The MUonE experiment: a novel way to measure the hadronic contribution to the muon g-2

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Liverpool HEP Seminars, June 28th 2024

Outline

- The muon g-2 and the hadronic contribution to the muon anomaly.
- The MUonE experiment.
- Test Run 2023.
- Proposal for MUonE-phase1 in 2025.

Magnetic anomalies

- Particles with spin have an intrinsic magnetic moment: $\vec{\mu} = g\frac{e}{2m}\vec{S}$

  g = gyromagnetic ratio

- Dirac's theory (1928): g = 2 for spin-1/2 point-like particles.

Magnetic anomalies

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  g = gyromagnetic ratio

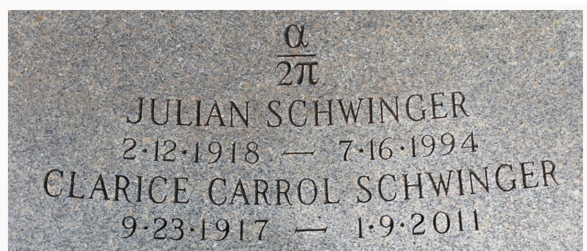
- Dirac's theory (1928): g = 2 for spin-1/2 point-like particles.

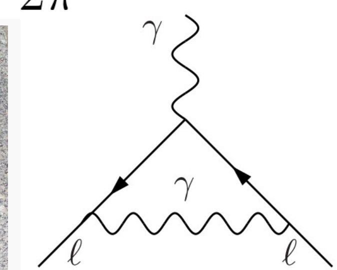
- Kush&Foley experiment (1948):
  hyperfine structure of atomic spectra.
  Probing electron magnetic anomaly → $g_e \neq 2$.

  $$a_e = \frac{g_e - 2}{2} = 0.00119 \pm 0.00005$$

  $$a_e = \frac{\alpha}{2\pi} \simeq 0.00116$$

- Calculation by Schwinger (1948):
  the magnetic anomaly is due to
  interactions with virtual particles.

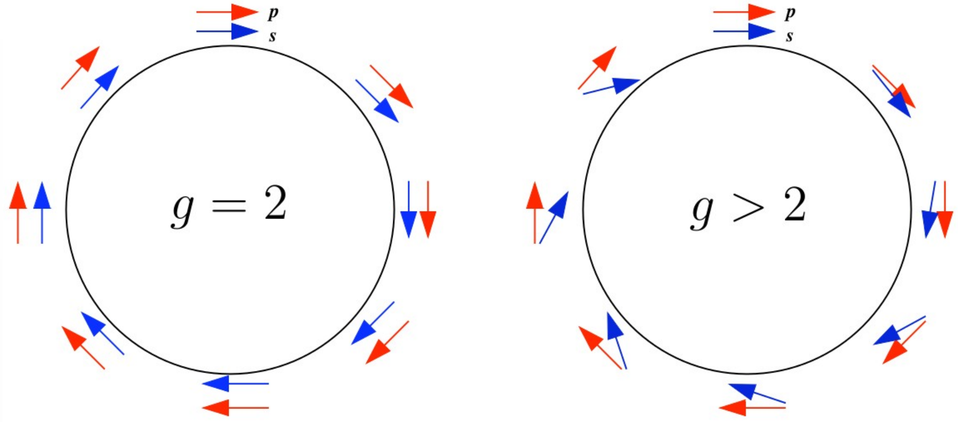




The muon g-2: measurement principle

Store polarized μ^+ in a ring with a uniform dipole magnetic field.

If $g_\mu \neq 2$, muons spin precesses around the direction of the magnetic field.



$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

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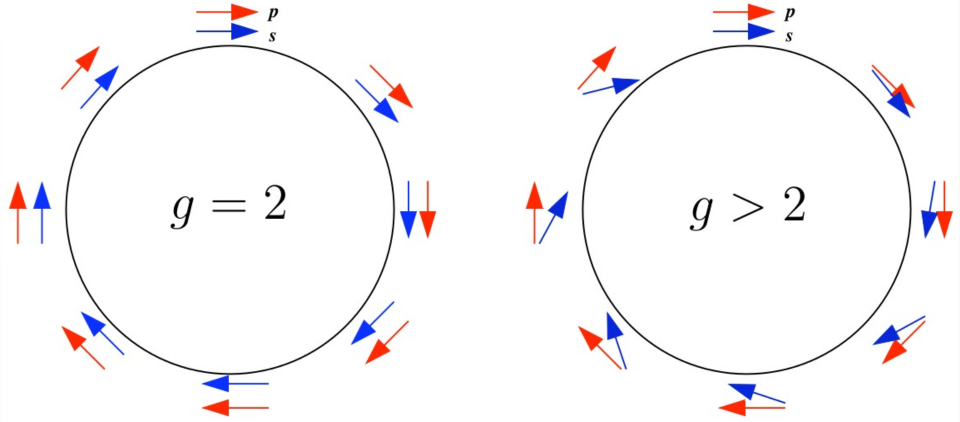
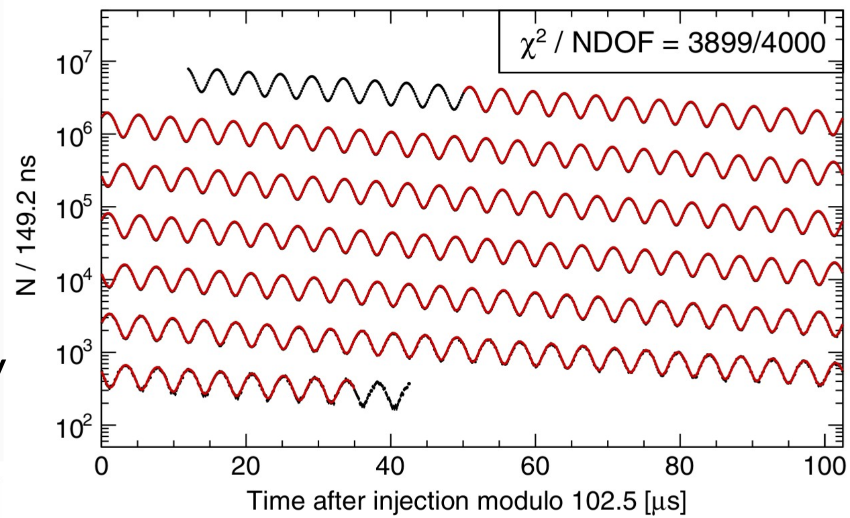


$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

anomalous precession frequency

e^+ emitted preferably in the direction of the muons spin: measure the number of high energy e^+ from the μ^+ decay vs time.

$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$



Phys. Rev. D 103, 072002

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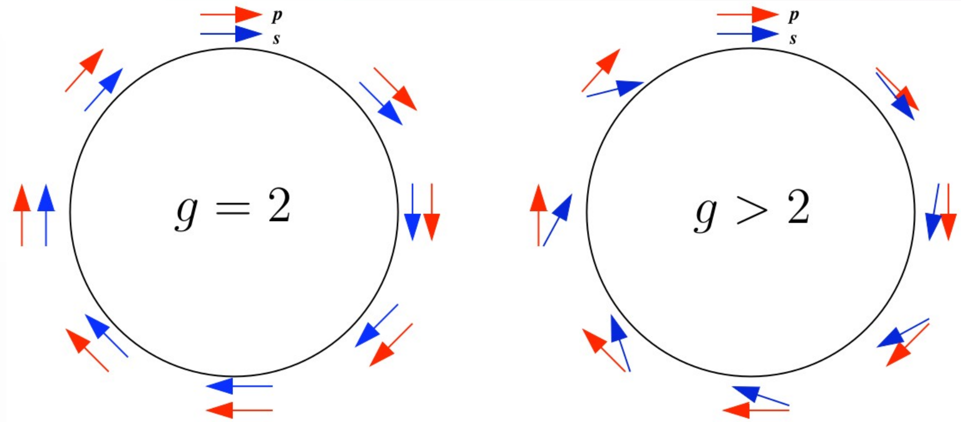
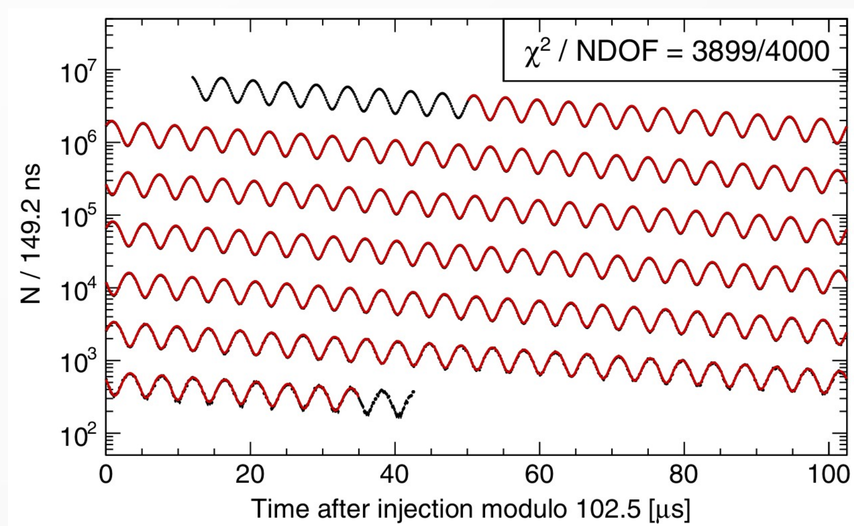


If $g_\mu \neq 2$, muons spin precesses around the direction of the magnetic field.

magnetic field

$$\omega_a = a_\mu \frac{eB}{m_\mu}$$



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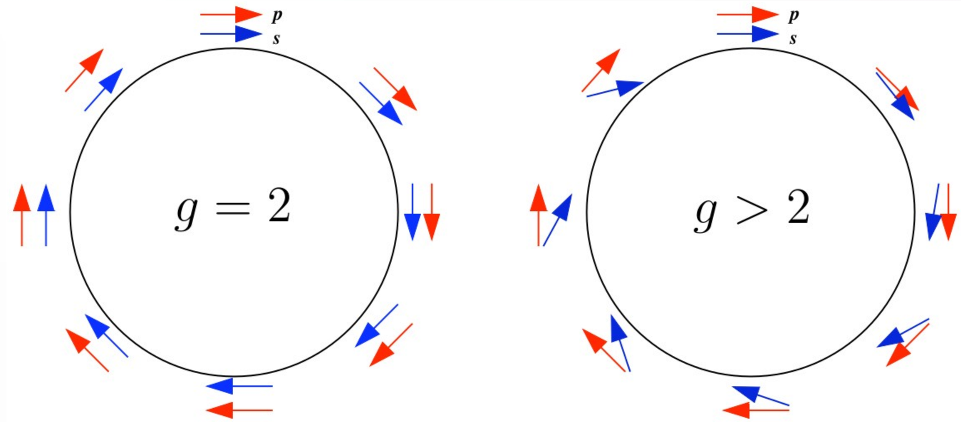
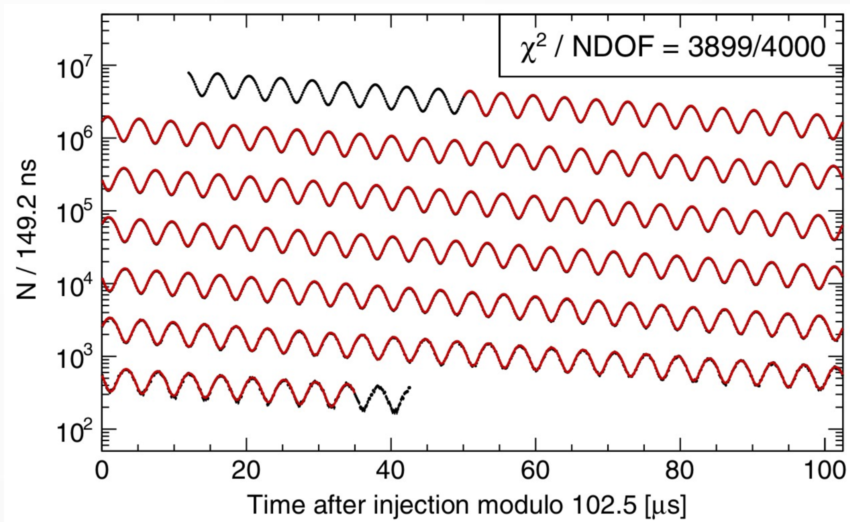


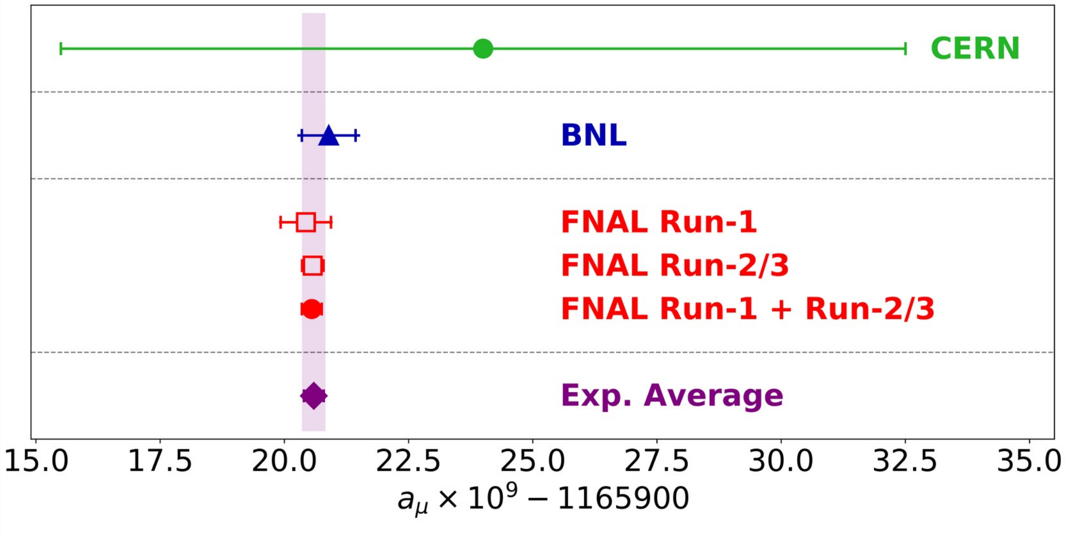
$$\omega_a = a_\mu \frac{eB}{m_\mu}$$

Extract the muon anomaly



Phys. Rev. D 103, 072002

The muon g-2: experimental results



[7.1 ppm] (1979)

[0.63 ppm] (2006)

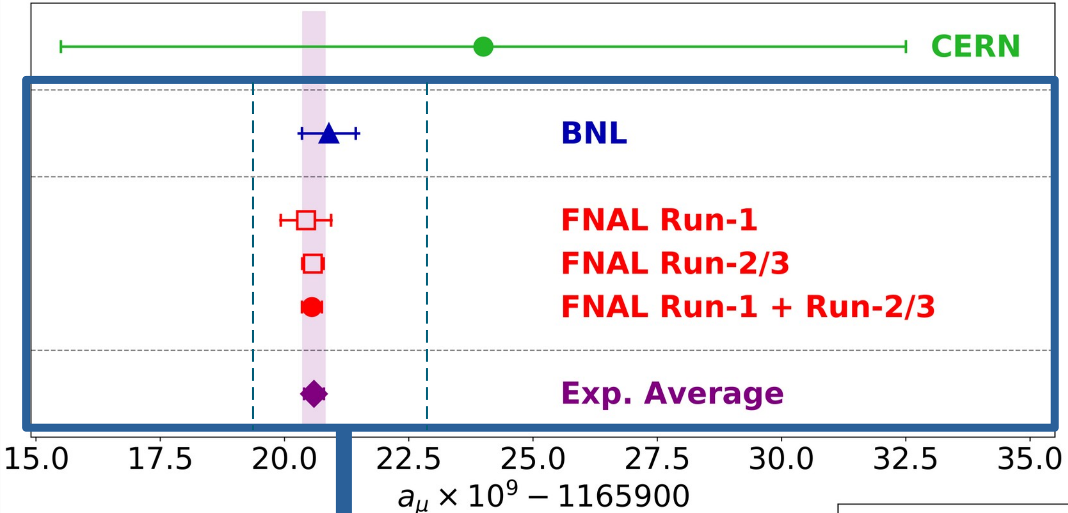
[0.46 ppm] (2021)

[0.21 ppm] (2023)

[0.20 ppm] (2023)

[0.19 ppm] (2023)

The muon g-2: experimental results



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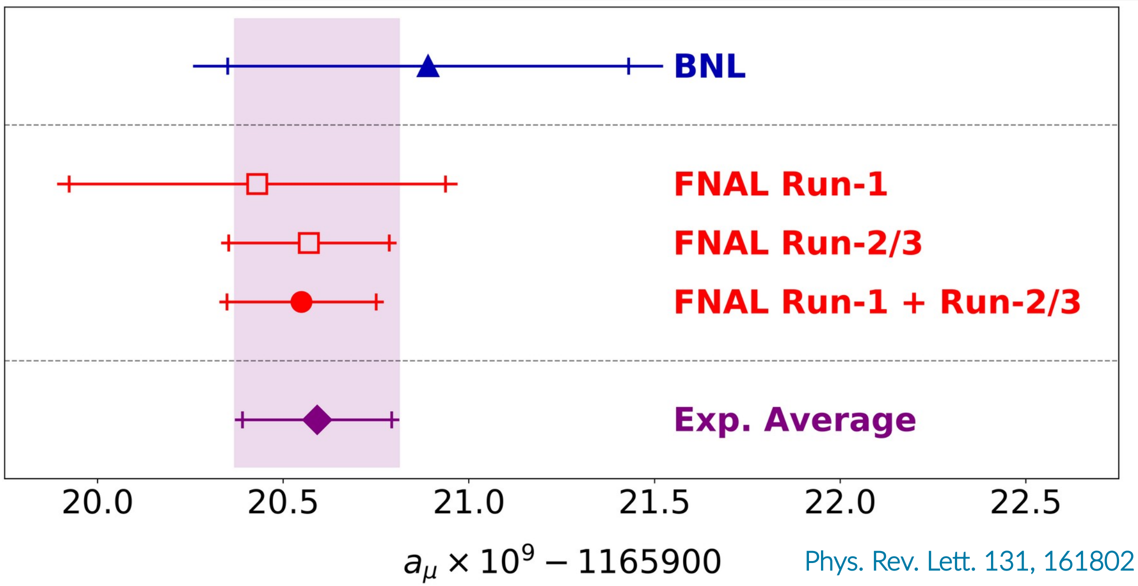


$$a_\mu^{\text{Exp. avg}} = 116\ 592\ 05.9(2.2) \times 10^{-10}$$

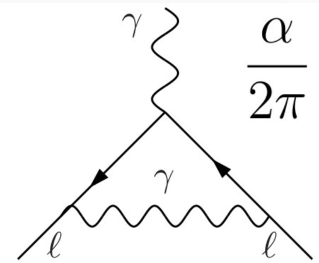
Phys. Rev. Lett. 131, 161802

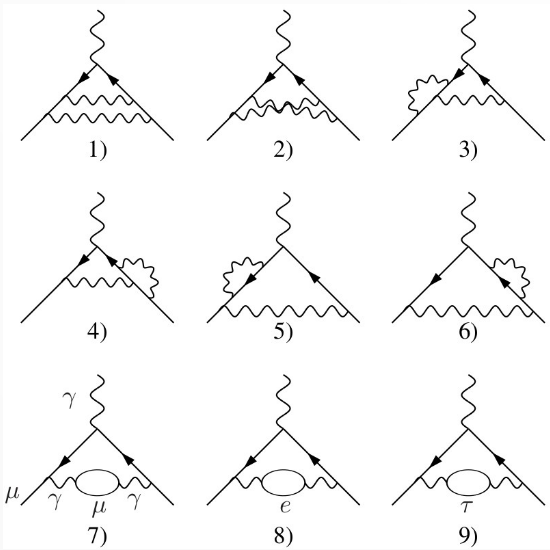
The muon g-2: Standard Model calculation

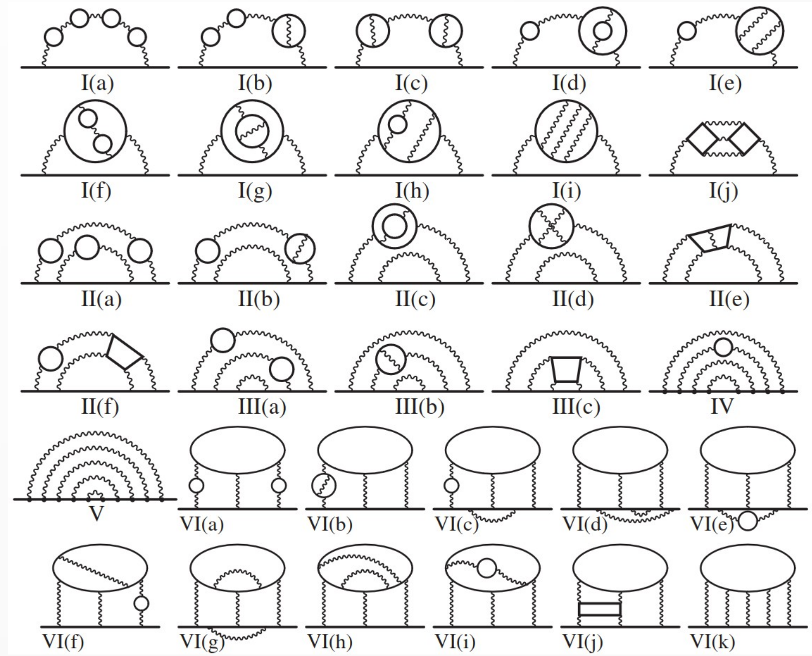
$$a_\mu^{\mathrm{SM}} = \boxed{a_\mu^{\mathrm{QED}}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{HAD}}$$

A triumph of perturbative QFT:
up to 5 loops calculations!

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







1 loop 2 loops … … … … … 5 loops

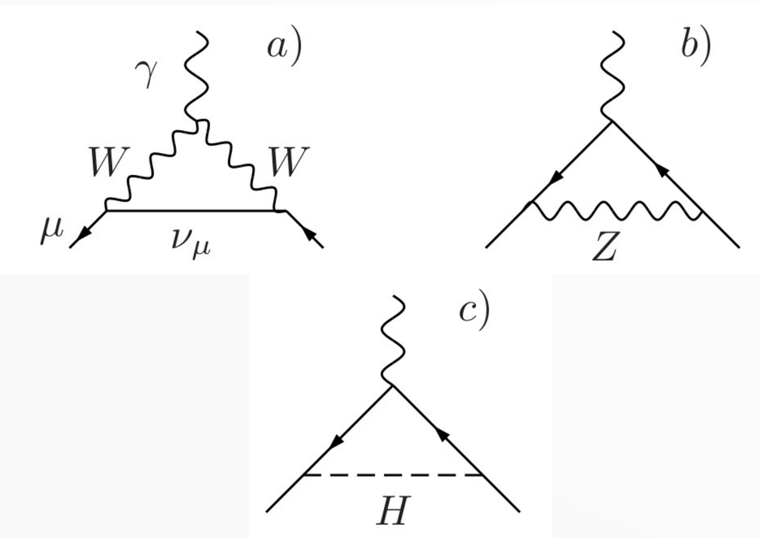
The muon g-2: Standard Model calculation

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

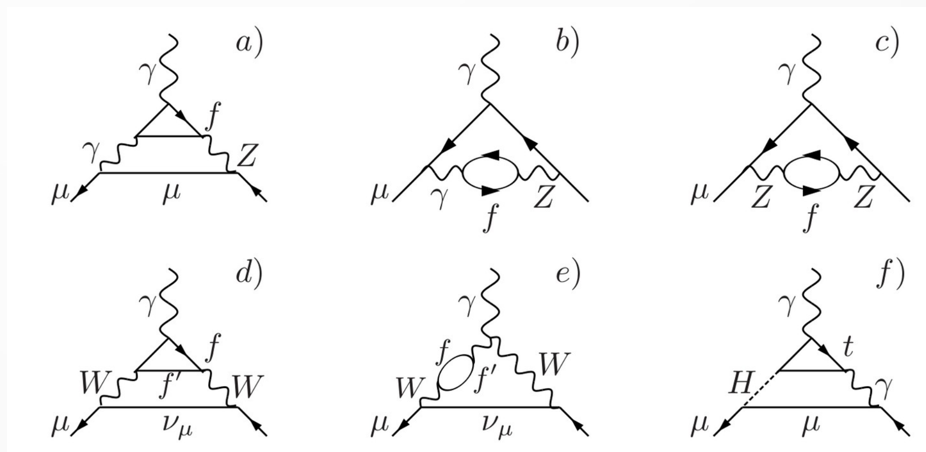
High precision calculations using perturbation theory: up to 2 loops!

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

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



1 loop



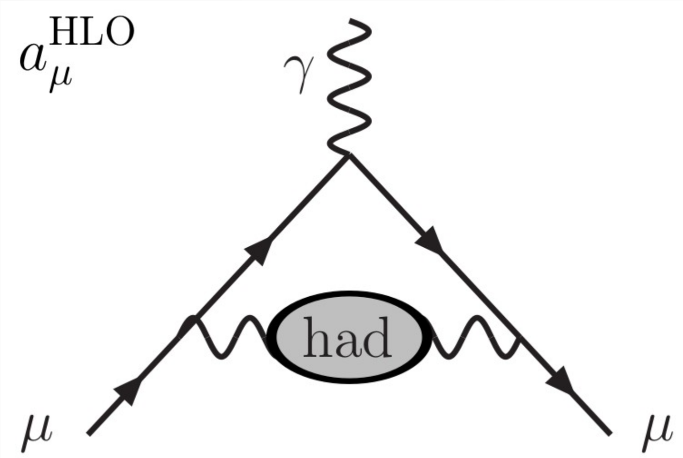
some representative 2 loops diagrams

The muon g-2: Standard Model calculation

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

Cannot be computed using perturbation theory!
(involves low-energy QCD)

$$a_\mu^{\mathrm{QED}} = 116\ 584\ 71.8931(104) \times 10^{-10}$$
$$a_\mu^{\mathrm{EW}} = (15.36 \pm 0.10) \times 10^{-10}$$
$$a_\mu^{\mathrm{HLO}} \sim 690 \times 10^{-10}$$
$$\Delta a_\mu^{\mathrm{HLO}} \sim 4 \times 10^{-10} \quad (\sim 0.6\%)$$

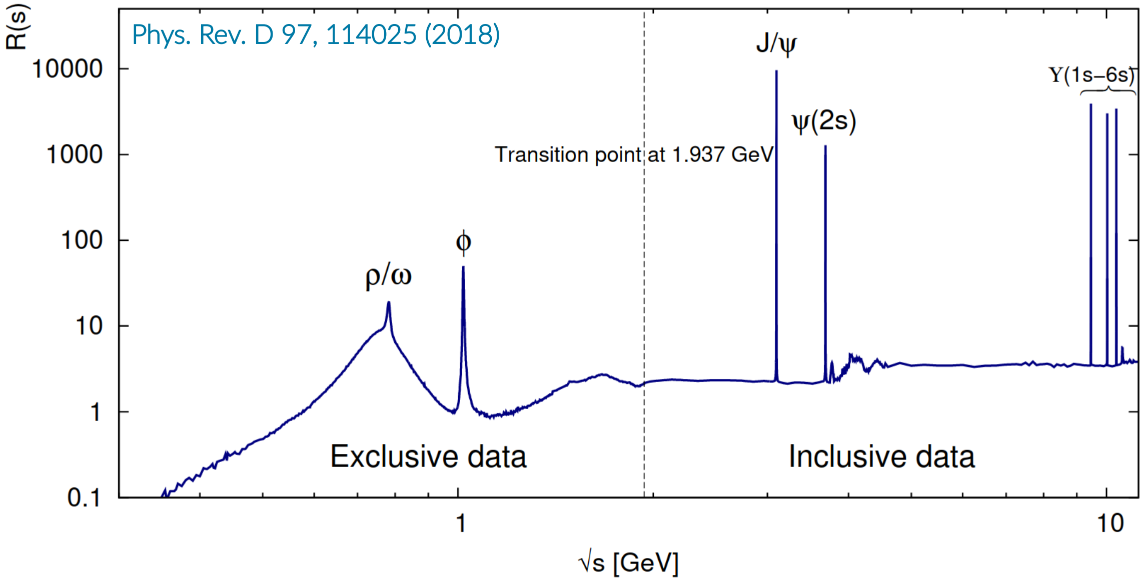


The leading order hadronic contribution represents the main source of uncertainty for the theoretical prediction.

$a_\mu^{\rm HLO}$: data-driven dispersive approach

$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2}\int_{m^2_{\pi^0}}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) \propto \sigma(e^+e^- \to \text{hadrons})$$



- Large fluctuations at low energy due to the hadronic resonances;
- Merge measurements of different hadronic channels from different experiments.
- Huge work to combine all the input data and evaluate the systematic uncertainties.

a_μ^{HLO}: data-driven dispersive approach

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2} \int_{m_{\pi^0}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

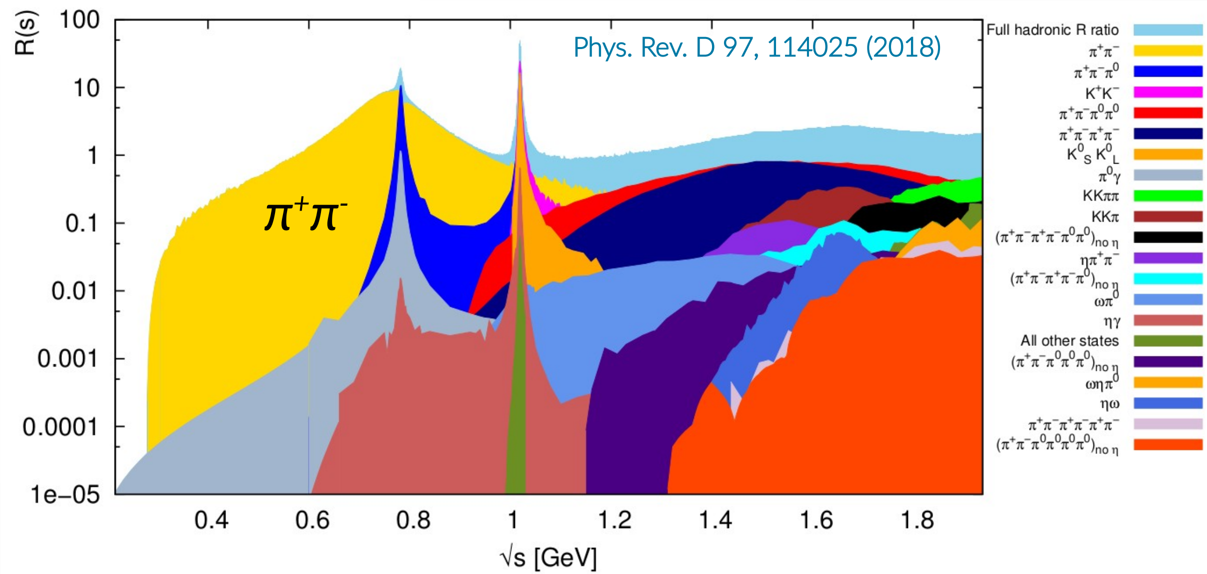
$$R(s) \propto \sigma(e^+e^- \to \mathrm{hadrons})$$

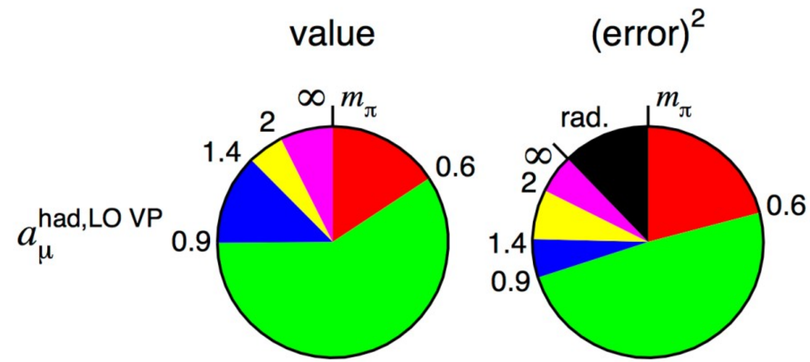
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)s/m_\mu^2}$$

$$K(s) \sim 1/s$$

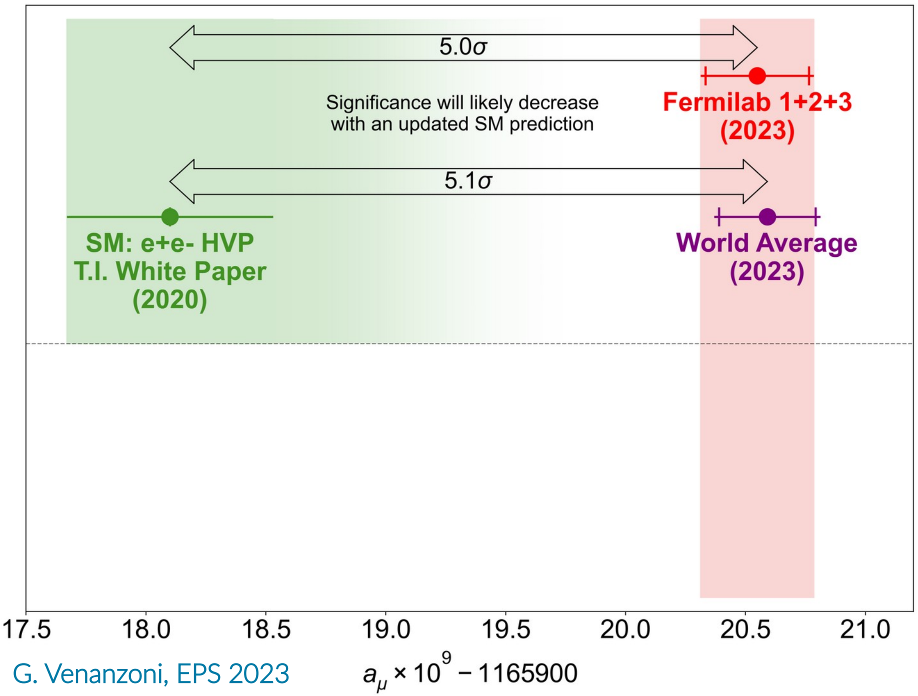
The low energy contribution is enhanced by the kernel function

The main contribution comes from the $\pi^+\pi^-$ channel (~75% of the total)





Muon g-2: current status

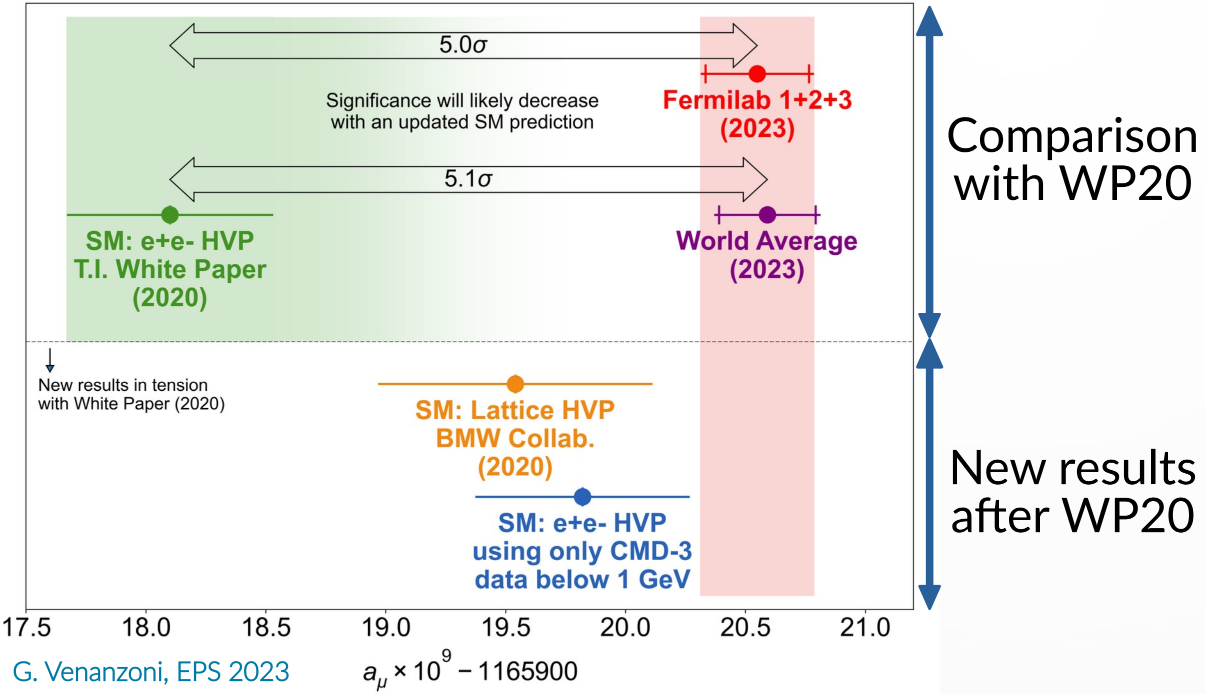


G. Venanzoni, EPS 2023

Comparison between experiment and the latest Standard Model prediction from the g-2 Theory Initiative:
> 5σ discrepancy

Why we are not claiming for physics beyond Standard Model?

Muon g-2: current status



G. Venanzoni, EPS 2023

- New lattice QCD evaluation of a_μ^{HLO}
- CMD-3 result for the $\pi^+\pi^-$ channel

F. Ignatov, HEP Seminar, July 2023

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.

MUonE:
a new data-driven approach
to calculate a_μ^{HLO}

From time-like to space-like

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha^2}{3\pi^2}\int_{m_{\pi^0}^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

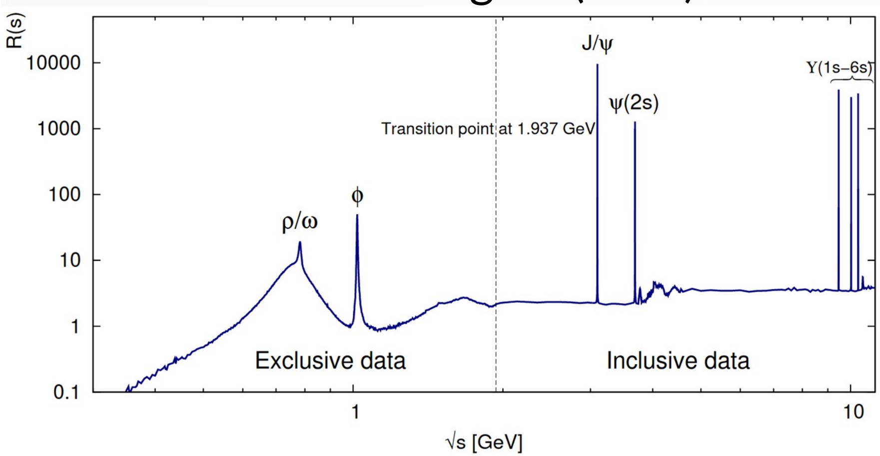
$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)s/m_\mu^2}$$

Swap the order of
x and *s* integrations

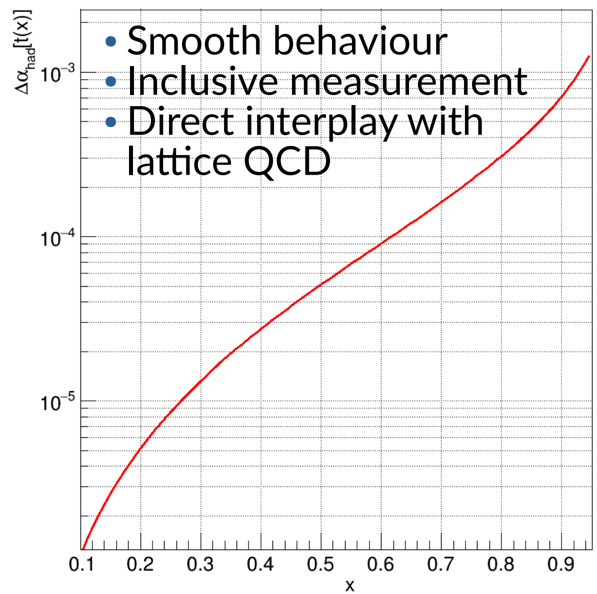
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

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

Input data: *R(s)* in the time-like region (*s* > 0)

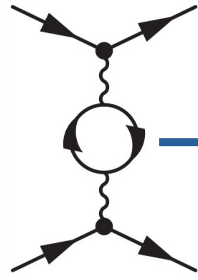


Input data: $\Delta\alpha_{had}$ in the space-like region (*t* < 0)



The running of α

- The electromagnetic coupling constant runs as a function of the momentum tranfer, due to vacuum polarization effects.
- Virtual particles act a screening effect between two real interacting particles.

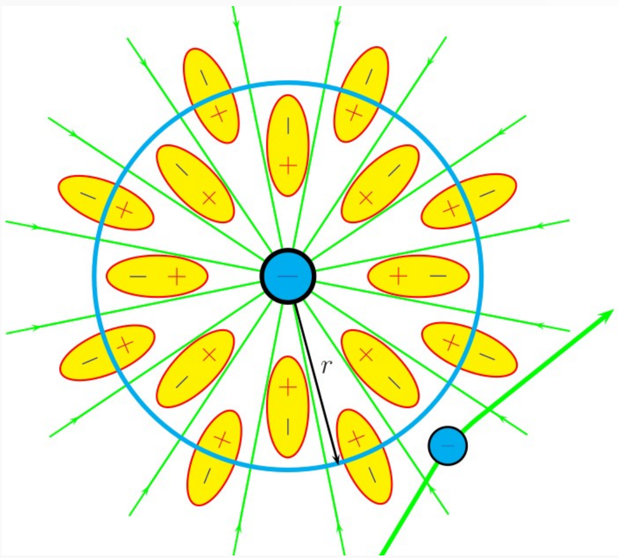


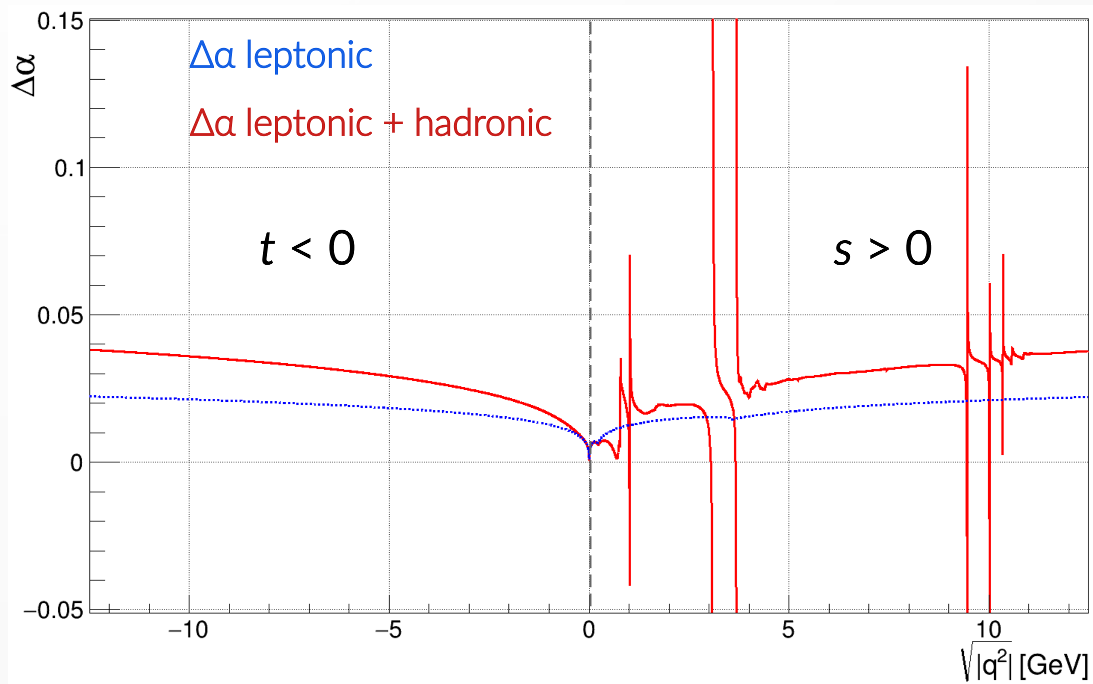
$$\Delta\alpha(q^2) = \Delta\alpha_{\mathrm{lep}}(q^2) + \Delta\alpha_{\mathrm{had}}(q^2) + \Delta\alpha_{\mathrm{top}}(q^2)$$

$$\alpha(q^2) = \frac{\alpha}{1 - \Delta\alpha(q^2)}$$

$\alpha(0) \sim 1/137$

$\alpha(M^2_Z) \sim 1/127$





The MUonE experiment

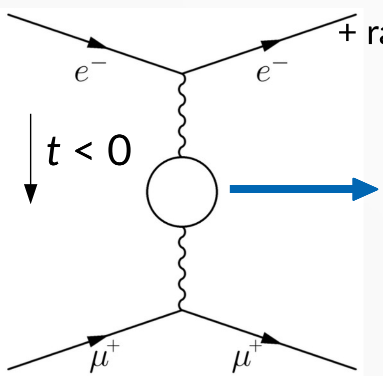
Extraction of $\Delta\alpha_{had}(t)$ from the *shape* of the $\boldsymbol{\mu e \rightarrow \mu e}$ differential cross section

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

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

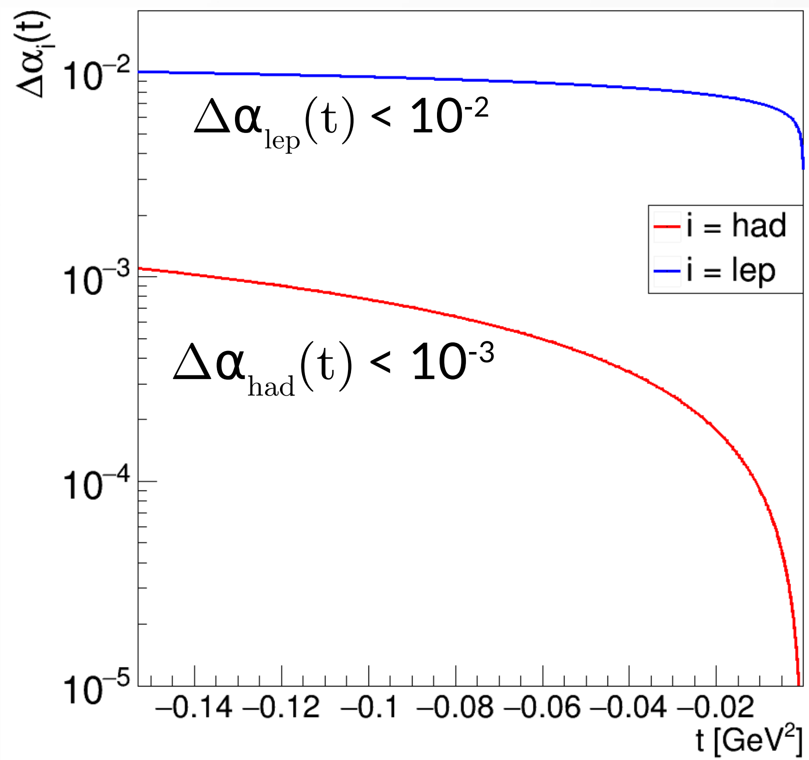
$$a_\mu^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

Phys. Rep. C 3 (1972), 193



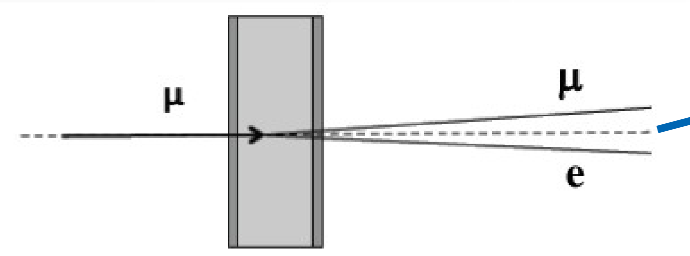
+ radiative corrections

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



MUonE kinematic range

The *μ-e* elastic scattering

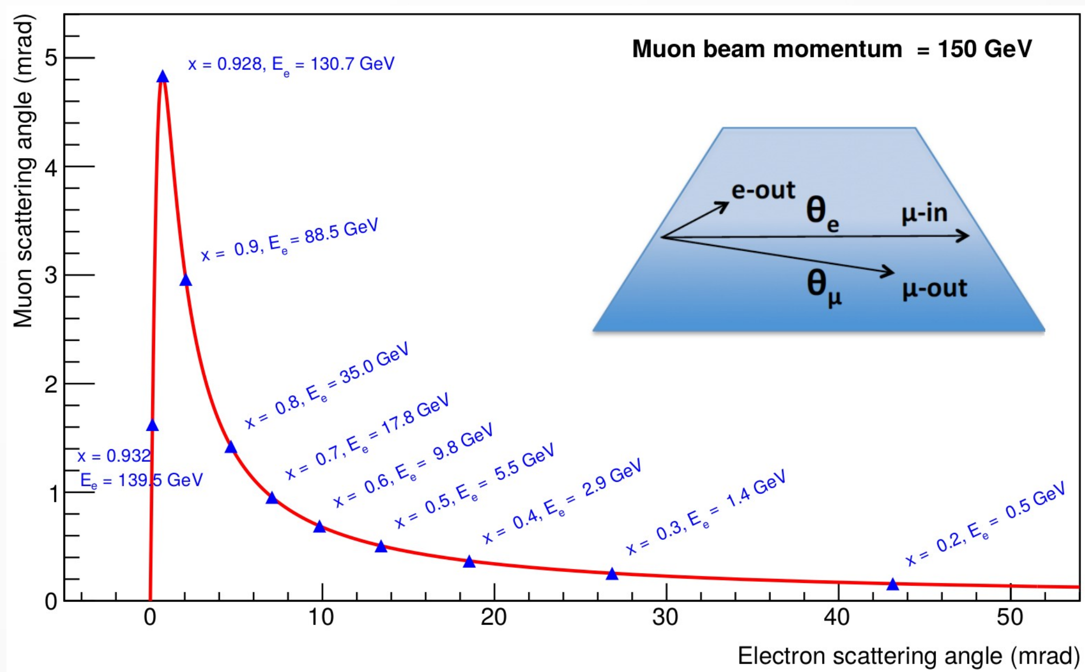


$$\frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}}=0)} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$

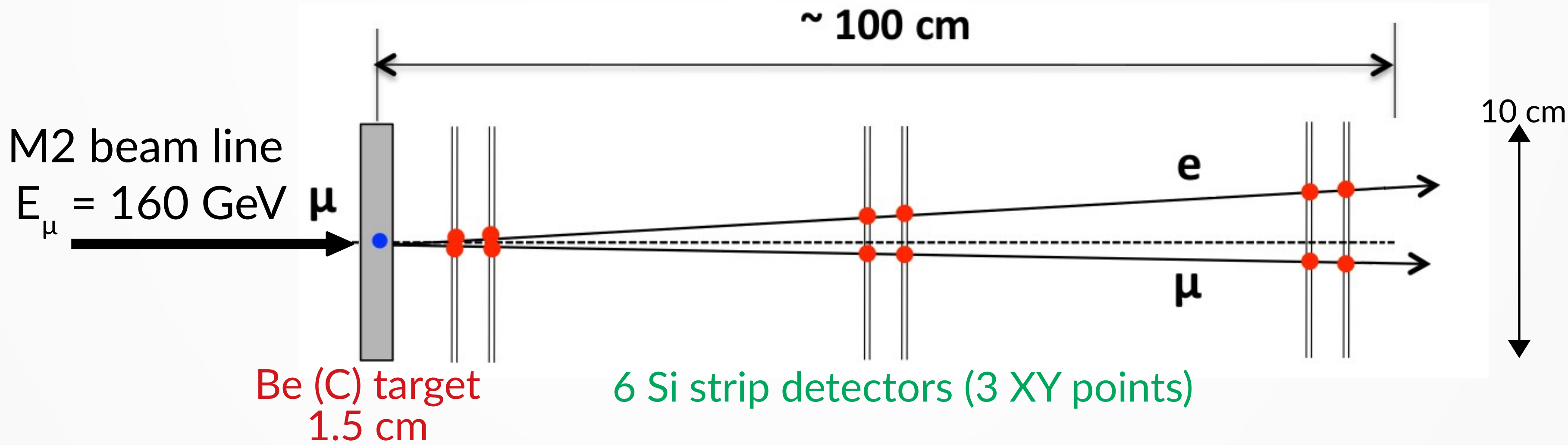
From theoretical calculation (>NNLO needed)

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: $\mu N \to \mu N e^+e^-$).
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



The experimental apparatus



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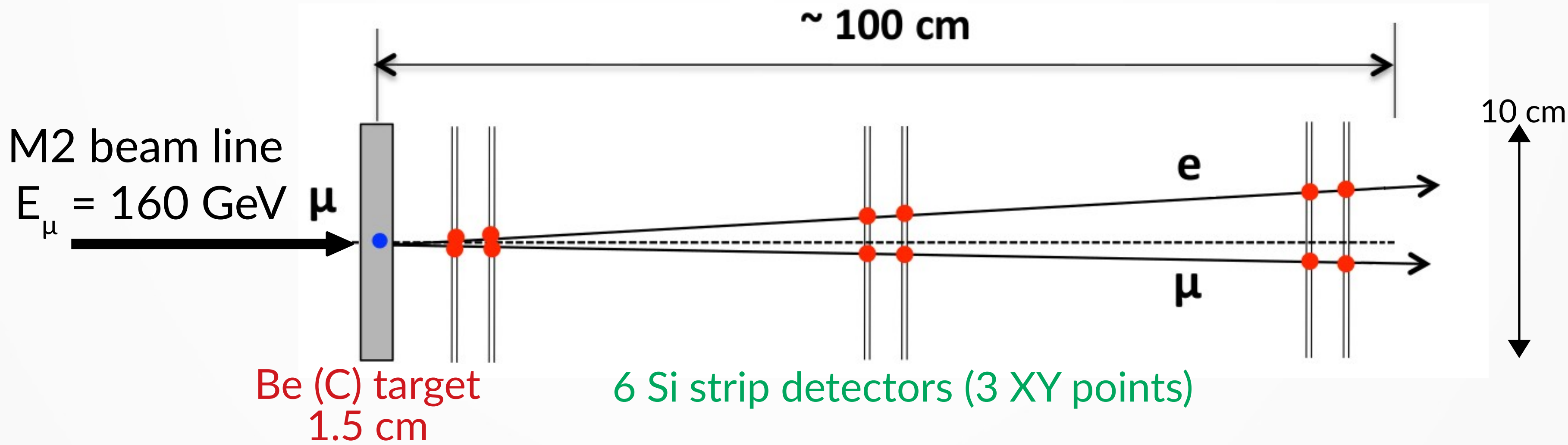


In principle, it's a table-top experiment…
if you can wait **~120 years**
to have competitive results!

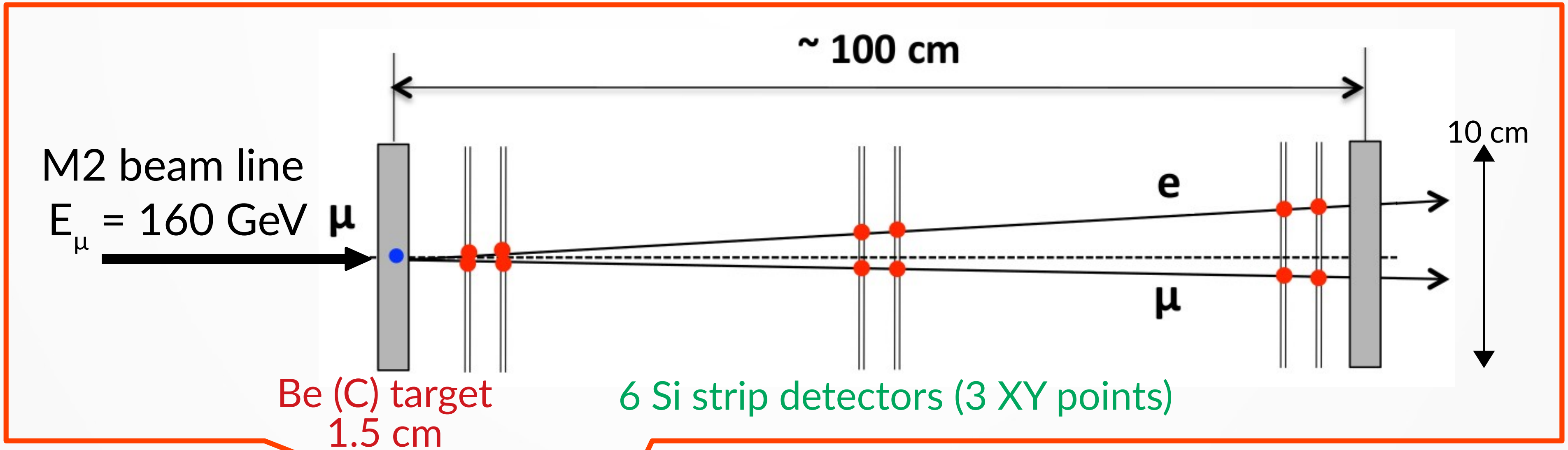
If you don't want to wait:

- Increase the target thickness (but multiple scattering will break μ-e correlation)

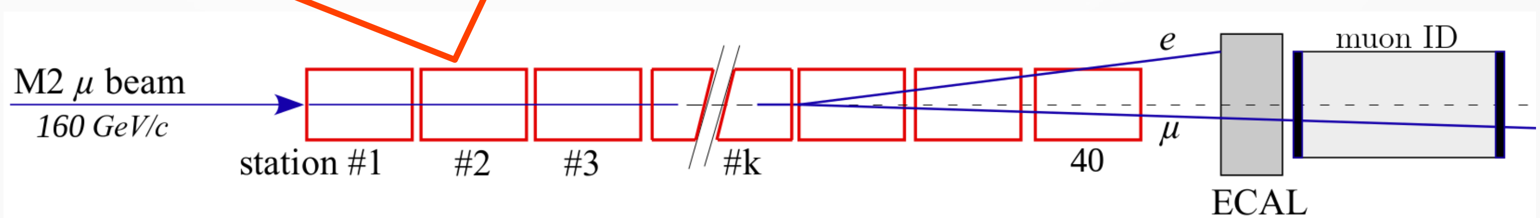
or…

- Instrument more stations!

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}

(~4×10^{12} events $E_e > 1$ GeV)

Competitive with the latest theoretical predictions (~0.6% accuracy)

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

$\Delta\alpha_{had}$ parameterization

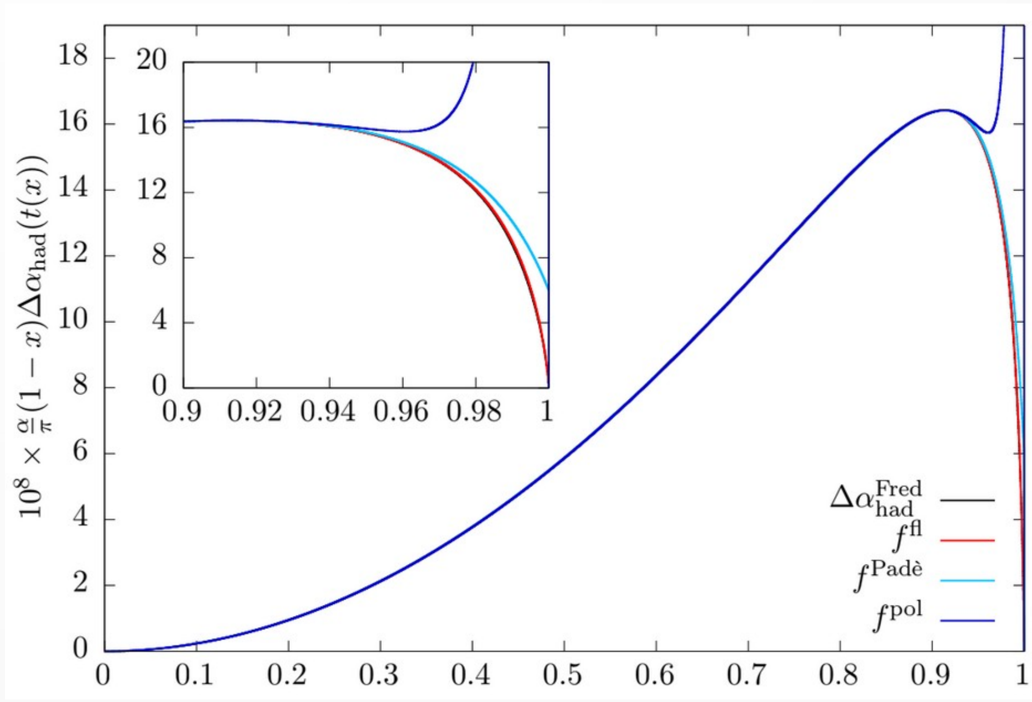
Inspired from the 1 loop QED contribution of lepton pairs and top quark at t < 0

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

2 parameters:
K, M

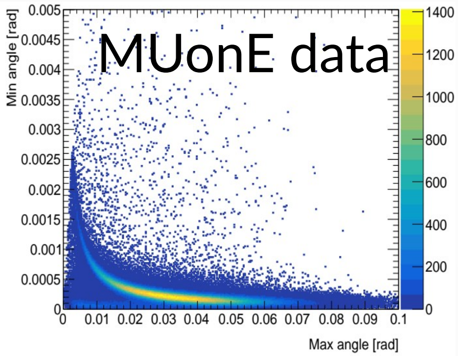
Dominant behaviour in the MUonE kinematic region:

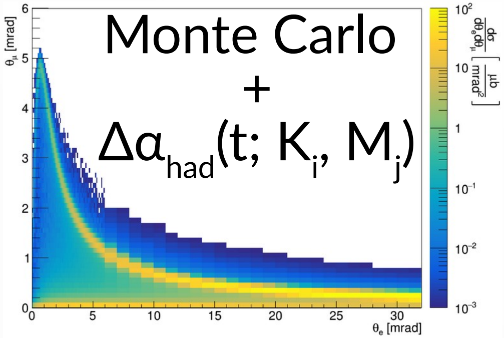
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$



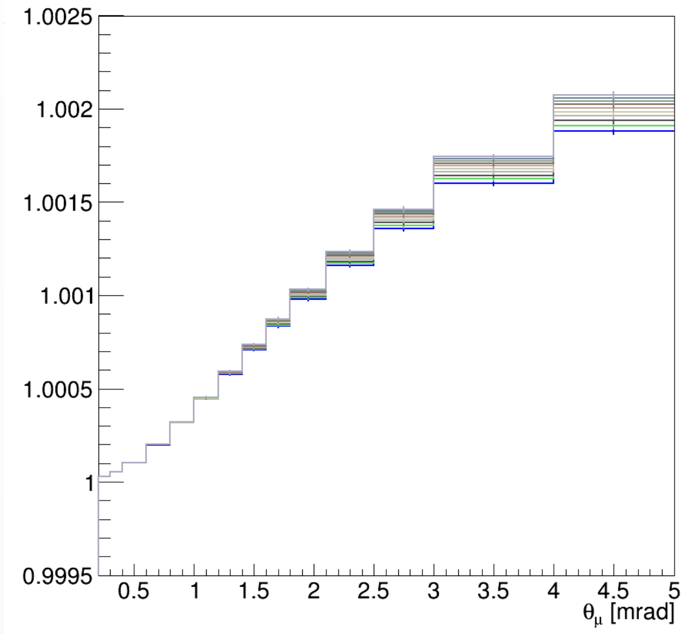
Extraction of a_μ^{HLO}

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





Templates for
different values of K



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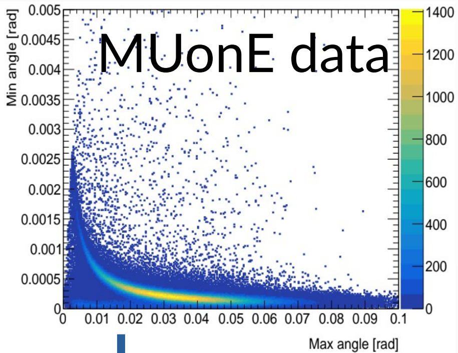
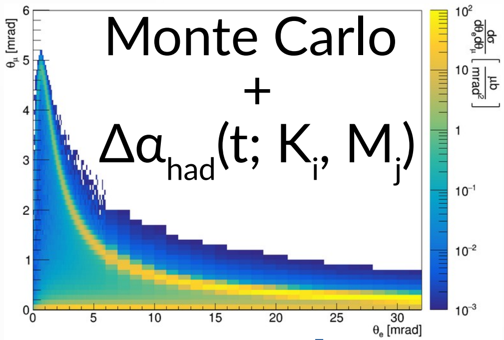
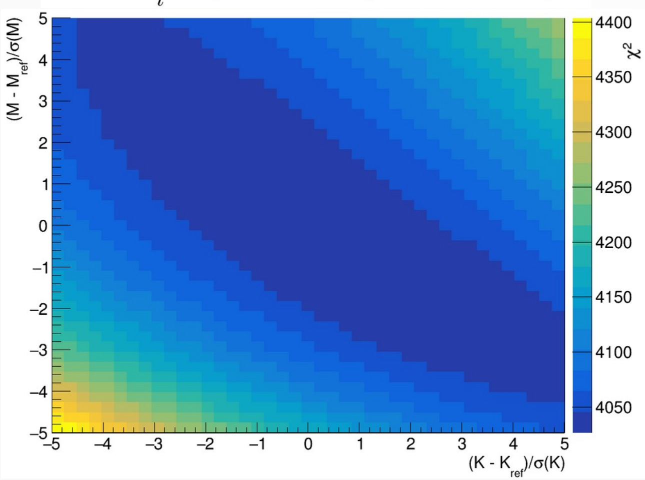




$$\chi^2 = \sum_i^{\mathrm{bins}} \left(\frac{\mathrm{data}_i - \mathrm{templ}(K, M)_i}{\sigma_i^{\mathrm{data}}} \right)^2$$



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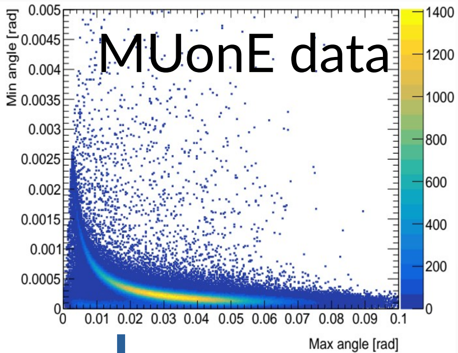
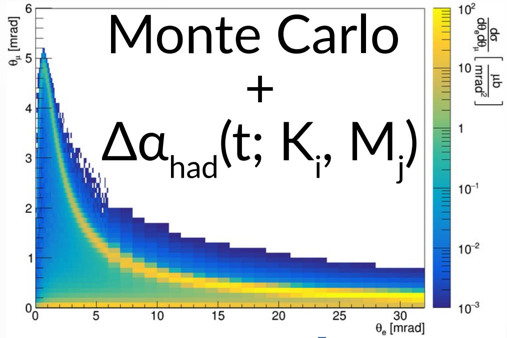
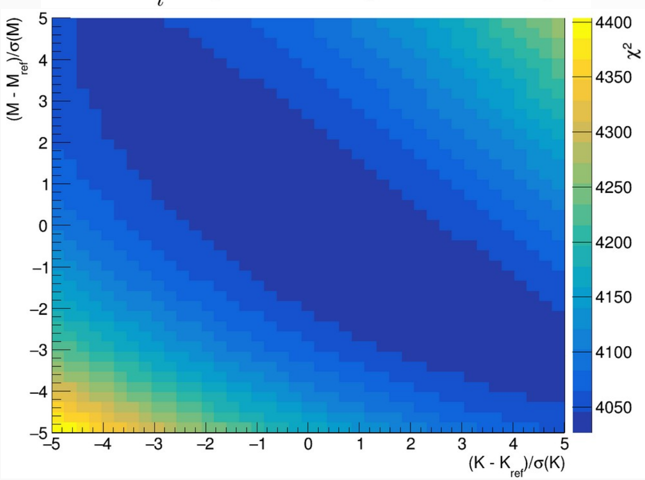




$$\chi^2 = \sum_i^{\mathrm{bins}} \left(\frac{\mathrm{data}_i - \mathrm{templ}(K,M)_i}{\sigma_i^{\mathrm{data}}} \right)^2$$



(K_{best}, M_{best})

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

Simulation of the final MUonE statistics:

a_μ^{HLO} = (688.8 ± 2.4) 10^{-10}

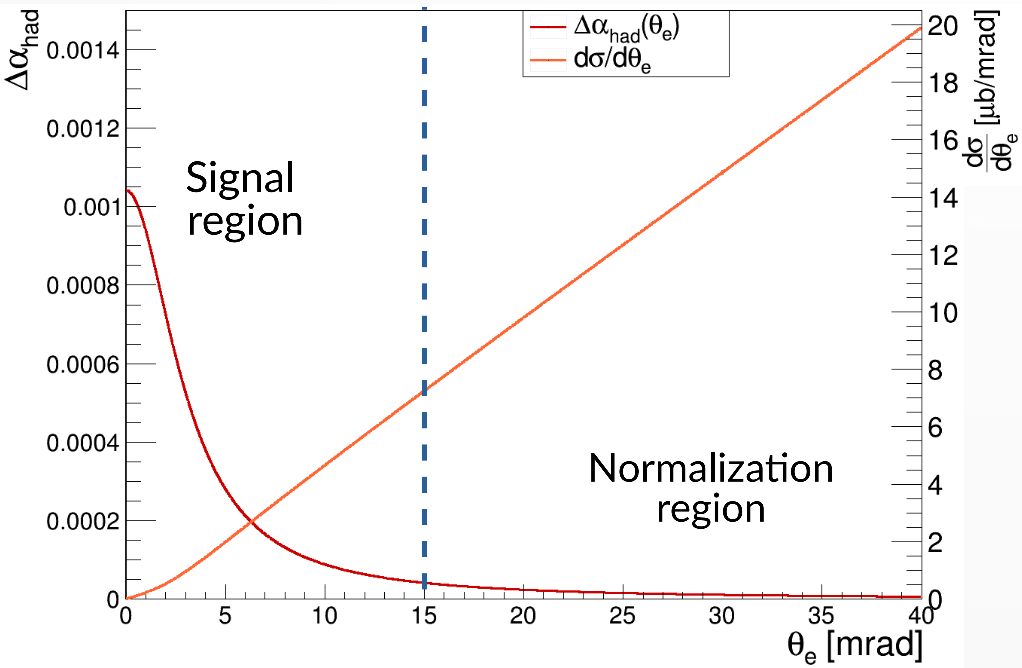
Input value:

a_μ^{HLO} = 688.6 10^{-10}

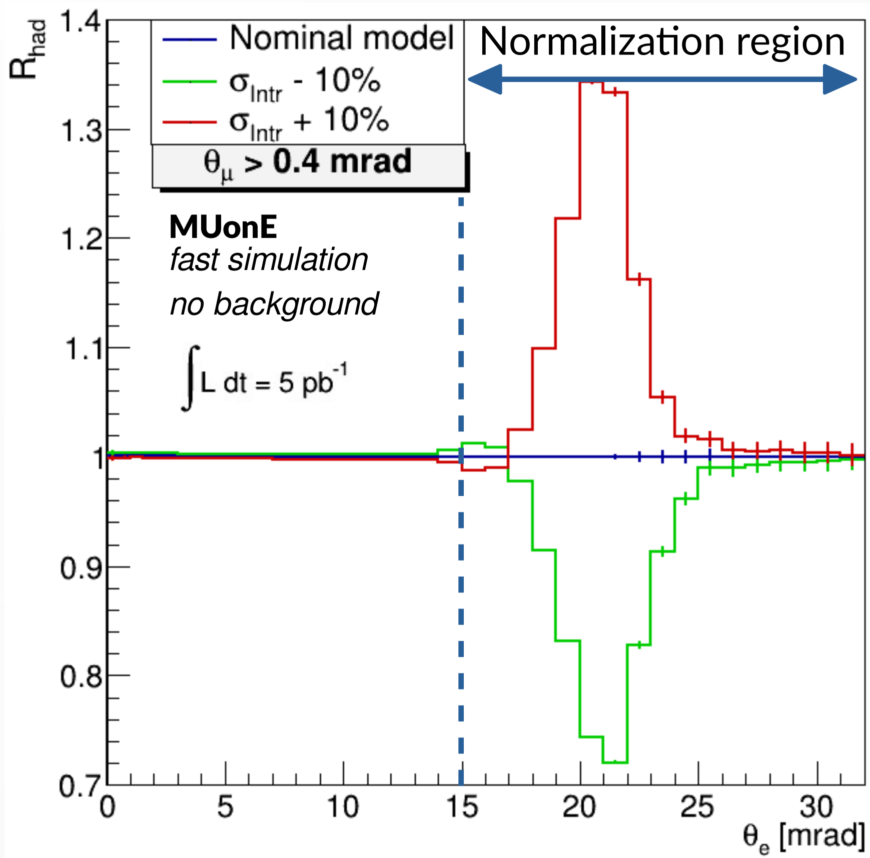
Systematic effects

Promising strategy:

- Study the main systematics in the normalization region (no sensitivity to $\Delta\alpha_{had}(t)$ here).
- Include residual systematics as nuisance parameters in a combined fit with signal.



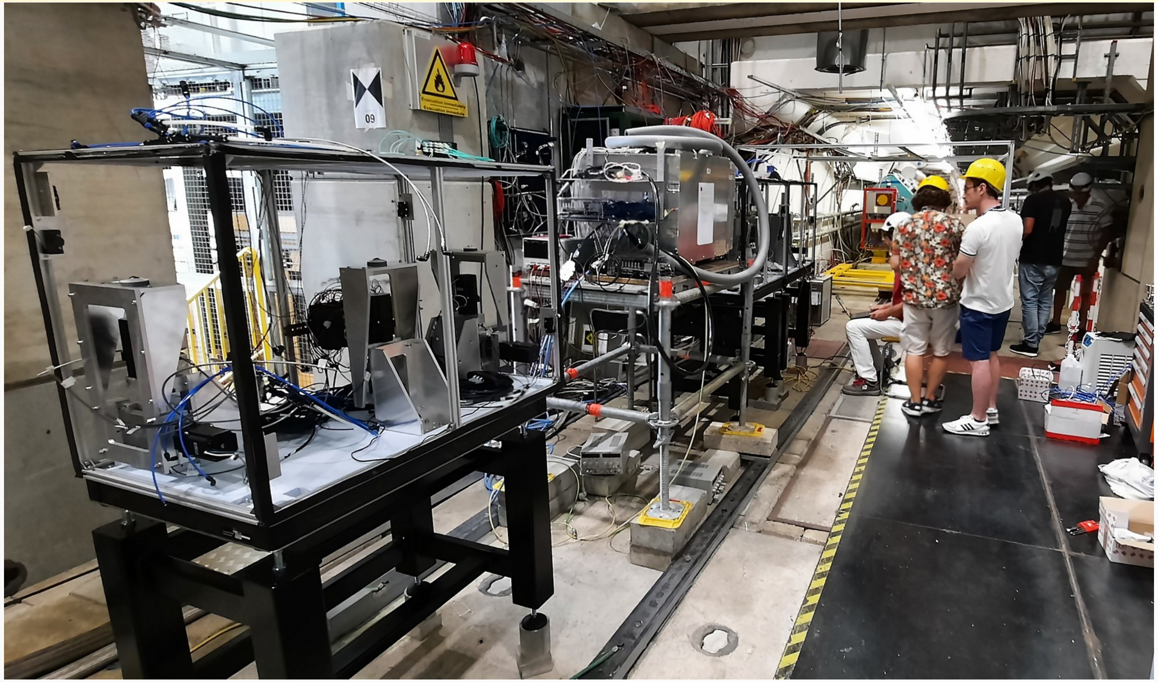
Example:
±10% systematic error
on the intrinsic resolution



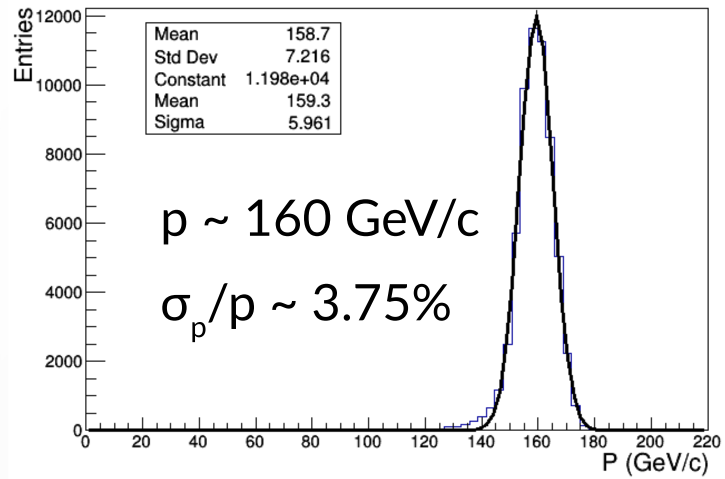
Staged approach towards the full experiment

- 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).

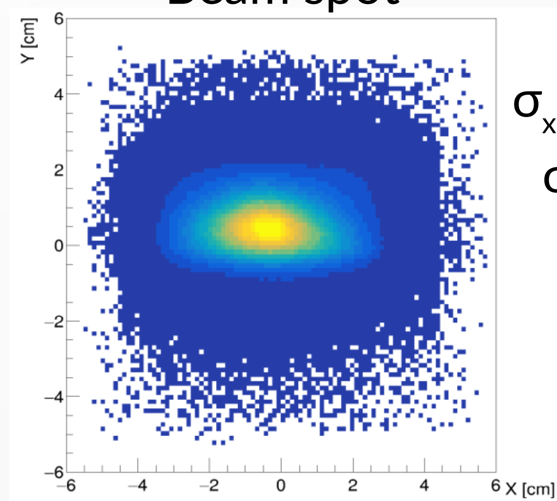
Location: M2 beamline at CERN



Beam momentum



Beam spot



σ_x ~ 13 mm

σ_y ~ 7 mm

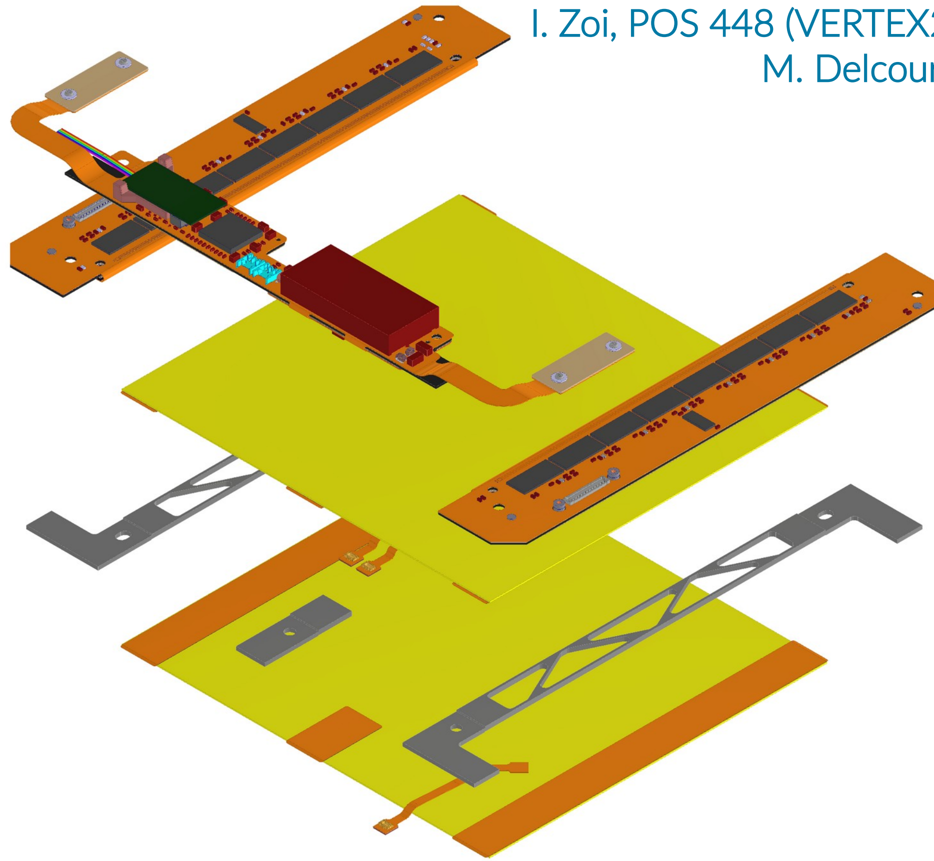
- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} < 1$ mrad.
- Spill duration ~ 5 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 2-3x10^8 μ^+/spill).

Tracker: CMS 2S modules

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

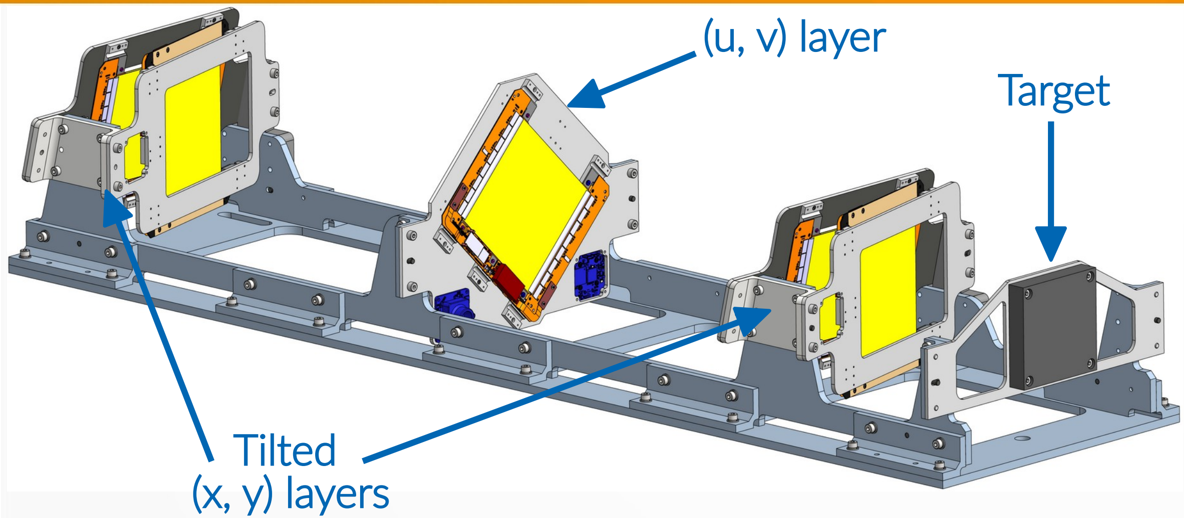
TDR CMS Tracker Phase2 Upgrade
I. Zoi, POS 448 (VERTEX2023), 021
M. Delcourt, BTTB12

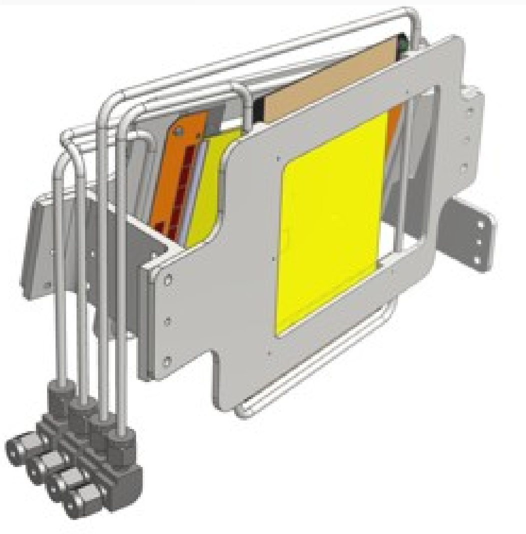
Two close-by strip sensors reading the same coordinate and read out by the same electronics



- 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)

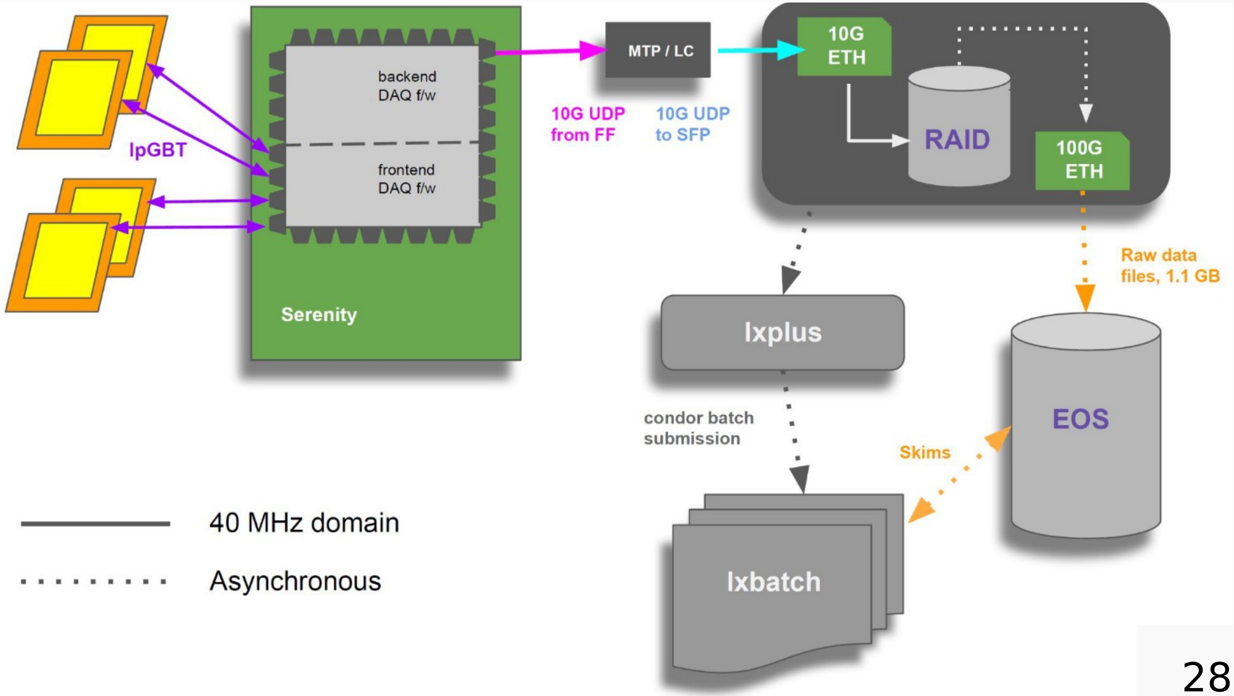
Laser holographic system
to monitor stability

- (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.

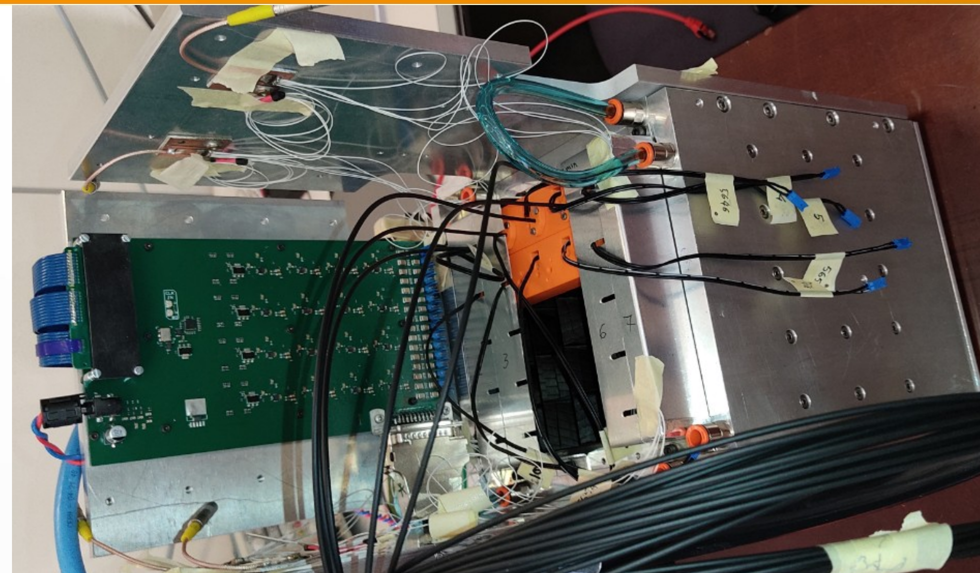


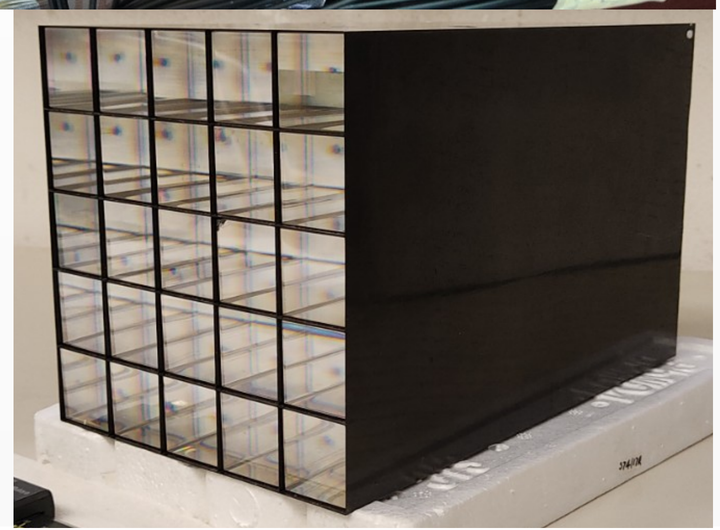
Calorimeter

- 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.

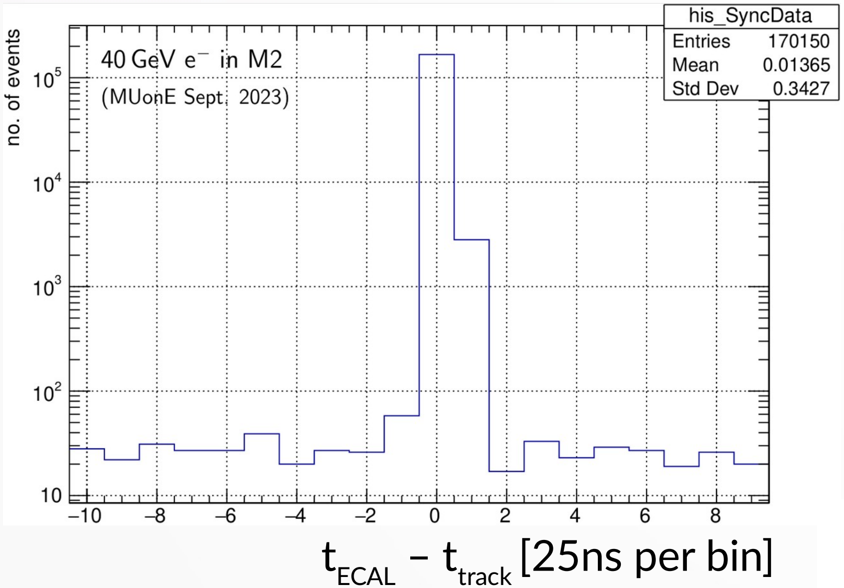
- Integration in the main DAQ @40 MHz achieved at the end of Test Beam 2023.

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

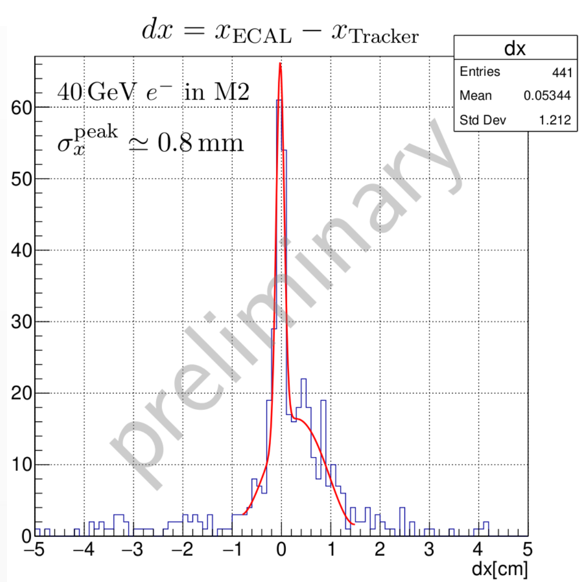


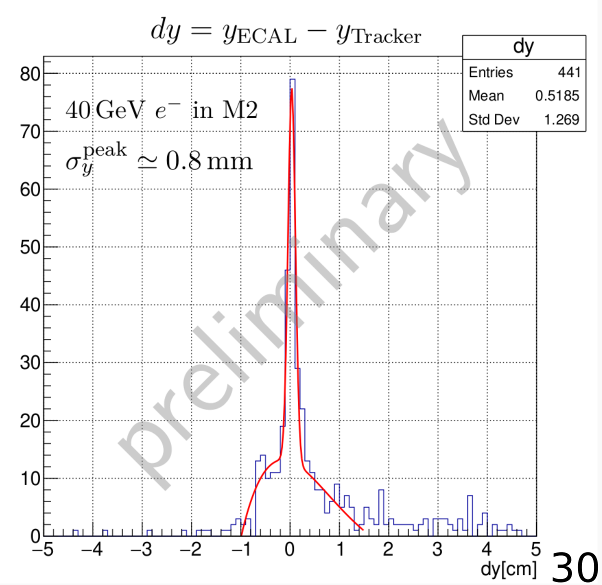


Calorimeter preliminary analysis: synchronization and spatial resolution



- Sharp peak for $\Delta t = 0$: very good time synchronization (resolution limited by the 25 ns readout).
- Accidental background ~ 10^{-3}.

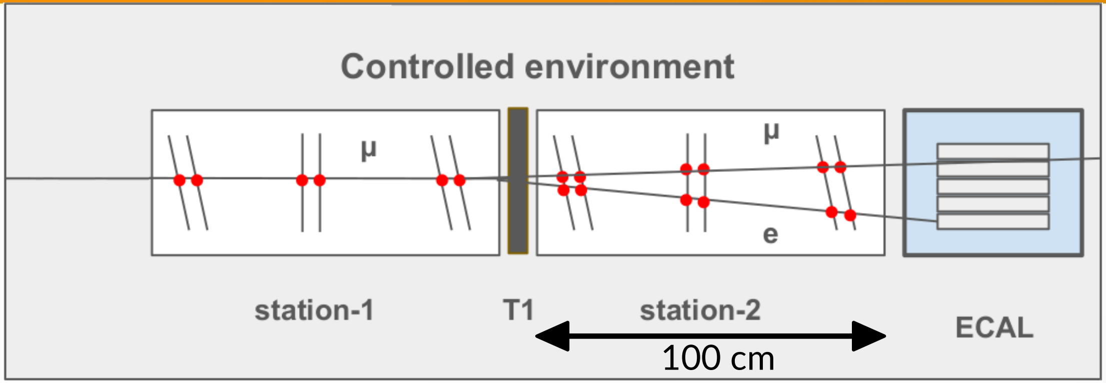




- Sub-mm peak resolution in good agreement with simulations.
- Residual background to be further investigated.

Test Beam 2023 (3 weeks Aug/Sep)

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



Achievements:

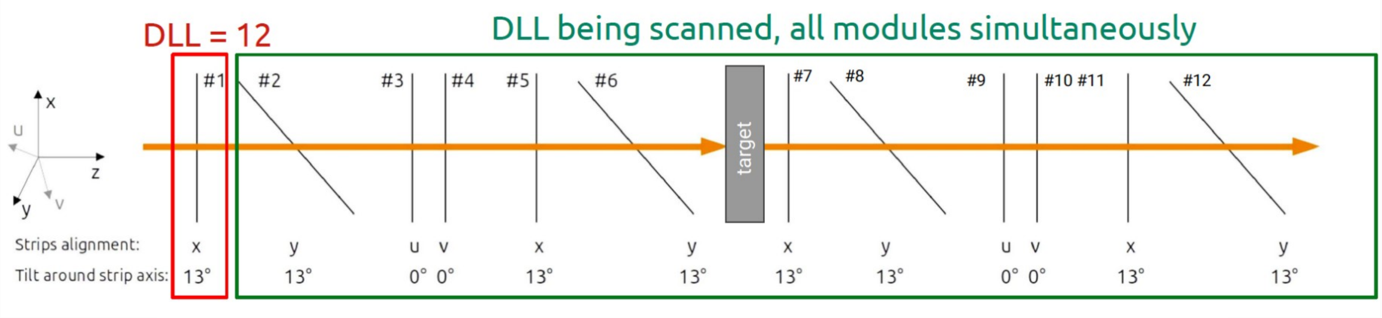
- Demonstrated continuous readout @40 MHz.
- 350 TB raw data recorded to disk:
  - 3 cm (2 cm) target: ~1(2)×10^8 elastic events;
- ECAL integrated in the DAQ @40 MHz in the final part of the run.
- Achieved online tracking on FPGA.

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

Work in progress:

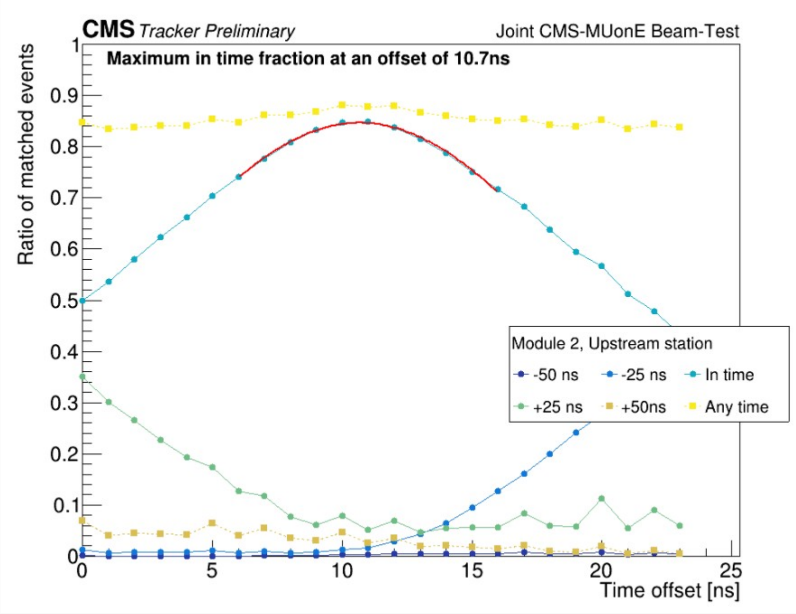
- Study the background processes and the main sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{lep}(t)$ with $O(5\%)$ stat. accuracy.

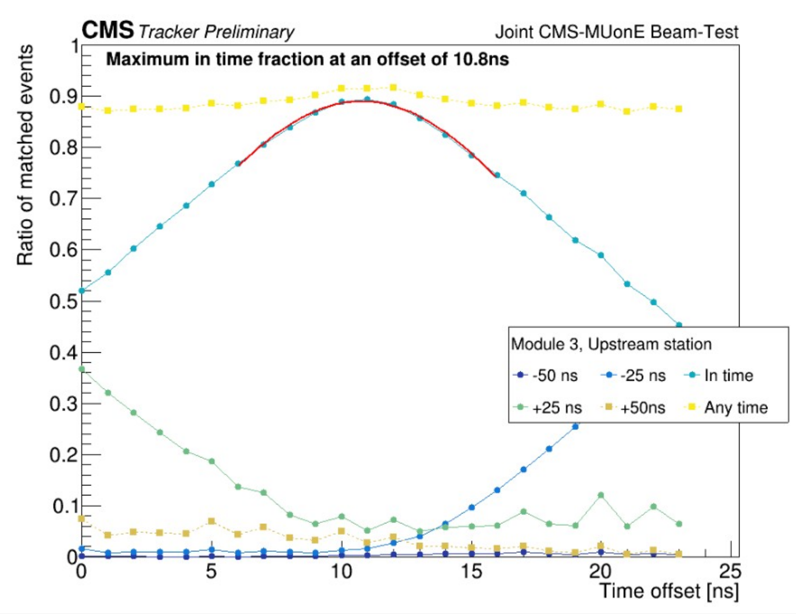
TB 2023
2S modules synchronization



Compute the fraction of events with a hit in #1, if a hit is found in the DUT.

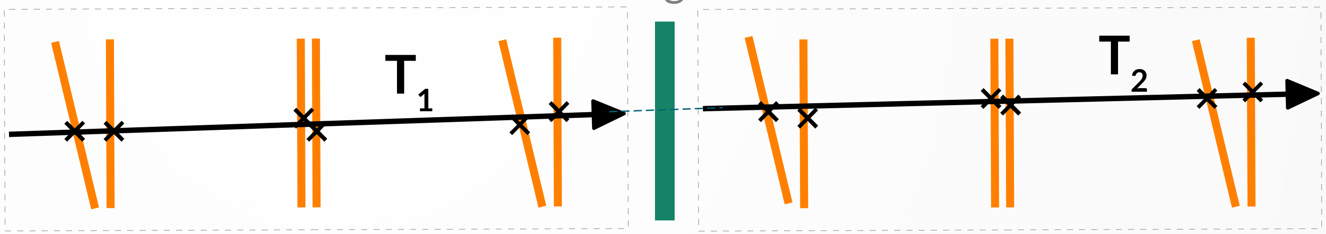
Determine the relative timing of the modules (i.e. ~0.1 ns for #2 and #3).



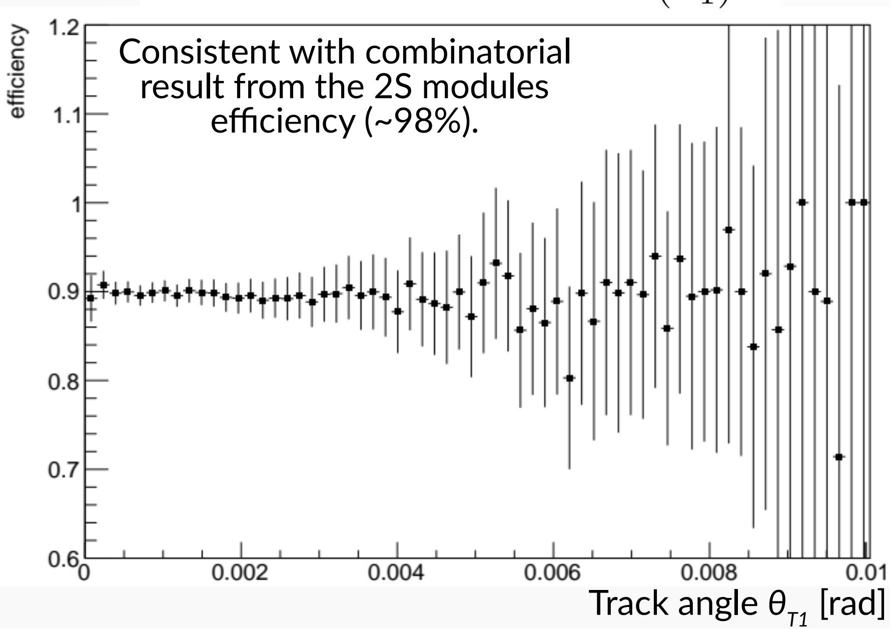


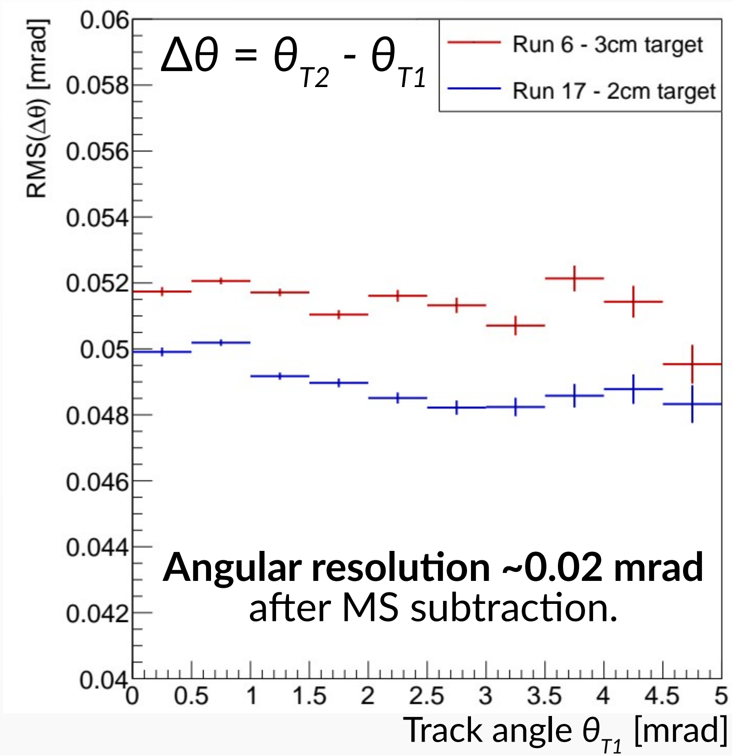
TB 2023 - tracking performance: efficiency and angular resolution

Select events with <u>single passing muons</u>.



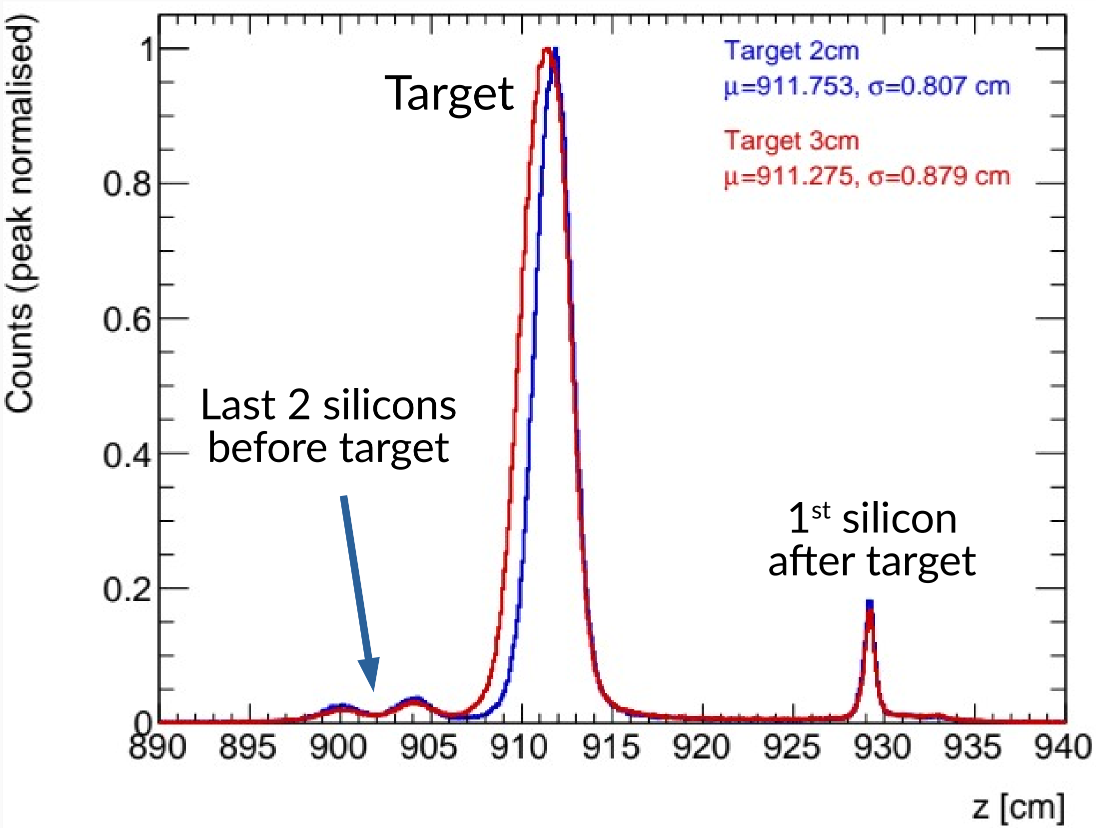
$$\text{Tracking efficiency} = \frac{N(T_2 \cdot T_1)}{N(T_1)}$$





TB 2023 – vertexing

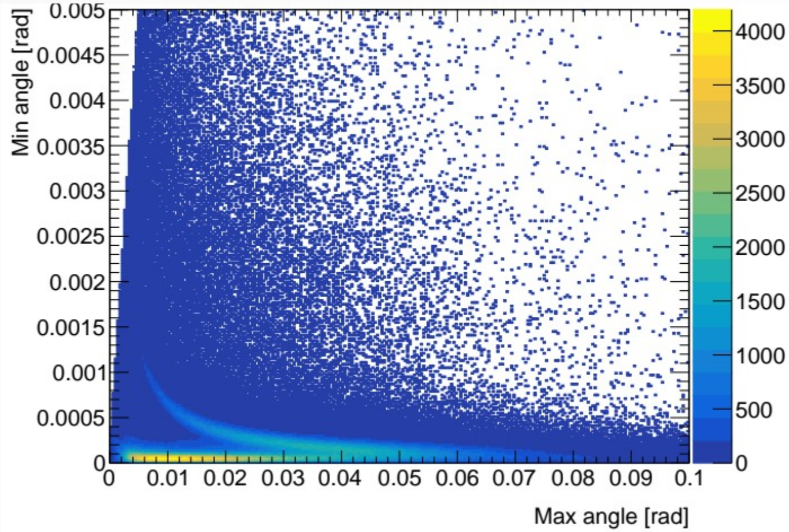
Simple selection: events with 2 outgoing tracks within geometrical acceptance (0.2 – 32 mrad).



- The target center is shifted by 0.5 cm by changing between 3cm and 2cm target (OK!).
- **Vertex resolution: ~0.8 cm**. (Slightly worse for 3cm target due to MS).

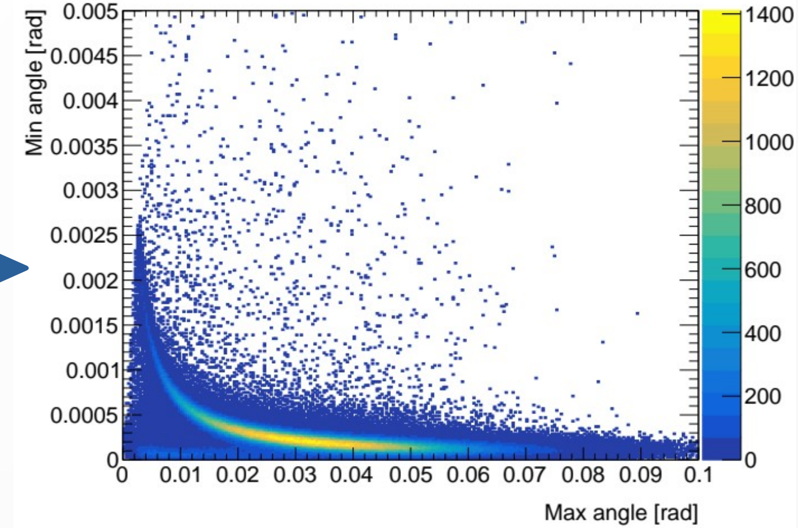
TB 2023
μ-e elastic scattering event selection

- 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:
  - Signal generator: exact NLO + approximated NNLO.
  - Pair production generator: tree level.
- 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

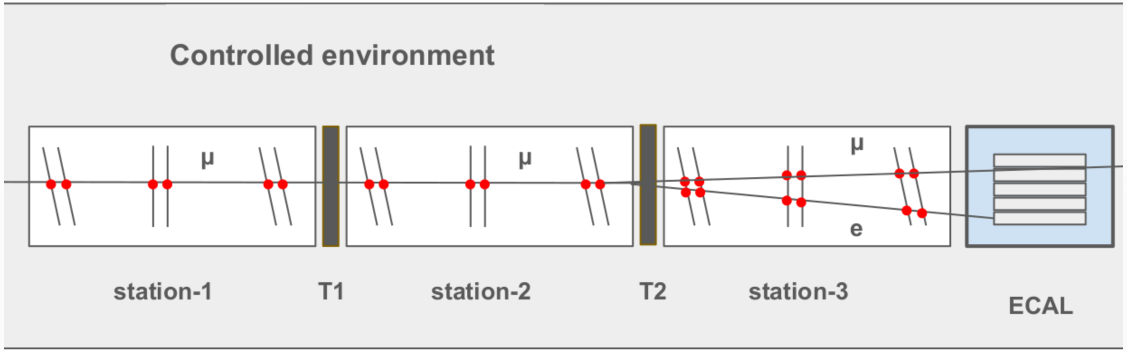
MUonE Phase 1 Experiment Proposal

April 25, 2024

Proposal for phase 1 of the MUonE Experiment

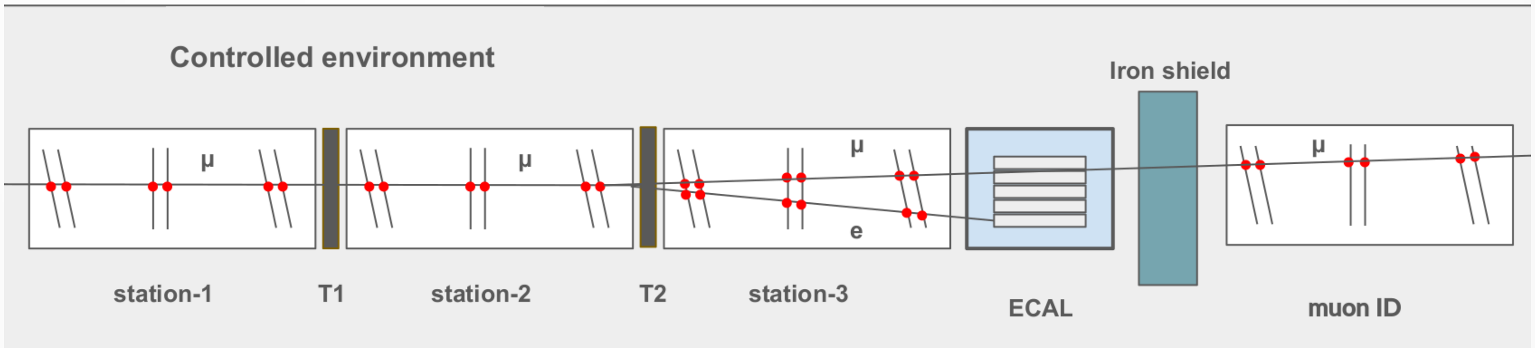
The MUonE Collaboration

Run 2025: the apparatus



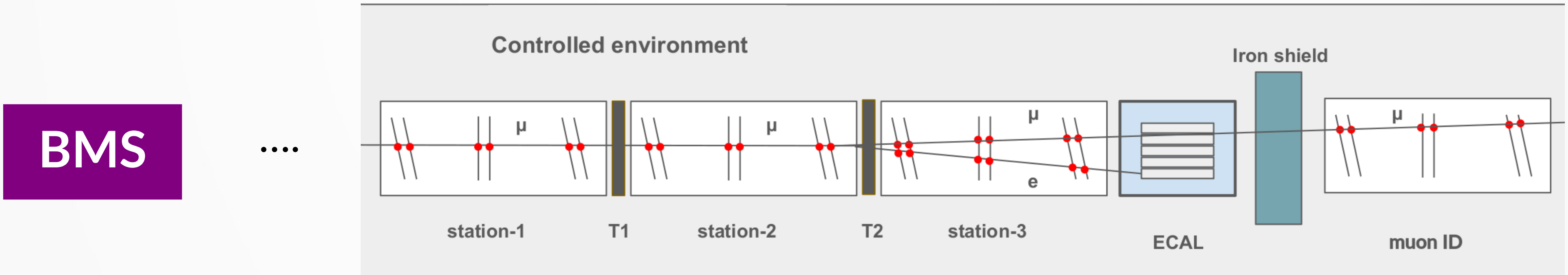
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.

Run 2025: the apparatus



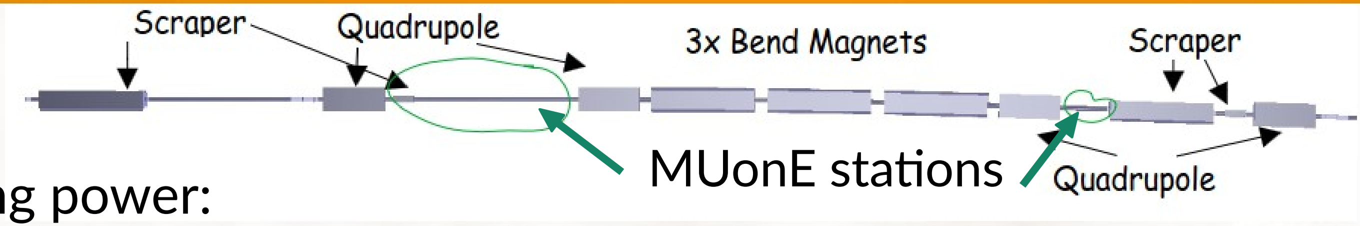
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).

Run 2025: the apparatus

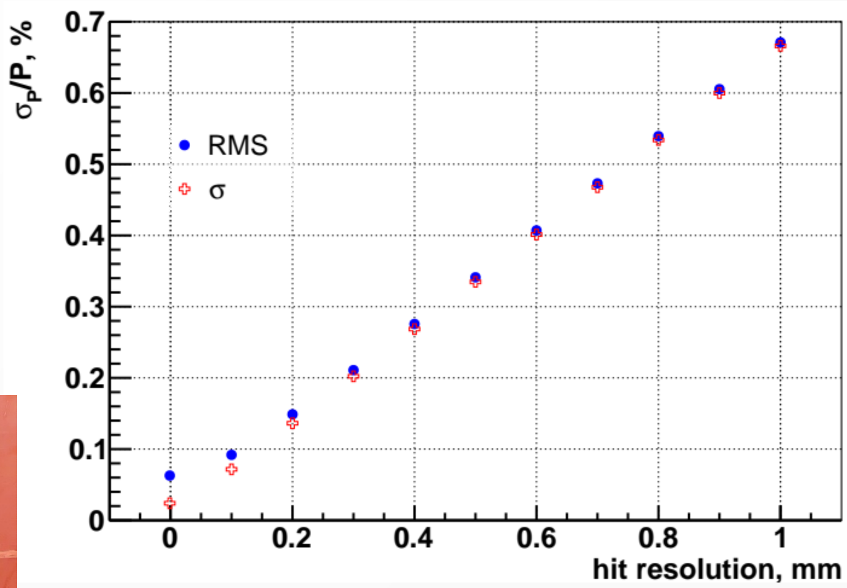


- 3 tracking stations.
- 2 graphite targets (2 cm thickness each).
- ECAL:
  - Full acceptance for interactions in both targets.
  - Provide independent measurements of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).
- BMS:
  - Event-by-event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

BMS (Beam Momentum Spectrometer)



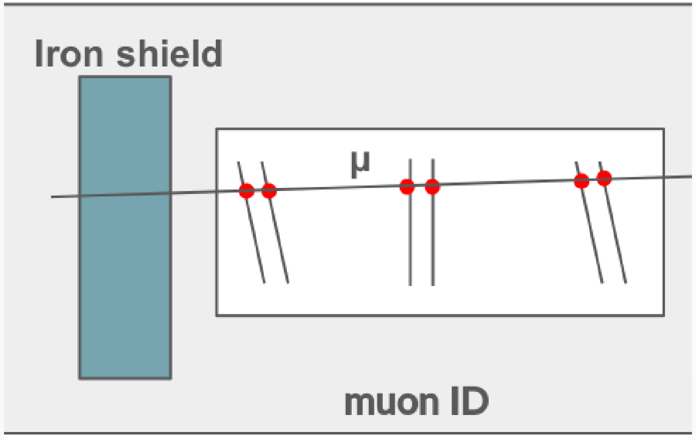
- Bending power:
  16 T*m (30 mrad @160 GeV).
- Determine the muon momentum event by event.
- Goal: < 0.5% momentum resolution.
- In 2025, limited by the precise knowledge of the magnetic field.



Muon ID

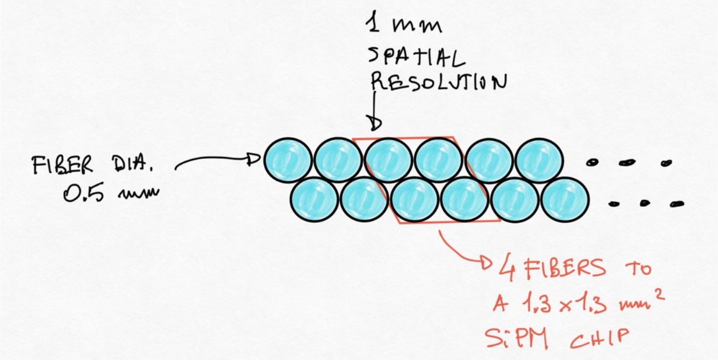
- Detect potential π^+ contamination in the M2 beam.
- Complete the PID in combination with ECAL.
- Help to distinguish between scattered muons and beam pileup muons.

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.

Conclusions

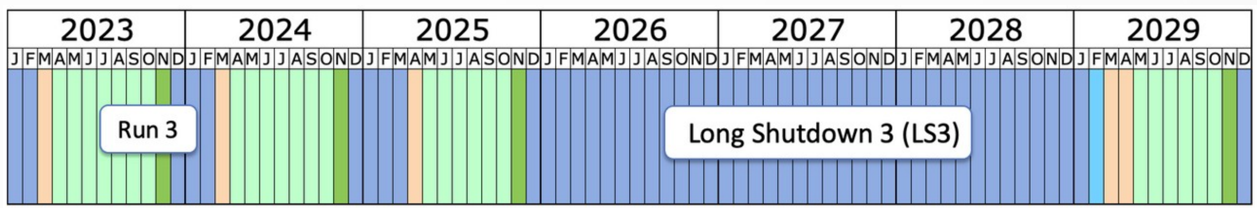
MUonE web site

- MUonE aims to provide an independent calculation of a_μ^{HLO}, competitive with the latest evaluations.

- 3 weeks Test Run 2023: proof of concept of the experimental proposal. Data analysis ongoing.

- Experiment proposal to be submitted soon to the SPSC, to request for a ~1 month run in 2025 instrumenting more tracking stations: first sensitivity to $\Delta\alpha_{\mathrm{had}}(t)$.

- Full apparatus (40 stations) after CERN Long Shutdown 3 to achieve the target precision (~0.3% stat and similar syst).

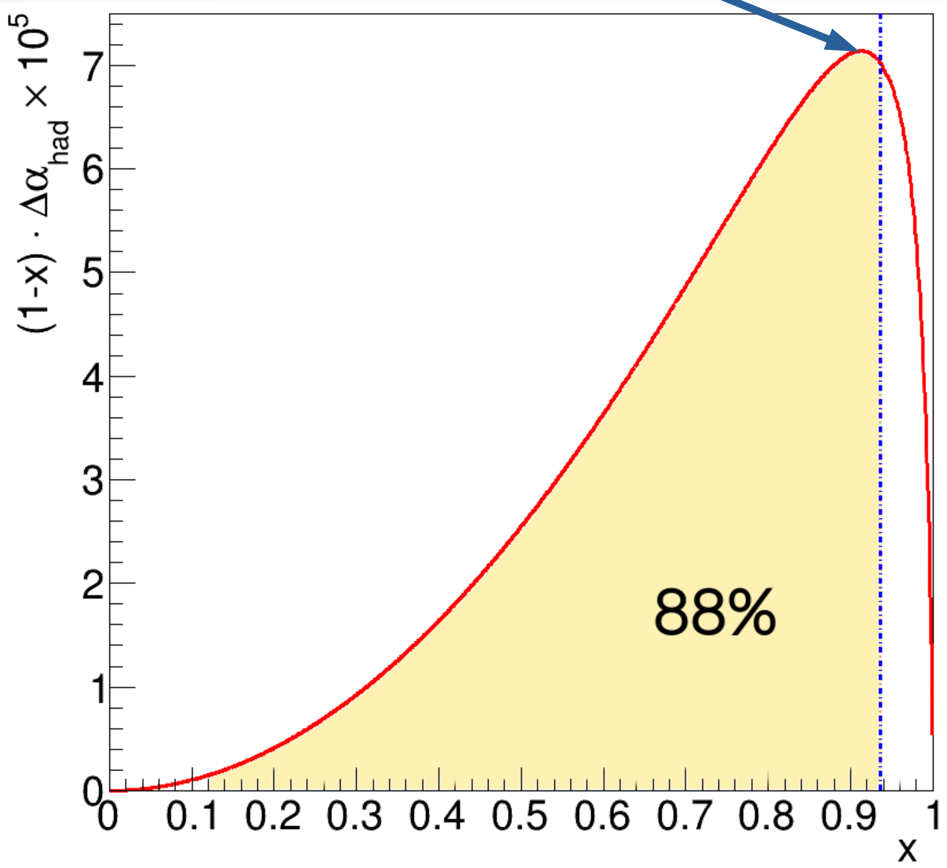


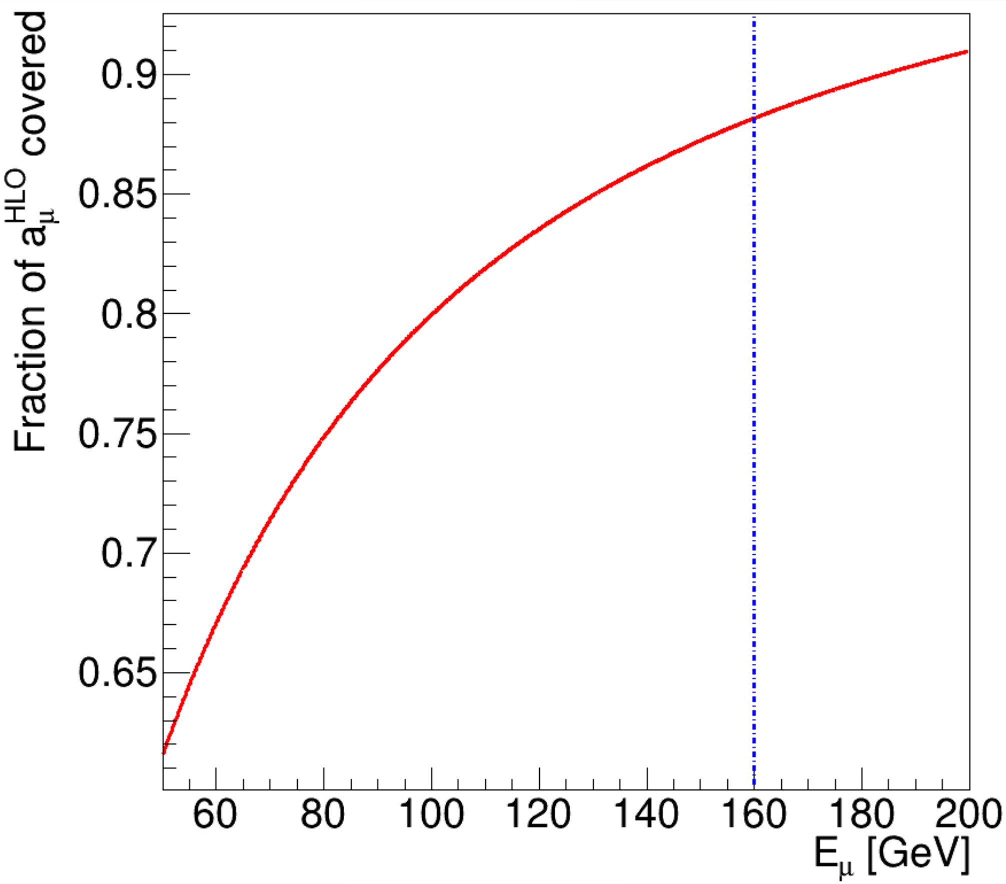
BACKUP

$x < 0.936$

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

$x_{peak} \sim 0.92$



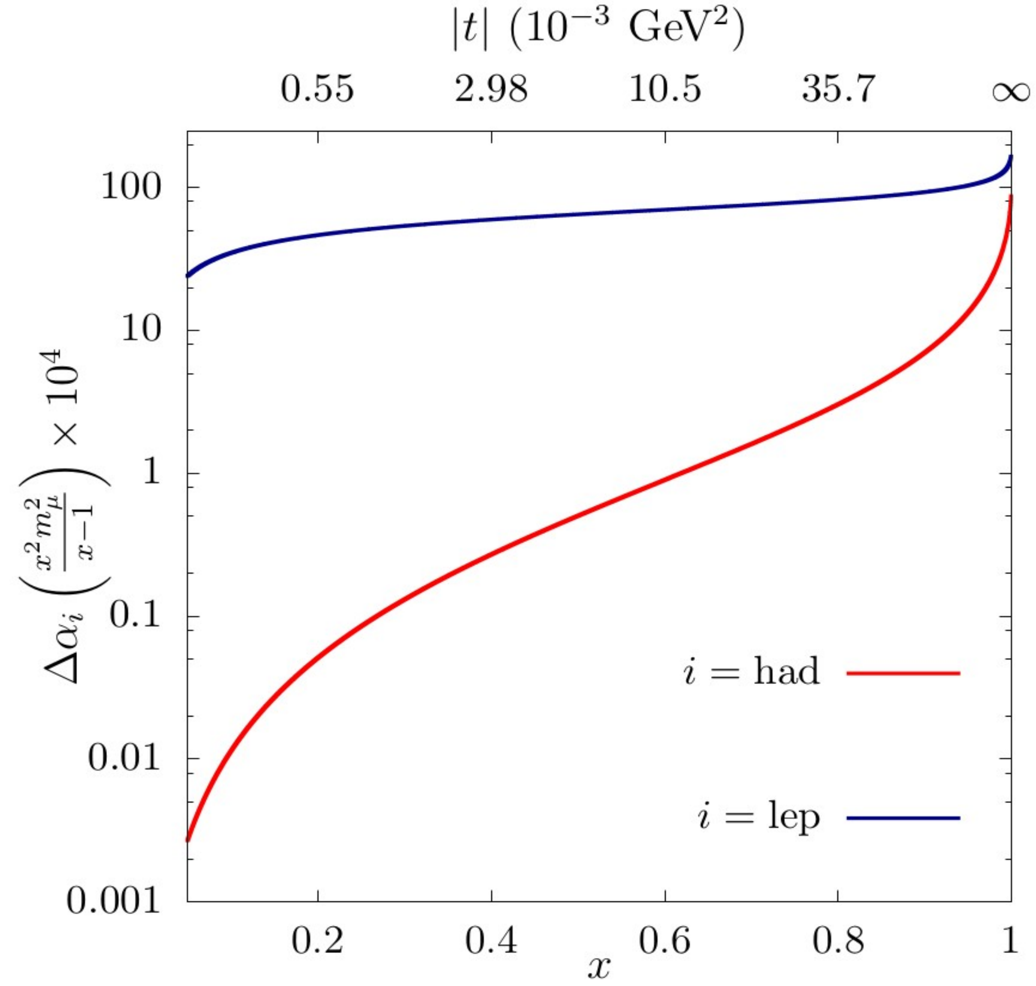


- 160 GeV muon beam on atomic electrons.

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

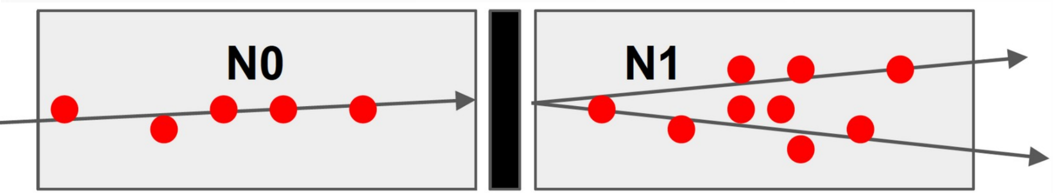
$$-0.153\,\mathrm{GeV}^2 < t < 0\,\mathrm{GeV}^2$$

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



Test Run Analysis

Online event selection



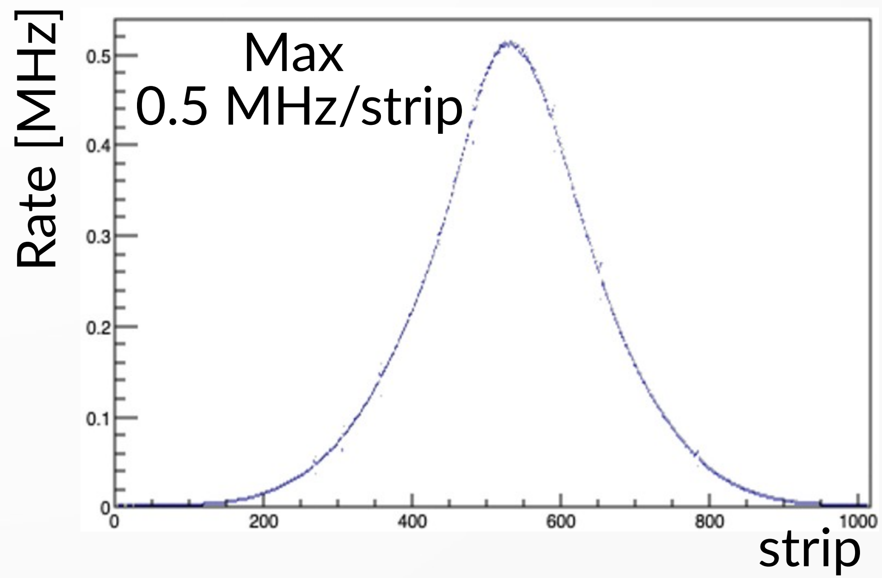
Select potential elastic events by looking at the number of hits in two consecutive stations:

- $N_{hits}^{0} \geq 5$ &&
- $N_{hits}^{1} \geq 5$ &&
- $N_{hits}^{1} - N_{hits}^{0} \geq 3\text{-}5$

Reduce the data flow to 1%-2%
Can be easily implemented on FPGA.

Beam rate

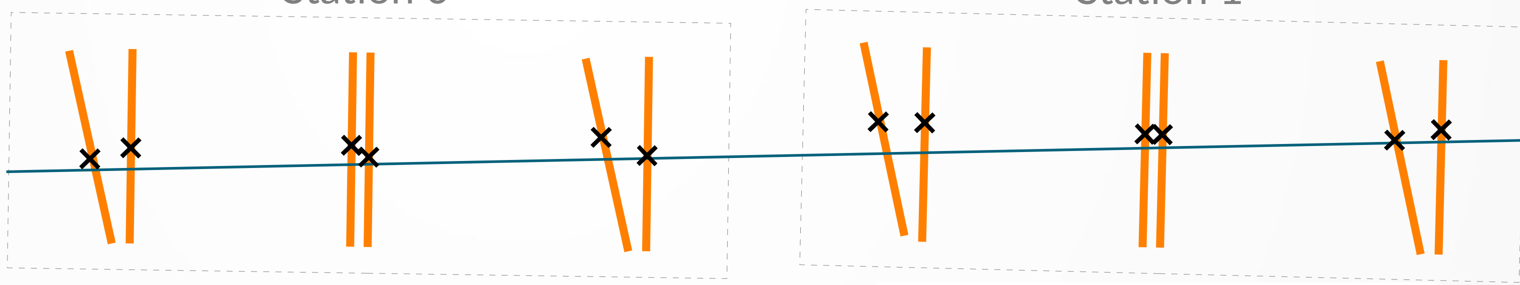
$1\text{-}2 \times 10^{8}$ μ/spill
(1 spill = 5s)



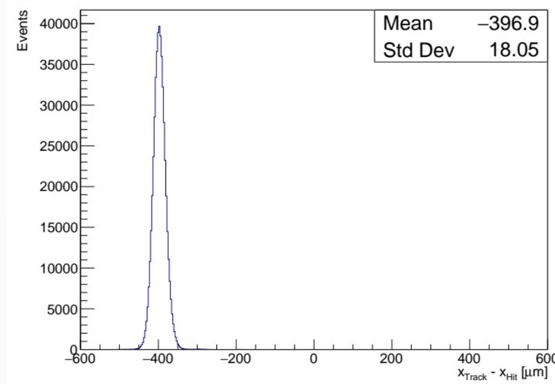
Goal:
count the total number of muons per run (input for expected luminosity)

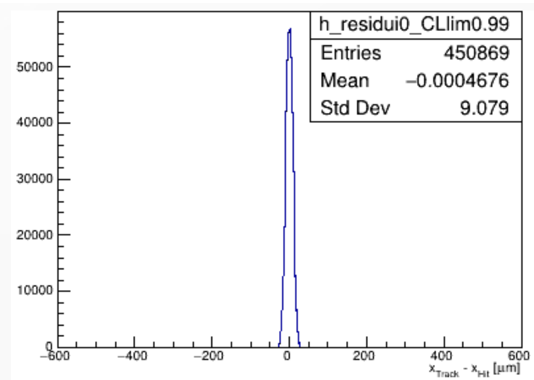
Alignment TB 2023

Alignment

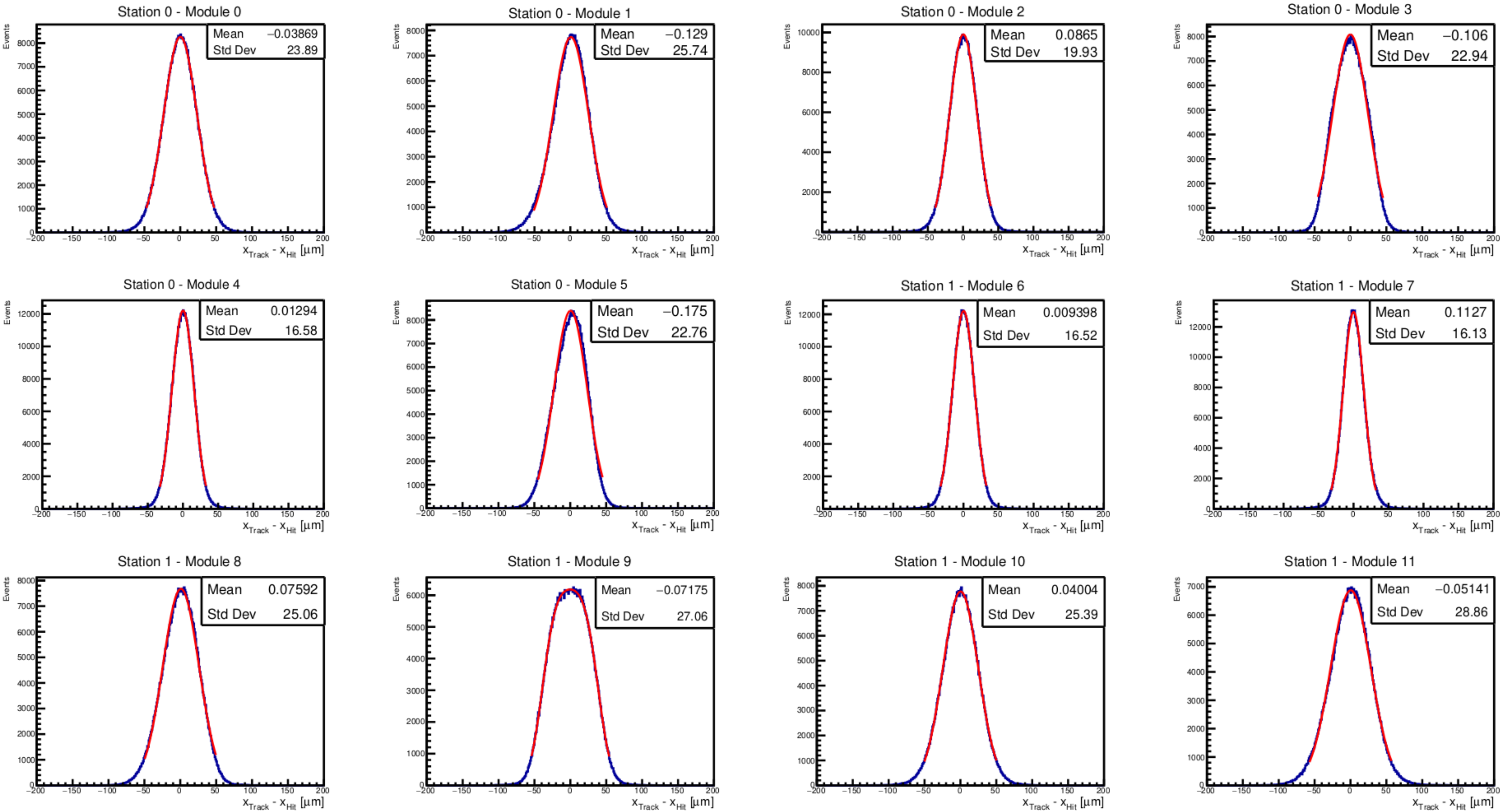


- Track based iterative procedure: 2 alignment parameters per module (offset in the measured direction and rotation angle around the beam axis).
- Align the coordinate orthogonal to the measurement direction by measuring the image of module's middle line.

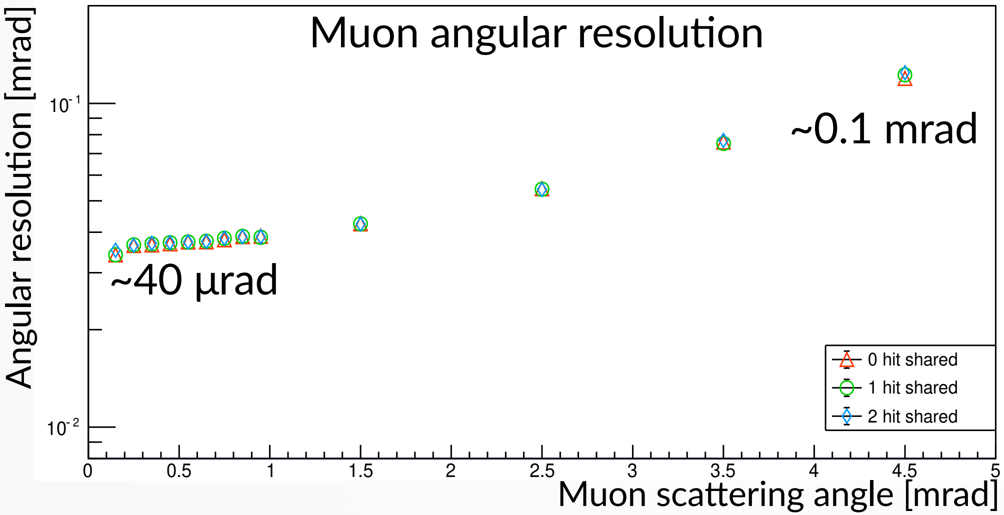


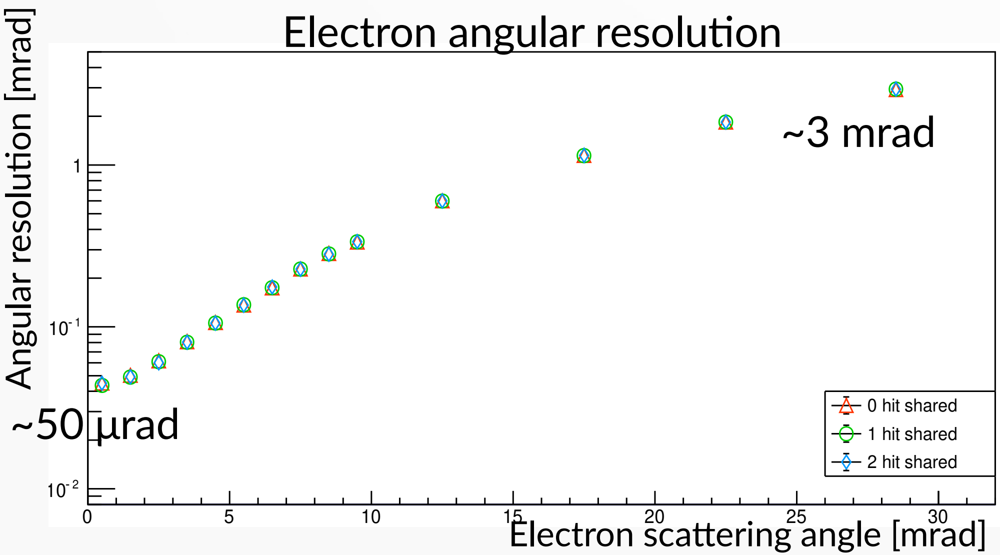


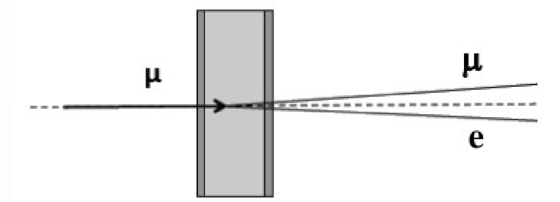
Alignment – TB 2023



TB 2023 - MC performance: angular resolution of scattered particles







- Compare track reconstruction with MC truth.
- Muon angle: ~40 μrad resolution for small scattering angles.
- Electron angle: stronger impact of MS. Resolution is ~3 mrad for large scattering angles (E_e ~1–2 GeV).

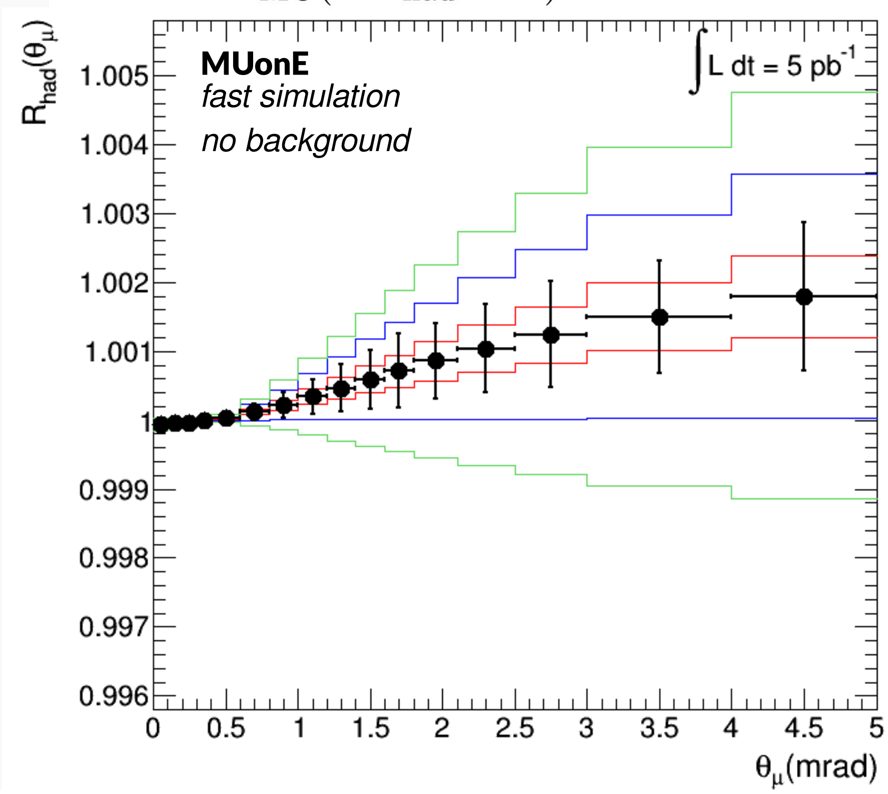
Work in progress:

Data / MC comparison.

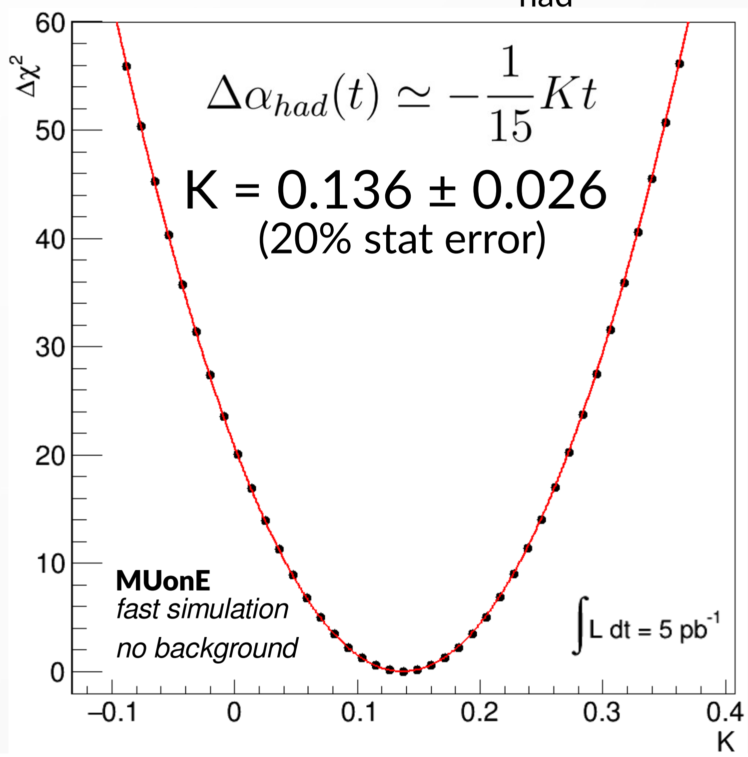
First measurement of $\Delta\alpha_{had}(t)$

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

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

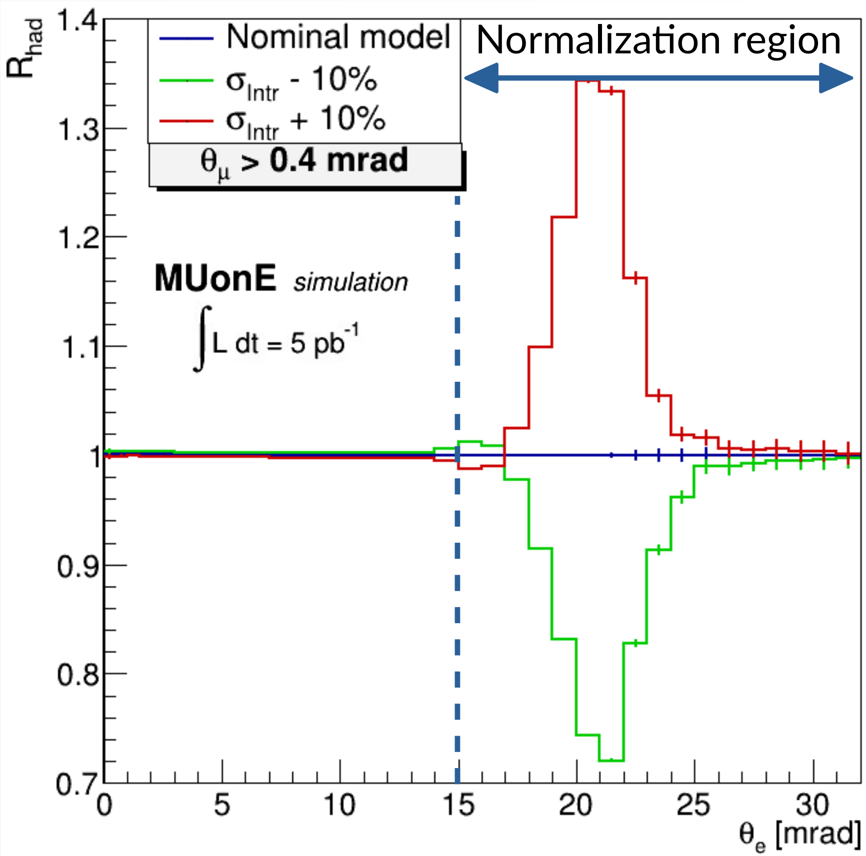


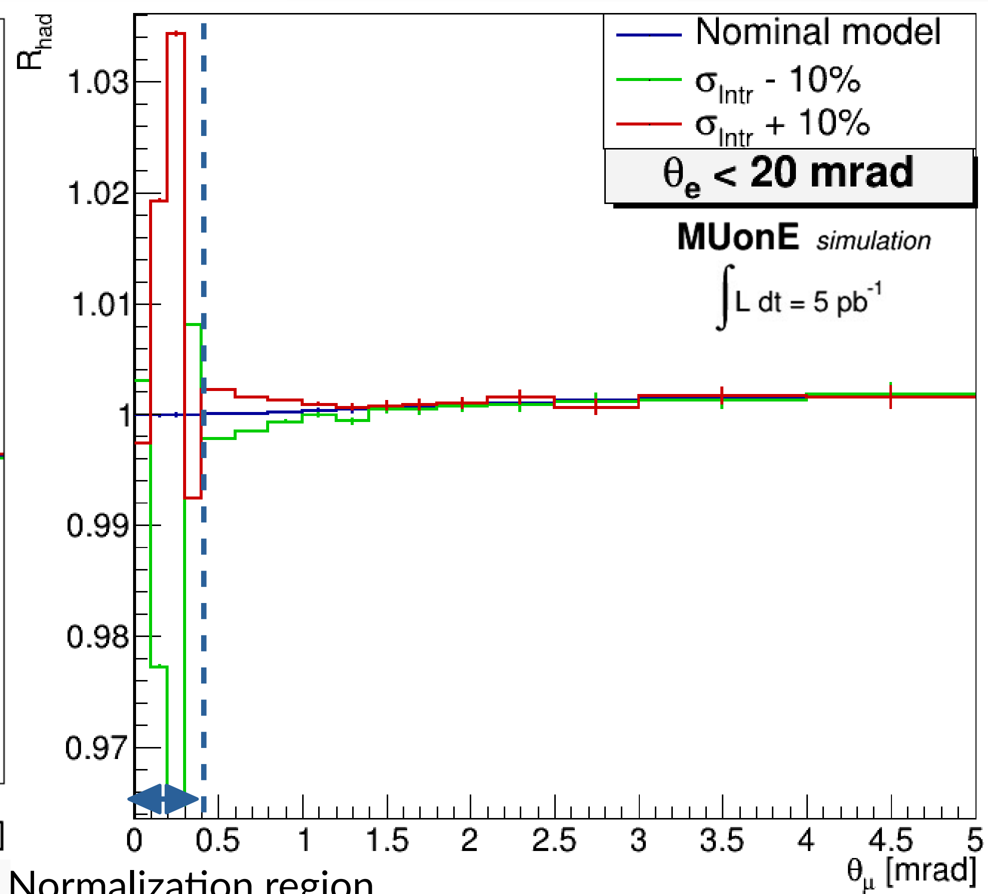
Template fit procedure
to extract $\Delta\alpha_{had}$(t)



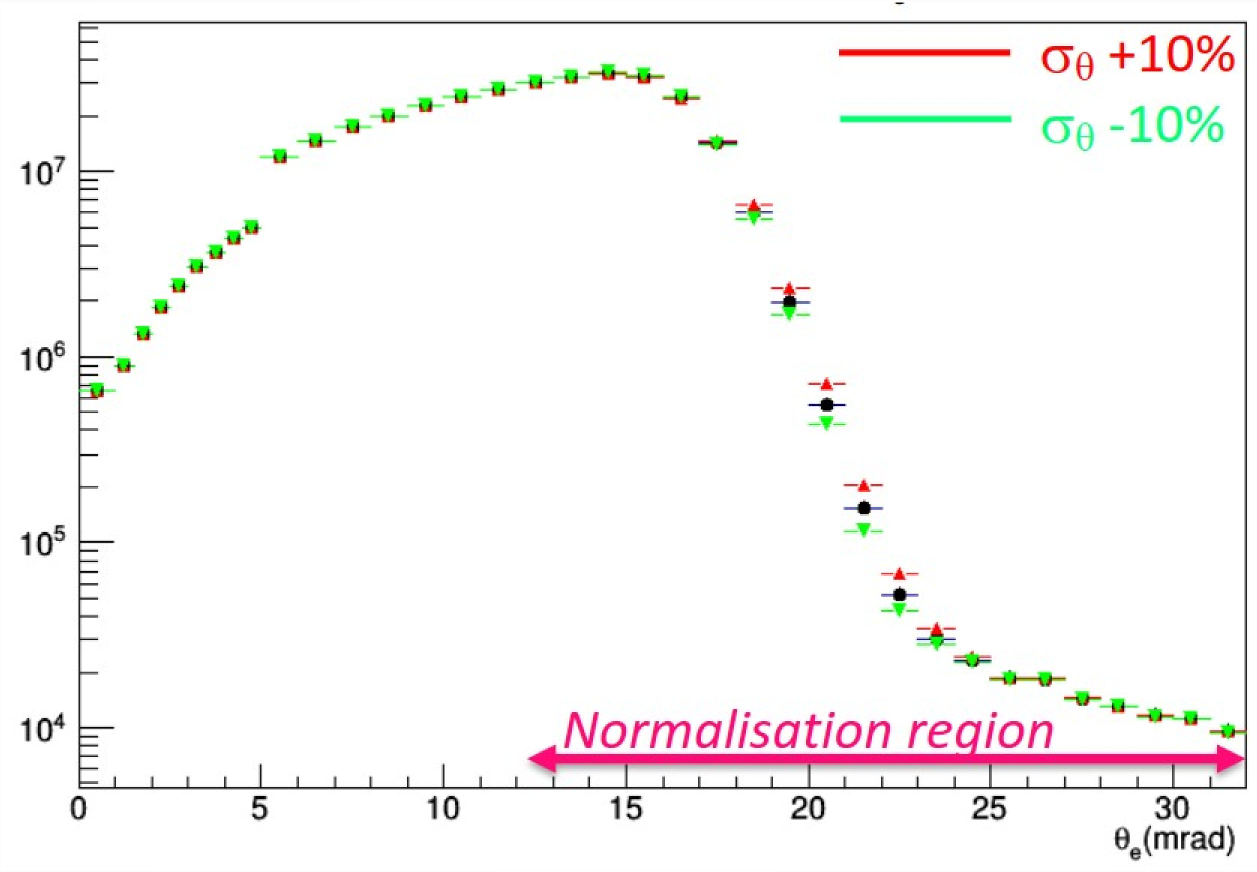
Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution.





Normalization region



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

The need of including systematic effects in the analysis

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

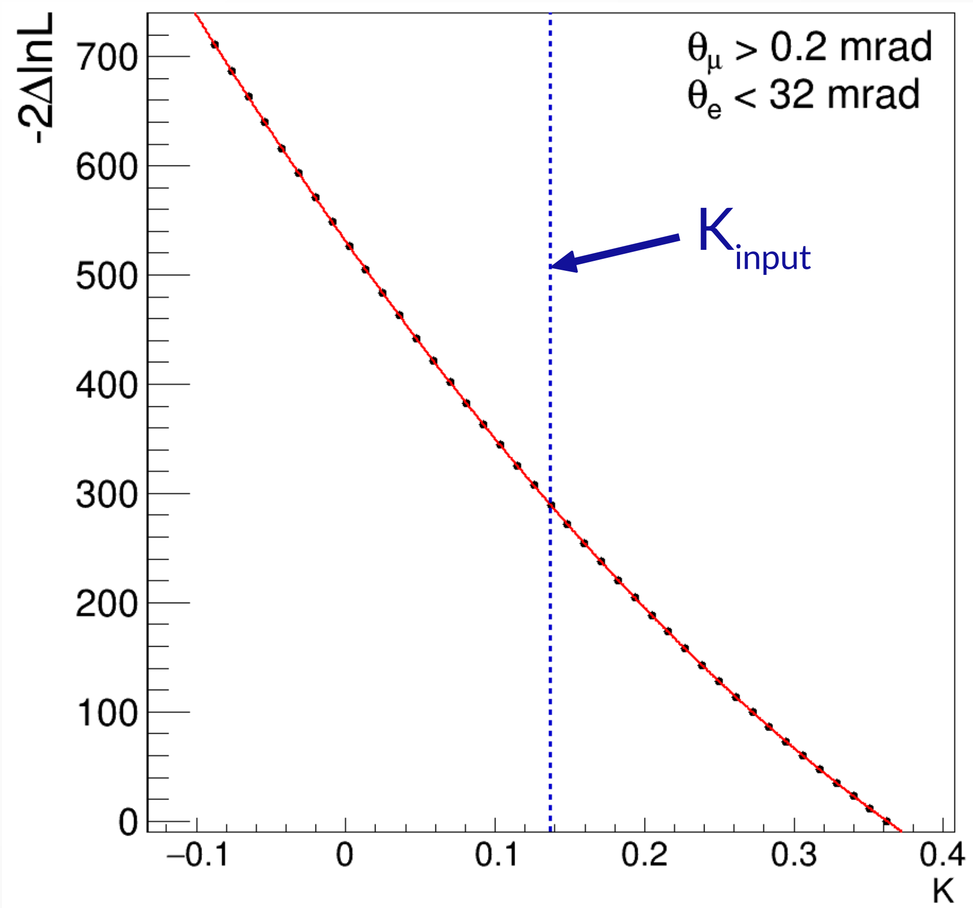
Simplified situation:

- 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)

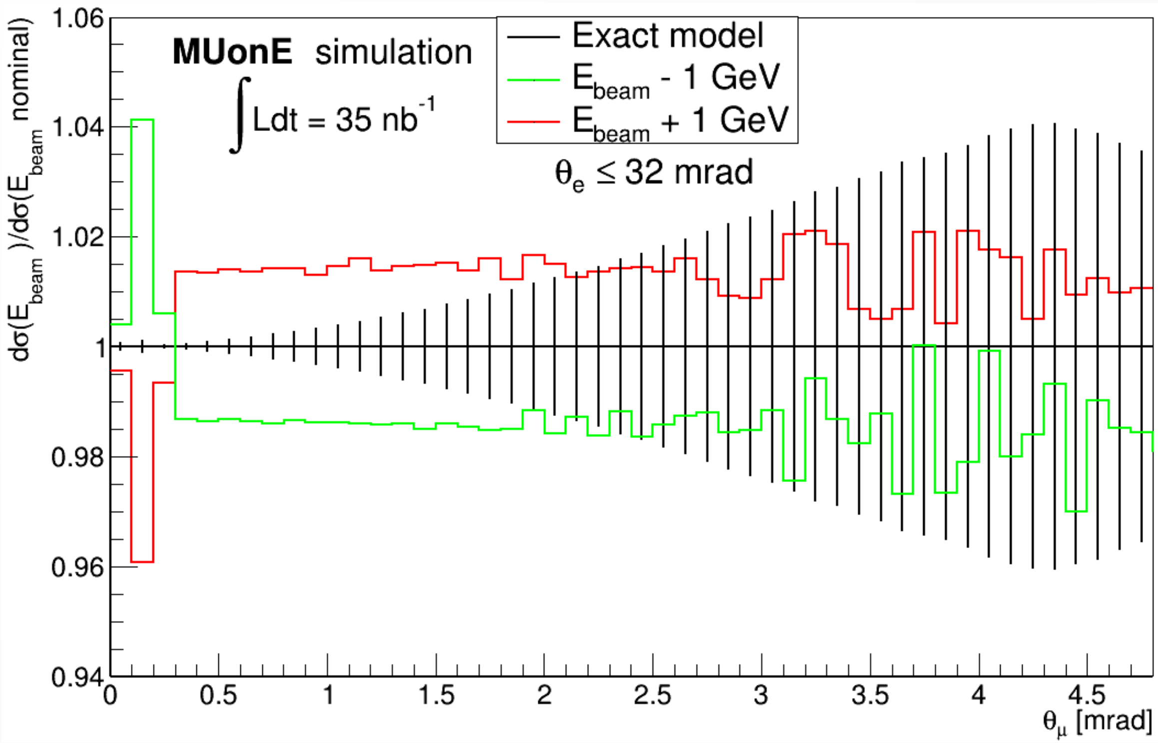
- Shift in the pseudo-data sample:
  $\sigma_{Intr} \rightarrow \sigma_{Intr} + 5\%$.



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%

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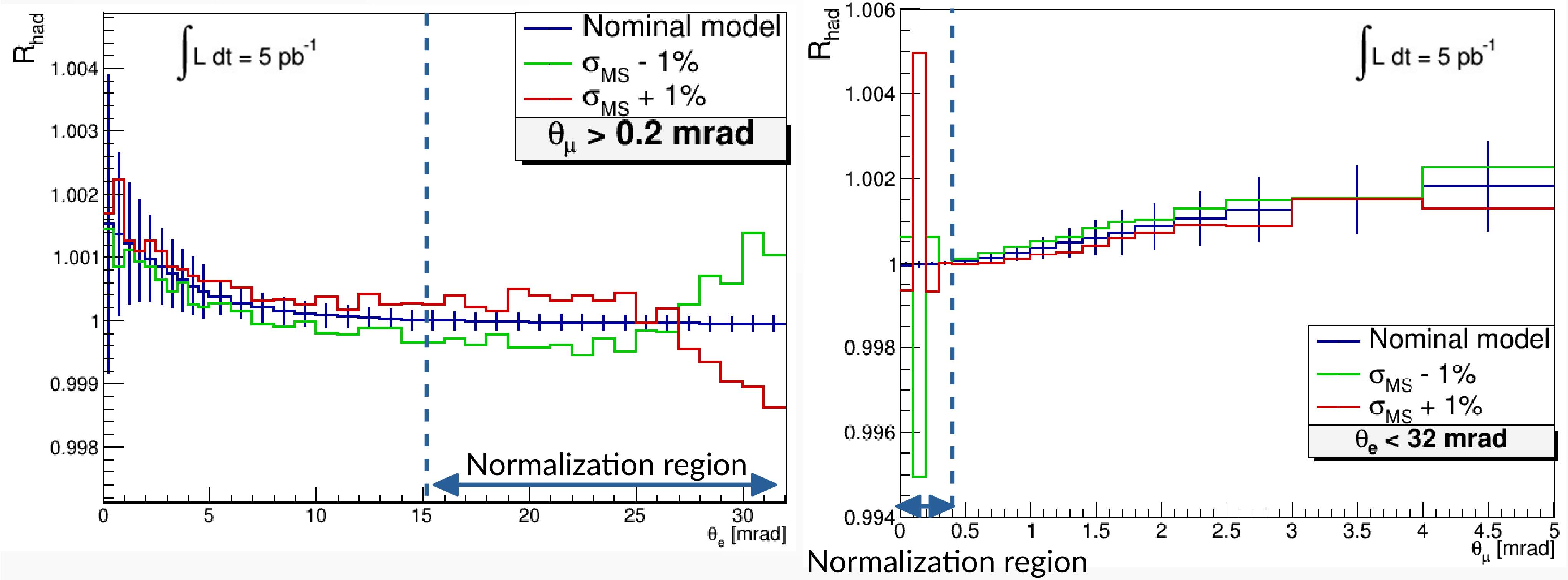
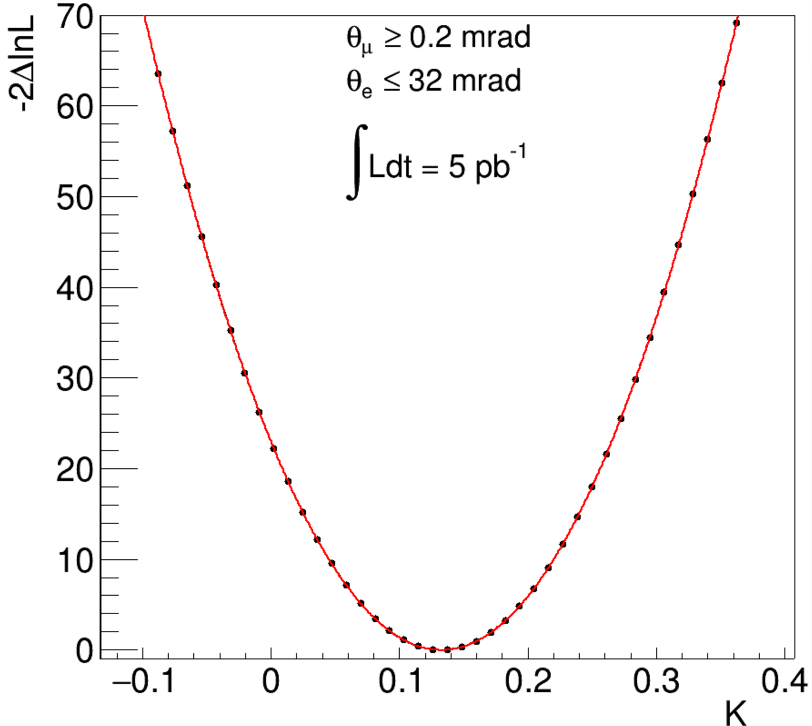


Combined fit
signal + systematics

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



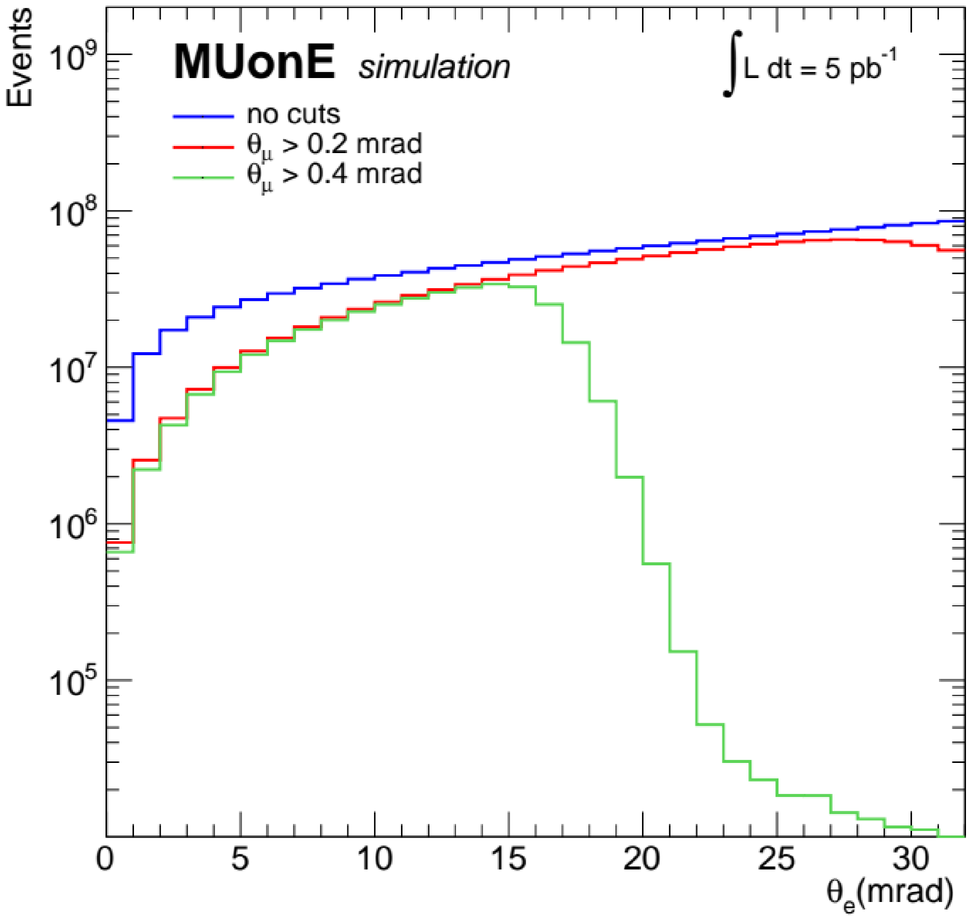
- $K_{ref} = 0.137$
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

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

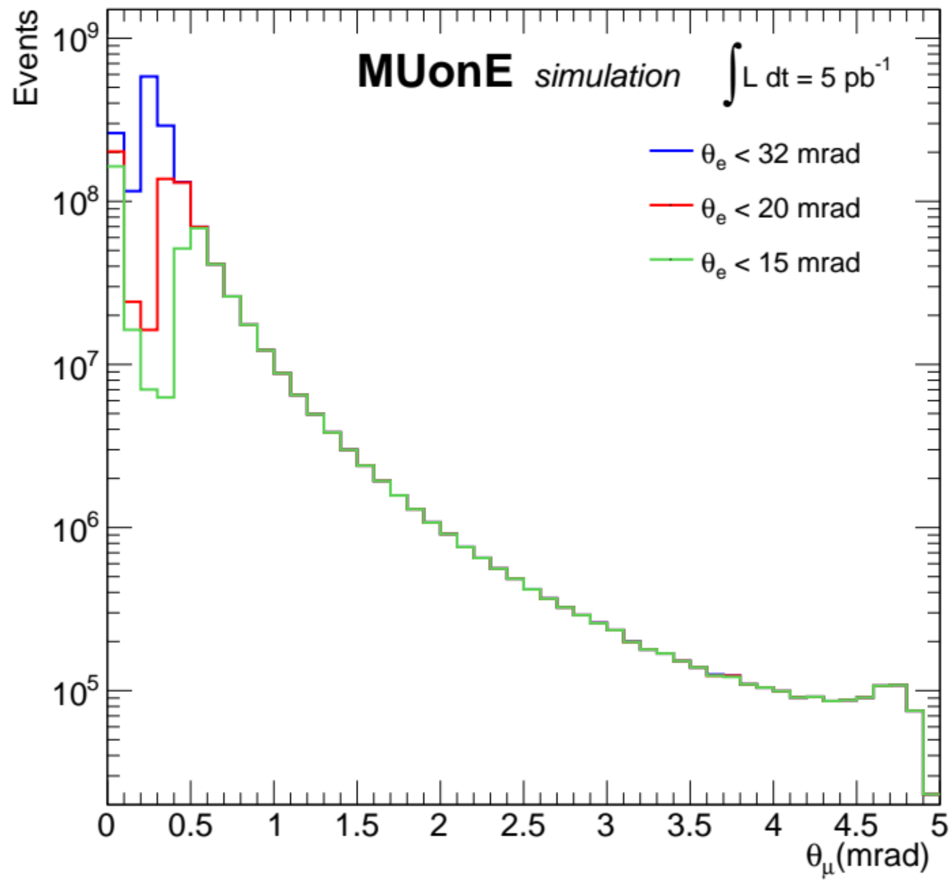
Similar results also for different selection cuts.

Next steps:

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



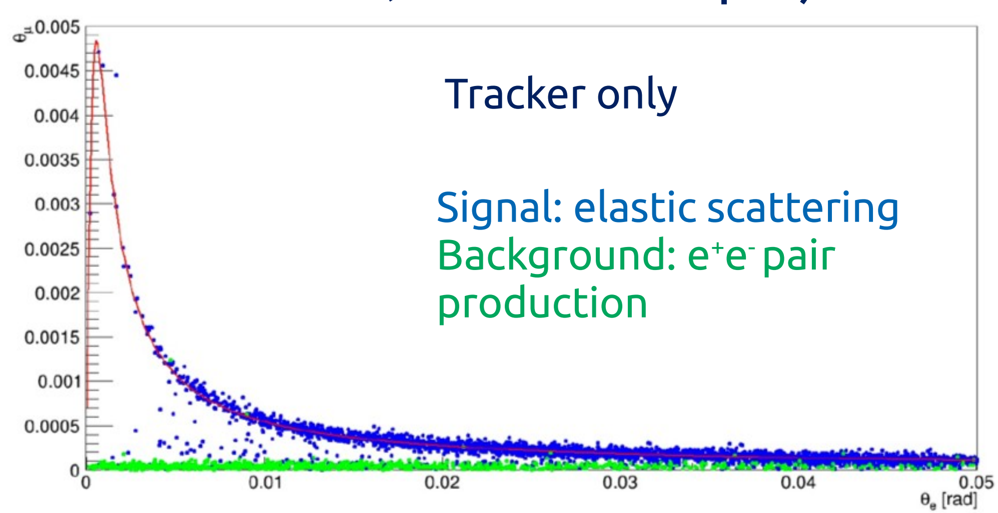
MUonE simulation
$\int L\,dt = 5\ pb^{-1}$
Events
no cuts
$\theta_\mu > 0.2$ mrad
$\theta_\mu > 0.4$ mrad
θ_e(mrad)

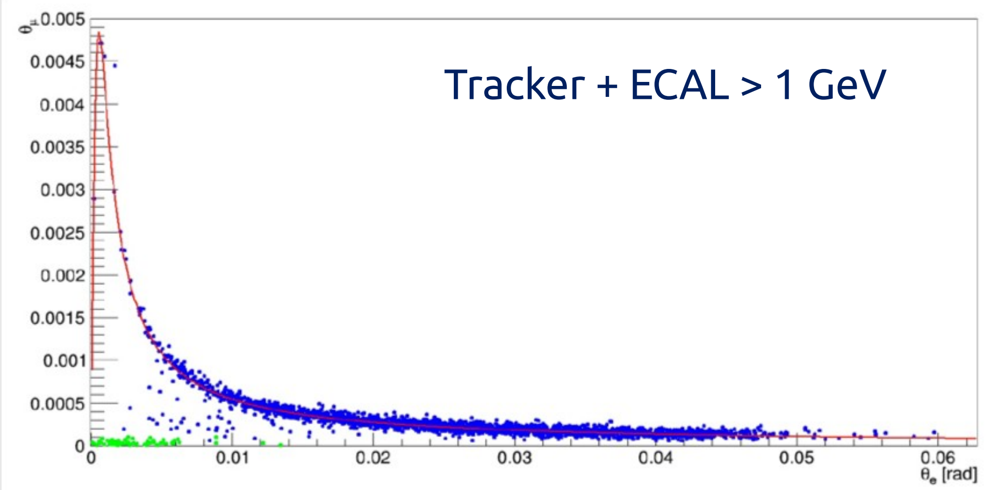


MUonE simulation
$\int L\,dt = 5\ pb^{-1}$
Events
$\theta_e < 32$ mrad
$\theta_e < 20$ mrad
$\theta_e < 15$ mrad
θ_μ(mrad)

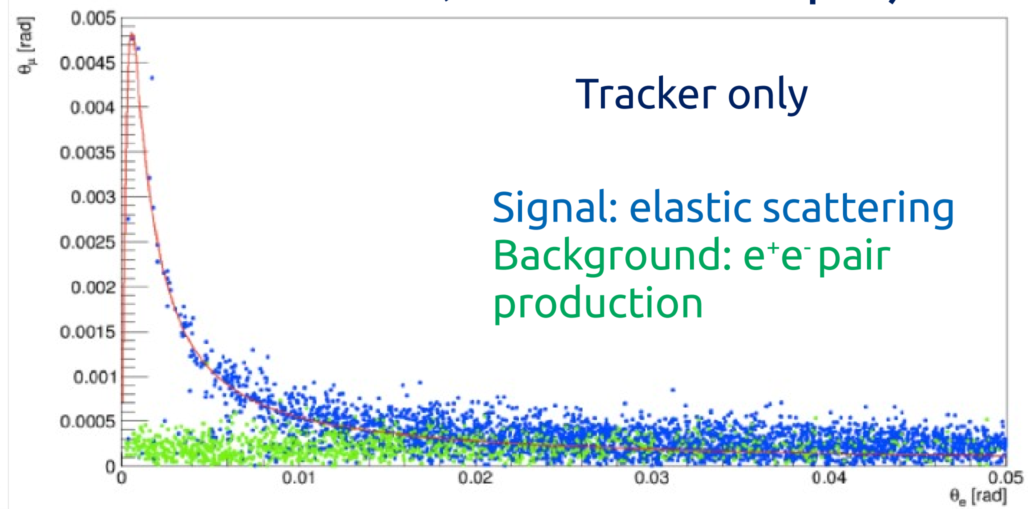
GEANT4 simulations

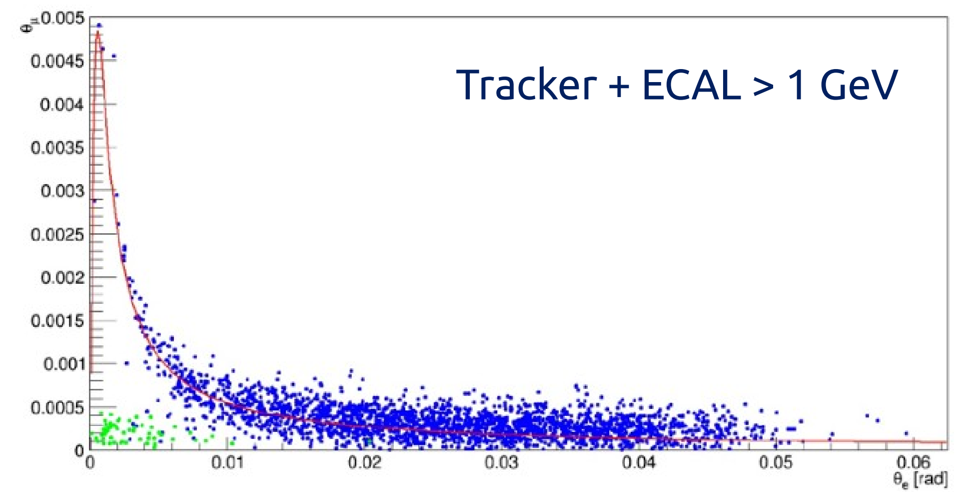
TB2017 (resolution ~7μm)



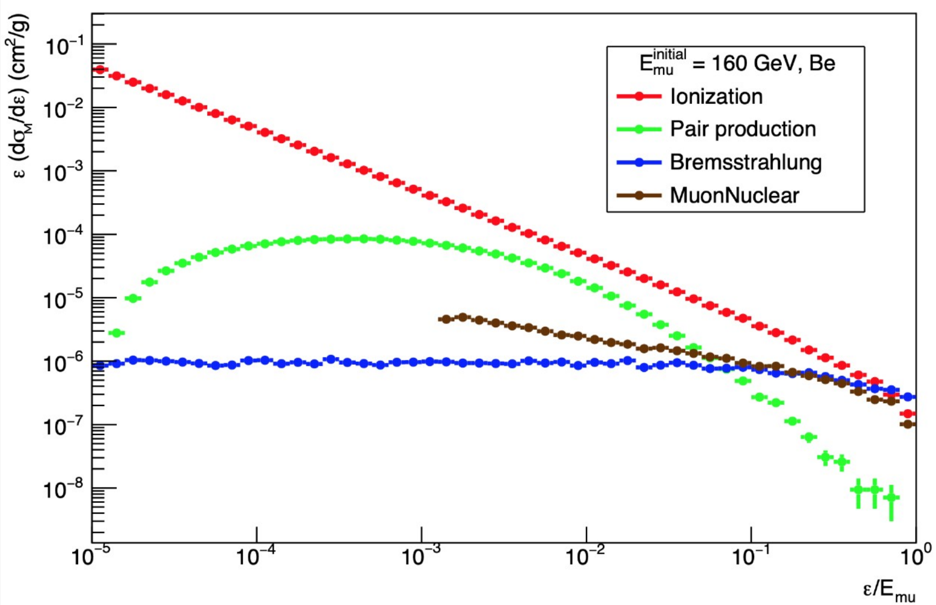


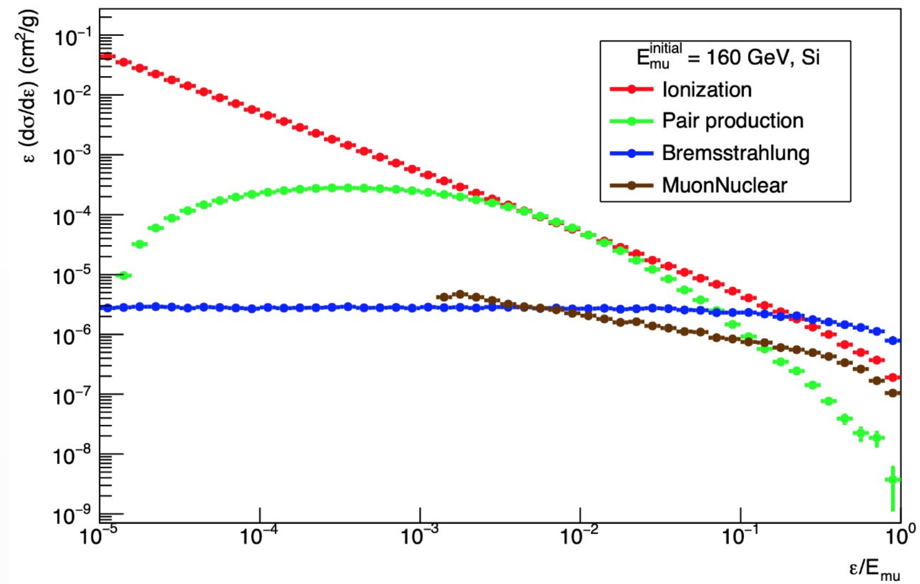
TB2018 (resolution ~40μm)





Backgrounds





MESMER

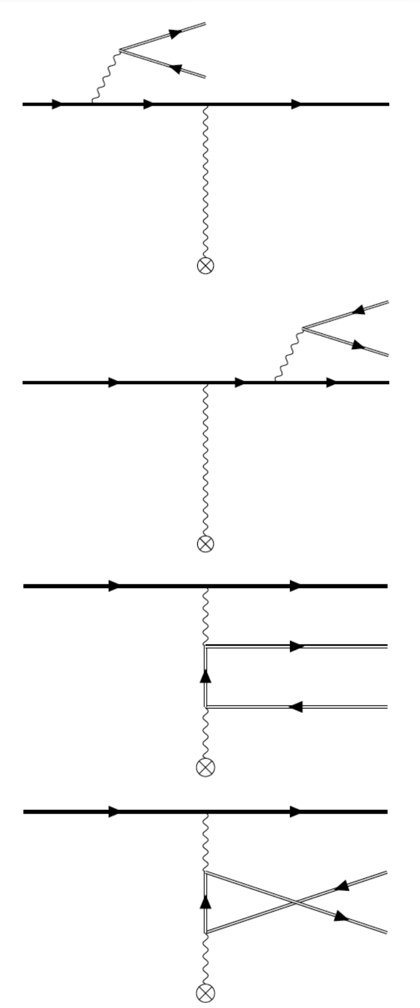
- $\mu e^- \to \mu e^- \gamma$
- $\mu e^- \to \mu e^- e^+ e^-$
- $\mu N \to \mu N e^+ e^-$

GEANT4

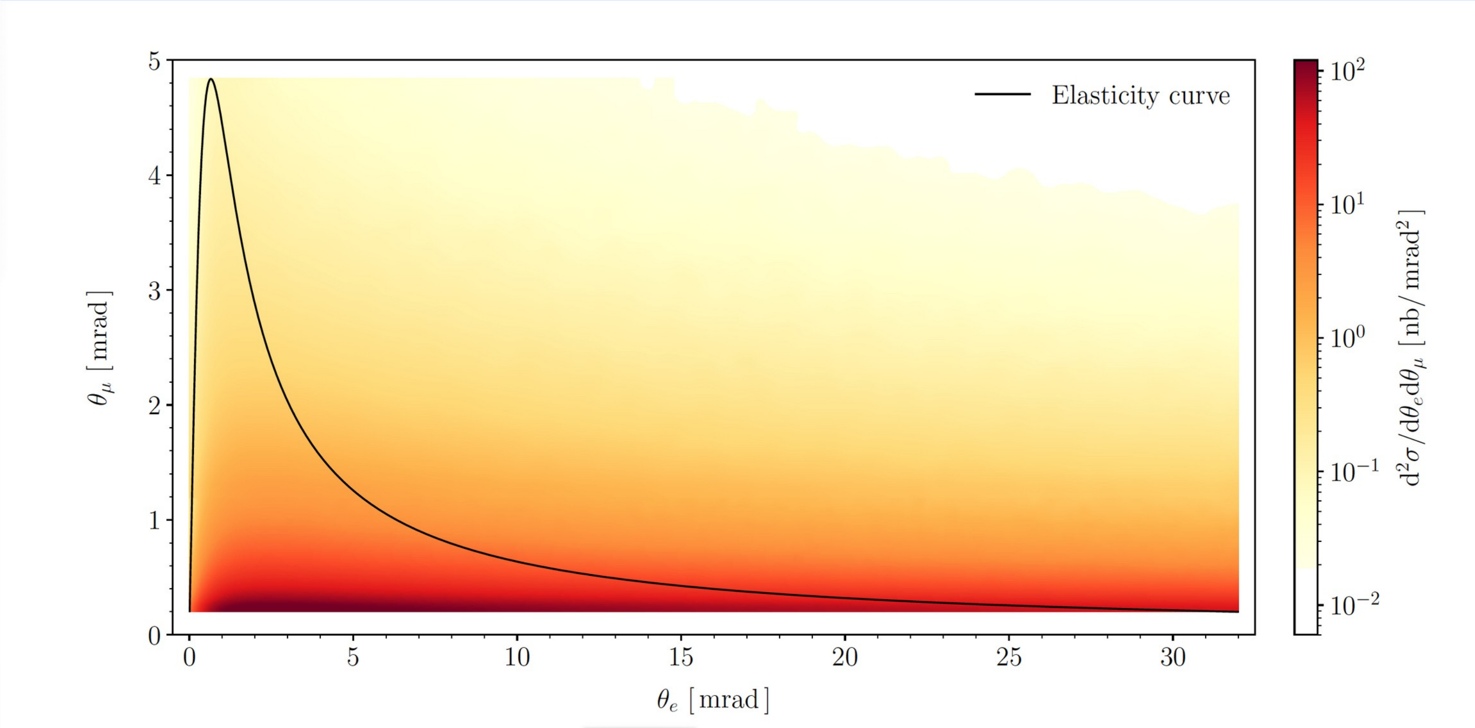
- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$

New Background MC generator

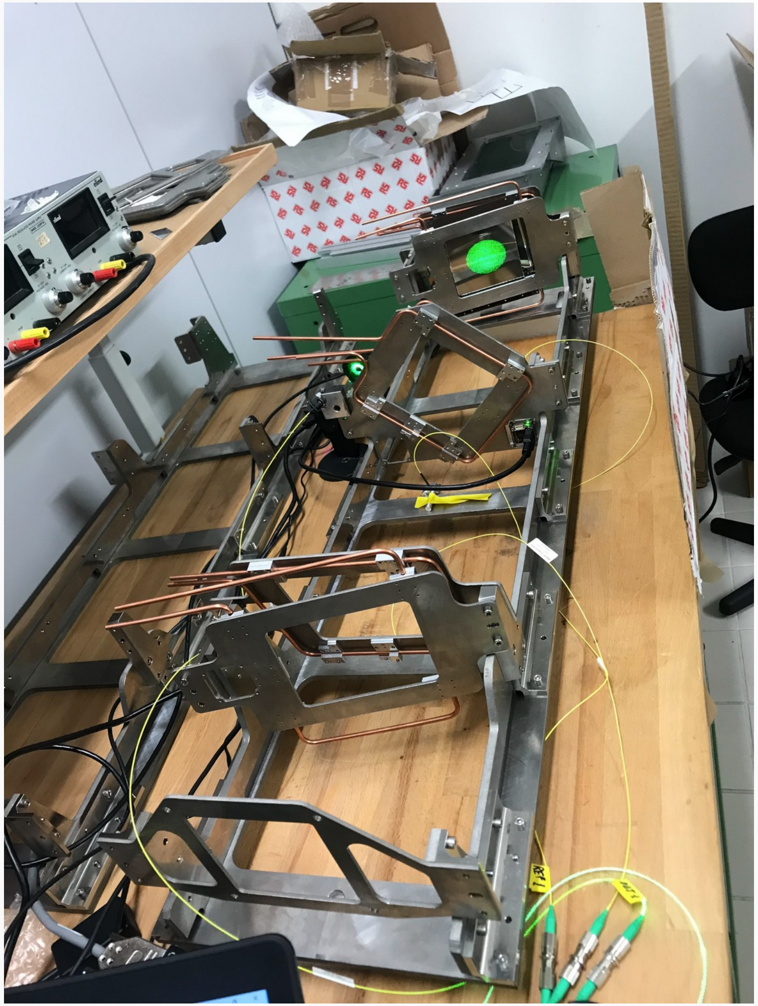
Main background: e+e- pair production
Implemented in MESMER
and interfaced with the MUonE detector simulation



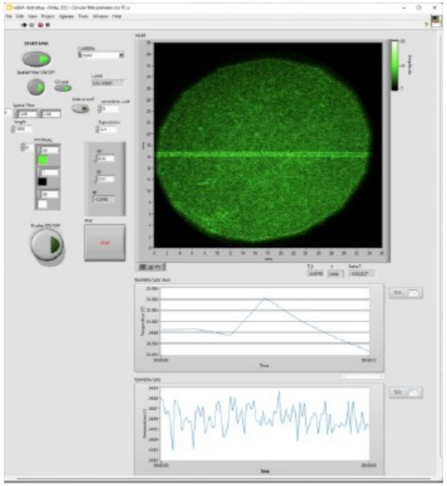
Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)

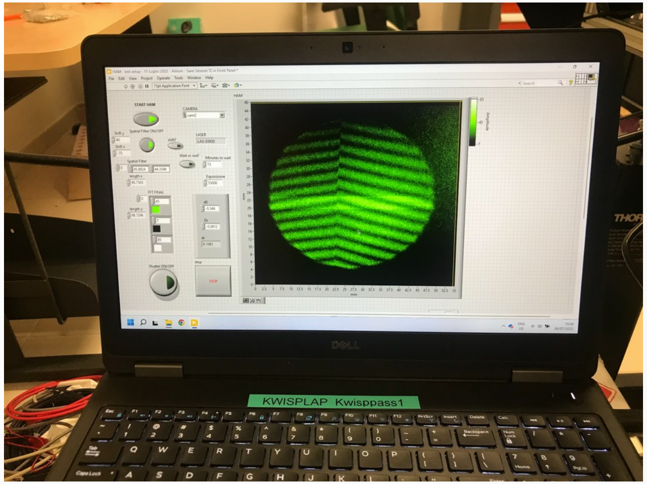


Laser holographic system



Initial state

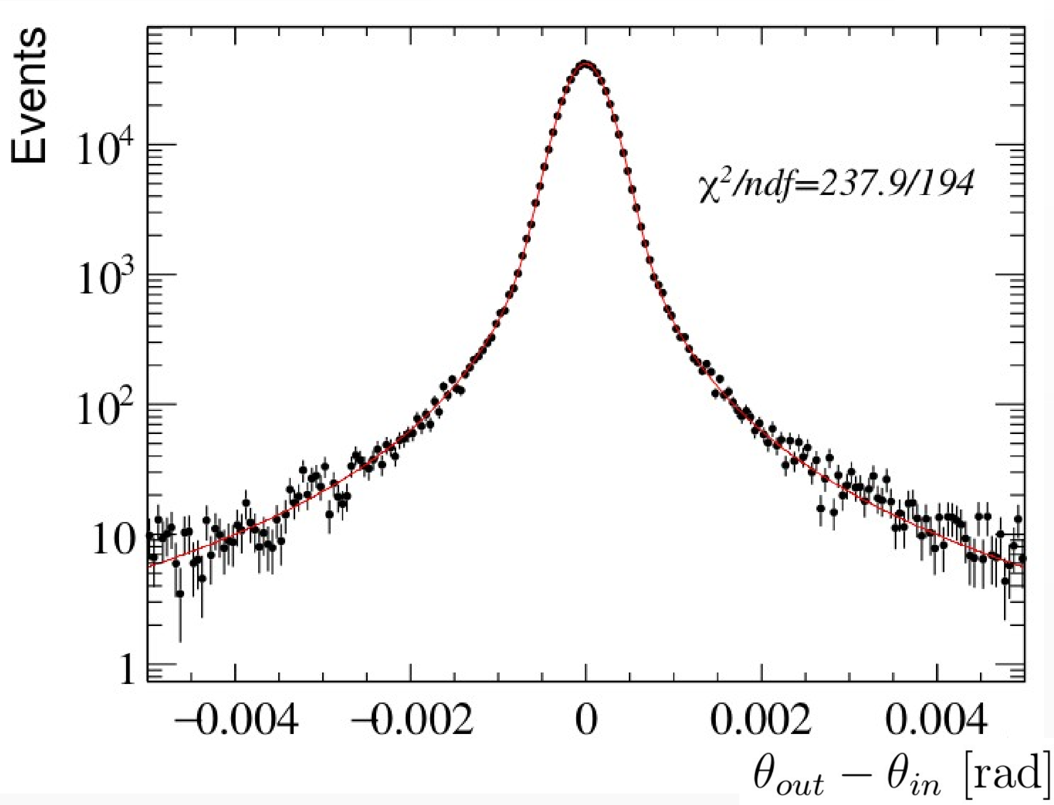




- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.

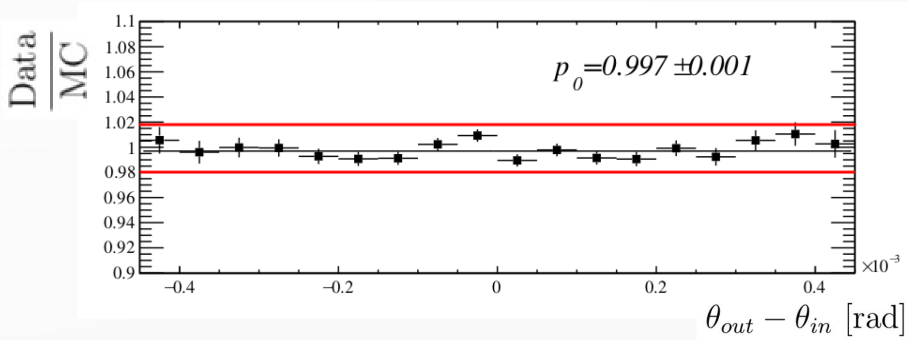
Multiple scattering: results from TB2017

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



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

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



Alternative method to compute a_μ^{HLO} from MUonE data

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO\ (I)}} + a_\mu^{\mathrm{HLO\ (II)}} + a_\mu^{\mathrm{HLO\ (III)}} + a_\mu^{\mathrm{HLO\ (IV)}}$$

$$a_\mu^{\mathrm{HLO\ (I)}} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

MUonE
99%

$$a_\mu^{\mathrm{HLO\ (II)}} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\ \Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO\ (III)}} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s)-K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO\ (IV)}} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s)-\tilde{K}_1(s)]R(s)$$

Time-like data + pQCD
1%

Insensitive to the parameterization chosen to fit $\Delta\alpha_{had}(t)$.

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