Proposal for phase 1 of the MUonE experiment

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on behalf of the MUonE Collaboration

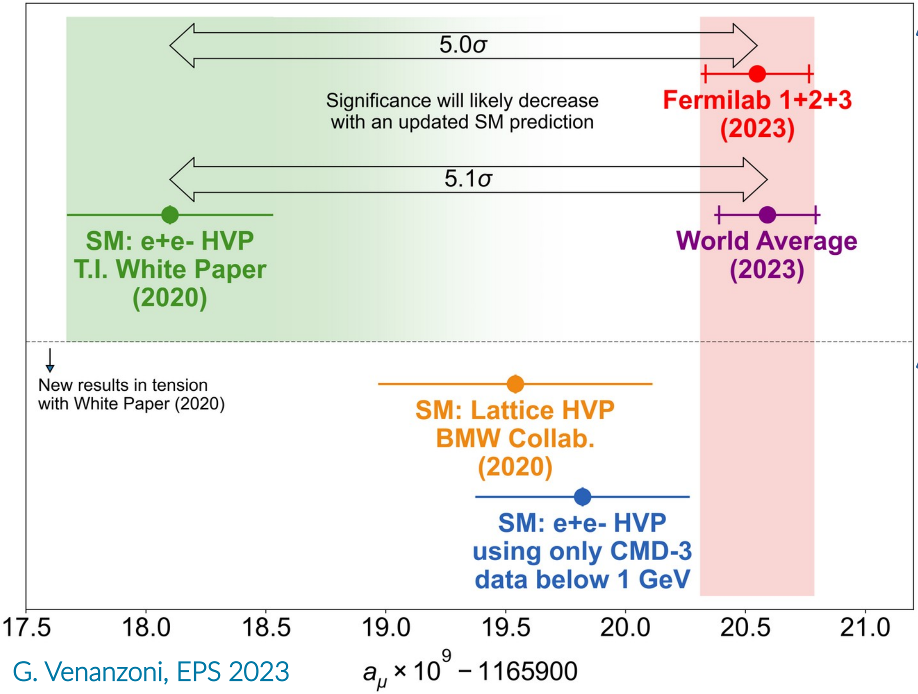
CERN-SPSC-2024-015

153rd SPSC Meeting
7 May 2024

Outline

- The MUonE experiment
- Test Beam 2023
- Run 2025: MUonE phase 1.
  Request for 4 weeks of running time
  at the M2 beam line
- Conclusions

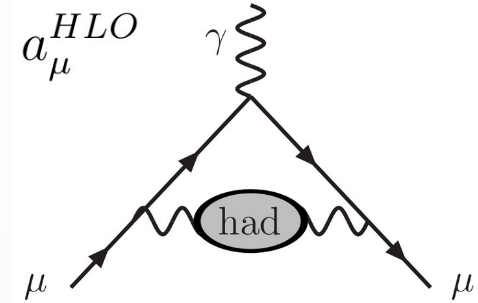
Muon g-2: current status



G. Venanzoni, EPS 2023

Comparison with WP20

New results after WP20



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

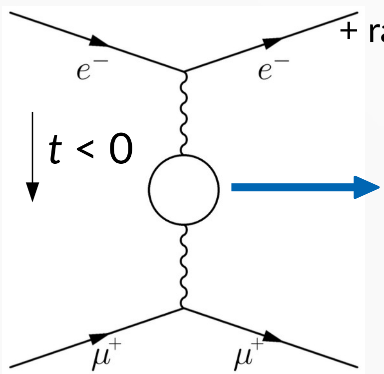
Phys. Lett. B 746 (2015), 325
Eur. Phys. J. C 77.3 (2017), 139
Letter of Intent CERN-SPSC-2019-026

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

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

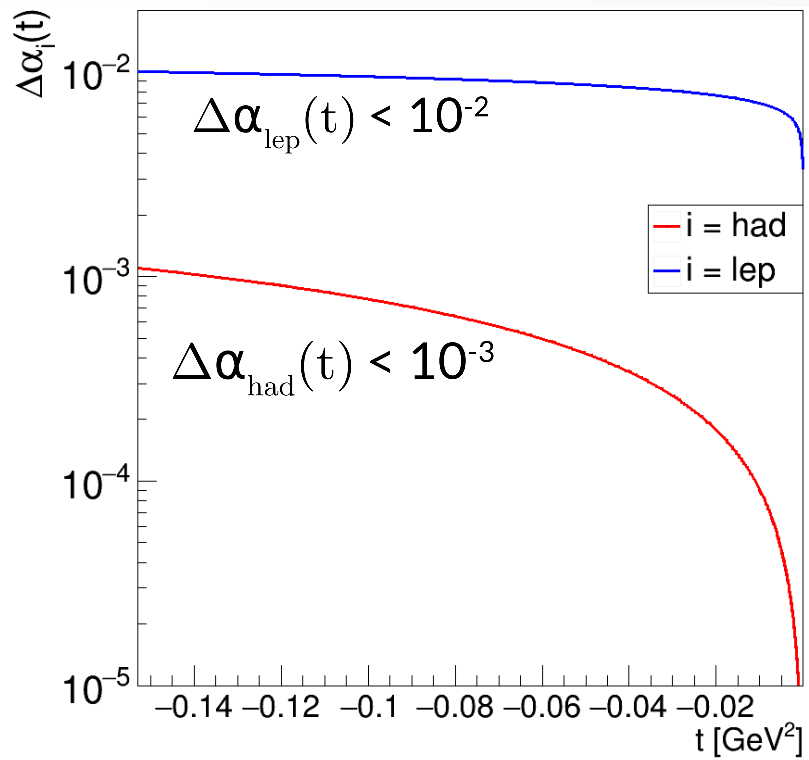
Phys. Rep. C 3 (1972), 193

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



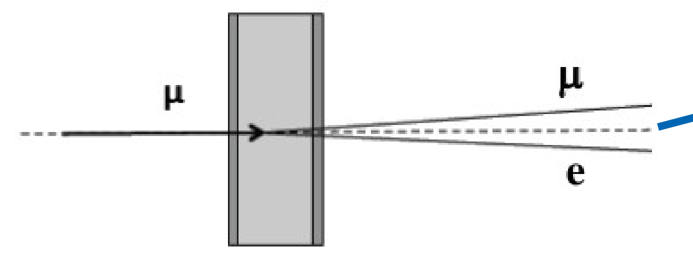
+ radiative corrections

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



MUonE kinematic range

The μ-e elastic scattering



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

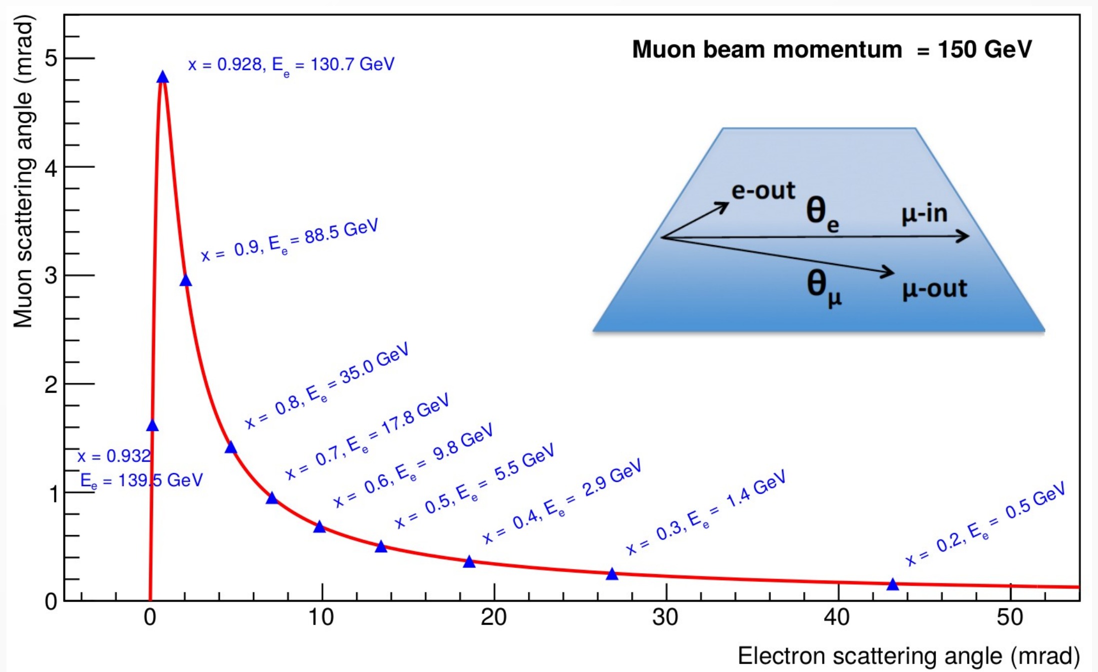
From theoretical calculation (>NNLO needed)

To be measured

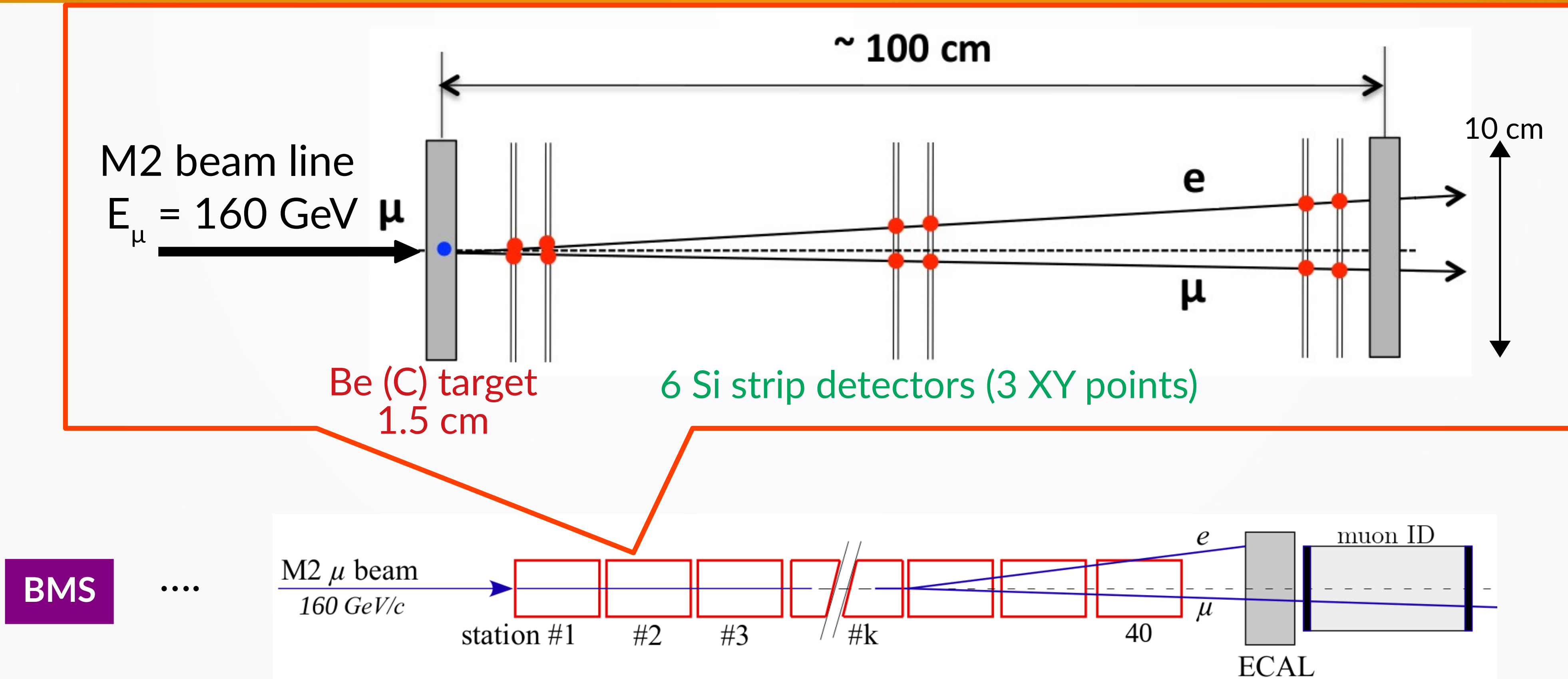
Great effort of the theory community:

Report of the MUonE Theory Initiative
Eur. Phys. J. C 80, 591 (2020)

- 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



After LS3:
full apparatus
with 40 stations

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

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).

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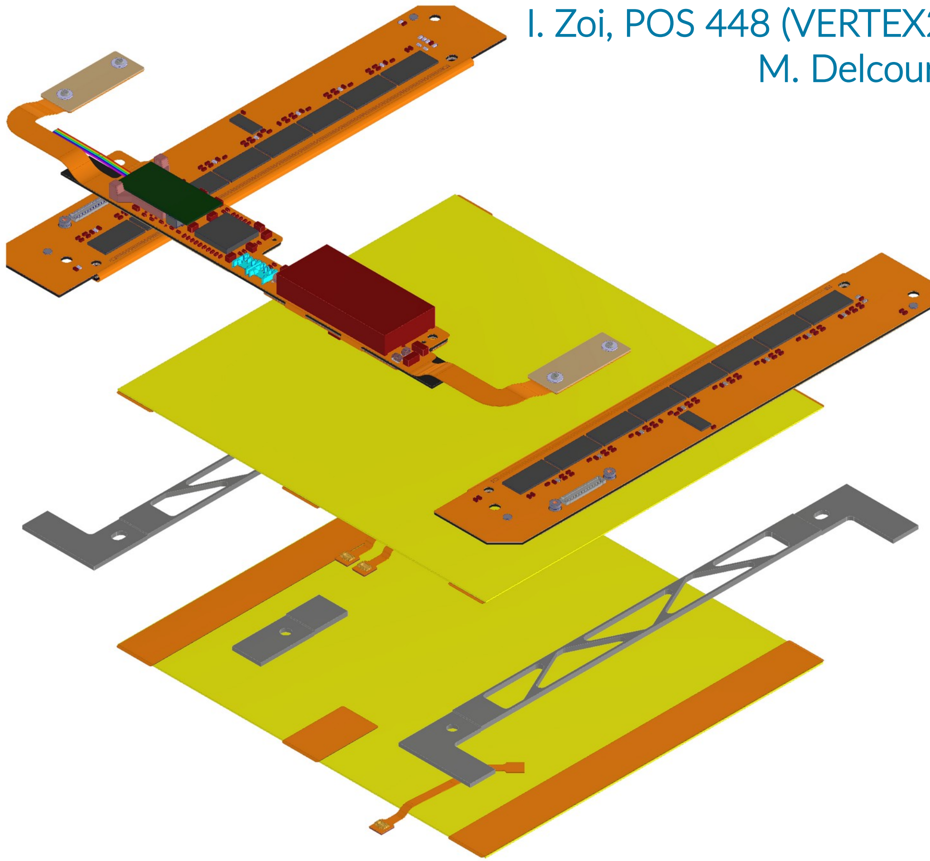
  - Muon ID;
  - Beam Momentum Spectrometer (BMS).

Tracker: CMS 2S modules

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

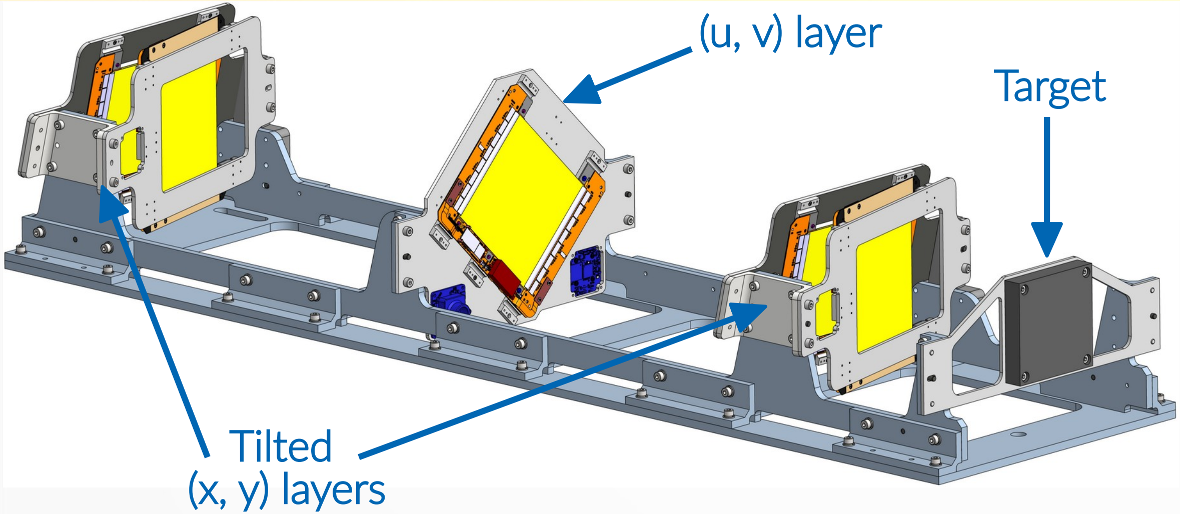
TDR CMS Tracker Phase2 Upgrade
I. Zoi, POS 448 (VERTEX2023), 021
M. Delcourt, BTTB12

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.

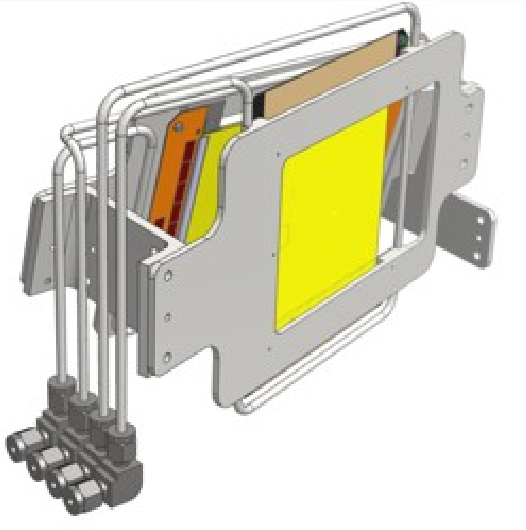
Tracking station



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

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

Laser holographic system
to monitor stability.

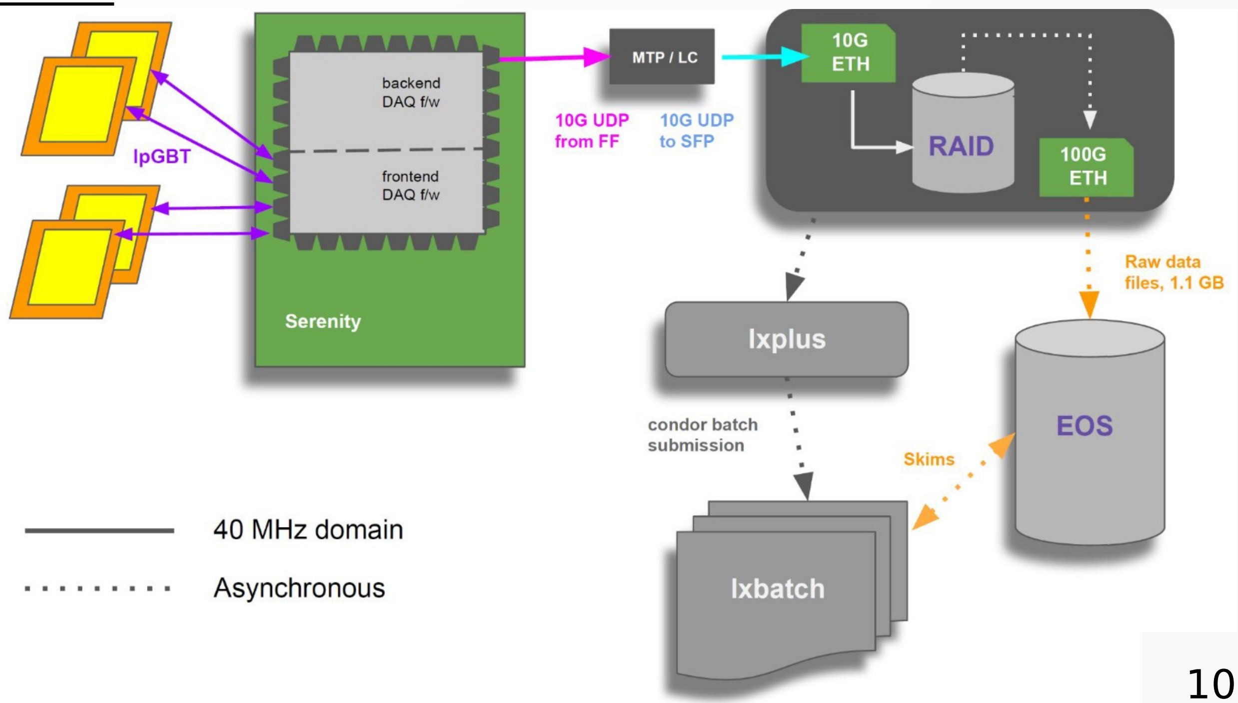


- (x, y) layers tilted by 233 mrad:
  improve hit resolution.
- (u, v) layers: solve reconstruction ambiguities.

DAQ system

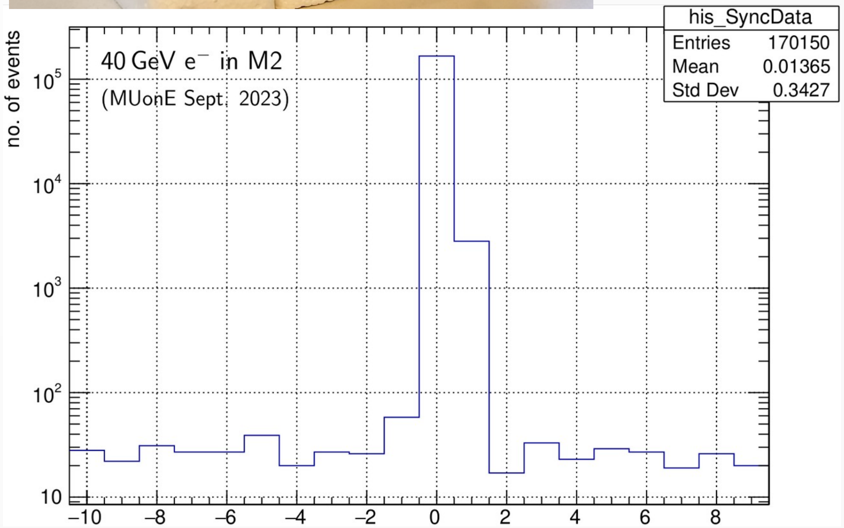
Frontend control and readout via Serenity board
(developed for the CMS-Phase2 upgrade).

- 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.



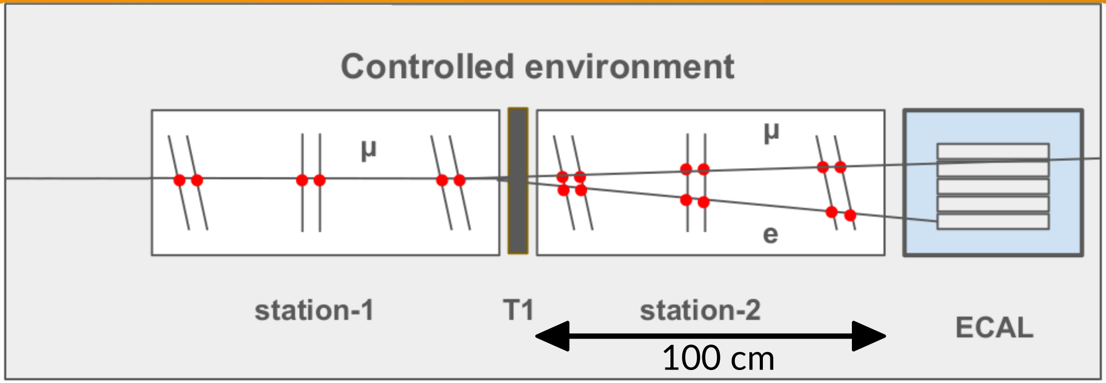
Calorimeter

- 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.



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)$\times 10^8$ elastic events;
- ECAL integrated in the DAQ @40 MHz in the final part of the run.
- Achieved online tracking on FPGA.

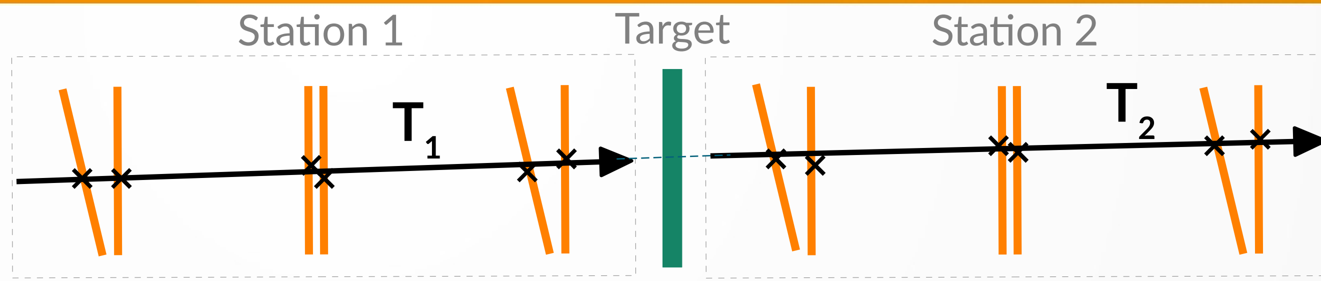
- Test the detector performance.
- Test the reconstruction algorithms and event selection.

Work in progress:

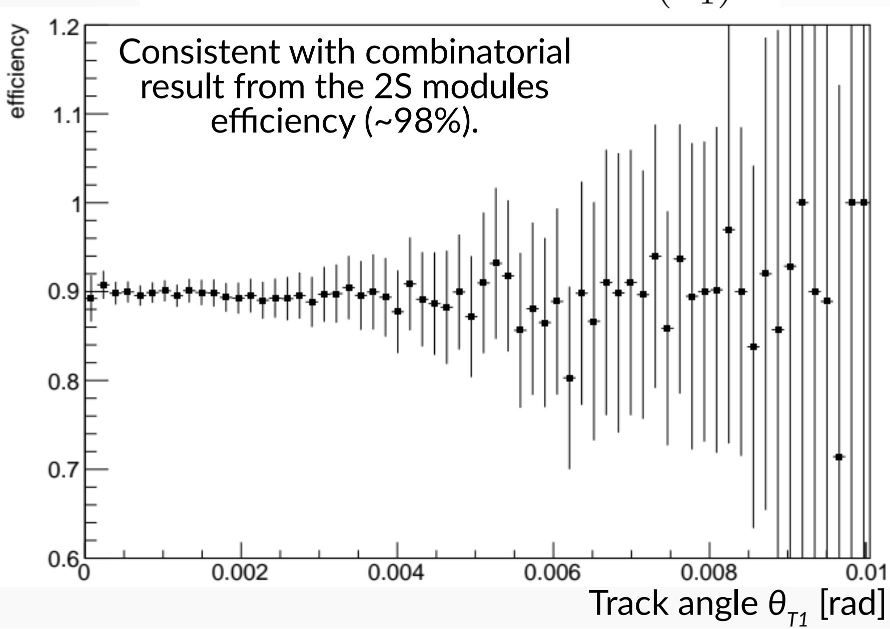
- Study the background processes and the main sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{lep}(t)$ with $O(5\%)$ stat. accuracy.

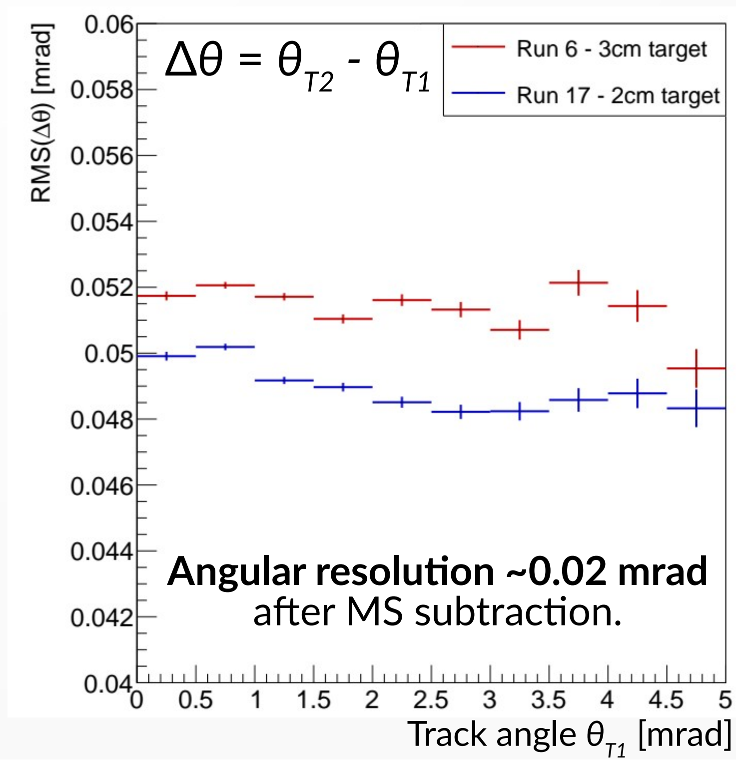
TB 2023 - tracking performance: efficiency and angular resolution

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

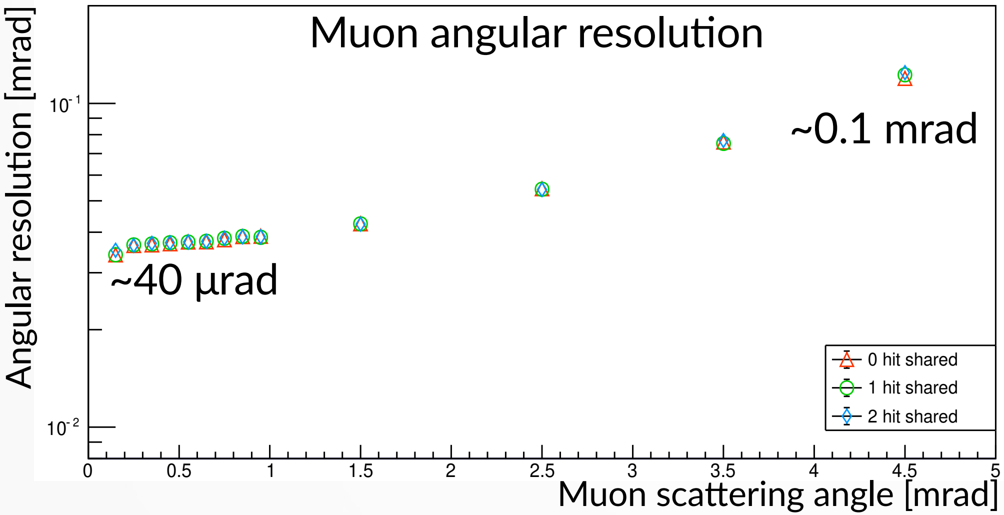


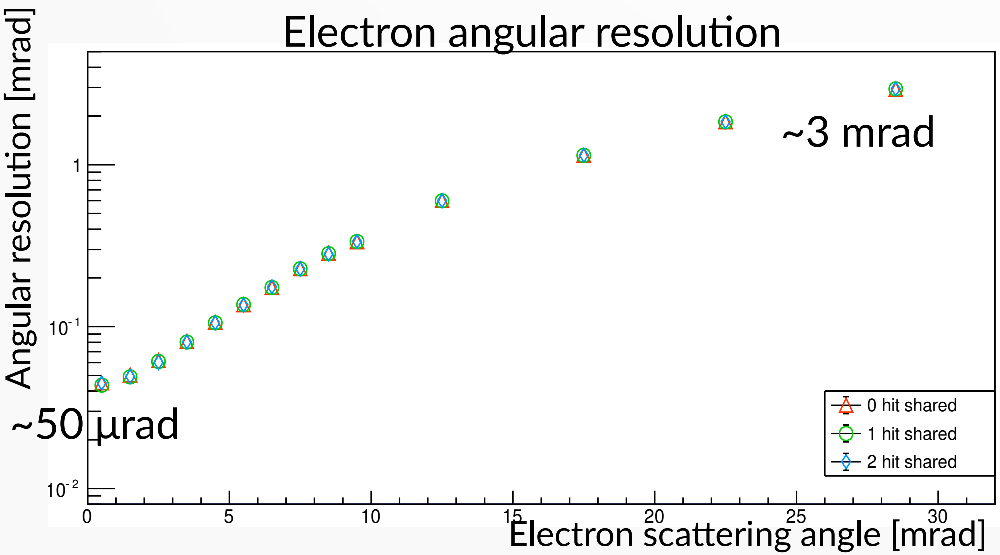
$$\text{Tracking efficiency} = \frac{N(T_2 \cdot T_1)}{N(T_1)}$$

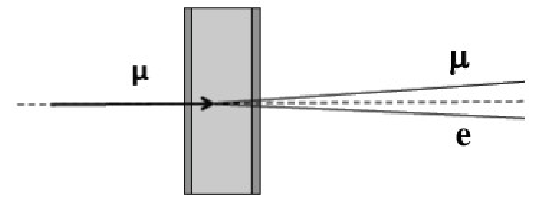




TB 2023 - MC performance: angular resolution of scattered particles







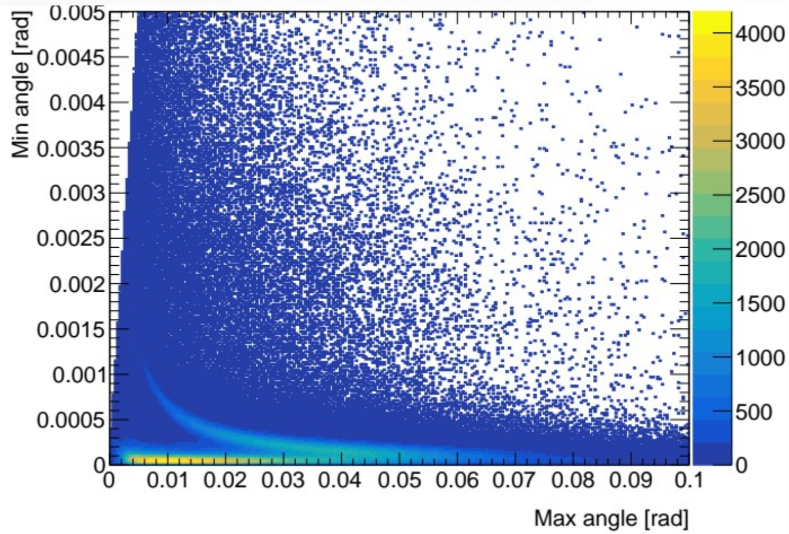
- Compare track reconstruction with MC truth.
- Muon angle: ~40 µrad resolution for small scattering angles.
- Electron angle: stronger impact of MS. Resolution is ~3 mrad for large scattering angles (E_e ~1–2 GeV).

Work in progress:

Data / MC comparison.

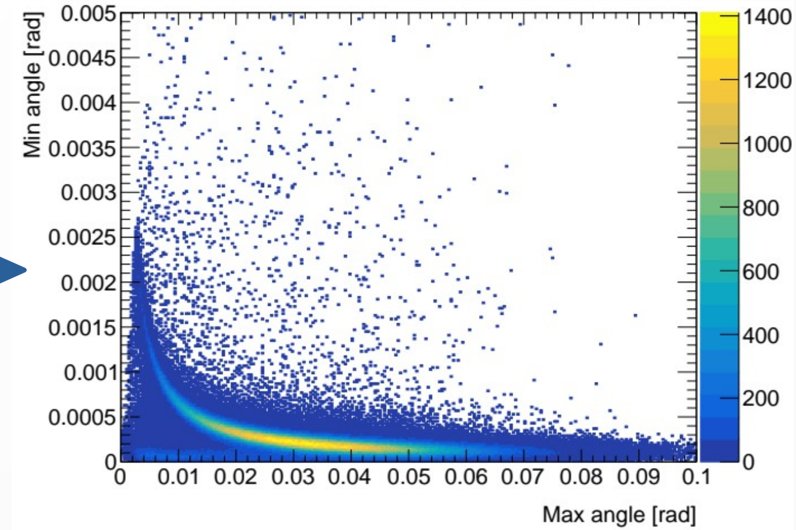
TB 2023
μ-e elastic scattering event selection

- 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:

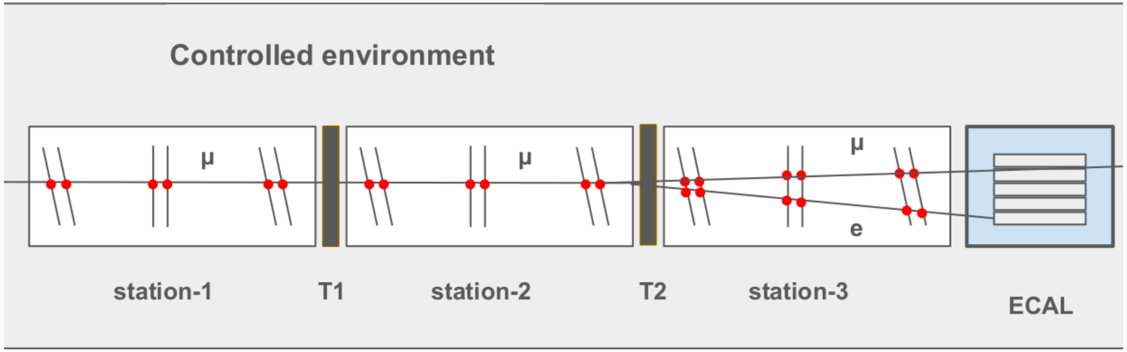
- Exploit dedicated MC generators to study the backgrounds:
  - Signal generator: exact NLO + approximated NNLO.
  - Pair production generator: tree level.
- Study the main sources of systematic error using tracker data:
  - Angular intrinsic resolution;
  - Beam energy scale.

Run 2025: motivations

- The apparatus used in 2023 does not represent the complete detector foreseen for the final experiment:
  - No BMS;
  - No muon ID;
  - ECAL integrated in the main DAQ only in the final part of the run.

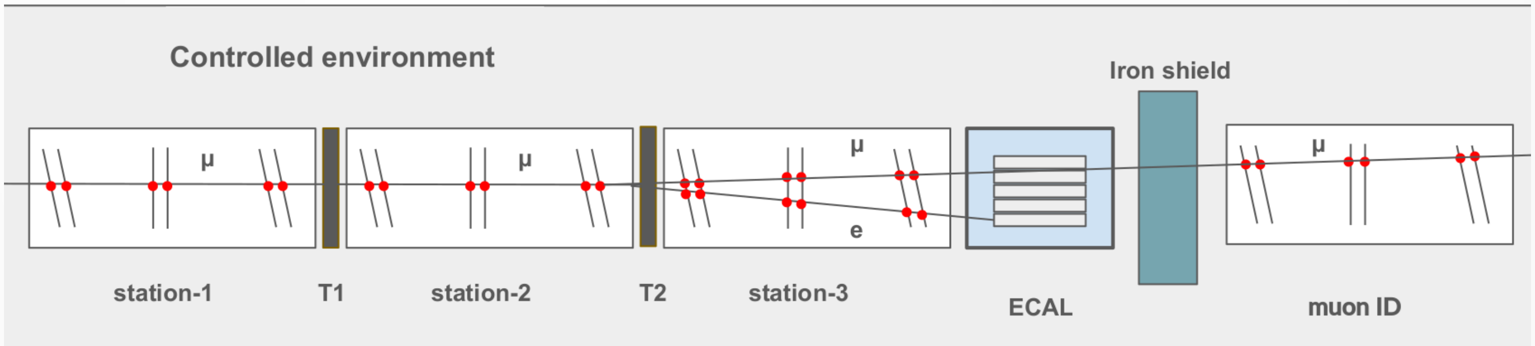
- In 2025 MUonE requests **4 weeks** of data taking to run with a scaled version of the complete apparatus, including all the detector components.

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:
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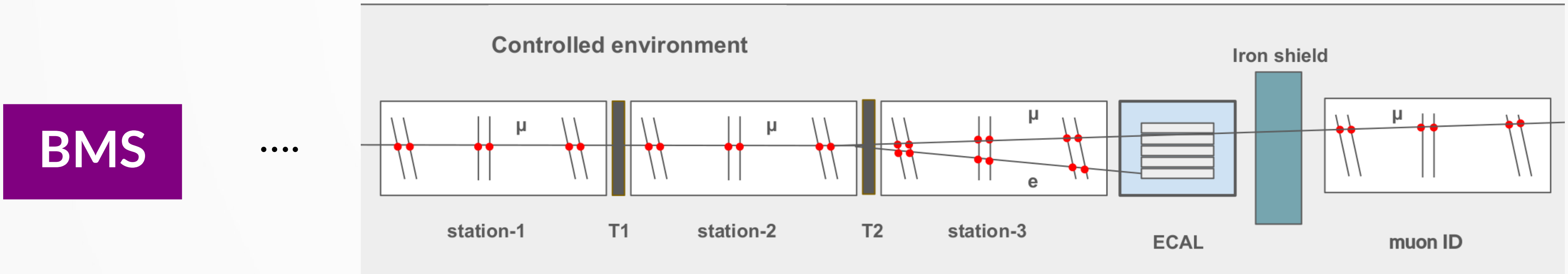
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).

Run 2025: the apparatus



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- ECAL:
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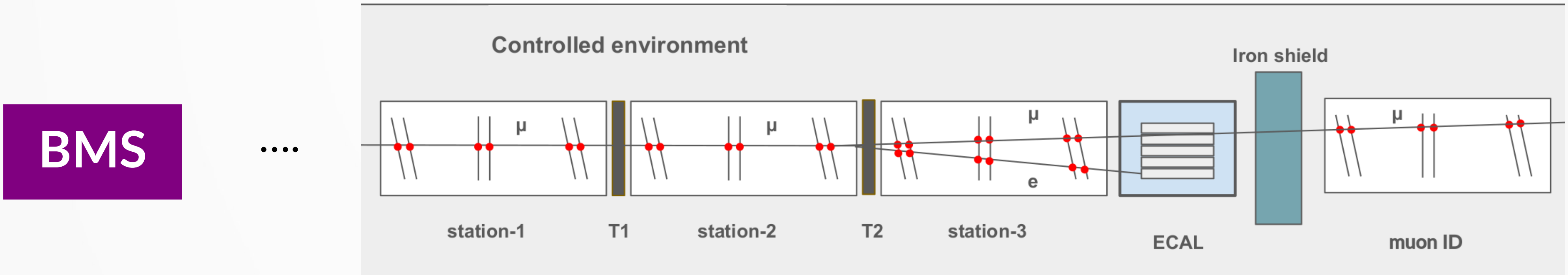
- Muon ID:
  - Iron shield + tracking station.
  - Full PID (in combination with ECAL).
- BMS:
  - Event-by-event p_μ measurement:
    reduce systematics related to the
    beam energy scale.

Run 2025: the apparatus



- 3 tracking stations.
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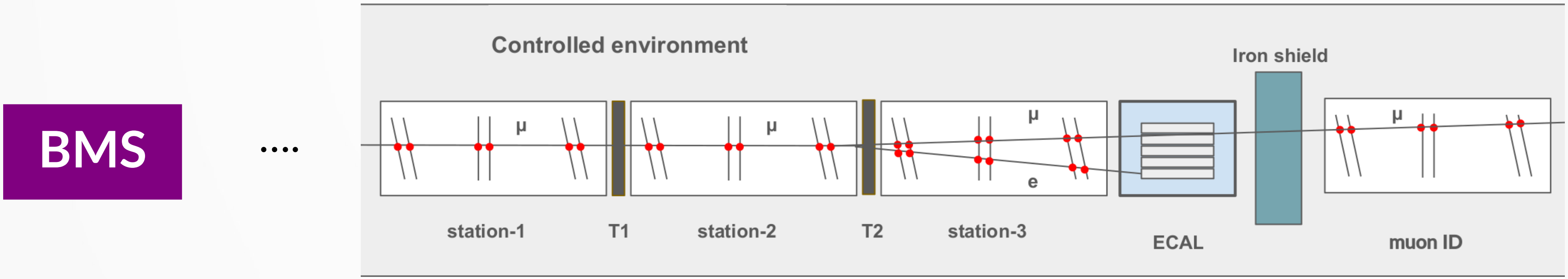
The entire apparatus is fully funded

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.”

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.

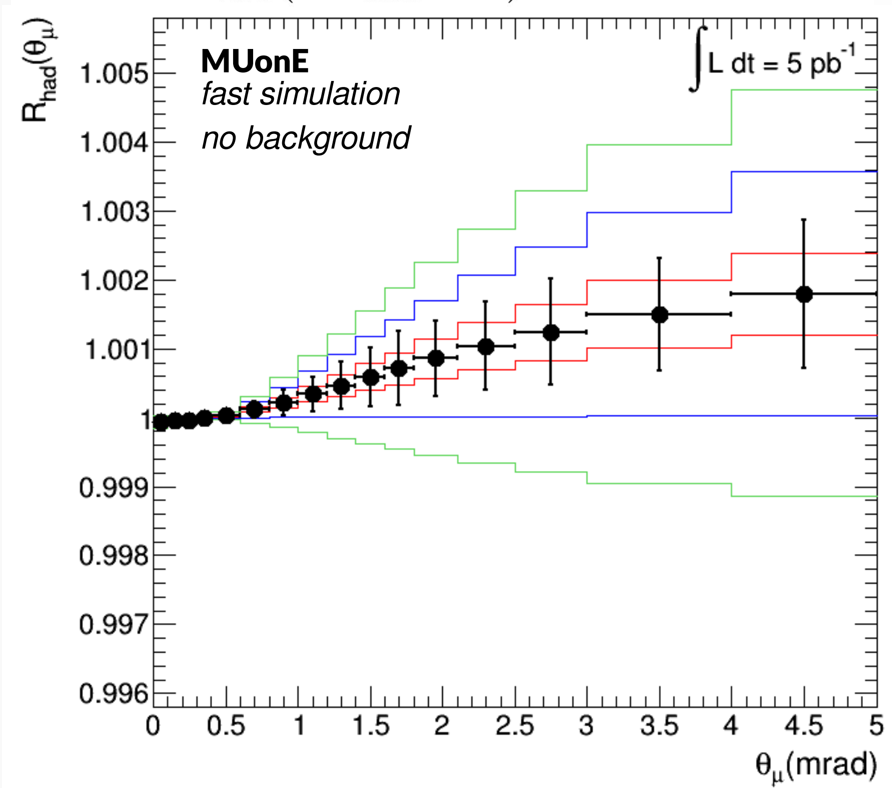
- **Systematic error studies:**
  - Exploit data from all the sub-detectors to study backgrounds and systematics.
  - Study uniformity of tracking efficiency, PID, backgrounds, detector modelization, beam control.
  - Demonstrate control of the systematic errors at O(500ppm).

- **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.

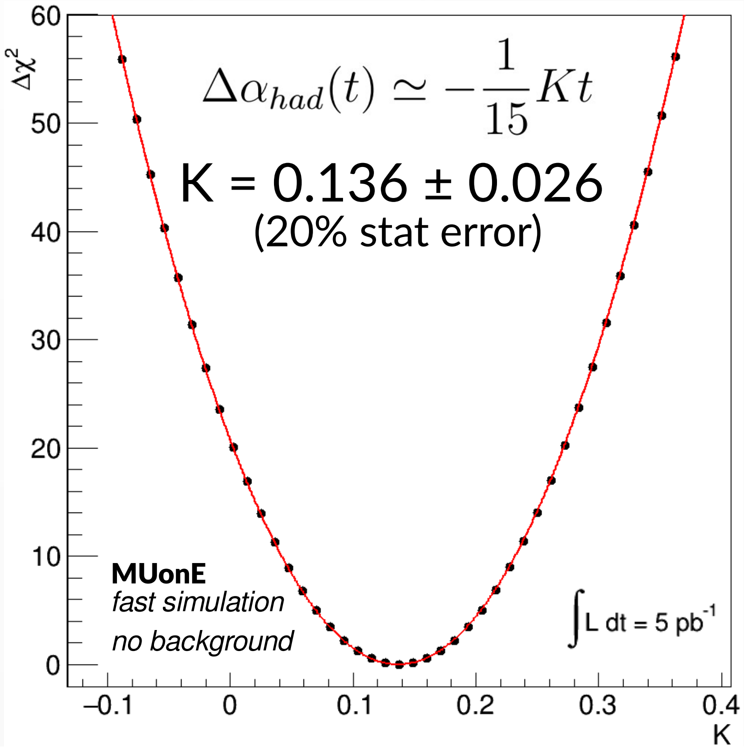
First measurement of $\Delta\alpha_{had}(t)$

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

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



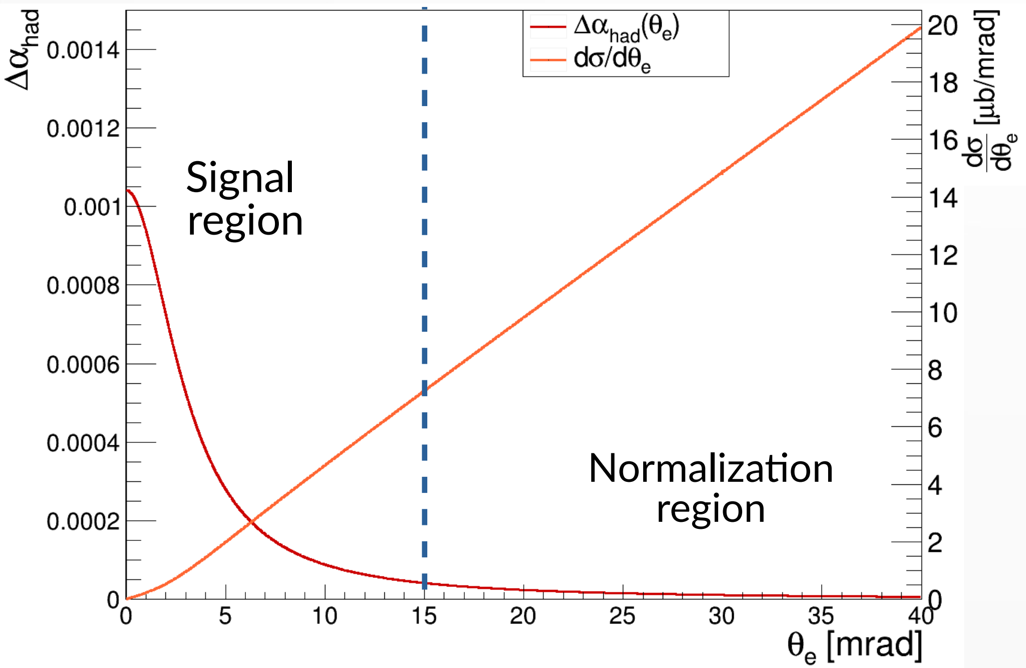
Template fit procedure to extract $\Delta\alpha_{had}(t)$



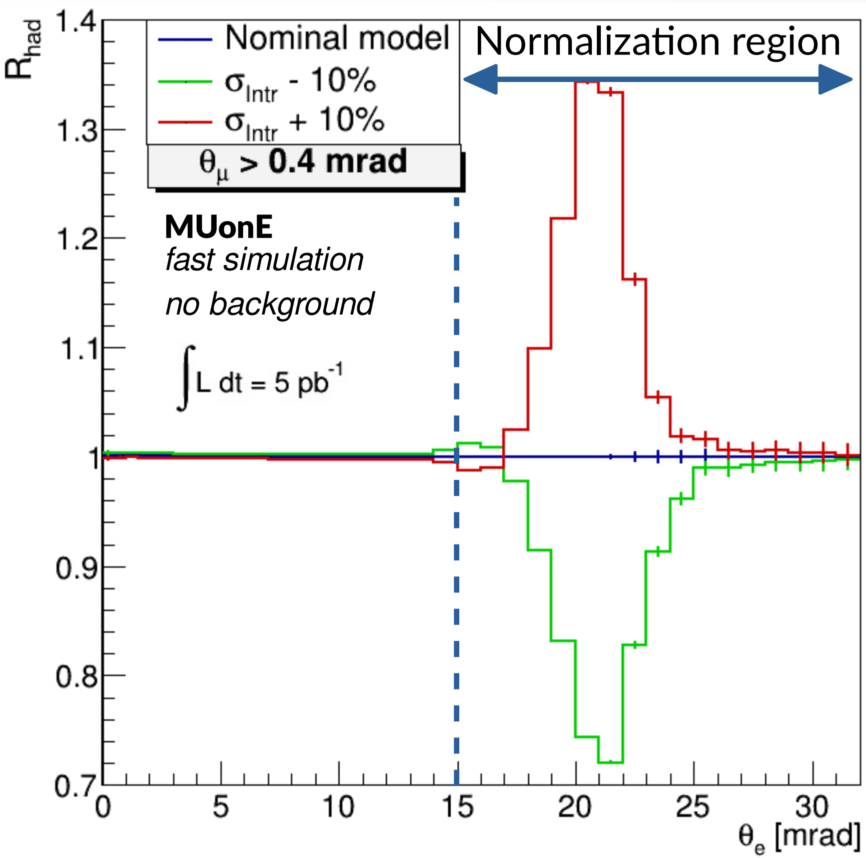
Systematic effects

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 MUonE Collaboration

Group	Senior	post-doc	PhD	students
Bologna	5		1	
Cornell University	1			
Imperial College(*)				
Krakow	2	1	2	
Milano-Bicocca	1			
Northwestern U.	1	1	1	
Padova	5	2		
Perugia	3	2		
Pisa	3	2	2	
Trieste	2		2	2
Shanghai	1	1		
Regis U.	1			3
U. of Virginia	2		2	
U. of Liverpool	5	3	3	
Total	32	12	13	5

Great contribution from early-career collaborators!

(*) Imperial College participation in MUonE R&D and this proposal has been possible because of the very significant synergy of its CMS tracker upgrade activities and MUonE goals, especially the implementation of the new tracker readout system and its evaluation in high rate beam tests.

Conclusions

MUonE web site

- The MUonE Collaboration submitted the proposal for a phase 1 of the experiment. It concerns a small scale version of the final apparatus, composed of 3 tracking stations, a calorimeter, a muon ID and the BMS.

- The detector for MUonE Phase 1 and operations until LS3 are fully funded.

- In case the proposal will be approved, MUonE will request **4 weeks of running time in 2025** at the M2 beam line.

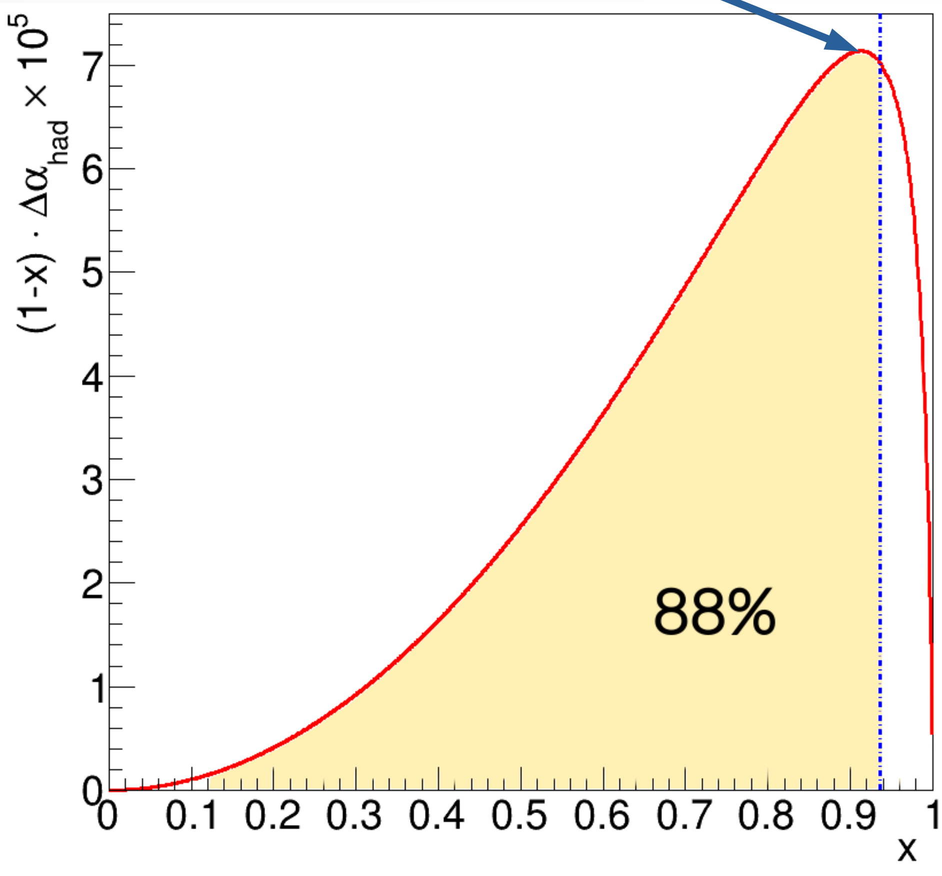
- Goals: carefully study the expected systematic errors and background under realistic conditions and make preliminary measurements of $\Delta\alpha_{had}(t)$. This will provide essential information in view of the final version of the experiment (40 tracking stations + ancillary detectors).

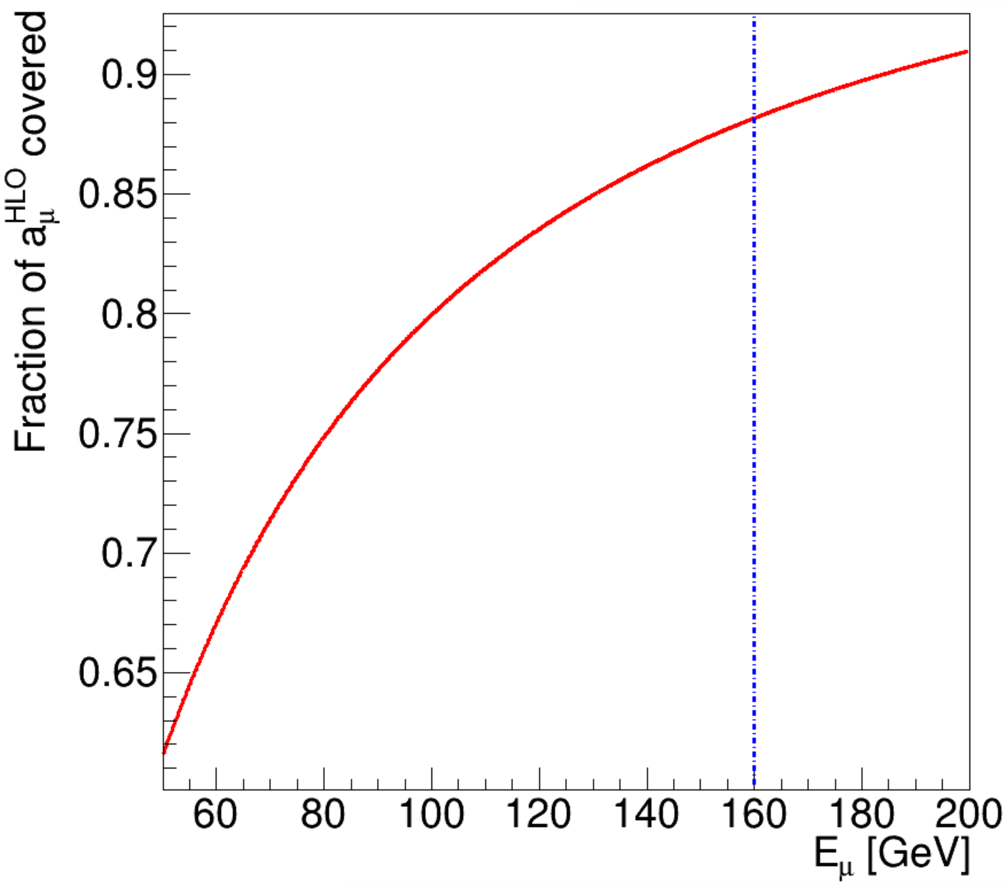
- Obtaining the status of approved experiment will significantly ease access to CERN services and support. This will encourage more institutions to get involved in the project.

BACKUP

$x < 0.936$

$t_{peak} \sim -0.108\ \mathrm{GeV}^2$ $x_{peak} \sim 0.92$



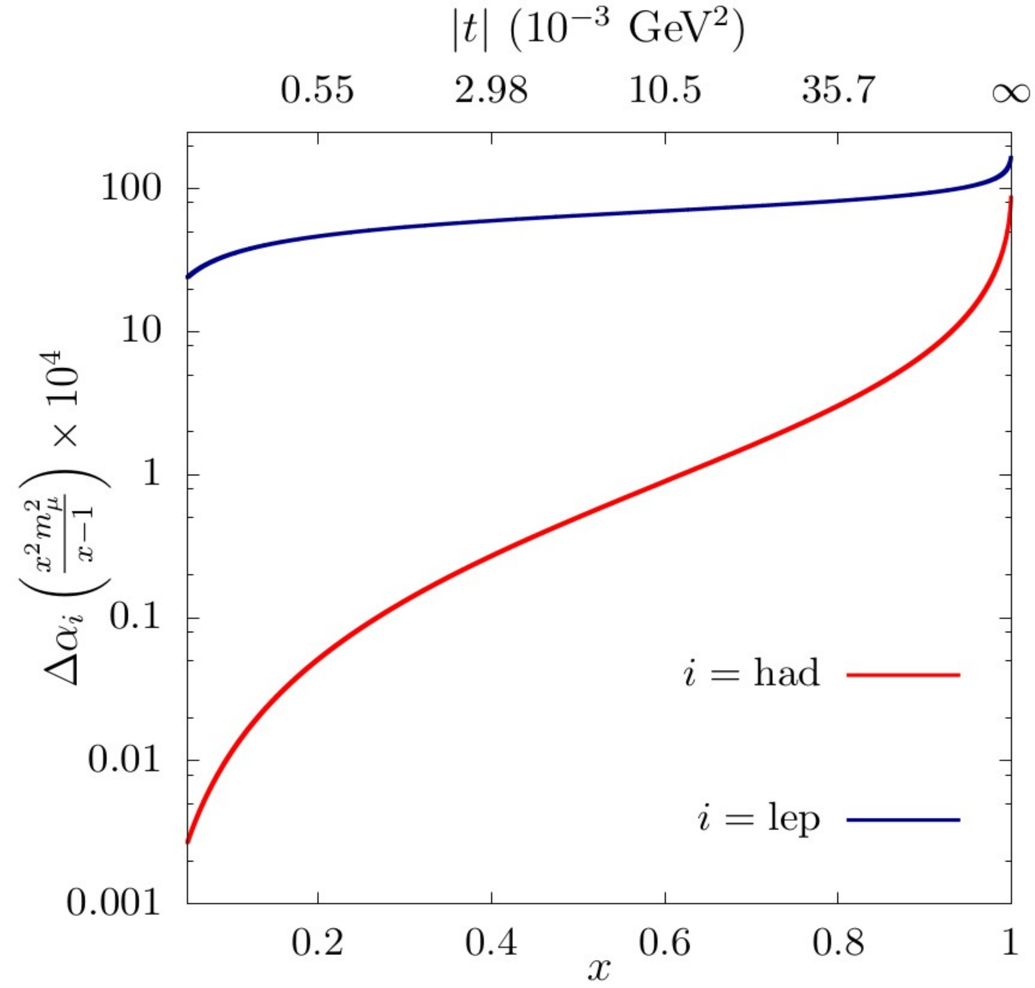


- 160 GeV muon beam on atomic electrons.

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

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

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



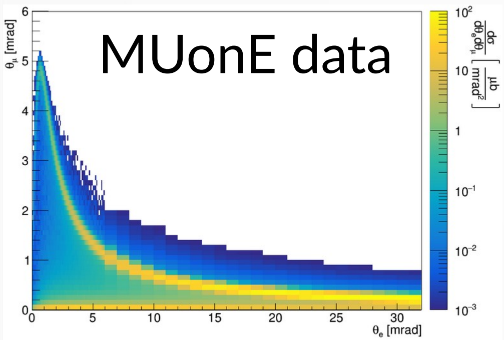
Extraction of $\Delta\alpha_{had}(t)$

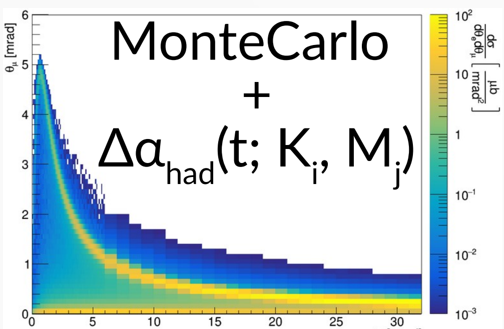
$\Delta\alpha_{had}(t)$ parameterization:
inspired from the 1 loop QED contribution of lepton pairs and *t*-quark at $q^2<0$

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

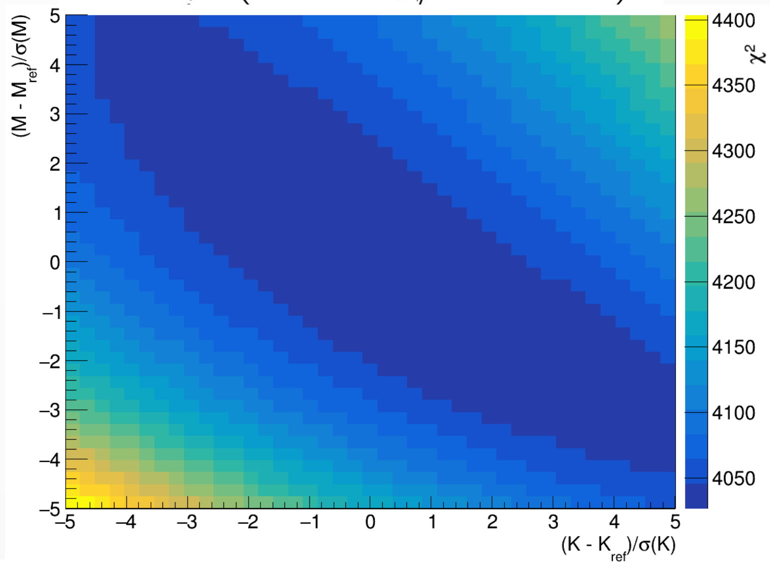
2 parameters:
K, M

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

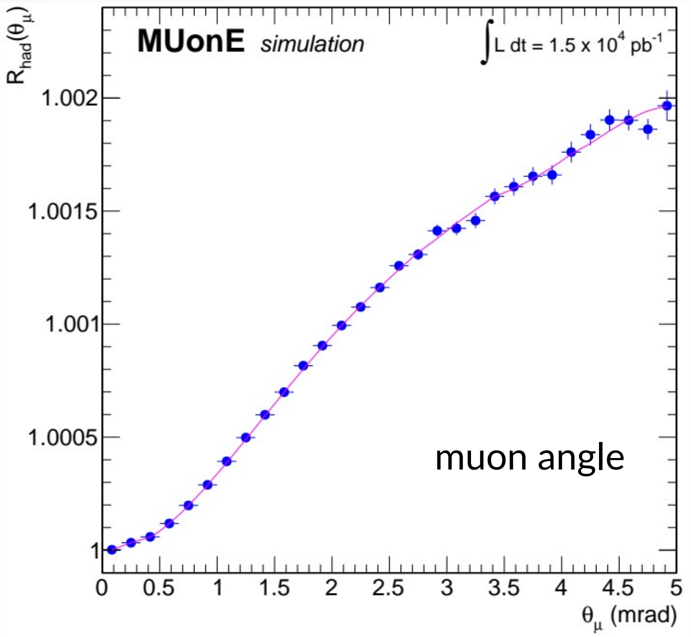


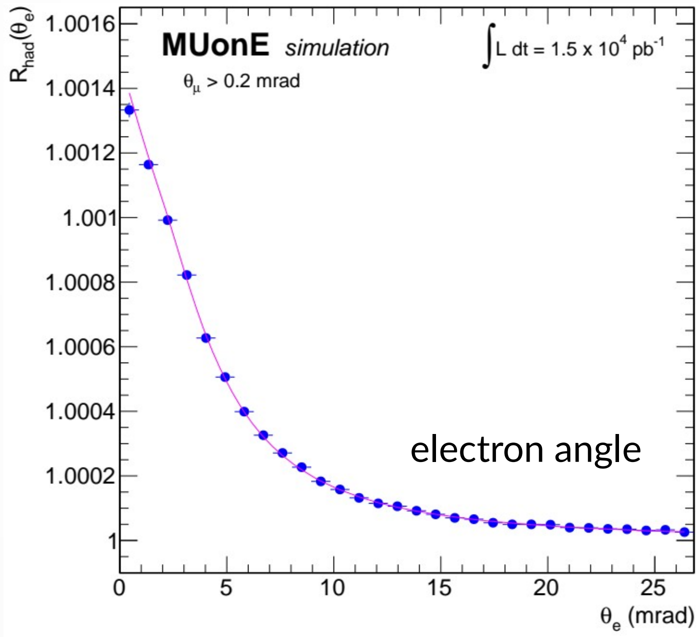


$$\chi^2 = \sum_i^{\text{bins}}\left(\frac{\text{data}_i - \text{templ}(K,M)_i}{\sigma_i^{\text{data}}}\right)^2$$



Extraction of a_μ^{HLO}





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

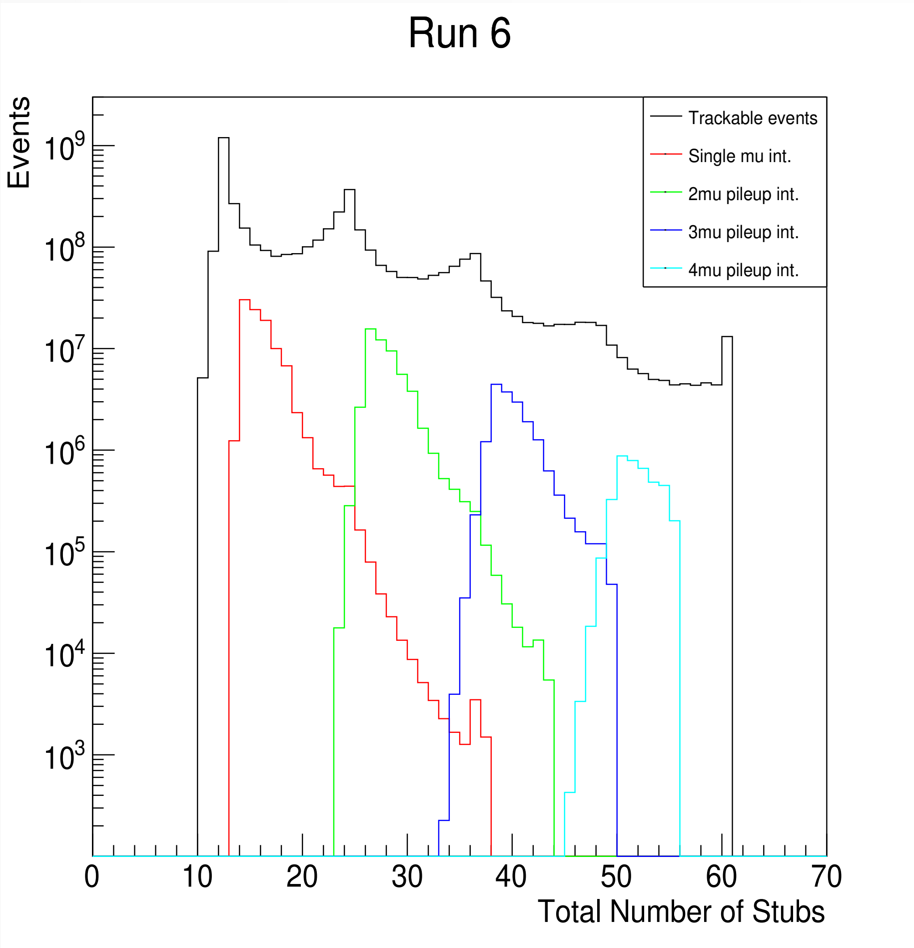
$$a_\mu^{\mathrm{HLO}} = (688.8 \pm 2.4)\ 10^{-10}$$

Input value:

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

TB 2023

Data preselection (*skimming*)



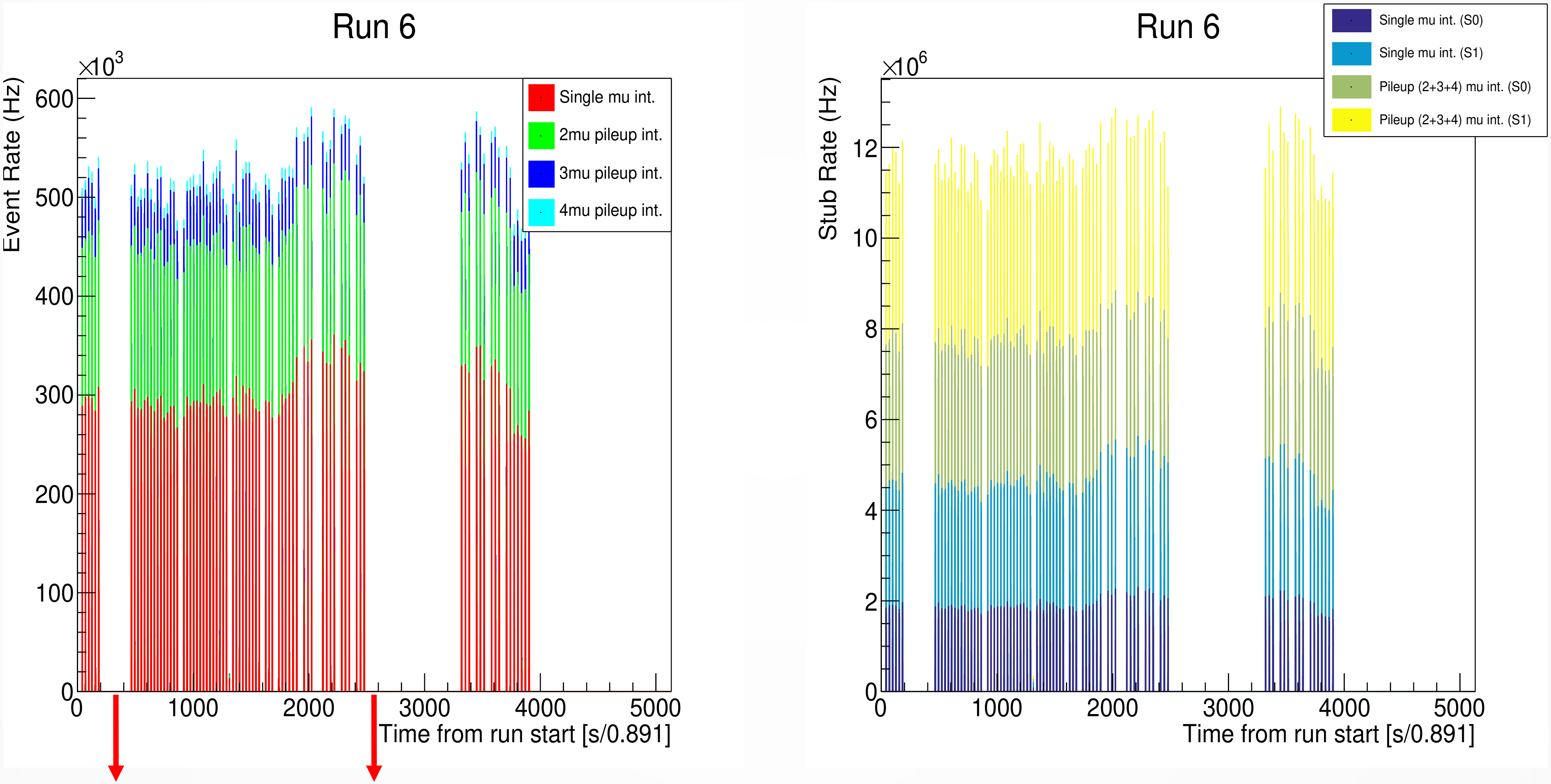
- 2023 Test Run operated with a Triggerless DAQ
  - Large Data volumes processed offline
- Skimming is aimed to preselect all the reconstructible events that can be associated to interactions in the target (from both signal and background processes)
- The algorithm is based simply on the hit patterns observed in the two stations
- The loosest requirements are imposed, to avoid biases, still the event reduction is about a factor 100

On ~12 B merged events, the skimming selects:
0.8% ~97 M Single-Mu interaction candidates
0.6% ~75 M PU (2,3,4) Mu interaction candidates

The different classes are well separated:

- Single muon interactions
- 2,3,4 pile-up muons with interactions

Event and Hit rates after Skimming Preselection



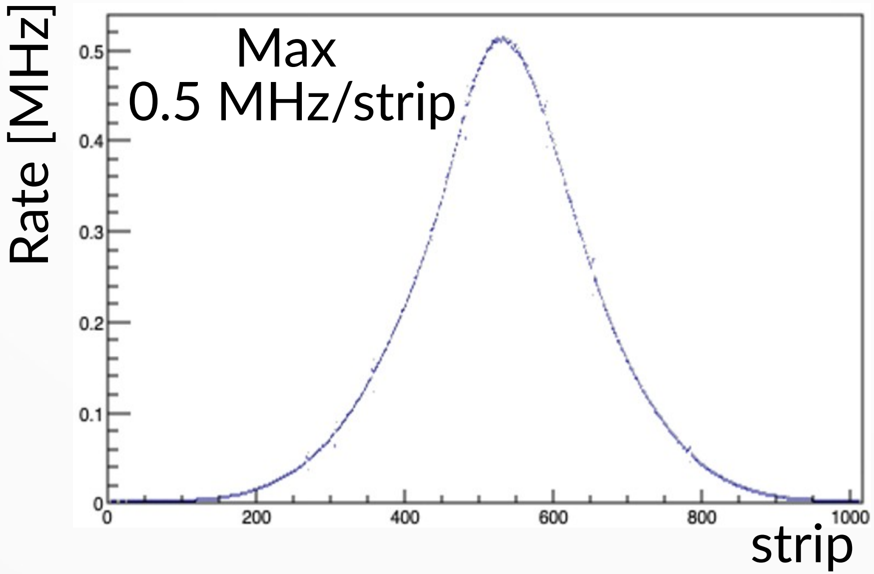
No beam in some time intervals: DAQ was carried on (nights)

Rate ~500 KHz: algorithm can easily be implemented online on FPGA

Beam rate

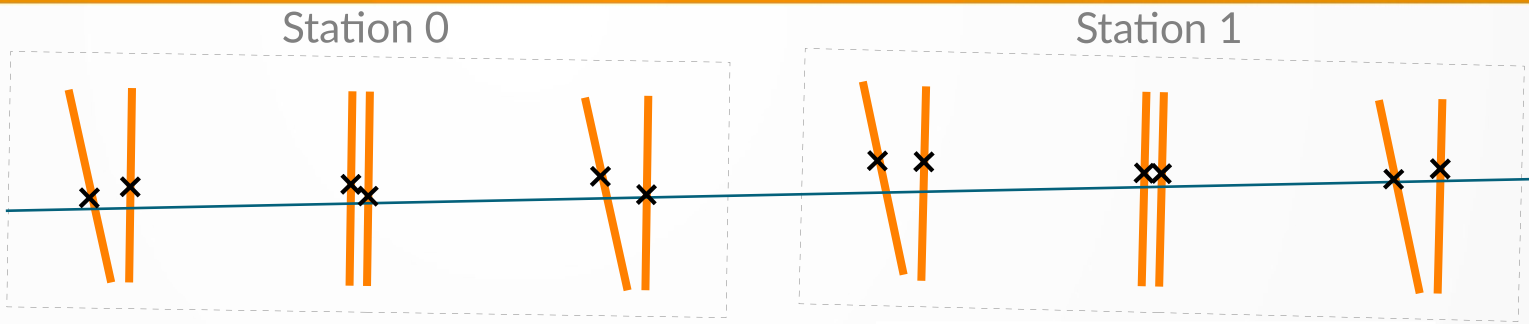
~2×10[8] μ/spill

(1 spill = ~5s)

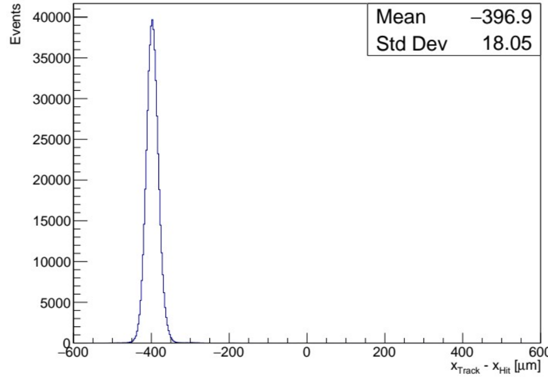


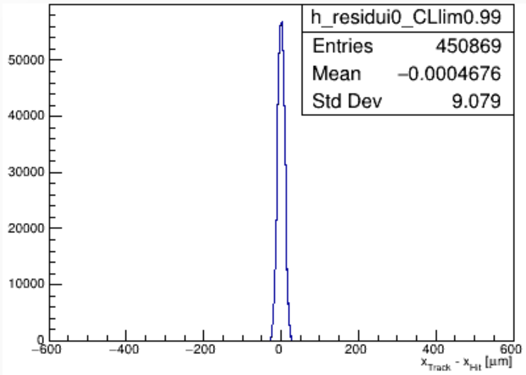
Alignment TB 2023

Alignment

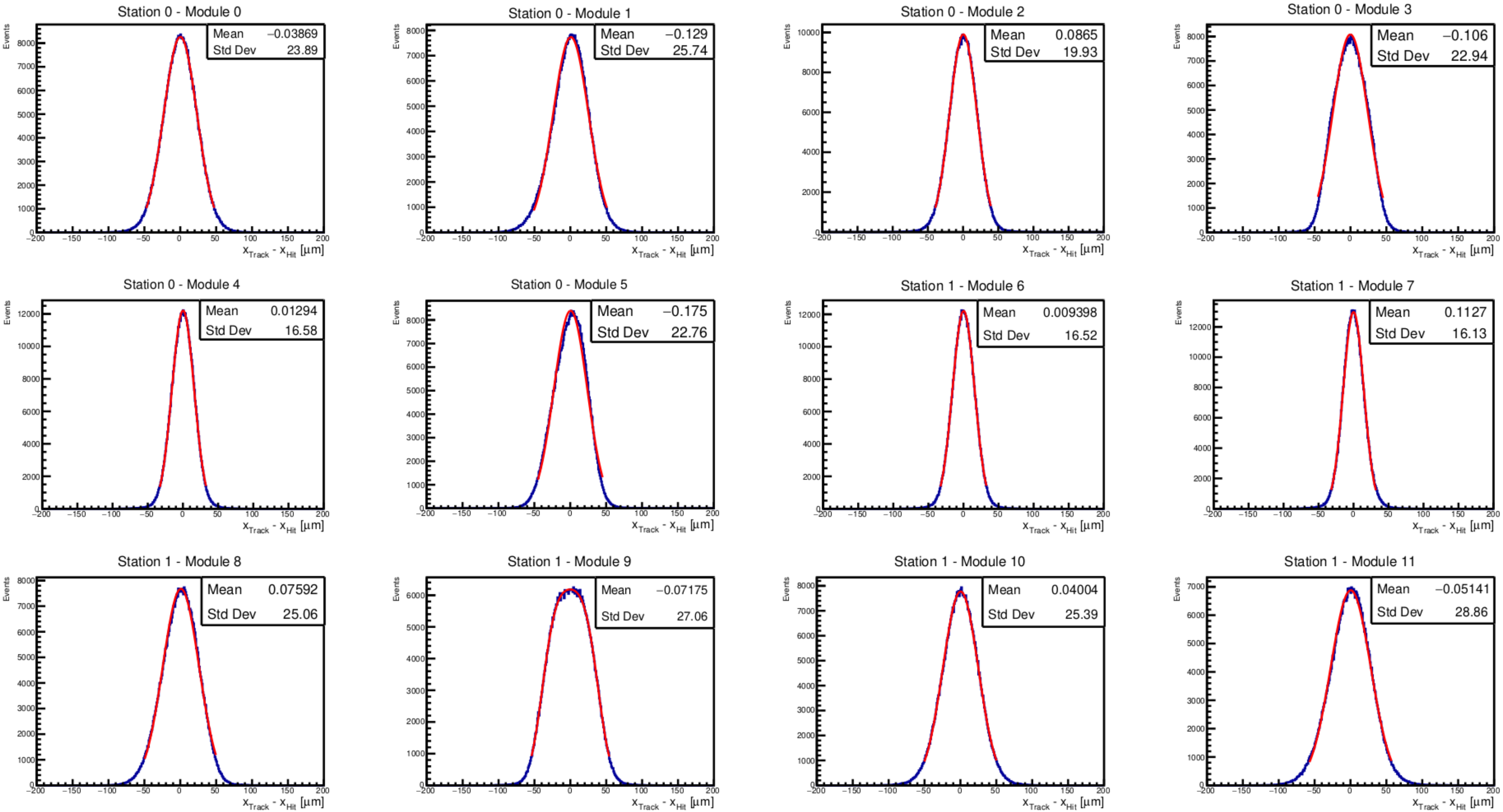


- Track based iterative procedure:
  2 alignment parameters per module
  (offset in the measured direction
  and rotation angle around the beam axis).
- Align the coordinate orthogonal to the measurement direction by measuring the image of module's middle line.



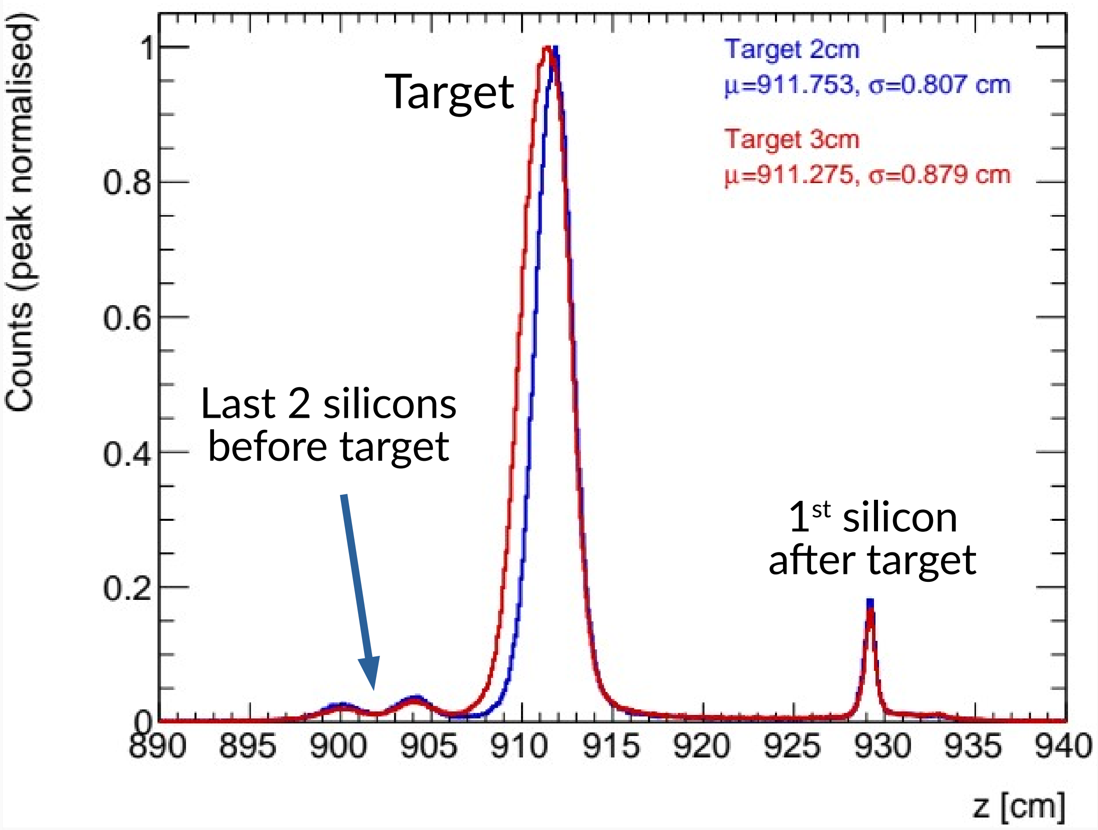


Alignment – TB 2023



Vertexing

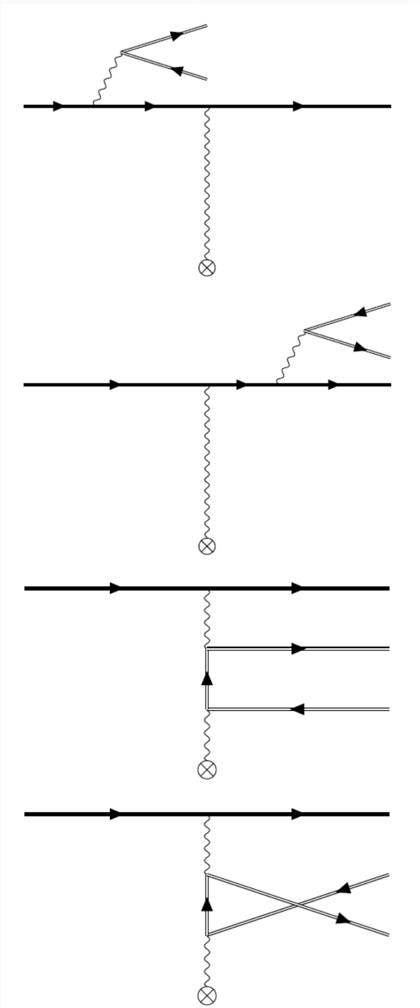
Simple selection: events with 2 outgoing tracks within geometrical acceptance (0.2 – 32 mrad).



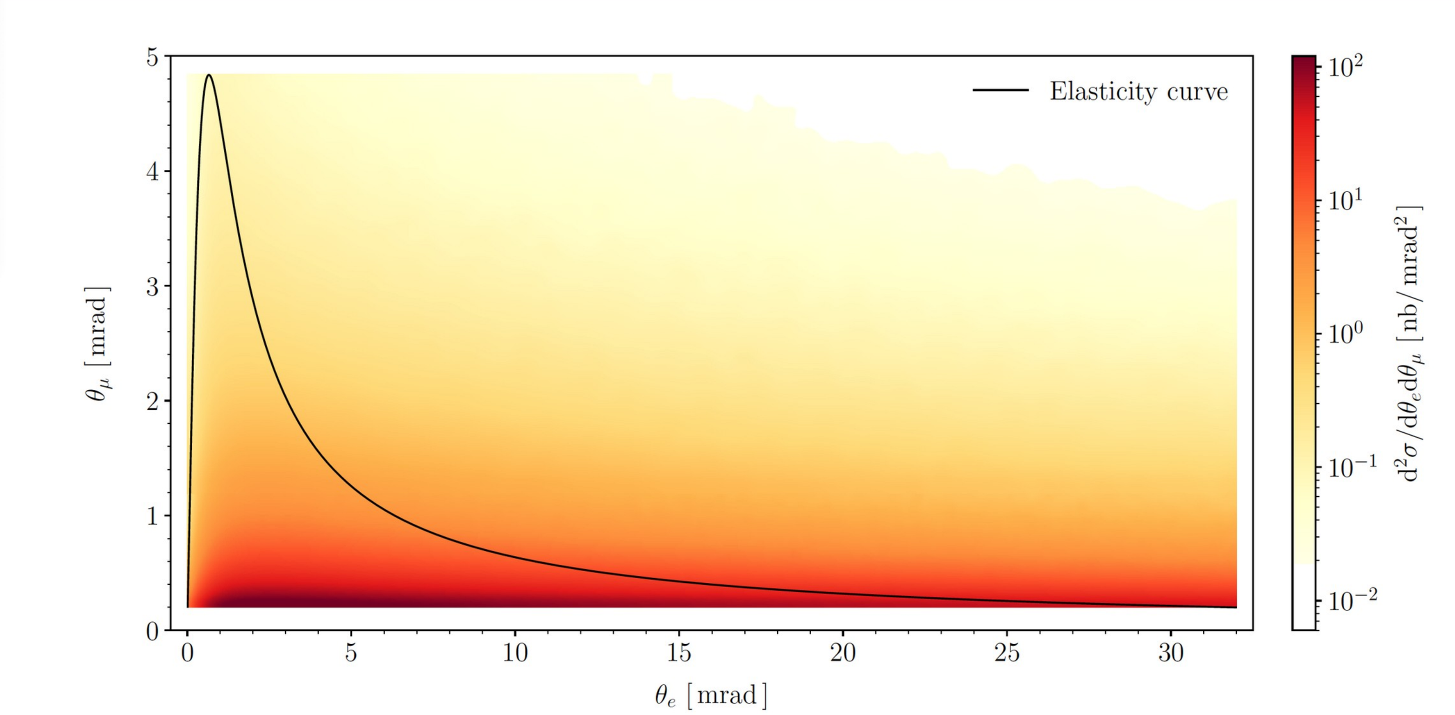
- Vertex Z fitted using the convolution between a box (target thickness) and a Gaussian (resolution).
- The target center is shifted by 0.5 cm by changing between 3cm and 2cm target (OK!).
- **Vertex resolution: ~0.8 cm**. (Slightly worse for 3cm target due to MS).

New Background MC generator

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

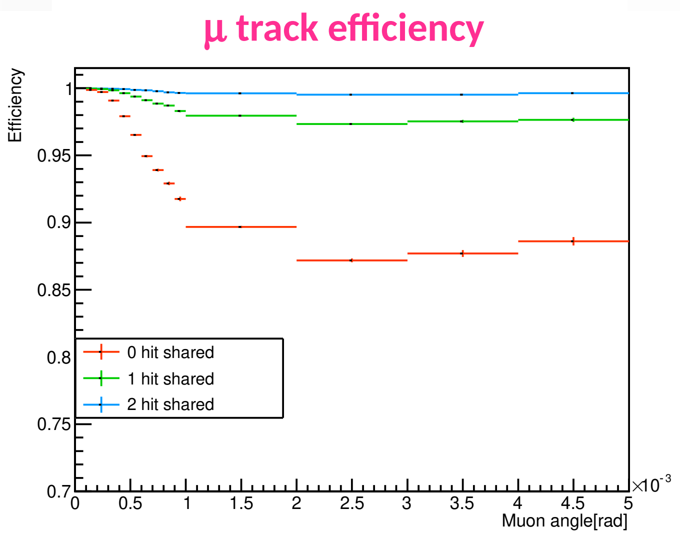


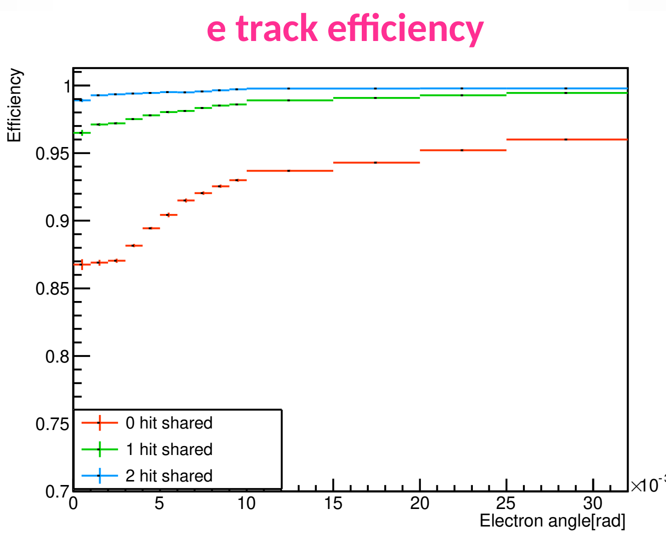
Numerical results for $\mu^+ C \to \mu^+ C\, e^+ e^-$ (3)

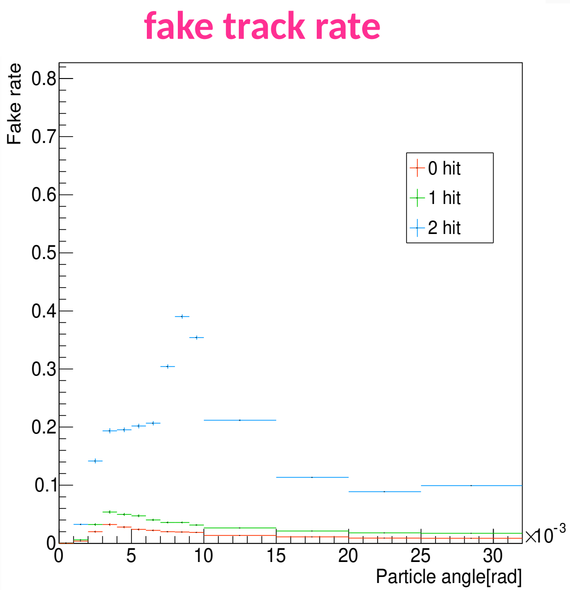


MC performance - Track reconstruction in μe elastic scattering events

Algorithmic reconstruction performance for reconstructible particles, with 3cm Target, for different setting of the reco configuration:
maximum number of shared hits between two tracks = 0,1,2
The efficiency is defined by matching the MC truth with a Quality cut of Q>0.65, i.e. at least 4/6 hits have to be correctly taken in the reconstructed trajectory







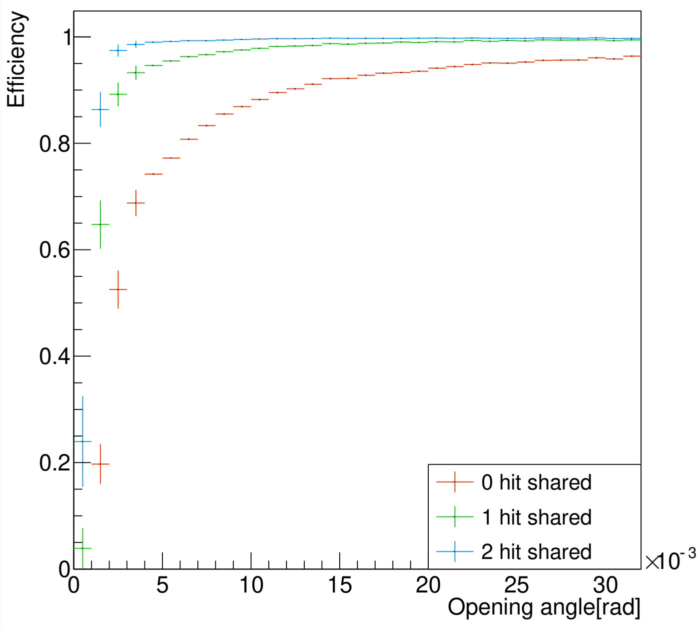
Flat and high efficiency for 2 max shared hits (close tracks in the first pair of modules nearest to the target)
Drawback: fake rate due to clone and background tracks, but can be easily rejected by later steps (vertexing)

MC performance –
μe elastic event reconstruction

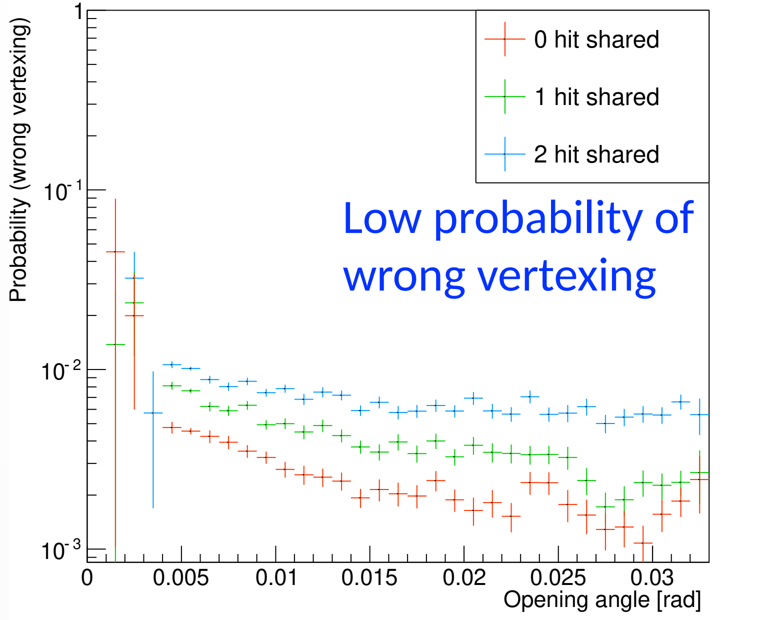
Algorithmic reconstruction performance for reconstructible events, with 3 cm Target, for different setting of the reco configuration:
maximum number of shared hits between two tracks = 0,1,2
The efficiency is defined by matching the MC truth with a Quality cut of Q>0.65, i.e. at least 4/6 hits have to be correctly taken in the reconstructed trajectory

Flat efficiency for 2 max shared hits (close tracks in the first pair of modules nearest to the target)

μe event efficiency



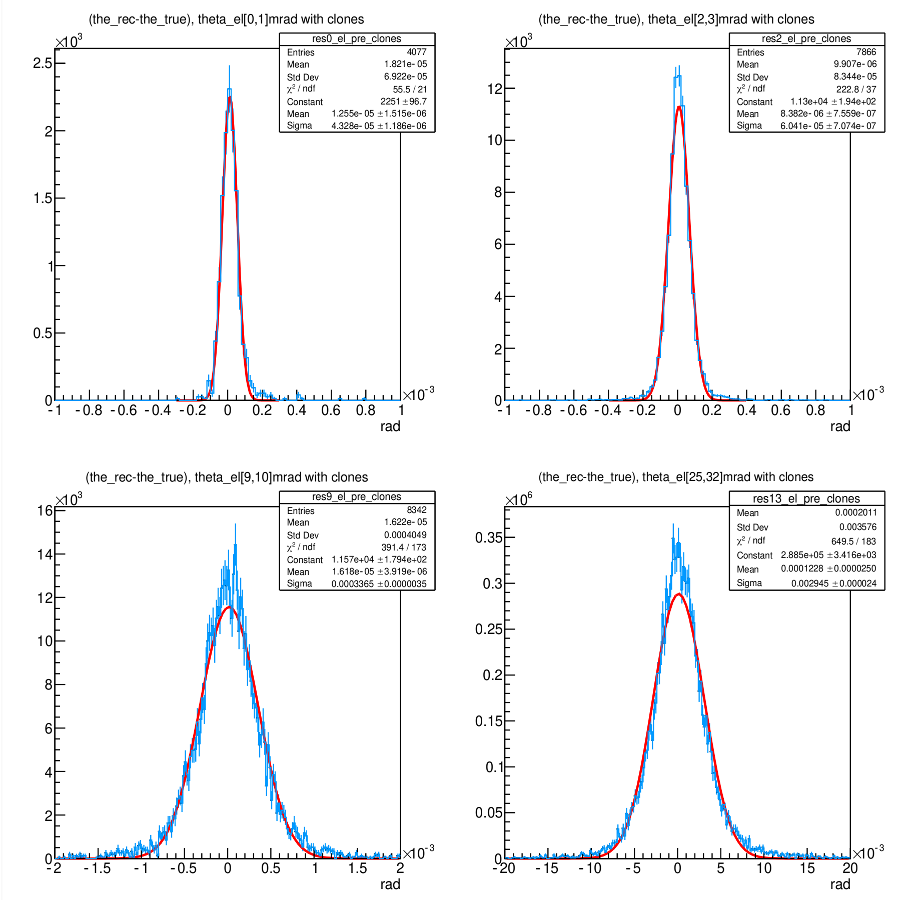
wrong vertex probability



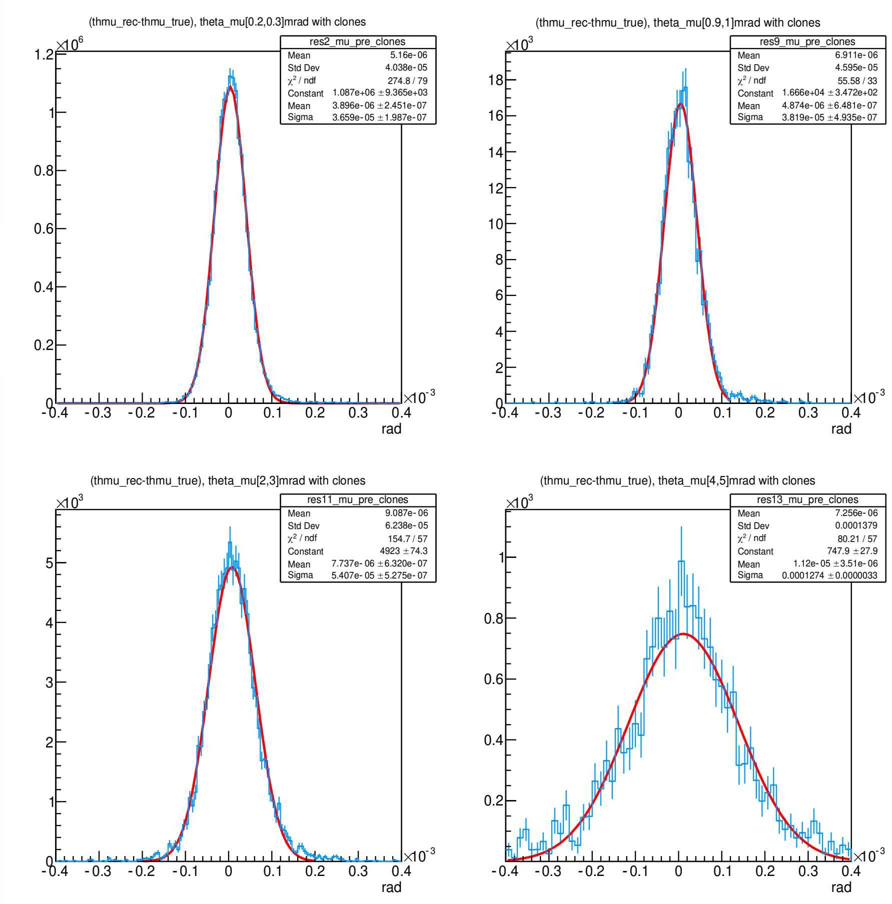
MC performance – Angular Resolution vs Scattering Angle

in different angular bins

electron



muon

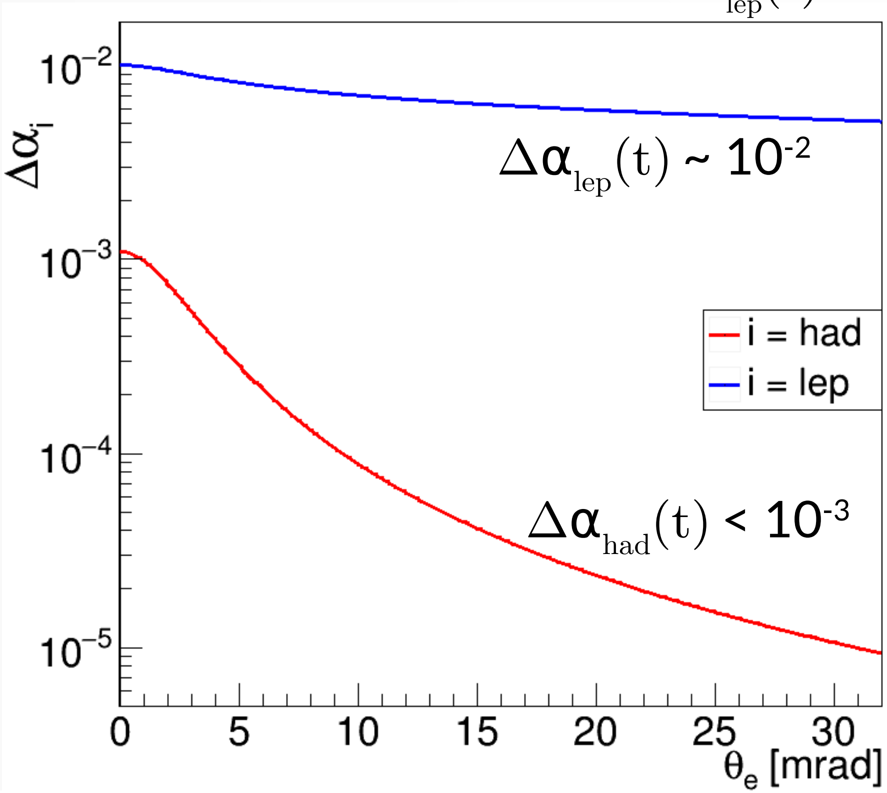


TB 2023 - extraction of $\Delta\alpha_{lep}(t)$: expectations

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%

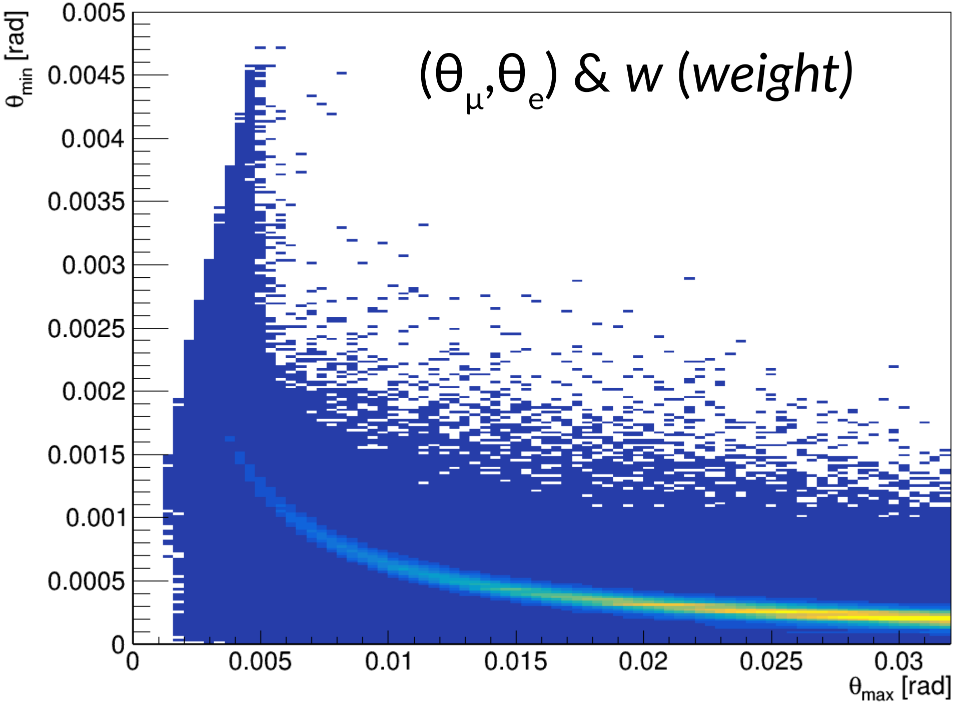
Studied on fast simulation neglecting background.

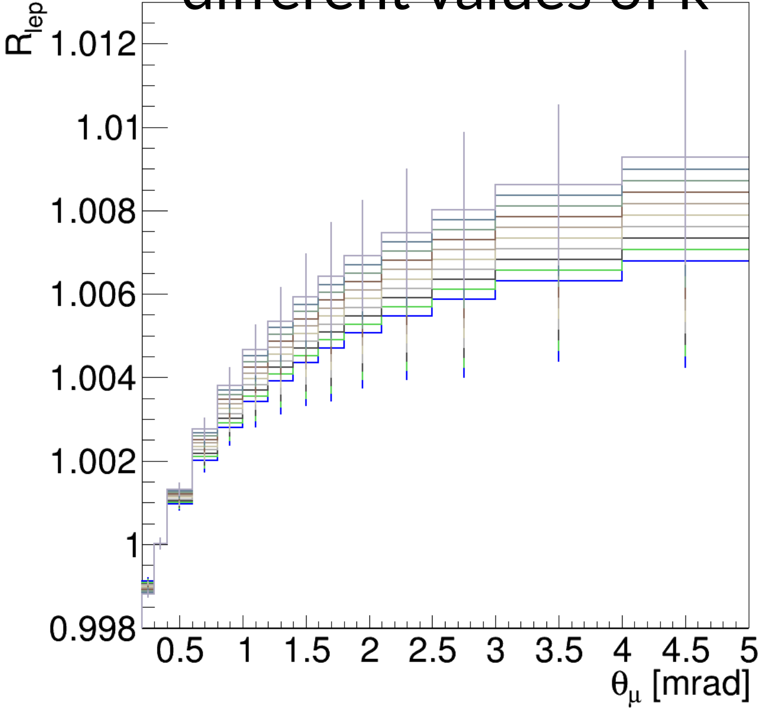
Production of Monte Carlo templates

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

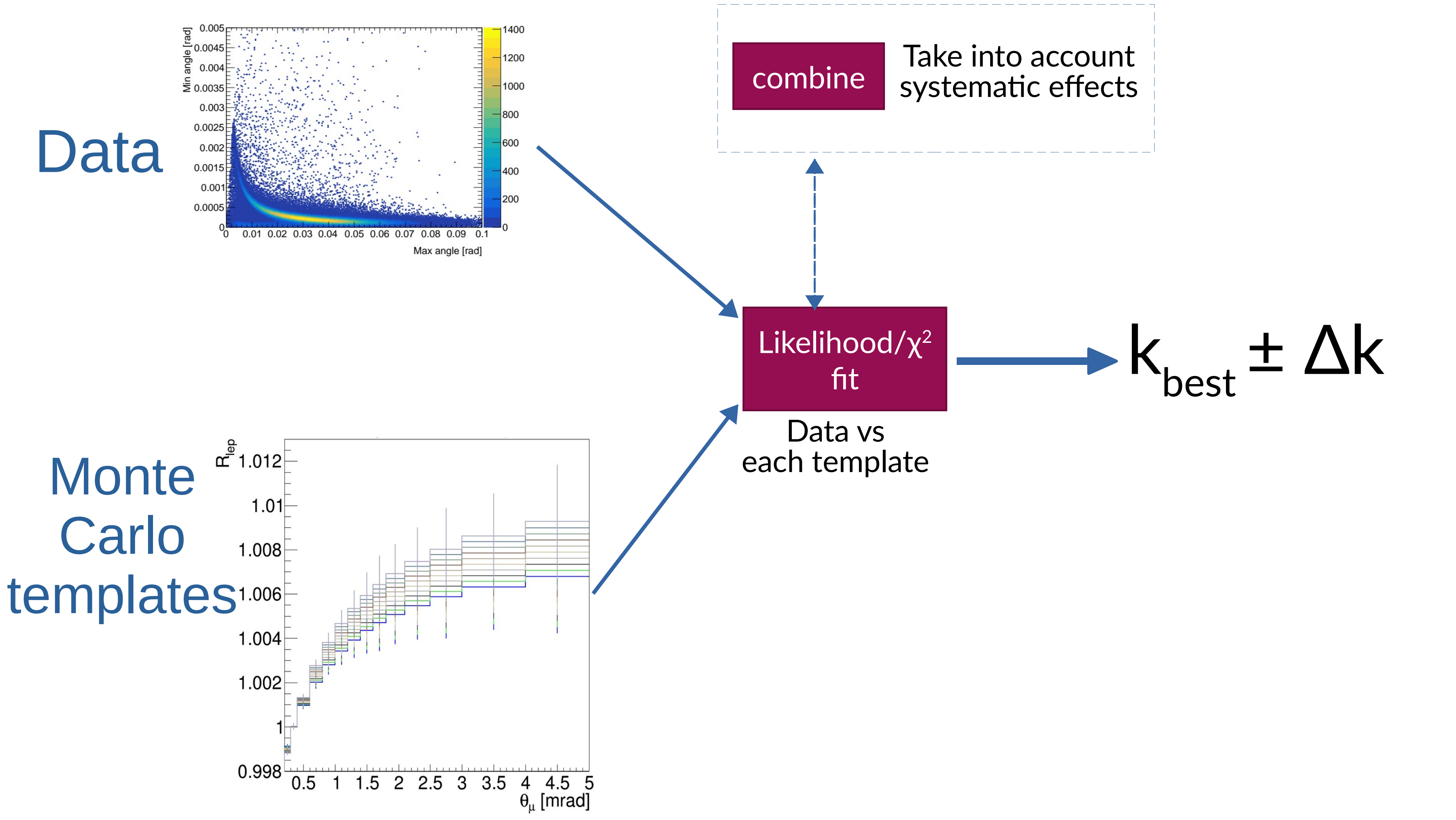
- Geant4 simulation
- Track reconstruction

Templates for different values of k



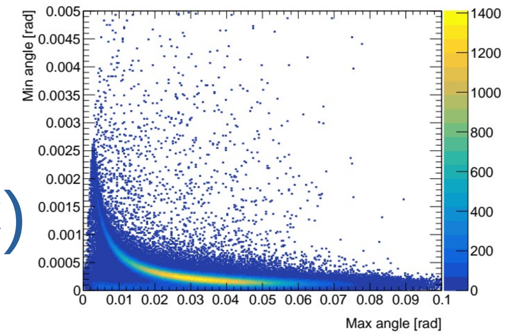


Analysis workflow

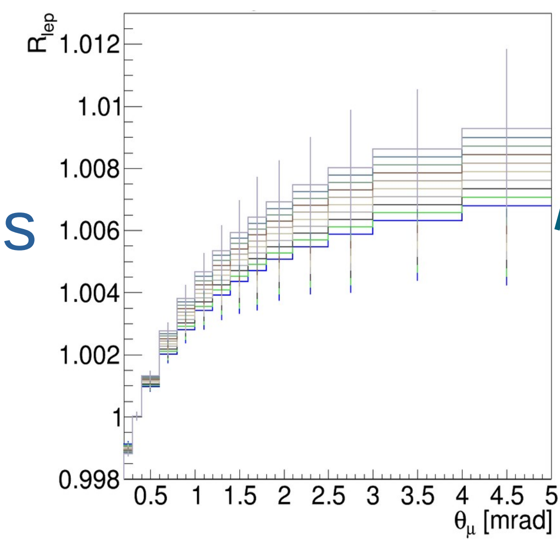


Test using pseudodata (Monte Carlo)

Pseudo data (MC)



Monte Carlo templates

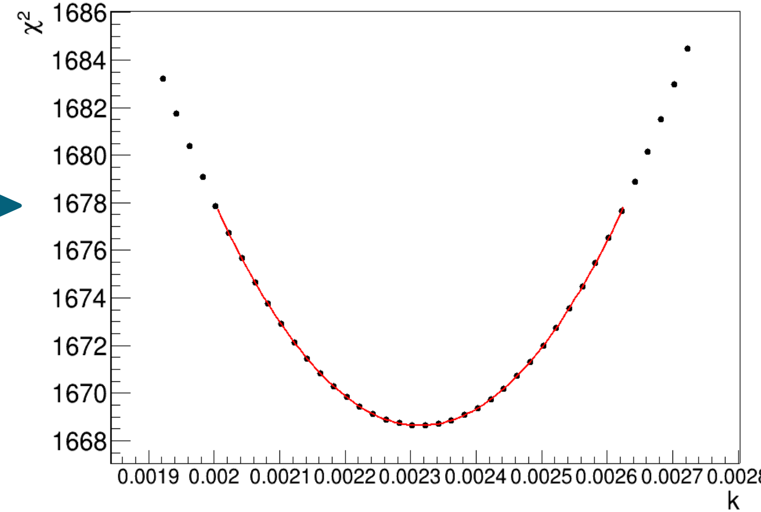


combine

Take into account systematic effects

Likelihood/χ^2 fit

Data vs each template

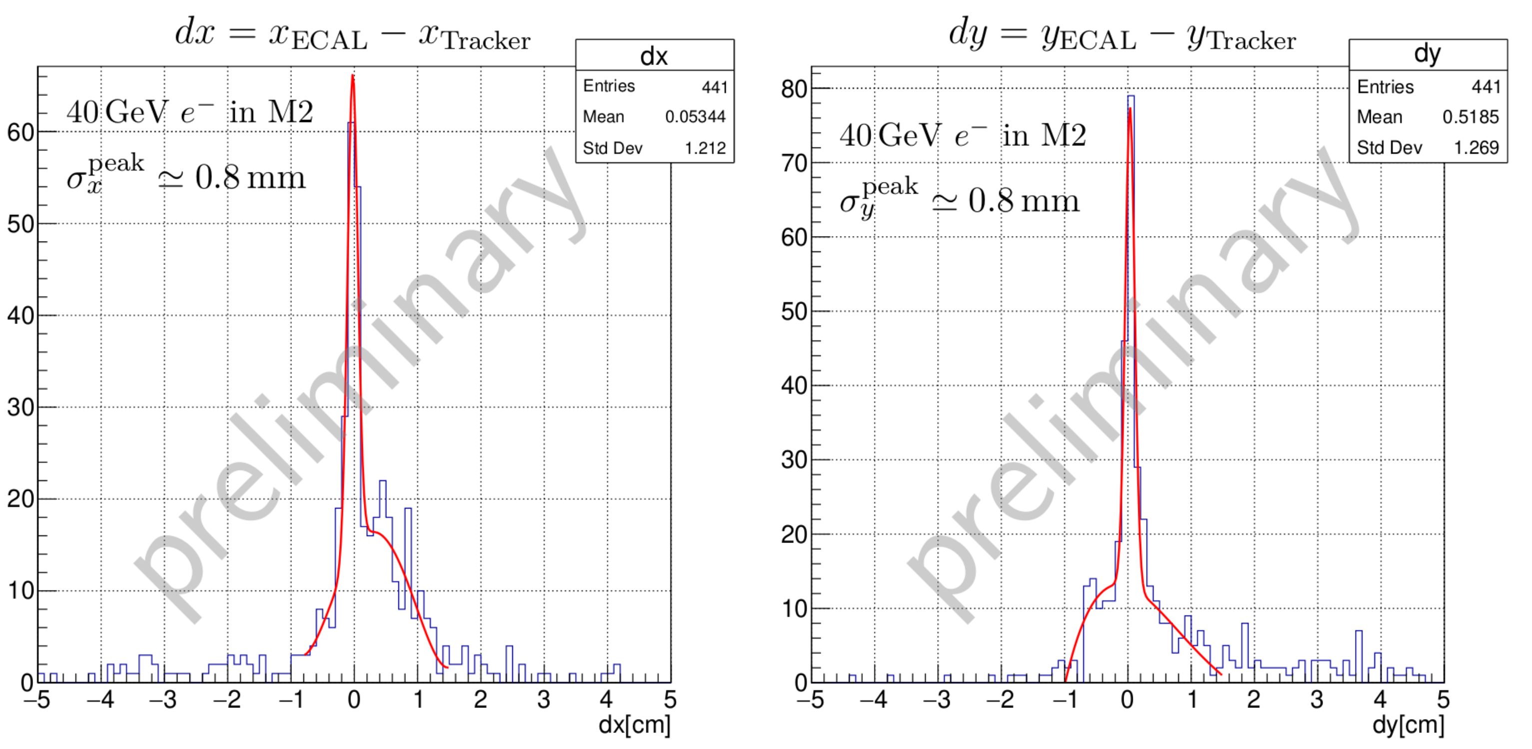


k_{best} = 0.00232(10) → ~5%

k_{input} = 0.00232

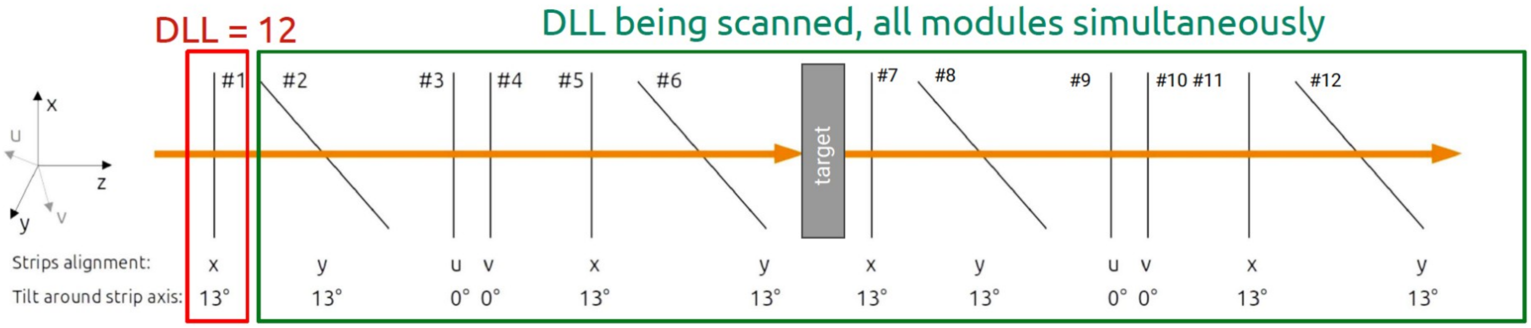
ECAL – spatial resolution

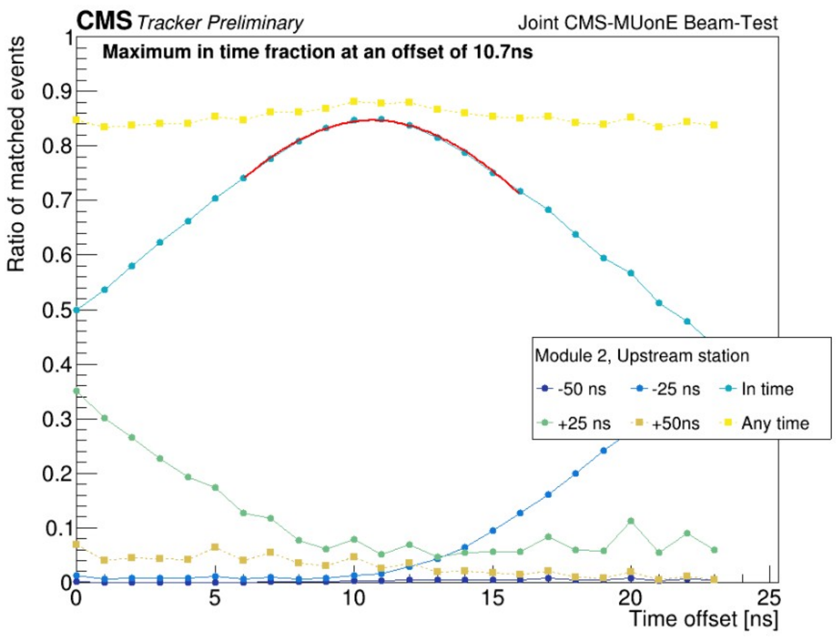
Sub-mm peak resolution in good agreement with simulations.

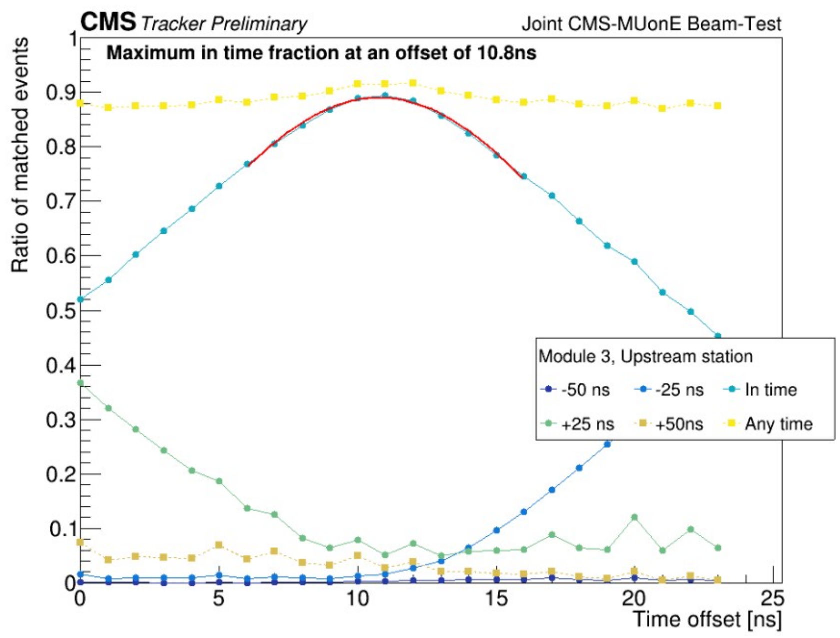


- Small sample (ECAL integrated in the main DAQ only at the end of the run).
- Technical issues limited ECAL data quality (now solved).

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).

The need of including systematic effects in the analysis

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

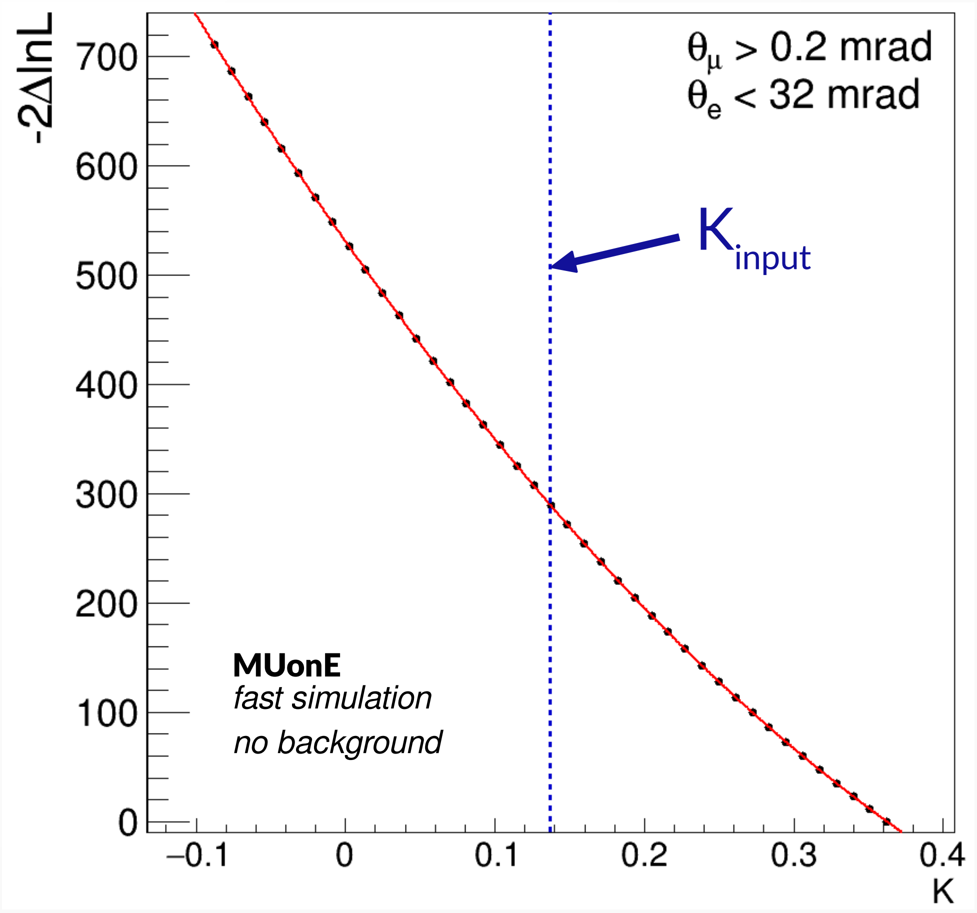
Simplified situation:

- 1 fit parameter (K).

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

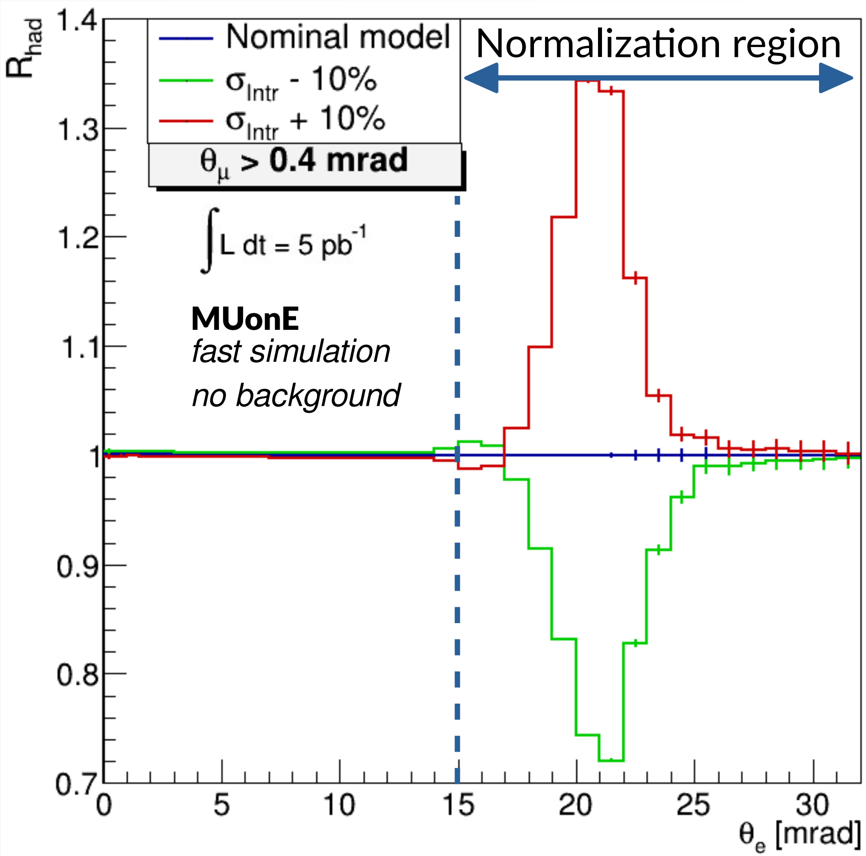
- L = 5 pb^{-1}.
  ~10^9 elastic events
  (~4000 times less than the final statistics)

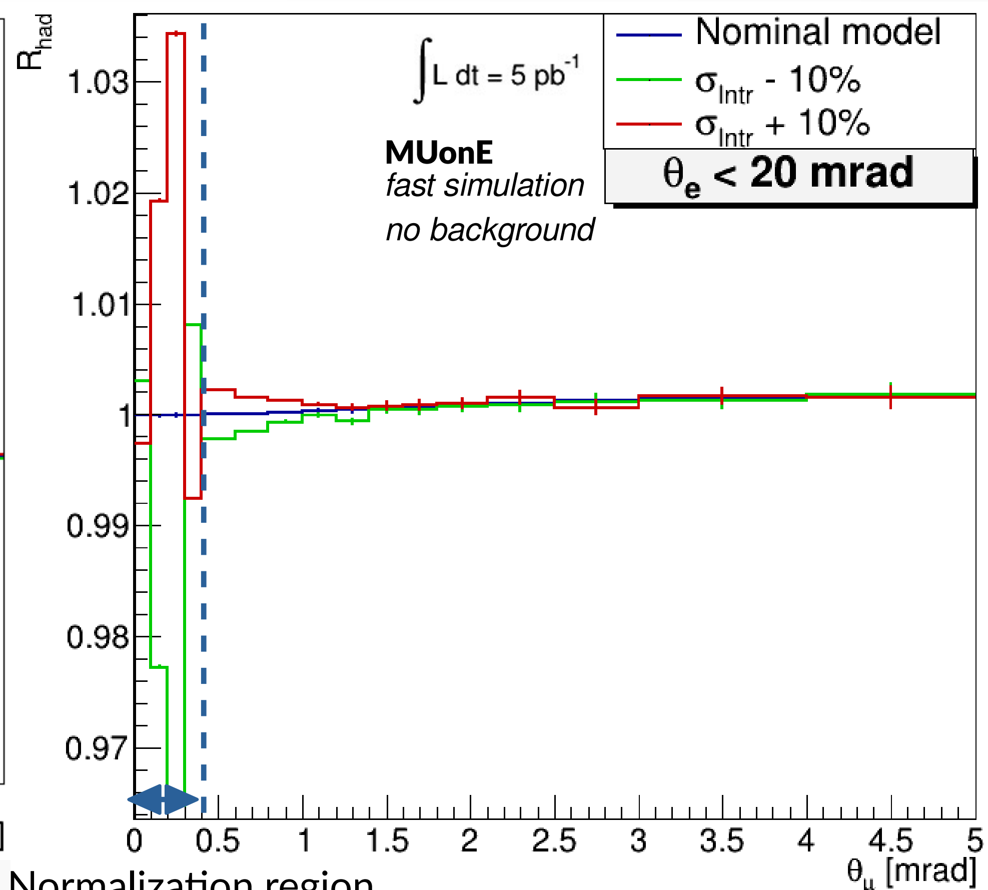
- Example: shift the pseudo-data sample by $\sigma_{Intr} \rightarrow \sigma_{Intr}$ + 5%.



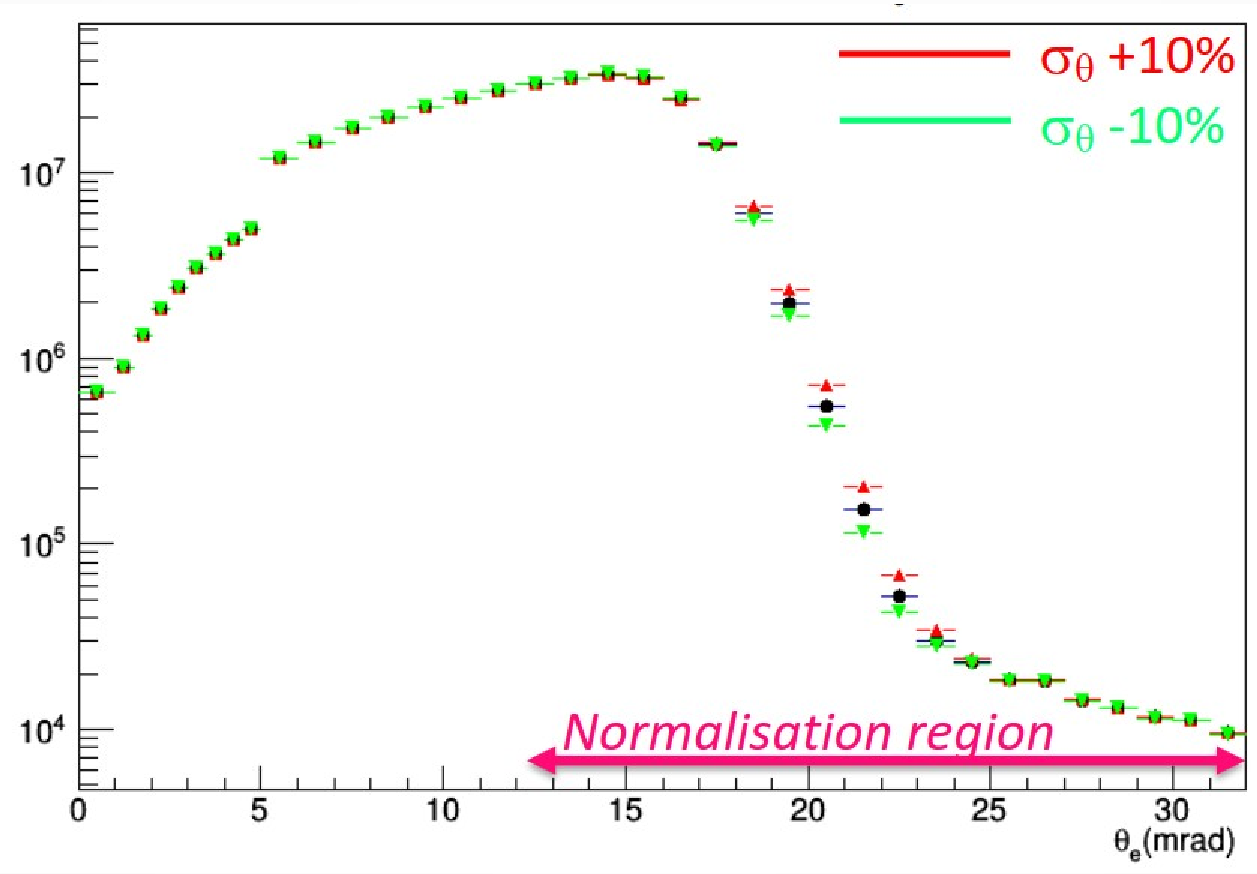
Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution.





Normalization region

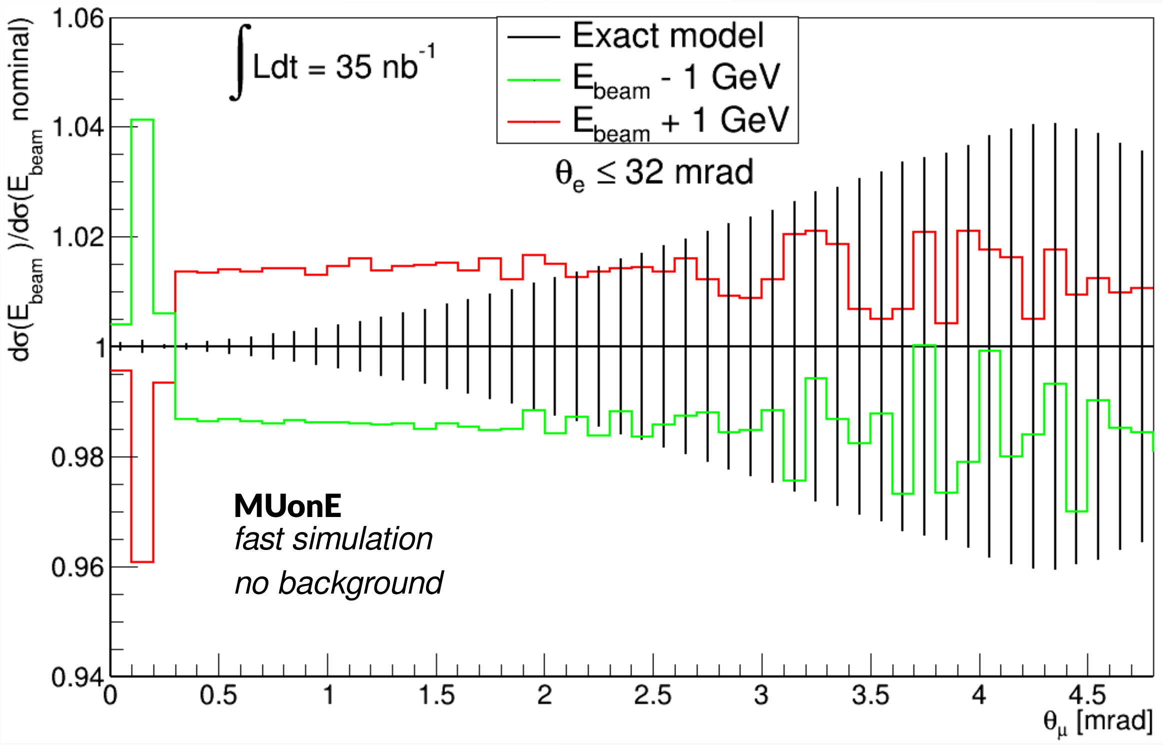


σθ +10%
σθ -10%
Normalisation region
10^7
10^6
10^5
10^4
0
5
10
15
20
25
30
θe(mrad)

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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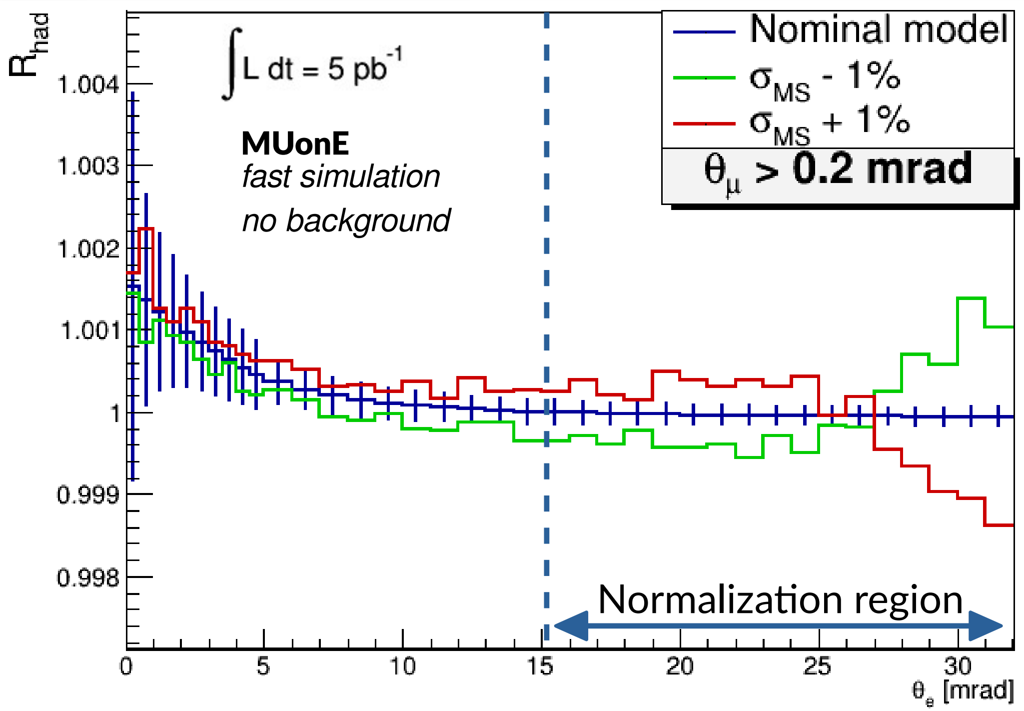
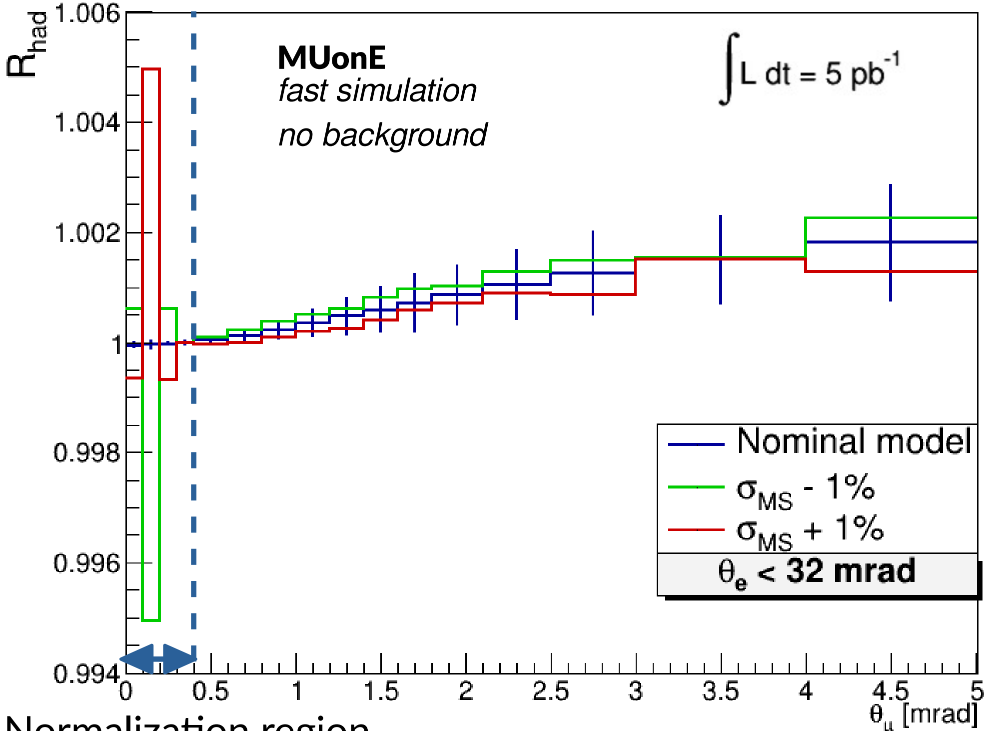
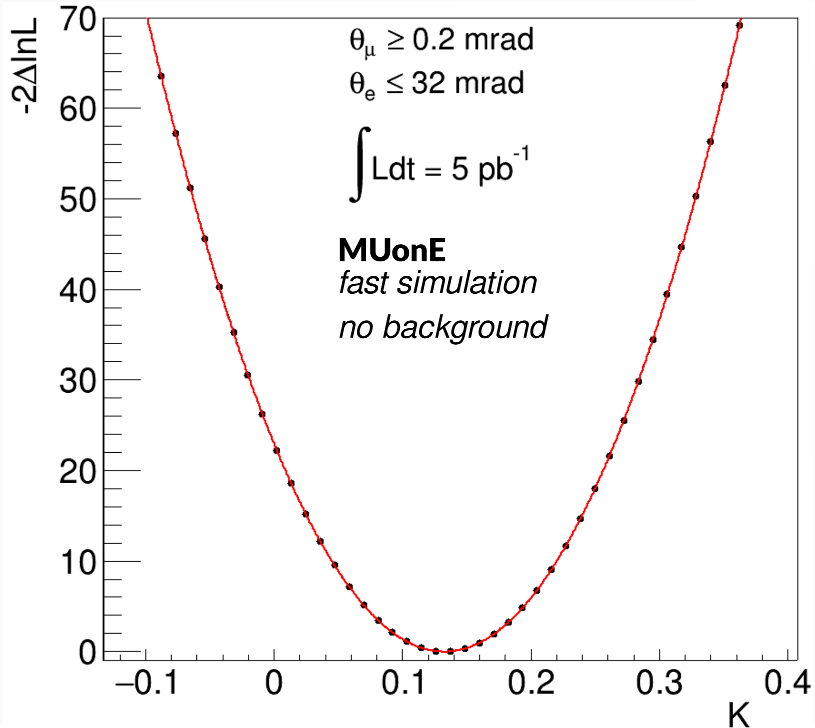




Normalization region

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

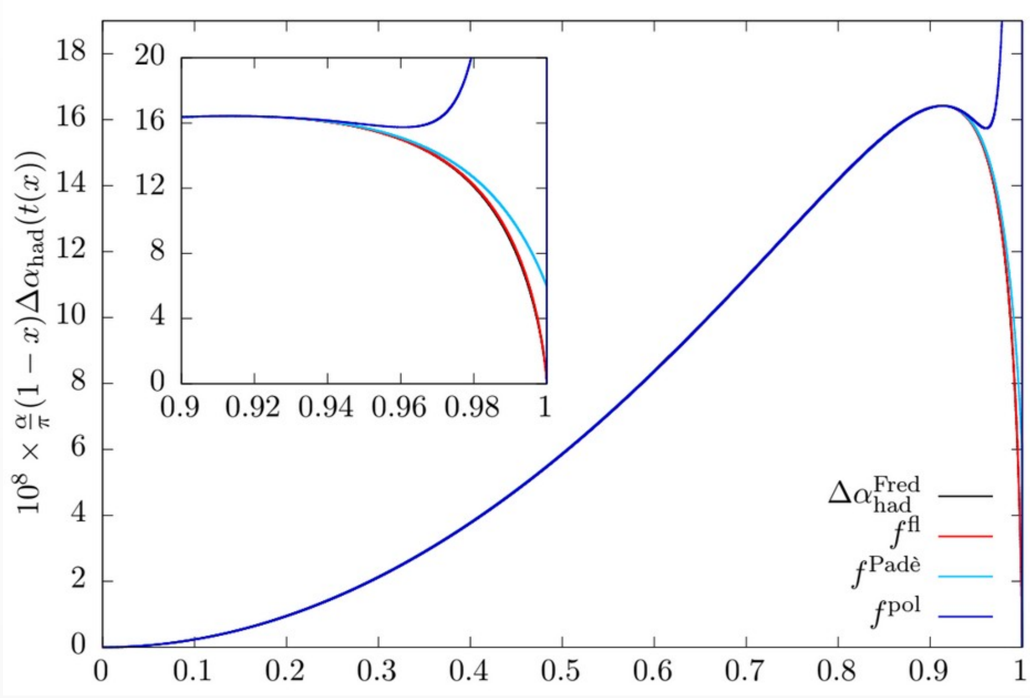
$$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$

2 parameters:
K, M

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

Dominant behaviour in the MUonE kinematic region:

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



Alternative method to compute a_μ^{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%

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

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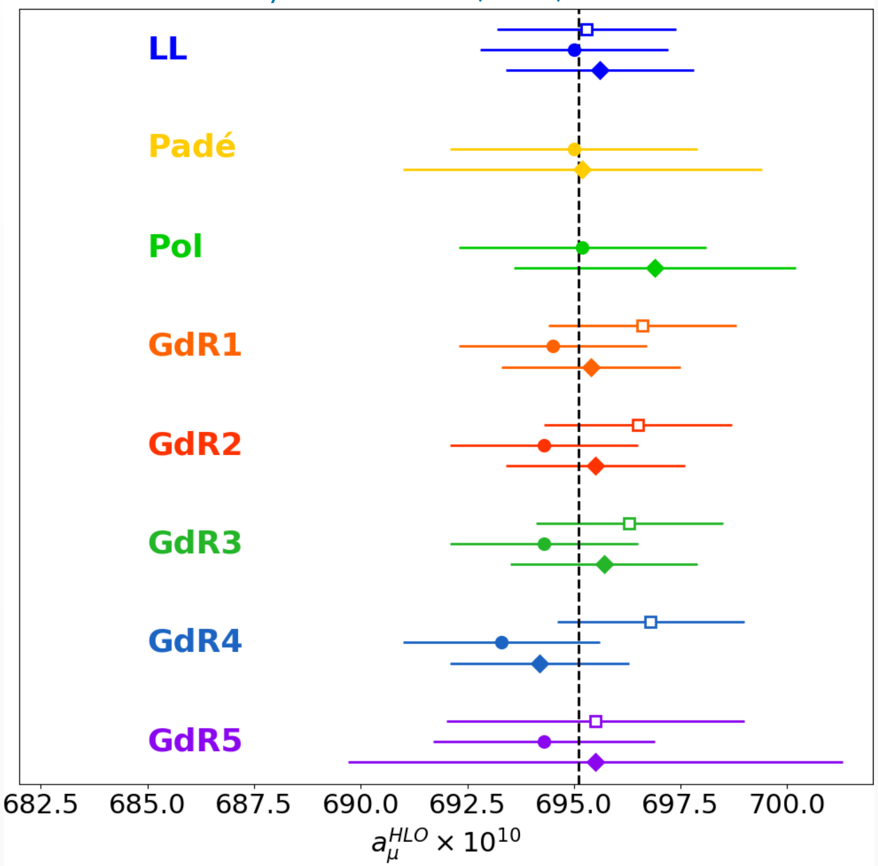
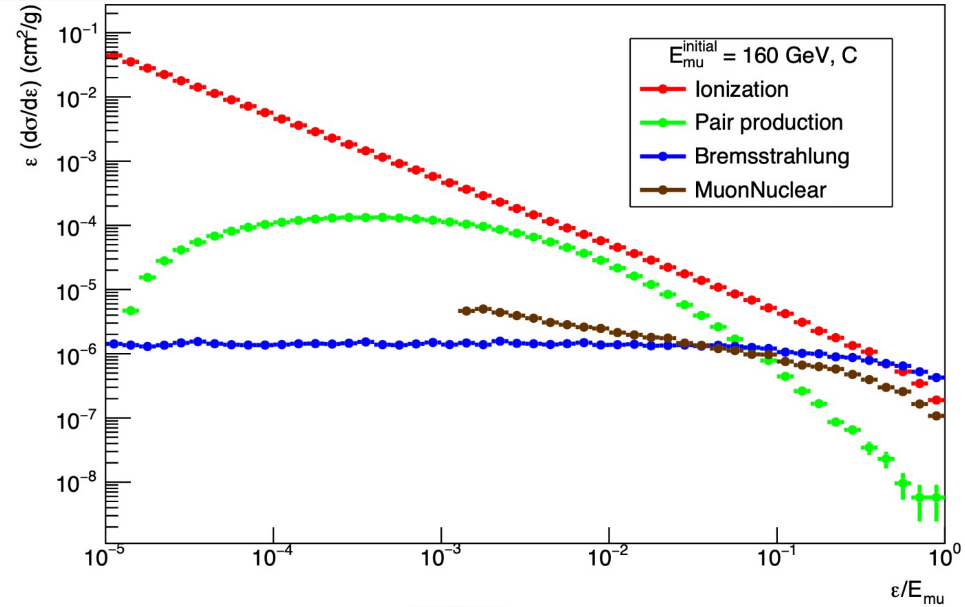
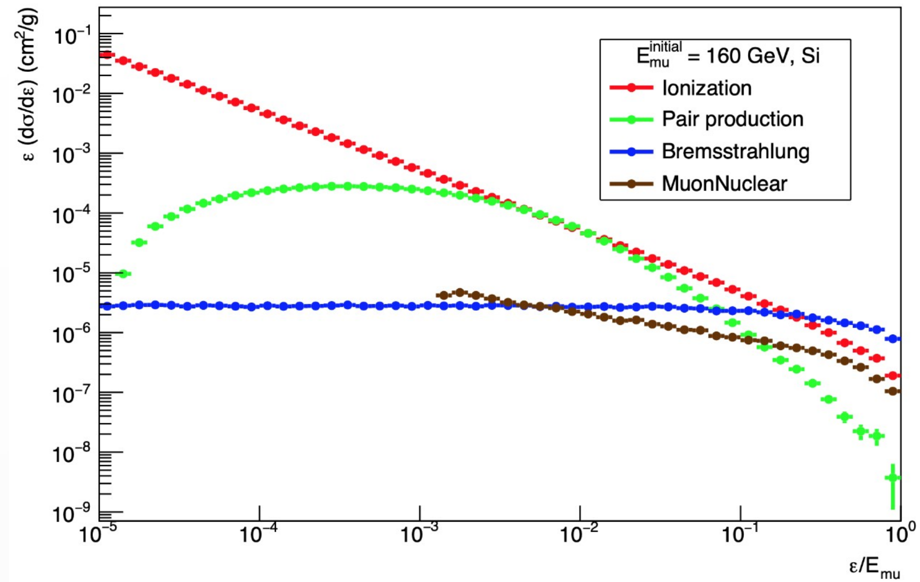


Backgrounds





θ_e [mrad] 32 0

GEANT4

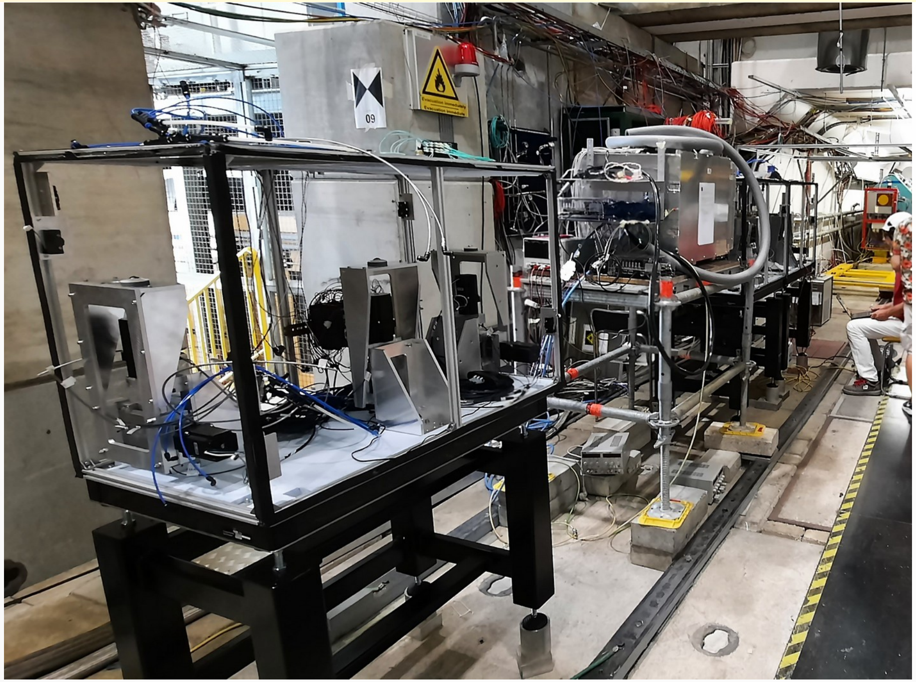
MESMER

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

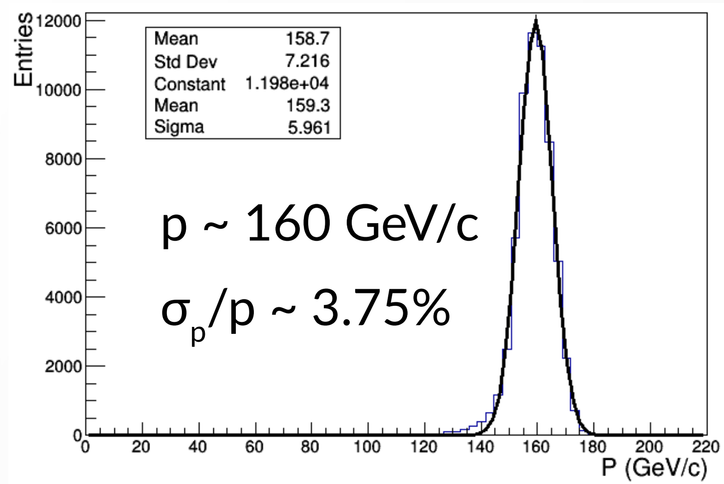
$l = e, \mu$

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

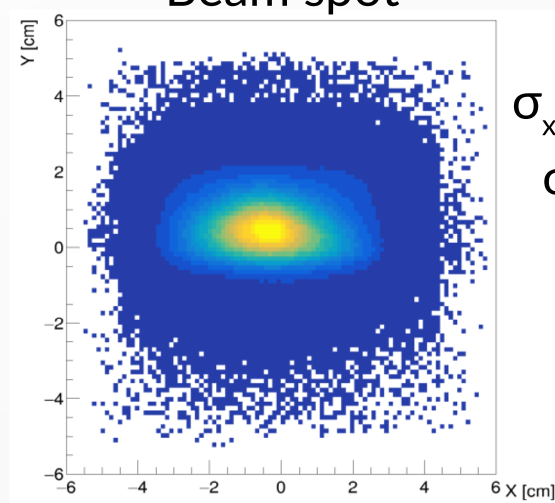
The M2 beamline



Beam momentum



Beam spot

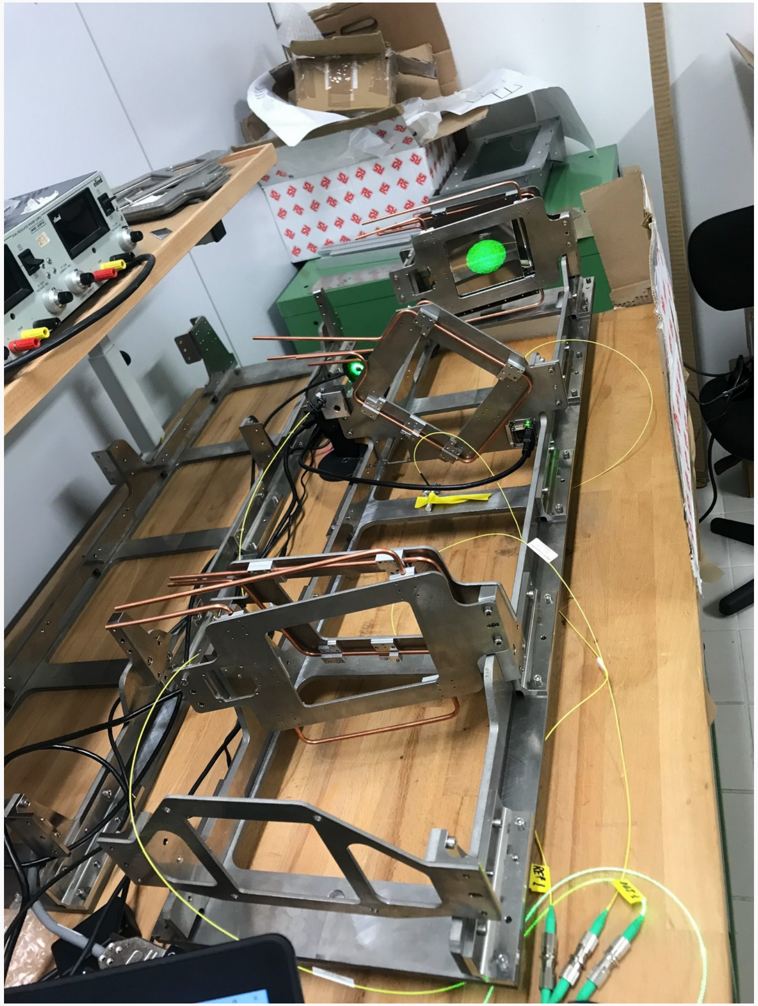


σ_x ~ 13 mm

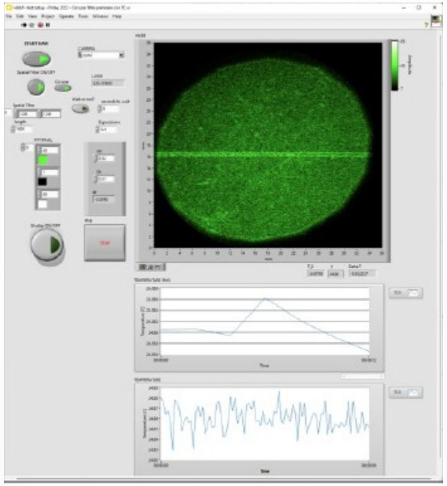
σ_y ~ 7 mm

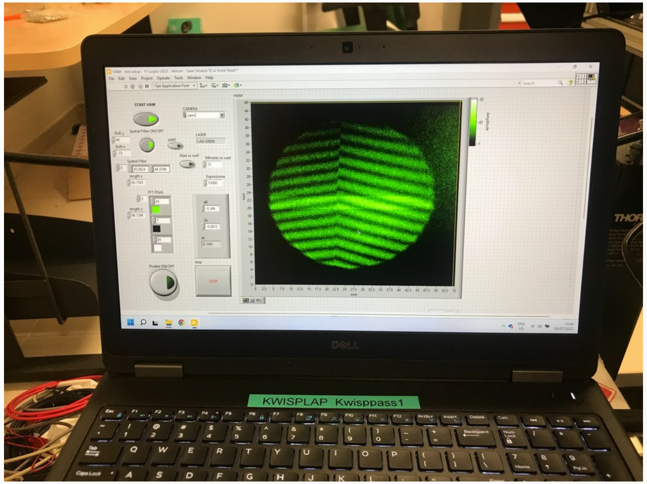
- MUonE location:
  upstream of the AMBER detector (EHN2).
- Low divergence muon beam: $\sigma_{x'}$, $\sigma_{y'}$ < 1 mrad.
- Spill duration ~5 s. Duty cycle ~ 25%.
- Maximum rate: **50 MHz** (~ 2×10^8 μ^+/spill).

Laser holographic system



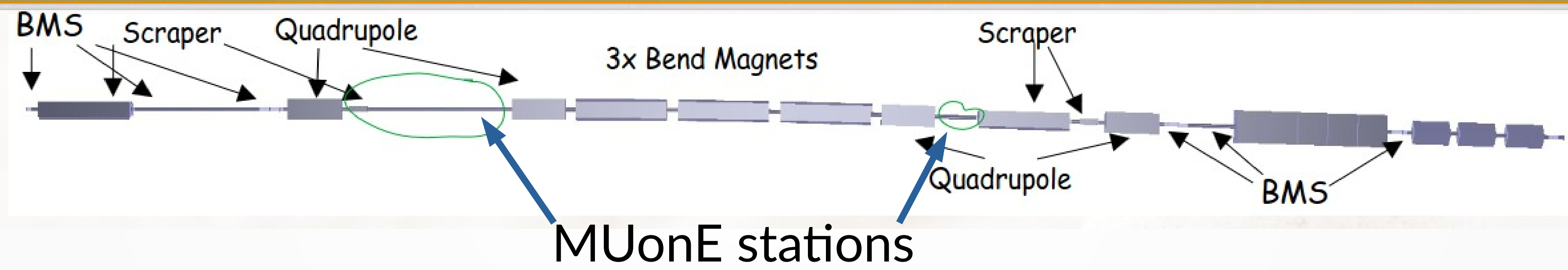
Initial state



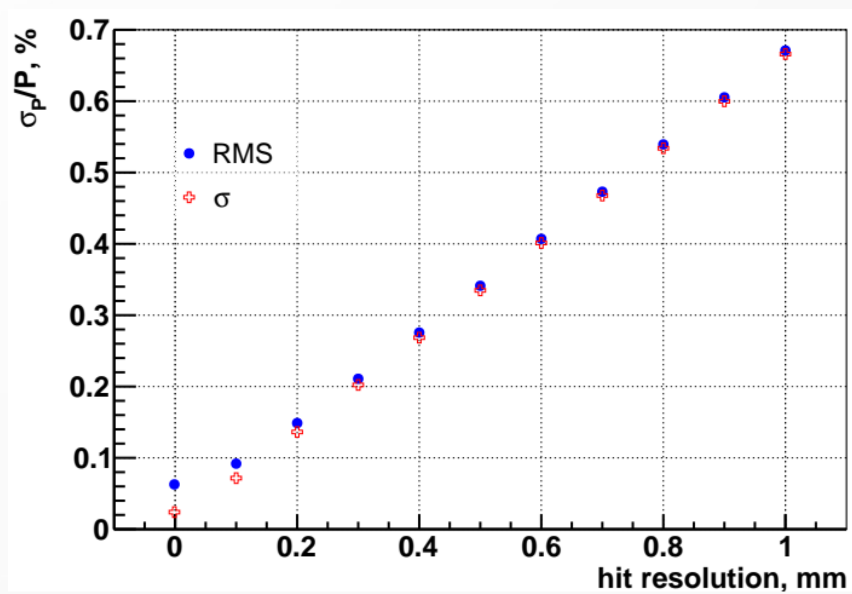


- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.

BMS (Beam Momentum System)

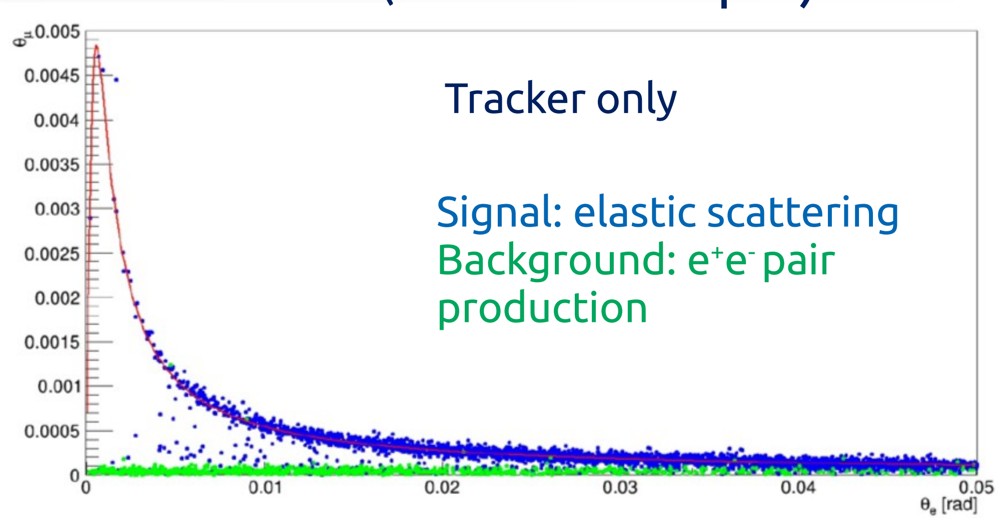


- Bending power: 16 T*m (30 mrad @160 GeV)
- Replace the current scintillator detectors used by COMPASS/AMBER with MUonE tracking stations, fully equipped with prototype 2S modules.
- Determine the muon momentum event by event.
- Improve the momentum resolution from ~1% to ~0.3% (limited by the knowledge of the magnetic field).

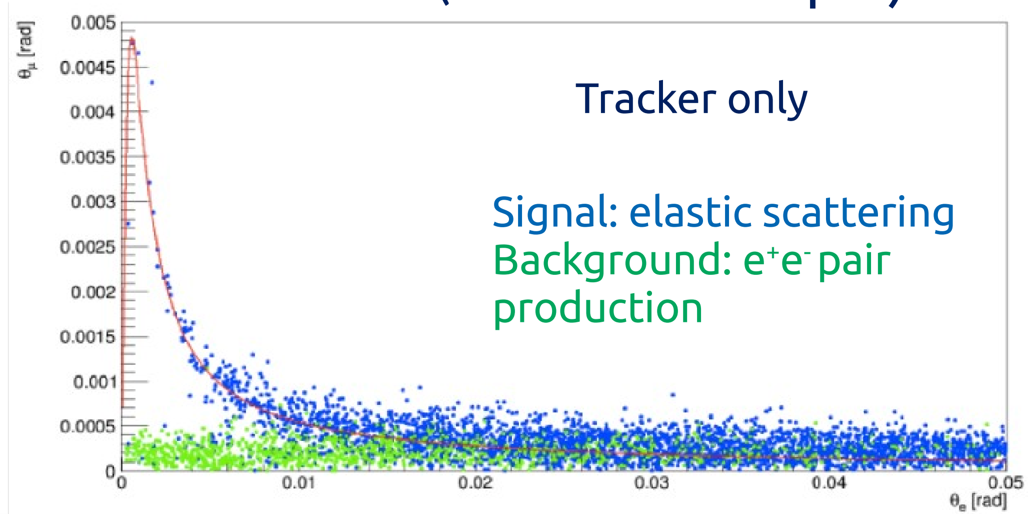


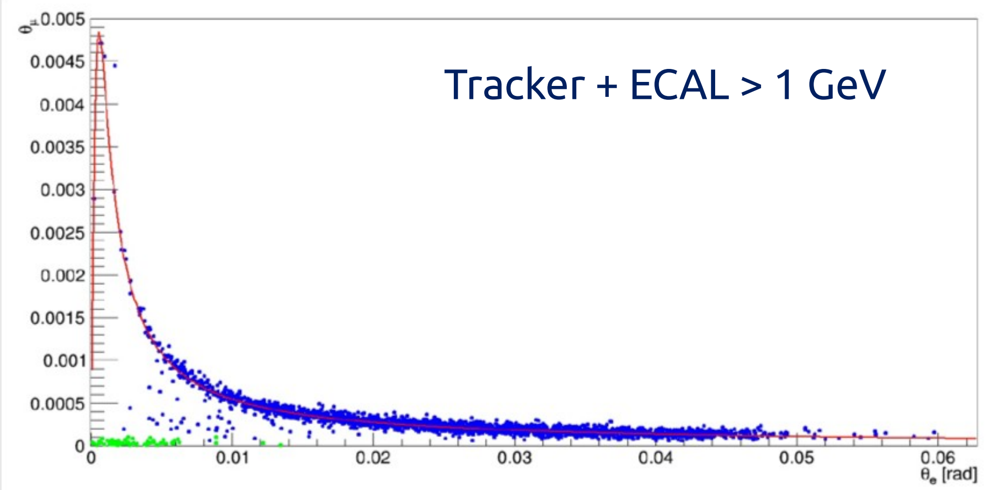
GEANT4 simulations

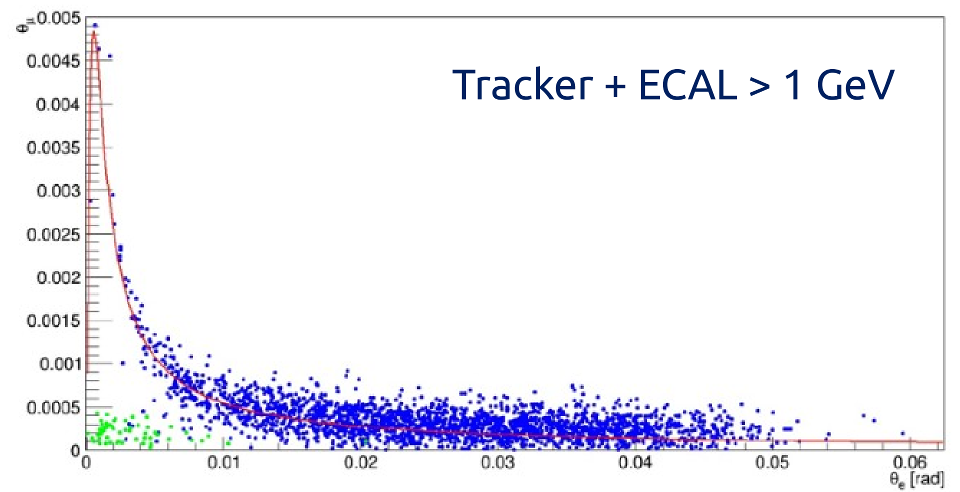
TB2017 (resolution ~7μm)



TB2018 (resolution ~40μm)

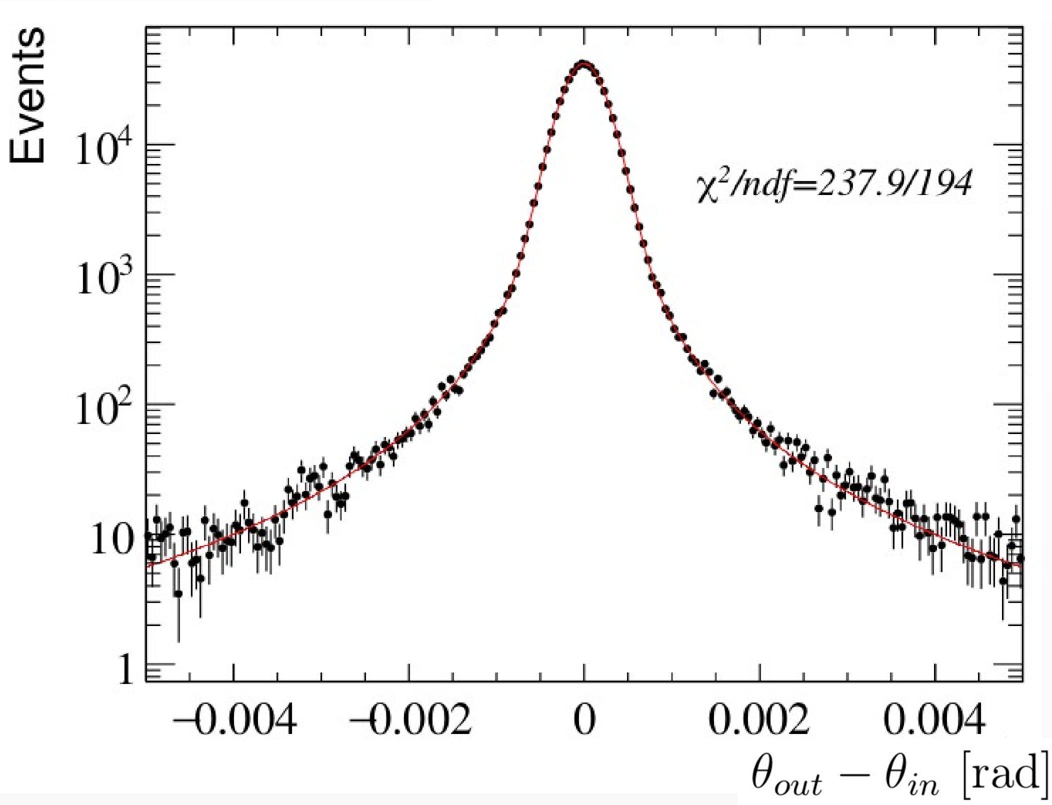






Multiple scattering: results from TB2017

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



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

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