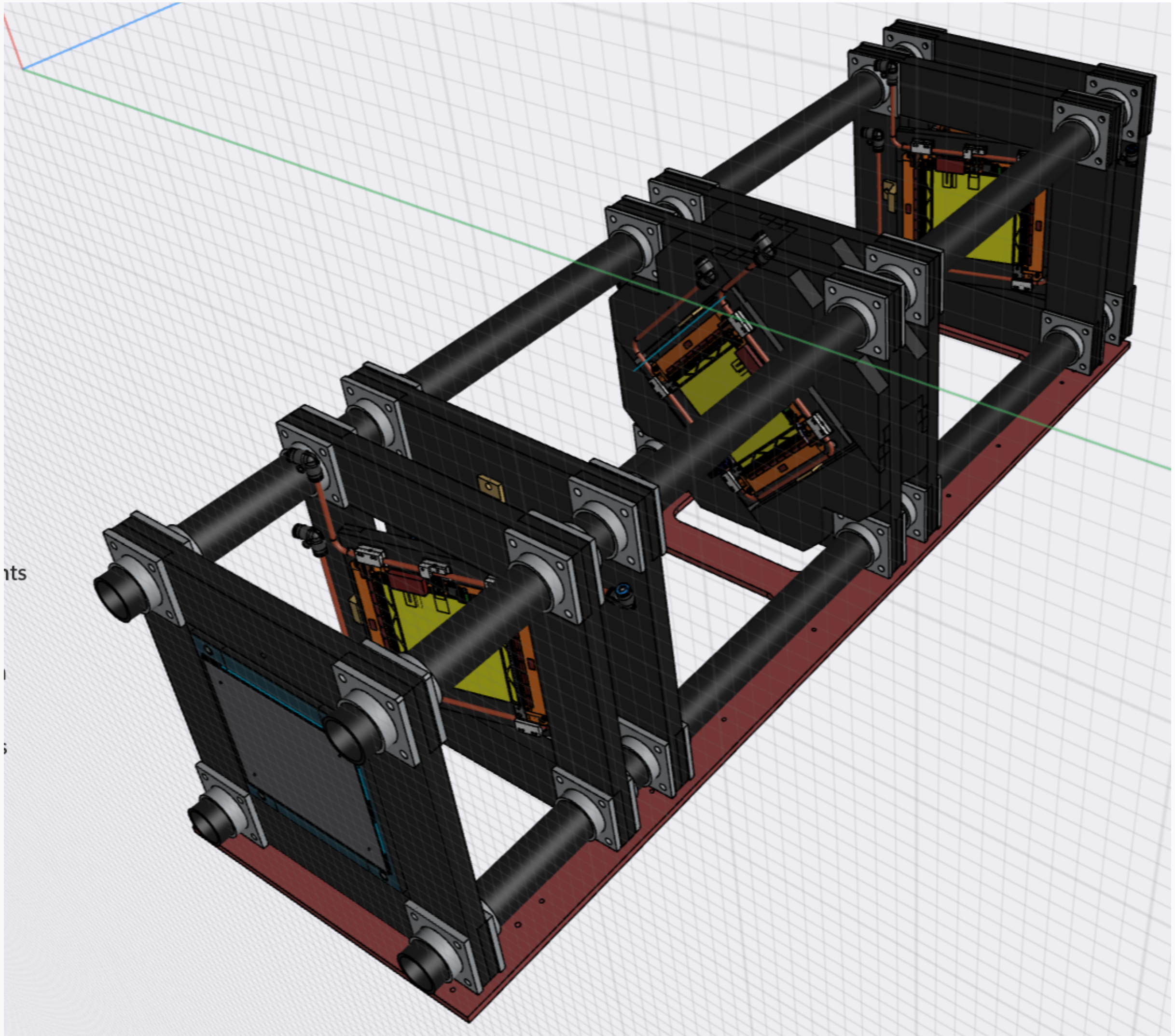
↓

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

Laser holographic system
to monitor stability.

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

Tracking station

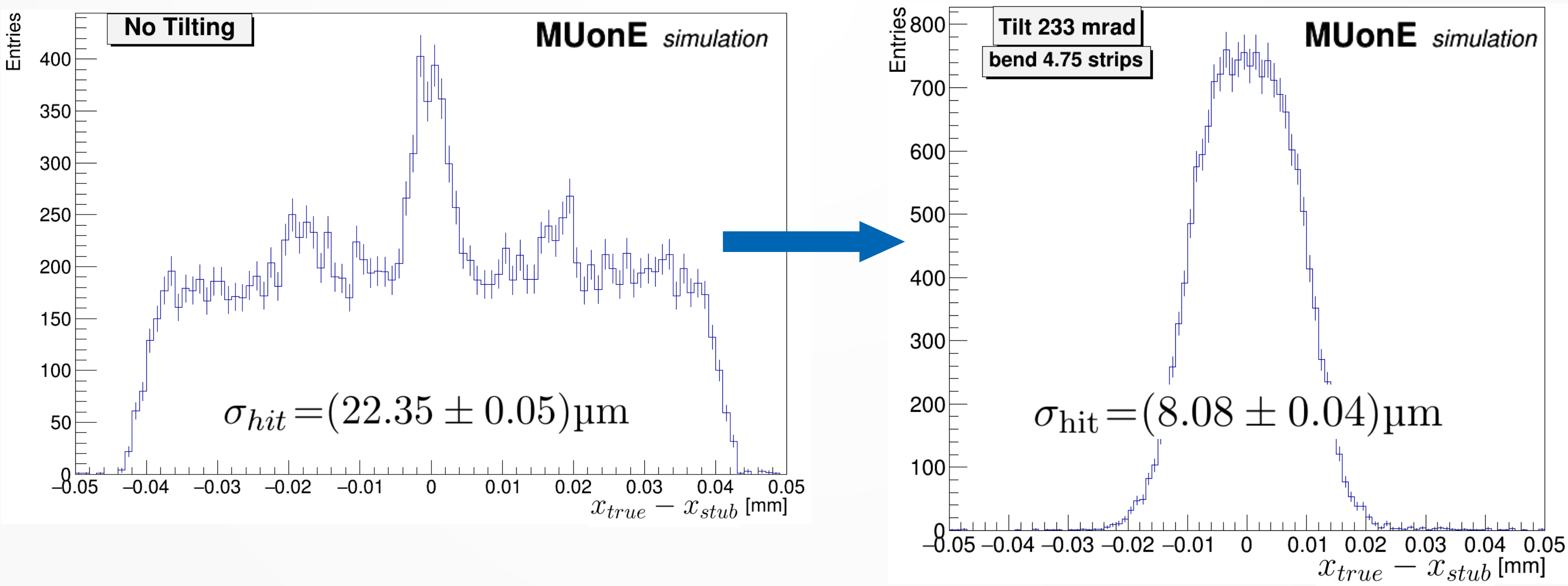


A new design under development at Liverpool.

Carbon Fiber tubes for the mechanical structure: (sub ppm) 0 CTE along the longitudinal direction.

First prototype to be assembled in the next weeks.

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.

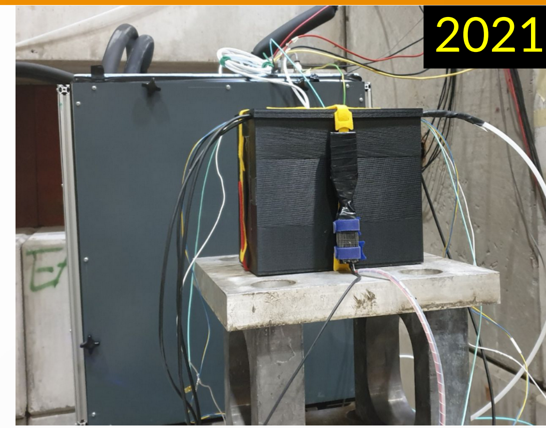
Final resolution

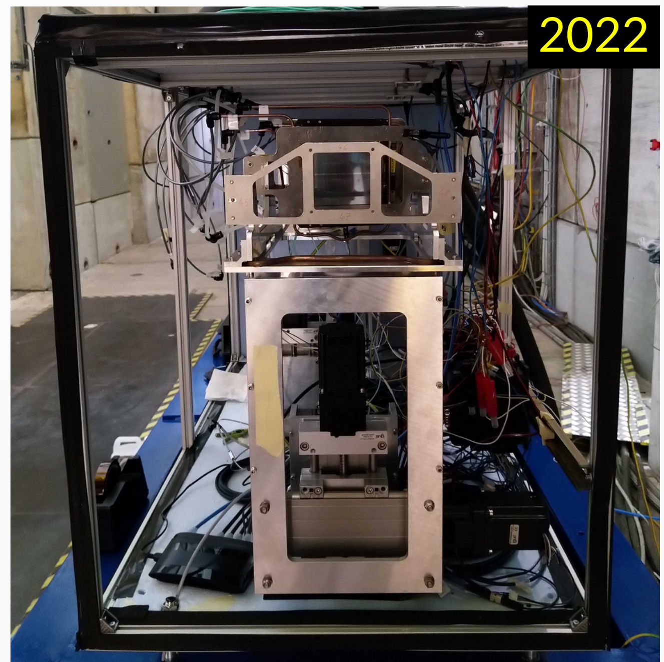
22 µm → ~10 µm

Beam Test 2021-2022

- Fall 2021: parasitic beam test.
  - Low beam rate (~10kHz).
  - 2 modules in the MUonE station +
    2 modules in an external box.
- Summer 2022: intermittent beam test at the final MUonE location.
  - 4 modules in the MUonE station.
- October 2022: 1 week beam test as main users.
  - Fully equipped tracking station + ECAL.

Positive results on the thermal stability of the tracking system and the 2S modules synchronization.

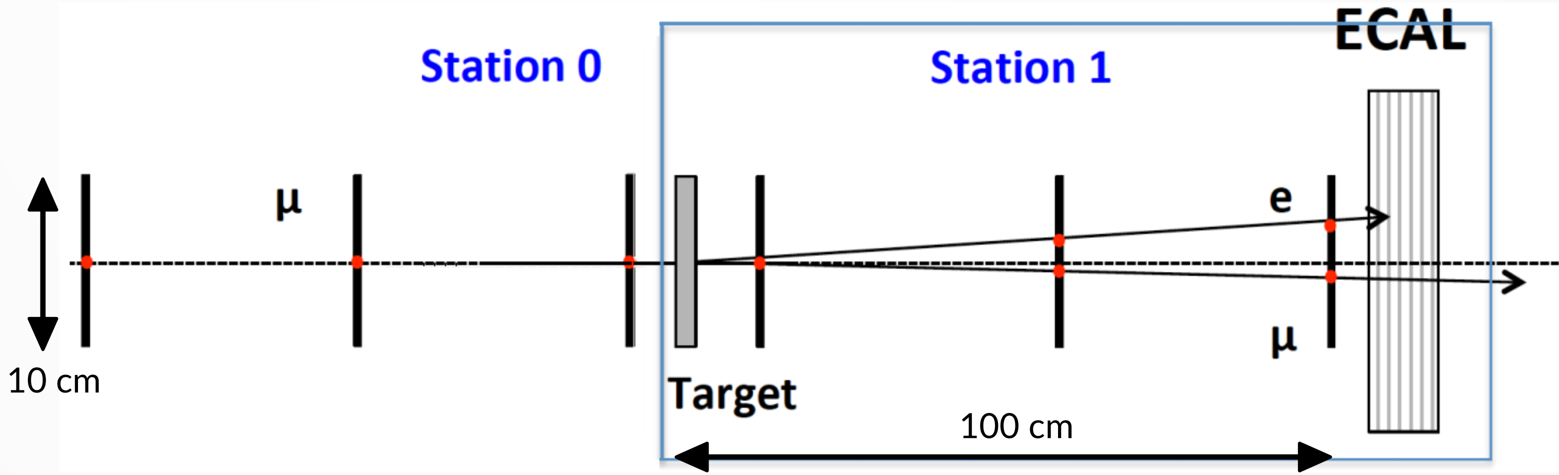




Test Run 2023

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

- Pretracker +
- 1 station +
- ECAL

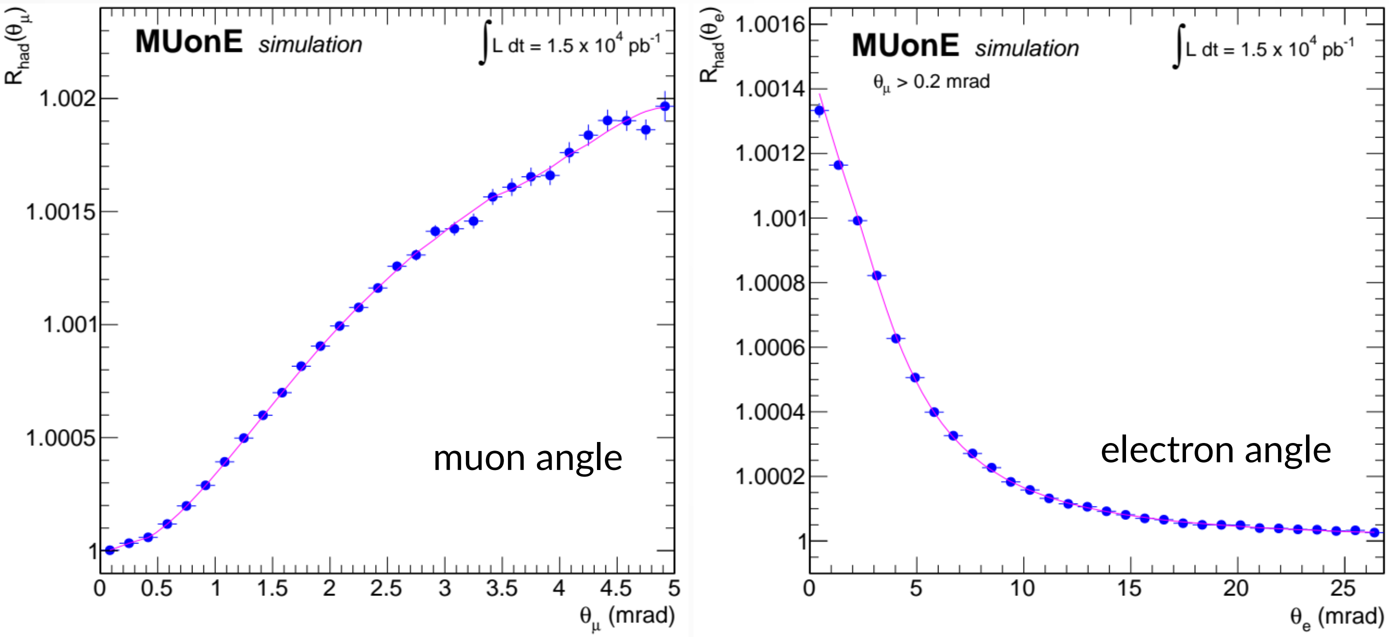


Main goals:

- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Test the detector performance.
- Assess the strategy for the systematic errors.
- Measure $\Delta\alpha_{lep}(t)$ with a few % precision.

→ Test the analysis strategy

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



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

$$R_{had} \sim 1 + 2\Delta\alpha_{had}(t)$$

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

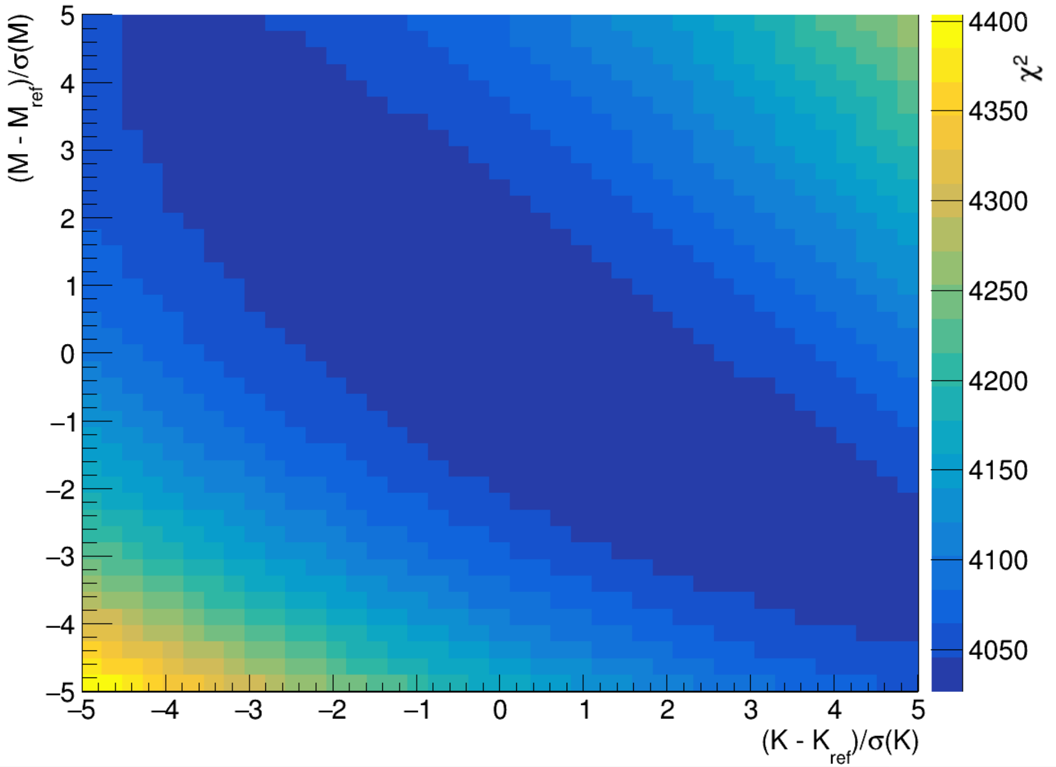
$\Delta\alpha_{had}(t)$ parameterization: inspired from the 1 loop QED contribution at $t < 0$:

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

2 parameters: K, M

Calculation of a_μ^{HLO}

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



Simulation
@ final luminosity: 1.5×10^4 pb^{-1}

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

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

(0.35% stat error)

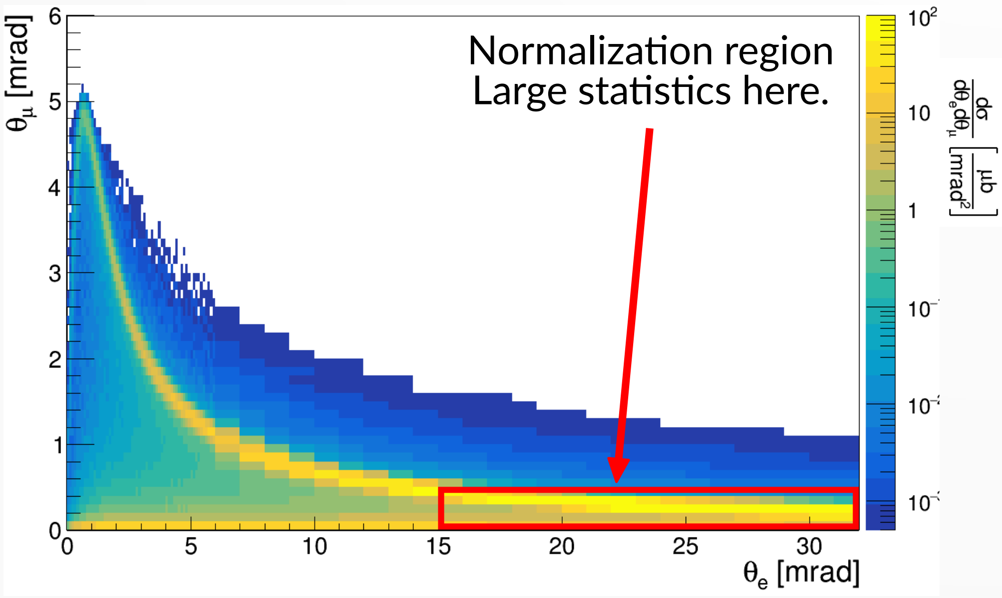
Input value:

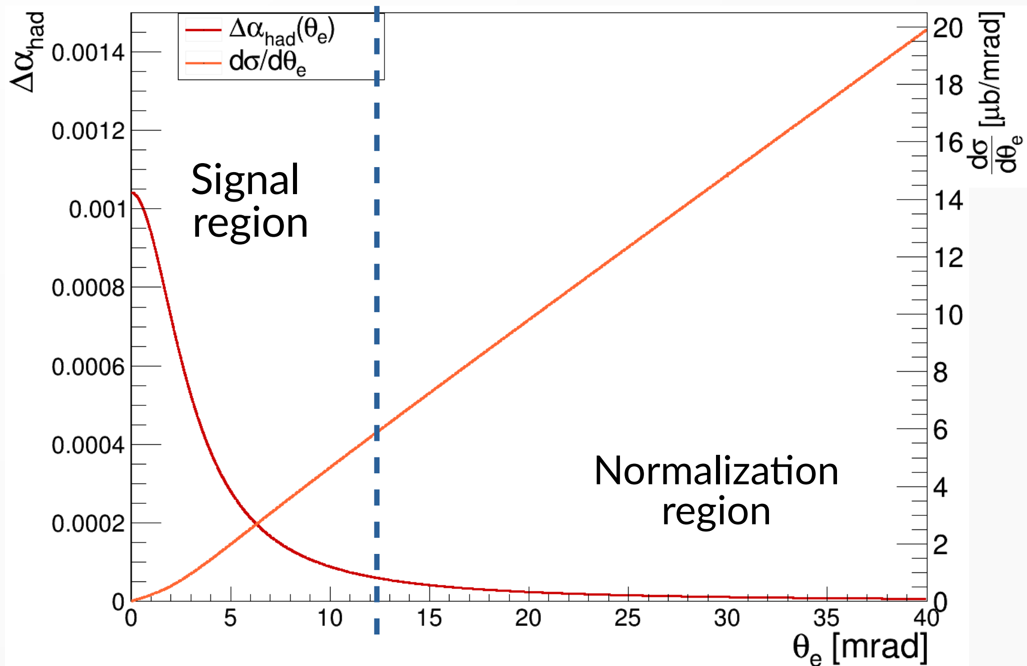
$$a_\mu^{\mathrm{HLO}} = 688.6 \times 10^{-10}$$

Strategy for the systematic effects

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

- Multiple scattering model.
- Detector angular resolution.
- Beam energy scale.





Example: systematic error on the multiple scattering

G. Abbiendi et al JINST (2020) 15 P01017

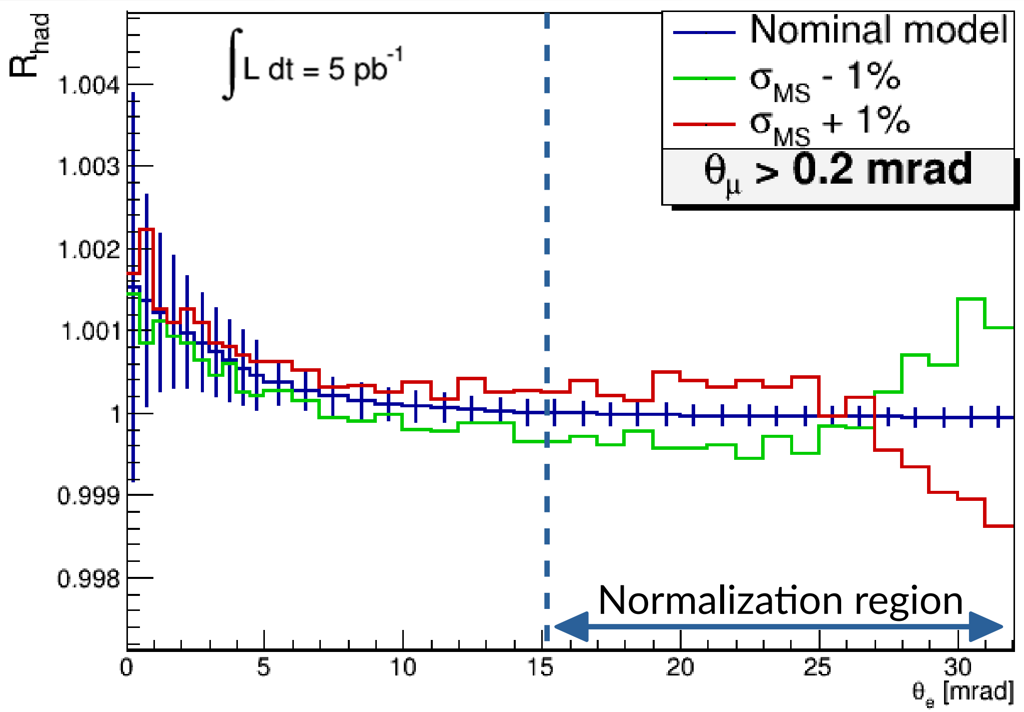
Expected agreement data/MC on the core of multiple scattering: ± 1%

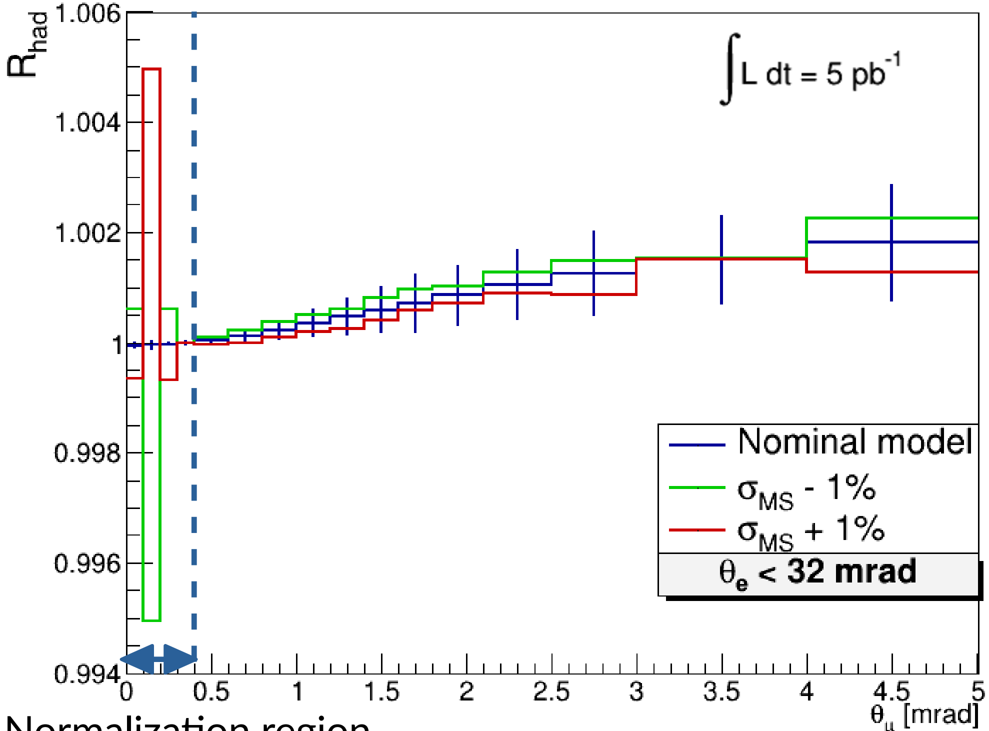
PDG parameterization:

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

x = target thickness

X_0 = radiation length



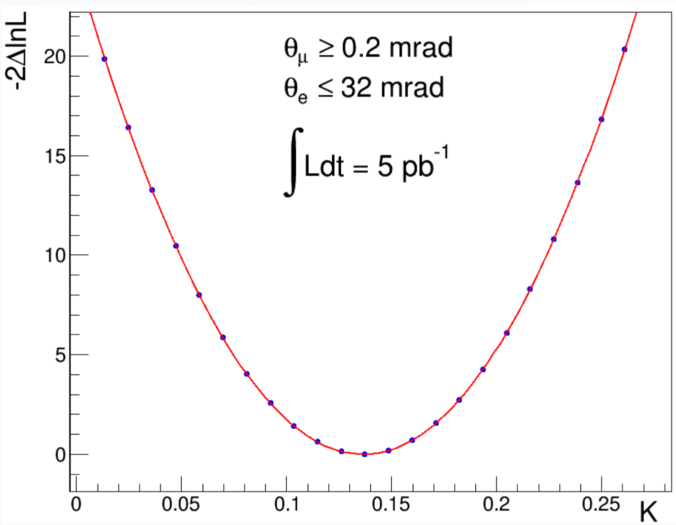


Normalization region

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

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

Next steps:

- Test the procedure using the FullSim (TB23 $\Delta\alpha_{lep}(t)$ ideal for this).
- Improve the modelization of systematic effects.
- Move to the final statistics.

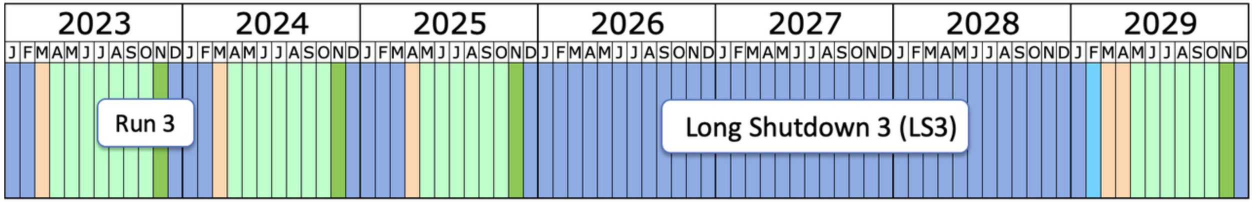
Time schedule

- 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 1 tracking station + ECAL.

- Towards the full experiment: 5-10 stations before LS3 (2026).
  2-4 months data taking: first measurement (few % precision) of a_μ^{HLO}.

- After LS3 (>2029) 3 years of running with the full apparatus (40 stations)
  to reach the aimed precision on a_μ^{HLO} (~0.3% stat, same syst)



MUonE activity in Liverpool

- Hardware:
  - Mechanical structure made of Carbon Fiber (0 CTE in the longitudinal direction).

- Simulation & Analysis:
  - Upgrade of the Beam Magnet Spectrometer (BMS) at the M2 beamline → precise determination of the beam energy profile.
  - Signal contamination due to pair production background.
  - Development of the final analysis strategy to extract $\Delta\alpha_{had}$.

MUonE group:

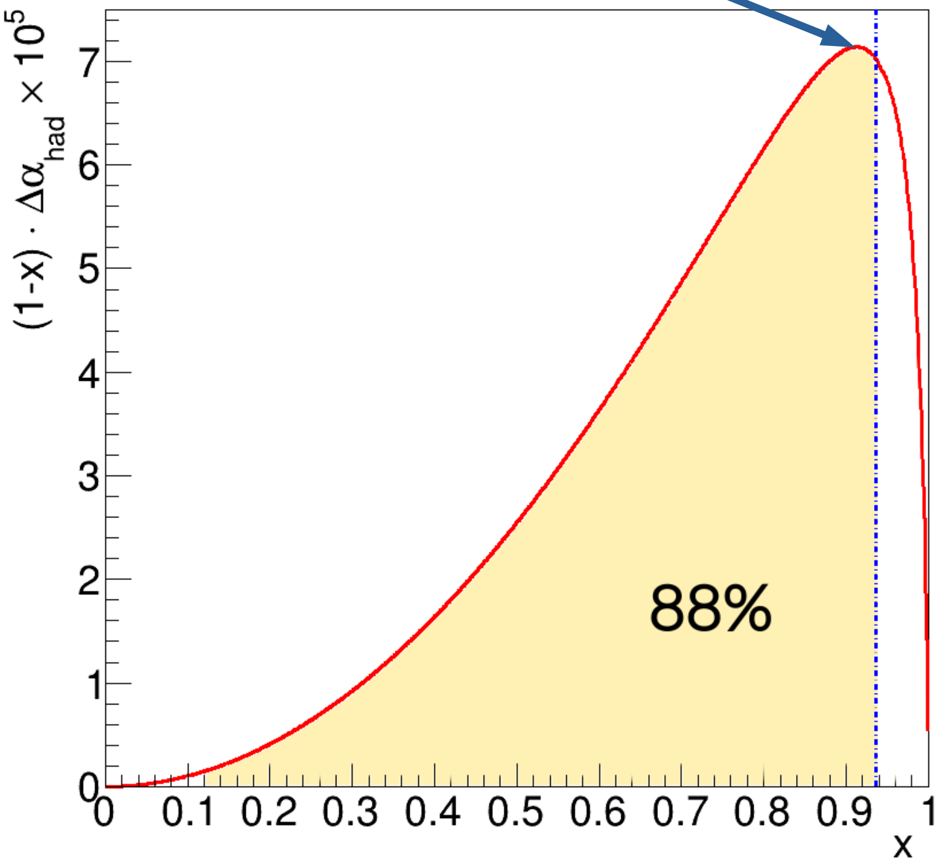
T. Bowcock, J. Carroll, G. Casse, S. Charity, K. Ferraby, K. Hennessy, F. Ignatov, T. Jones, R. Pilato, J. Price, K. Rinnert, T. Smith, T. Teubner, G. Venanzoni, J. Vossebeld, C. Zhang.

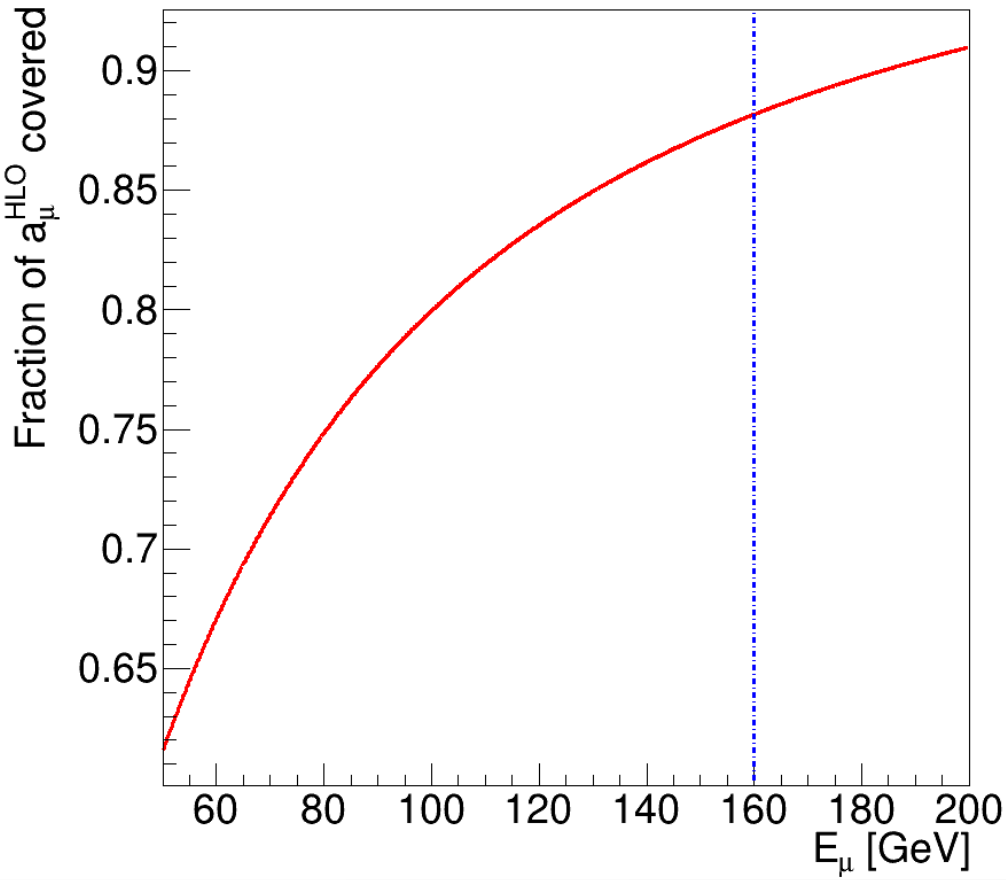
BACKUP

$x < 0.936$

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

$x_{peak} \sim 0.92$



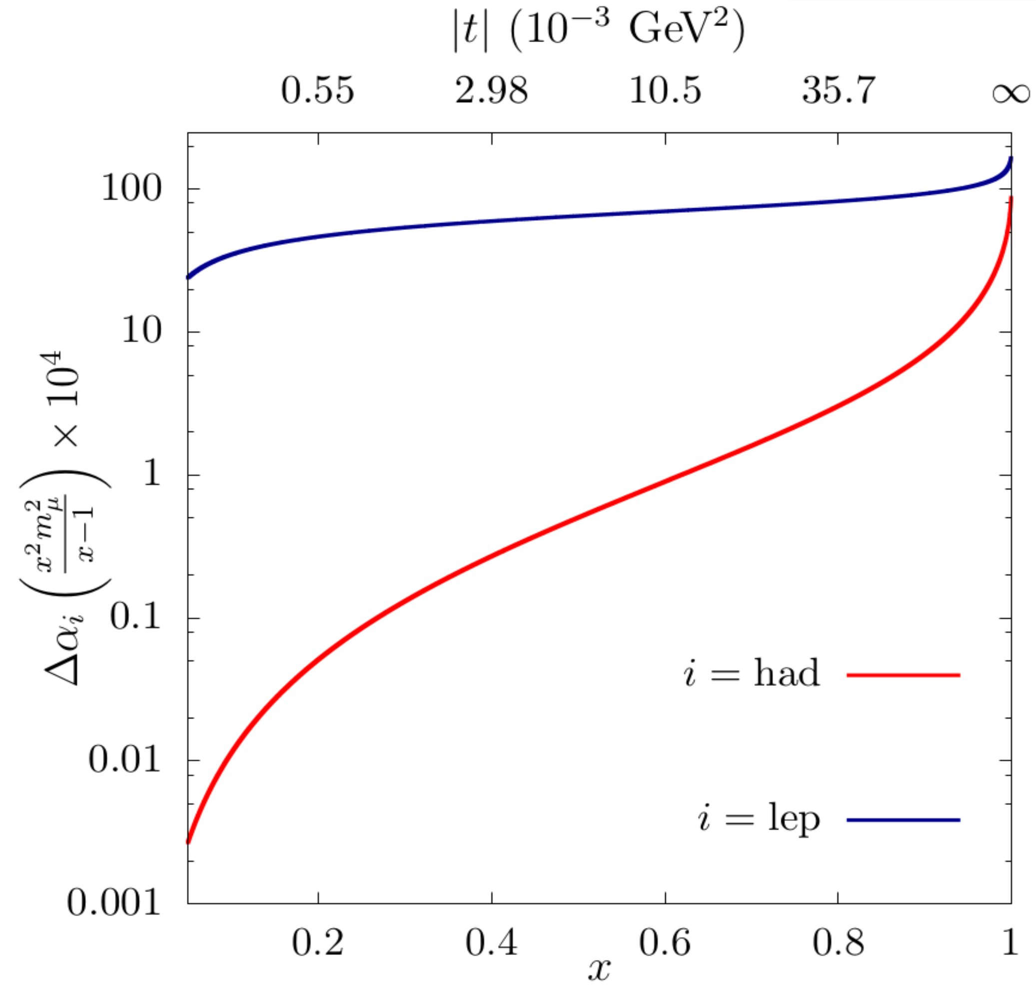


- 160 GeV muon beam on atomic electrons.

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

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

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



$\Delta\alpha_{had}$ parameterization

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

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

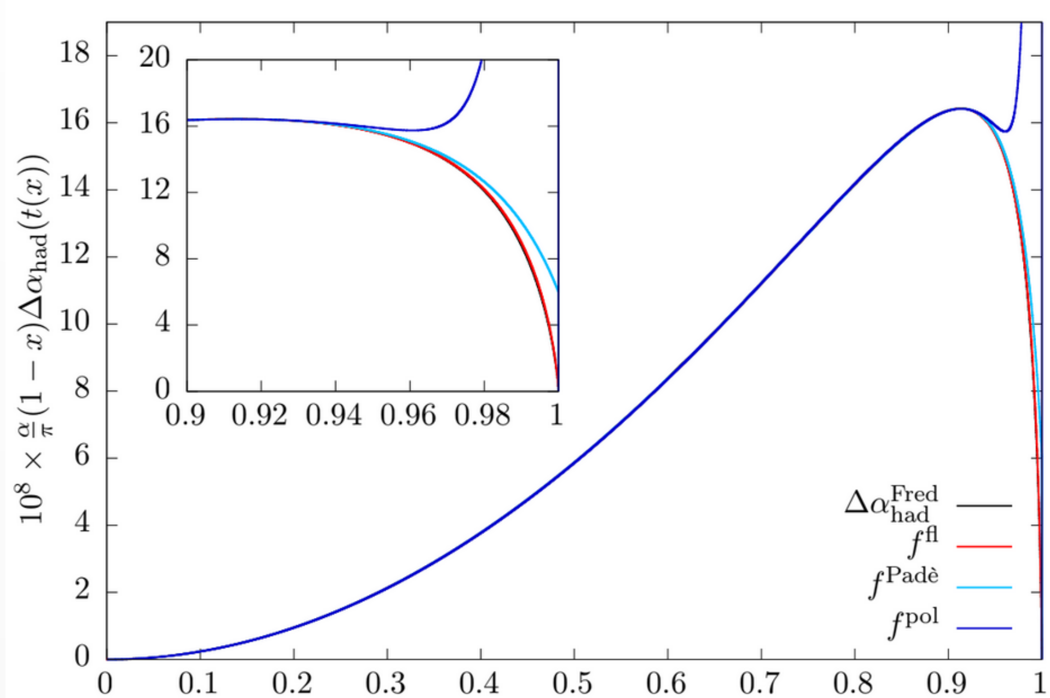
2 parameters:
K, M

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

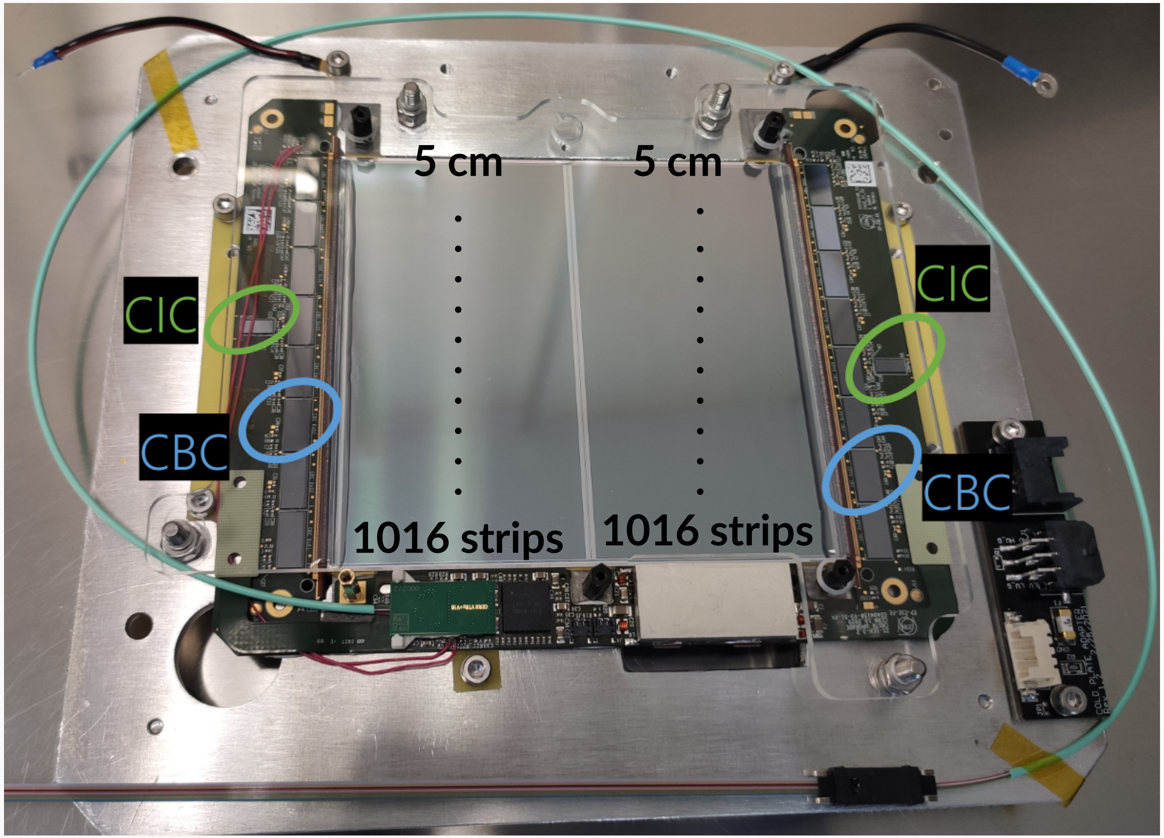
Dominant behaviour in the MUonE kinematic region:

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

Other possible parameterizations are being investigated



Tracker: CMS 2S modules



- Each module is divided in two independent halves.
- Each half is composed of 1016 strips, 5 cm long.
- Each half is read-out by a CIC (Concentrator Integrated Circuit).
- A single half is divided in 8 sectors. Each sector is read-out by a CBC (CMS Binary Chip).
- Data from the CBCs are transmitted to the corresponding CIC, then sent to the back-end.

Tracker: CMS 2S modules

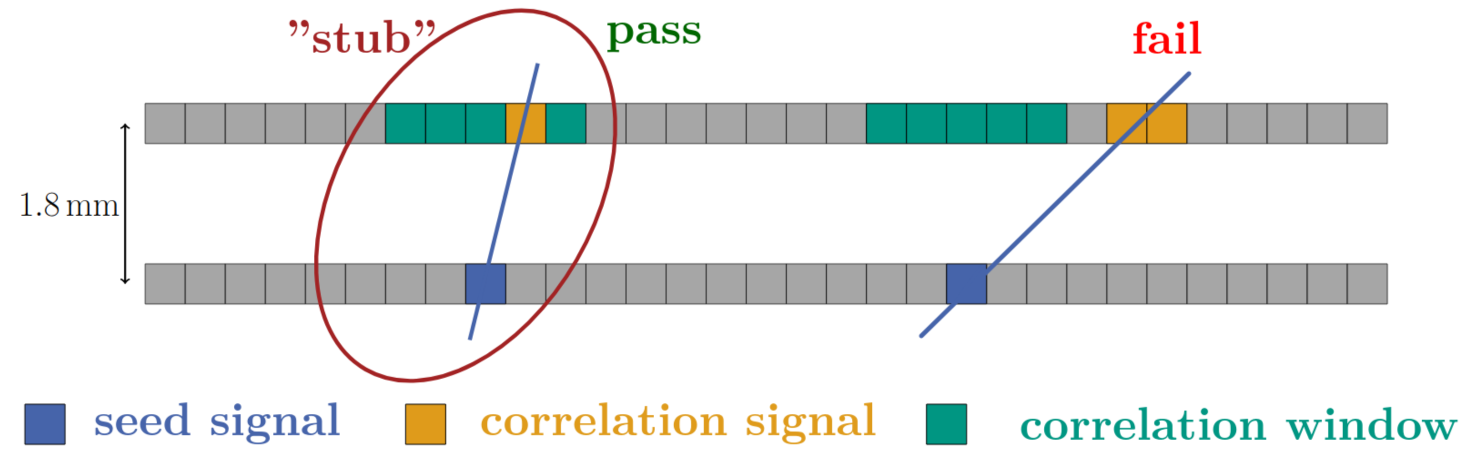
CMS Tracker Phase2 Upgrade - TDR

Two sensors reading the same coordinate:

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

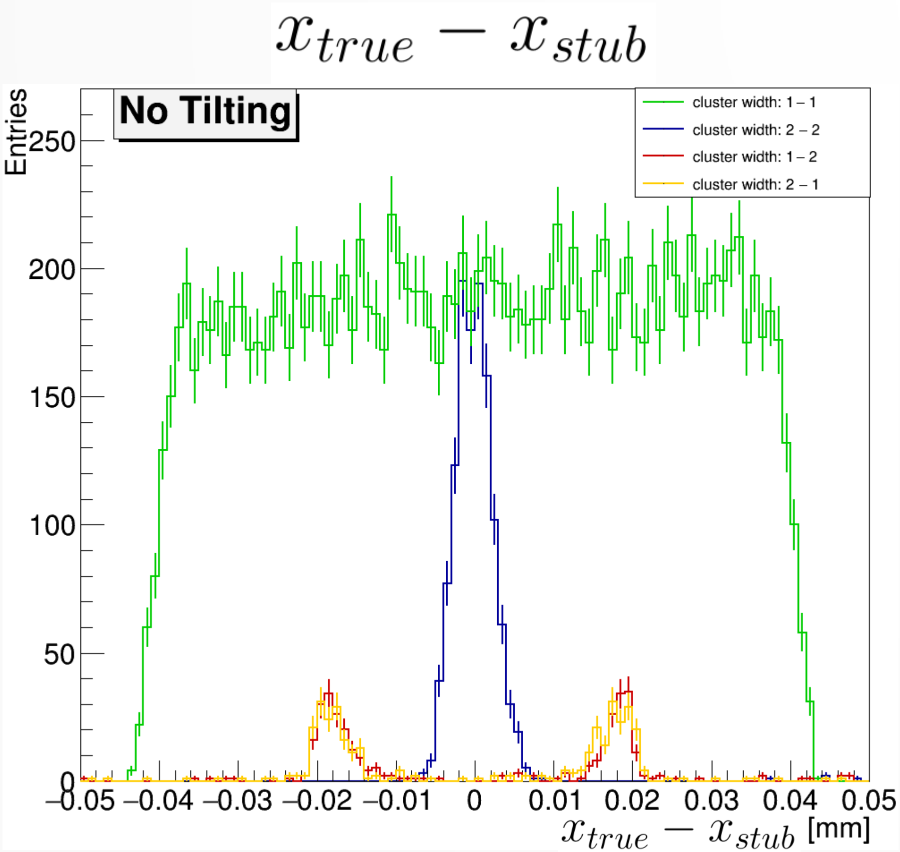
- x_{seed}
- bend = $x_{corr} - x_{seed}$

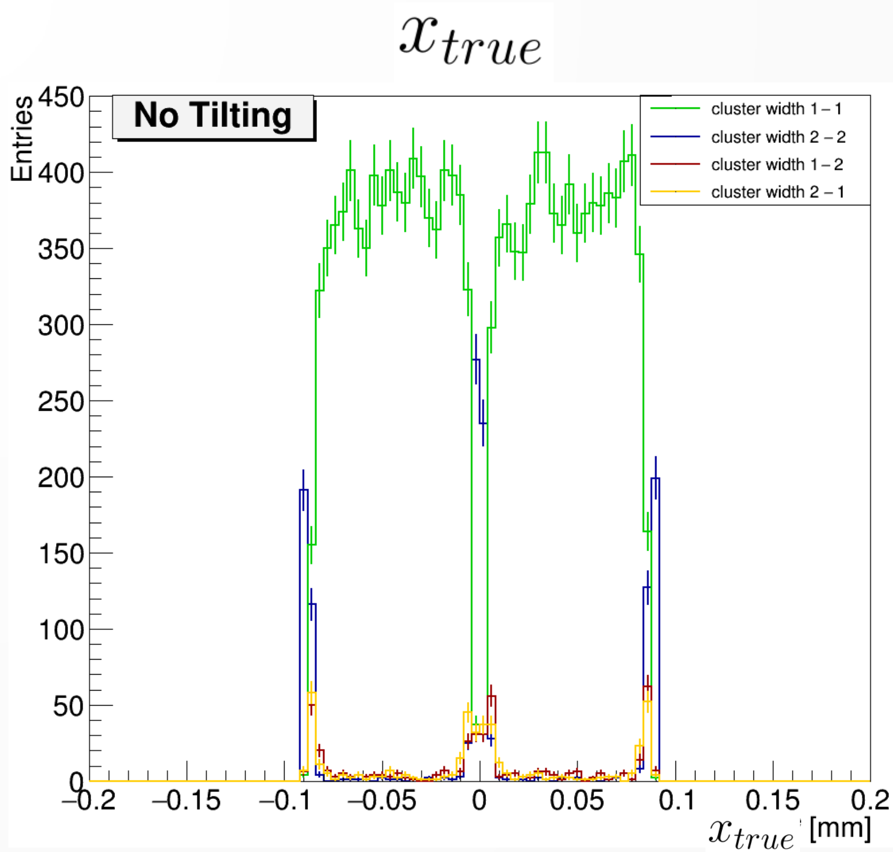
$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$



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

2S modules intrinsic resolution



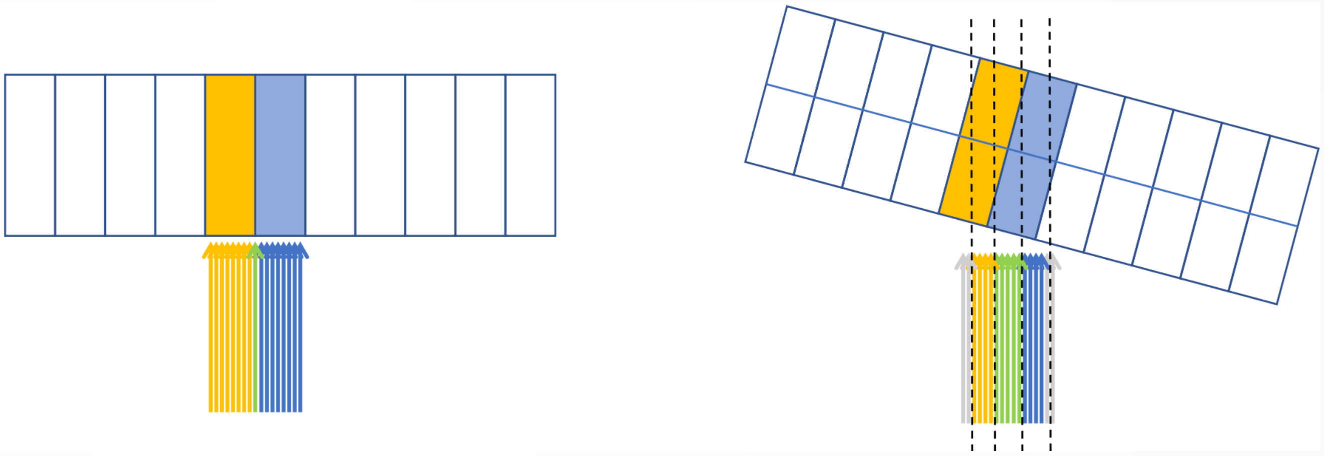


Position of particles hitting the module at the boundary of two strips is reconstructed with higher precision (blue distribution).

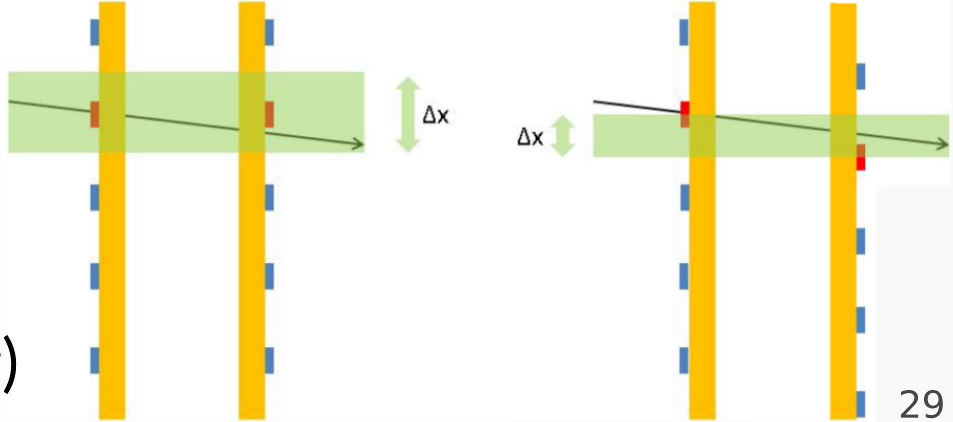
Improve the intrinsic resolution

Tilt a 2S module around an axis parallel to the strip direction.

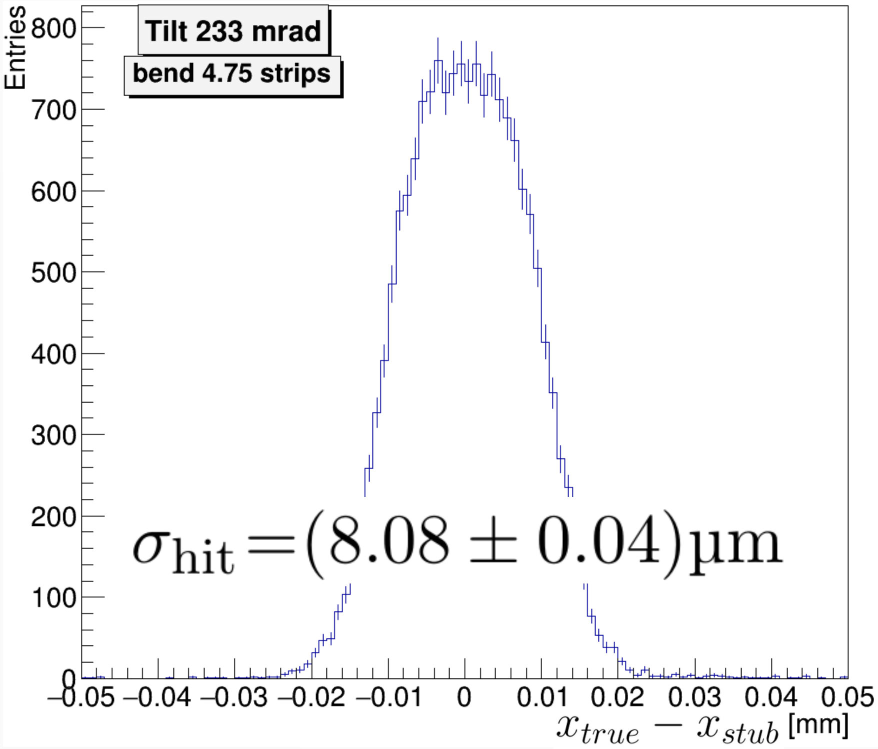
- Charge sharing: energy deposition of particles in the Silicon is shared among adjacent strips.

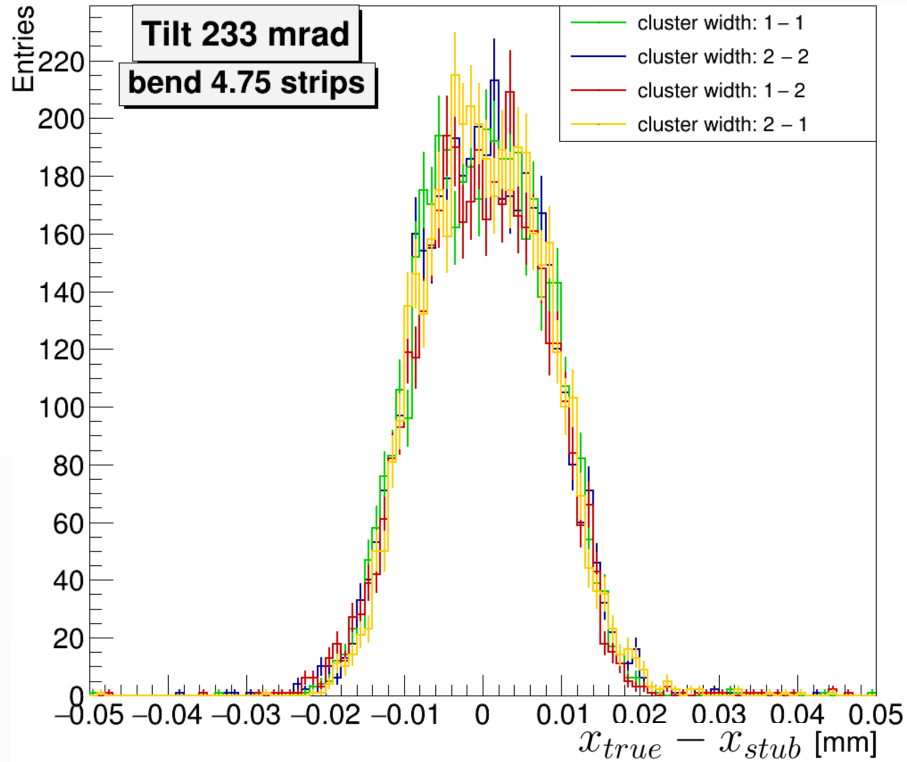


- Effective staggering: tilting a 2S module by a small angle will provide two measurements which are not redundant. (i.e. 25 mrad tilt = ½pitch staggering)



Improving the intrinsic resolution: tilted geometry





Best tilt angle: 233 mrad

threshold: 6000 e^- ($6\sigma_{noise}$)

Tolerances in the assembly of the 2S modules and the mechanical structure: expected resolution is 8 – 11 µm

2S modules intrinsic resolution

Tilt angle [mrad]	Bend [strips]	Digitization threshold [σ_{noise} units]	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

Orthogonal displacement [µm]	Resolution [µm]
0	8.0
5	8.4
10	9.4
15	10.4
20	11.3
25	11.2
30	10.4

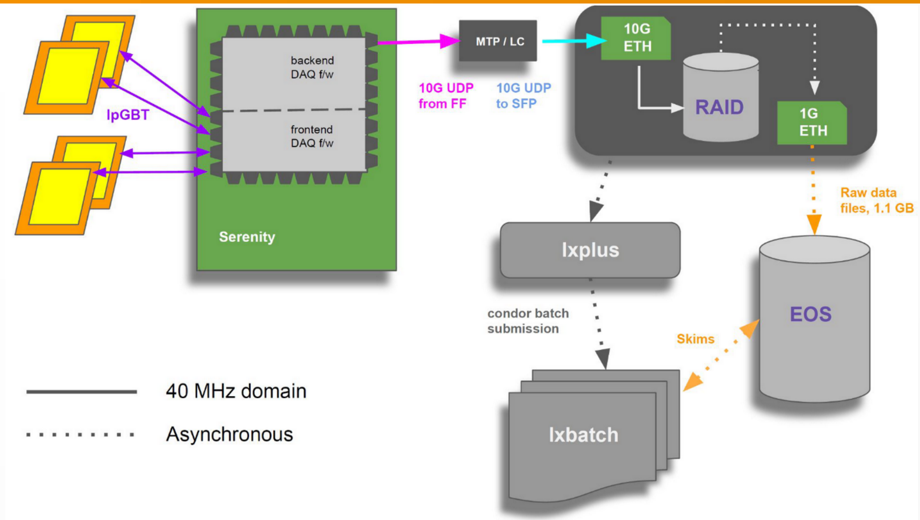
Tolerance in the mechanical structure: 233 ± 6 mrad

Tolerance in the 2S modules assembly: ± 50 µm

Expected resolution: 8 – 11 µm

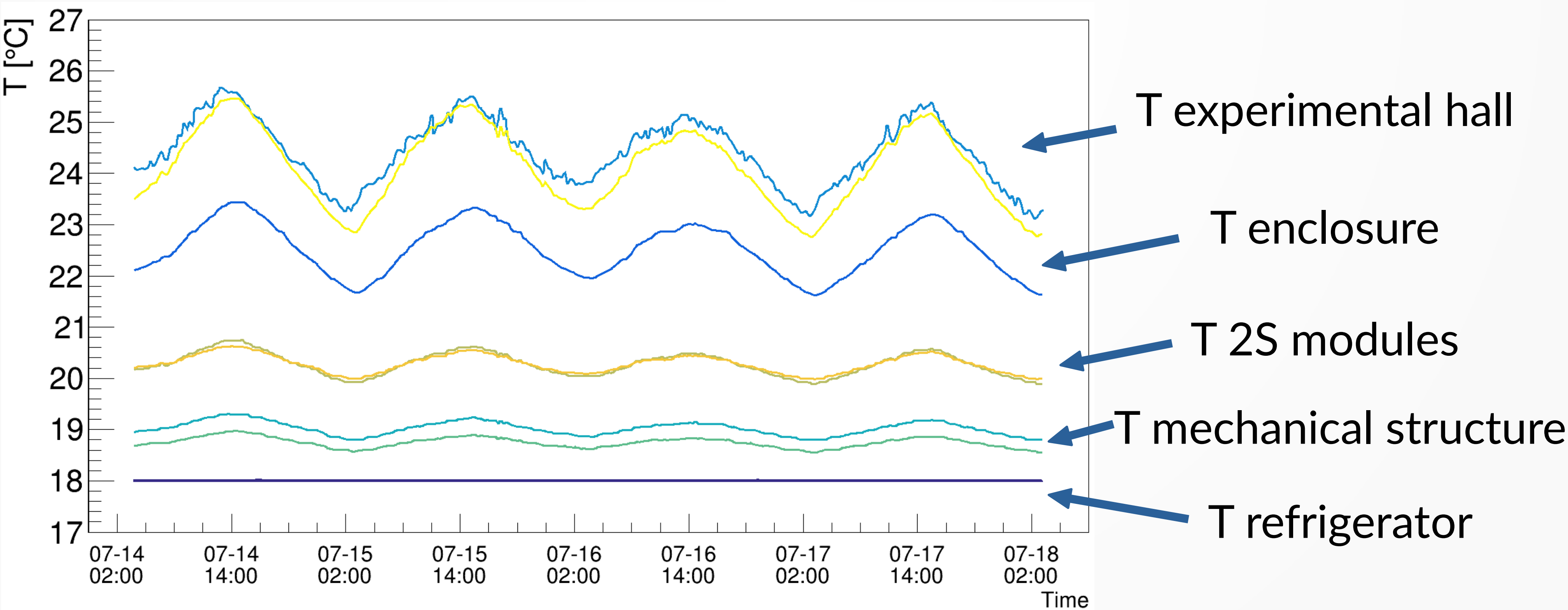
Beam Test 2021

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).
- Demonstration of 2S modules time synchronization.

Thermal stability of the tracking station

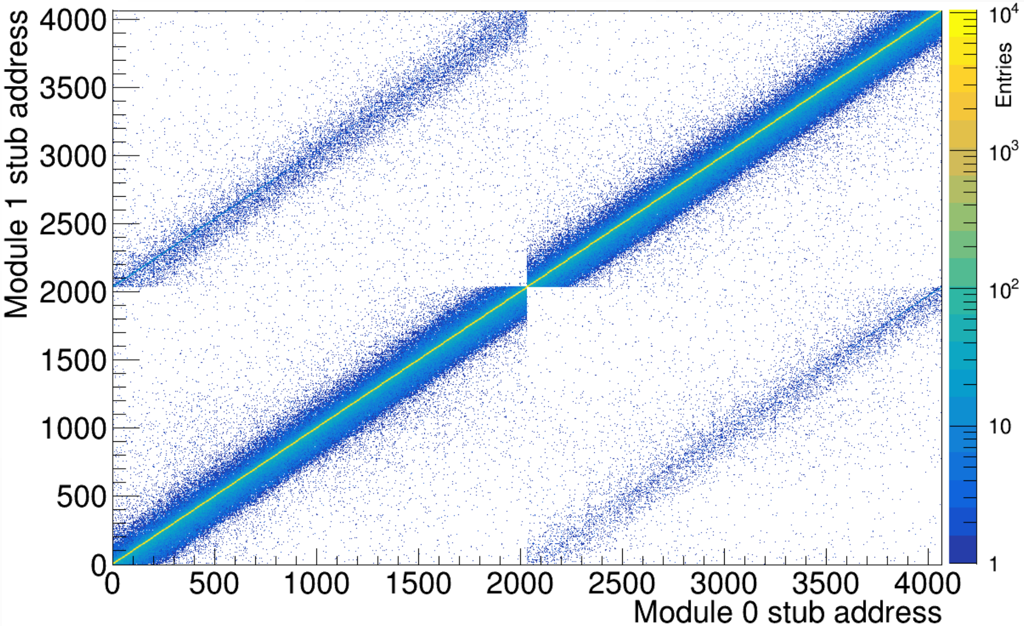


ΔT mechanical structure ~ 1°C

Day/night variations can be reduced by installing the apparatus in a controlled environment.

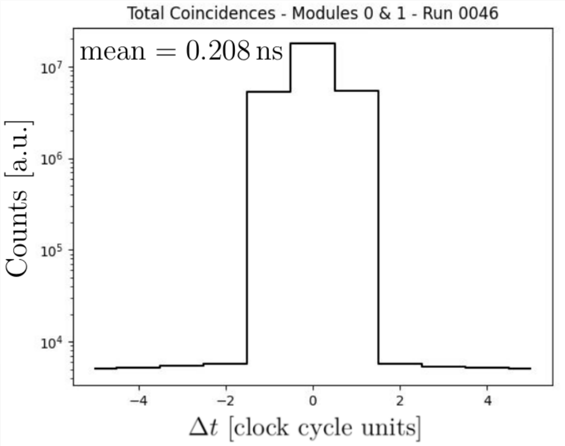
Beam Test 2021-2022

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



- Continuous stream of 40 MHz data from 2S modules captured to disk.

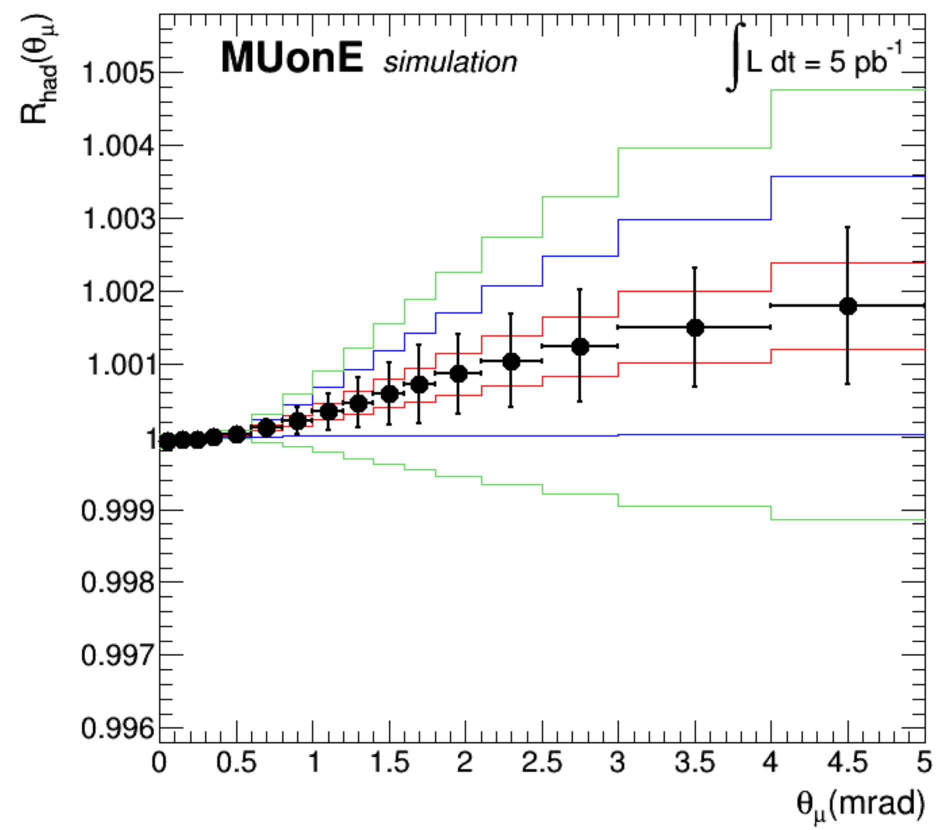
- Demonstration of 2S modules time synchronization.



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)

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



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

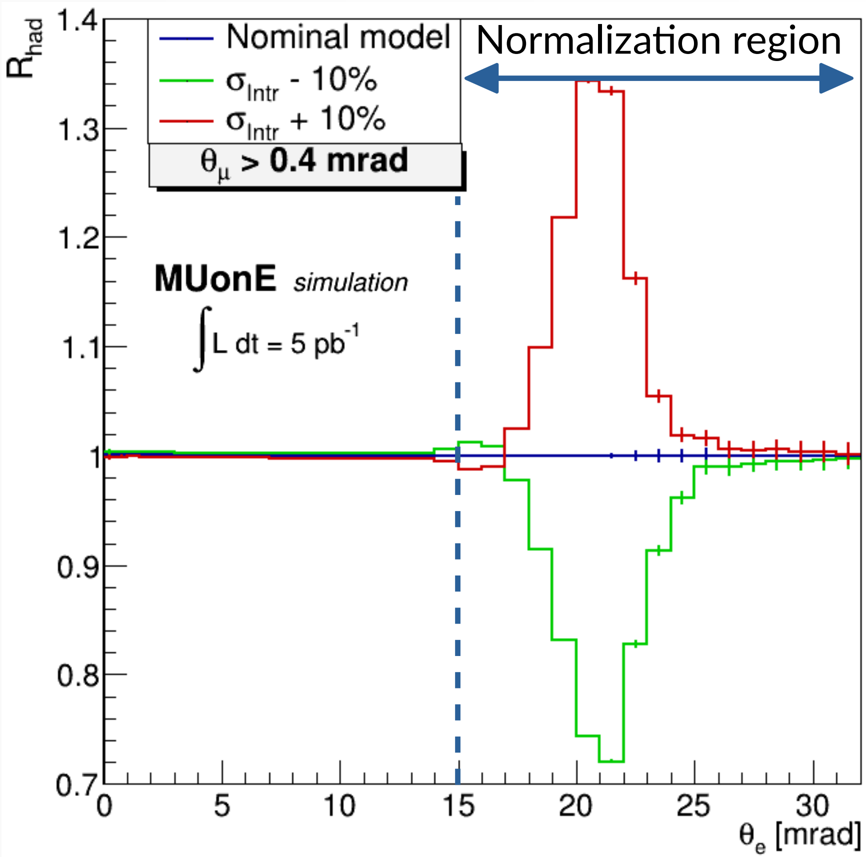
Low sensitivity to the hadronic running ($\Delta\alpha_{had}(t)$ < 10^{-3})

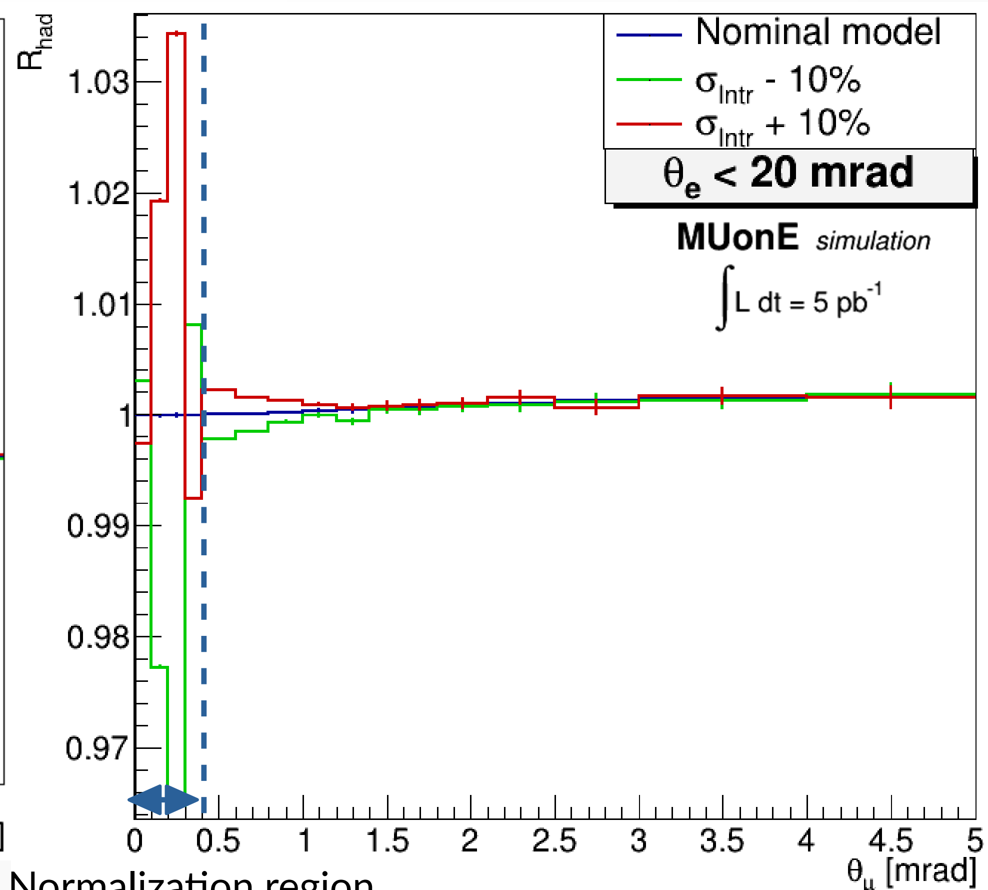
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$

K = 0.136 ± 0.026
(20% stat error)

Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution.



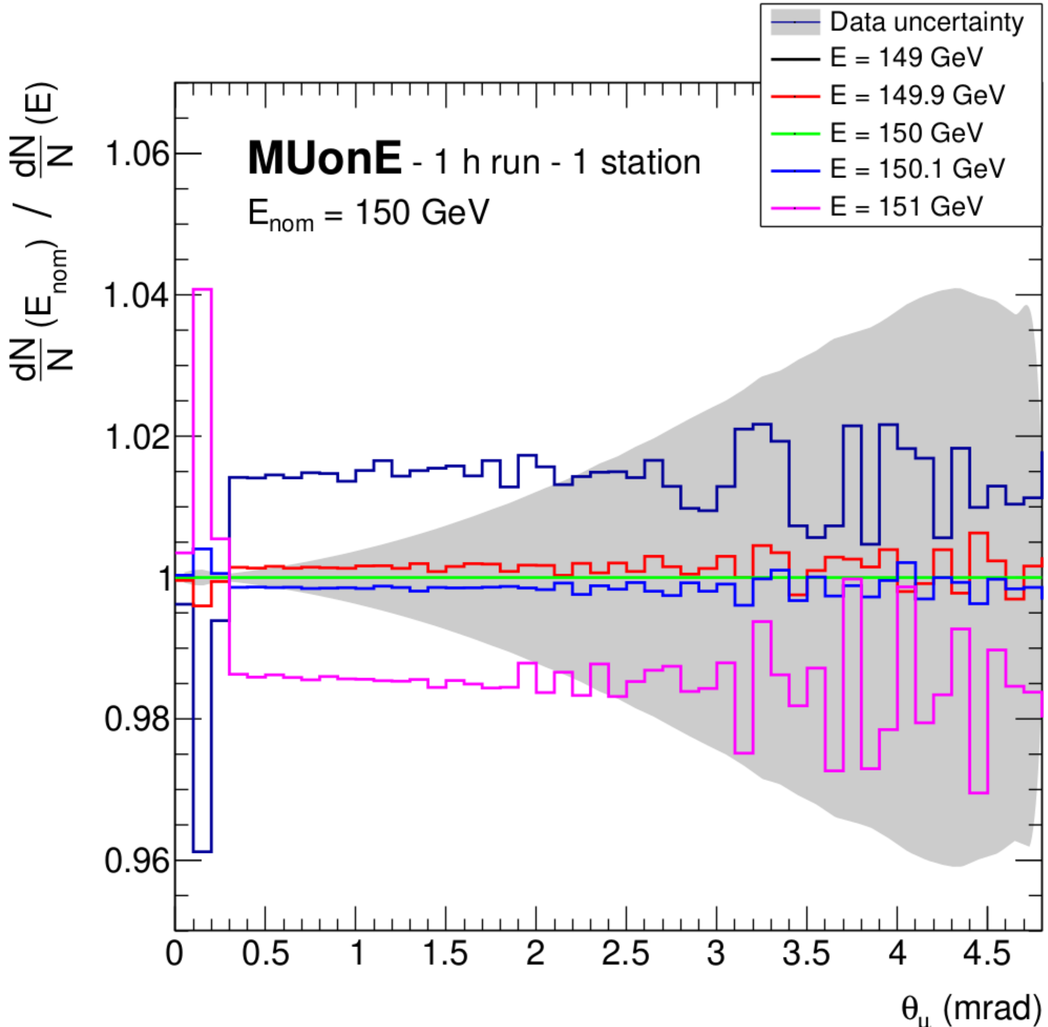


Normalization region

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.



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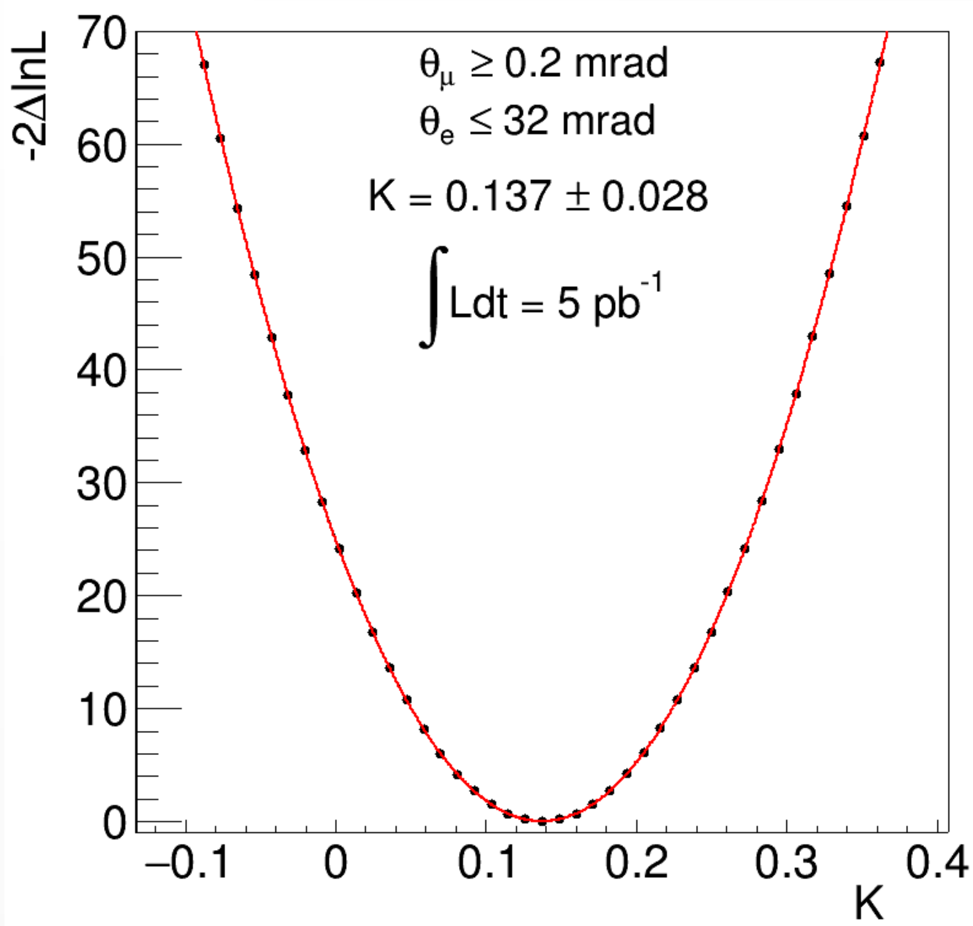
Framework used for the analysis

- NLO MonteCarlo generator: MESMER
  - Allows to change the muon beam energy and simulate the beam energy spread.
- C++ fast simulation to include detector effects:
  - Multiple scattering effects in the target.
  - Angular intrinsic resolution.
  - Effects applied to (θ_e, θ_μ) taken from the NLO generator: track reconstruction effects are currently neglected.
  - Further effects to be included: MS non-Gaussian tails, background effects, MS in the silicon sensors.

Analysis workflow

- Combine performs a likelihood fit to the nuisance parameters for each template.
- Obtain the profile likelihood as a function of K.
- Best fit value of K is determined by parabolic interpolation among the template points.
- Nuisance parameters values for $K = K_{best\ fit}$ are obtained by interpolation among the values obtained in the first step.

Statistical fit @$L_{TR} = 5\ pb^{-1}$



Analysis workflow

Promising strategy: staged approach.

1. Use a small fraction of data to refine the knowledge of the main sources of systematic error with respect to the initial modelization.

2. Include the residual systematics as nuisance parameters in a combined fit with the signal parameter on the entire dataset.

Currently tested on the Test Run statistics including the main systematic errors.

Testing the procedure

Generate a pseudo-data sample introducing shifts in the main sources of systematic error with respect to the expectations.

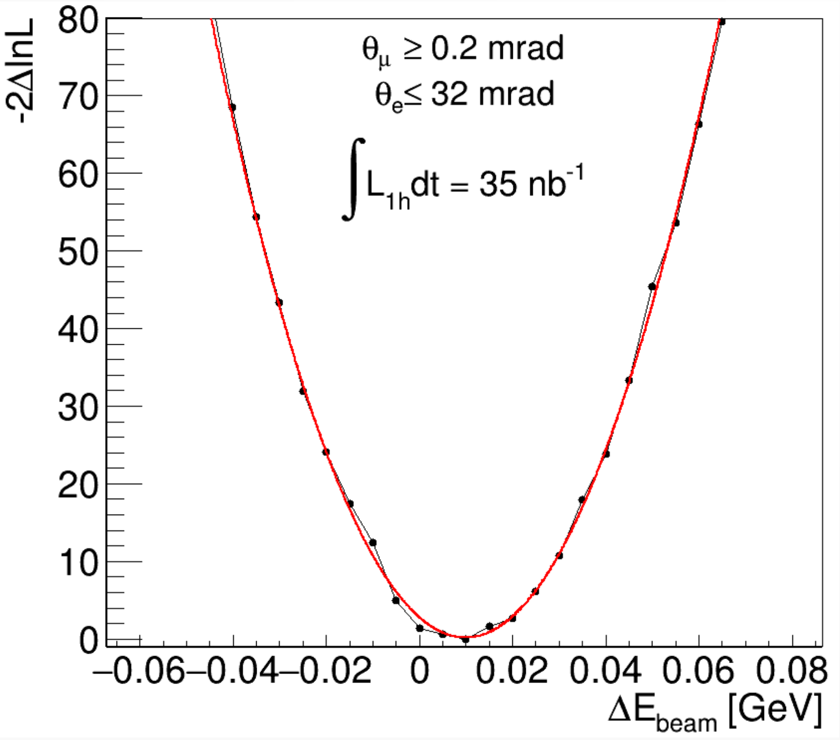
Source of systematics	Shift in the pseudo-data	Expected uncertainty
Beam energy scale	$E_{beam} \to E_{beam} + 6\,\mathrm{MeV}$	$\Delta E_{beam} = \pm 1\,\mathrm{GeV}$
Multiple scattering	$\sigma_{MS} \to \sigma_{MS} + 0.5\%$	$\Delta\sigma_{MS} = \pm 1\%$
Angular intrinsic resolution	$\sigma_{Intr} \to \sigma_{Intr} + 5\%$	$\Delta\sigma_{Intr} = \pm 10\%$
Luminosity		$\varepsilon = 1\%$

Are we able to determine precisely K and the nuisance parameters using this analysis strategy?

Step 1: identify the main systematic effects

1h of data taking per single station.

Allows to assume a fixed model for $\Delta\alpha_{had}$.



- Template fit as a function of E_{beam}.
- μ_{MS}: nuisance parameter for systematics on the multiple scattering.
- μ_{Intr}: nuisance parameter for systematics on the angular intrinsic resolution.
- ν: nuisance parameter for systematics on the normalization.

Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$ $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$\Delta E_{beam} = (0.006 \pm 0.006)$ GeV $\mu_{Intr} = (4.9 \pm 0.1)\%$ $\mu_{MS} = (0.6 \pm 0.1)\%$ $\nu = 0.01 \pm 0.03$

Similar results also for different selection cuts.

Update the knowledge on the sources of systematic error

Exploit results obtained in step 1 to refine the knowledge on the sources of systematic error.

Source of systematics	Expected uncertainty
Beam energy scale	$\Delta E_{\text{beam}} = \pm 1\,\text{GeV}$
Multiple scattering	$\Delta\sigma_{\text{MS}} = \pm 1\%$
Angular intrinsic resolution	$\Delta\sigma_{\text{Intr}} = \pm 10\%$

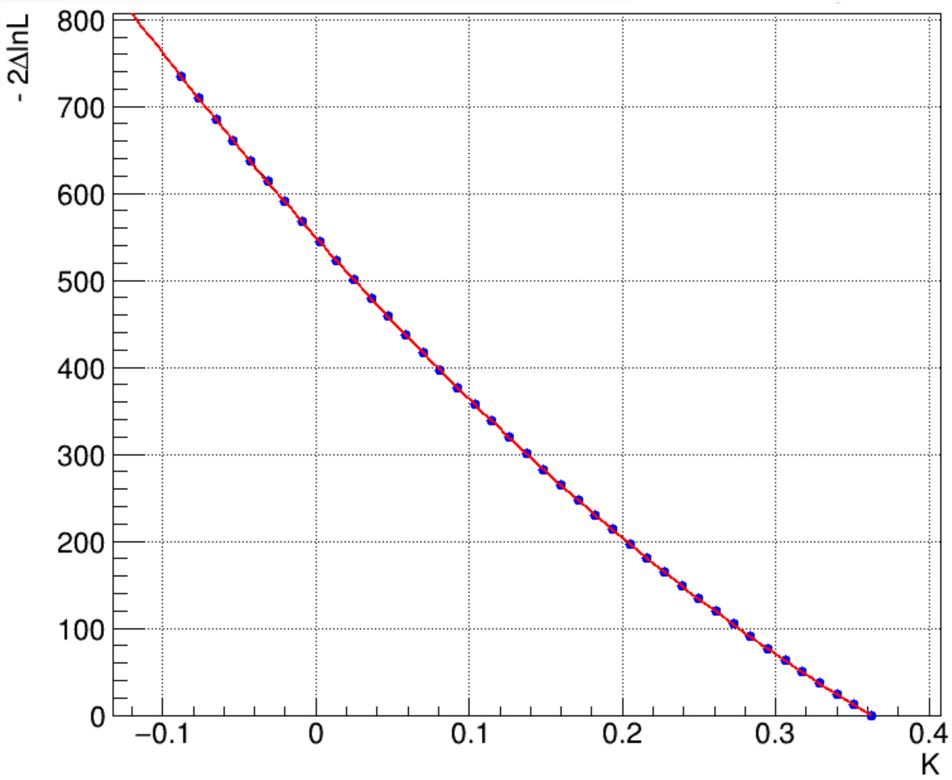
→

Updated model
$\Delta E_{\text{beam}} = \pm 20\,\text{MeV}$
$\sigma_{\text{MS}} \to \sigma_{\text{MS}} + 0.6\%$ $\Delta\sigma_{\text{MS}} = \pm 0.5\%$
$\sigma_{\text{Intr}} \to \sigma_{\text{Intr}} + 5\%$ $\Delta\sigma_{\text{Intr}} = \pm 0.6\%$

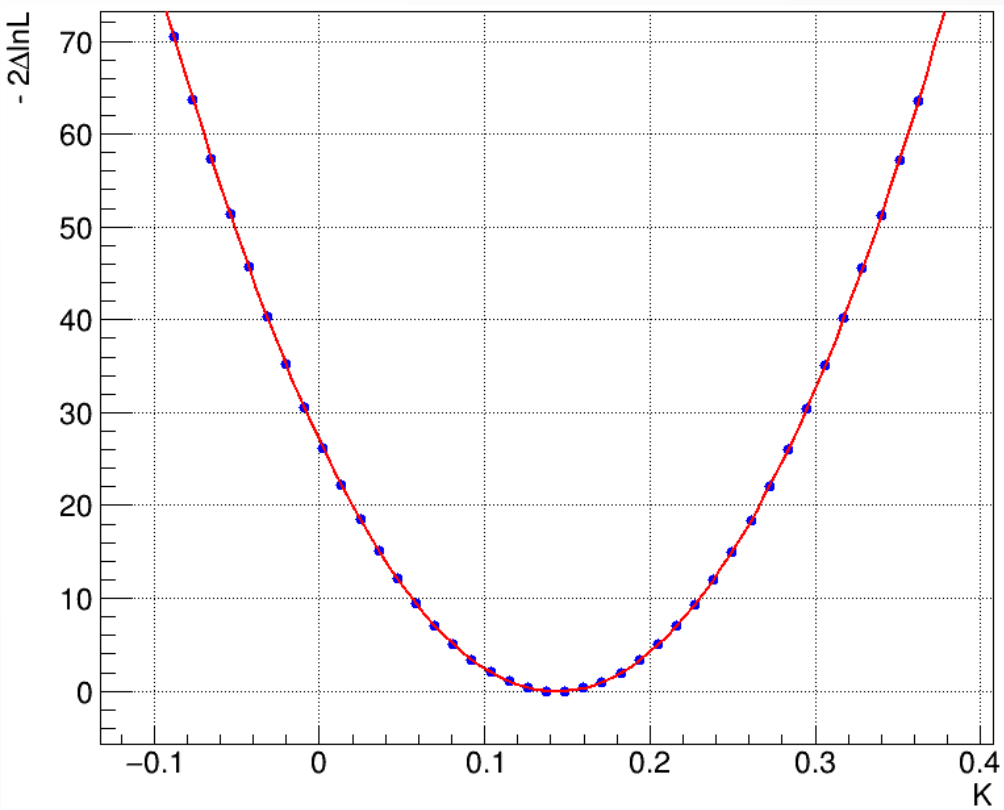
Use this improved modelization to perform the combined fit to K and the residual systematics.

Simultaneous fit signal + nuisance parameters @L_{TR}

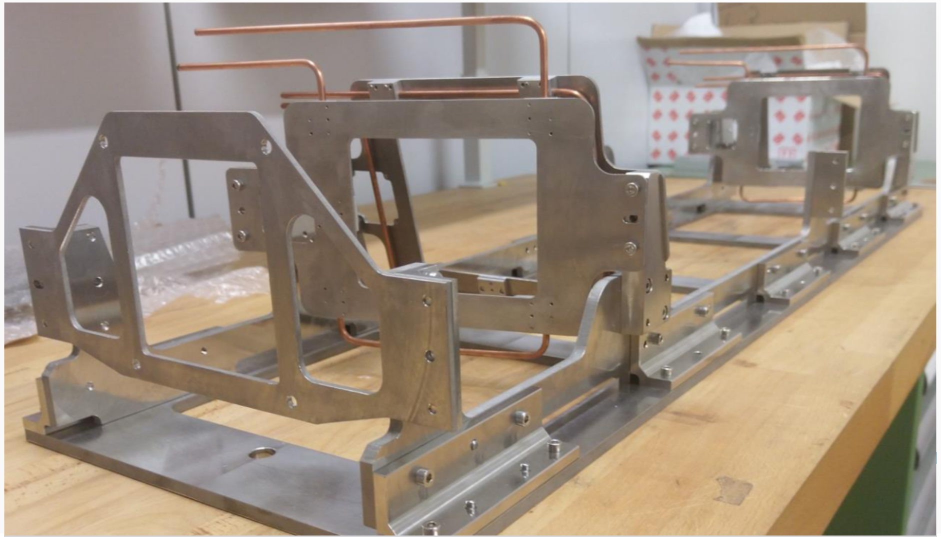
If the systematics are not taken into account in the fit…



If the nuisance parameters are introduced in the fit procedure…

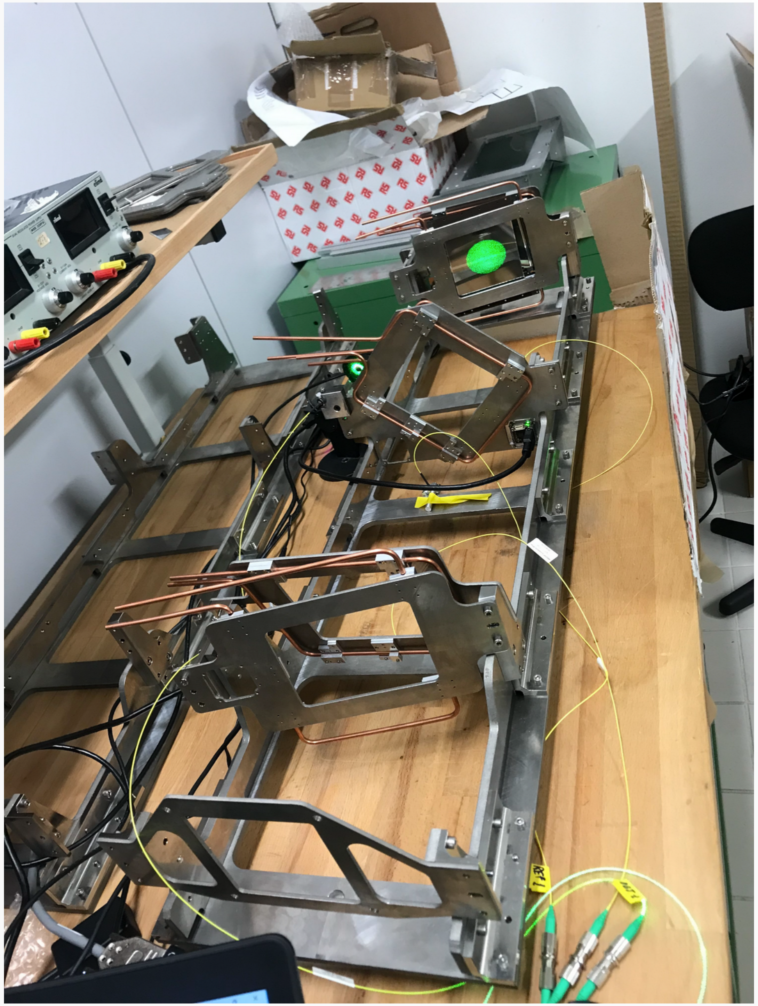


Tracking station

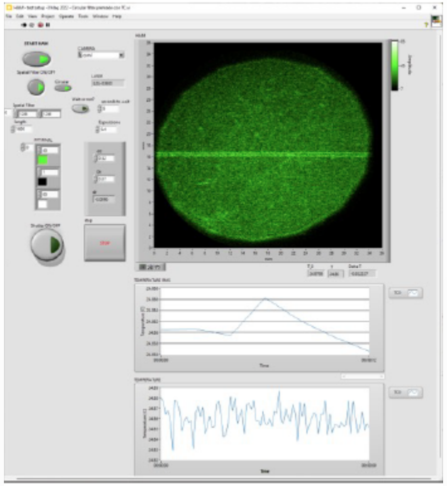


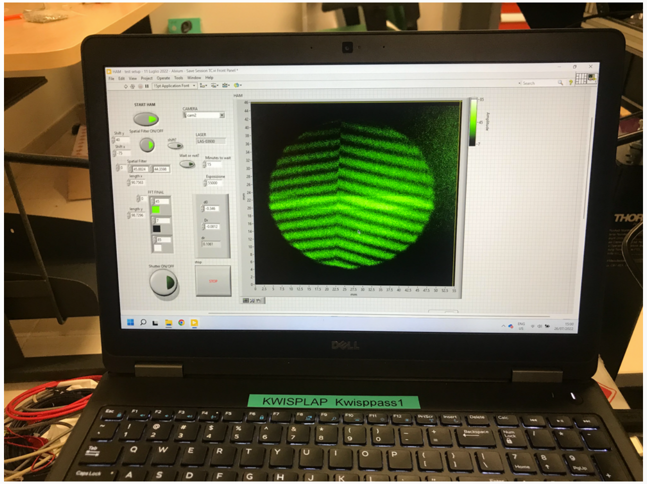
3 INVAR stations assembled at INFN Pisa.

Laser holographic system



Initial state

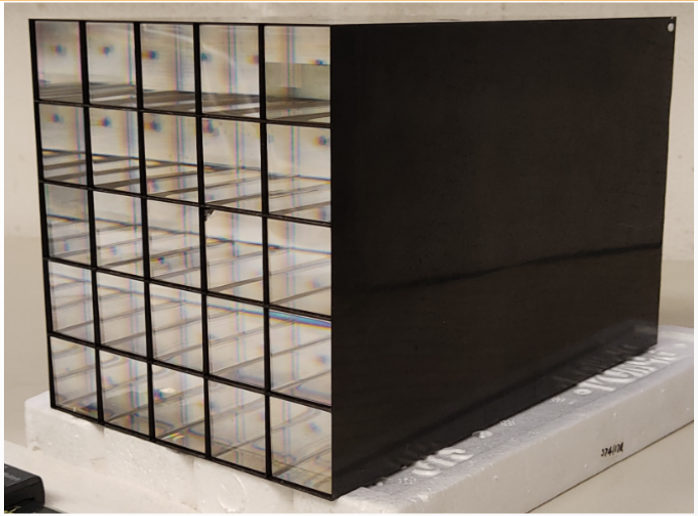




- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.
- Developed at INFN Trieste, tested in 2022 at CERN.

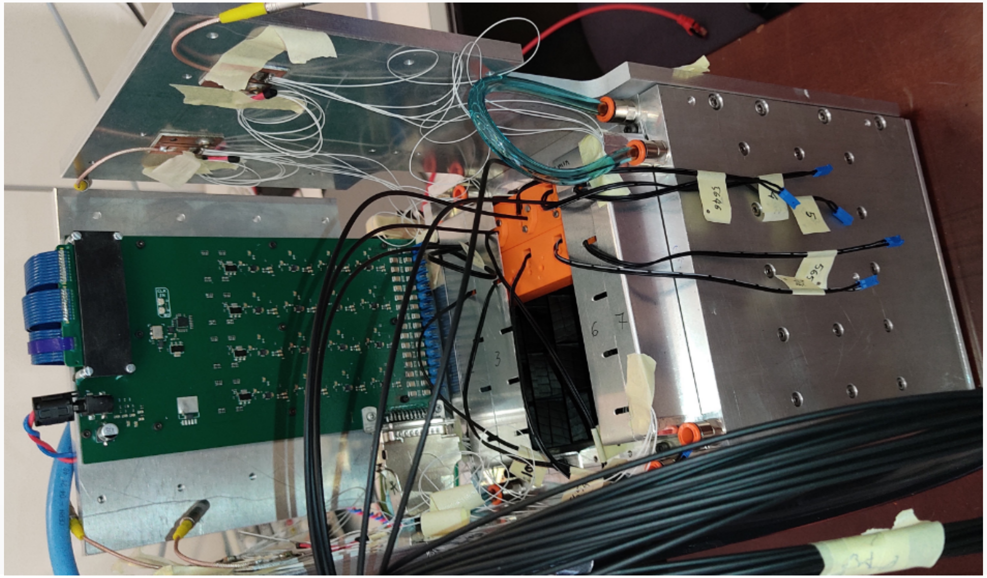
Calorimeter

- 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: 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.



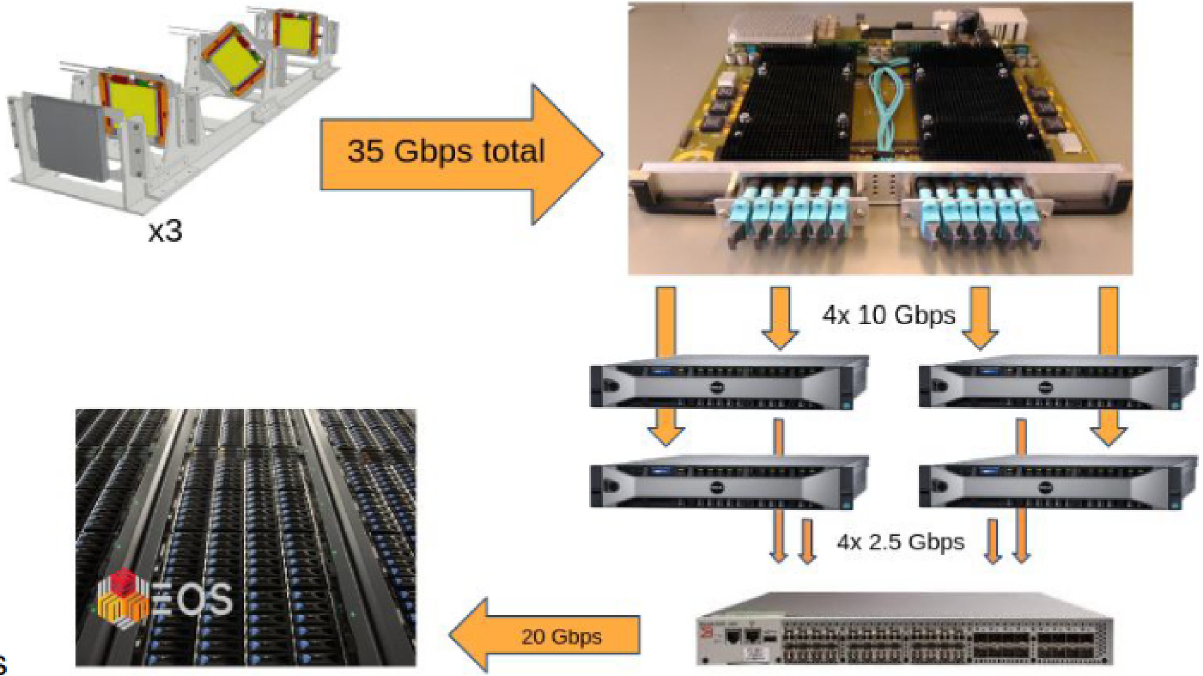
DAQ architecture

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

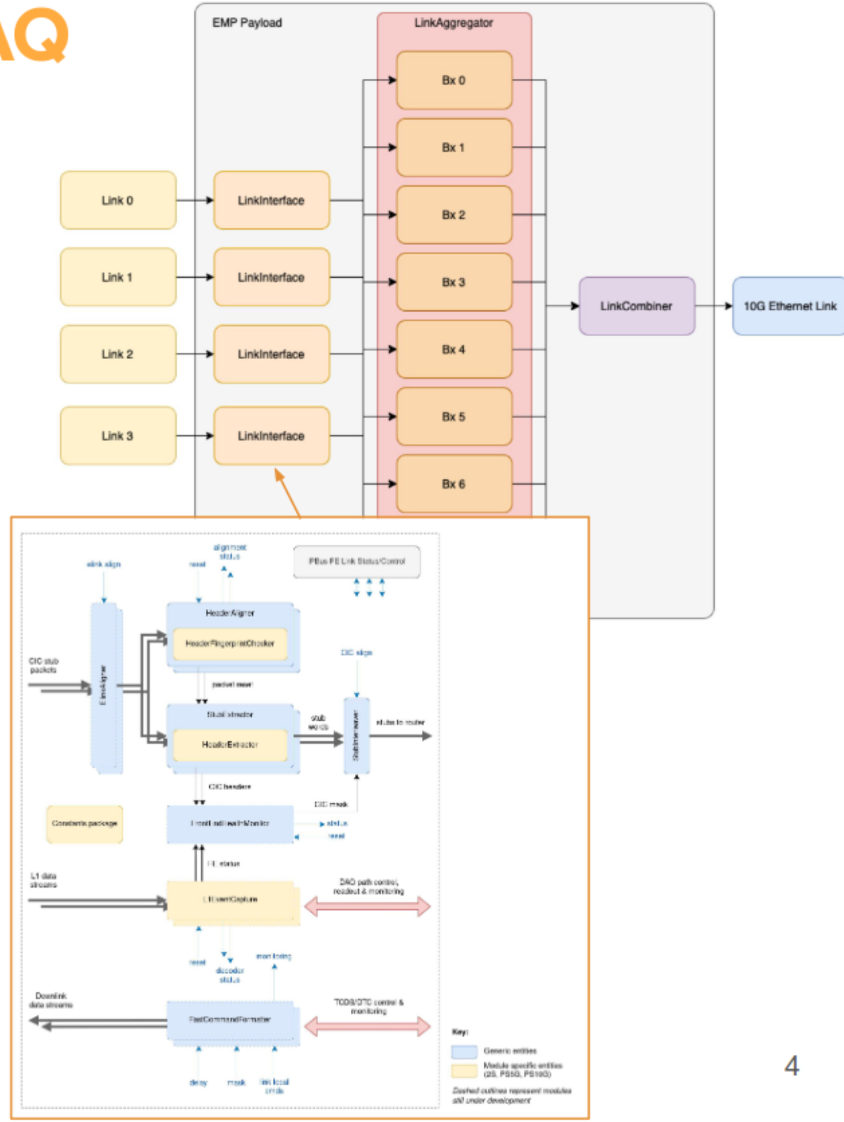
- Book-keep empty frames but do not forward to switch
- From switch to EOS/CTA with 20 Gbps



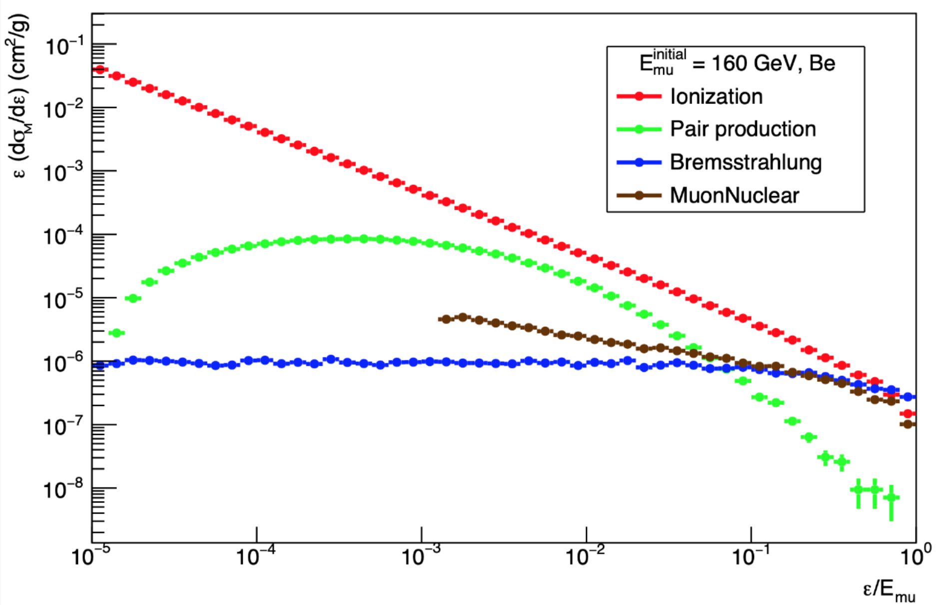
- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

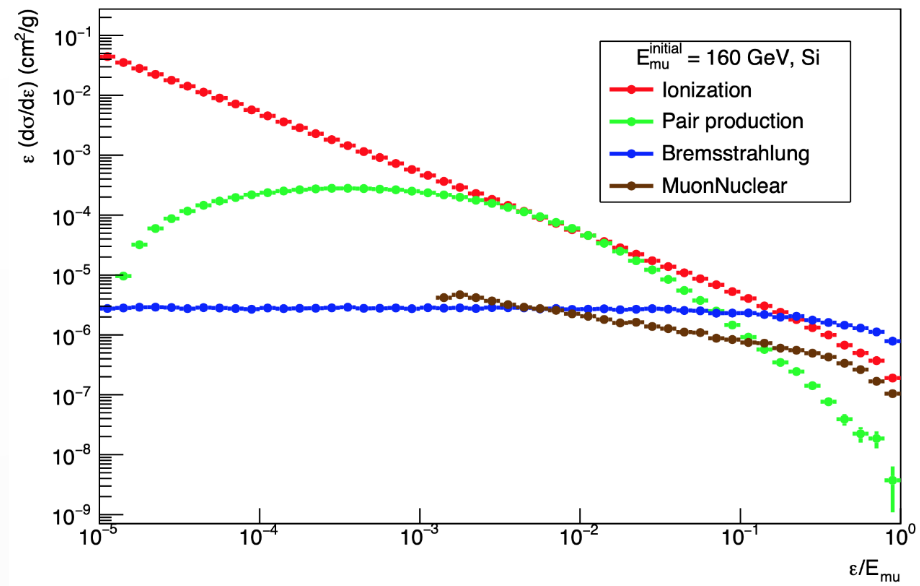
Frontend DAQ

- Serenity card served as interface between the FE modules and downstream PC
- Firmware consisted of a number of blocks
  - lpGBT link interface firmware, and module control
  - Decoder to unpack stub packets from the modules
  - Aggregator to sort and collate stubs from each BX
  - Combiner to recombine these streams and send on to the ethernet link
  - Stub histogrammer to monitor stubs from a single link over a macroscopic time period (up to 30s)
- Large fraction of firmware in common with CMS
  - Hit data is under development/testing
  - Aggregator + Combiner are MUonE dedicated
- FE control software entirely in common with CMS
  - Based on Ph2ACF, adapted for Serenity
  - Allows us to configure modules, run calibrations etc.



Backgrounds





MESMER

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

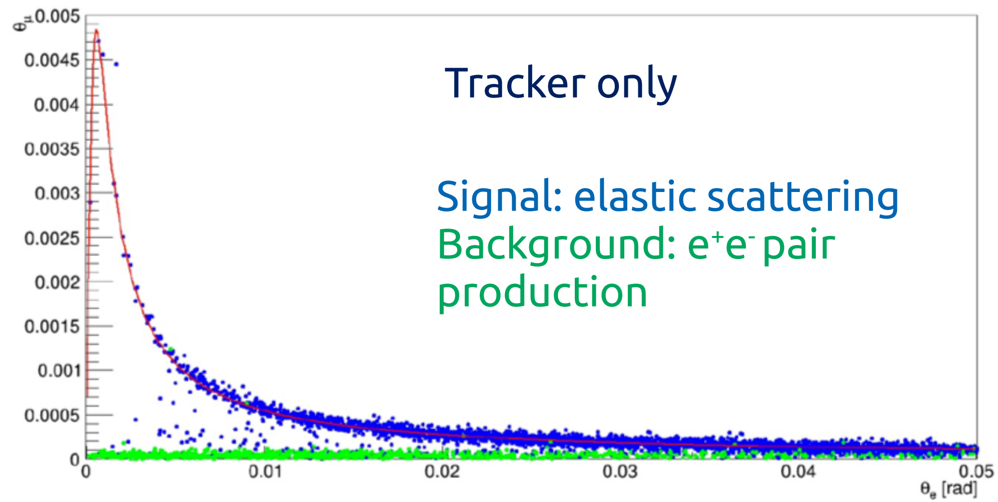
GEANT4

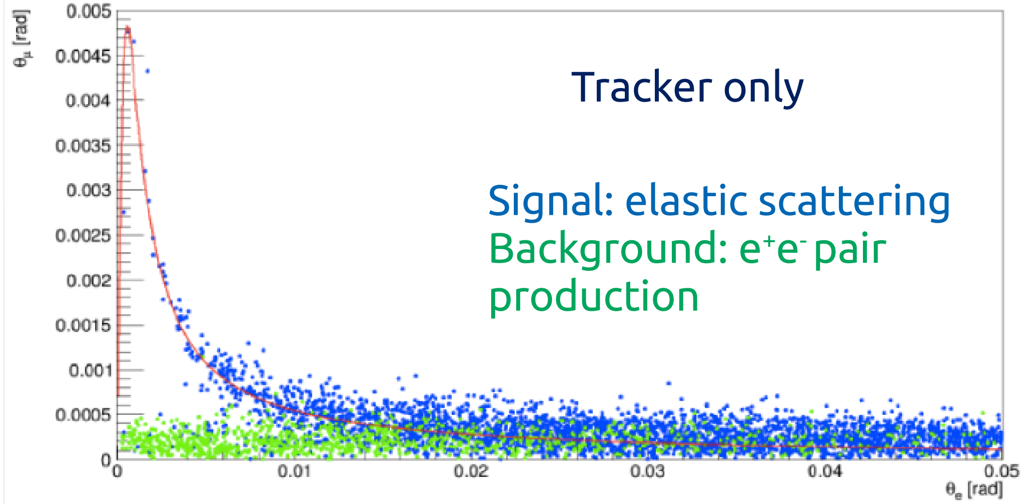
- $\mu N \to \mu N \gamma$
- $\mu N \to \mu N e^+ e^-$
- $\mu N \to \mu X$

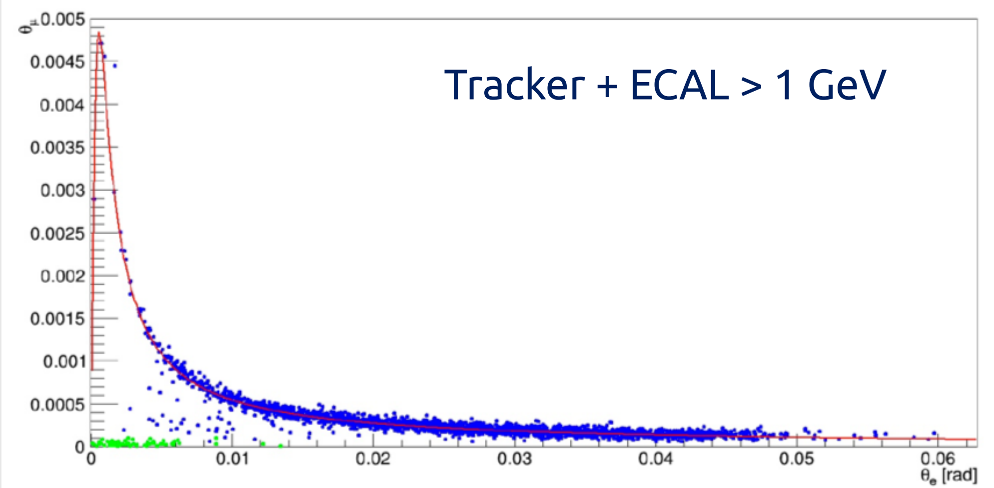
GEANT4 simulations

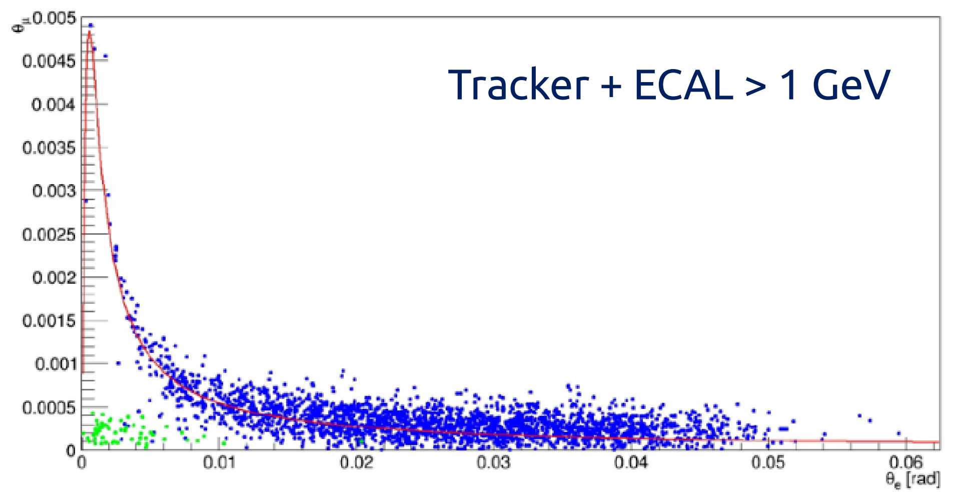
TB2017 (resolution ~7μm)

TB2018 (resolution ~40μm)







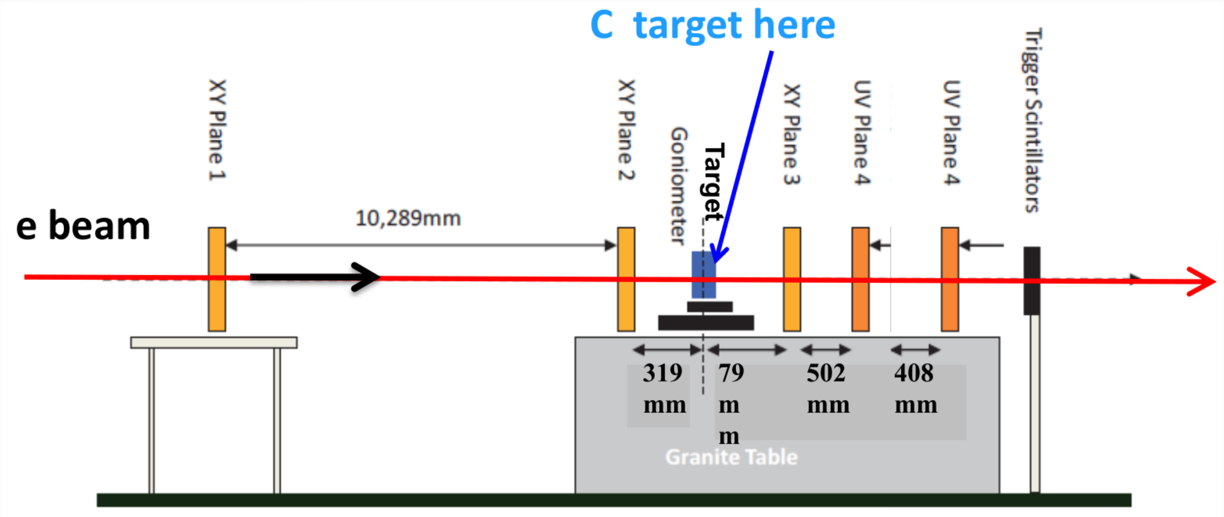


Multiple scattering: results from TB2017

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

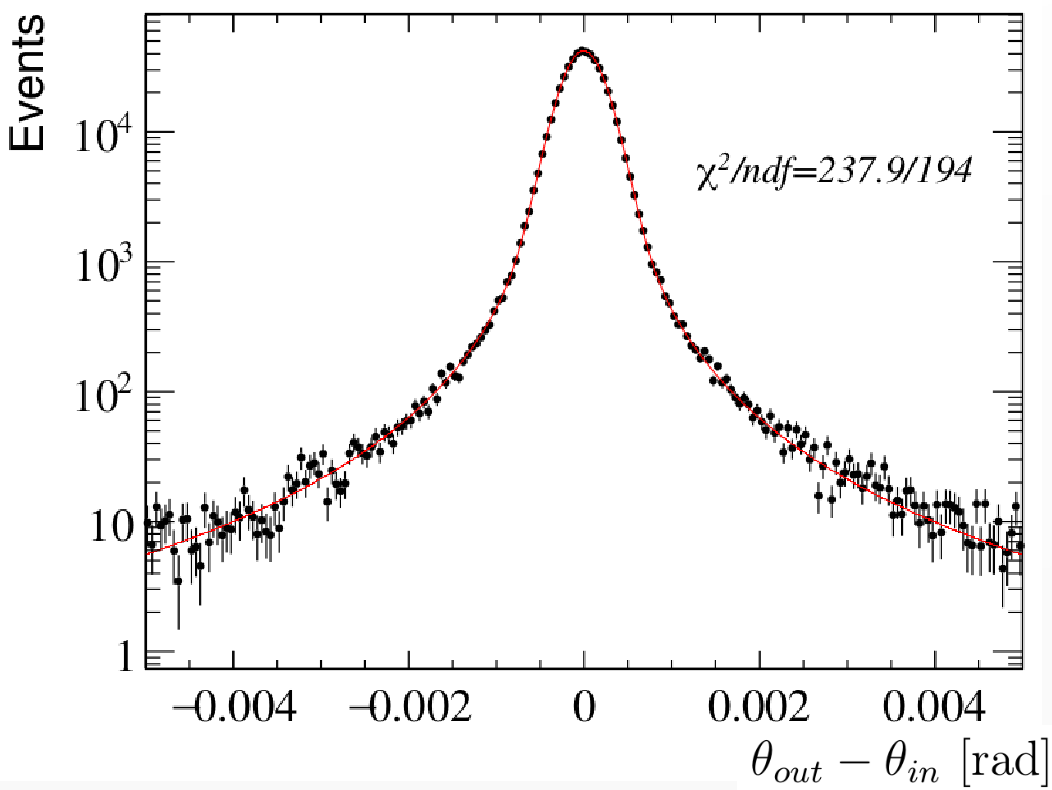
Main goals:

- 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