Status of the MUonE experiment

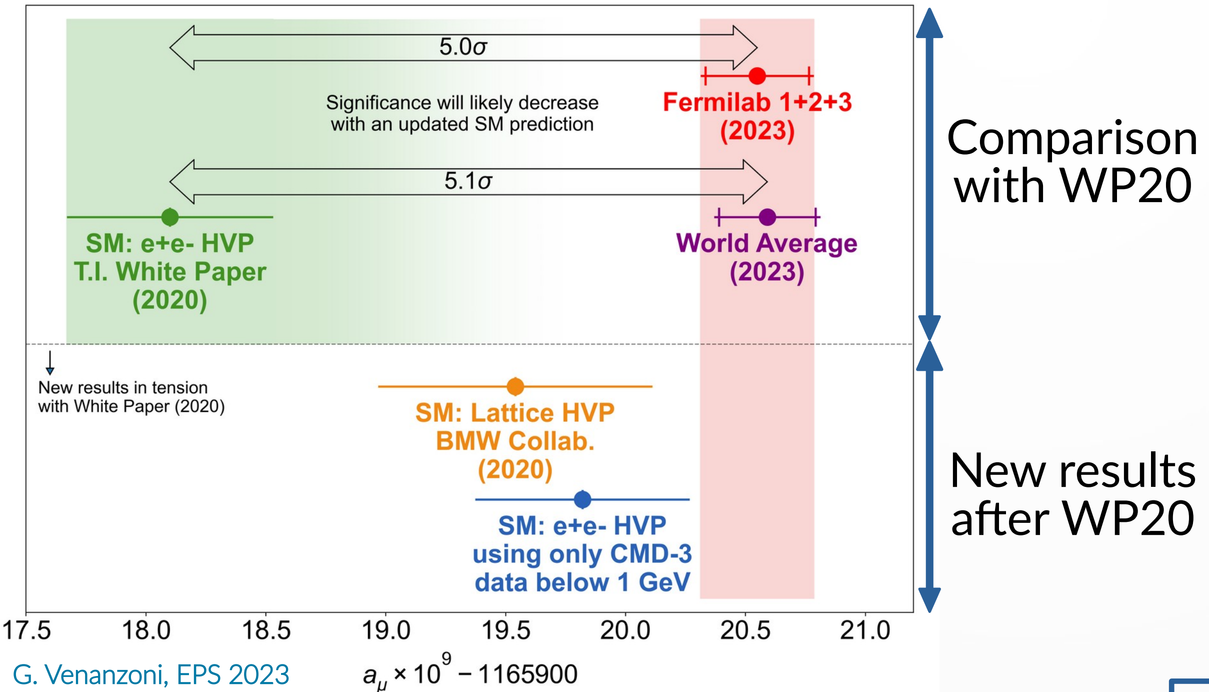
Riccardo Nunzio Pilato

University of Liverpool

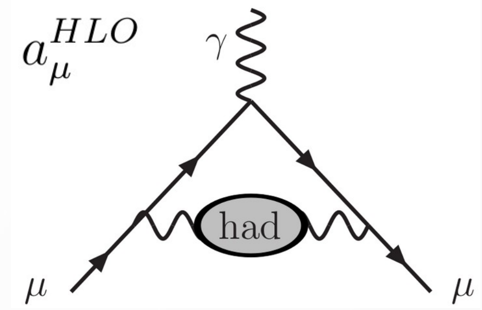
r.pilato@liverpool.ac.uk

The Evaluation of the Leading Hadronic Contribution to the Muon g-2:
Consolidation of the MUonE Experiment and Recent Developments in Low Energy e^+e^- Data
Mainz, 3rd June 2024

Muon g-2: current status



G. Venanzoni, EPS 2023



Main source of uncertainty of the theoretical prediction

Disclaimer on new results after WP20:

- Plot is purely for demonstration purposes. It does not represent an update from the g-2 Theory Initiative.
- Lattice HVP taken from A. Keshavarzi, Lattice 2023 talk.
- Prediction from CMD3: subsitute TI White Paper by CMD3 only for [0.33-1] GeV (see A. Keshavarzi, Lattice 2023).

A clarification of the theoretical prediction is needed

The MUonE experiment

New independent evaluation of a_μ^{HLO}, based on the measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant

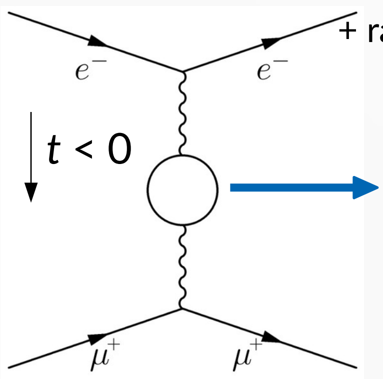
Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026

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

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

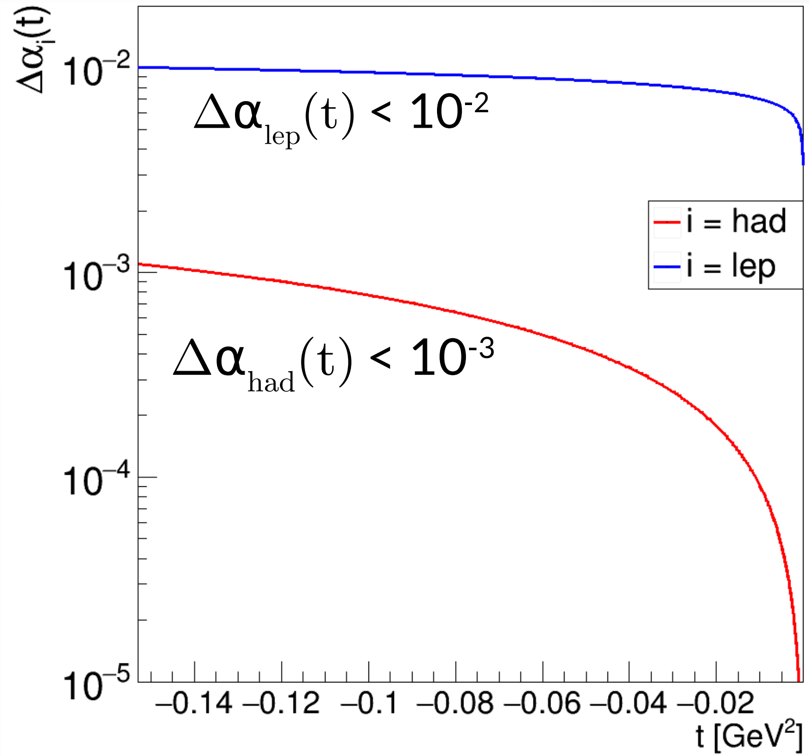
Phys. Rep. C 3 (1972), 193

Extraction of $\Delta\alpha_{had}(t)$ from the *shape* of the ***μe* → *μe*** differential cross section



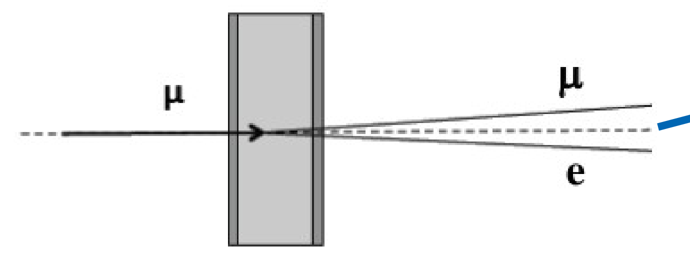
+ radiative corrections

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



MUonE kinematic range

The μ-e elastic scattering



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

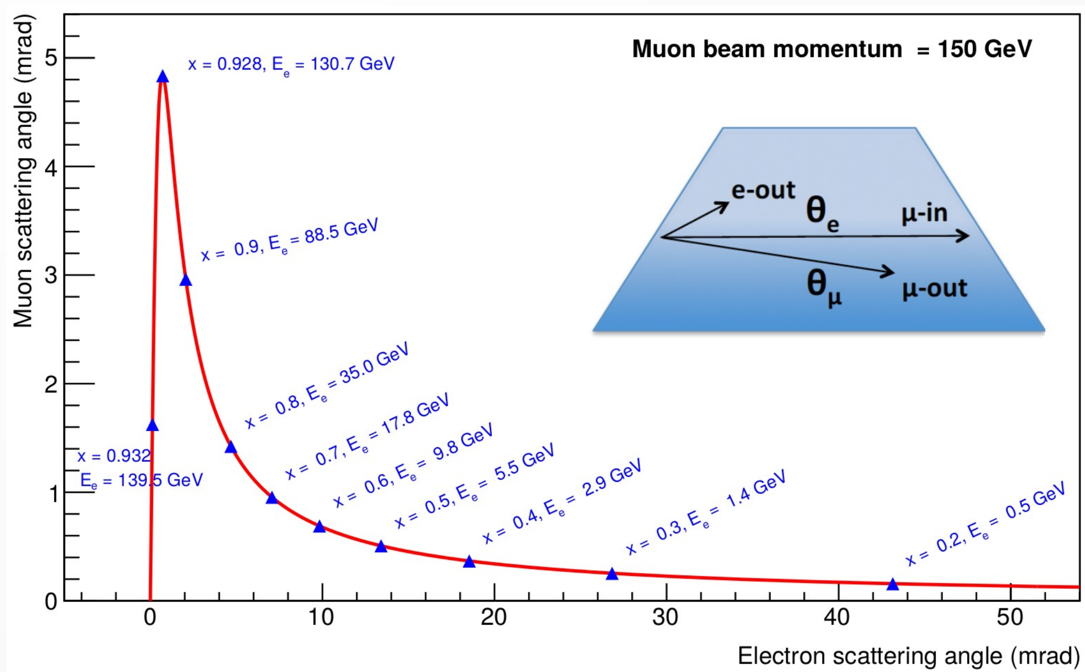
From theoretical calculation (>NNLO needed)

To be measured

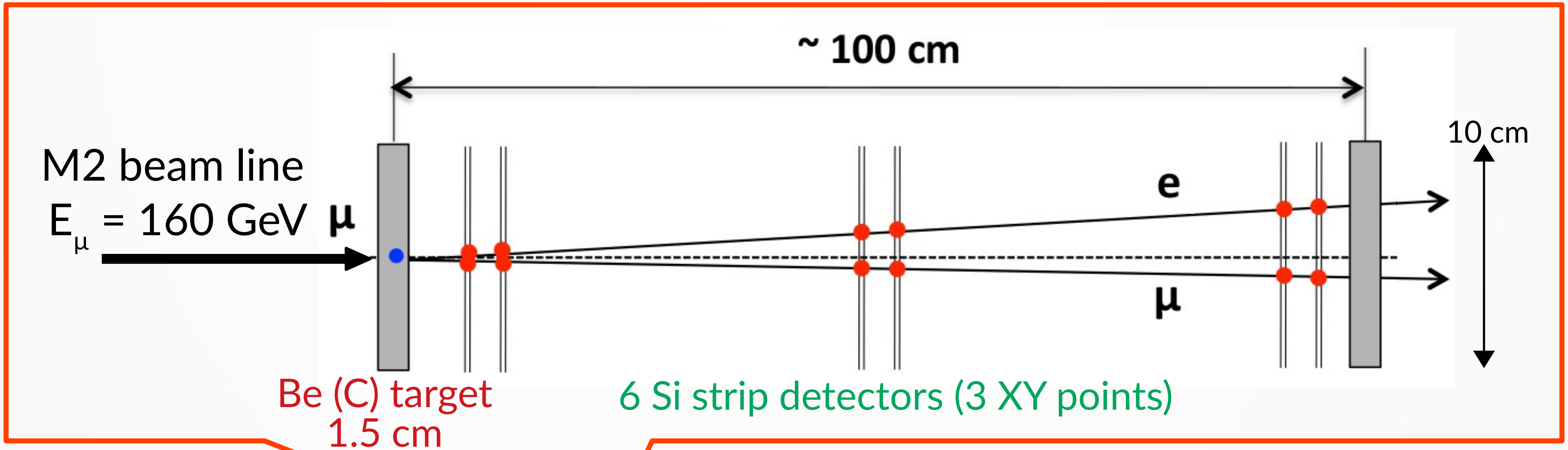
- Angular measurement: extract $\Delta\alpha_{had}(t)$ from the 2D distribution (θ_μ, θ_e).

- Correlation between θ_μ and θ_e allows to select elastic events and reject background (main source: $\mu N \rightarrow \mu N e^+e^-$).

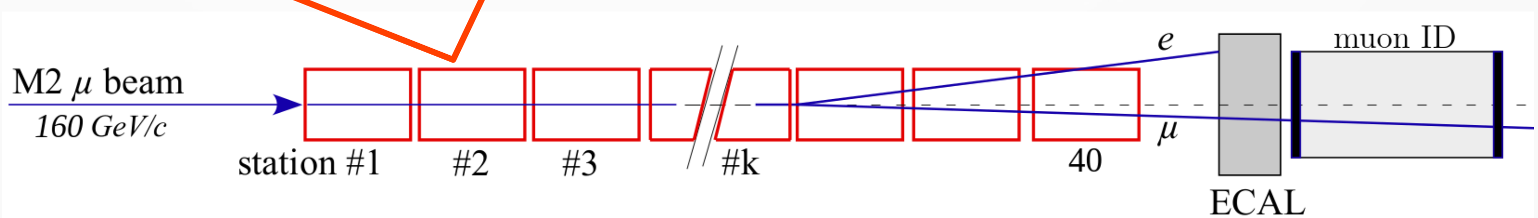
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



The experimental apparatus



BMS ....



After LS3:
full apparatus with 40 stations

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

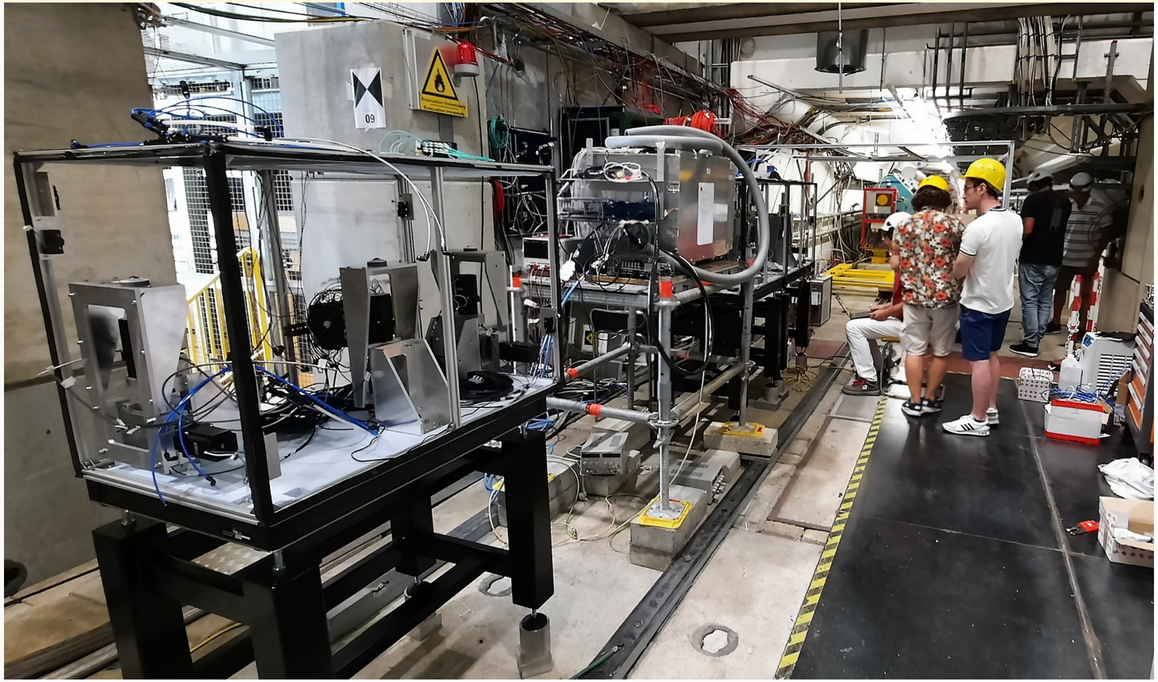
Main systematic effects:

- Longitudinal alignment (<10 µm)
- Knowledge of the beam energy (few MeV)
- Multiple scattering (<1%)
- Angular intrinsic resolution
- Non-uniform detector response

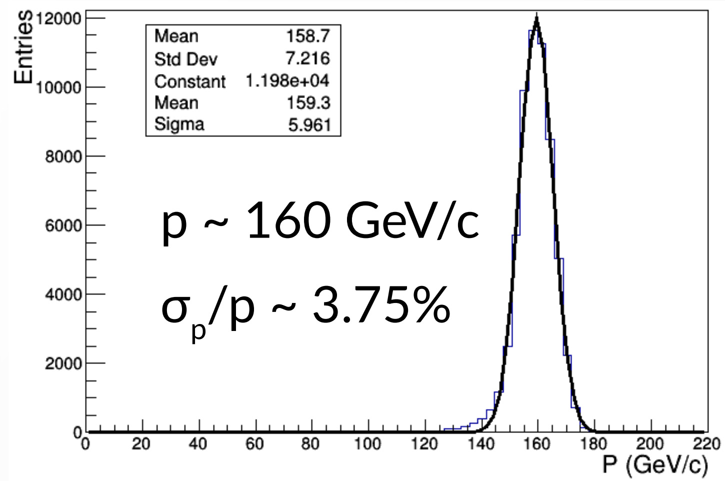
Staged approach towards the full experiment

- 2017: dedicated test beam to study multiple scattering.
- 2018: test beam to study elastic scattering properties and event selection.
- 2021: first joint test CMS-MUonE
  with a few 2S modules prototypes (parasitic).
- 2022:
  - test with 1 tracking station.
  - test the calorimeter.
- 2023: test with 2 tracking stations + calorimeter.
- 2025: run with a scaled version of the complete apparatus:
  - 3 tracking stations;
  - Calorimeter;
  - Muon ID;
  - Beam Momentum Spectrometer (BMS).

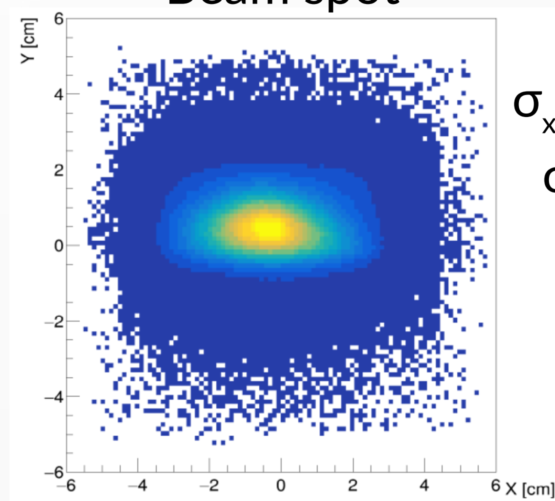
Location: M2 beamline at CERN



Beam momentum



Beam spot



$\sigma_x \sim 13$ mm

$\sigma_y \sim 7$ mm

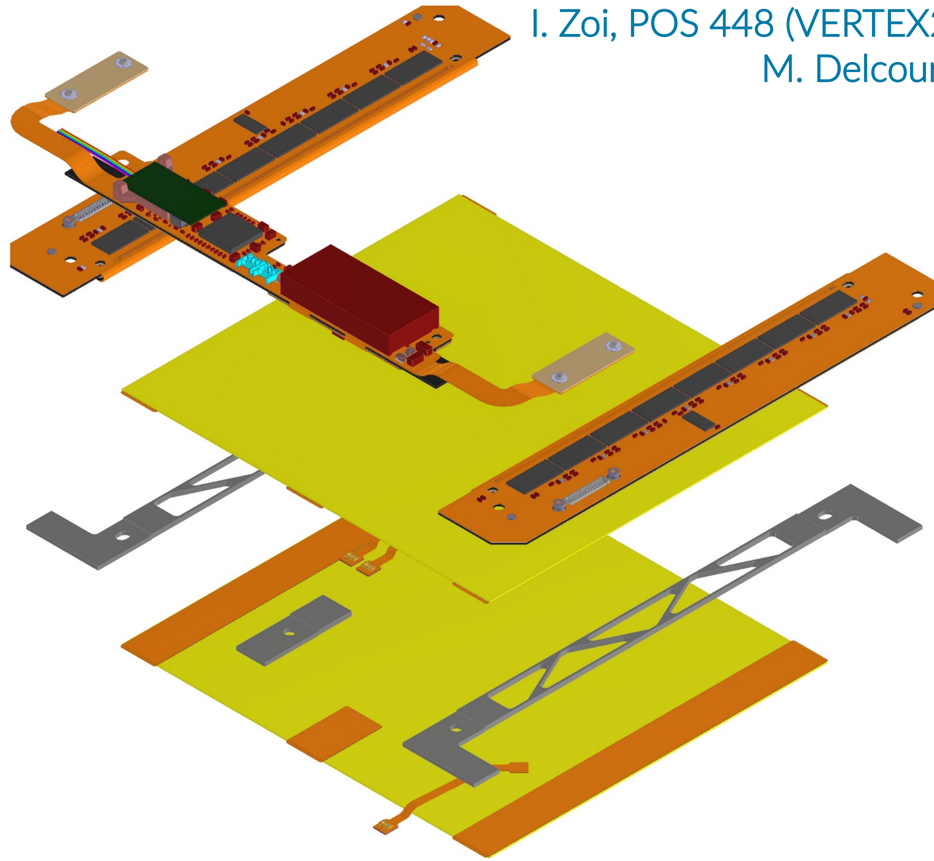
- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} < 1$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 2-3x10^8 μ^+/spill).

Tracker: CMS 2S modules

Silicon strip sensors developed for the CMS-Phase2 upgrade.
Pre-production started in 2024.

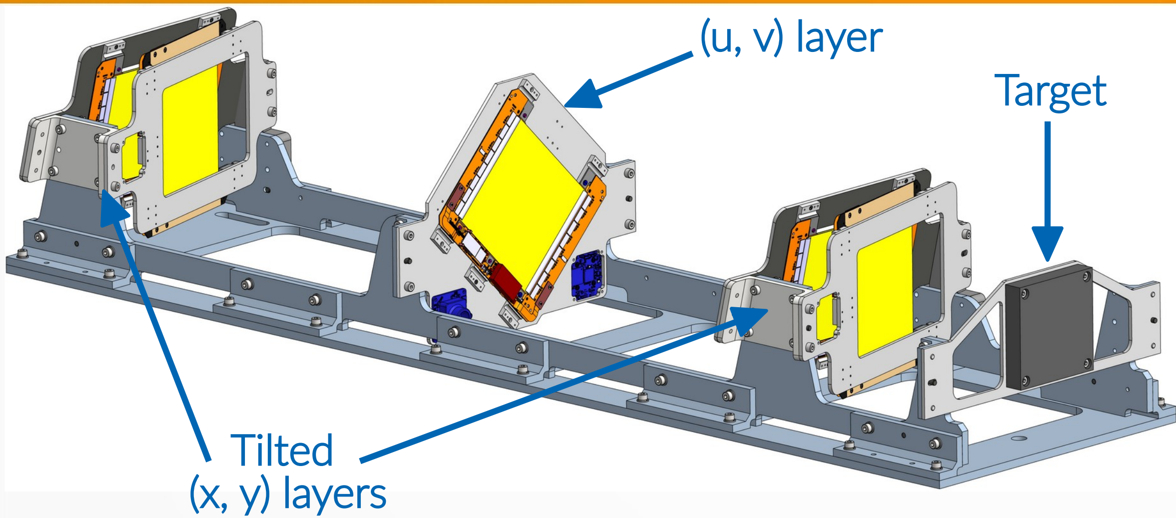
TDR CMS Tracker Phase2 Upgrade
I. Zoi, POS 448 (VERTEX2023), 021
M. Delcourt, BTTB12

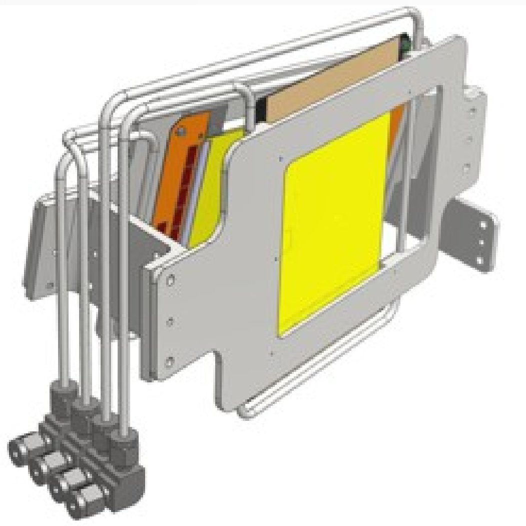
Two close-by strip sensors reading the same coordinate and read out by the same electronics



- Readout rate: 40 MHz.
- Area: 10×10 cm^2 (~90 cm^2 active).
- Digital readout, 90 μm pitch: ~26 μm resolution.
- Thickness: 2 × 320 μm.

Tracking station





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

Low CTE material: INVAR (CTE ~ 1.2 ppm/K)

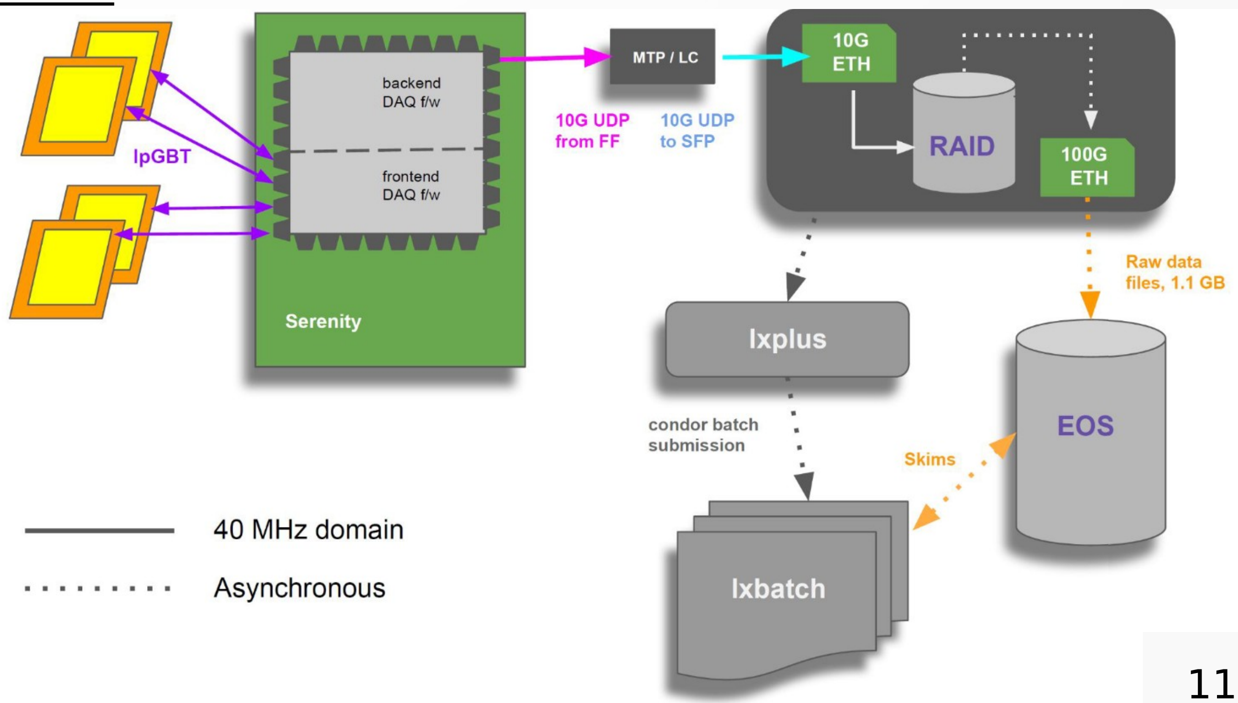
Laser holographic system to monitor stability

- (x, y) layers tilted by 233 mrad: improve hit resolution.
- (u, v) layers: solve reconstruction ambiguities.

DAQ system

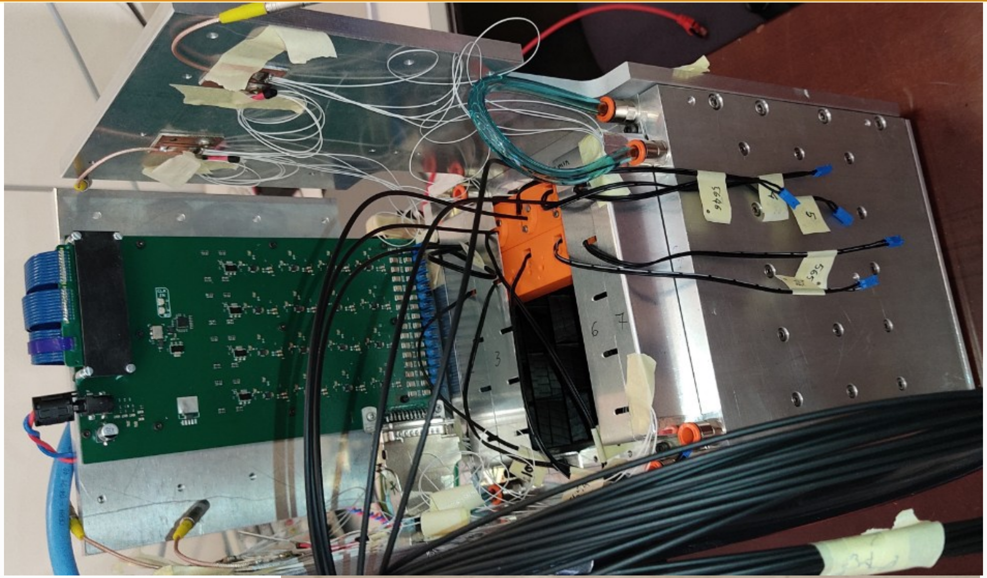
Frontend control and readout via Serenity board
(developed for the CMS-Phase2 upgrade)

- M2 beam asynchronous to the reference clock.
- Triggerless readout @40MHz.
- Event aggregator on FPGA (+ online event filtering in 2025).
- Further data aggregation on the PC.
- Transmission to EOS into ~1GB files.

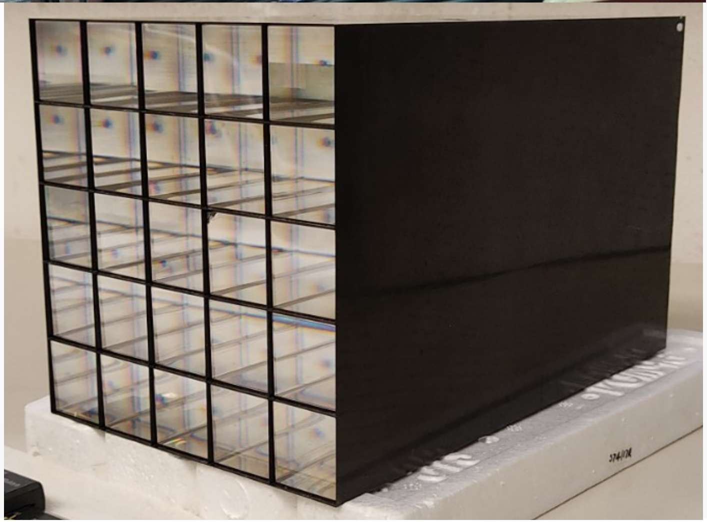


Calorimeter

- 5x5 $PbWO_4$ crystals, used in the CMS ECAL:
  - area: 2.85×2.85 cm^2;
  - length: 23 cm (~25 X_0).
- Total area: ~14×14 cm^2.
- Readout: 10x10 mm^2 APD.

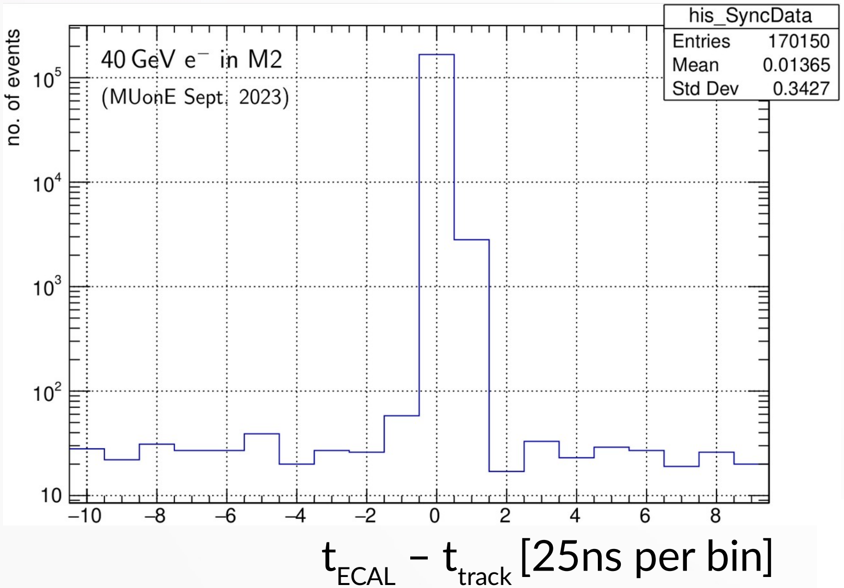


- Integration in the main DAQ @40 MHz achieved at the end of Test Beam 2023.



- ECAL commissioning in high muon rate environment must be completed.

Calorimeter preliminary analysis: synchronization and spatial resolution

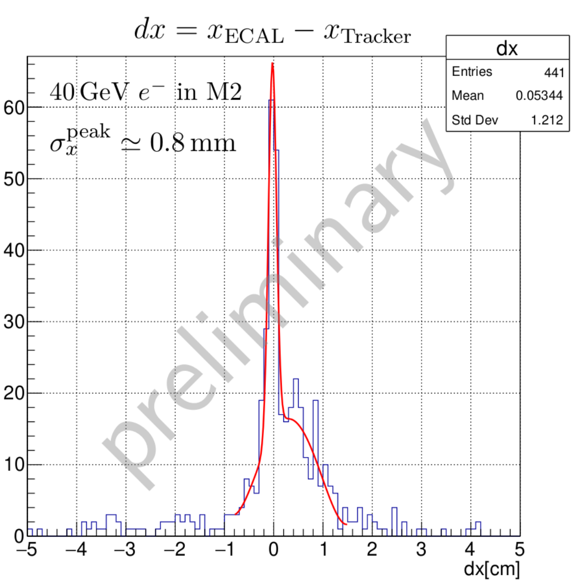


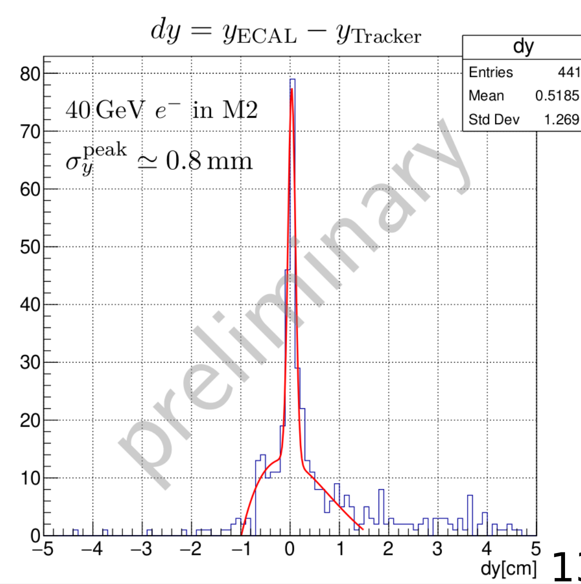
- Sharp peak for Δt = 0:
  very good time synchronization
  (resolution limited by the 25 ns readout).

- Accidental background ~ 10^{-3}.

- Sub-mm peak resolution in good agreement with simulations.

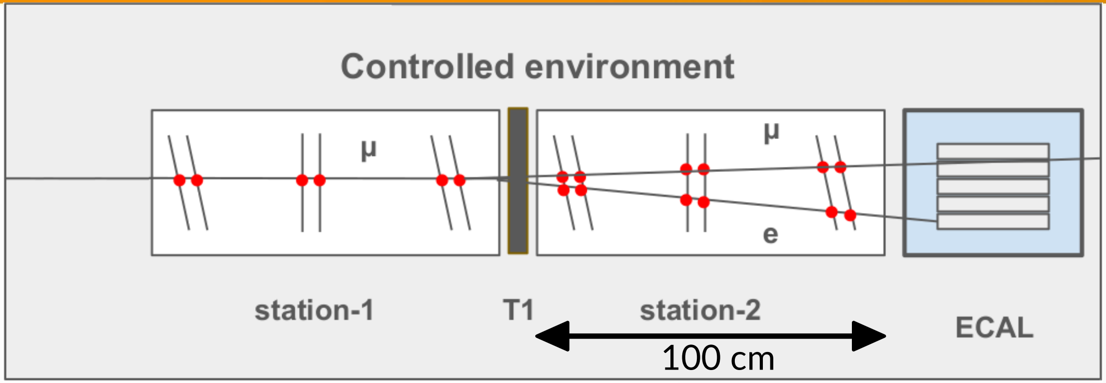
- Residual background to be further investigated.





Test Beam 2023 (3 weeks Aug/Sep)

- 2 tracking stations;
- 1 graphite target (2–3 cm thickness);
- ECAL.



Achievements:

- Demonstrated continuous readout @40 MHz.
- 350 TB raw data recorded to disk:
  - 3 cm (2 cm) target: ~1(2)×10^8 elastic events;
- ECAL integrated in the DAQ @40 MHz in the final part of the run.
- Achieved online tracking on FPGA.

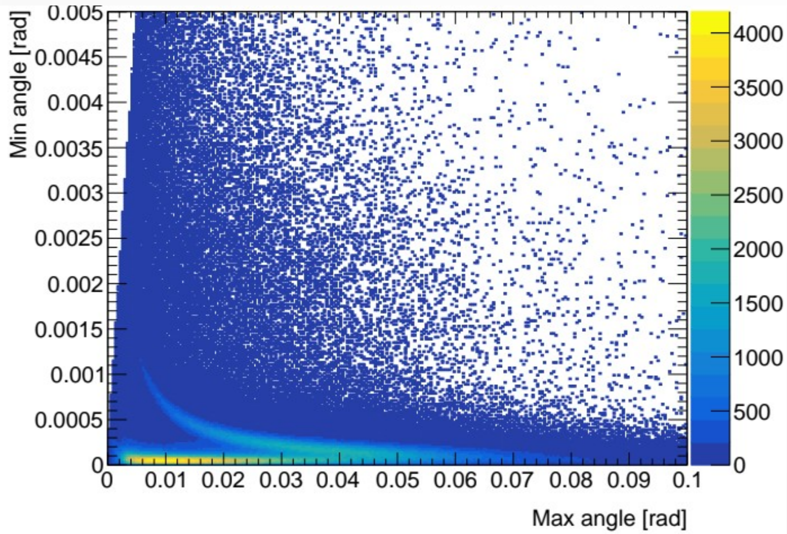
- Test the detector performance.
- Test the reconstruction algorithms and event selection.

Work in progress:

- Study the background processes and the main sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{lep}(t)$ with $O(5\%)$ stat. accuracy.

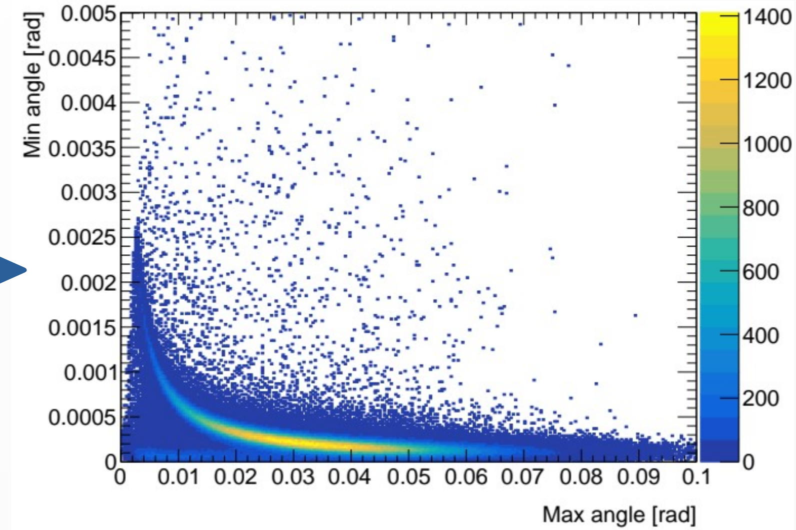
TB 2023
μ-e elastic scattering event selection

- Single μ_{in} candidate.
- μ_{out}, e_{out} pair candidate.



Initial selection

- Loose χ^2_{vtx} cut.
- $|z_{vtx} - z_{target}| < 3$ cm.
- Acoplanarity cut (elastic events are planar).



Work in progress:

- Exploit dedicated MC generators to study the backgrounds.
- Study the main sources of systematic error using tracker data:
  - Angular intrinsic resolution;
  - Beam energy scale.

Run 2025

- MUonE recently submitted a proposal for a phase 1 of the experiment to the SPSC, concerning a small scale version of the final apparatus.

- If approved, MUonE will request 4 weeks of data taking in 2025.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

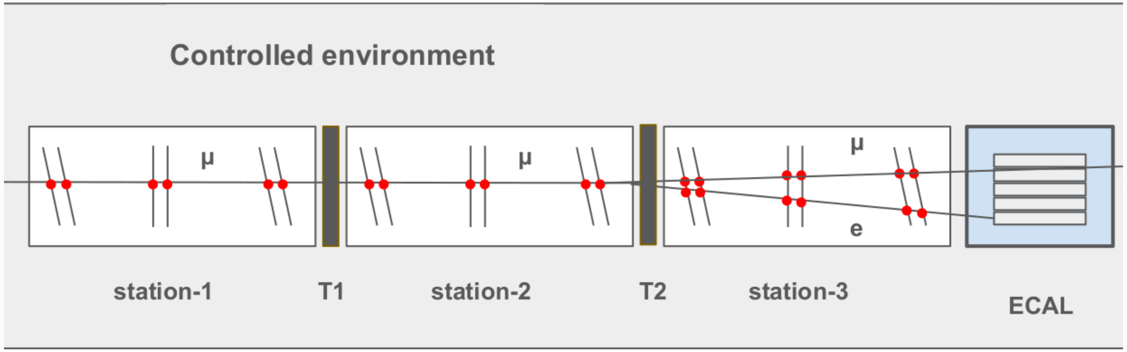
MUonE Phase 1 Experiment Proposal

April 25, 2024

Proposal for phase 1 of the MUonE Experiment

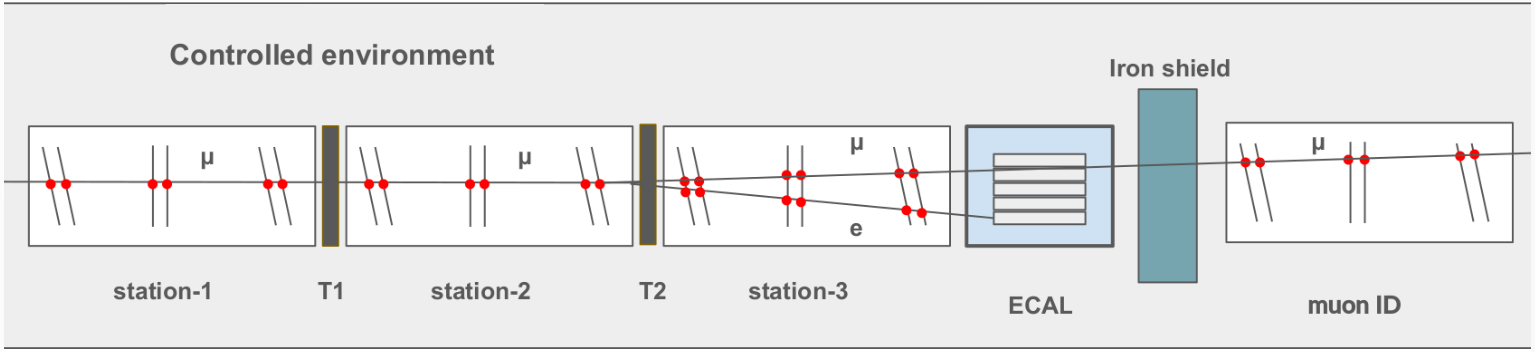
The MUonE Collaboration

Run 2025: the apparatus



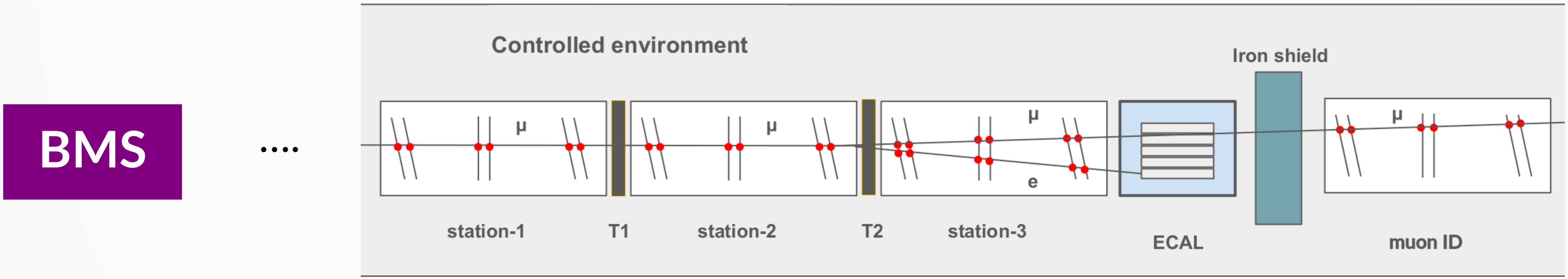
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.

Run 2025: the apparatus



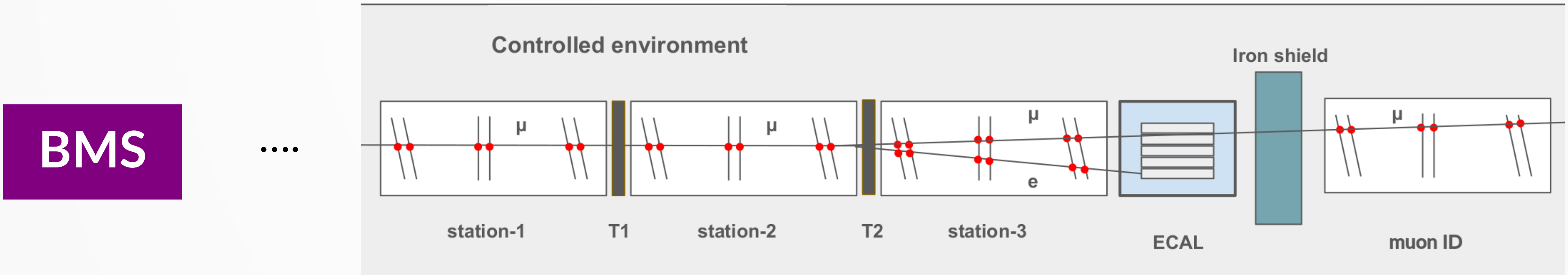
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).

Run 2025: the apparatus



- 3 tracking stations.
- 2 graphite targets (2 cm thickness each).
- ECAL:
  - Full acceptance for interactions in both targets.
  - Provide independent measurements of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).
- BMS:
  - Event-by-event p_μ measurement: reduce systematics related to the beam energy scale.

Run 2025: the apparatus

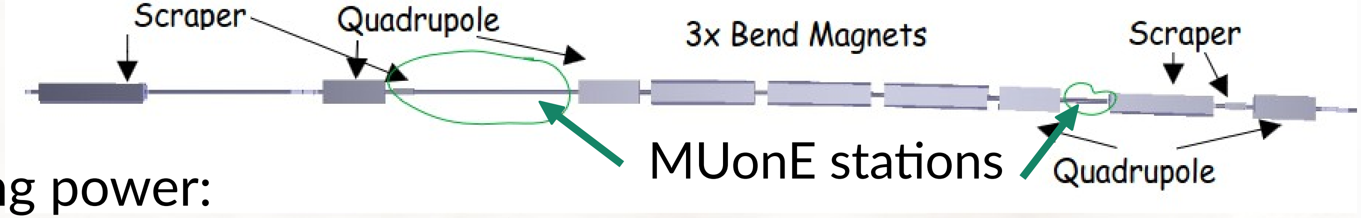


"To instrument the three stations for the proposed system, CMS agree to provide 18 pre-production 2S modules in time for integration activities in January 2025.

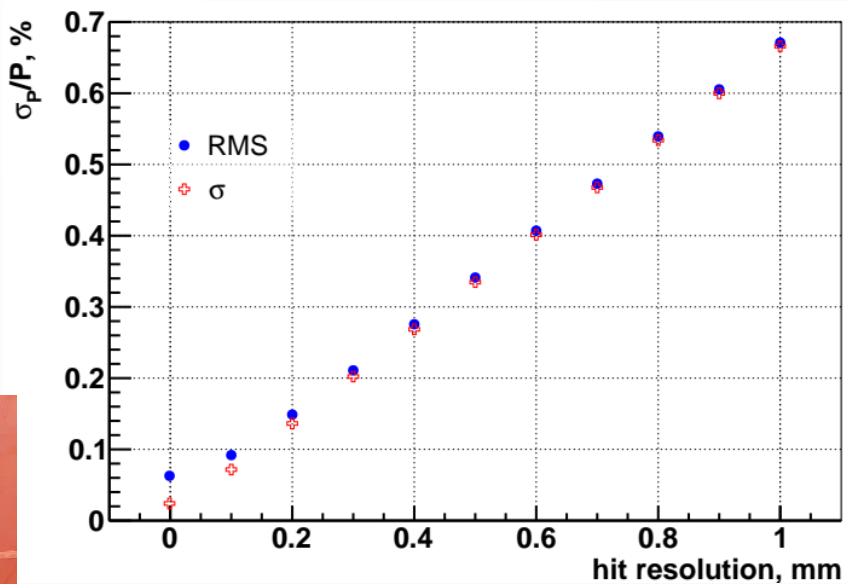
In addition to this, at least 12 good quality prototype 2S modules will be made available to complete the setup on the same timescale."

MUonE Phase 1 Experiment Proposal

BMS (Beam Momentum Spectrometer)



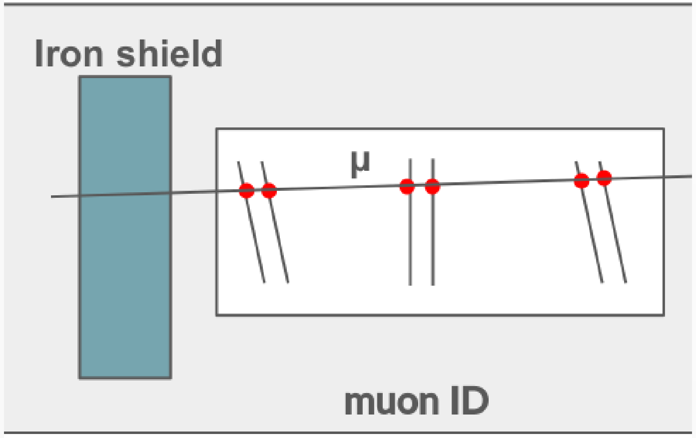
- Bending power:
  16 T*m (30 mrad @160 GeV).
- Determine the muon momentum event by event.
- Goal: < 0.5% momentum resolution.
- In 2025, limited by the precise knowledge of the magnetic field.



Muon ID

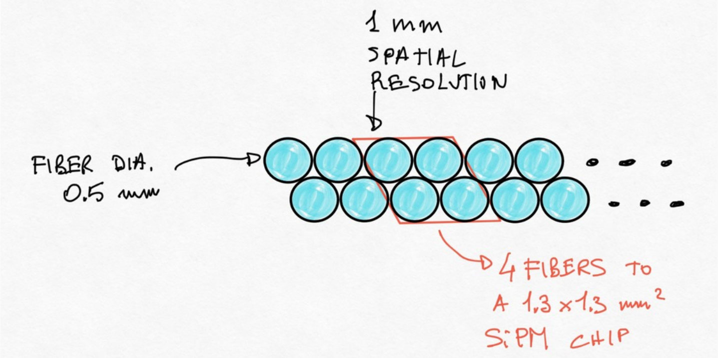
- Detect potential π^+ contamination in the M2 beam.
- Complete the PID in combination with ECAL.
- Help to distinguish between scattered muons and beam pileup muons.

Baseline solution for 2025



- Aluminum station (already used in the past Test Beams) instrumented with 2S modules.

Alternative solution (mid-longer term)



- Plastic scintillating fibers readout by SiPM.
- O(1mm) spatial resolution; <0.5ns timing resolution.
- Same technology could be used as timing detector between BMS and main tracker.

Run 2025: goals

- **Detector operations:**
  - Prove the capability of the DAQ to synchronize all the sub-detectors and operate efficiently in the 4 weeks run.
  - Verify real time data processing in FPGA firmware to reduce the data volume to be stored.
  - Exploit the ECAL full acceptance to get indications in optimizing its design for the final experiment.

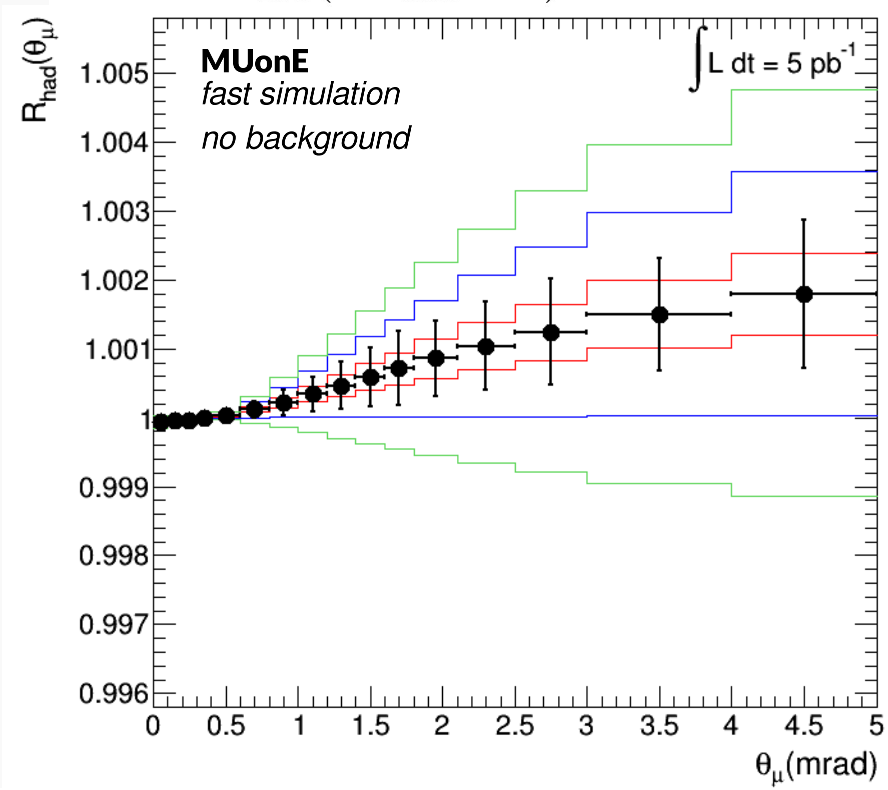
- **Systematic error studies:**
  - Exploit data from all the sub-detectors to study backgrounds and systematics.
  - Study uniformity of tracking efficiency, PID, backgrounds, detector modelization, beam control.
  - Demonstrate control of the systematic errors at *O*(500ppm).

- **Physics results:**
  - Preliminary measurement of $\Delta\alpha_{had}(t)$ with *O*(20%) statistical accuracy.
  - Measure $\Delta\alpha_{lep}(t)$ with a few percent precision, and compare with the measurement currently being performed with 2023 data.

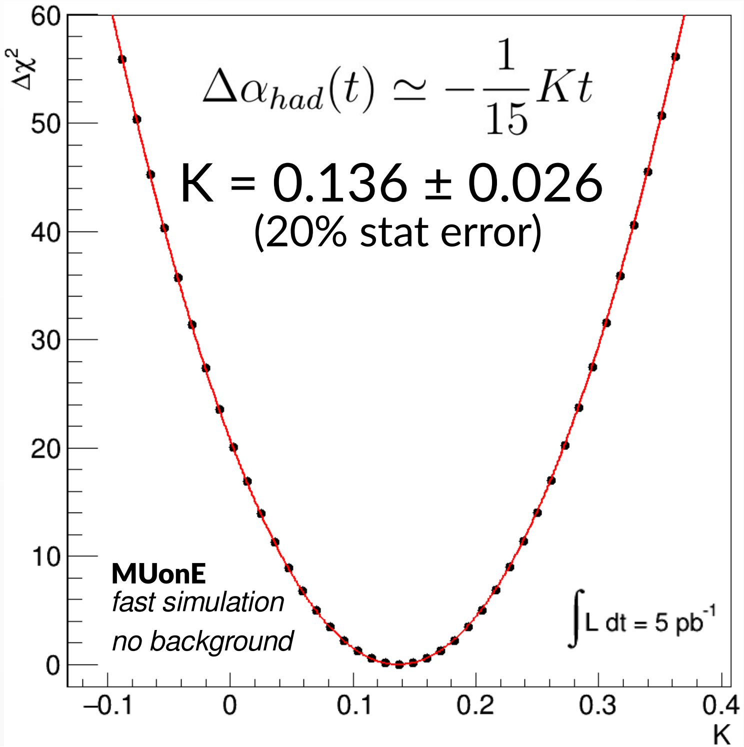
First measurement of $\Delta\alpha_{had}(t)$

Expected event yield: ~10^9 elastic events within acceptance
(one order of magnitude larger than 2023)

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



Template fit procedure
to extract $\Delta\alpha_{had}$(t)

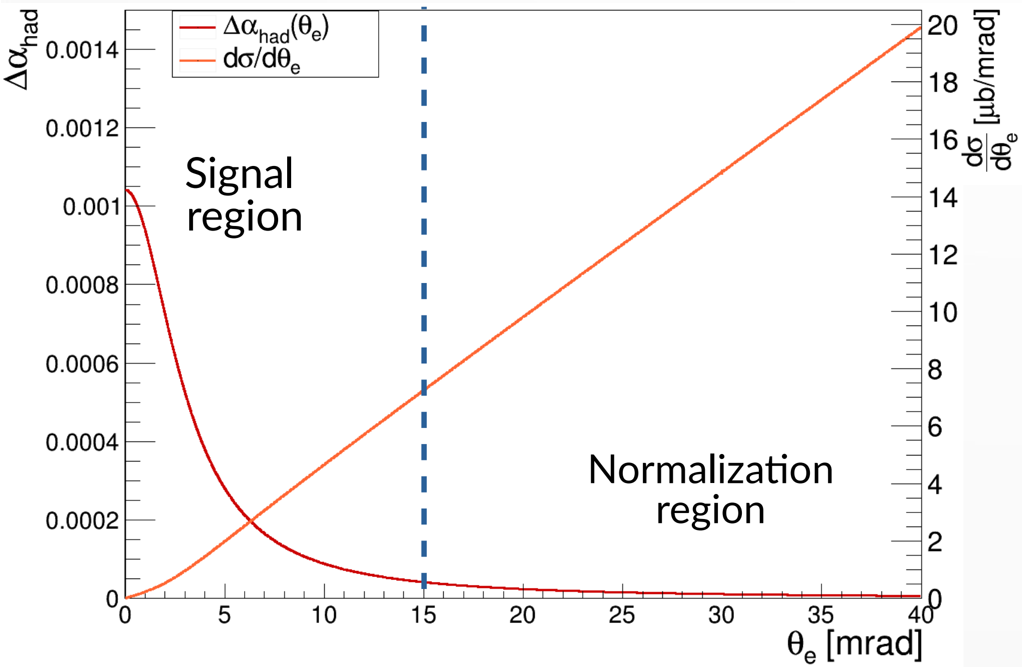


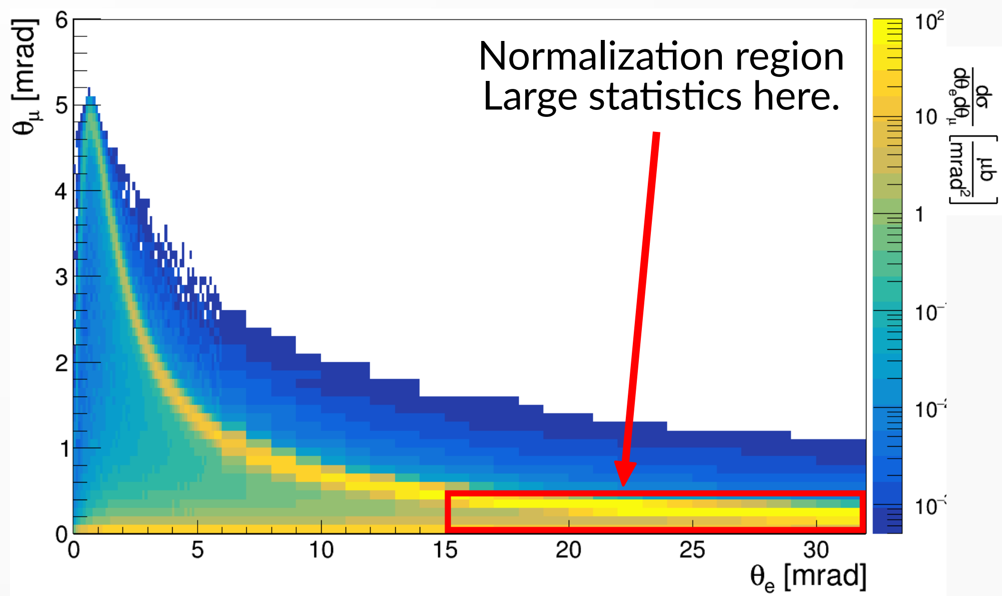
Strategy for the systematic effects

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

Promising strategy:

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

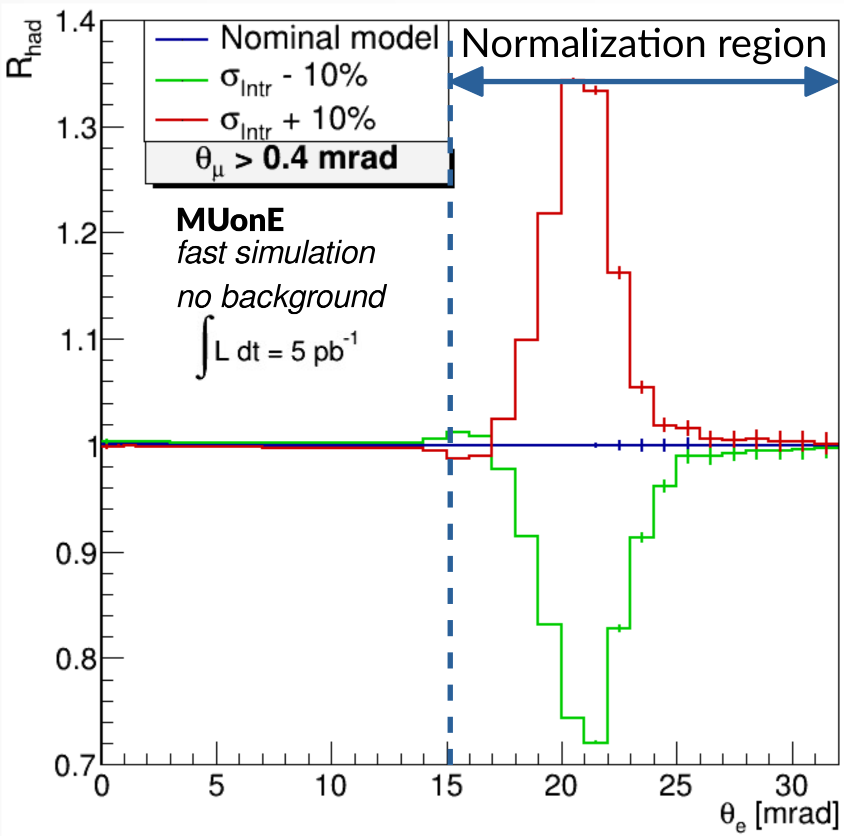


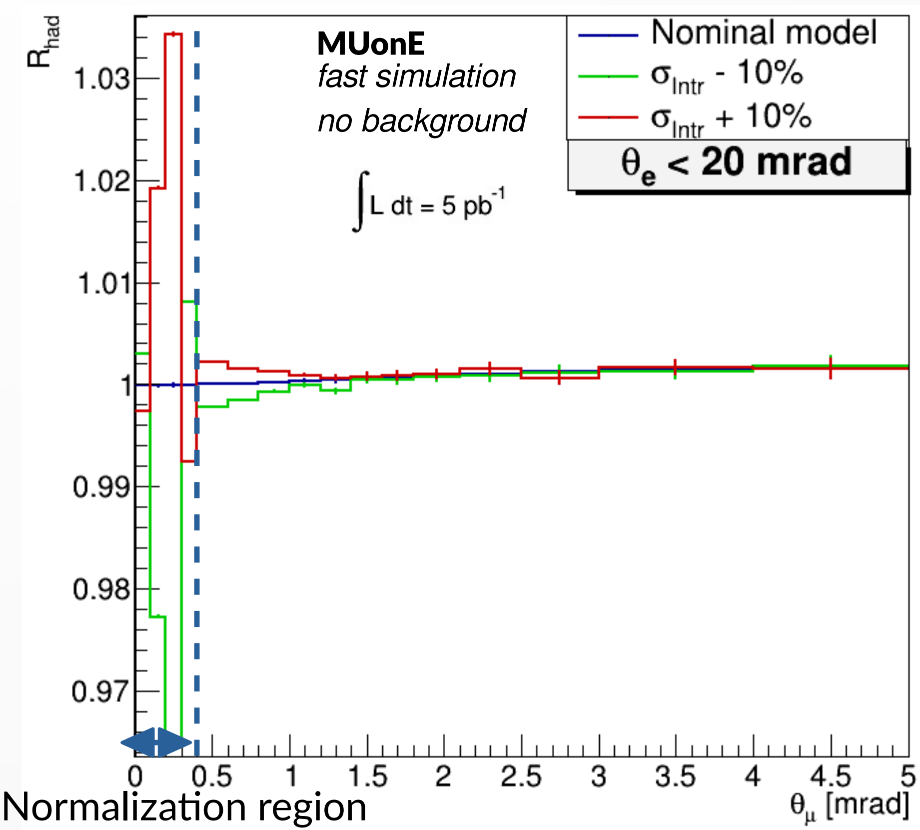


The need of including systematic effects in the analysis

Some systematic effects can produce huge distortions in the shape of the elastic scattering cross section

Example: ±10% error on the angular intrinsic resolution

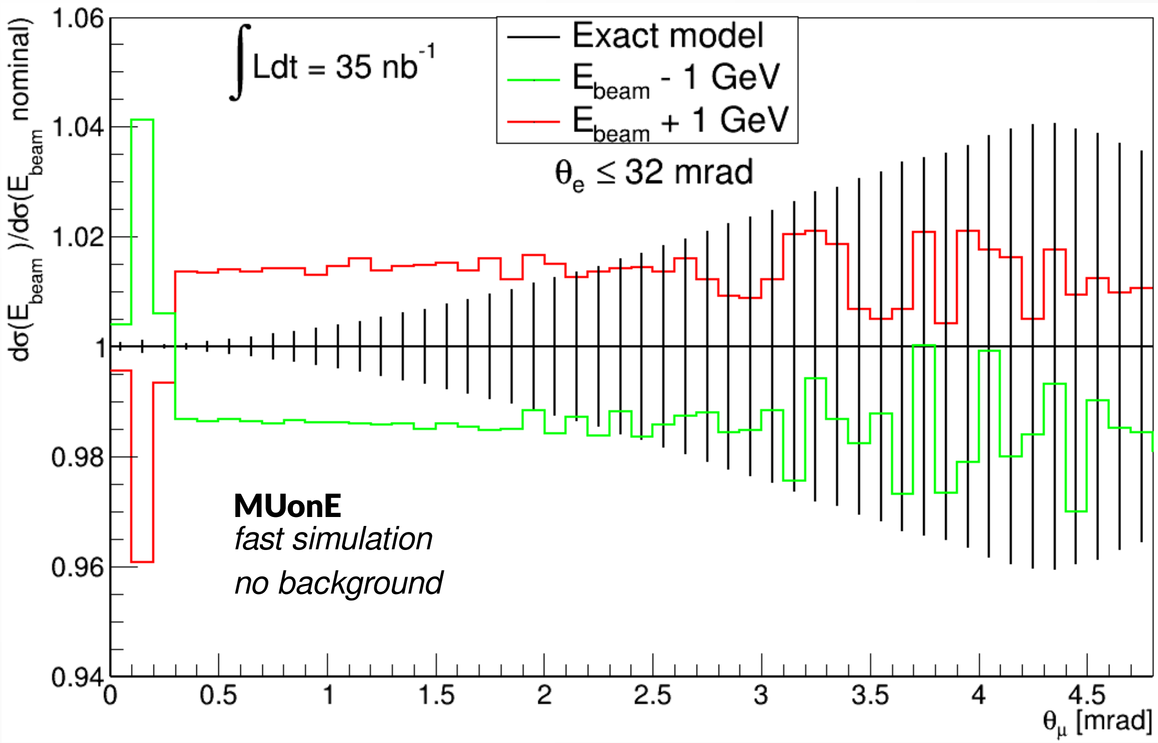




Systematic error on the muon beam energy

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

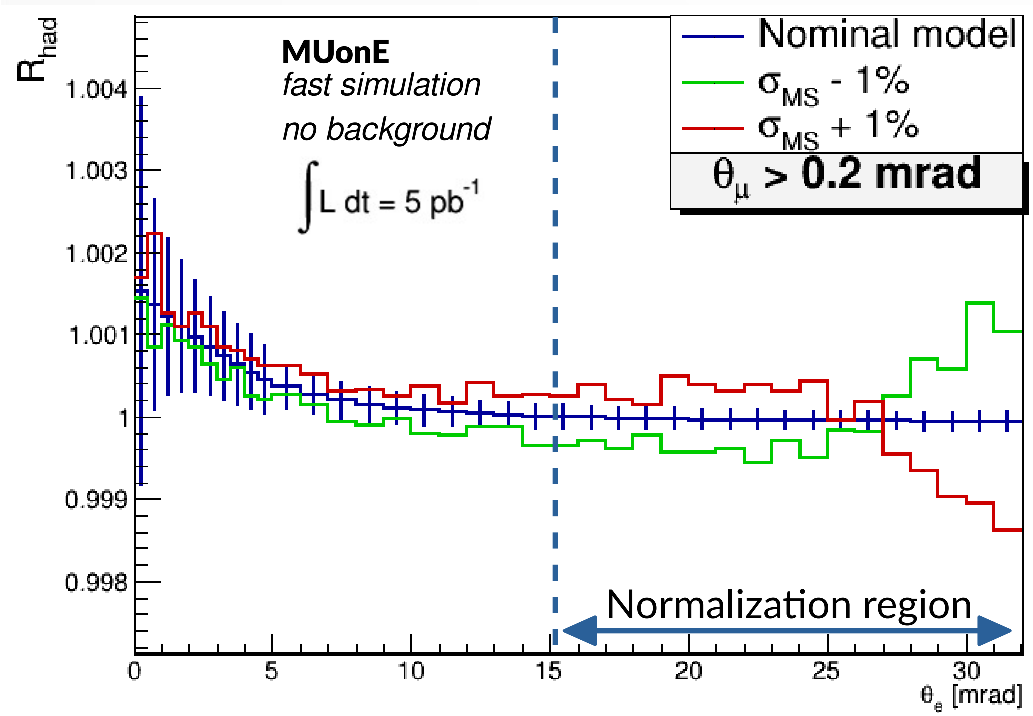
This effect can be seen from our data in 1h of data taking per station

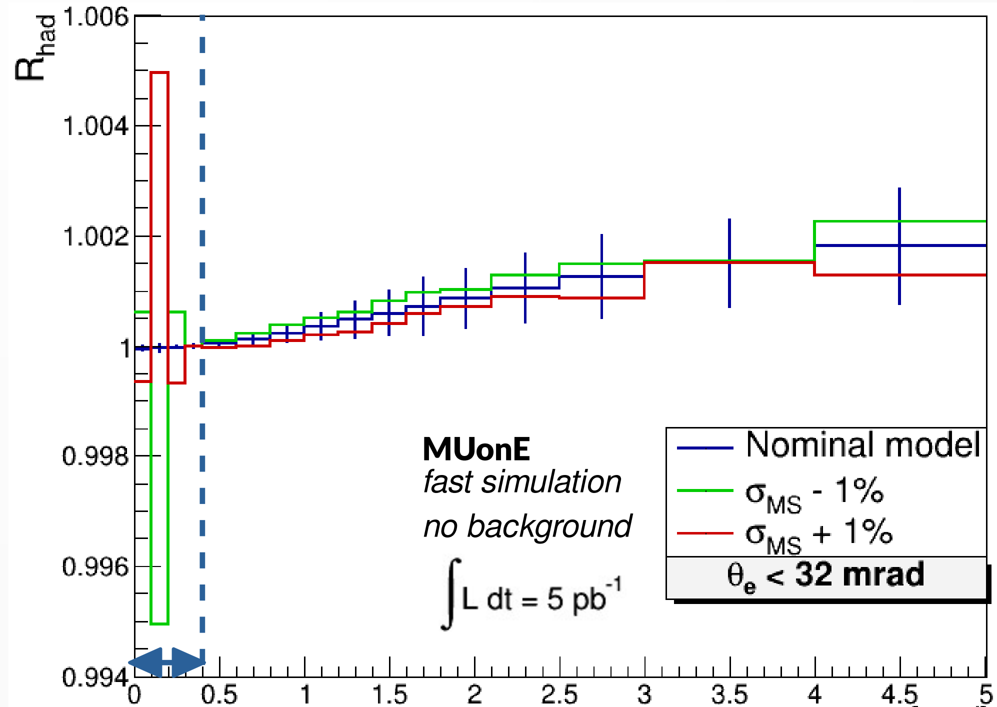


Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

G. Abbiendi et al JINST (2020) 15 P01017





Normalization region

The need of including systematic effects in the analysis

What if systematic effects are not included in the template fit?

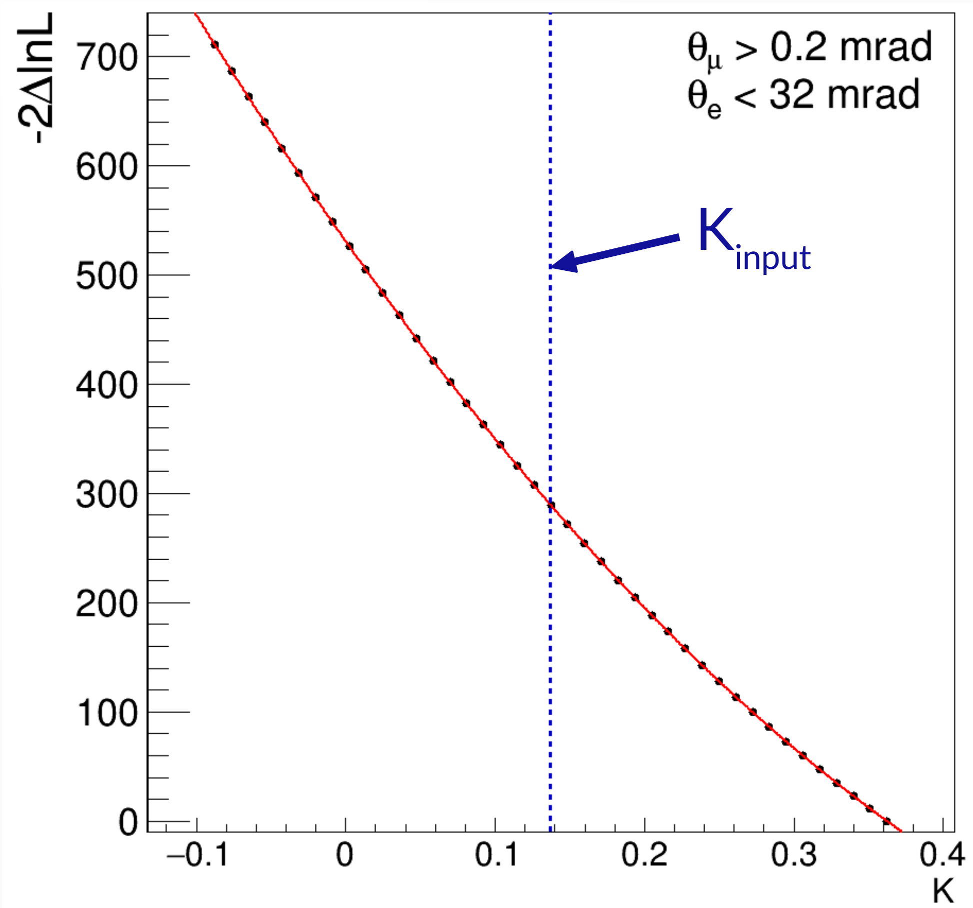
Simplified situation:

- 1 fit parameter (K).

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

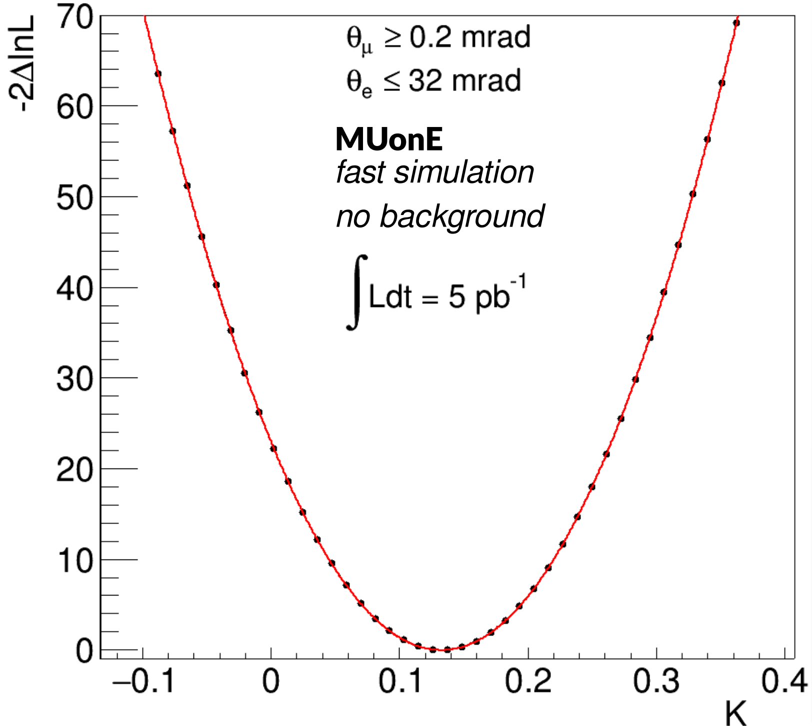
- L = 5 pb^{-1}.
  ~10^9 elastic events
  (~4000 times less than the final statistics).

- Shift in the pseudo-data sample:
  $\sigma_{Intr} \rightarrow \sigma_{Intr} + 5\%$.



Combined fit
signal + systematics

- Include residual systematics as nuisance parameters in the fit.
- Simultaneous likelihood fit to K and systematics using the Combine tool.



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

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 $\nu = -0.001 \pm 0.003$

Similar results also for different selection cuts

Input shifts identified correctly.
No degradation on the signal parameter

Conclusions

MUonE web site

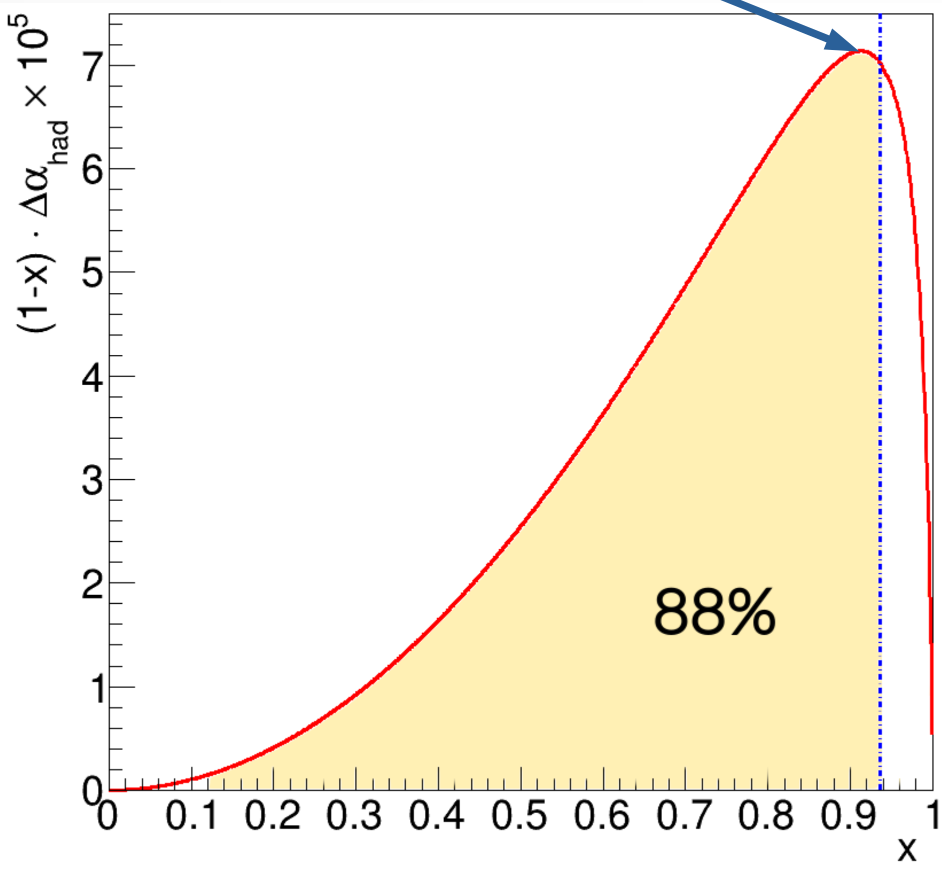
- Test beam 2023 analysis (further details tomorrow): first opportunity to study elastic scattering with a minimal setup.
- Recently submitted a proposal for MUonE phase 1:
    - 3 tracking stations;
    - Calorimeter;
    - Muon ID;
    - BMS.
- Requested 4 weeks of data taking in 2025, to study the expected systematic errors and background under realistic conditions and make a preliminary measurement of $\Delta\alpha_{had}(t)$.
- A further proposal is expected to be submitted for the final version of the experiment after LS3 (40 tracking stations + ancillary detectors).

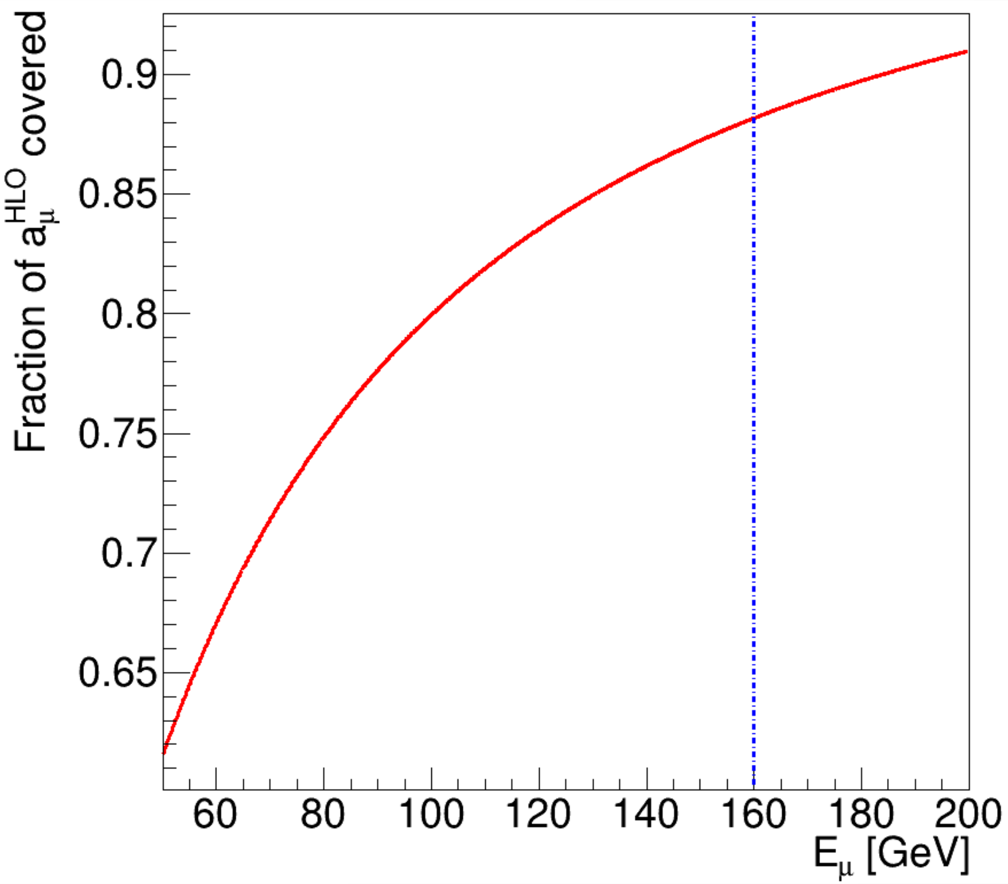
BACKUP

$x < 0.936$

t_{peak} ~ -0.108 GeV^2

x_{peak} ~ 0.92



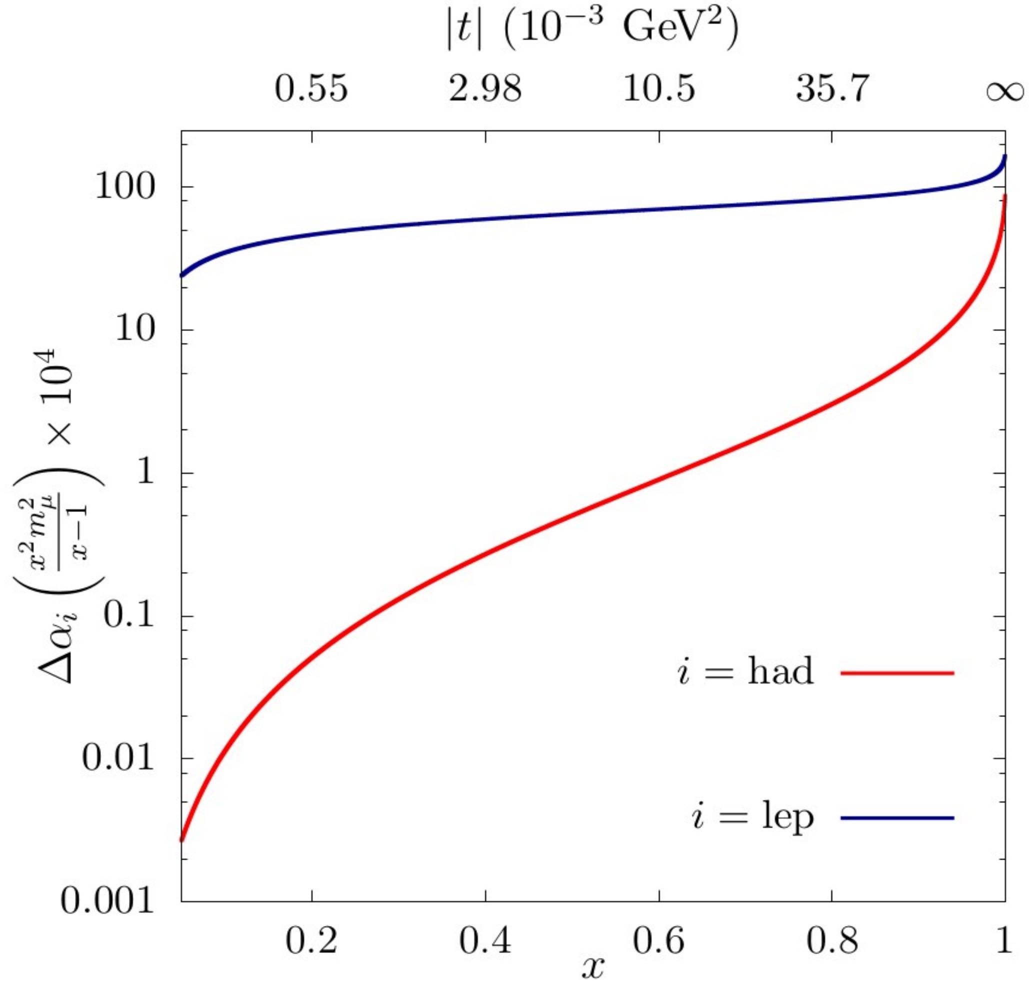


- 160 GeV muon beam on atomic electrons.

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

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

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



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

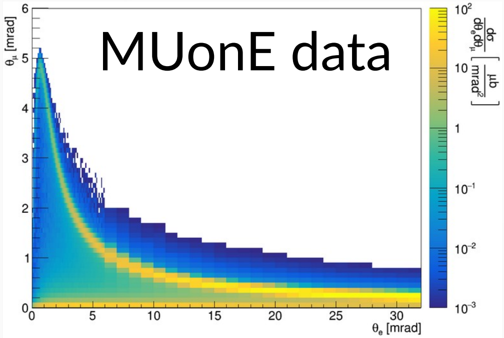
$\Delta\alpha_{had}(t)$ parameterization:

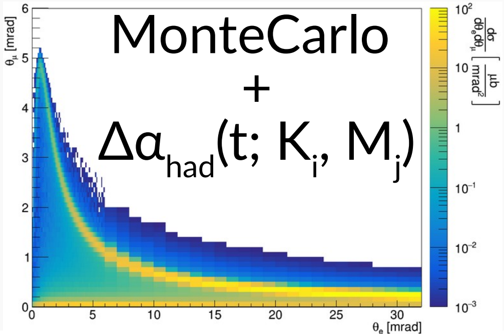
inspired from the 1 loop QED contribution of lepton pairs and *t*-quark at $q^2<0$

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

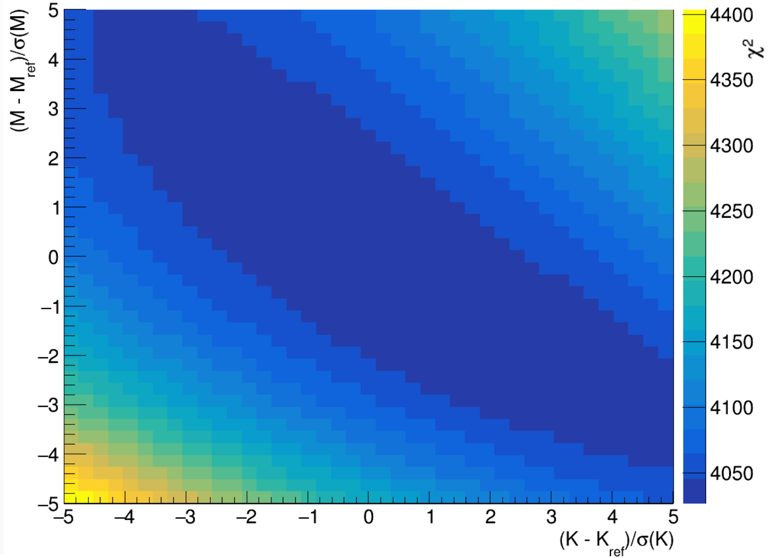
2 parameters:
K, M

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

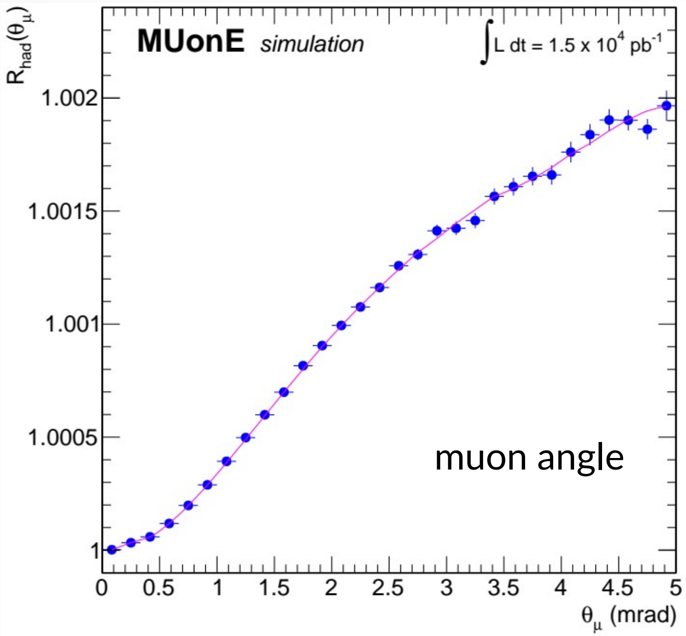


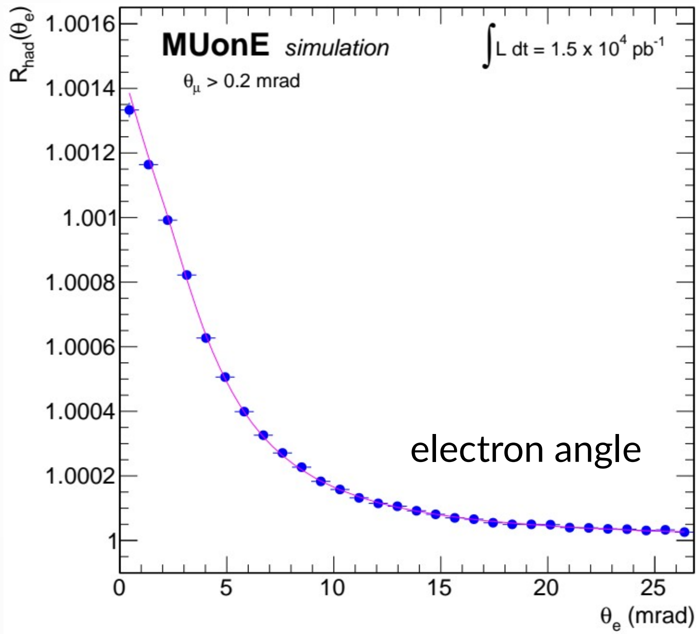


$$\chi^2 = \sum_i^{\text{bins}}\left(\frac{\text{data}_i - \text{templ}(K,M)_i}{\sigma_i^{\text{data}}}\right)^2$$



Extraction of a_μ^{HLO}





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

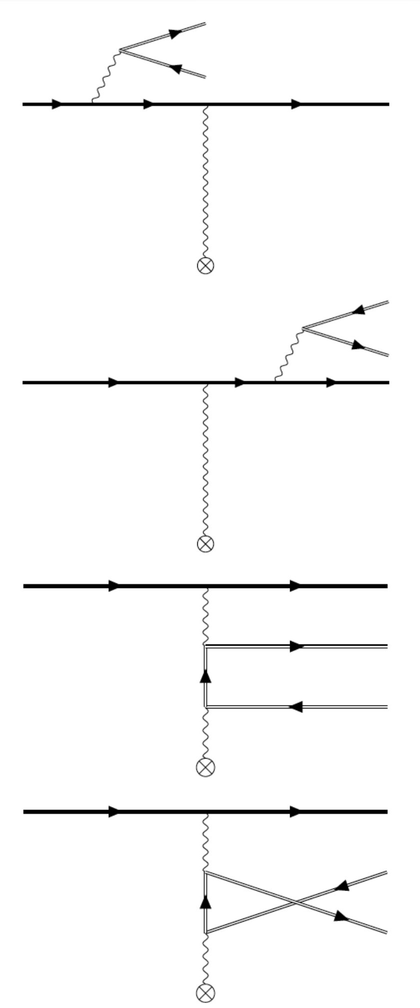
$$a_\mu^{HLO} = (688.8 \pm 2.4)\ 10^{-10}$$

Input value:

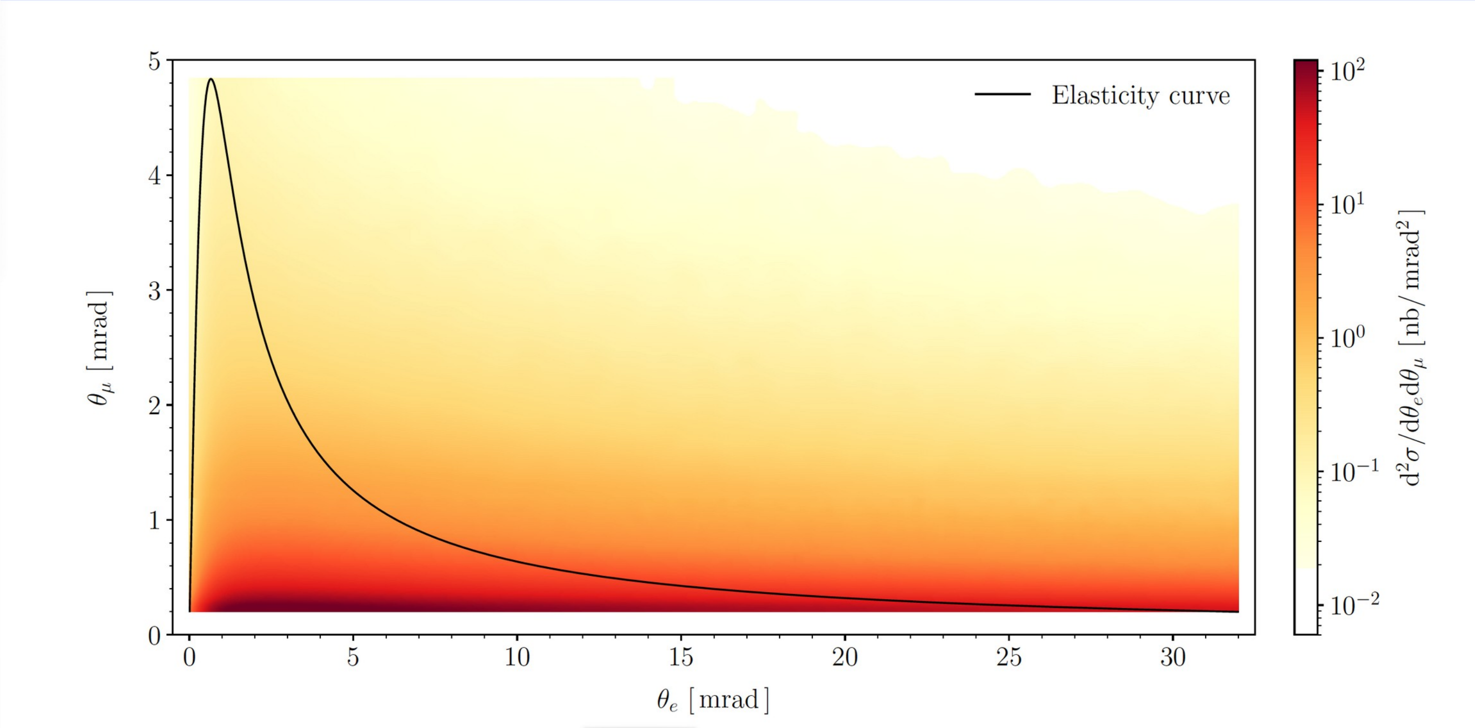
$$a_\mu^{HLO} = 688.6\ 10^{-10}$$

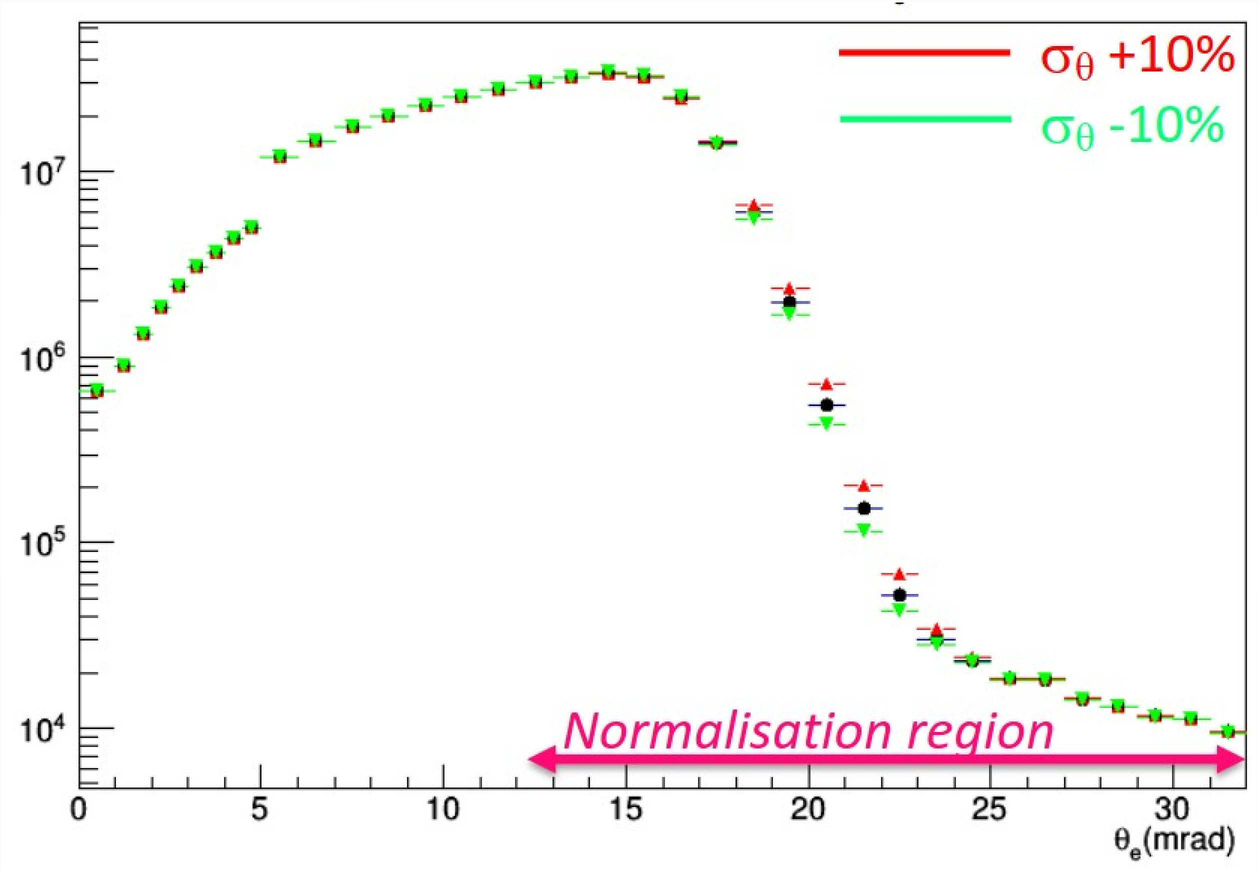
New Background MC generator

Main background: e+e- pair production
Implemented in MESMER
and interfaced with the MUonE detector simulation



Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)



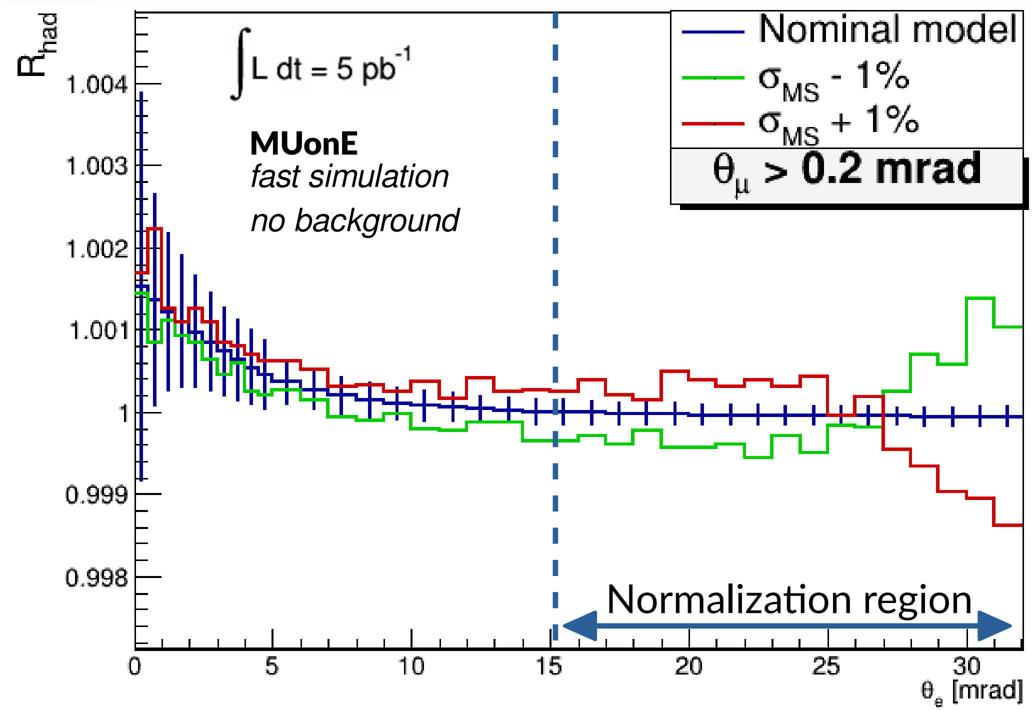


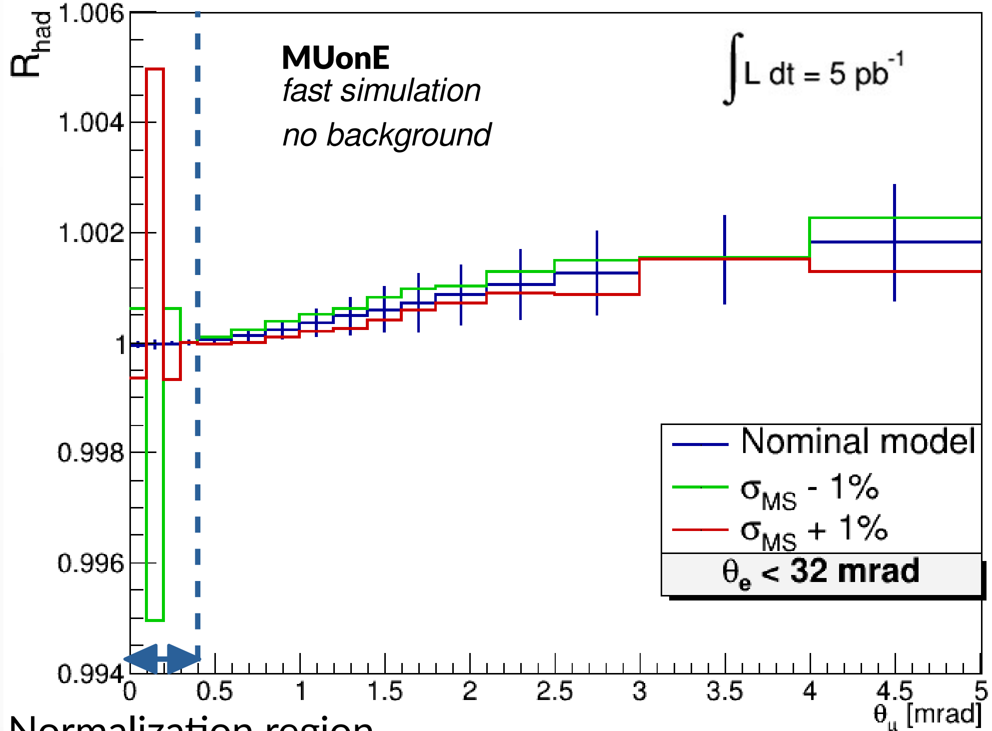
σ_θ +10%
σ_θ -10%
10^7
10^6
10^5
10^4
Normalisation region
0
5
10
15
20
25
30
θ_e(mrad)

Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

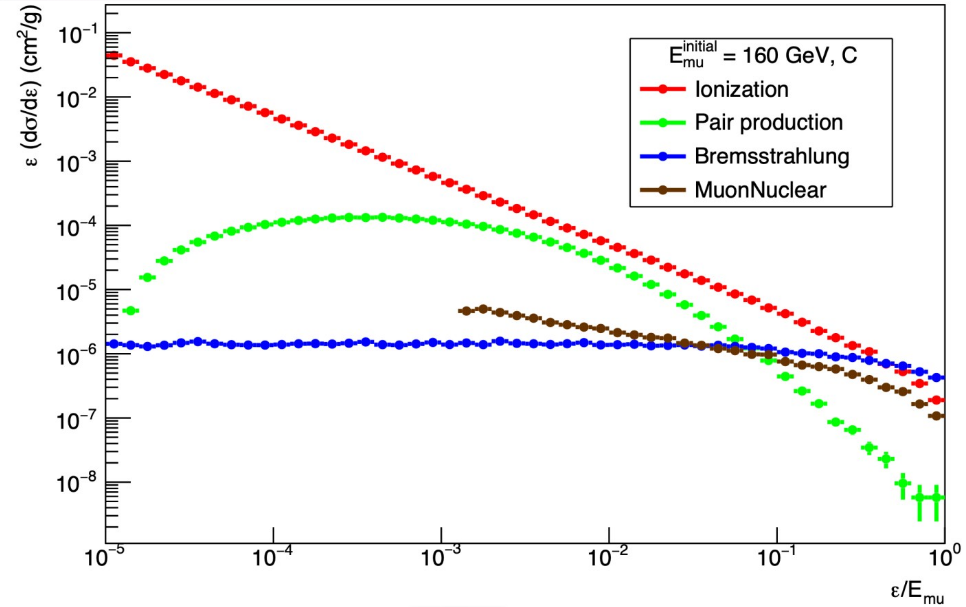
G. Abbiendi et al JINST (2020) 15 P01017

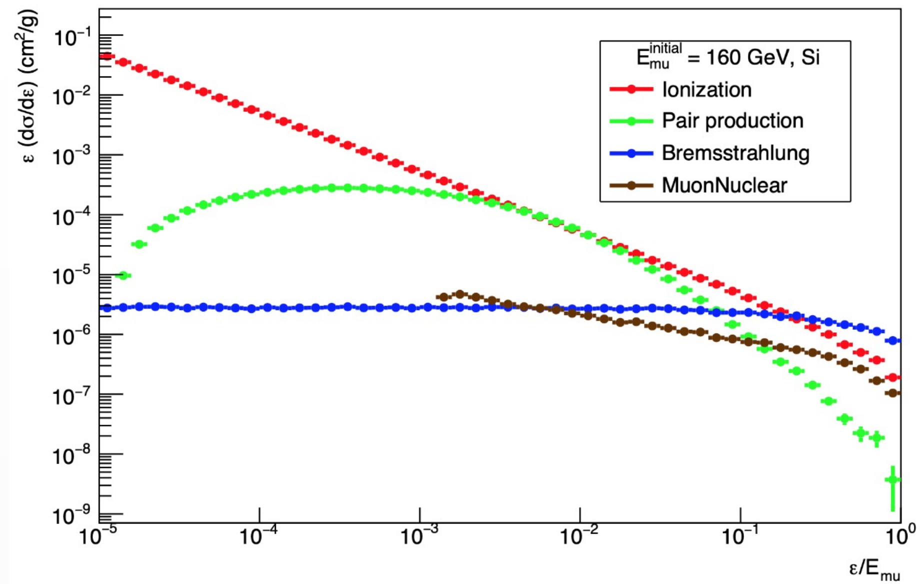




Normalization region

Backgrounds





θ_e [mrad] ← 32 — 0

MESMER

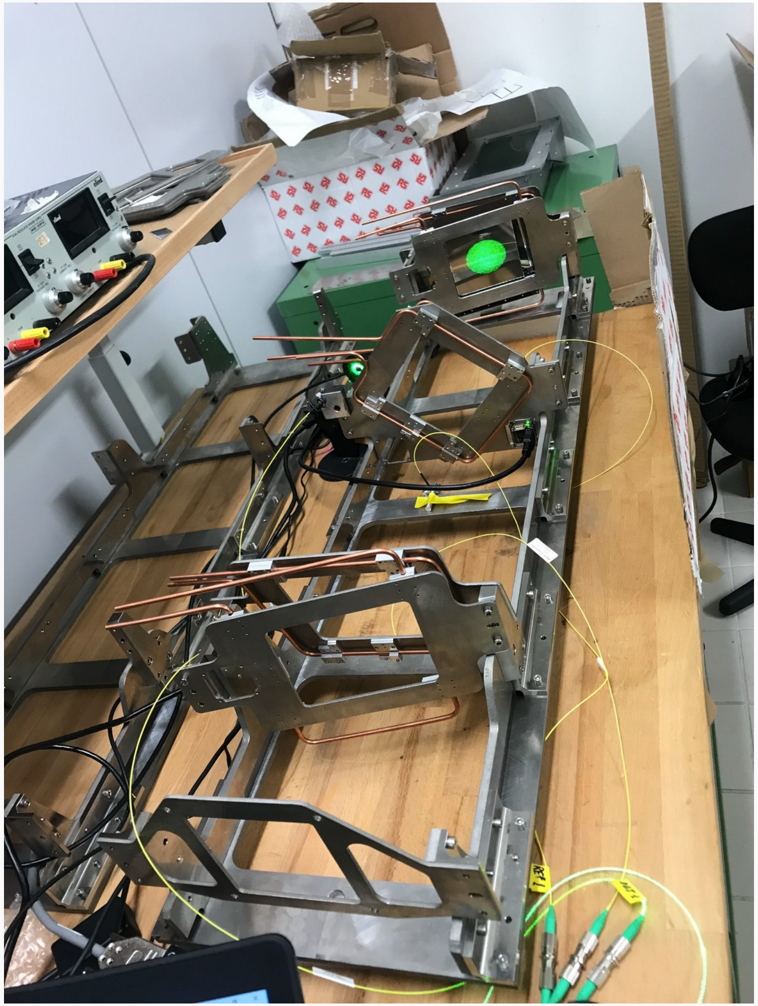
- $\mu e^- \to \mu e^- \gamma$
- $\mu e^- \to \mu e^- l^+ l^-$
- $\mu N \to \mu N l^+ l^-$

$l = e, \mu$

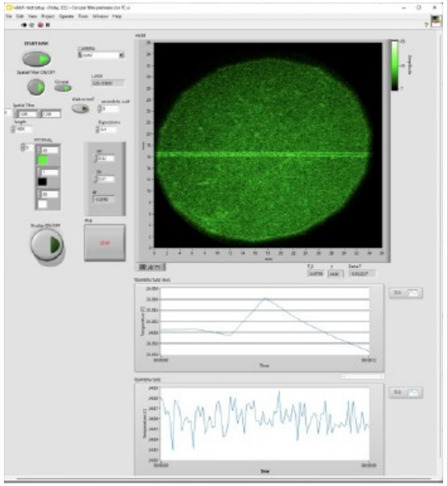
GEANT4

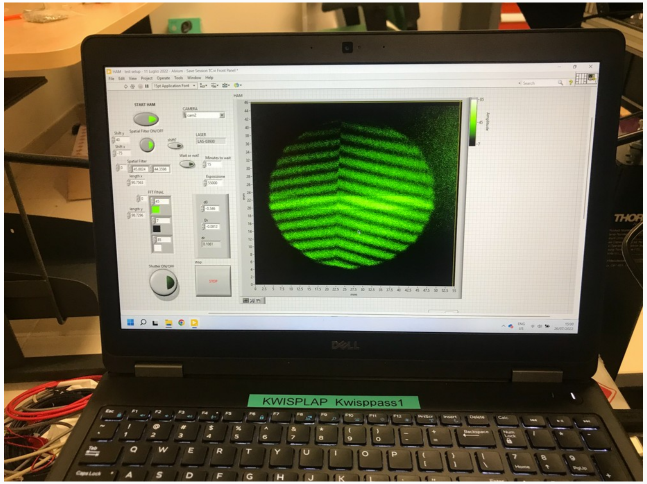
- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$

Laser holographic system



Initial state

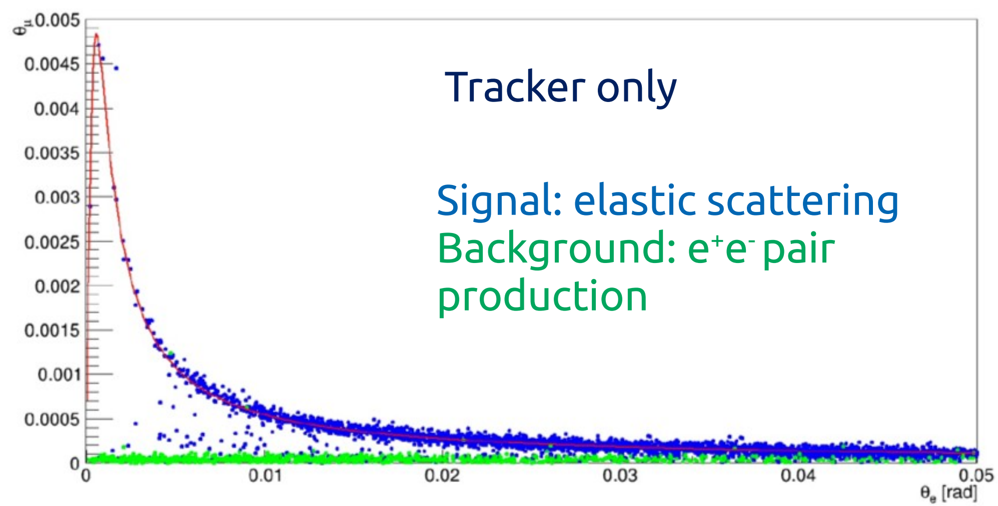


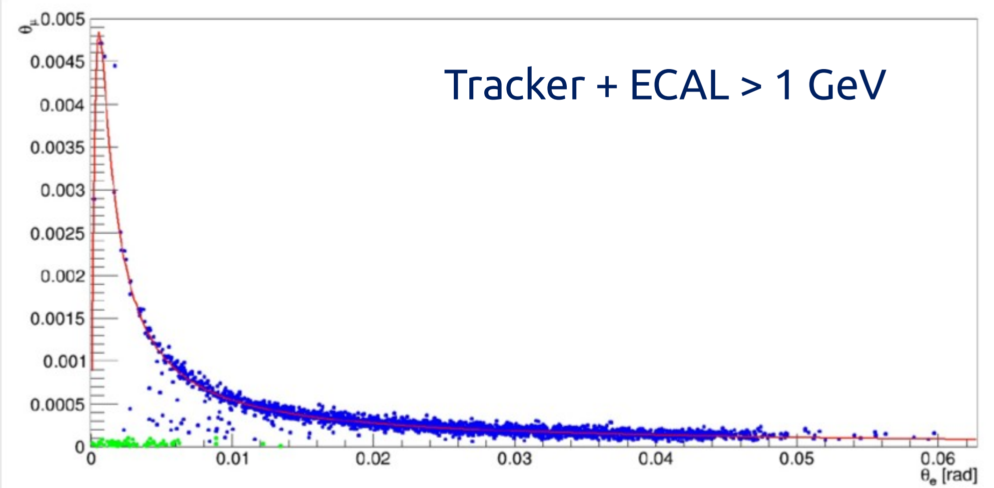


- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.

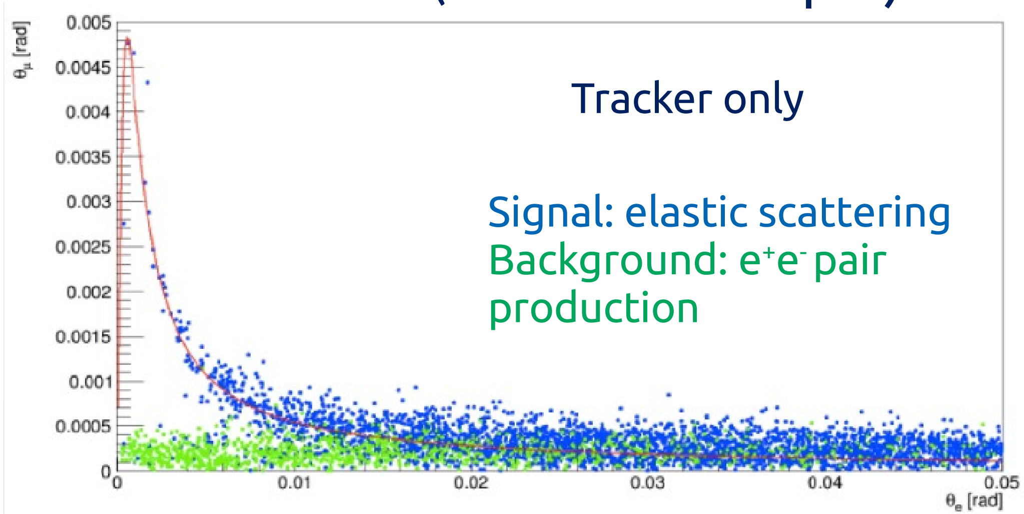
GEANT4 simulations

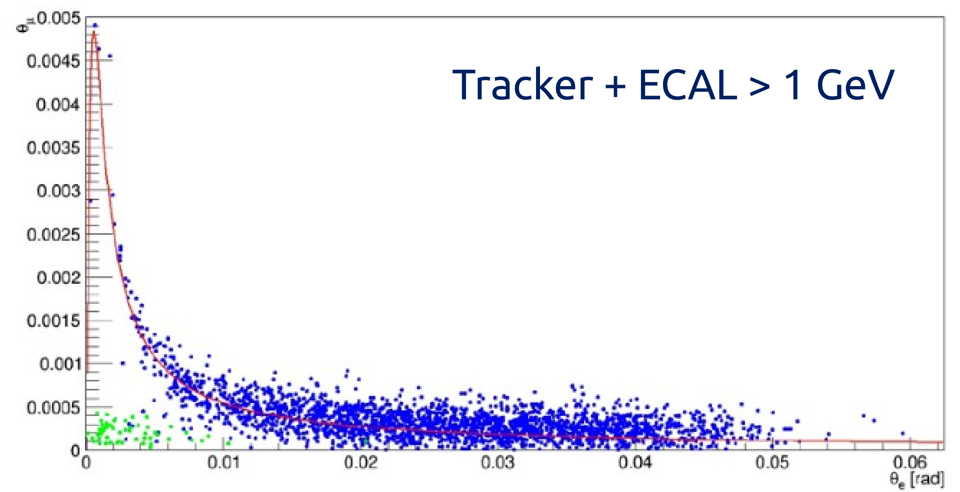
TB2017 (resolution ~7μm)





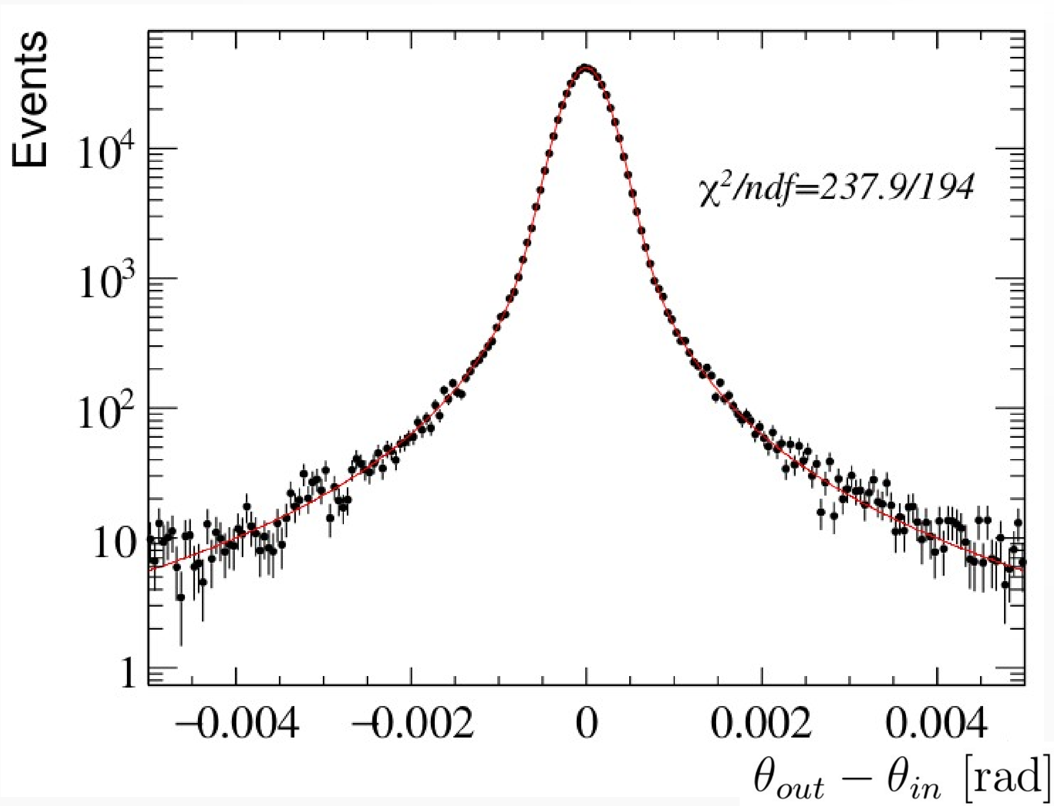
TB2018 (resolution ~40μm)





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