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LEVERHULME TRUST

Status of the MUonE experiment

Riccardo Nunzio Pilato

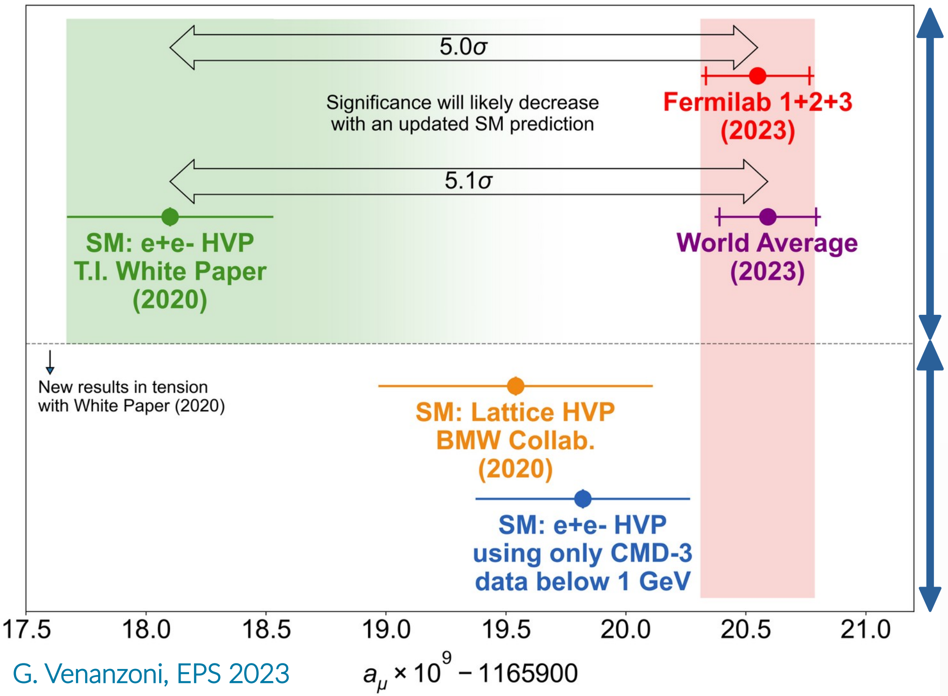
University of Liverpool

μONe

Particle Physics Annual Meeting

23 May 2024

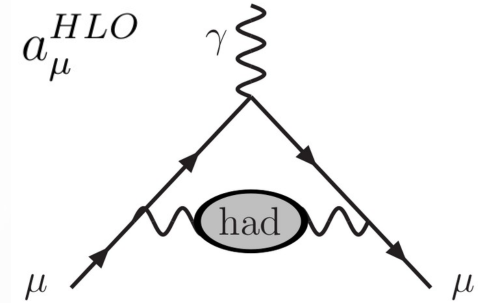
Muon g-2: current status



G. Venanzoni, EPS 2023

Comparison with WP20

New results after WP20



Main source of uncertainty of the theoretical prediction

A clarification of the theoretical prediction is needed.

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).

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

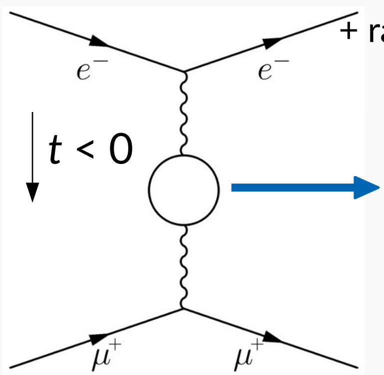
Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026

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

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

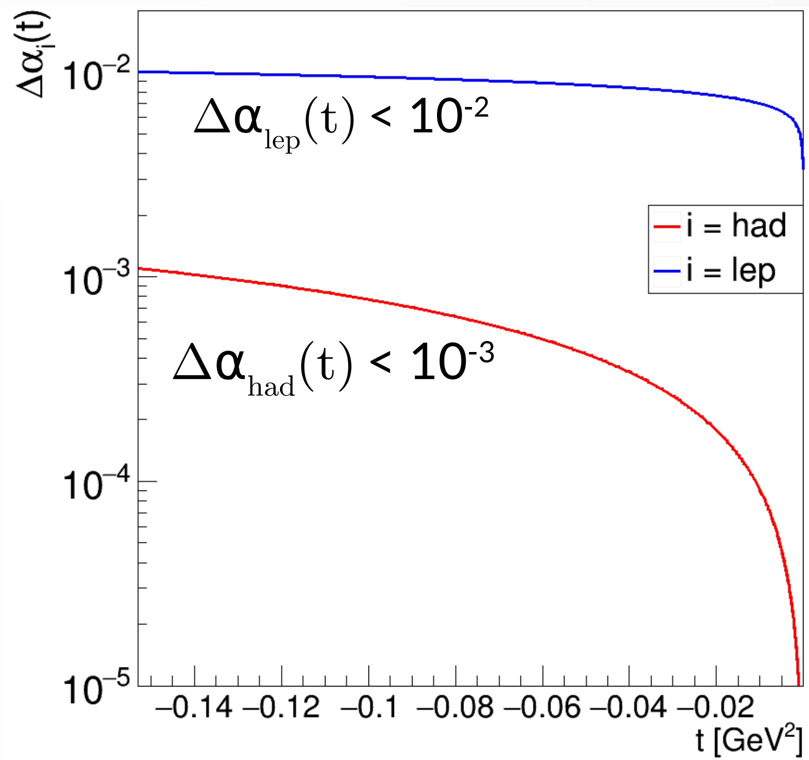
Phys. Rep. C 3 (1972), 193

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



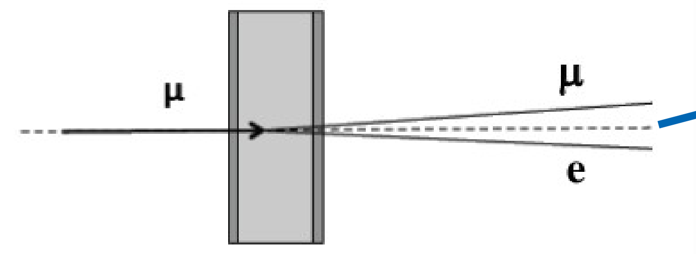
+ radiative corrections

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



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

Great effort of the theory community

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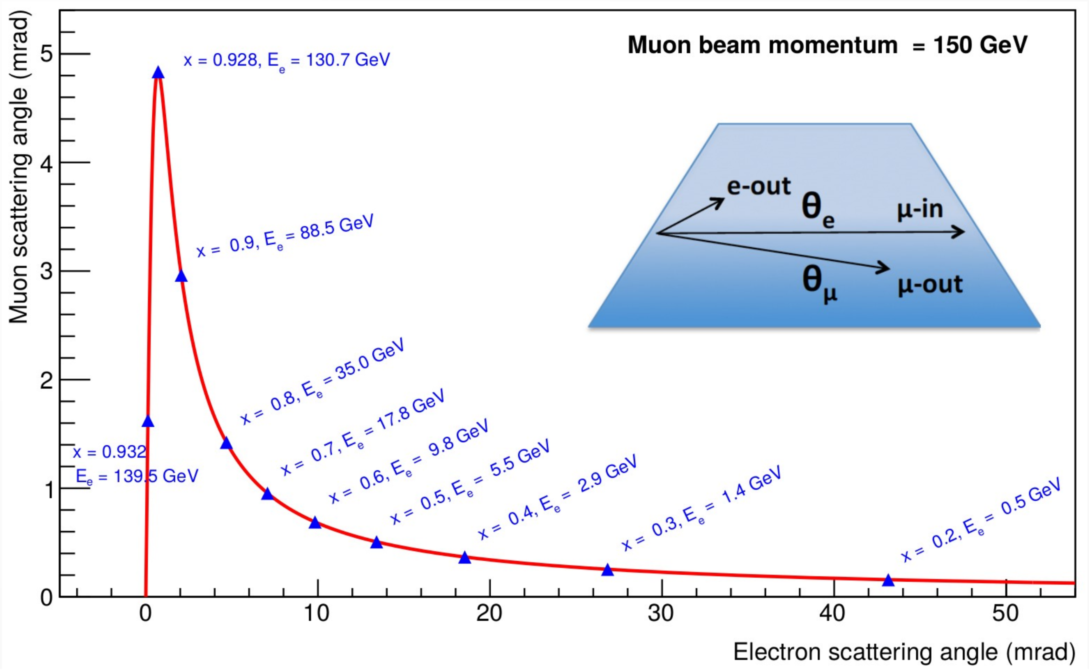
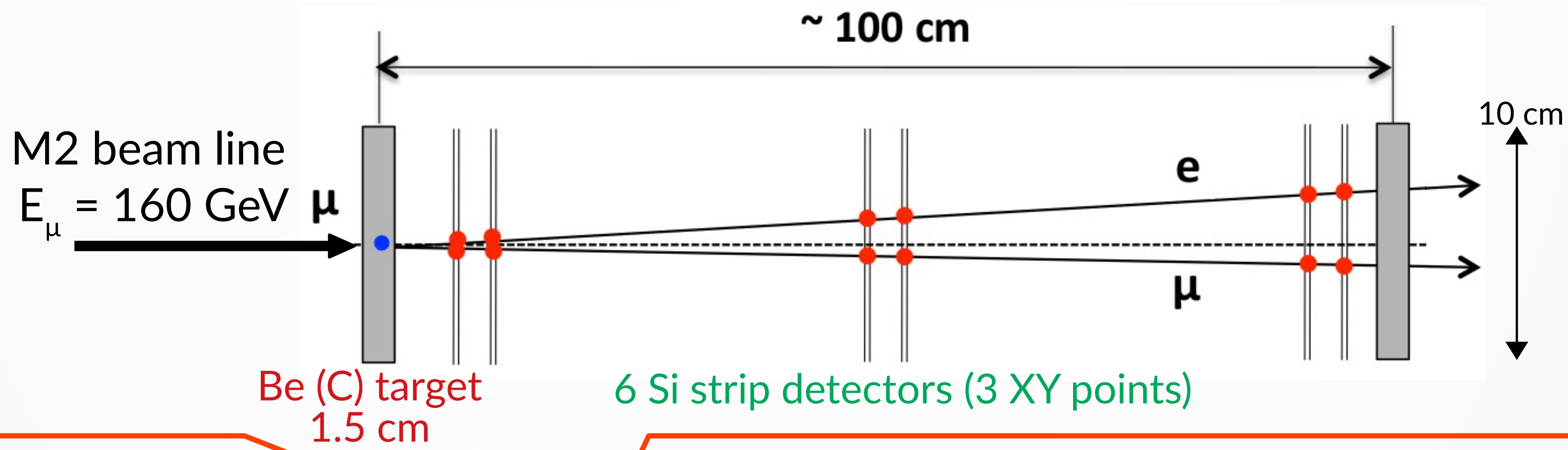
T. Dave
P. Petit Rosàs
T. Teubner
W. Torres Bobadilla

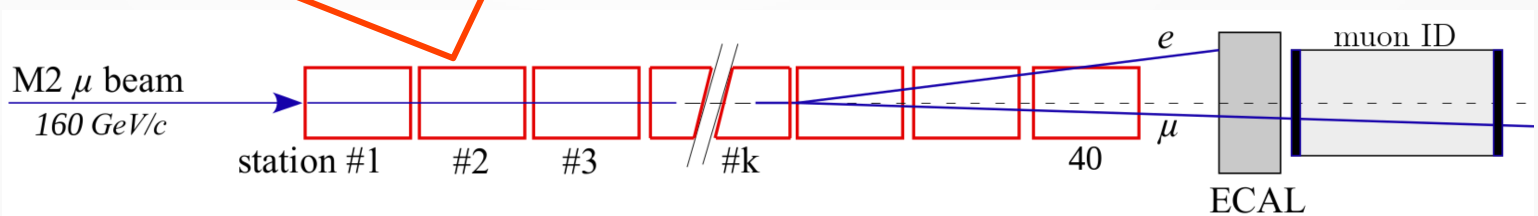
- Angular measurement: extract $\Delta\alpha_{had}(t)$ from the 2D distribution (θ_μ, θ_e).
- Correlation between θ_μ and θ_e allows to select elastic events and reject background (main source: $\mu N \to \mu N e^+e^-$).
- Boosted kinematics: $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



The experimental apparatus



BMS ....



After LS3:
full apparatus
with 40 stations

Final goal:
provide a measurement of a_μ^{HLO} competitive
with the current results (~0.6% precision)

Extraction of a_μ^{HLO}

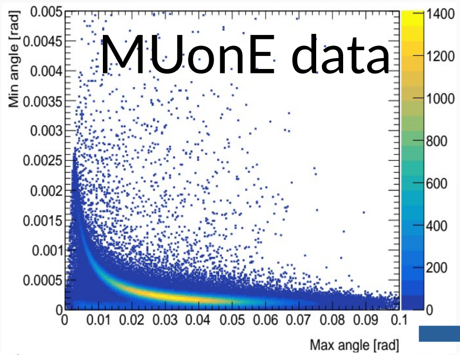
$\Delta\alpha_{had}(t)$ parameterization:

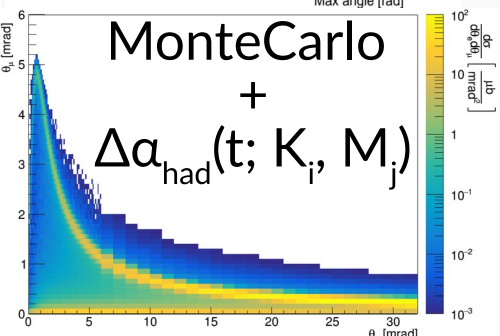
inspired from the 1 loop QED contribution of lepton pairs and *t*-quark at q^2<0

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

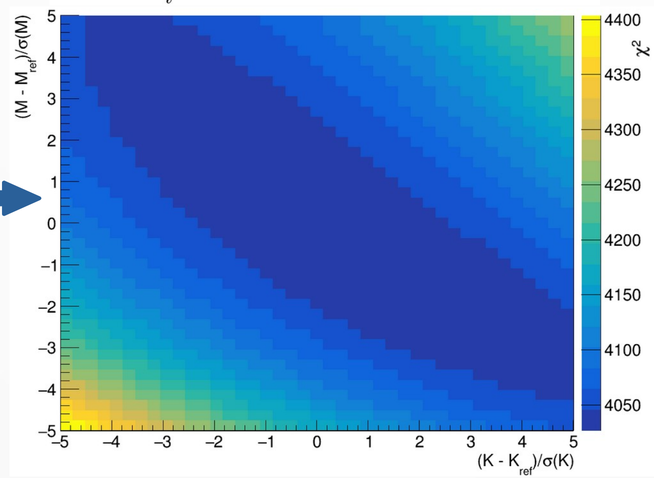
2 parameters:
K, M

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





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



(K_{best}, M_{best})

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

Alternative method to compute $a_\mu^{\rm HLO}$ from MUonE data

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

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

MUonE 99%

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

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

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

Time-like data + pQCD 1%

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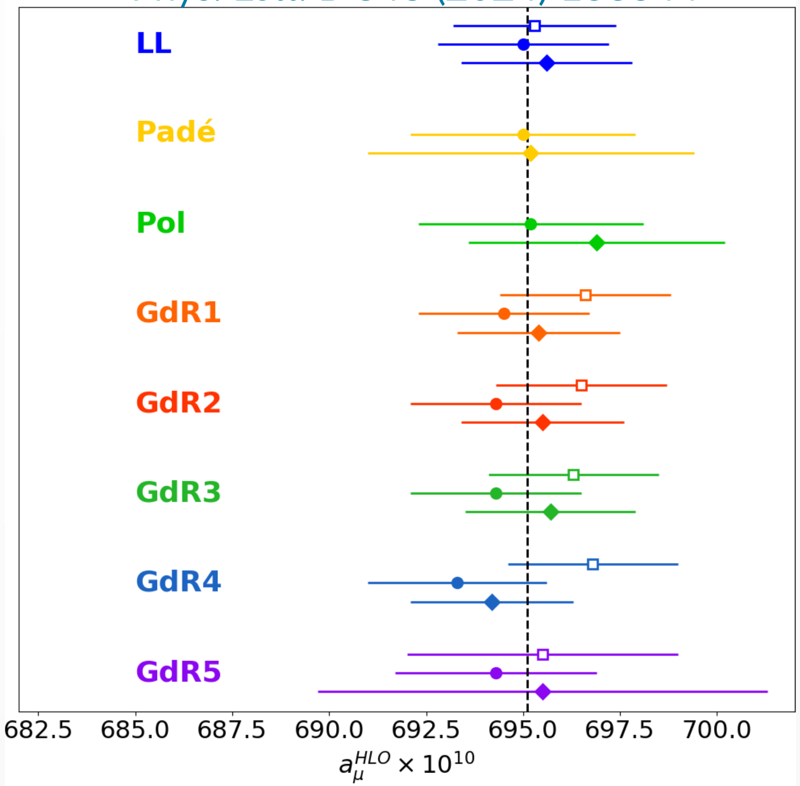
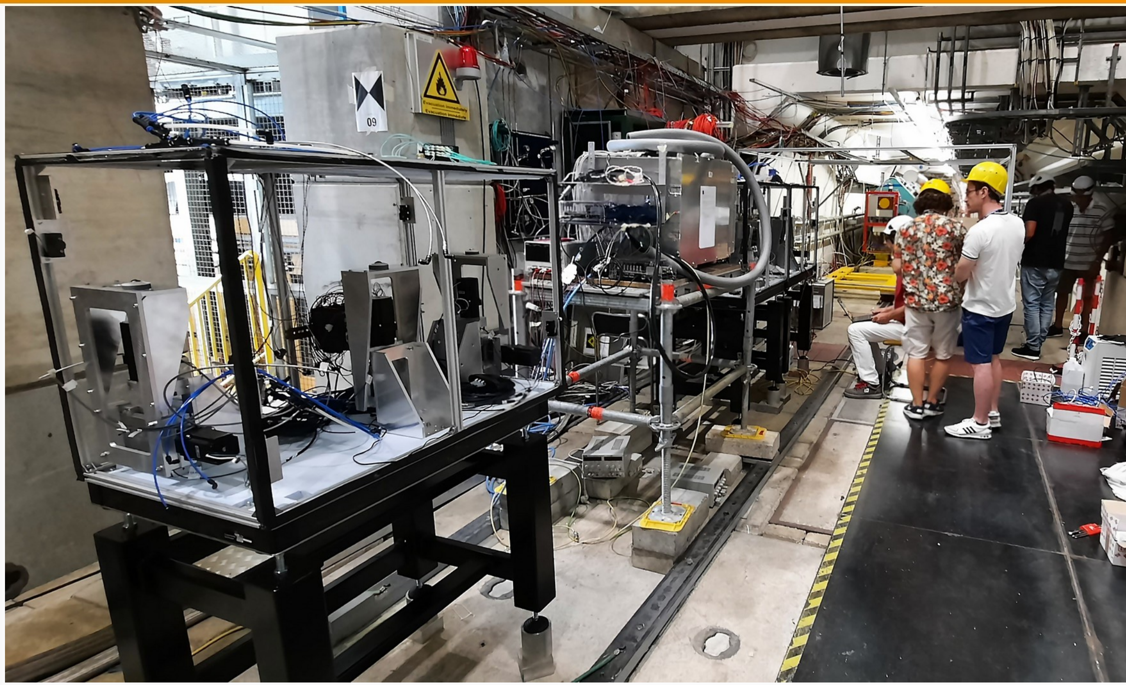
F. Ignatov, RP, T. Teubner, G. Venanzoni

Phys. Lett. B 848 (2024) 138344

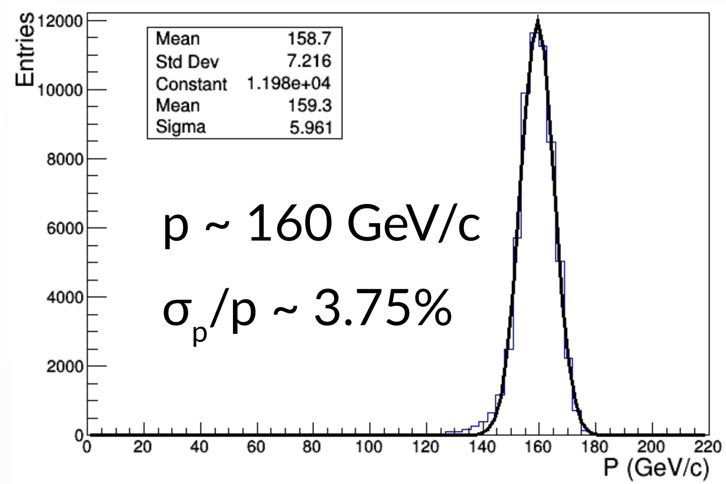


Competitive results independently of the $\Delta\alpha_{had}(t)$ fit function

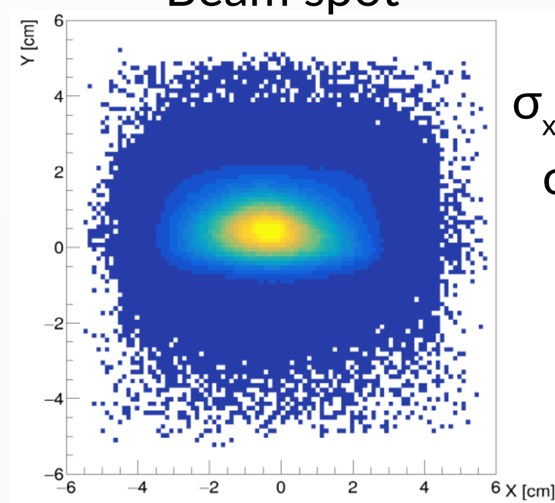
The M2 beamline



Beam momentum



Beam spot



σ_x ~ 13 mm

σ_y ~ 7 mm

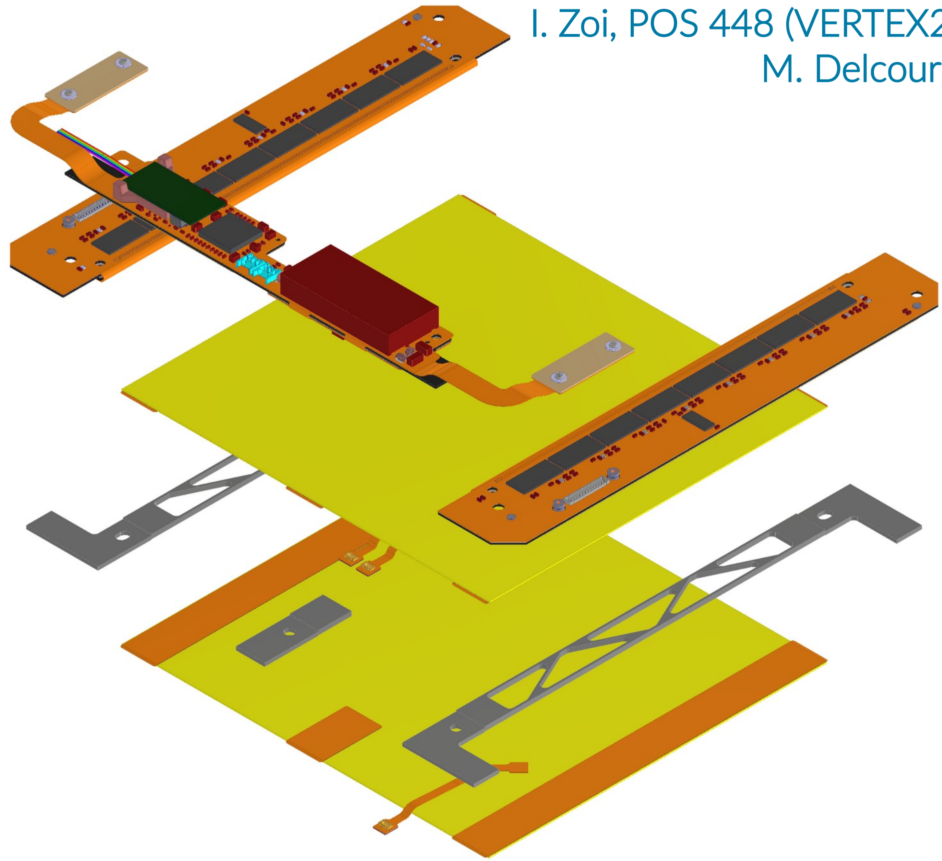
- MUonE location:
  upstream of the AMBER detector (EHN2).
- Low divergence muon beam: $\sigma_{x'}$, $\sigma_{y'}$ < 1 mrad.
- Spill duration ~5 s. Duty cycle ~ 25%.
- Maximum rate: **50 MHz** (~ 2×10^8 μ^+/spill).

Tracker: CMS 2S modules

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

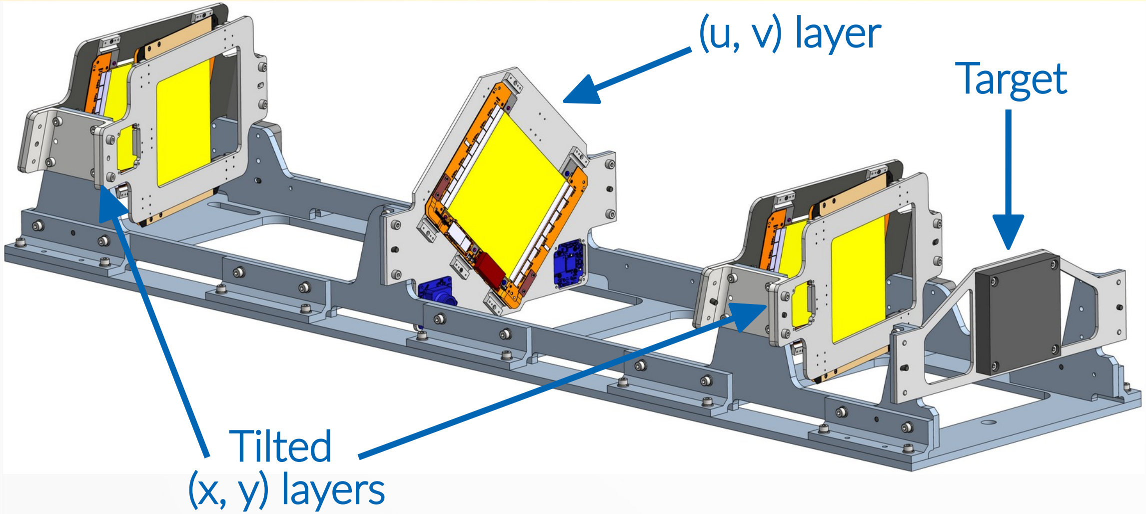
TDR CMS Tracker Phase2 Upgrade
I. Zoi, POS 448 (VERTEX2023), 021
M. Delcourt, BTTB12

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



- Readout rate: 40 MHz. Adequate to sustain the maximum beam rate of ~50 MHz.
- Area: 10×10 cm^2 (~90 cm^2 active).
- Digital readout, 90 µm pitch: ~26 µm resolution.
- Thickness: 2 × 320 µm.

Tracking station

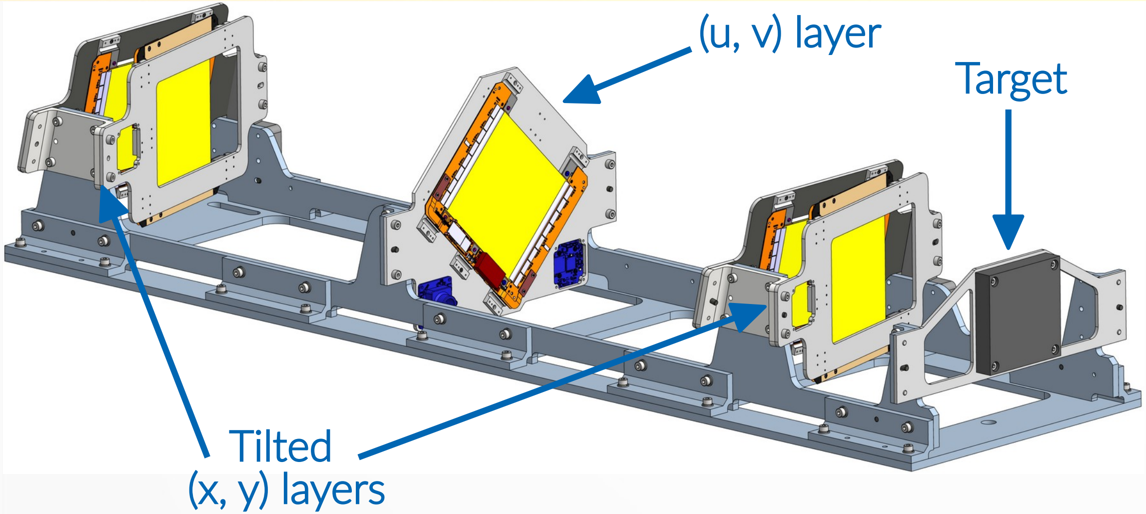


Stringent request:
relative position within a station
must be stable < 10 µm.

Low CTE material: INVAR

- Alloy: 65% Fe + 35% Ni
- CTE ~ 1.2 ppm/K

Tracking station



Stringent request:
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↓

Low CTE material: INVAR

- Alloy: 65% Fe + 35% Ni
- CTE ~ 1.2 ppm/K

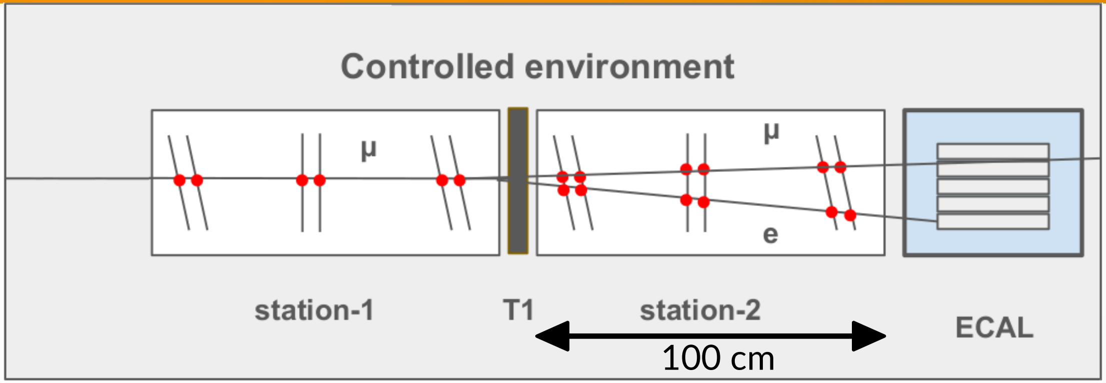
G. Cacciola
K. Ferraby
T. Bowcock
T. Jones

New layout under development at Liverpool: Carbon fiber

- Light material
- CTE < 1 ppm/K
- Lower cost
- Easy to machine

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.

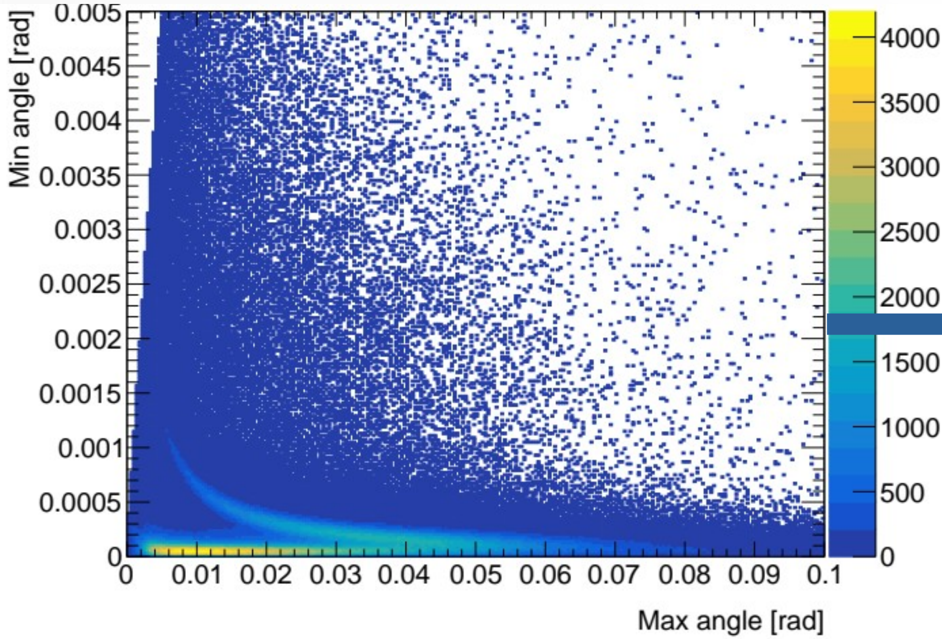
Data analysis: Liverpool is the leading group!

- Test the detector performance, reconstruction algorithms and event selection.
- Study background and main sources of systematic error.
- Goal: measure $\Delta\alpha_{lep}(t)$ with $O(5\%)$ stat. accuracy.

TB 2023
μ-e elastic scattering event selection

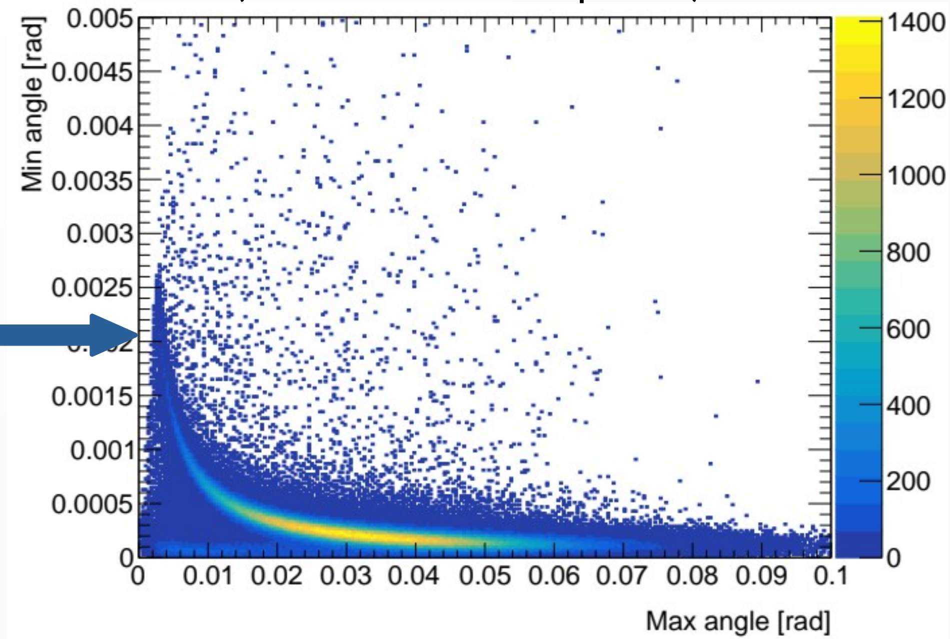
Pre-selection

- Single μ_{in} candidate.
- 2 outgoing tracks (μ_{out}, e_{out} candidates).



Initial selection

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



Liverpool Analysis Group:

G. Cacciola, S. Charity, C. Devanne, K. Ferraby, F. Ignatov, RP, G. Venanzoni, C. Zhang

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

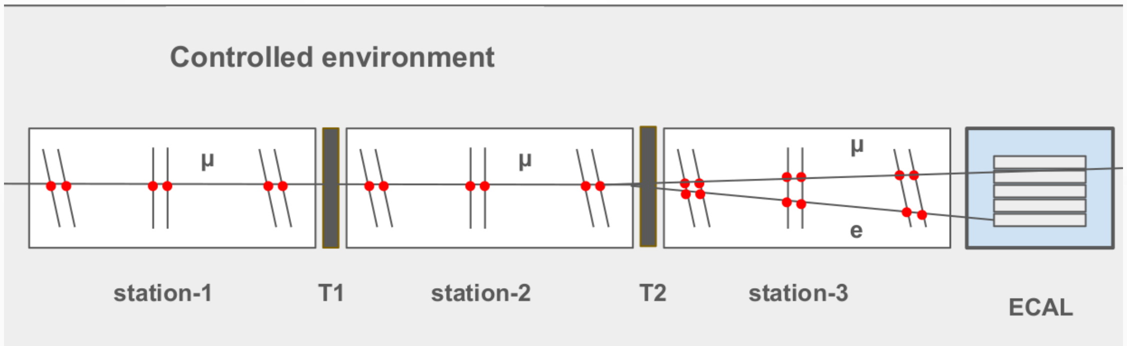
CERN

April 25, 2024

Proposal for phase 1 of the MUonE Experiment

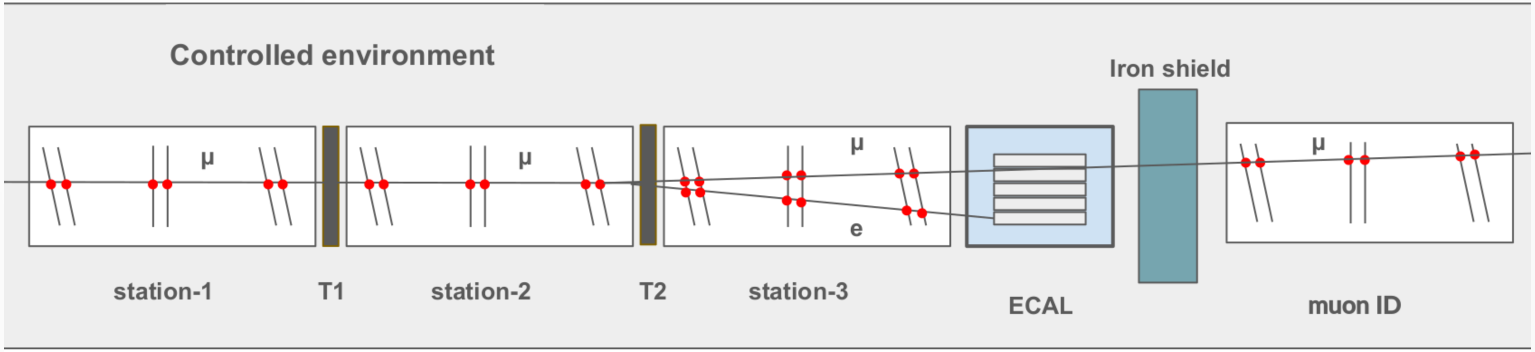
The MUonE Collaboration

Run 2025: the apparatus



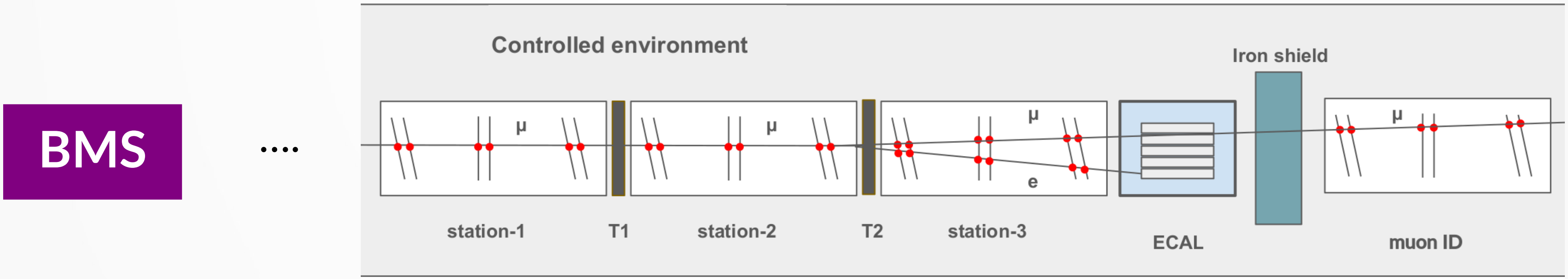
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.

Run 2025: the apparatus



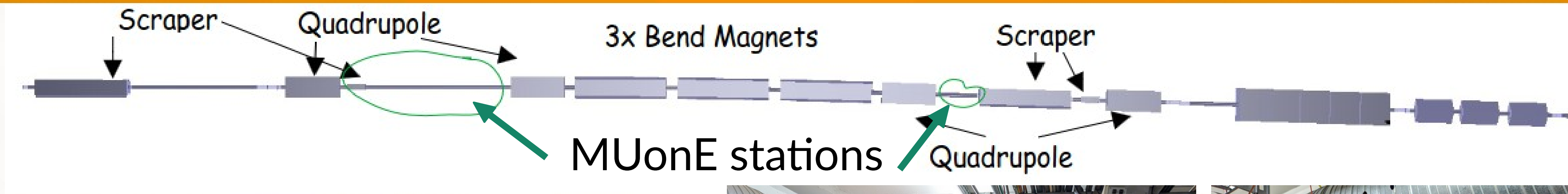
- 3 tracking stations.
- 2 graphite targets
  (2 cm thickness each).
- ECAL:
  - Full acceptance
    for interactions in both targets.
  - Provide independent measurements
    of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).

Run 2025: the apparatus

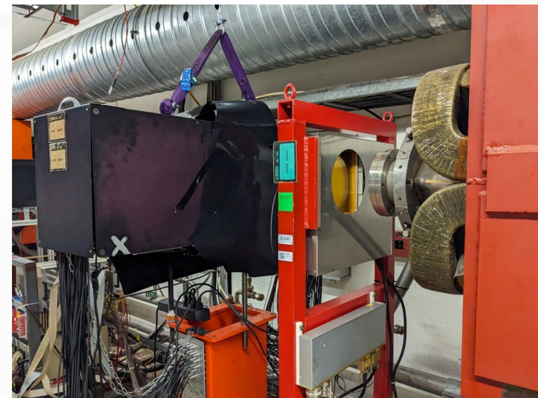


- 3 tracking stations.
- 2 graphite targets (2 cm thickness each).
- ECAL:
  - Full acceptance for interactions in both targets.
  - Provide independent measurements of the process kinematics.
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).
- BMS:
  - Event-by-event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



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- Mechanics.
- Simulation and analysis.

Longer term tasks:

- Magnetic field measurement.
- Development of new Si sensors.

T. Bowcock
S. Charity
F. Ignatov
G. Venanzoni

Run 2025: goals

- **Detector operations:**
  - Assemble a system containing all the basic elements of the final system.
  - Prove the capability of the DAQ to synchronize all the sub-detectors and operate efficiently in the 4 weeks run.

- **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

Exciting times for MUonE:

- Test beam 2023 analysis:
  first opportunity to study elastic scattering with a minimal setup.
- Recently submitted a proposal for MUonE phase 1
  (4 weeks of data taking in 2025).
- Great contribution of the Liverpool group:

  PhD students: G. Cacciola, C. Devanne, K. Ferraby.

  Staff: T. Bowcock, J. Carroll, S. Charity, A. Greenall, F. Ignatov,
  T. Jones, R. Pilato, T. Smith, G. Venanzoni, J. Vossebeld, C. Zhang.

  Theory:

  PhD students: T. Dave, P. Petit Rosàs.

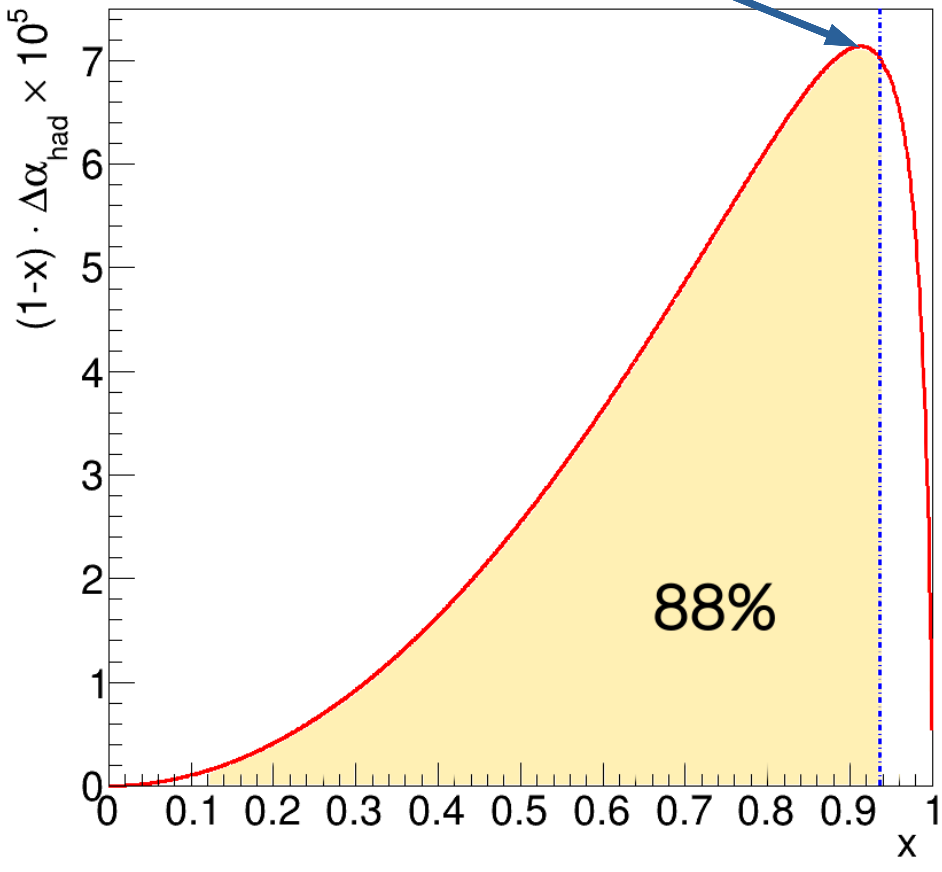
  Staff: T. Teubner, W. Torres Bobadilla.

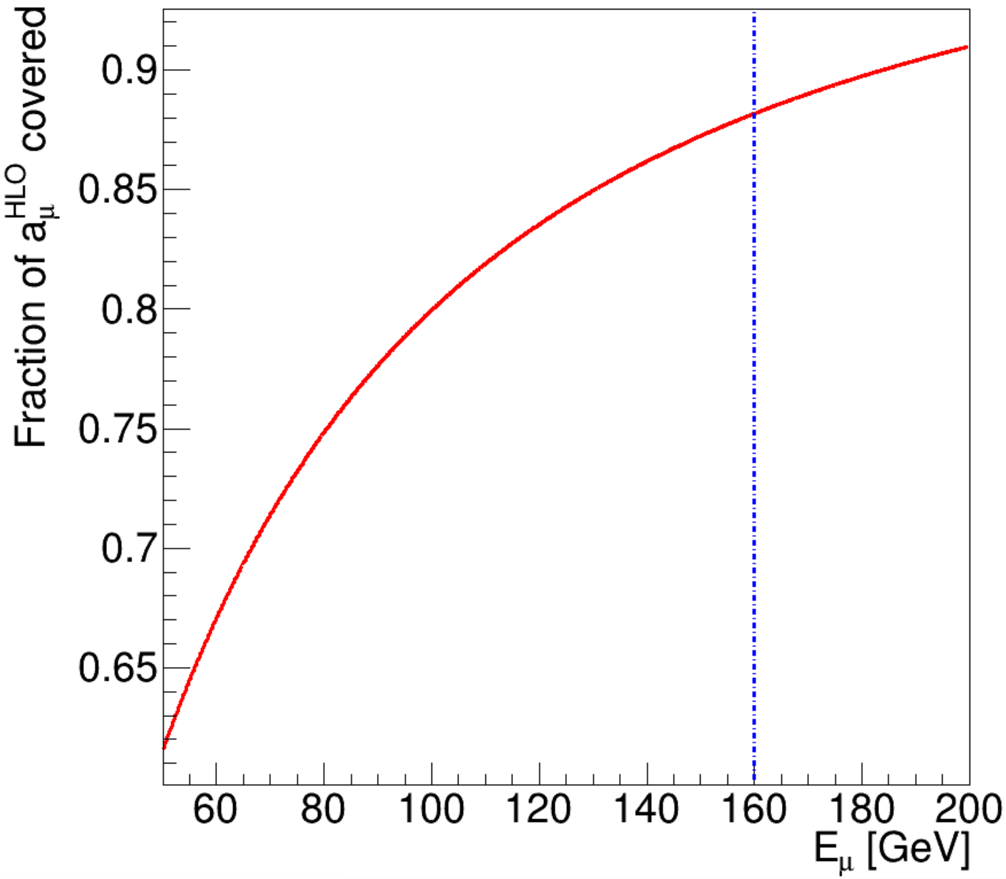
BACKUP

$x < 0.936$

t_{peak} ~ -0.108 GeV^2

x_{peak} ~ 0.92



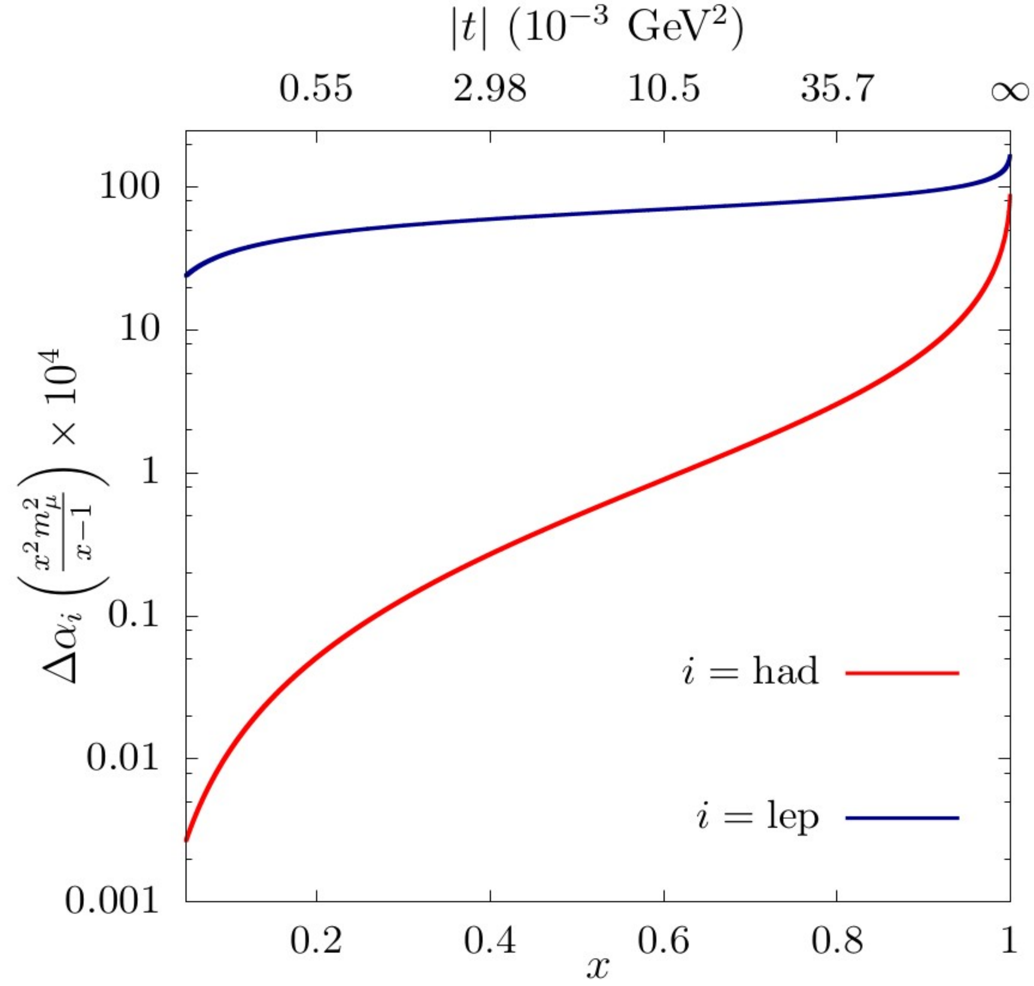


- 160 GeV muon beam on atomic electrons.

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

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

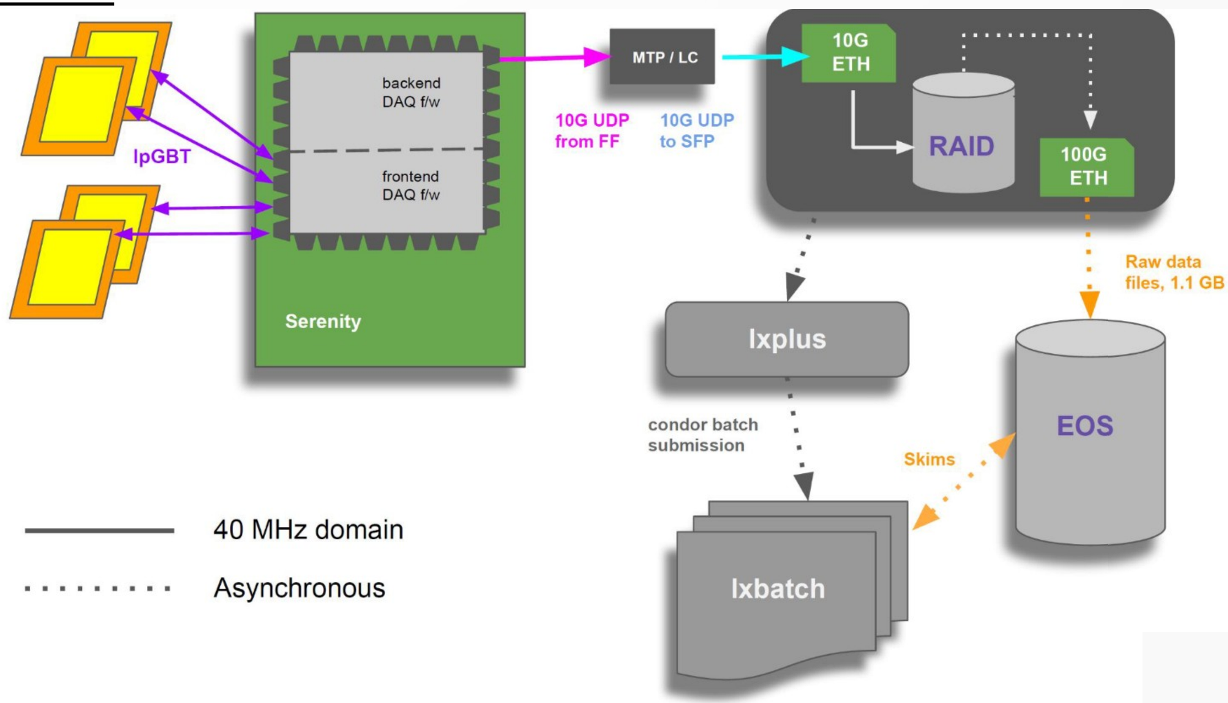
$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



DAQ system

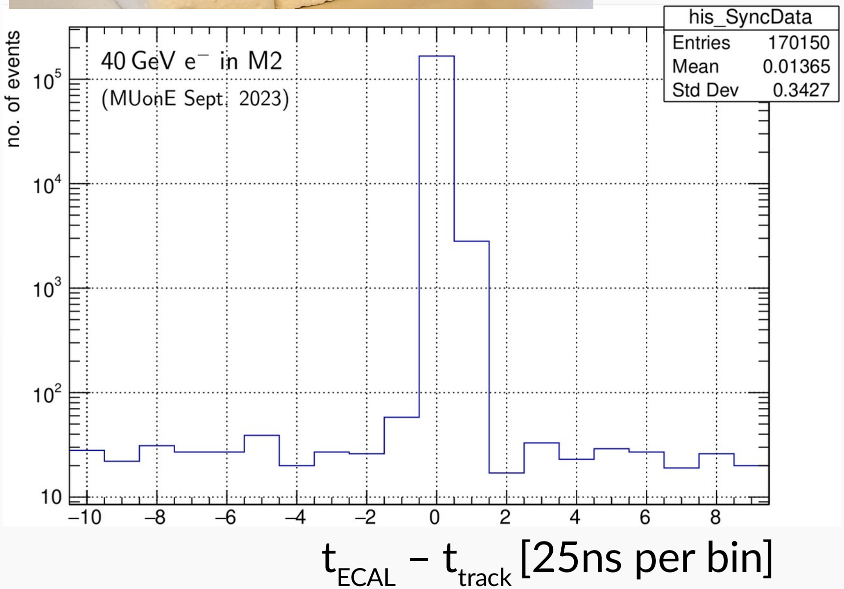
Frontend control and readout via Serenity board
(developed for the CMS-Phase2 upgrade).

- 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.

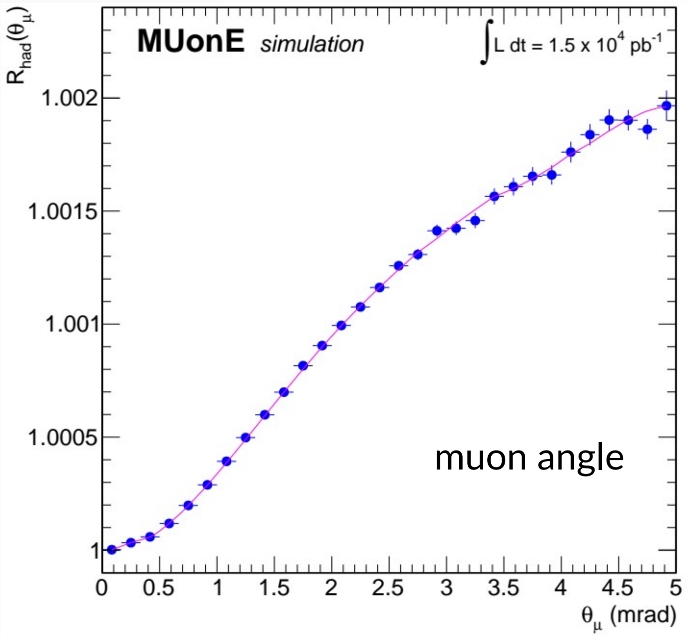


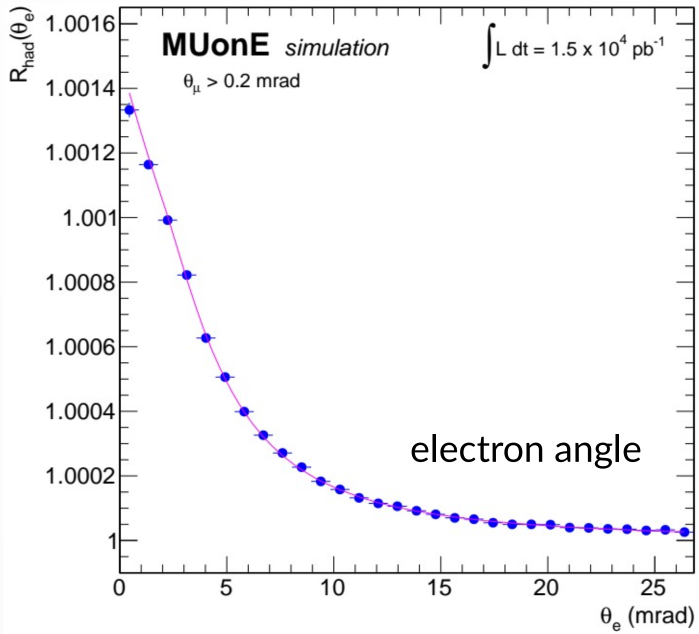
Calorimeter

- 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.



Extraction of a_μ^{HLO}





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

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

Input value:

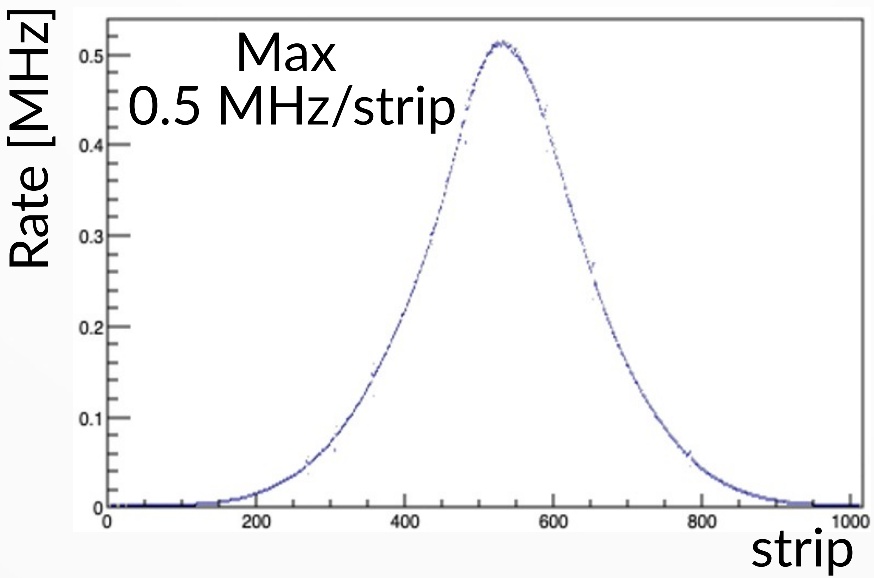
$$a_\mu^{\text{HLO}} = 688.6\ 10^{-10}$$

TB 2023

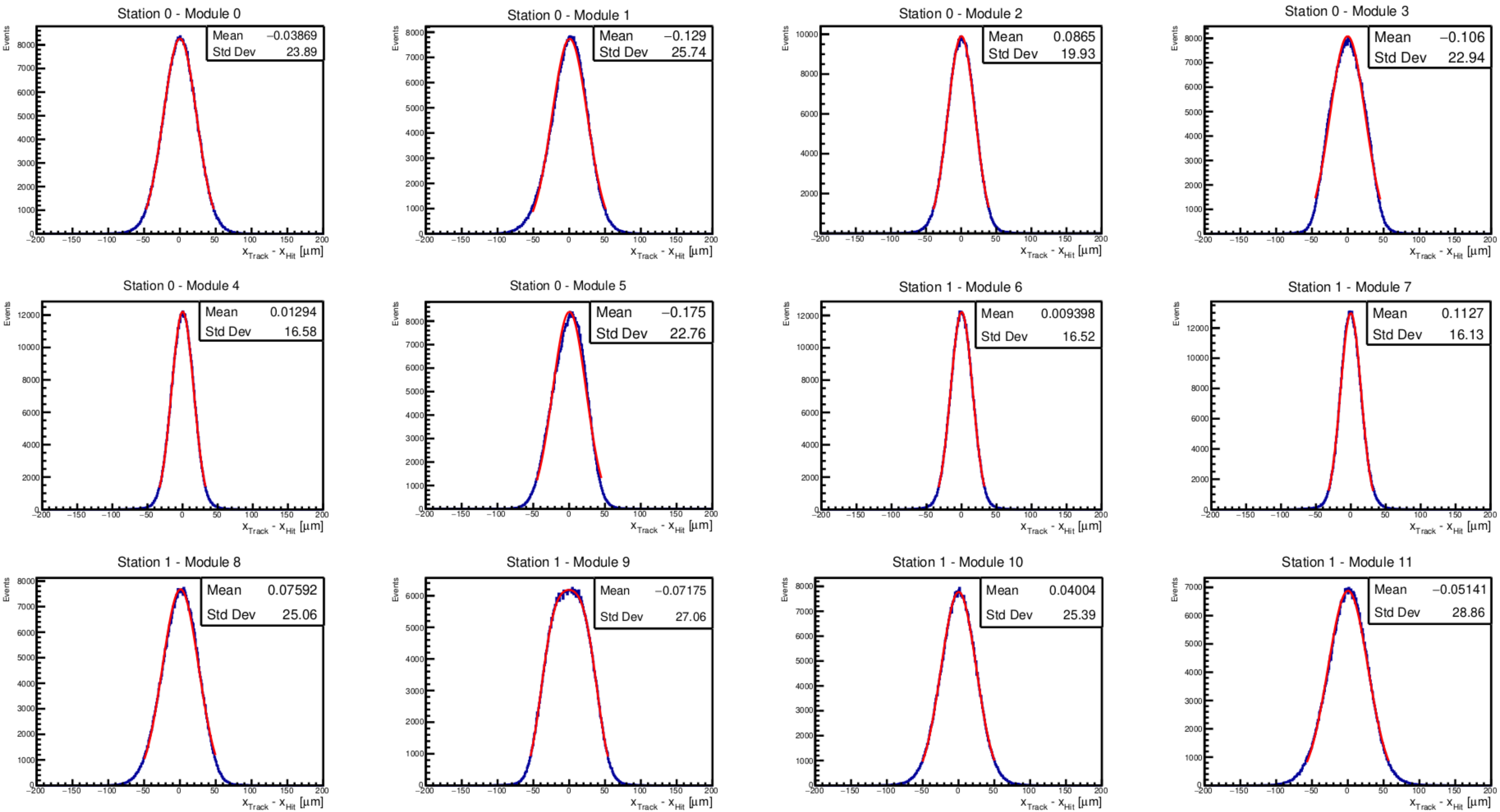
Beam rate

~2×10^{8} μ/spill

(1 spill = ~5s)

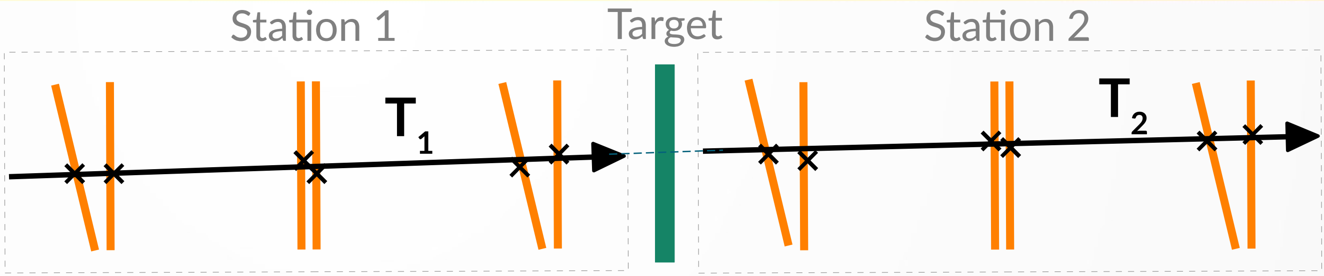


Alignment – TB 2023

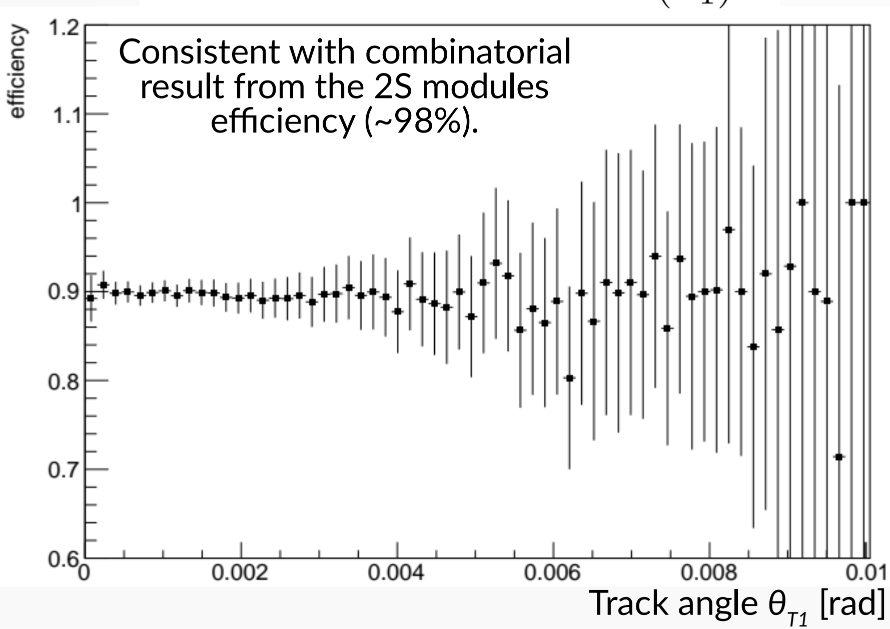


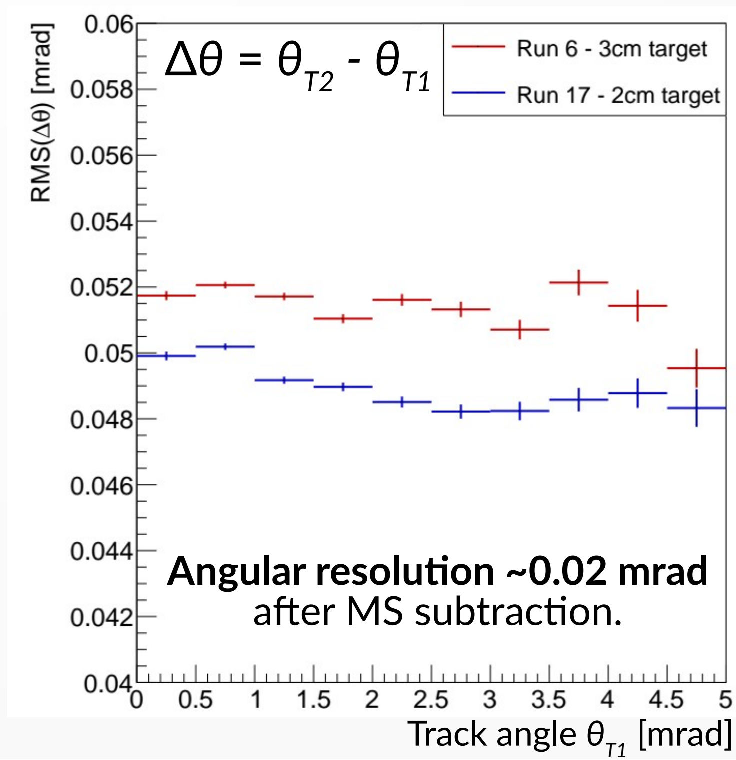
TB 2023 - tracking performance: efficiency and angular resolution

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



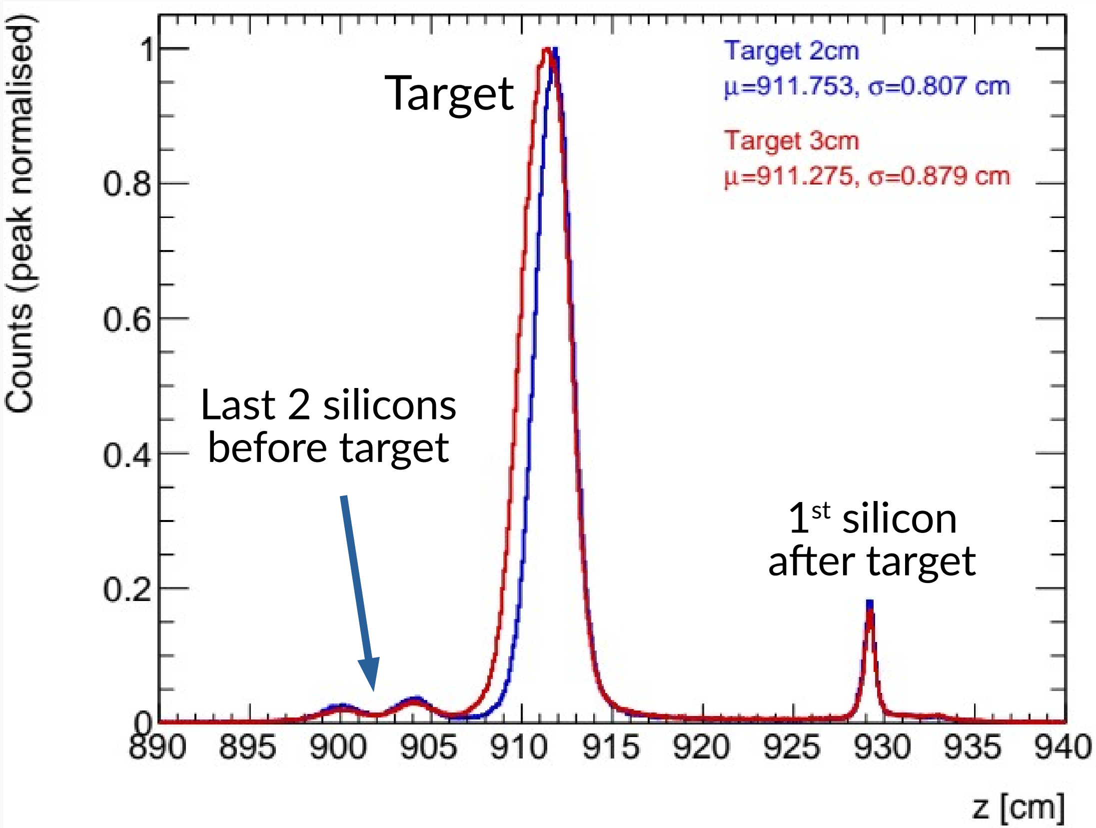
$$\text{Tracking efficiency} = \frac{N(T_2 \cdot T_1)}{N(T_1)}$$





Vertexing

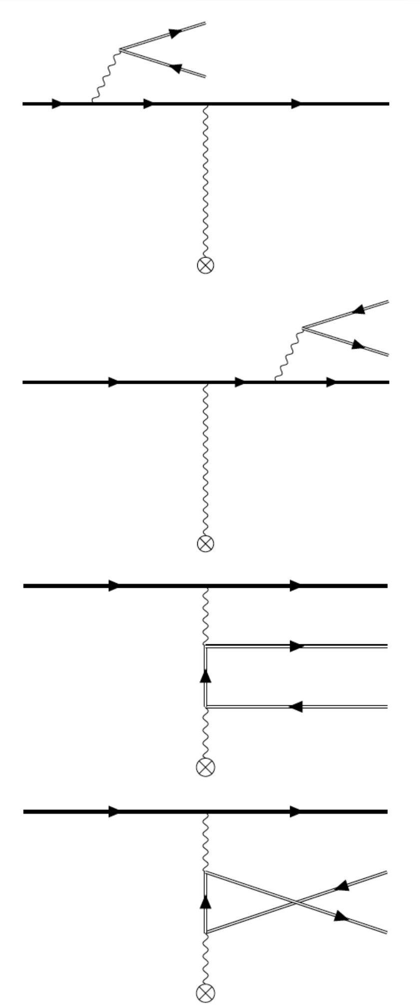
Simple selection: events with 2 outgoing tracks within geometrical acceptance (0.2 – 32 mrad).



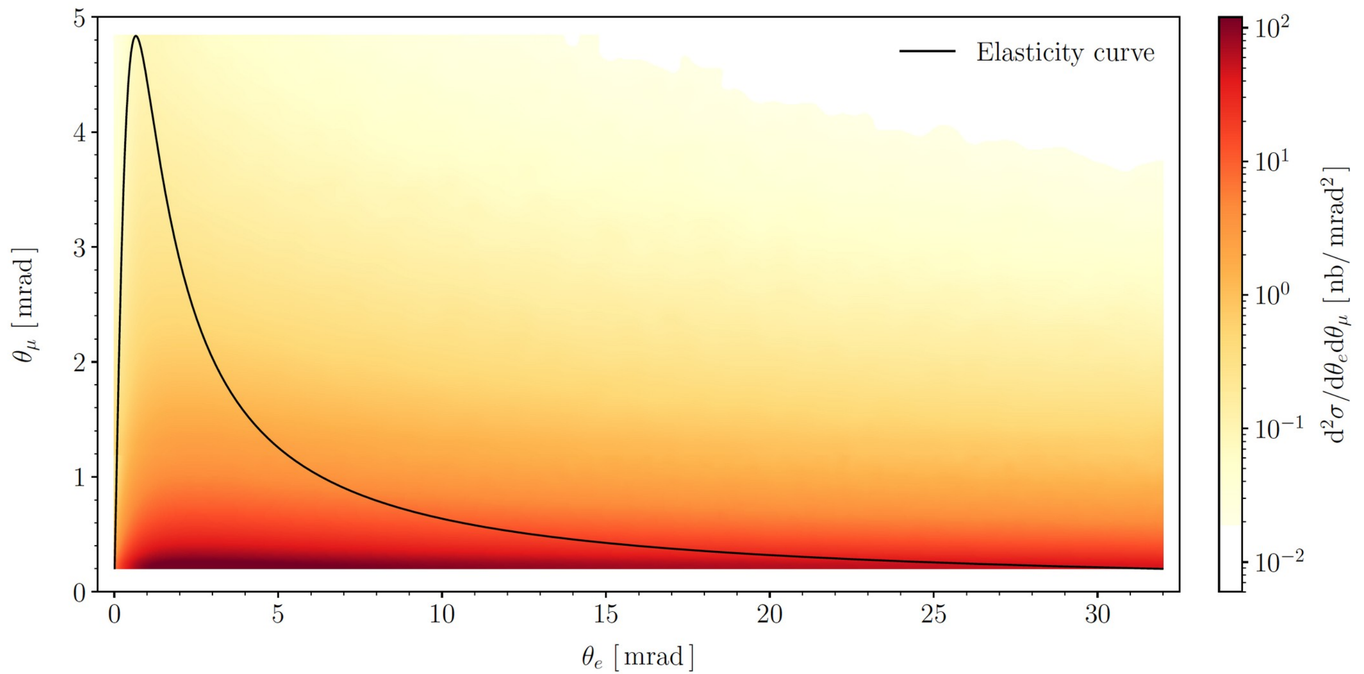
- The target center is shifted by 0.5 cm by changing between 3cm and 2cm target (OK!).
- **Vertex resolution: ~0.8 cm**. (Slightly worse for 3cm target due to MS).

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)

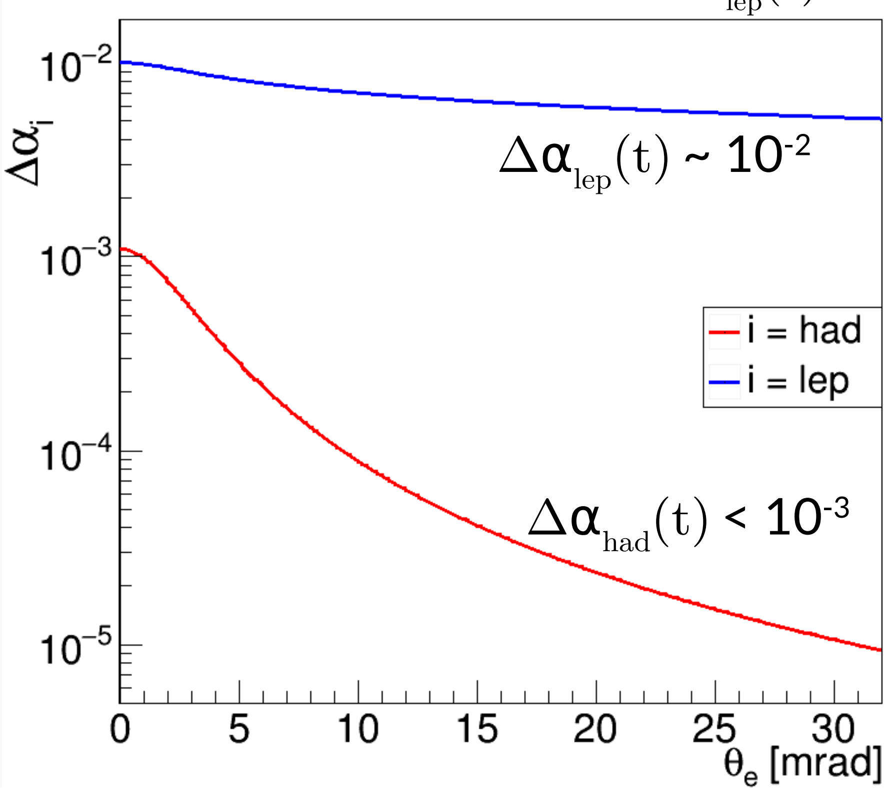


TB 2023 - extraction of $\Delta\alpha_{lep}(t)$: expectations

O(10^{12}) μ on target, expected ~2.5×10^{8} elastic events E_e > 1 GeV

Not enough for $\Delta\alpha_{had}(t)$,

but we can measure $\Delta\alpha_{lep}(t)$



1 loop QED contribution of lepton pairs:

$$\Delta\alpha_{lep}(t) = k\left[f(m_e) + f(m_\mu) + f(m_\tau)\right]$$

$$f(m) = -\frac{5}{9} - \frac{4}{3}\frac{m^2}{t} + \left(\frac{4}{3}\frac{m^4}{t^2} + \frac{m^2}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4m^2}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4m^2}{t}}}{1+\sqrt{1-\frac{4m^2}{t}}}\right|$$

1 parameter template fit:
Fix lepton masses and fit k

$$k = \frac{\alpha}{\pi}$$

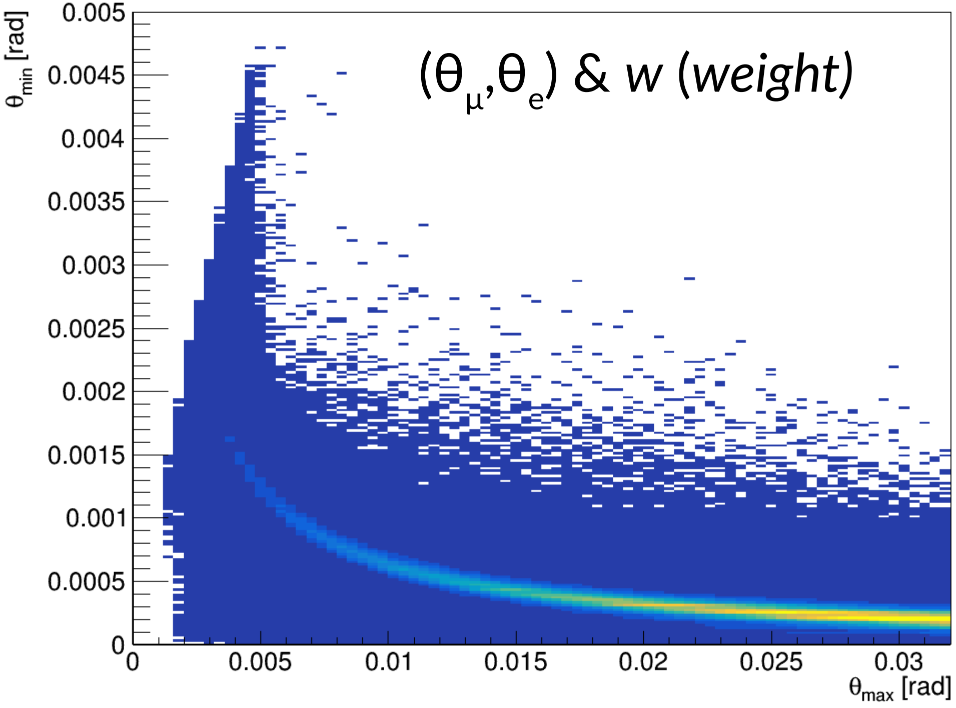
Expected precision: ~5%

Studied on fast simulation neglecting background.

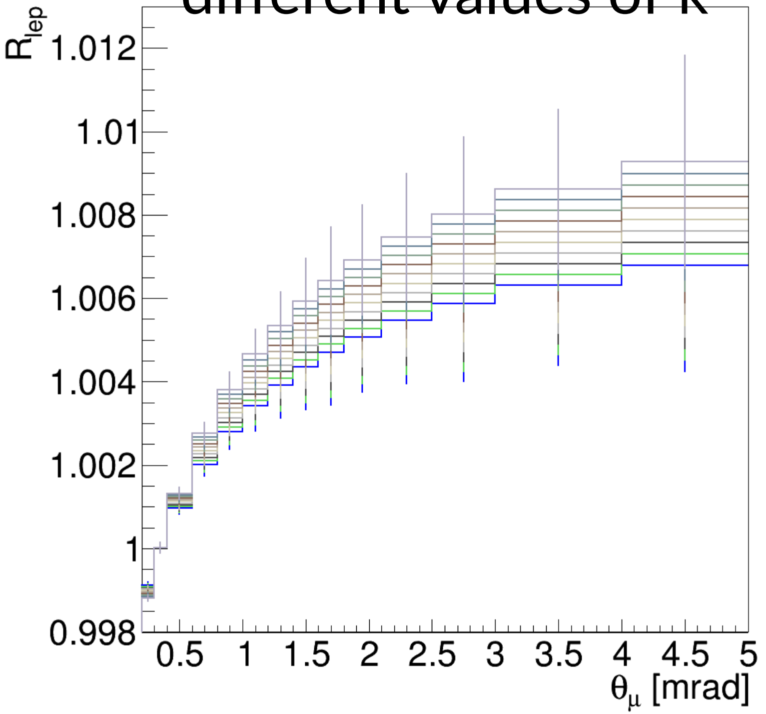
Production of Monte Carlo templates

FairMUonE → **Reweighting** (θ_μ,θ_e) & $w \rightarrow w(k_i)$

- Geant4 simulation
- Track reconstruction

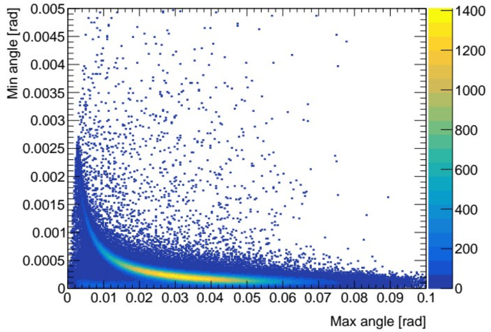


Templates for different values of k

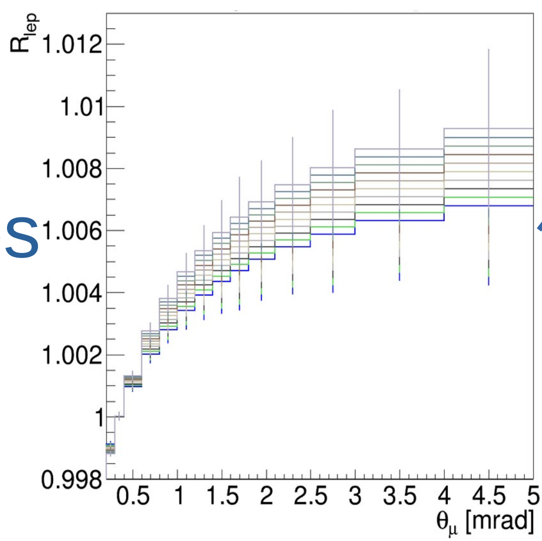


Analysis workflow

Data



Monte Carlo templates



combine

Take into account systematic effects

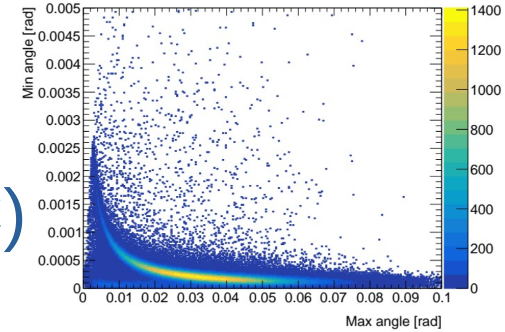
Likelihood/χ^2 fit

Data vs each template

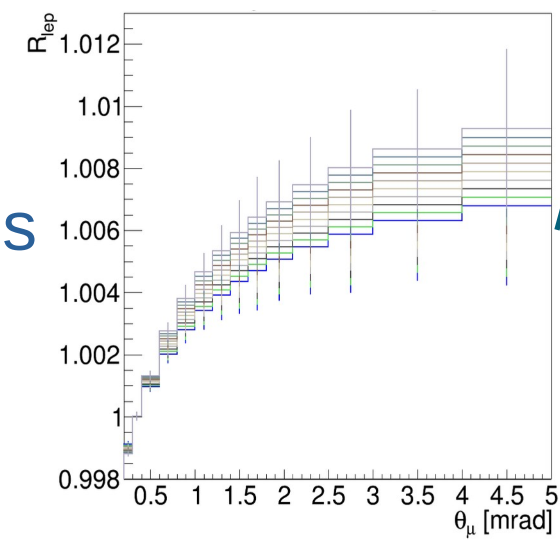
$k_{best} \pm \Delta k$

Test using pseudodata (Monte Carlo)

Pseudo data (MC)



Monte Carlo templates

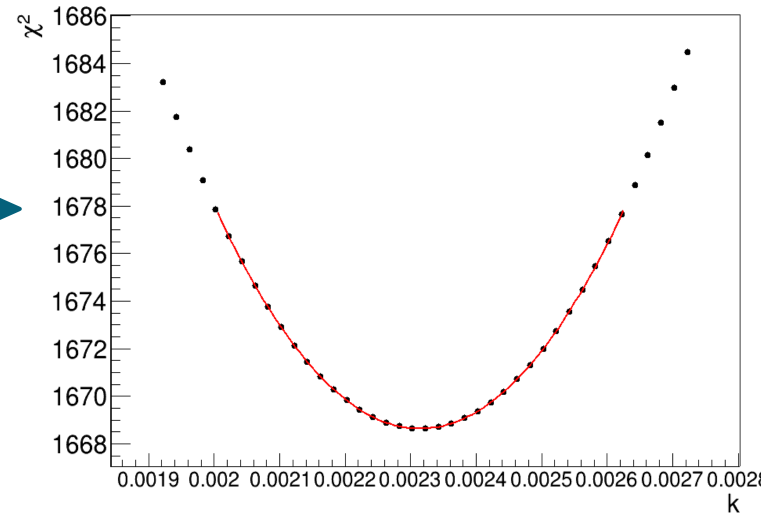


combine

Take into account systematic effects

Likelihood/χ^2 fit

Data vs each template

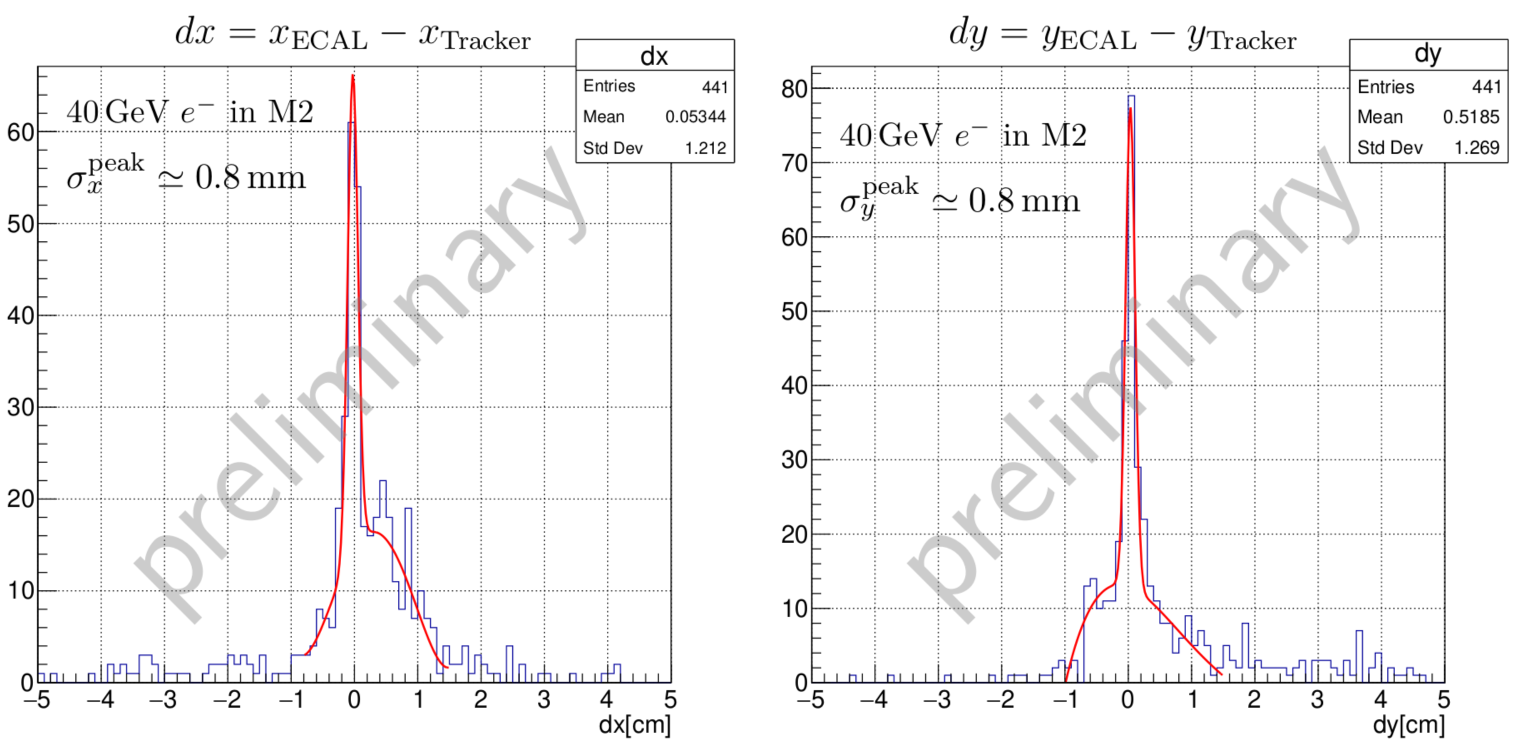


k_{best} = 0.00232(10) → ~5%

k_{input} = 0.00232

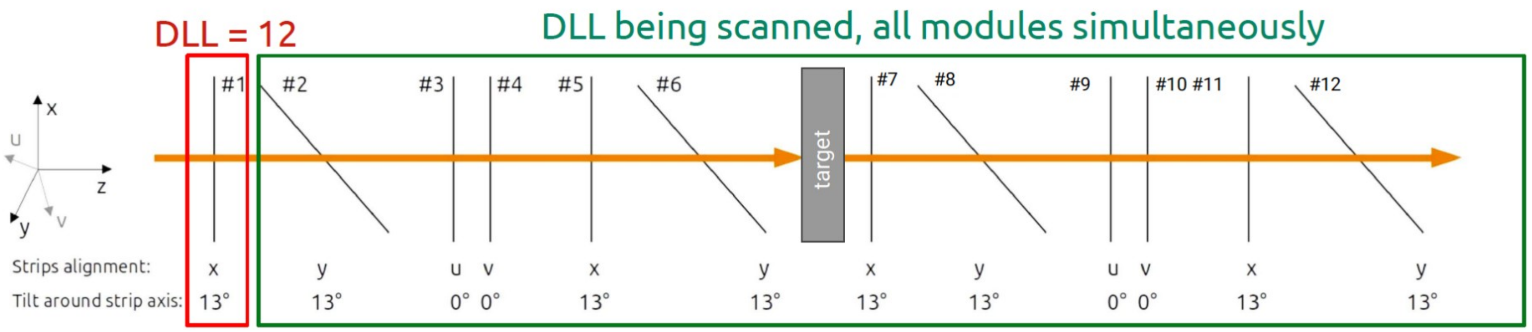
ECAL – spatial resolution

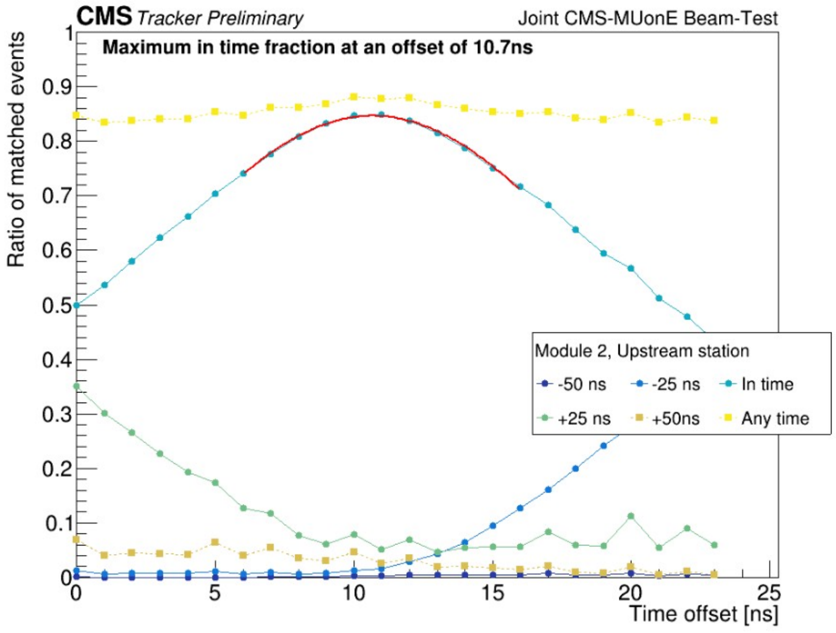
Sub-mm peak resolution in good agreement with simulations.

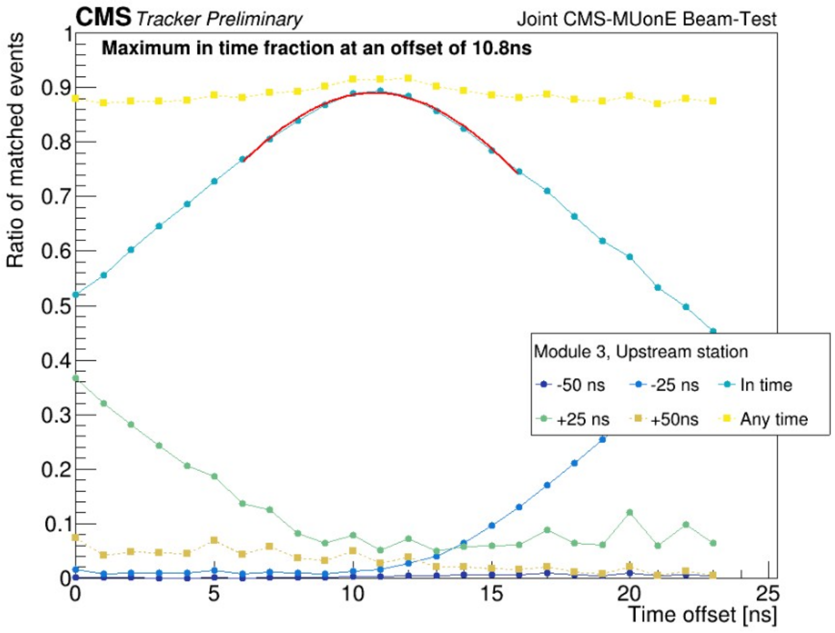


- Small sample (ECAL integrated in the main DAQ only at the end of the run).
- Technical issues limited ECAL data quality (now solved).

2S modules synchronization







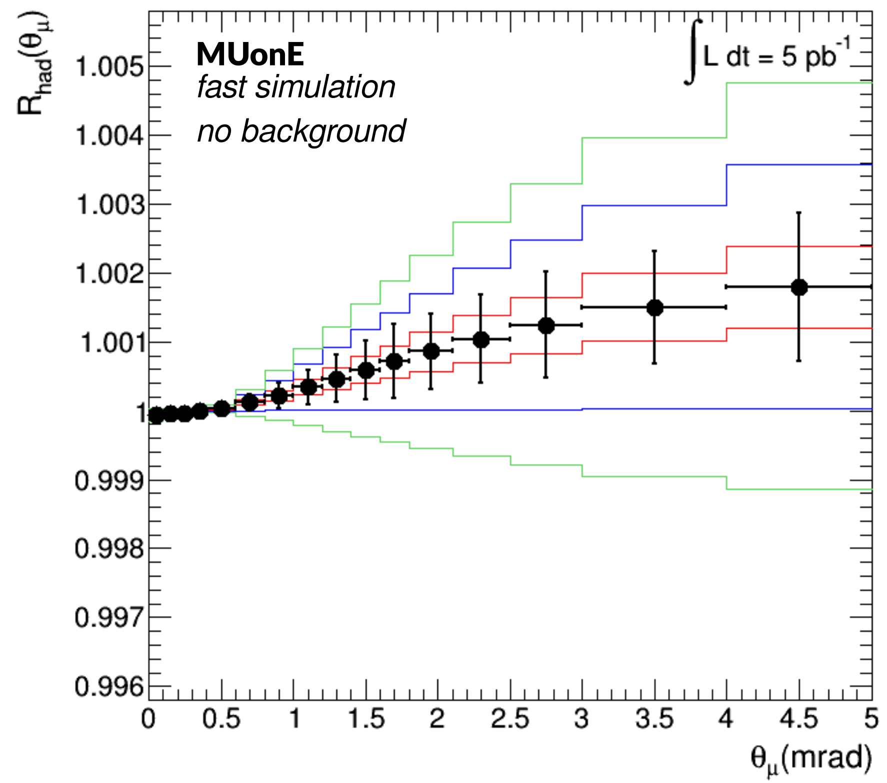
Compute the fraction of events with a hit in #1, if a hit is found in the DUT.

The relative timing of the modules can be determined (here ~0.1 ns between #2 and #3).

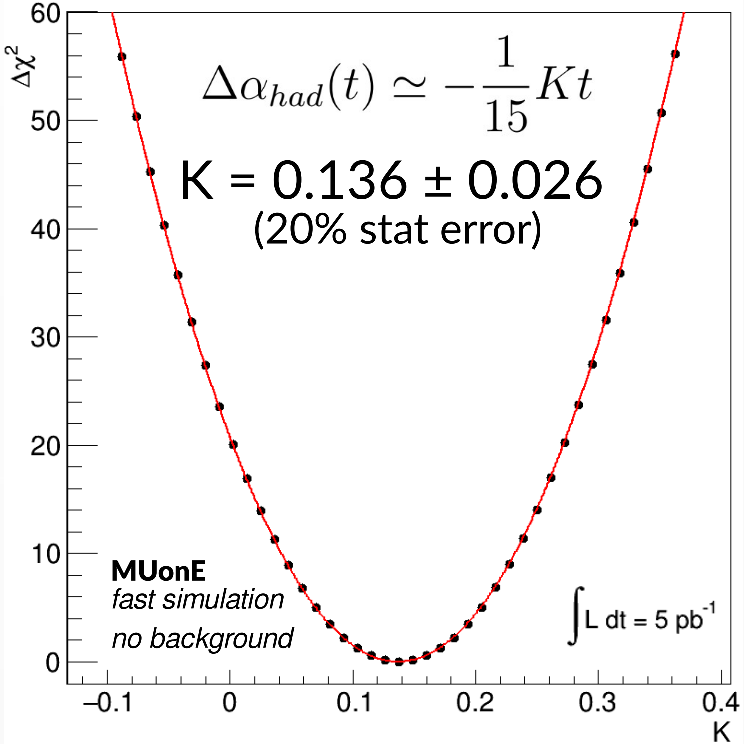
First measurement of $\Delta\alpha_{had}(t)$

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

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



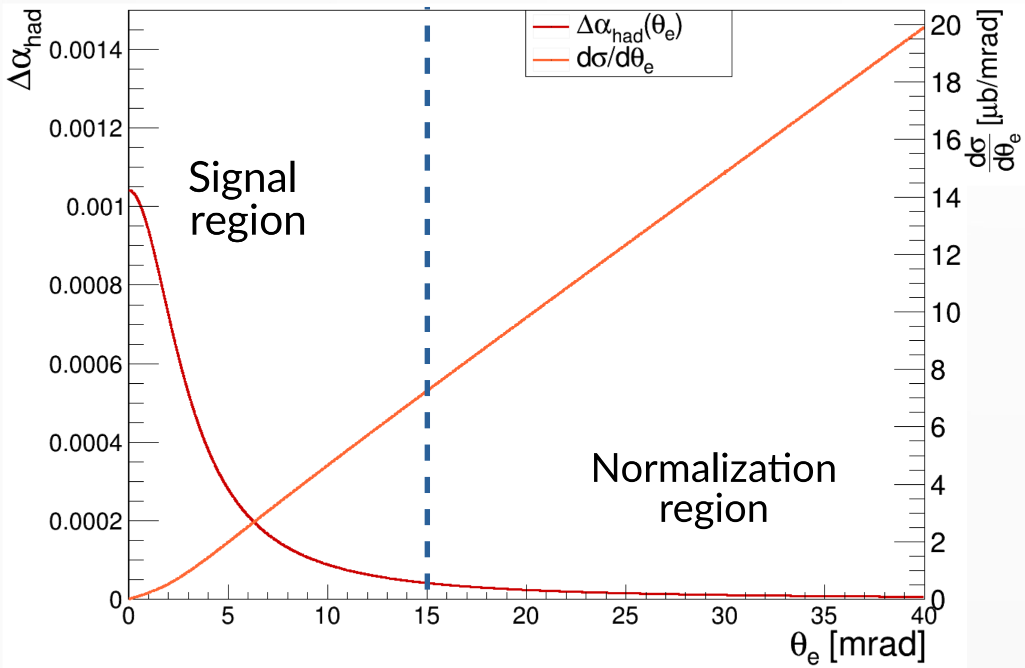
Template fit procedure
to extract $\Delta\alpha_{had}(t)$



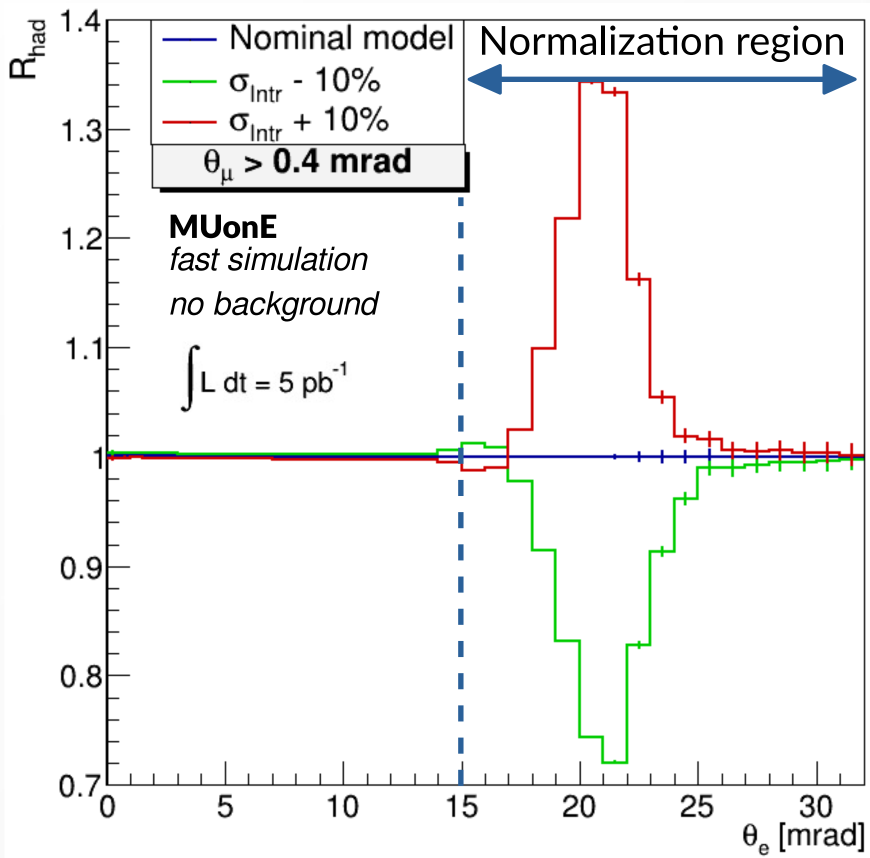
Systematic effects

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



The need of including systematic effects in the analysis

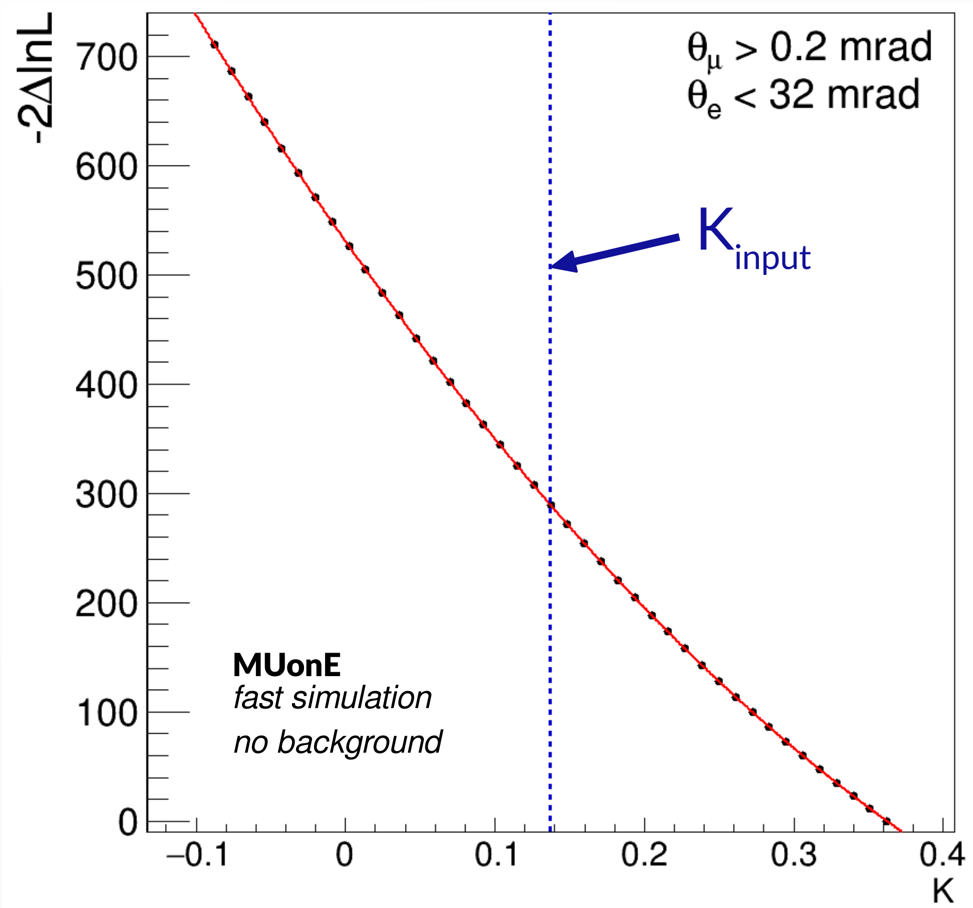
What if systematic effects are not included in the template fit?

Simplified situation:

- 1 fit parameter (K).

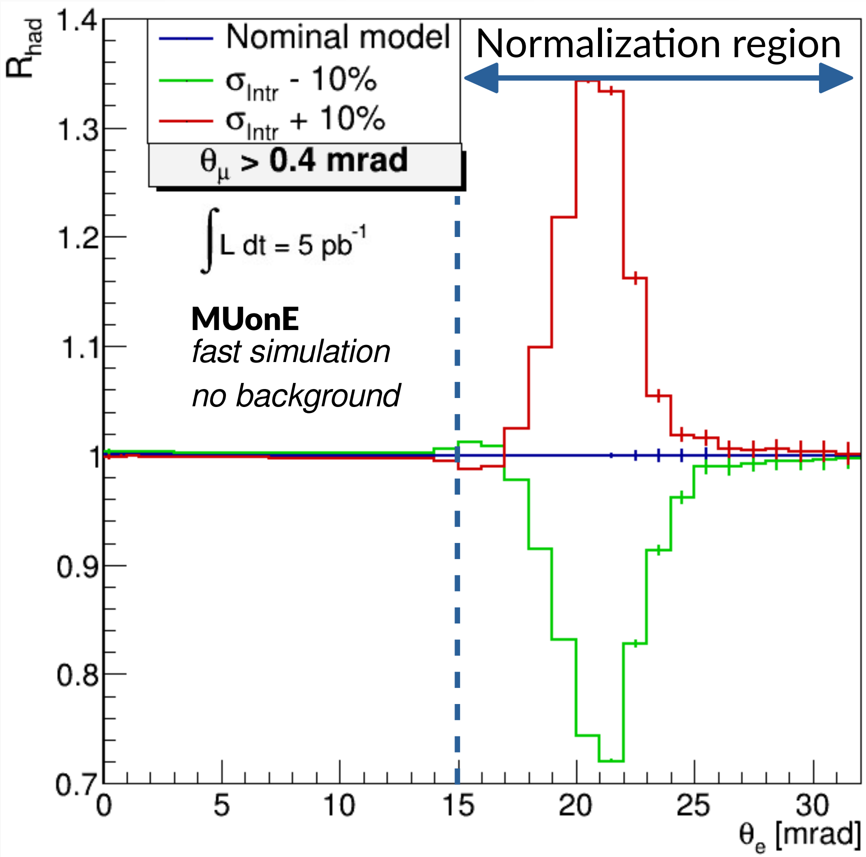
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}Kt$$

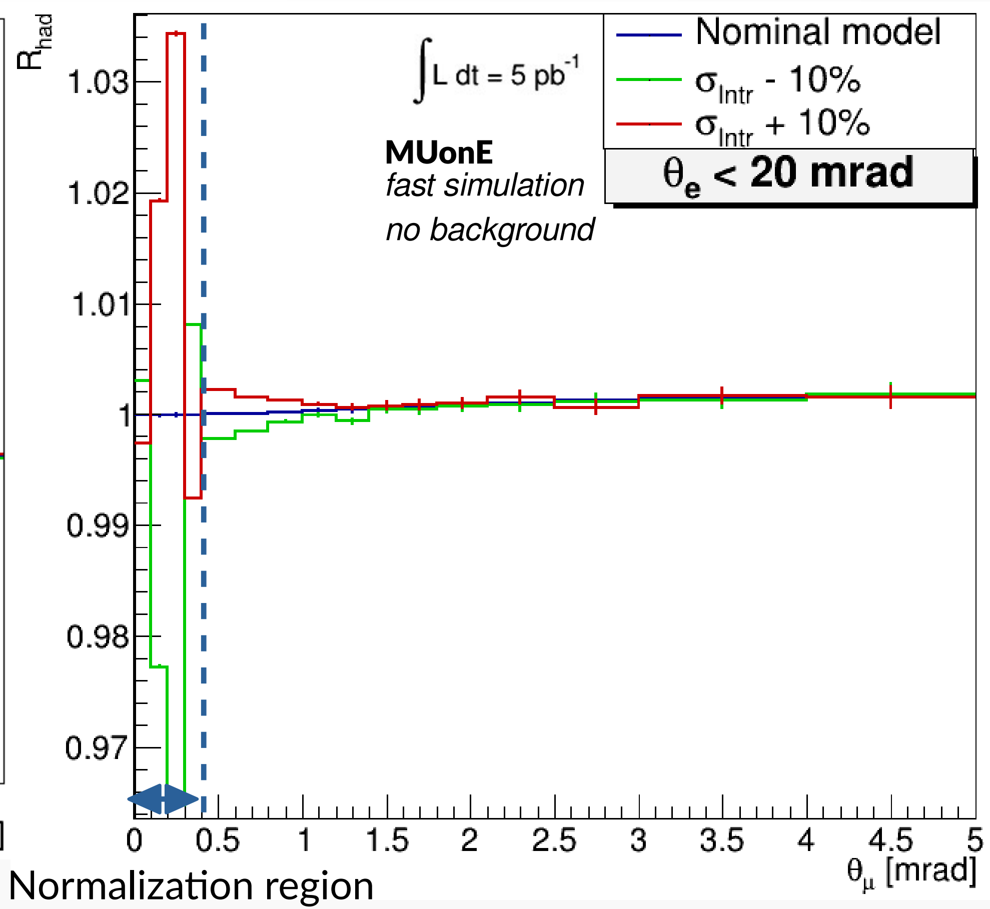
- L = 5 pb^{-1}.
  ~10^9 elastic events
  (~4000 times less than the final statistics)
- Example: shift the pseudo-data sample by $\sigma_{Intr} \rightarrow \sigma_{Intr} + 5\%$.



Systematic error on the angular intrinsic resolution

±10% error on the
angular intrinsic resolution.

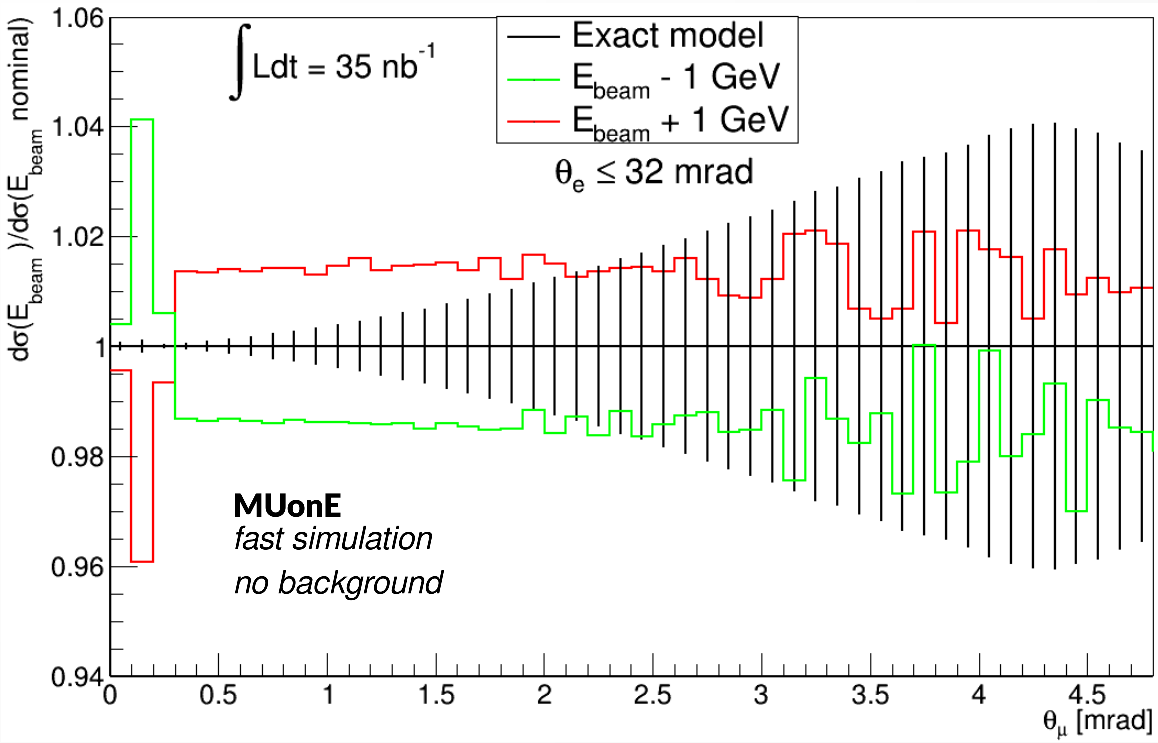




Systematic error on the muon beam energy

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%

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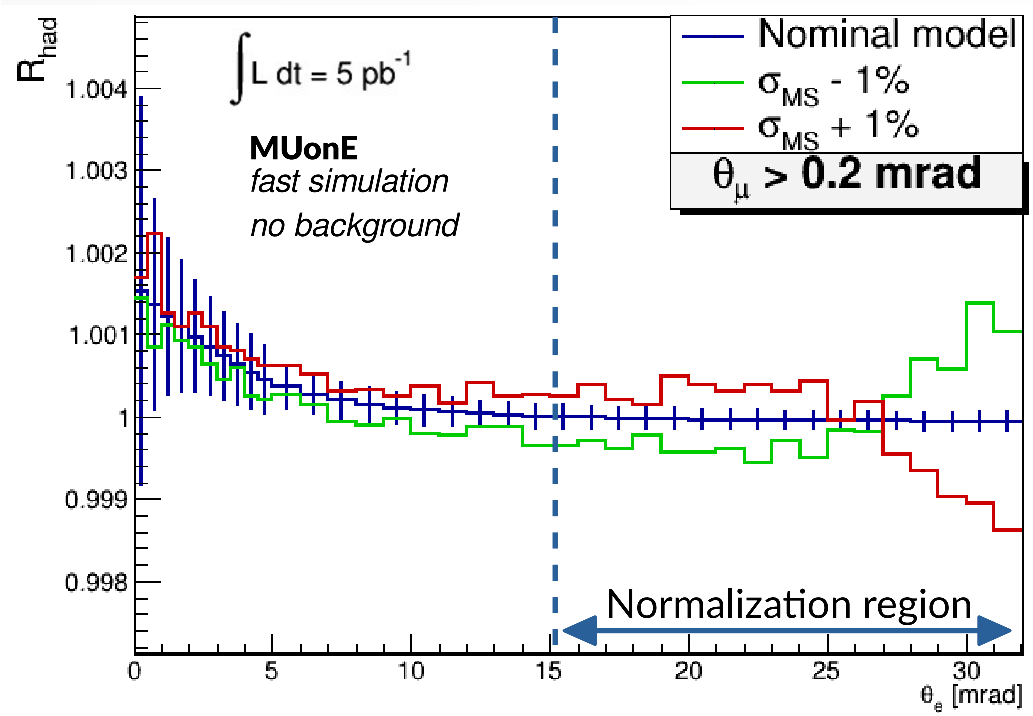
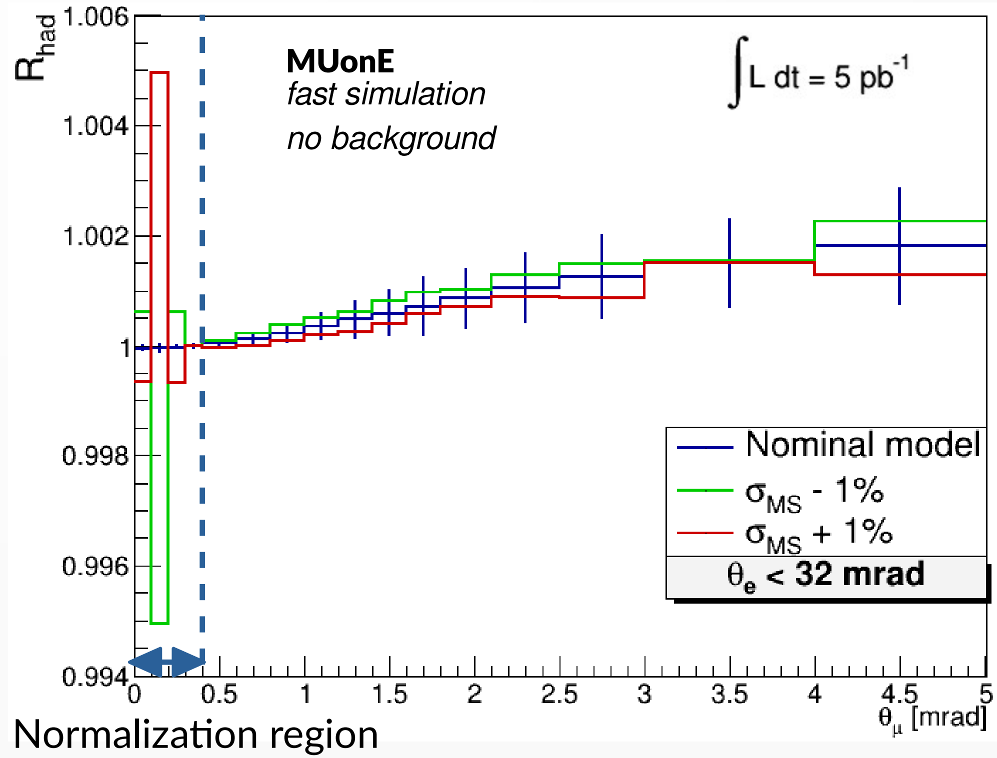
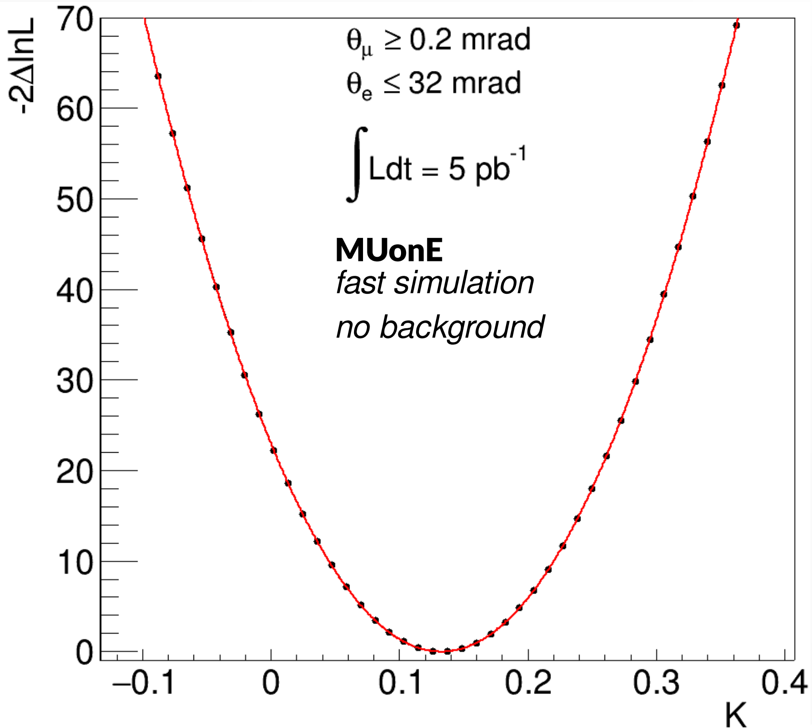




Combined fit
signal + systematics

- 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.

$\Delta\alpha_{had}$ parameterization

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

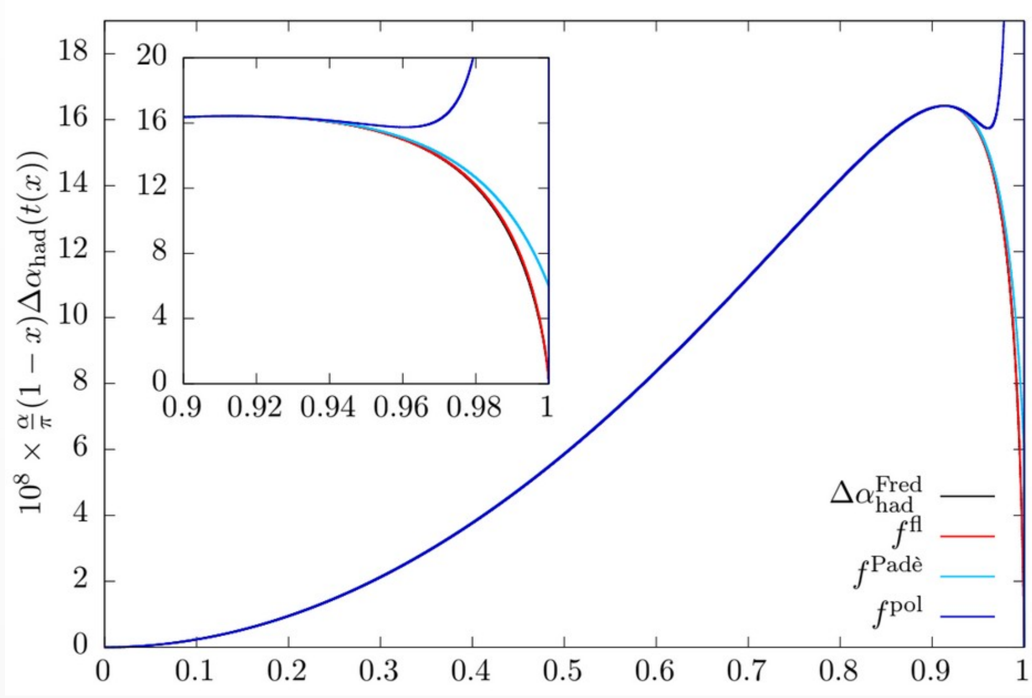
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters: K, M

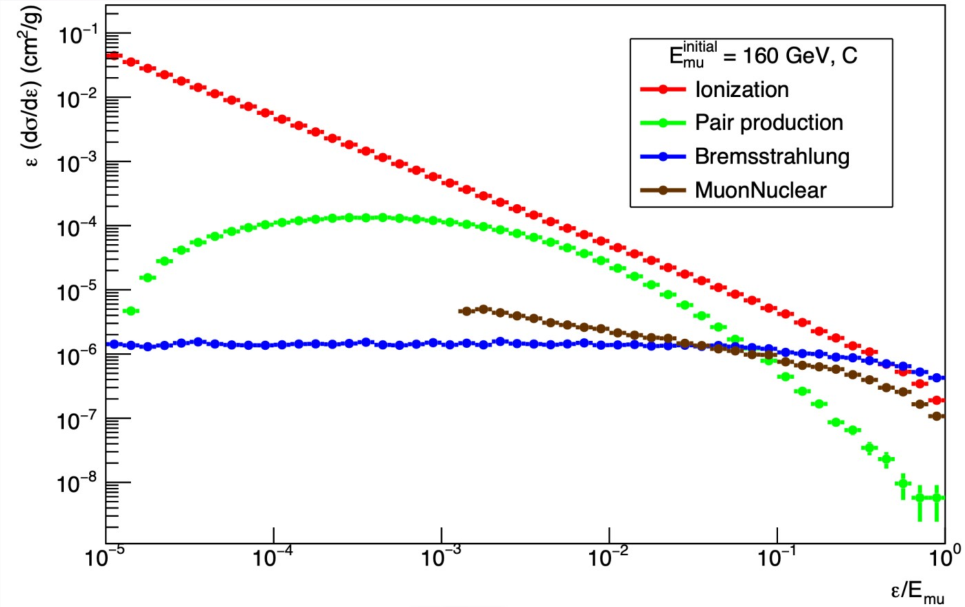
Allows to calculate the full value of a_μ^{HLO}

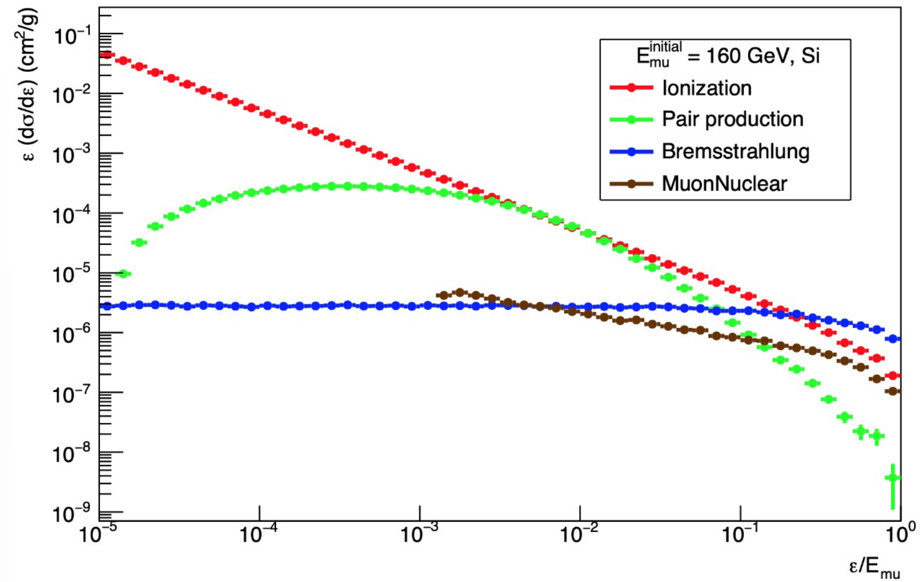
Dominant behaviour in the MUonE kinematic region:

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



Backgrounds





θ_e [mrad] 32 0

MESMER

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

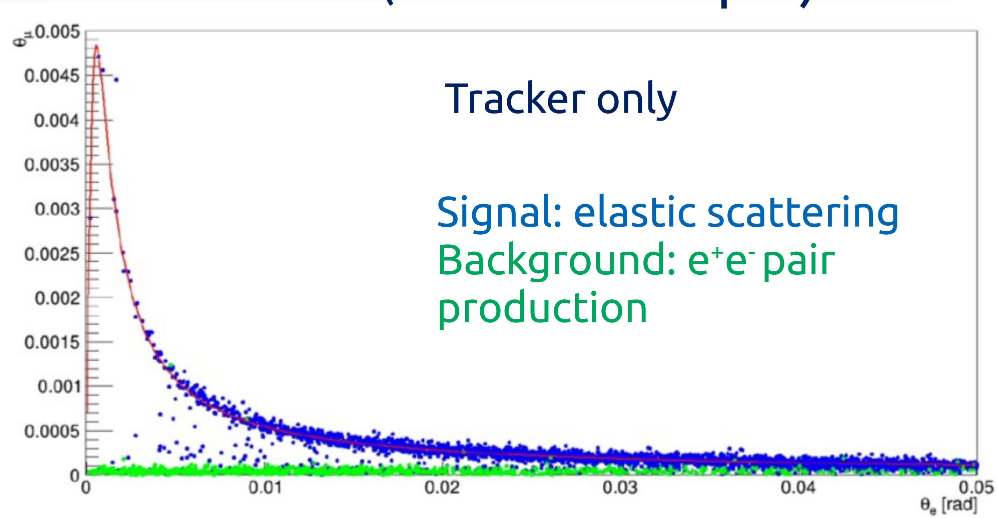
$l = e, \mu$

GEANT4

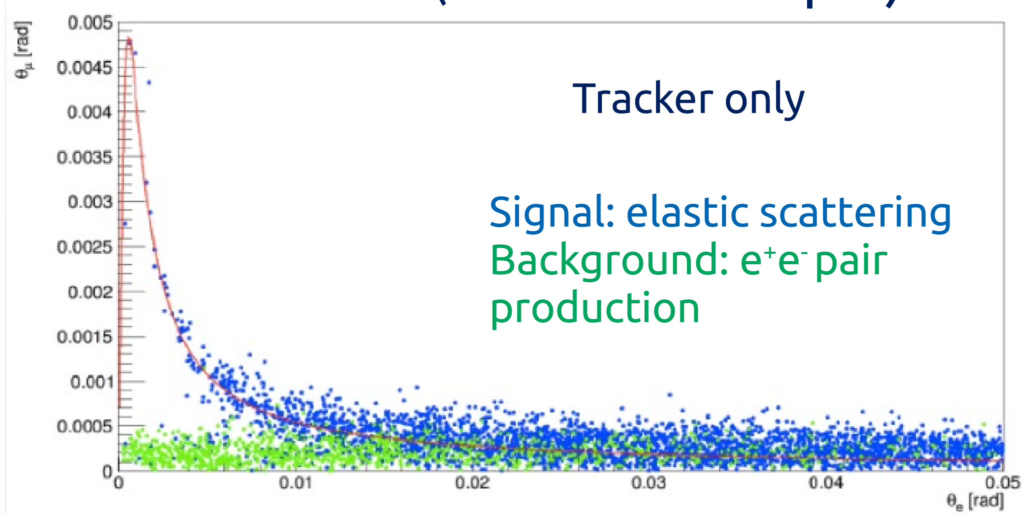
- $\mu N \to \mu N \gamma$
- $\mu N \to \mu X$

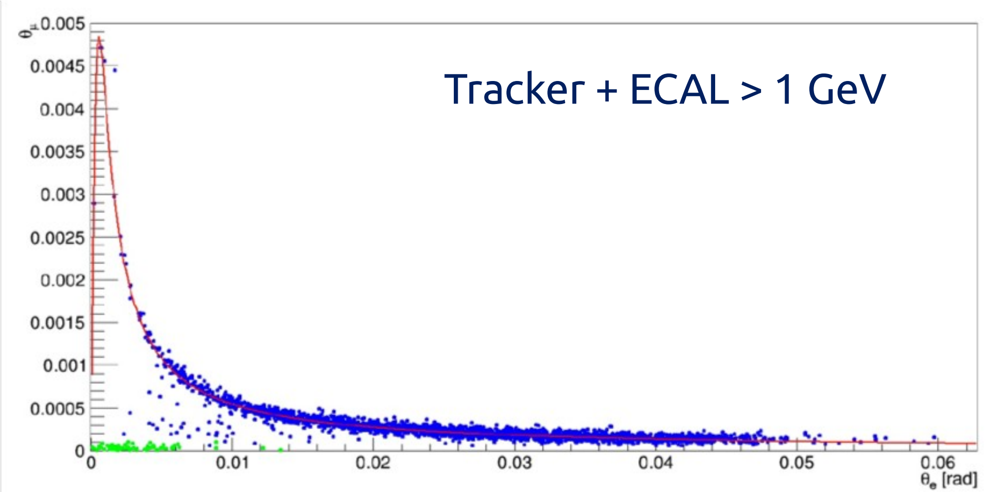
GEANT4 simulations

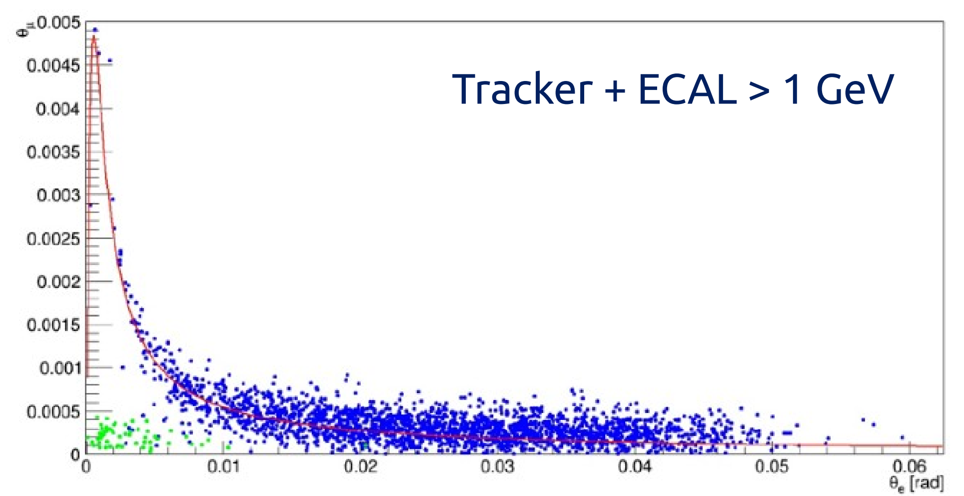
TB2017 (resolution ~7μm)



TB2018 (resolution ~40μm)

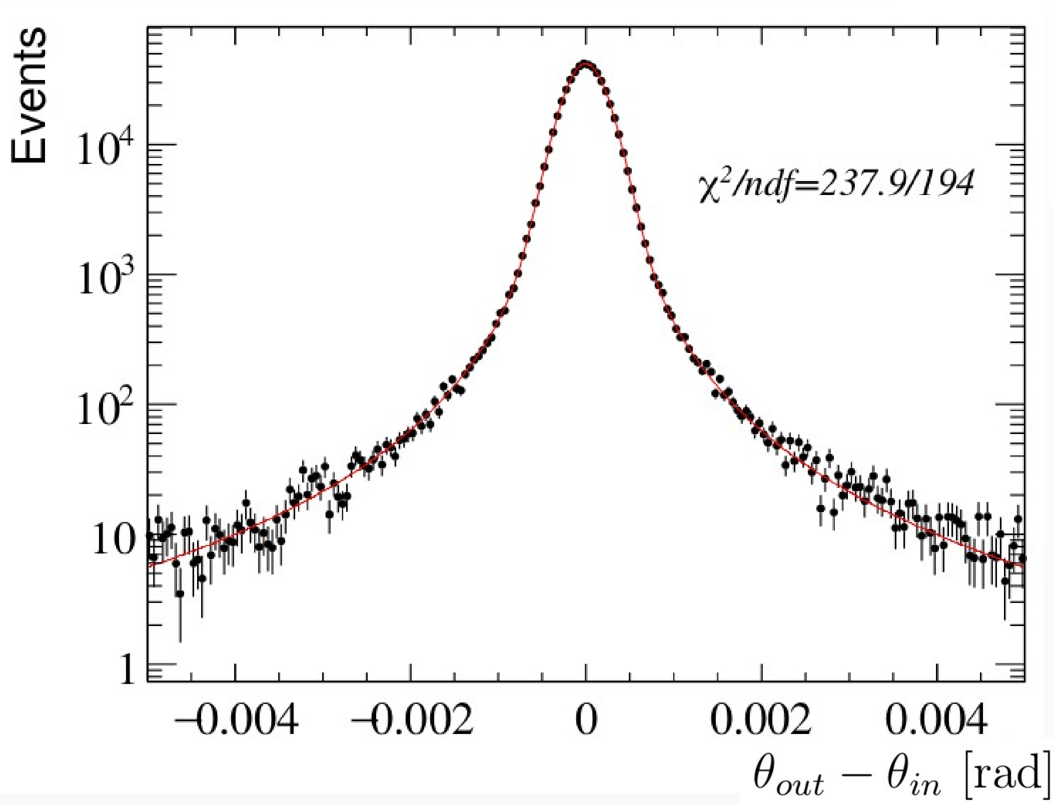






Multiple scattering: results from TB2017

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



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

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