Status of the MUonE experiment

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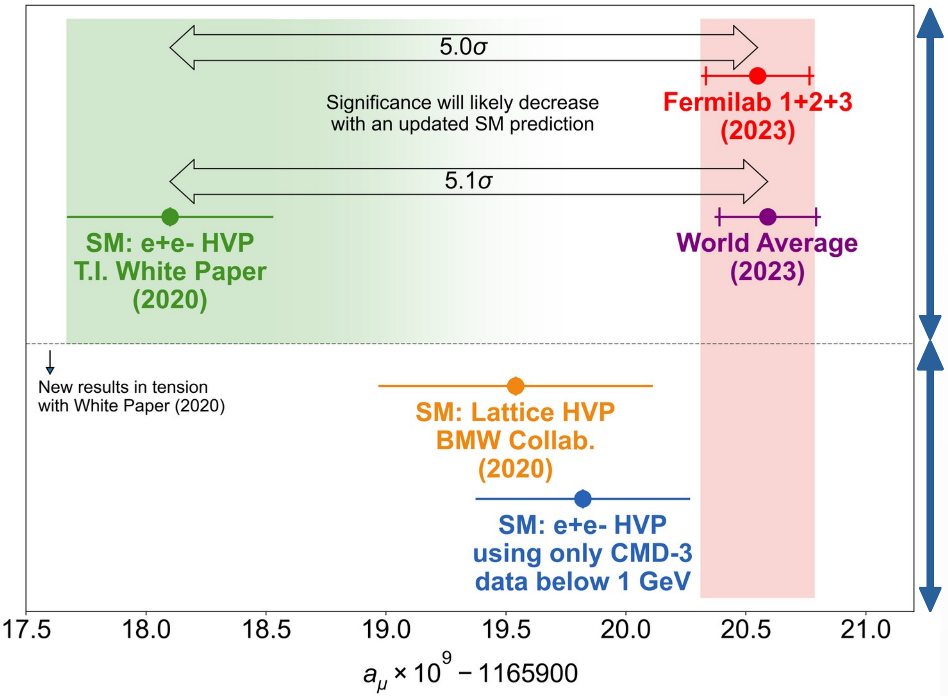
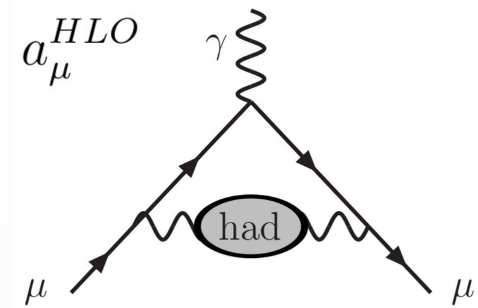
Muon g-2: current status

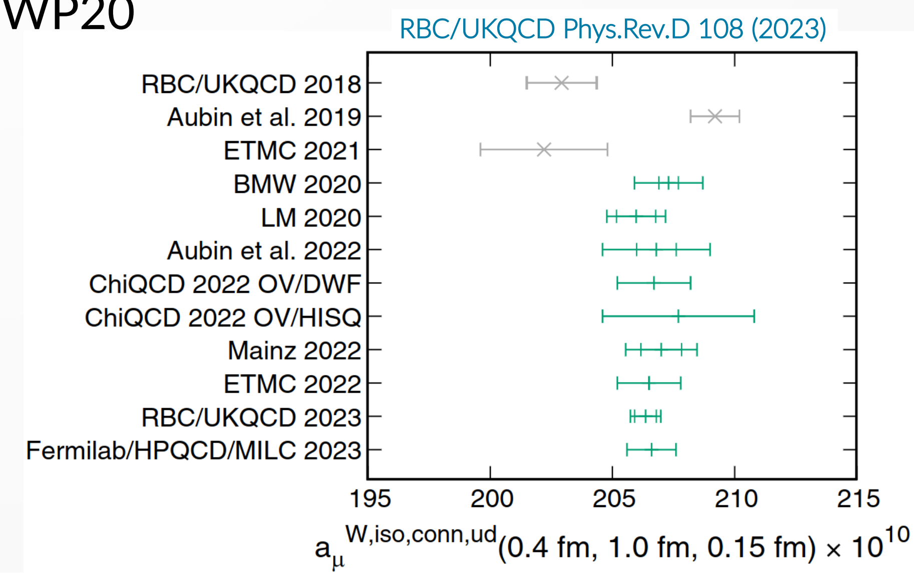


Comparison with WP20

New results after WP20



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



A clarification of the theoretical prediction is needed.

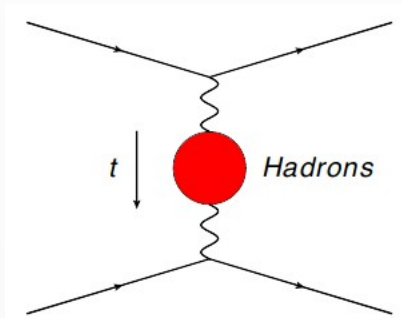
The MUonE experiment

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

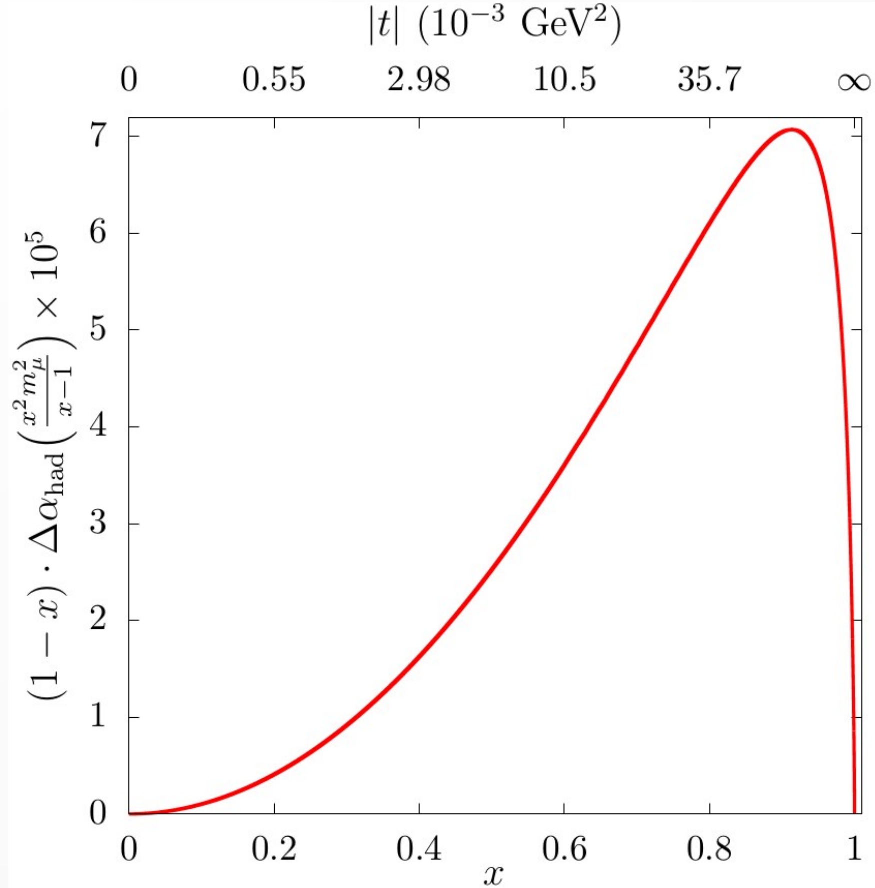
Phys. Rep. C 3 (1972), 193

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

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



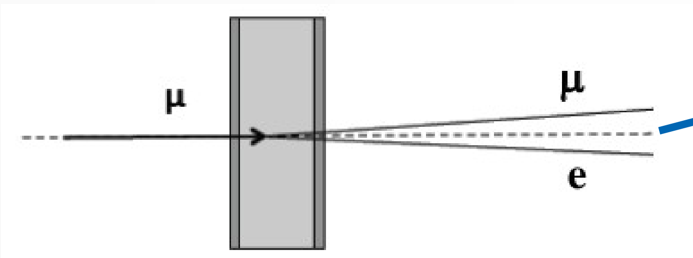
Based on the measurement of $\Delta\alpha_{\mathrm{had}}(t)$:
hadronic contribution to the running of the electromagnetic coupling constant.



Phys. Lett. B 746 (2015), 325

The MUonE experiment

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

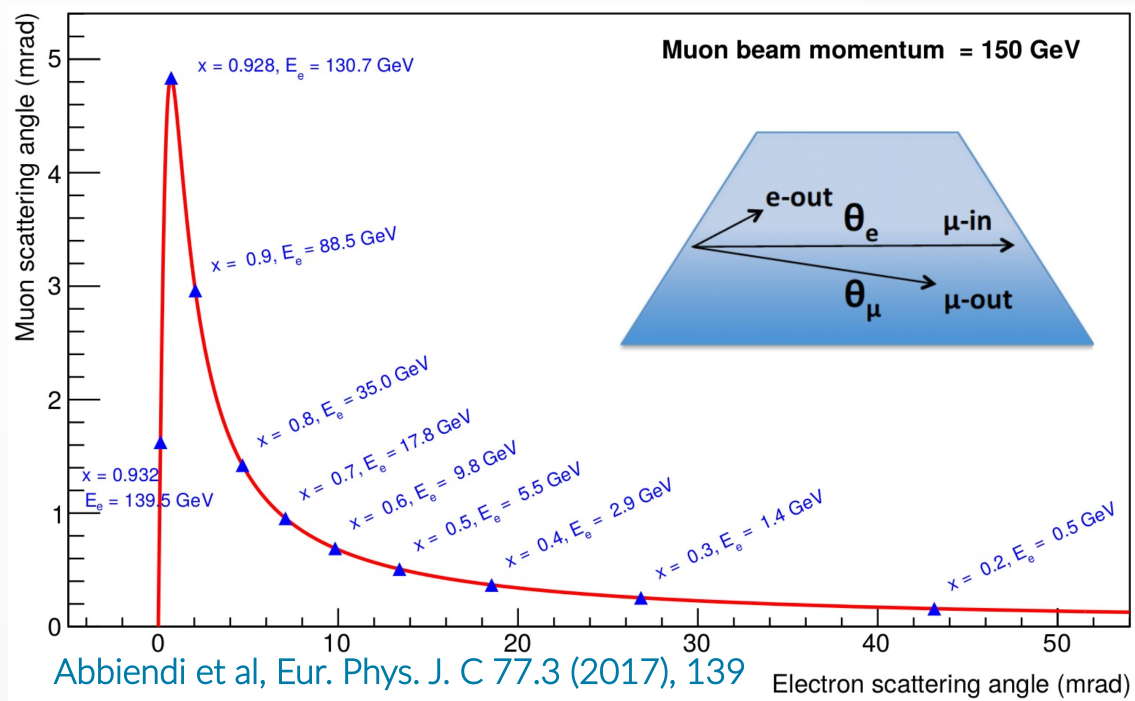


$$\frac{d\sigma_{\rm data}(\Delta\alpha_{\rm had})}{d\sigma_{\rm MC}(\Delta\alpha_{\rm had}=0)} \sim 1 + 2\Delta\alpha_{\rm had}(t)$$

From theoretical calculation

To be measured

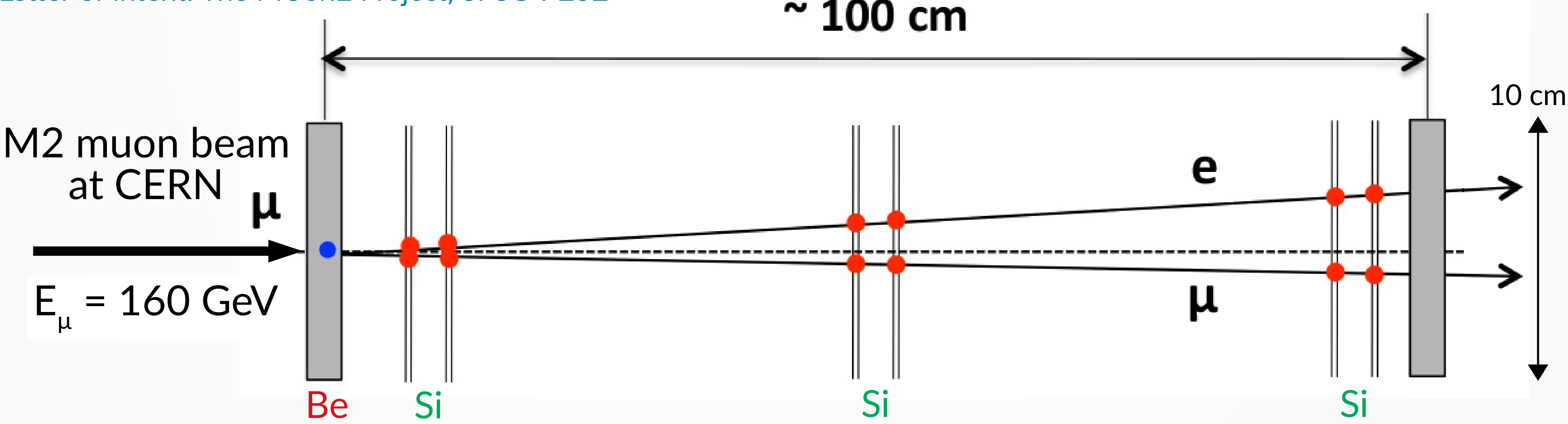
- Compute $a_\mu^{\rm HLO}$ using data from one single experiment.
- Correlation between muon and electron angles allows to select elastic events and reject background (μ N $\to \mu$ N e^+e^-).
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad.



Abbiendi et al, Eur. Phys. J. C 77.3 (2017), 139

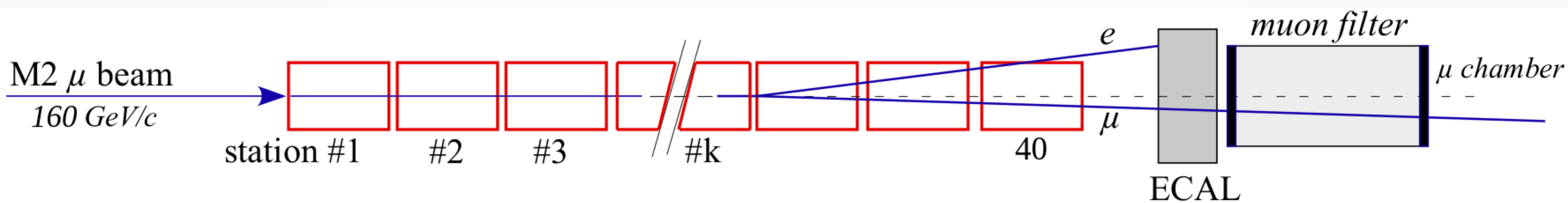
The experimental apparatus

Letter of Intent: The MUonE Project, SPSC-I-252



Be (or C) target
1.5 cm thickness

Tracking system:
3 pairs of silicon strip detectors (CMS 2S modules)



Achievable accuracy

40 stations (60 cm Be) + 3 years of data taking (~4x10^{12} events E_e > 1 GeV) = ~0.3% statistical accuracy on a_μ^{HLO}

Competitive with the latest theoretical predictions.

Main challenge:
keep systematic accuracy at the same level of the statistical one

Systematic uncertainty of 10 ppm in the signal region.

Main systematic effects:

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

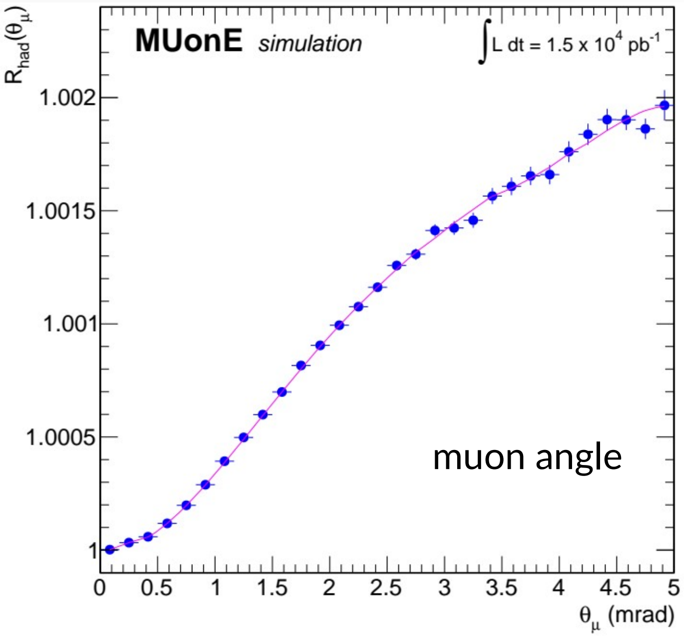
Extraction of $a_\mu^{\rm HLO}$

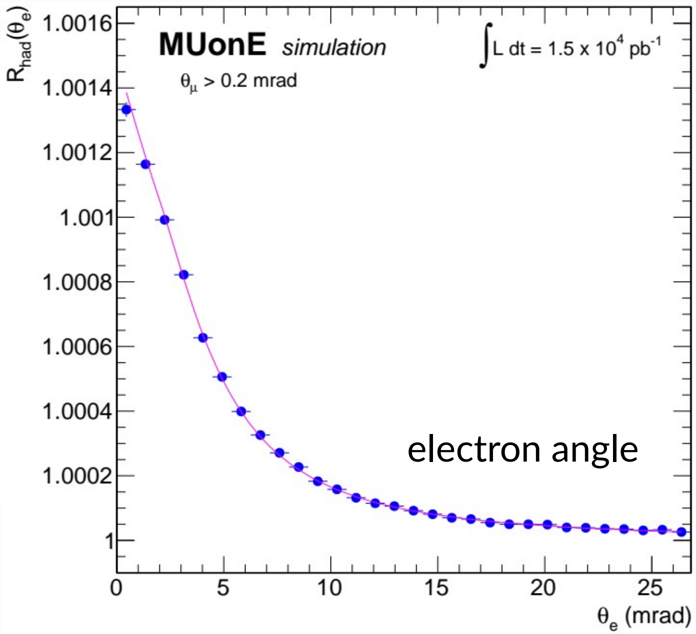
$\Delta\alpha_{\rm had}(t)$ parameterization: inspired from the 1 loop QED contribution of lepton pairs and top quark at *t* < 0

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

2 parameters:
K, M

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





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

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

Input value:

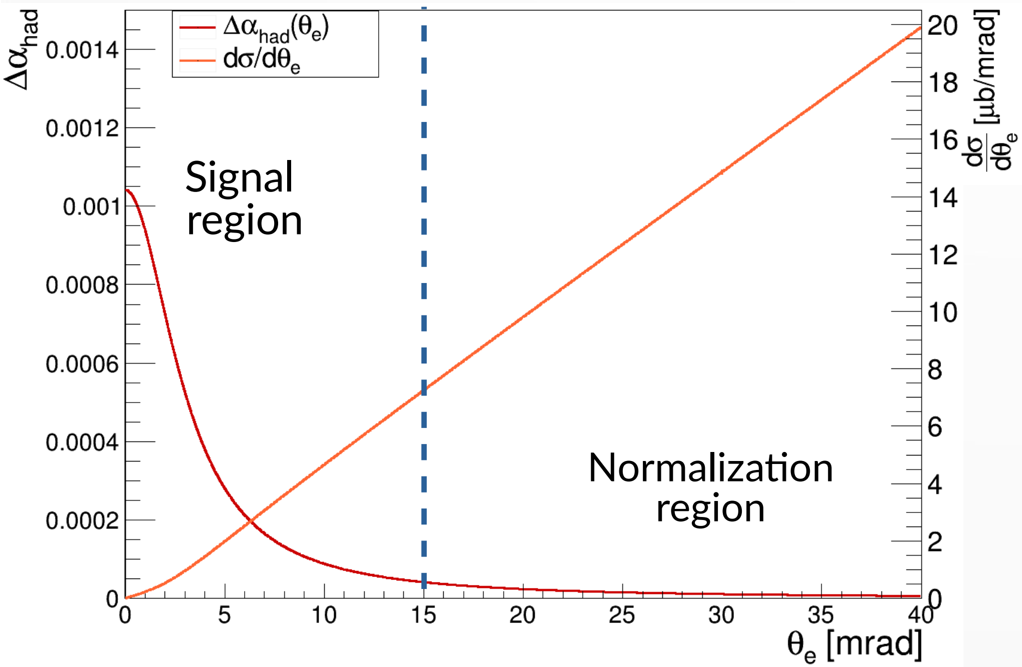
$a_\mu^{\rm HLO} = 688.6\ 10^{-10}$

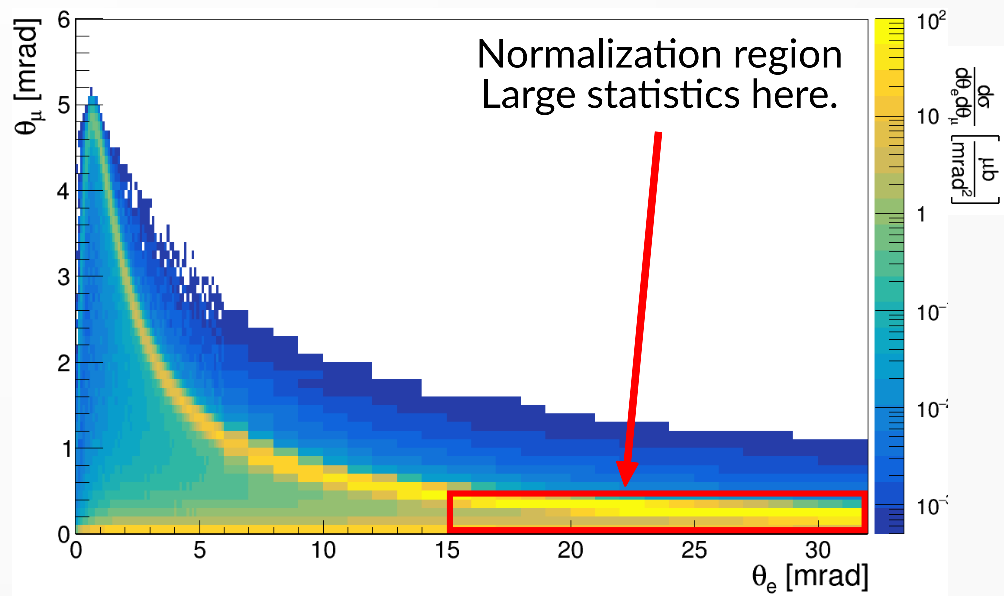
Strategy for the systematic effects

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

Promising strategy:

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

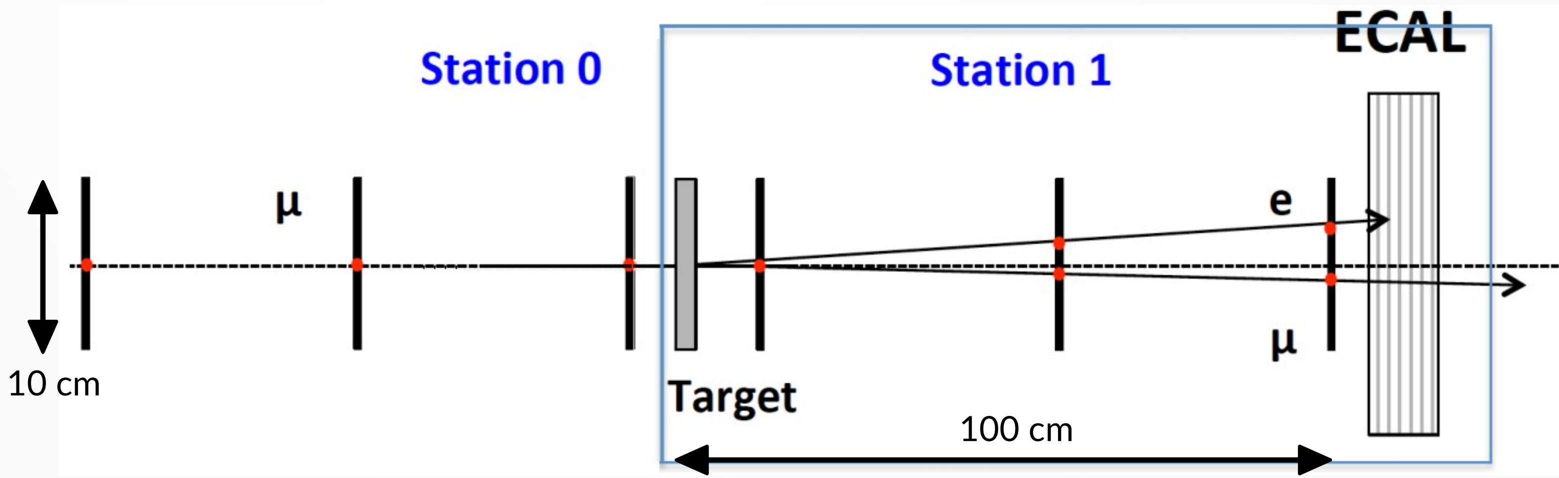




Test Run 2023 (21 Aug – 10 Sept)

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

- Pretracker +
- 1 station +
- ECAL

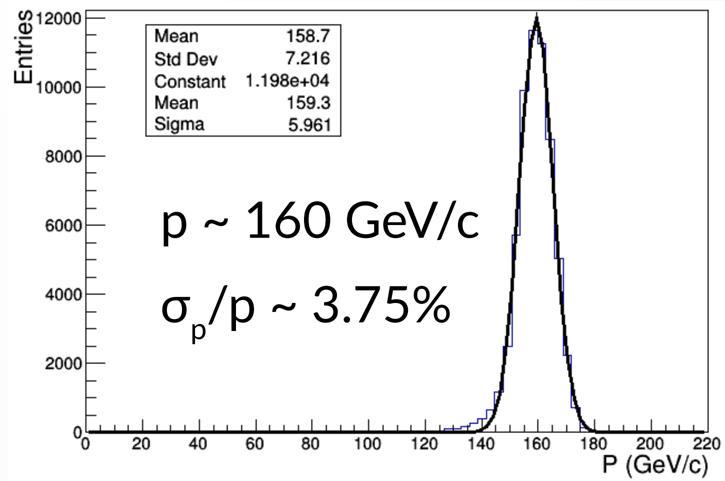


Main goals:

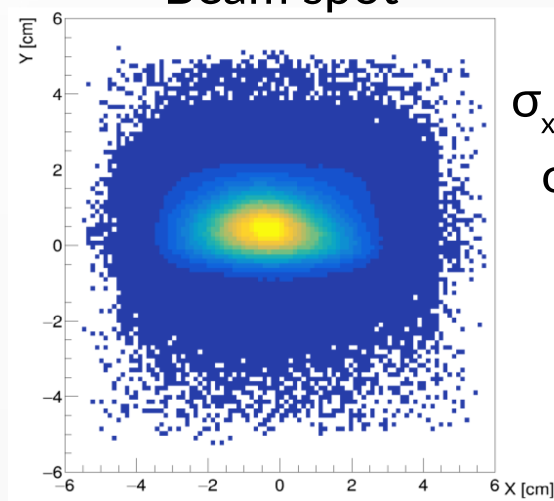
- Confirm the system engineering.
- Test the detector performance.
- Test the reconstruction algorithms and event selection.
- Study the background processes and the main sources of systematic error.
- Demonstration measurement: $\Delta\alpha_{\rm lep}(t)$.

Location: M2 beamline at CERN

Beam momentum



Beam spot



σ_x ~ 13 mm

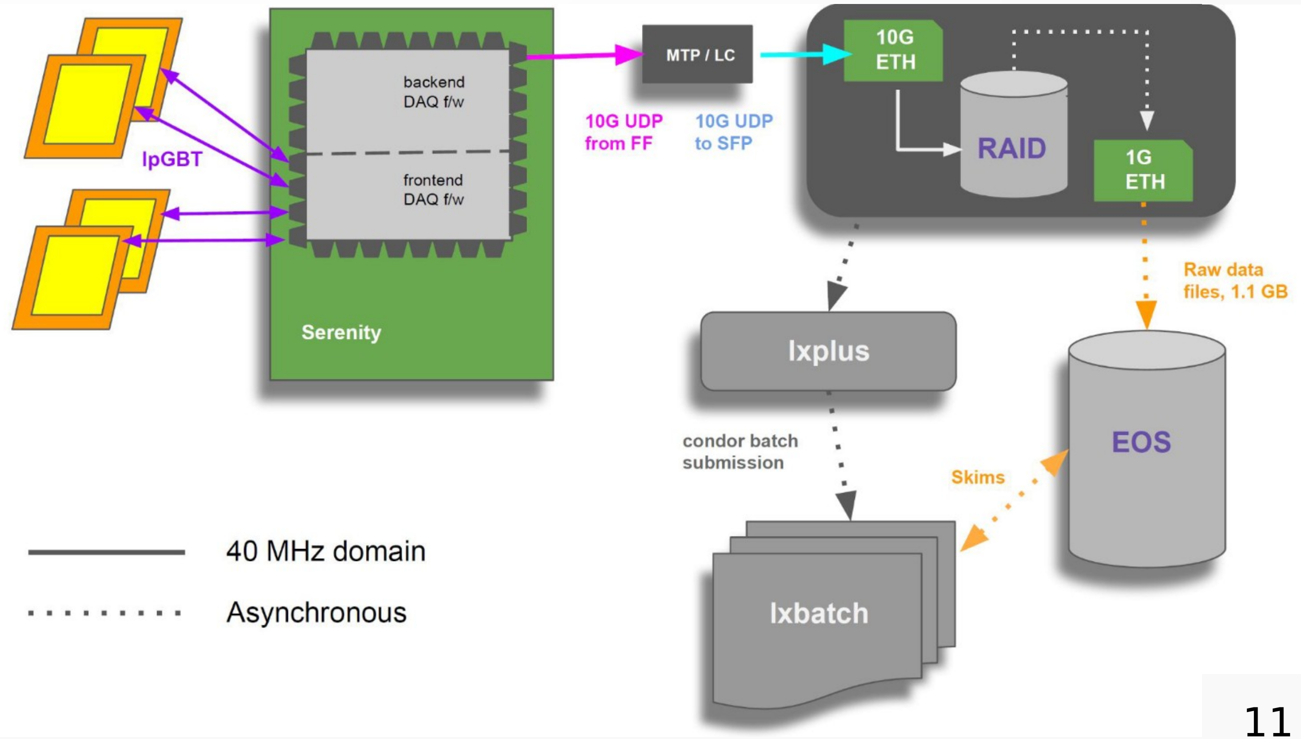
σ_y ~ 7 mm

- 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).

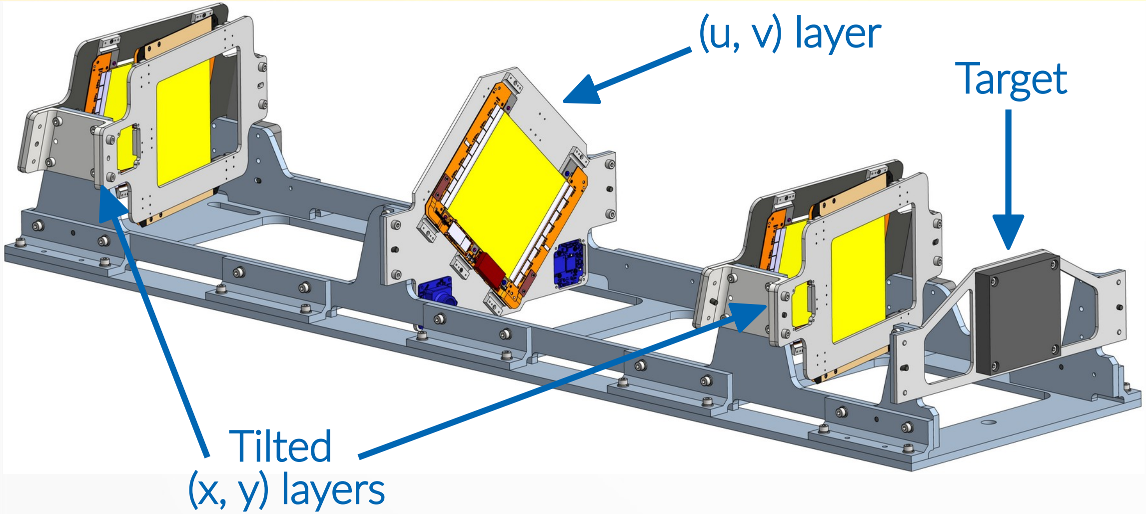
DAQ system

Frontend control and readout via Serenity board
(to be used in the CMS-Phase2 upgrade).

- Asynchronous beam: triggerless readout of the tracking modules @40MHz.
- Event aggregator on FPGA.
- Further data aggregation on the PC.
- Transmission to EOS into ~1GB files.



Tracking station

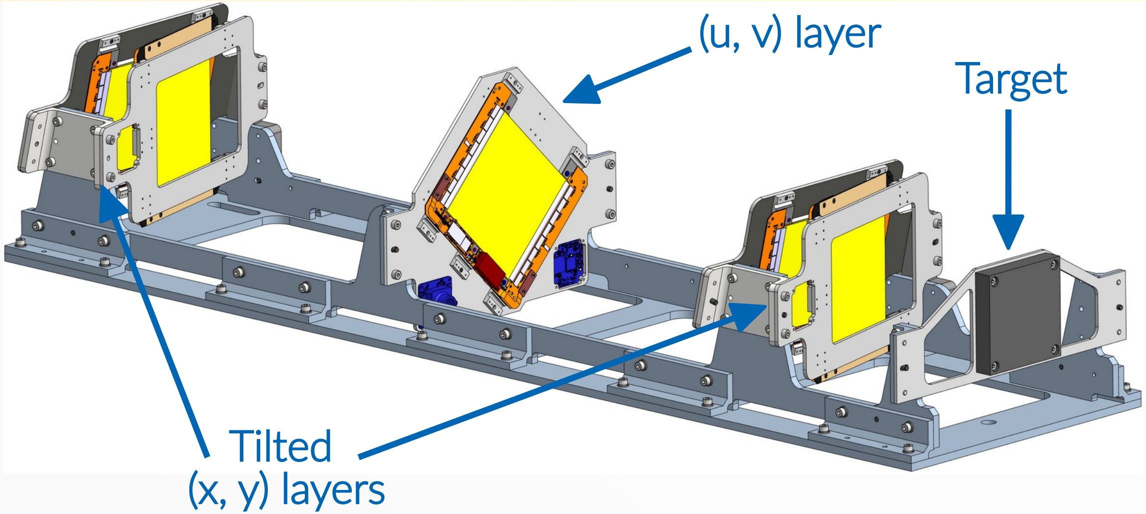


Stringent request:
relative position within a station
must be stable < 10 μm.

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

Laser holographic system
to monitor stability.

Tracking station



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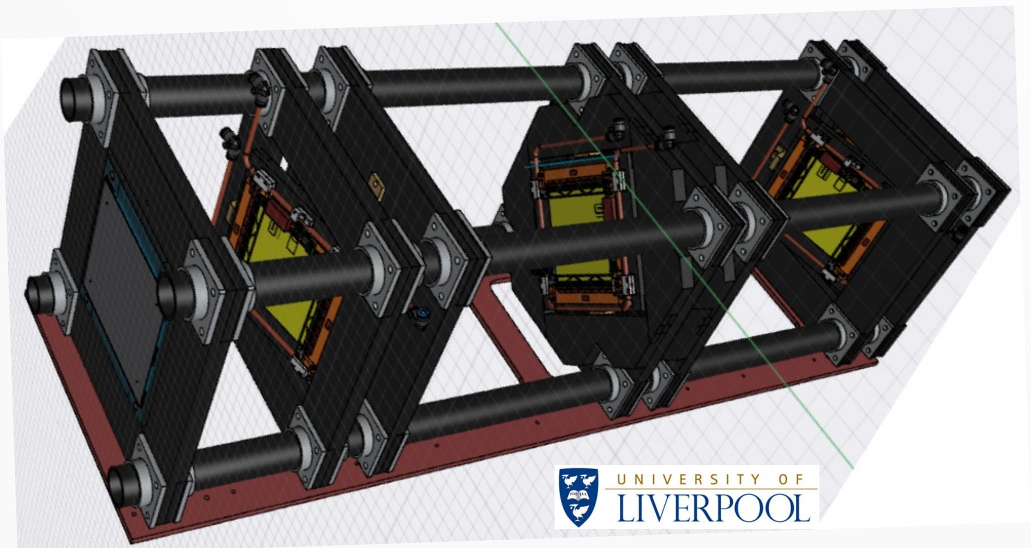
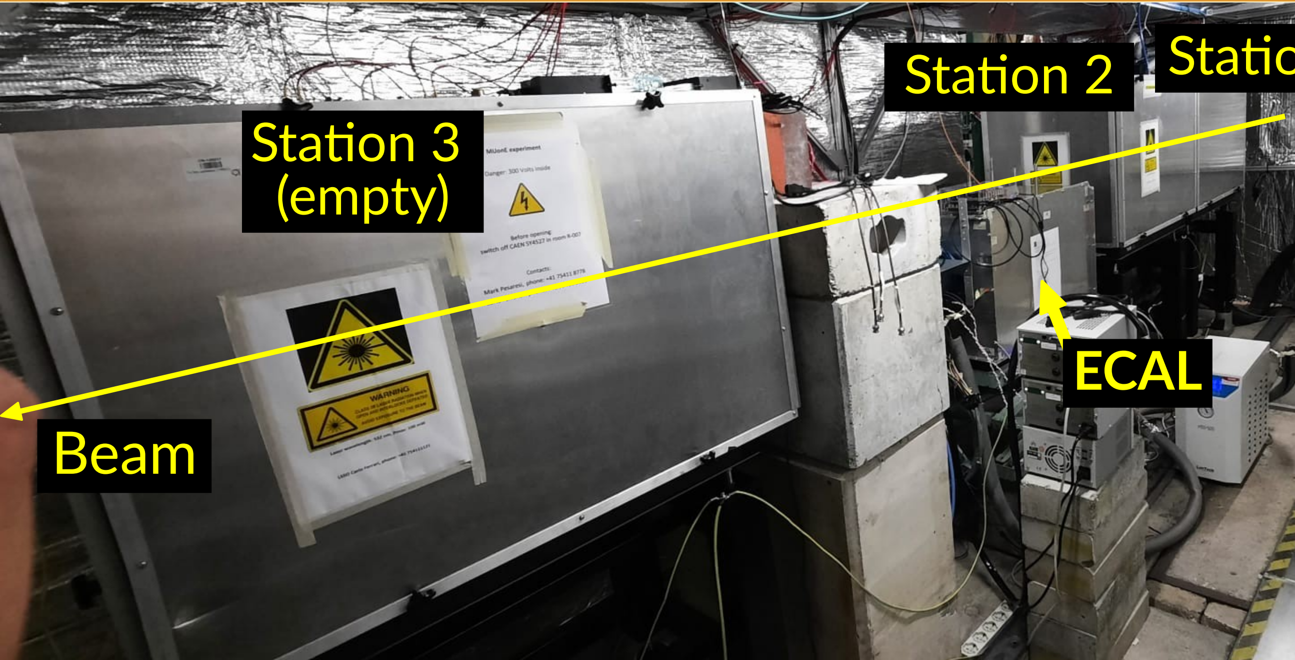
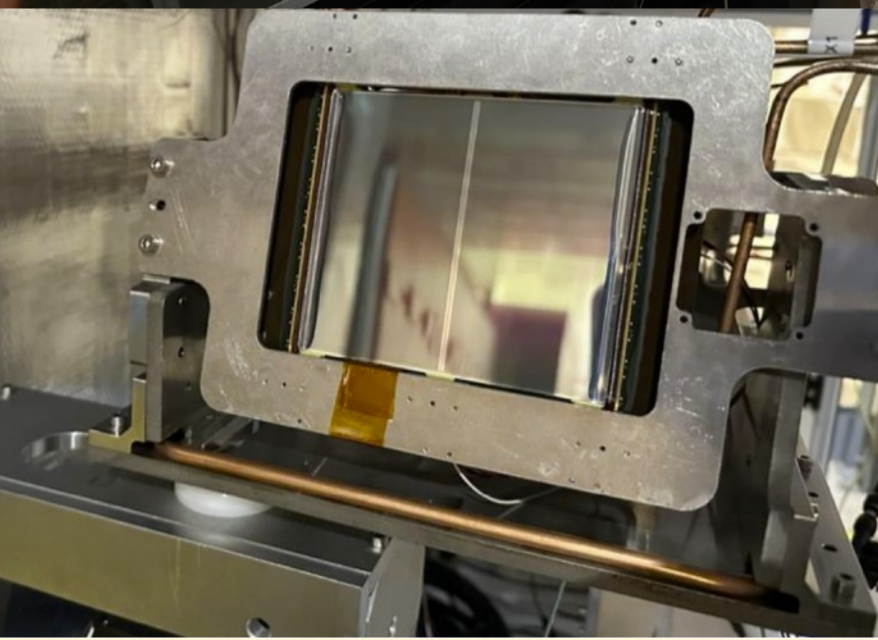


New layout under development at Liverpool: Carbon fiber

- Light material
- CTE < 1×10^{-6} K^{-1}
- Lower cost
- Easy to machine



Test Run Analysis

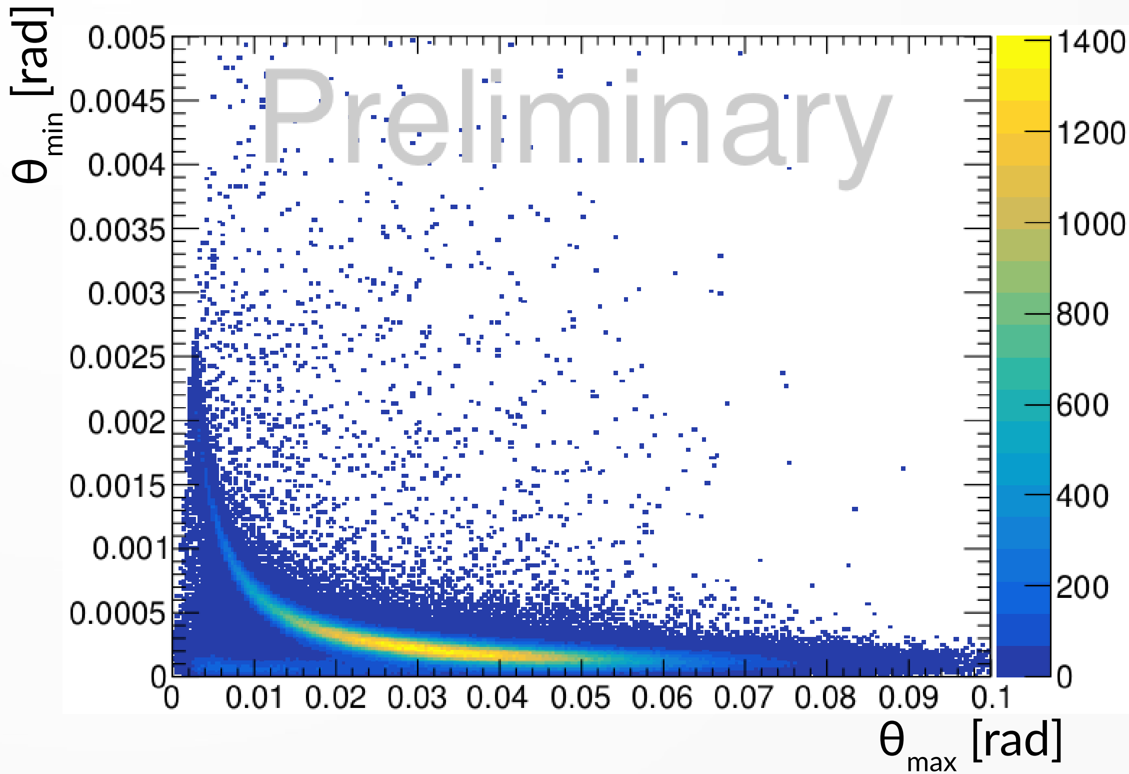


- Determine selection algorithms to be applied on FPGA.
- Beam rate measurements.
- Background suppression.
- Hardware metrology.
- Software alignment.
- Detector performance.

Test Run Analysis: elastic events

Golden event selection:

- 1 hit/module in 1st station.
- 2 hits/module in 2nd station.
- Vertex with 1 incoming and 2 outgoing tracks with good χ^2.
- Cut on z_{vertex} to select interactions in the target.
- Reject events where the 3 tracks are not planar.



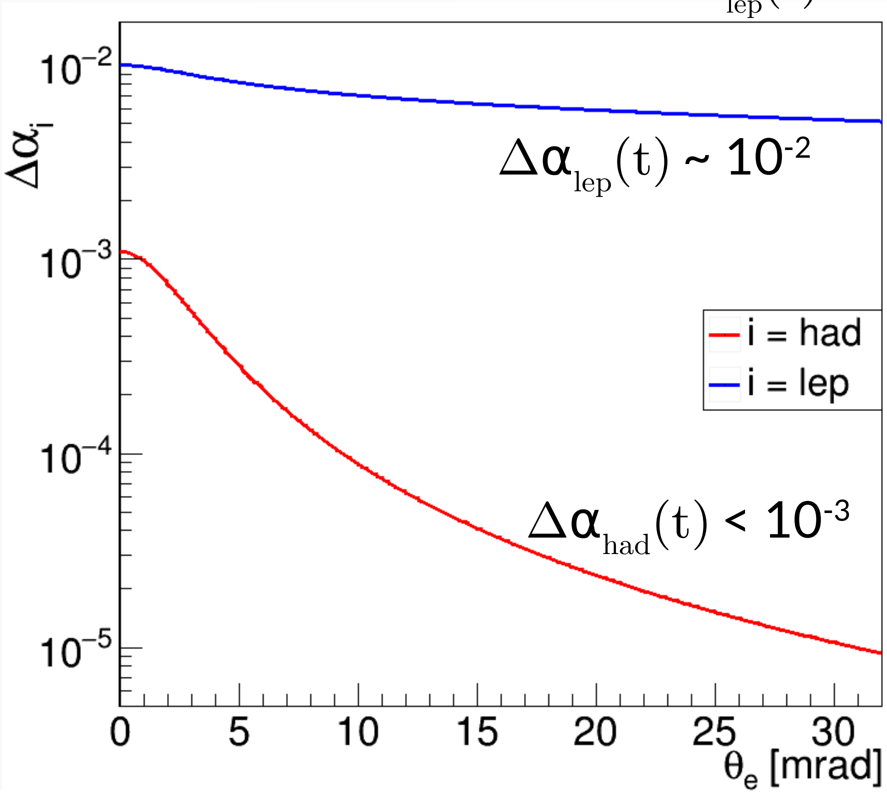
Ongoing work:

- Refine the selection cuts.
- Data/MC comparison to study the largest systematic effects.

Test Run 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

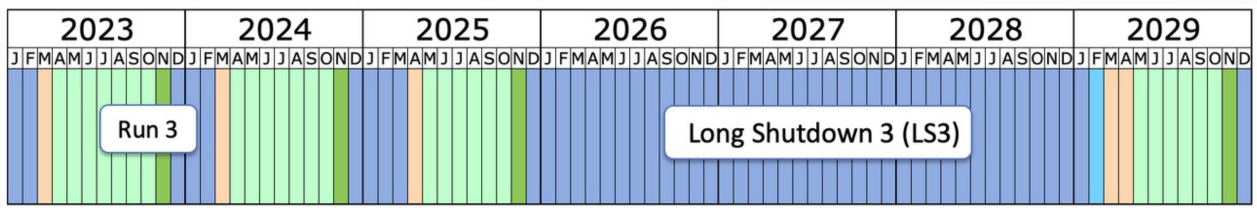
$$k = \frac{\alpha}{\pi}$$

Expected precision: ~5%

Conclusions

MUonE
web site

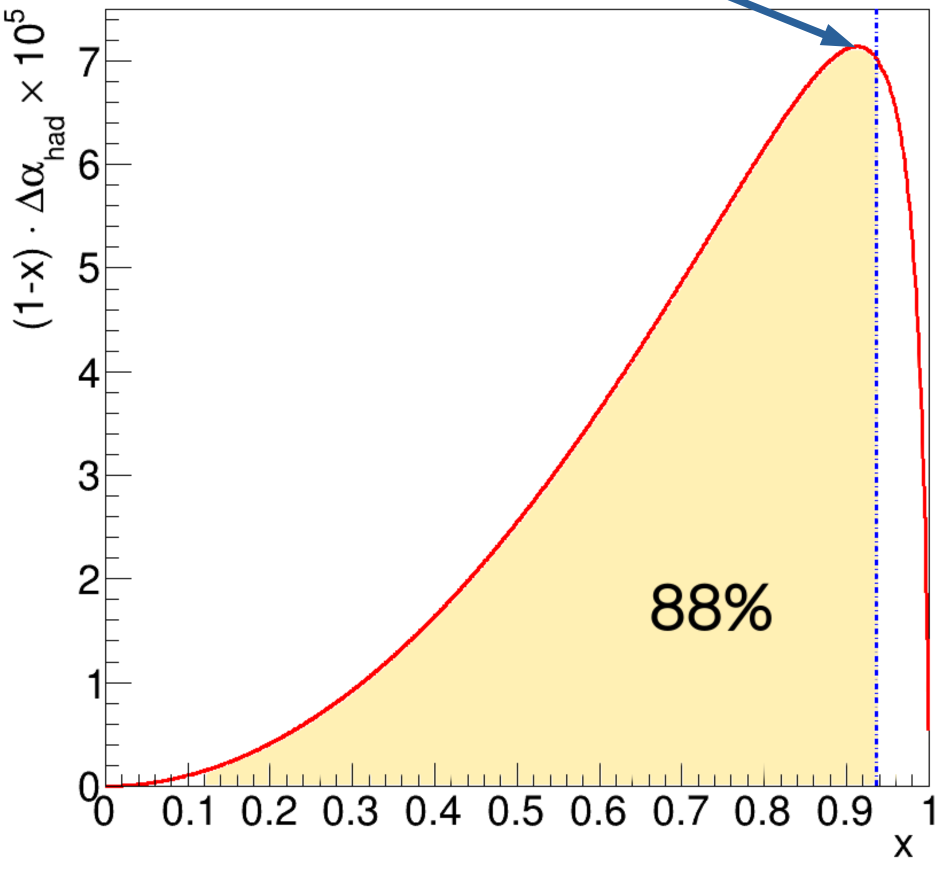
- MUonE will provide an independent calculation of a_{μ}^{HLO}, competitive with the latest evaluations.
- 3 weeks Test Run 2023: proof of concept of the experimental proposal. Data analysis ongoing.
- Experiment proposal to be submitted soon to the SPSC, to request for a ~1 month run in 2025 instrumenting 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).

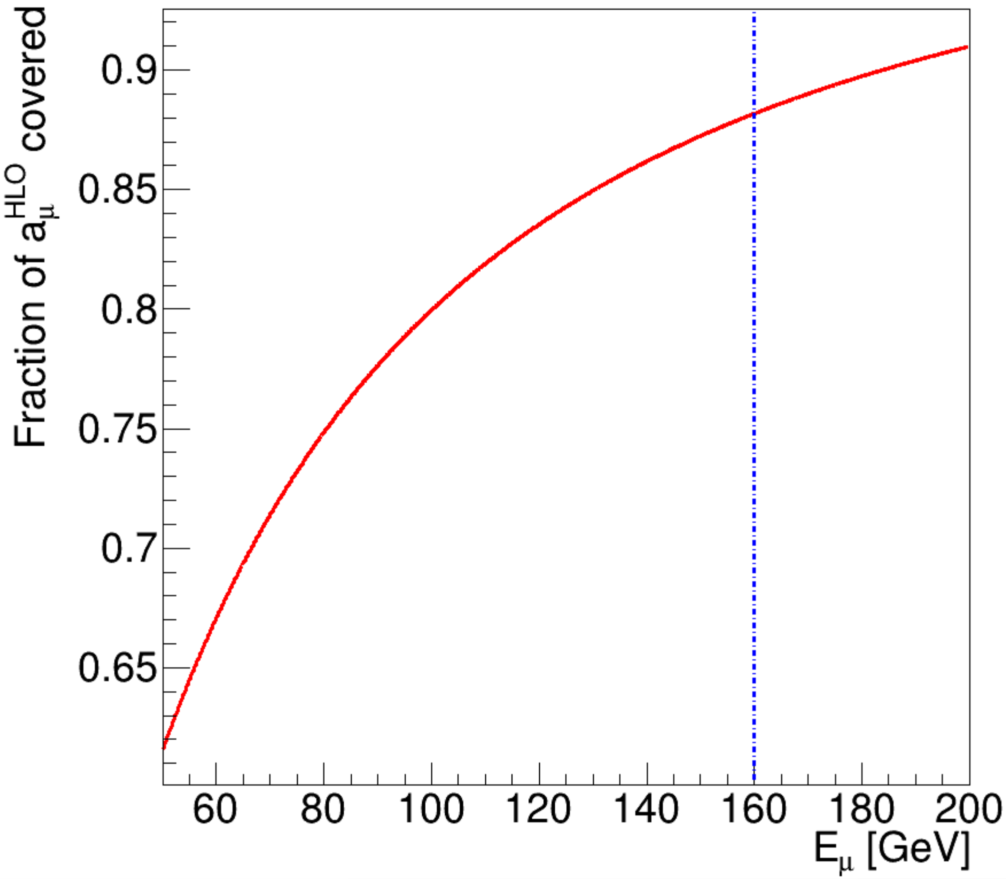


BACKUP

$\mathrm{x} < 0.936$

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



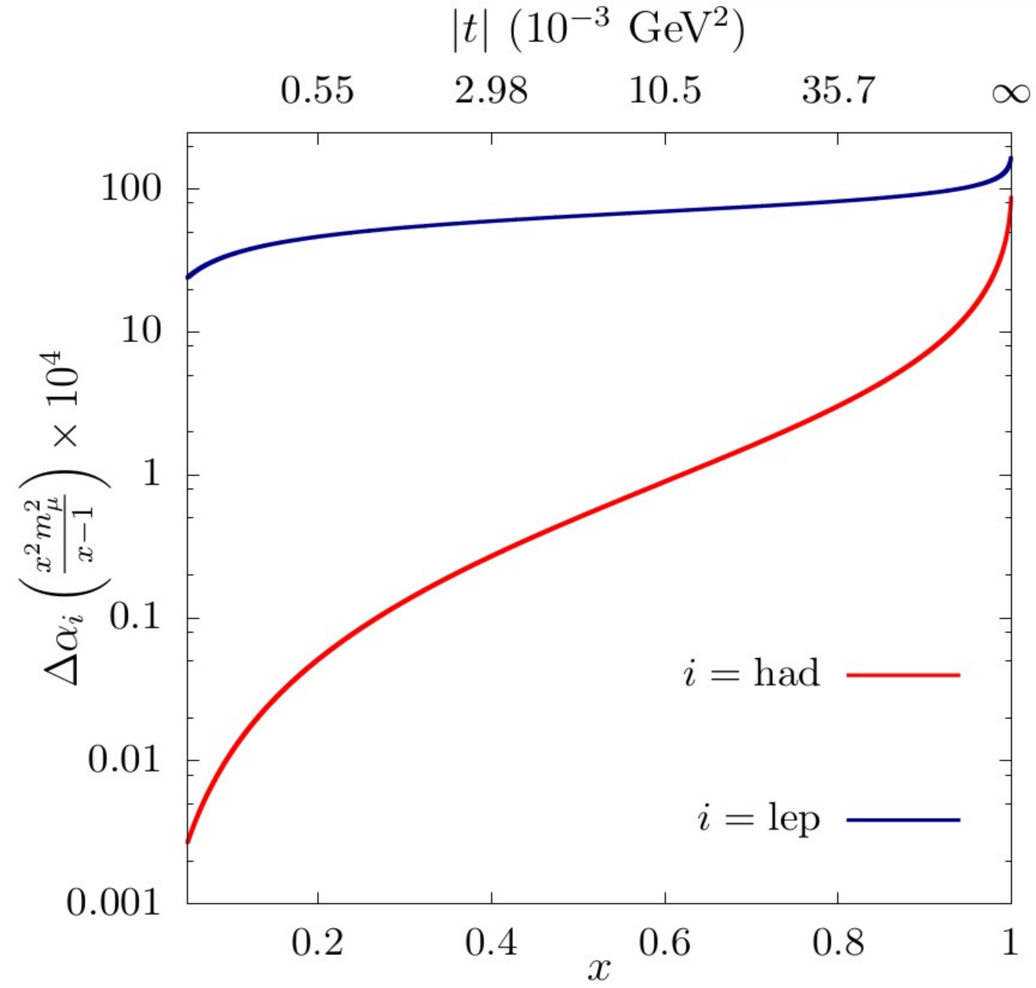


- 160 GeV muon beam on atomic electrons.

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

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

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



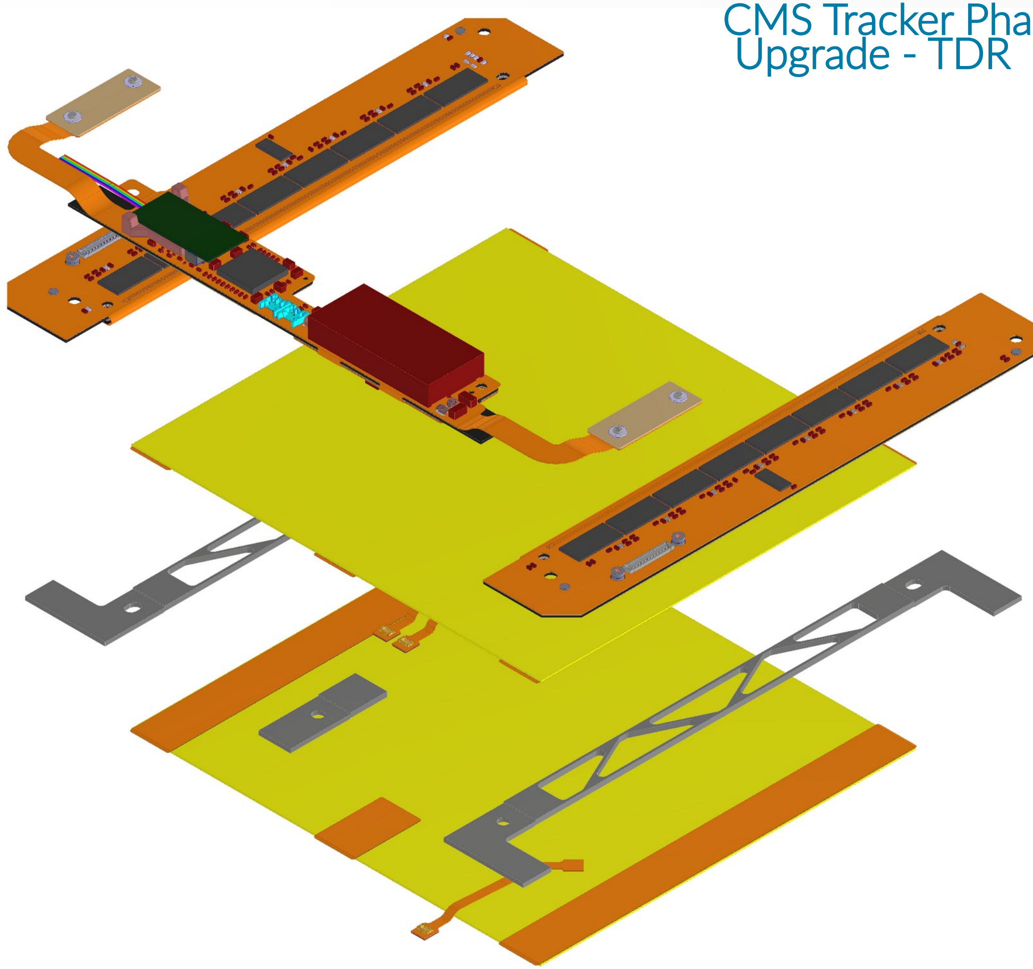
Tracker: CMS 2S modules

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

Two close-by strip sensors reading the same coordinate:

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

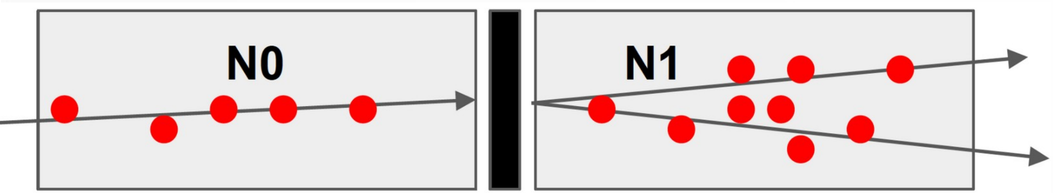
- Pitch: 90 µm
- Digital readout
- Readout rate: 40 MHz
- Area: 10×10 cm^2 (~90 cm^2 active)
- Thickness: 2 × 320 µm



CMS Tracker Phase2 Upgrade - TDR

Test Run Analysis

Online event selection



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

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

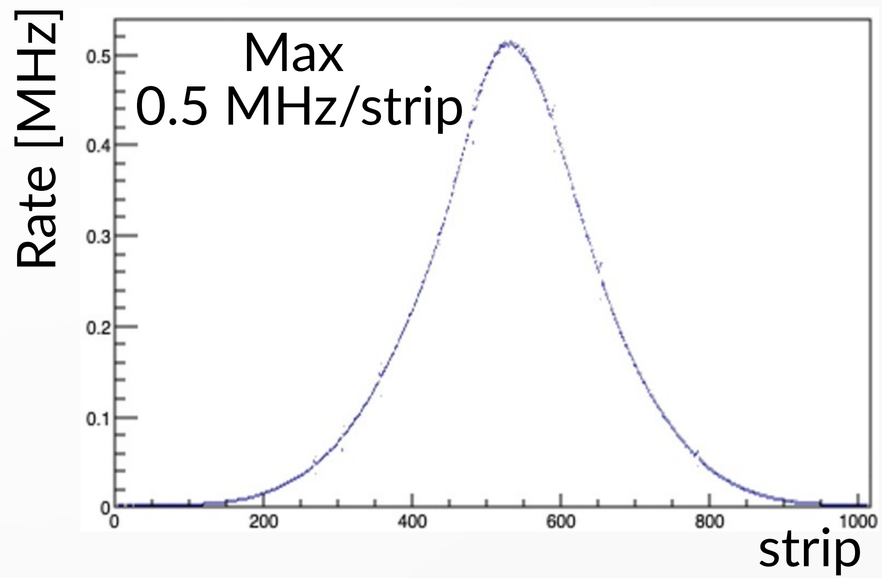
Reduce the data flow to 1%-2%

Can be easily implemented on FPGA.

Beam rate

$1\text{-}2 \times 10^{8}$ μ/spill

(1 spill = 5s)

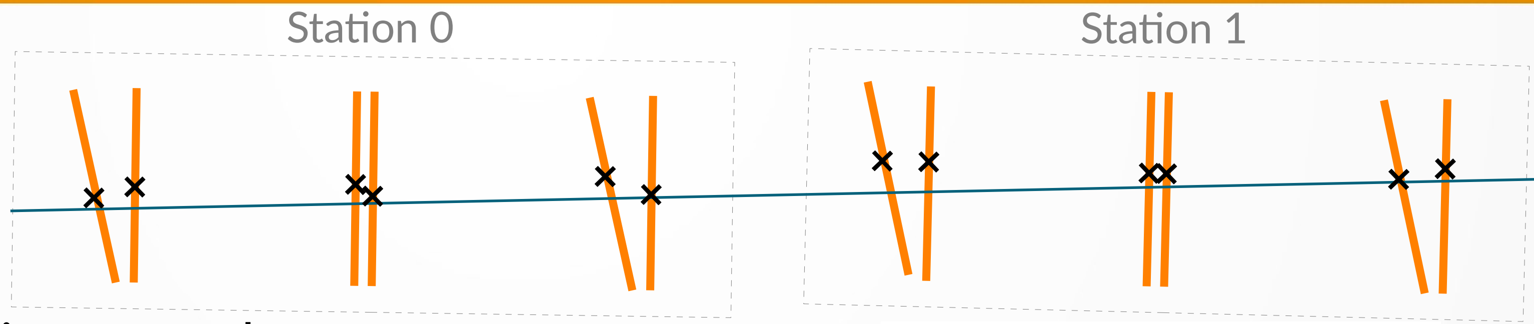


Goal:

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

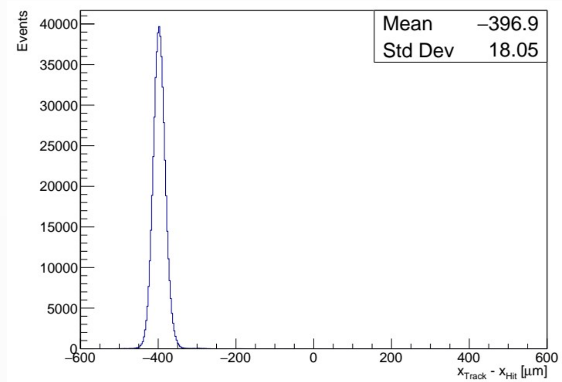
Test Run Analysis

Alignment

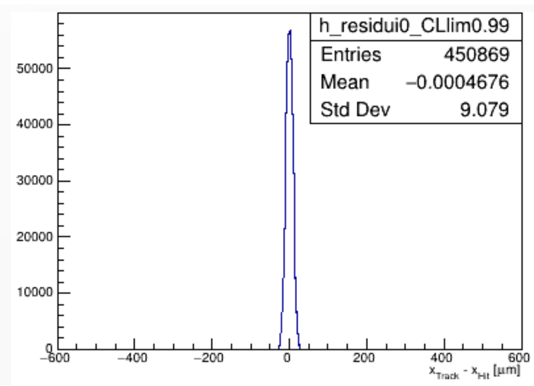


Currently:

- 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.



Ongoing work:

- Include the hardware metrology measurements as starting point of the track based alignment.
- Global alignment.

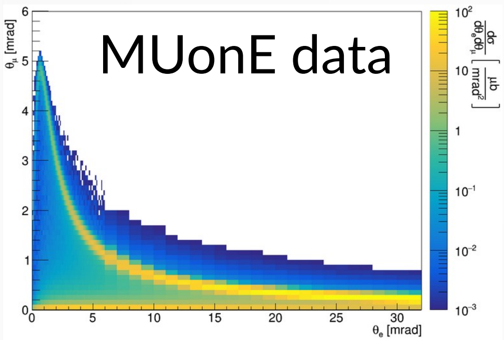
Extraction of $\Delta\alpha_{had}(t)$

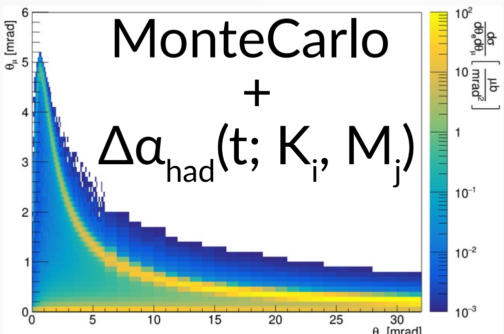
$\Delta\alpha_{had}(t)$ parameterization:
inspired from the 1 loop QED contribution of lepton pairs and *t*-quark at $q^2<0$

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

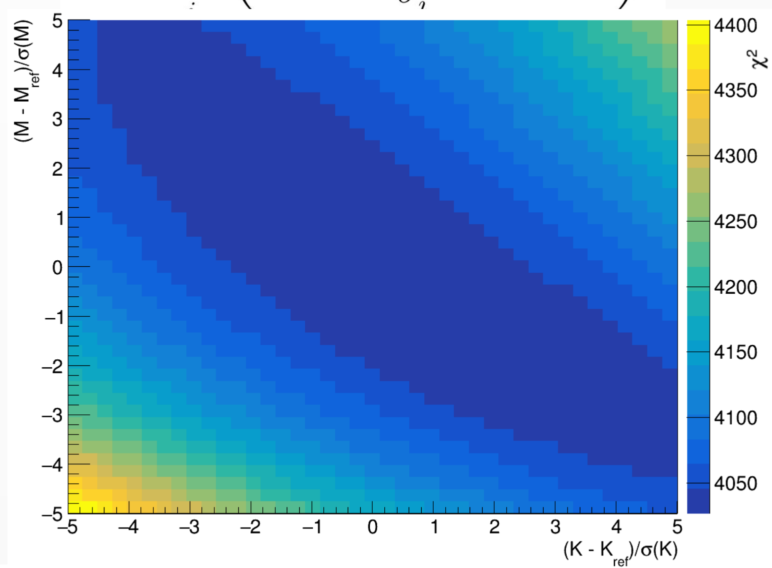
2 parameters:
K, M

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



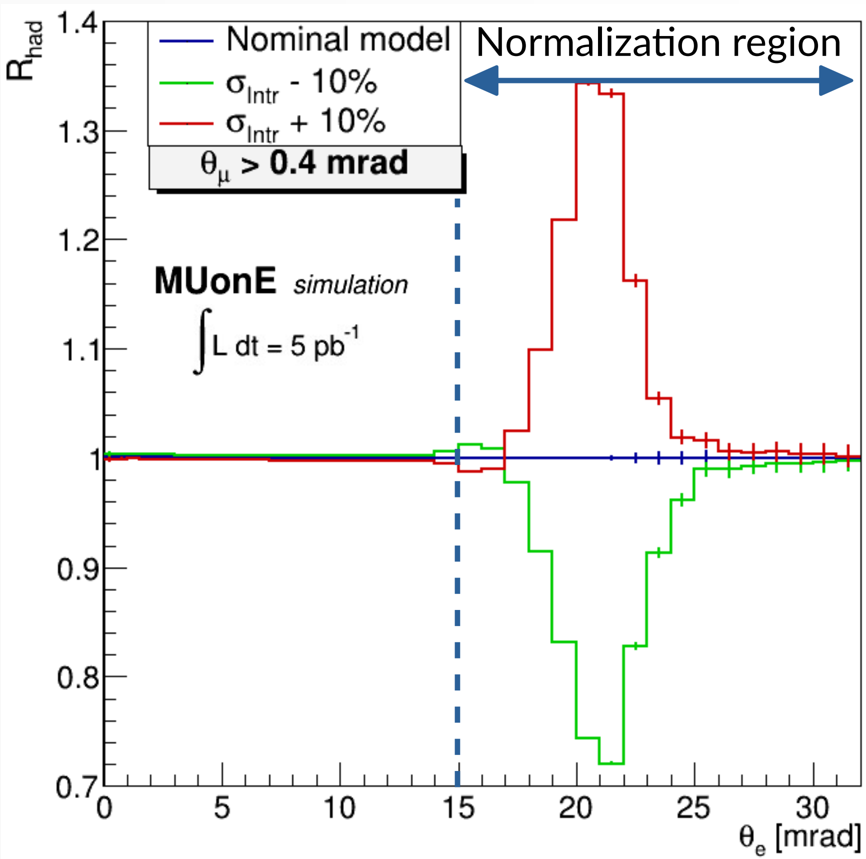


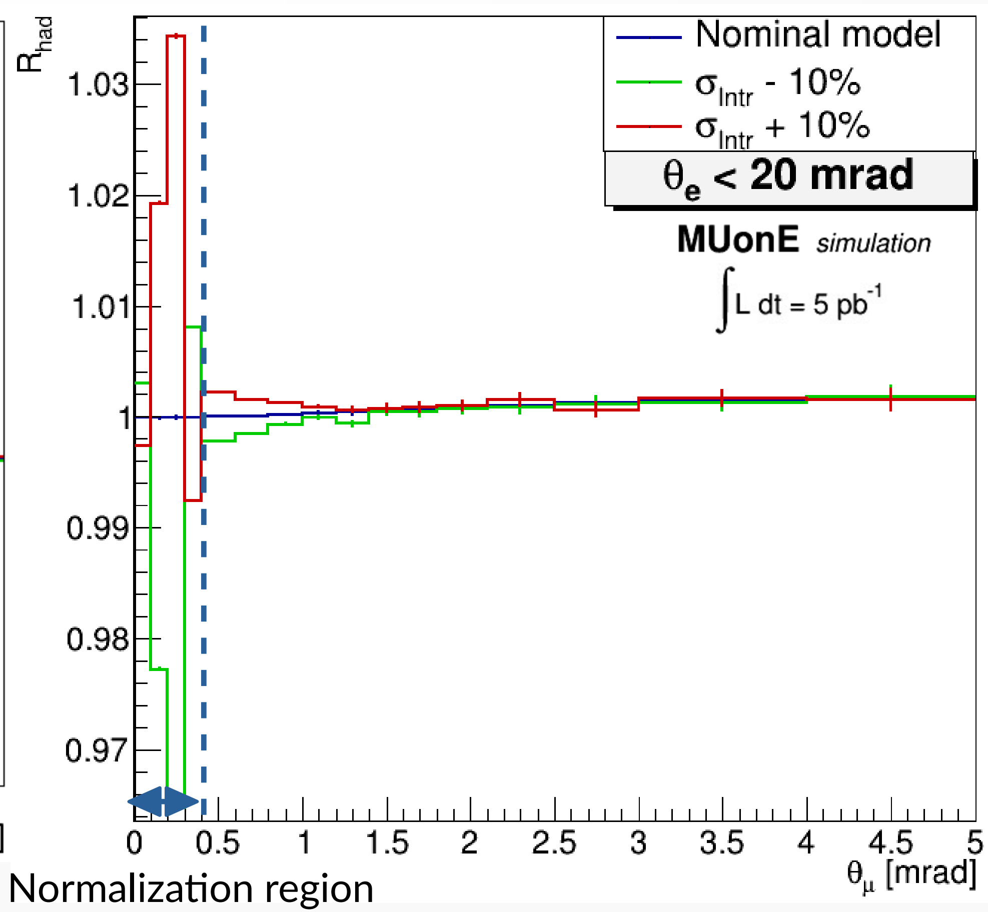
$$\chi^2 = \sum_i^{\text{bins}}\left(\frac{\text{data}_i - \text{templ}(K,M)_i}{\sigma_i^{\text{data}}}\right)^2$$

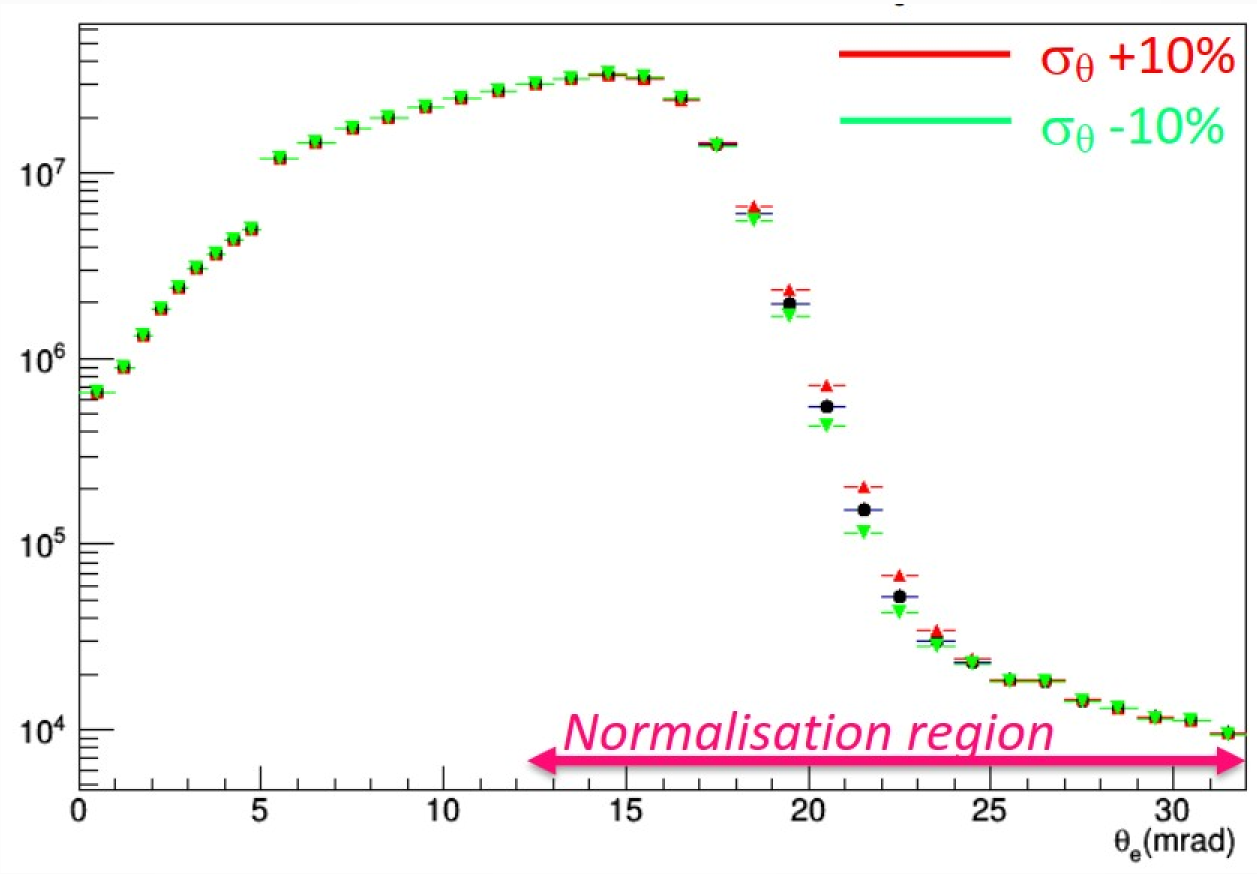


Systematic error on the angular intrinsic resolution

±10% error on the angular intrinsic resolution.







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

The need of including systematic effects in the analysis

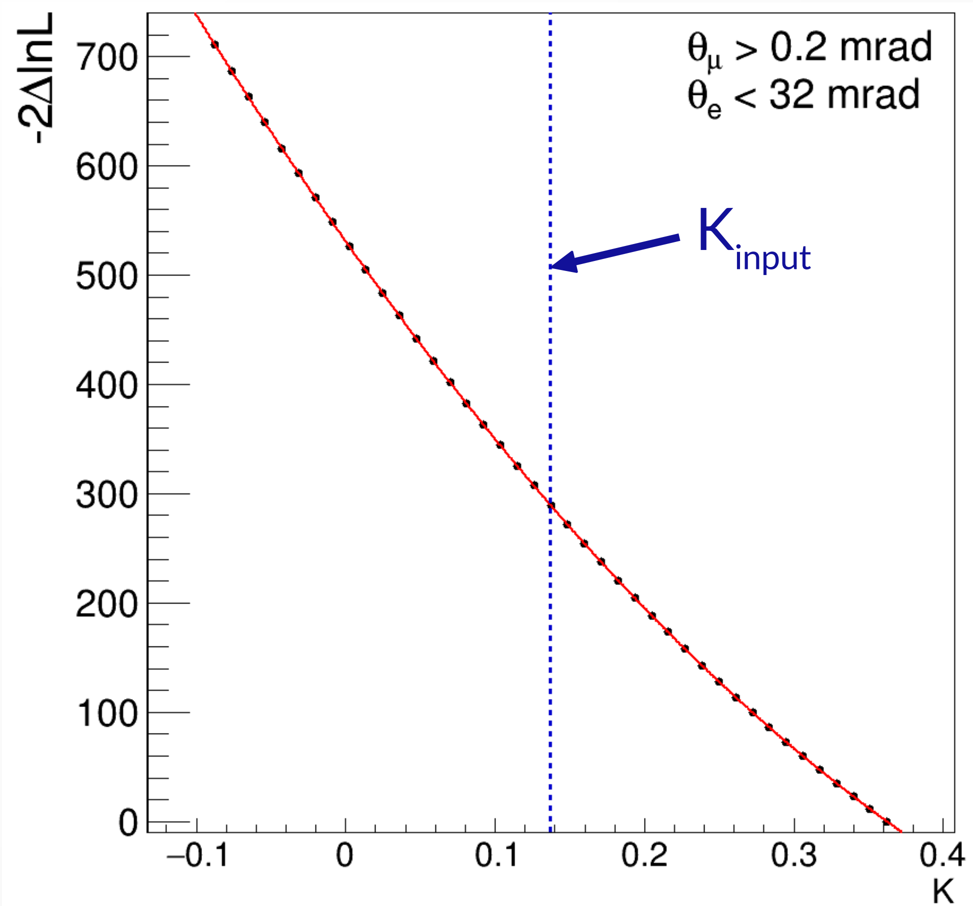
What if systematic effects are not included in the template fit?

Simplified situation:

- 1 fit parameter (K).

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

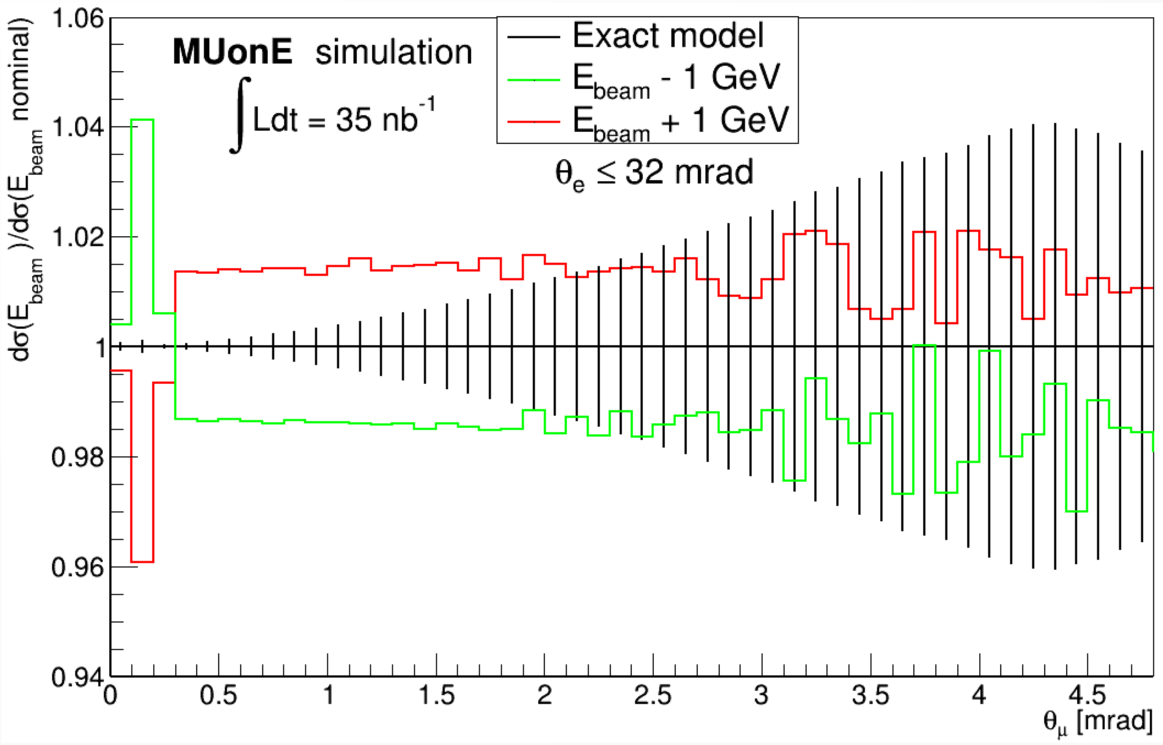
- L = 5 pb^{-1}.
  ~10^9 elastic events
  (~4000 times less than the final statistics)
- Shift in the pseudo-data sample:
  $\sigma_{Intr} \rightarrow \sigma_{Intr} + 5\%$.



Systematic error on the muon beam energy

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

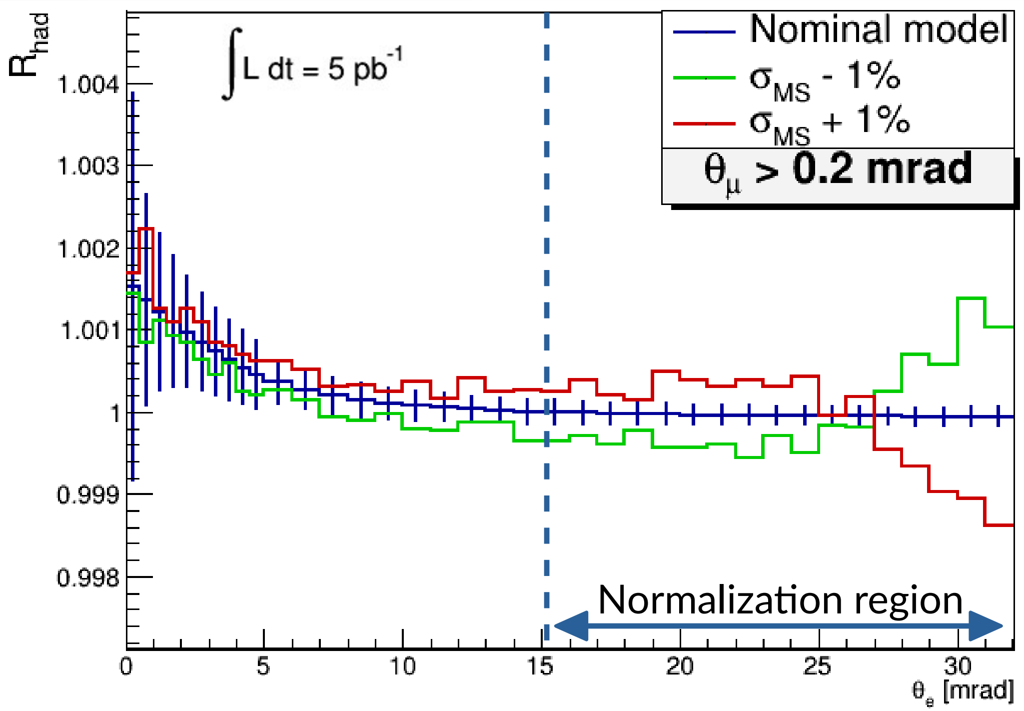
This effect can be seen from our data in 1h of data taking per station.

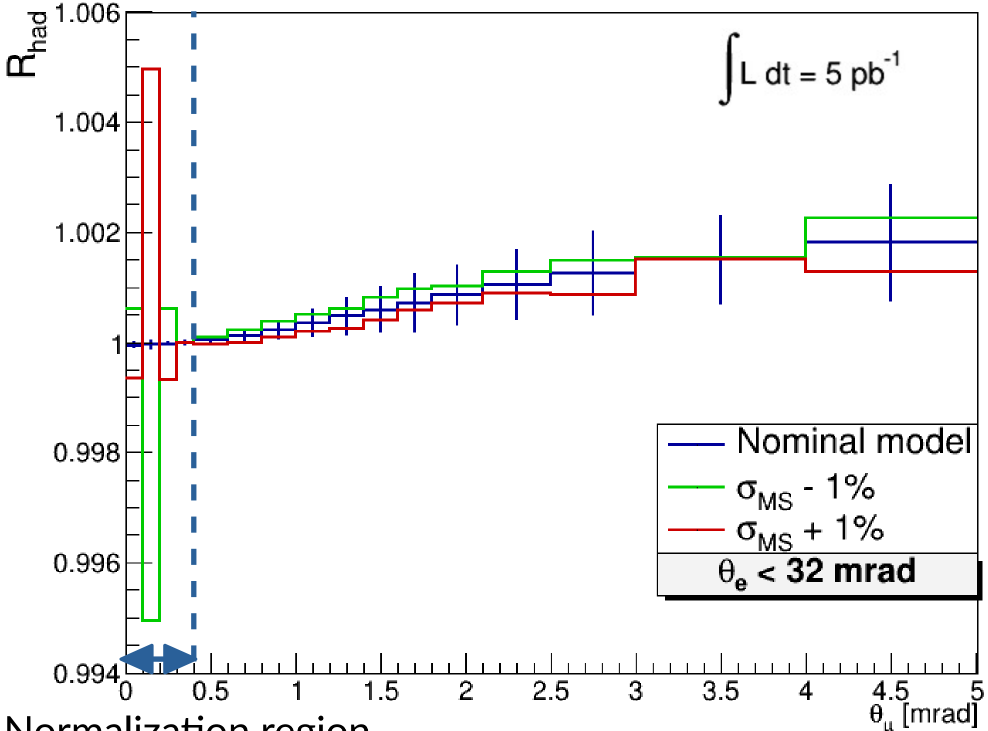


Systematic error on the multiple scattering

Expected precision on the multiple scattering model: ± 1%

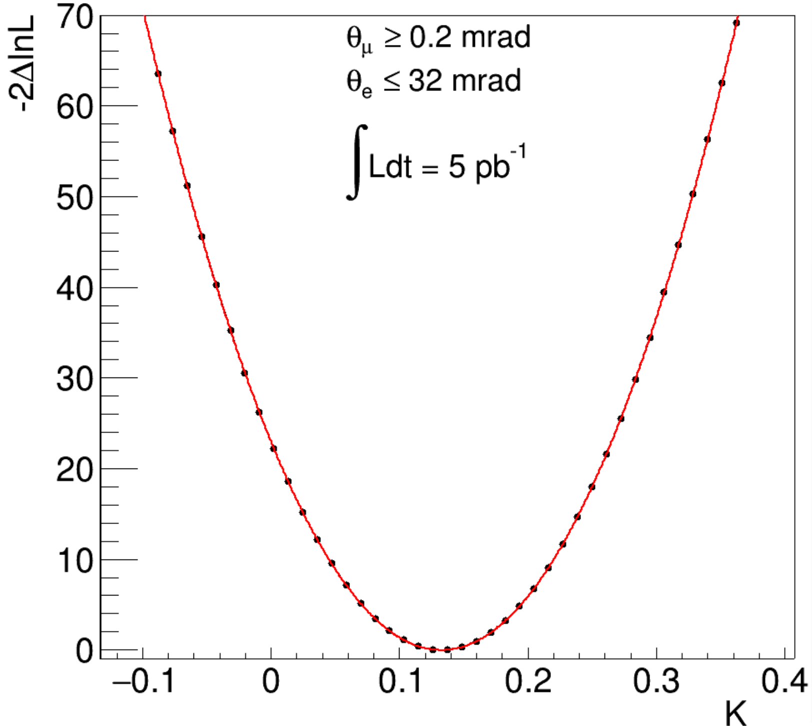
G. Abbiendi et al JINST (2020) 15 P01017





Combined fit
signal + systematics

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



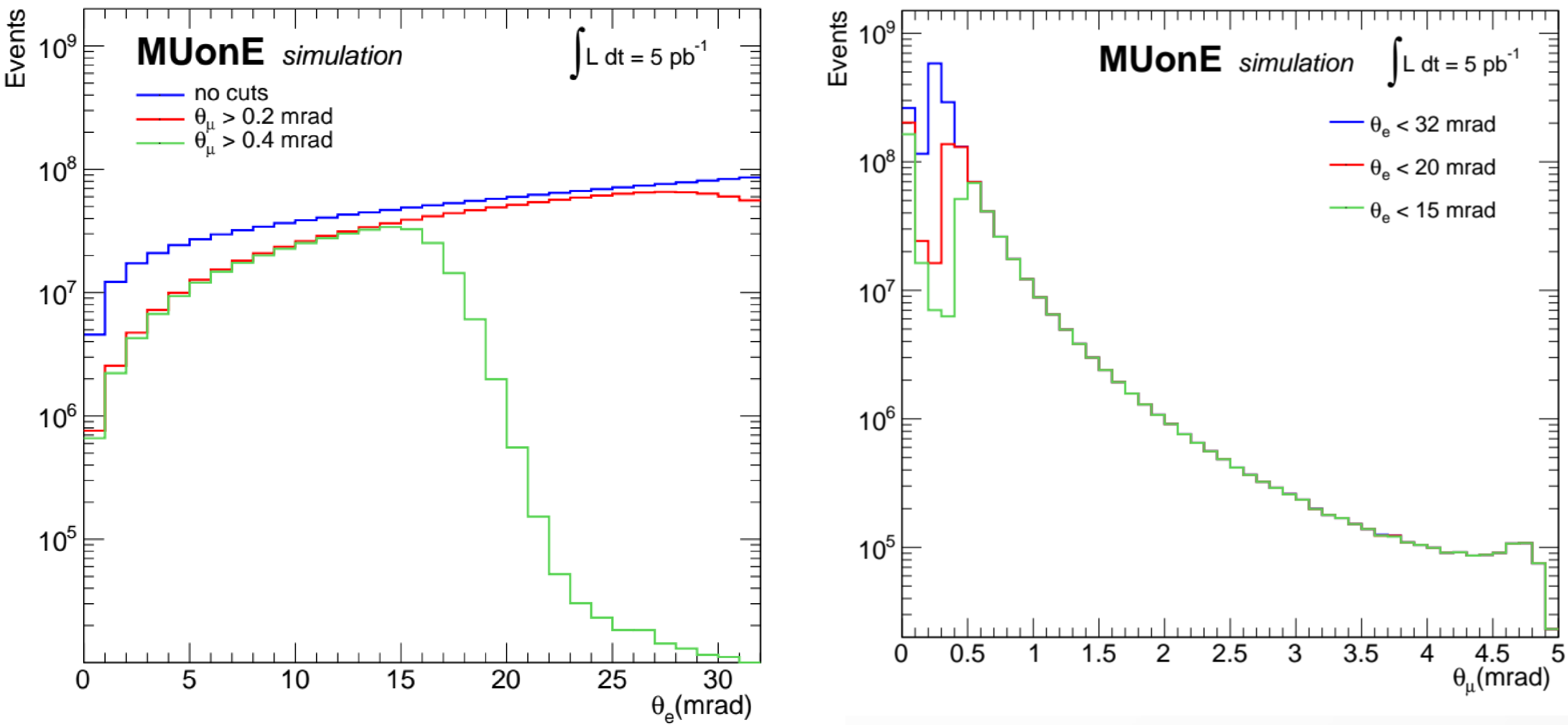
- K_{ref} = 0.137
- shift MS: +0.5%
- shift intr. res: +5%
- shift E_{beam}: +6 MeV

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:

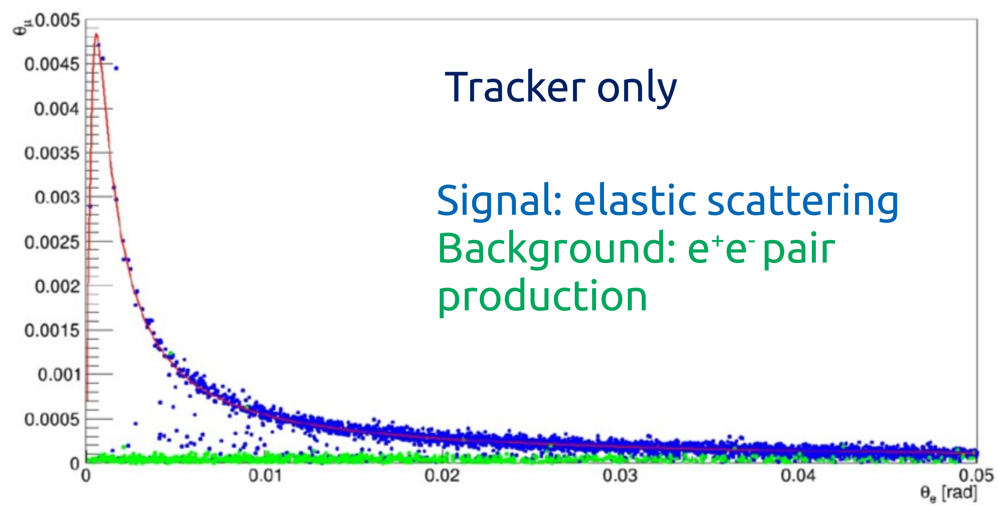
- Test the procedure for the MuonE design statistics.
- Improve the modelization of systematic effects.

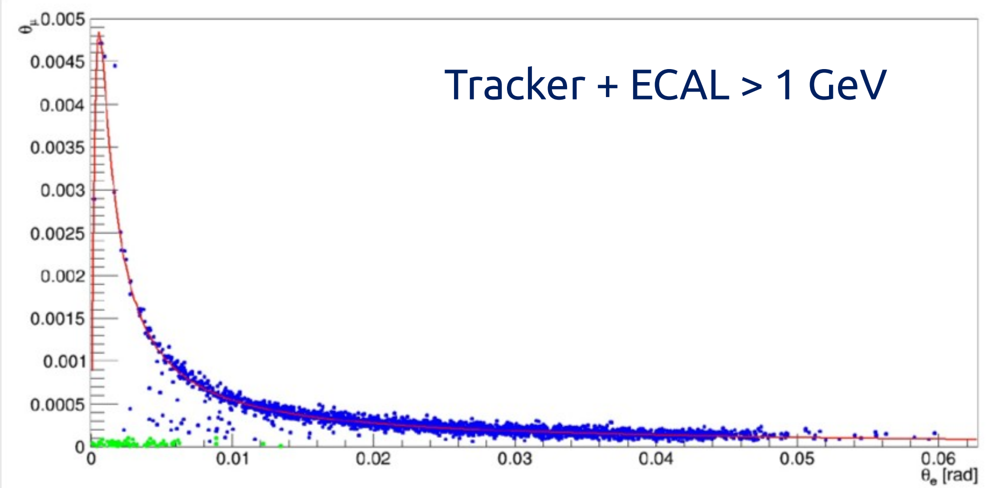


Events
MUonE simulation
∫L dt = 5 pb-1
no cuts
θμ > 0.2 mrad
θμ > 0.4 mrad
θe(mrad)
Events
MUonE simulation
∫L dt = 5 pb-1
θe < 32 mrad
θe < 20 mrad
θe < 15 mrad
θμ(mrad)

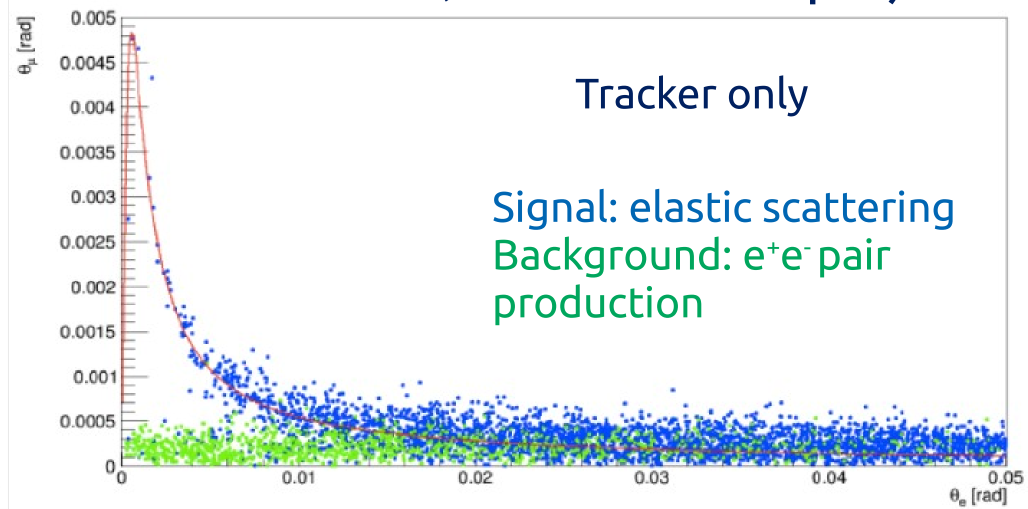
GEANT4 simulations

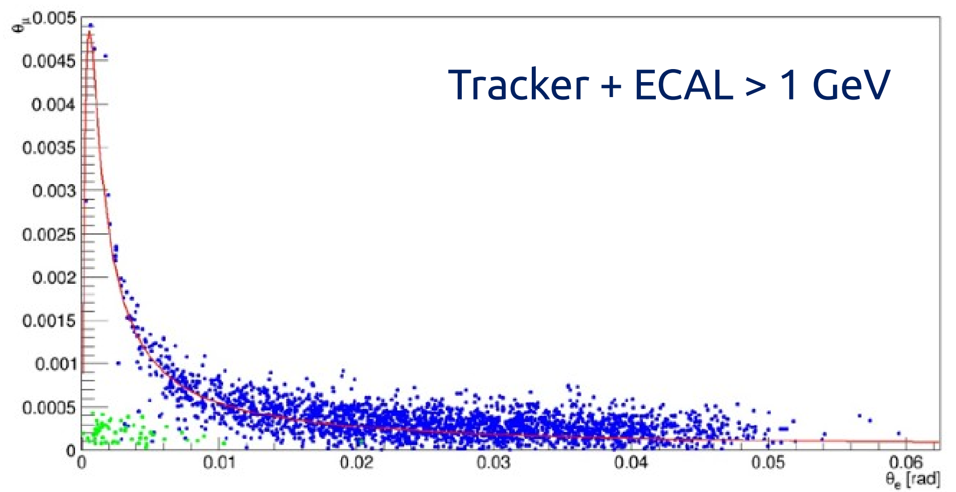
TB2017 (resolution ~7μm)



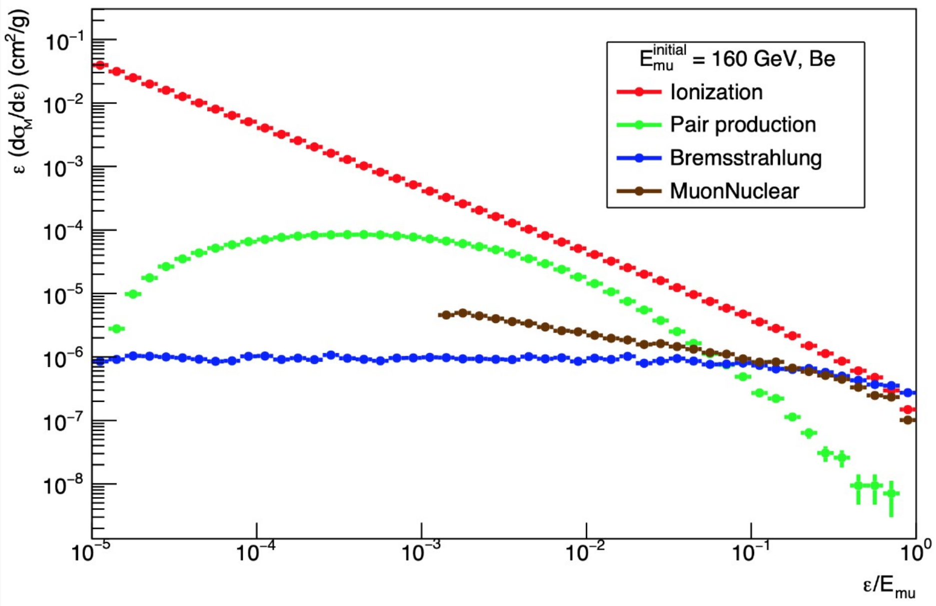


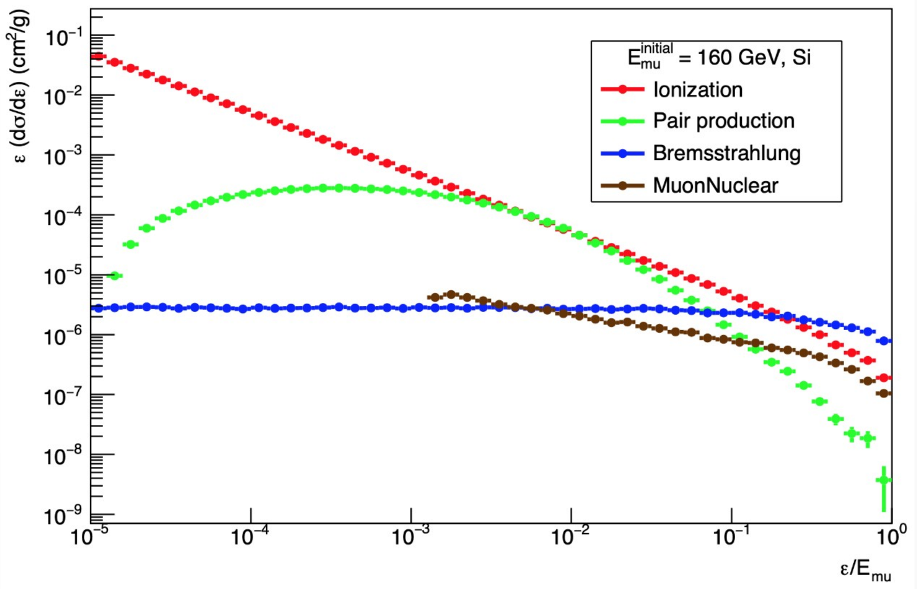
TB2018 (resolution ~40μm)





Backgrounds





MESMER

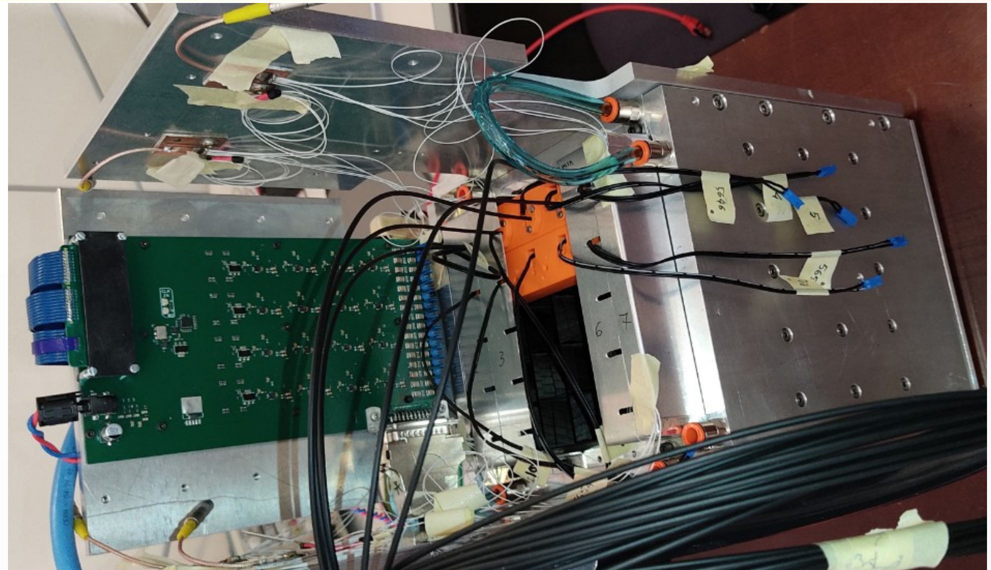
- $\mu e^- \rightarrow \mu e^- \gamma$
- $\mu e^- \rightarrow \mu e^- e^+ e^-$
- $\mu N \rightarrow \mu N e^+ e^-$

GEANT4

- $\mu N \rightarrow \mu N \gamma$
- $\mu N \rightarrow \mu X$

Calorimeter

- 5x5 $PbWO_4$ crystals:
  area: 2.85×2.85 cm^2 ,
  length: 22cm (~25 X_0).
- Total area: ~14×14 cm^2.
- Readout: APD sensors.



Dedicated beam tests:

- July 2022: 1-4 GeV.
  Overall detector & DAQ debug.
  Absolute energy calibration.
- 31/05–10/06 2023: 20–150 GeV e^-.
- 21-26/06 2023: 1-10 GeV e^-.
- Energy resolution studies ongoing.