The MUonE experiment

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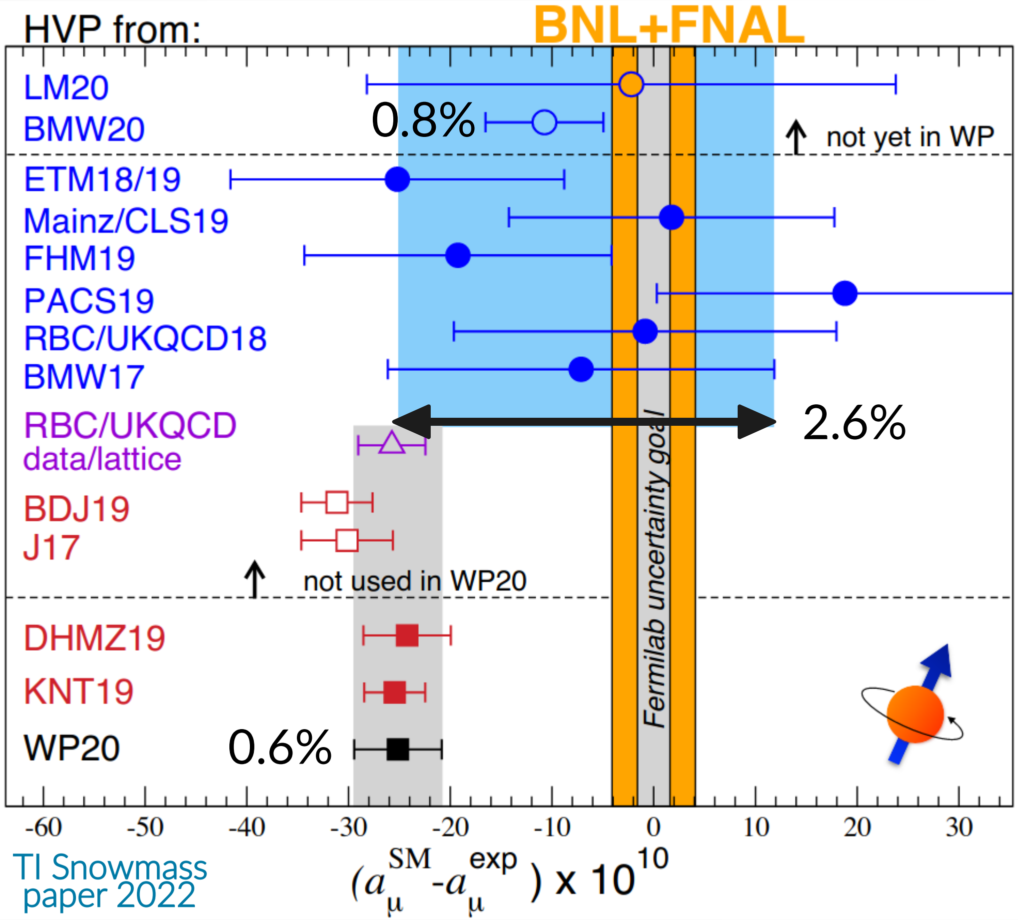
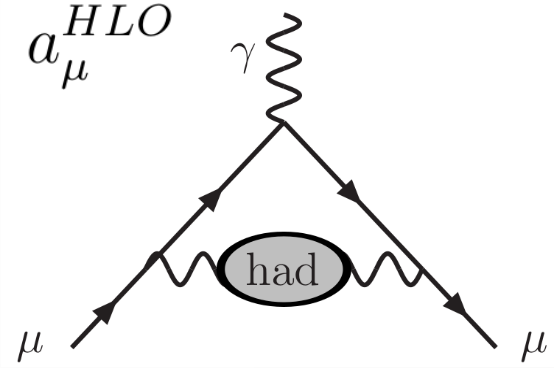
University of Liverpool

Particle Physics Annual Meeting
May 18th-19th 2023

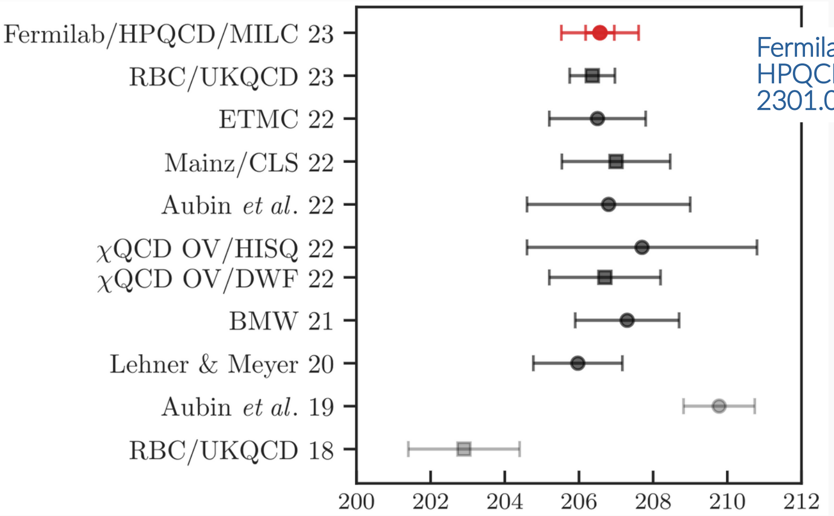
a_μ^{HLO} : present status



TI Snowmass paper 2022

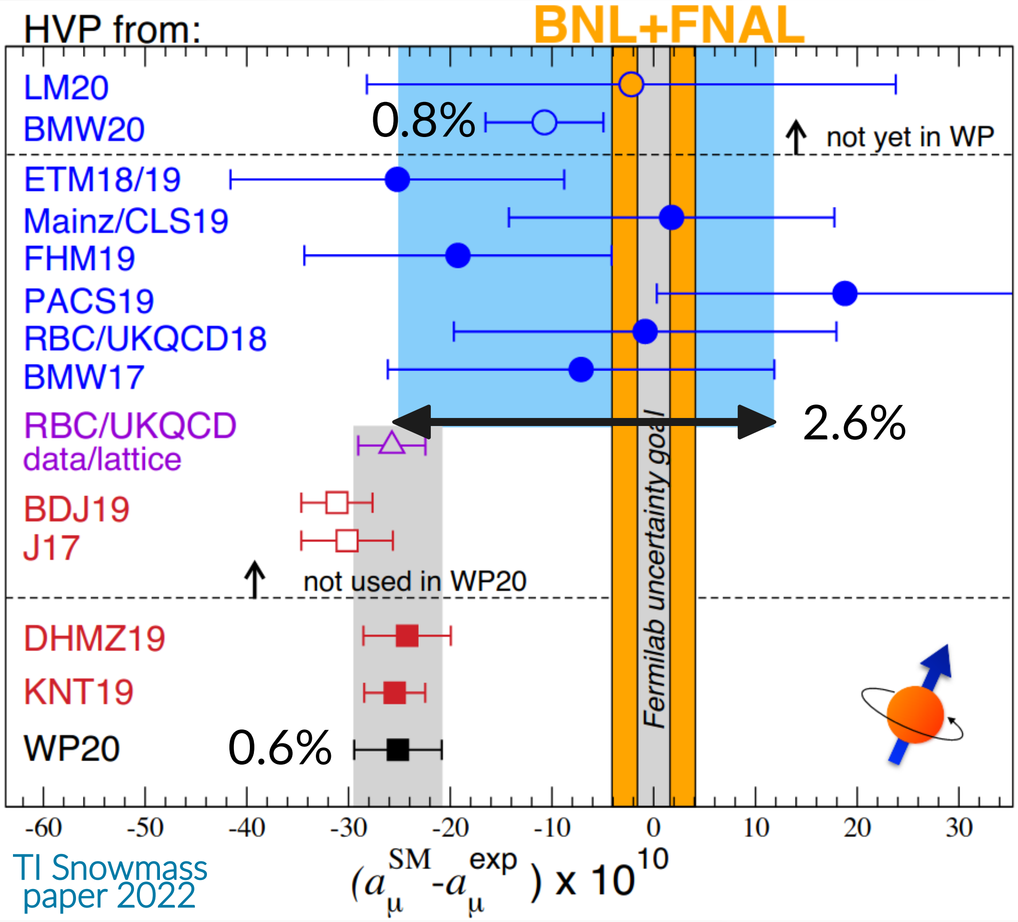


New lattice results in the intermediate window (~30% a_μ^{HLO}):



Fermilab/HPQCD/MILC 2301.08274

a_μ^{HLO} : present status



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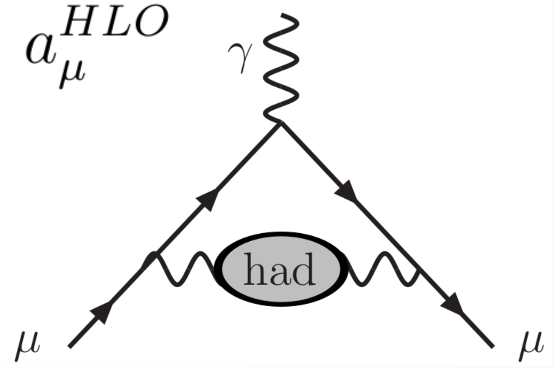
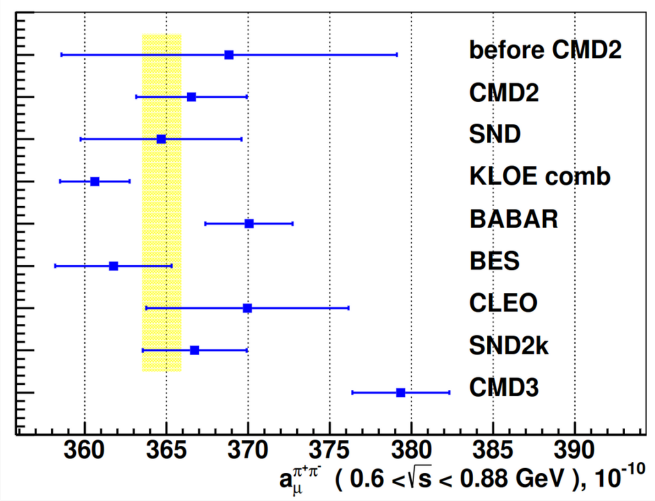


New CMD3 result for $a_\mu^{\mathrm{HLO}}(\pi^+\pi^-)$ (F.Ignatov talk)

2302.08834



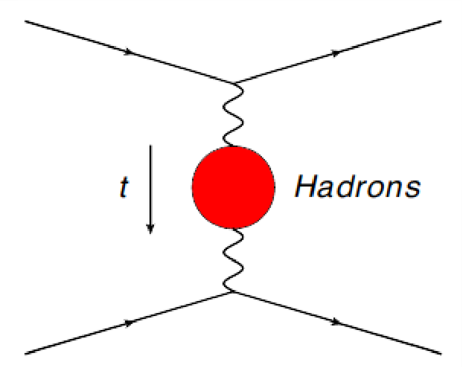
a_μ^{HLO} : space-like approach

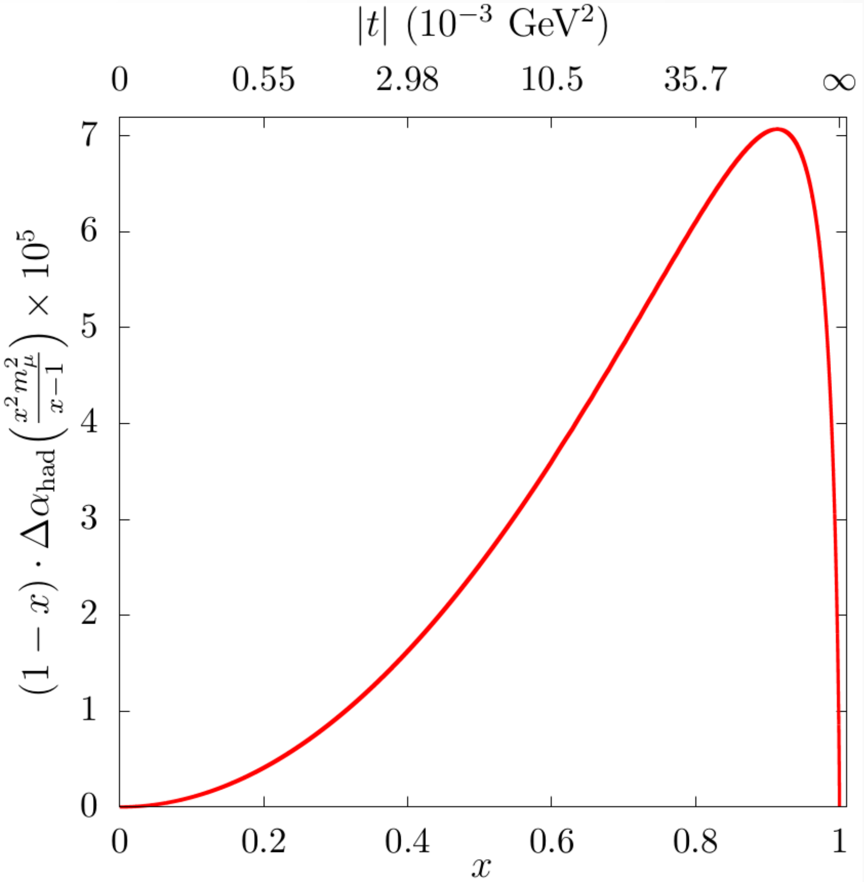
MUonE: a new independent evaluation of a_μ^{HLO}

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

Lautrup, Peterman, De Rafael, Phys. Rep. C3 (1972), 193

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



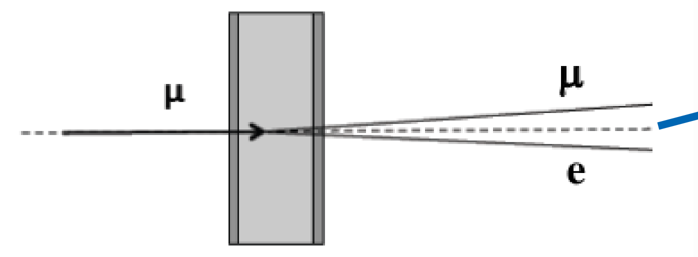


Carloni Calame, Passera, Trentadue, Venanzoni, Phys. Lett. B 746 (2015), 325

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

The MUonE experiment

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

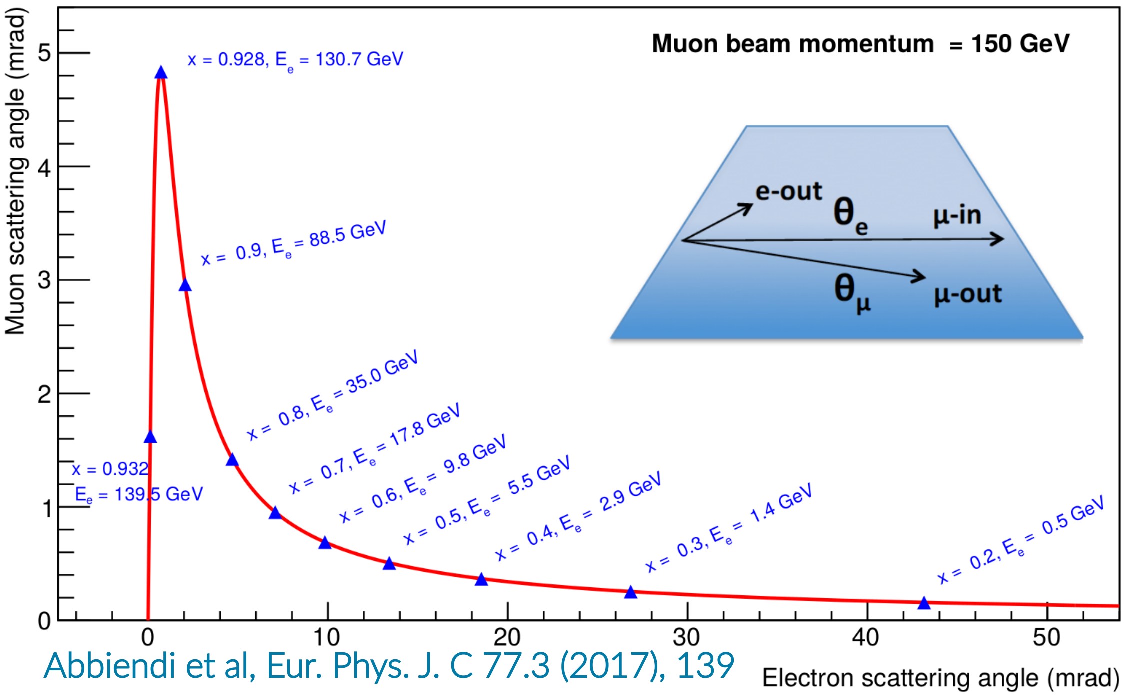


$$\frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}}=0)} \sim 1 + \underline{2\Delta\alpha_{\text{had}}(t)}$$

From theoretical calculation

To be measured

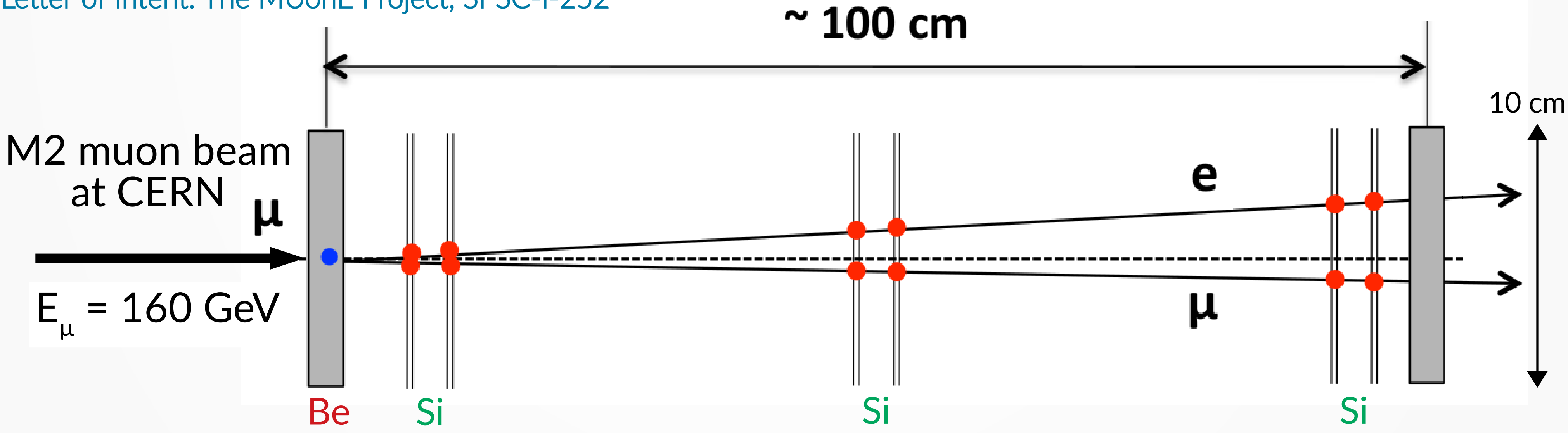
- Compute a_{μ}^{HLO} using data from a single experiment.
- Correlation between muon and electron angles allows to select elastic events and reject background (μ N → μ N $e^{+}e^{-}$).



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

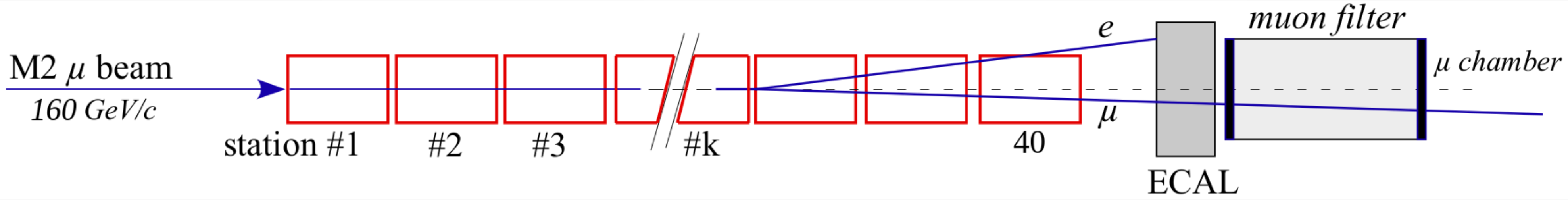
The experimental apparatus

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.

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.

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

Systematic uncertainty
of 10 ppm in the signal region.

Achievable accuracy

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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 (few %)

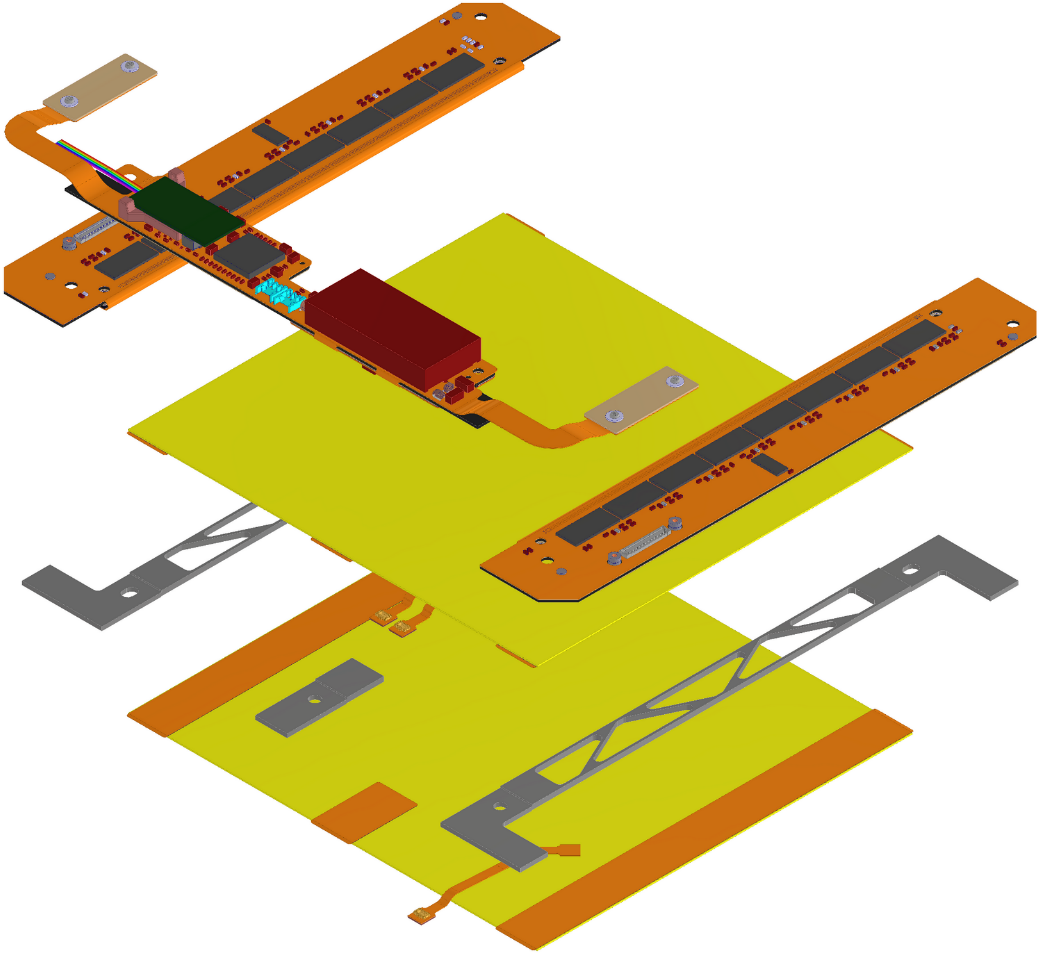
Tracker: CMS 2S modules

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

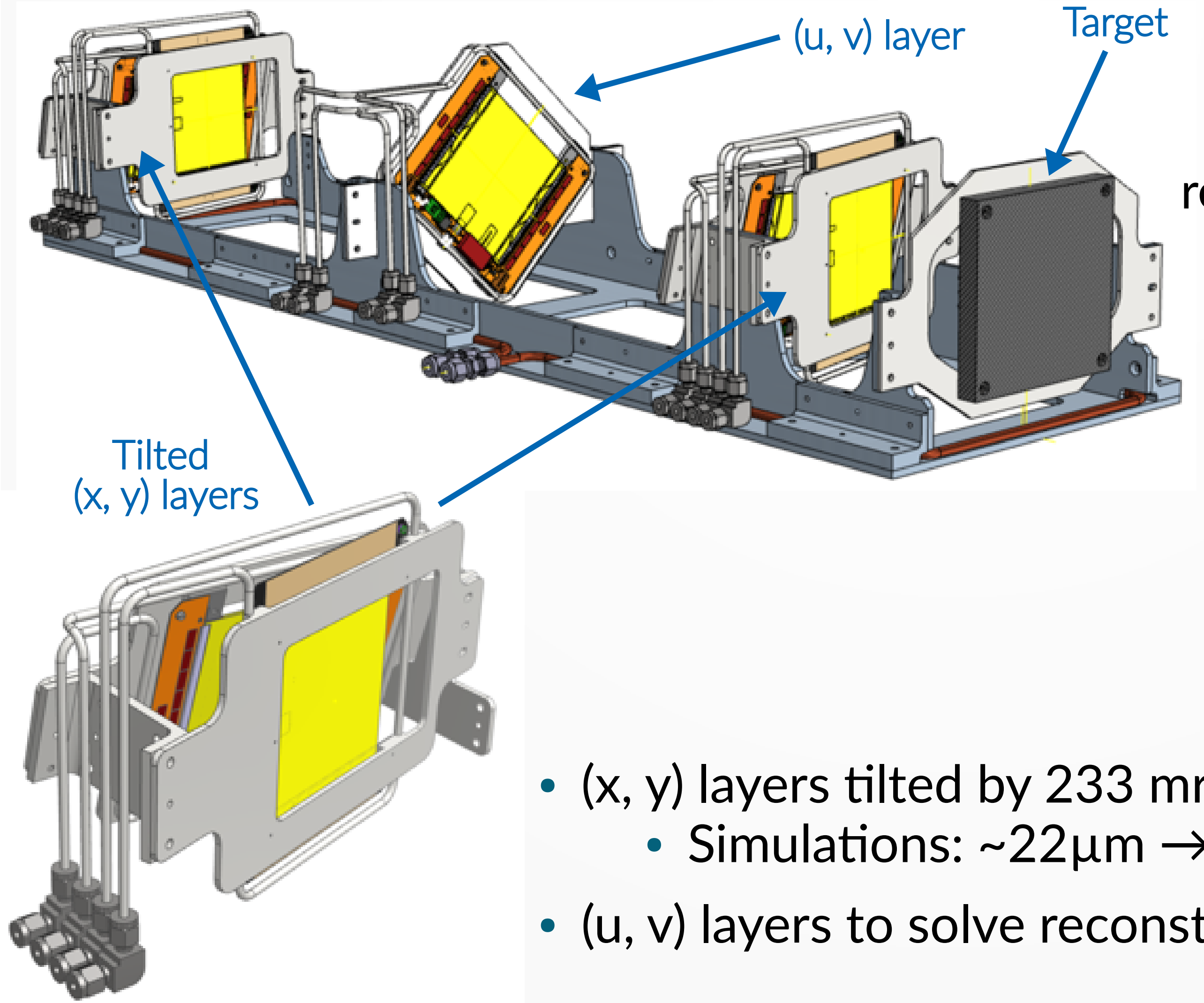
Two close-by strip sensors reading the same coordinate:

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

  - Pitch: 90 µm
  - Digital readout
  - Readout rate: 40 MHz
  - Sensitive area: 10×10 cm^2
  - Thickness: 2 × 320 µm



Tracking station



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

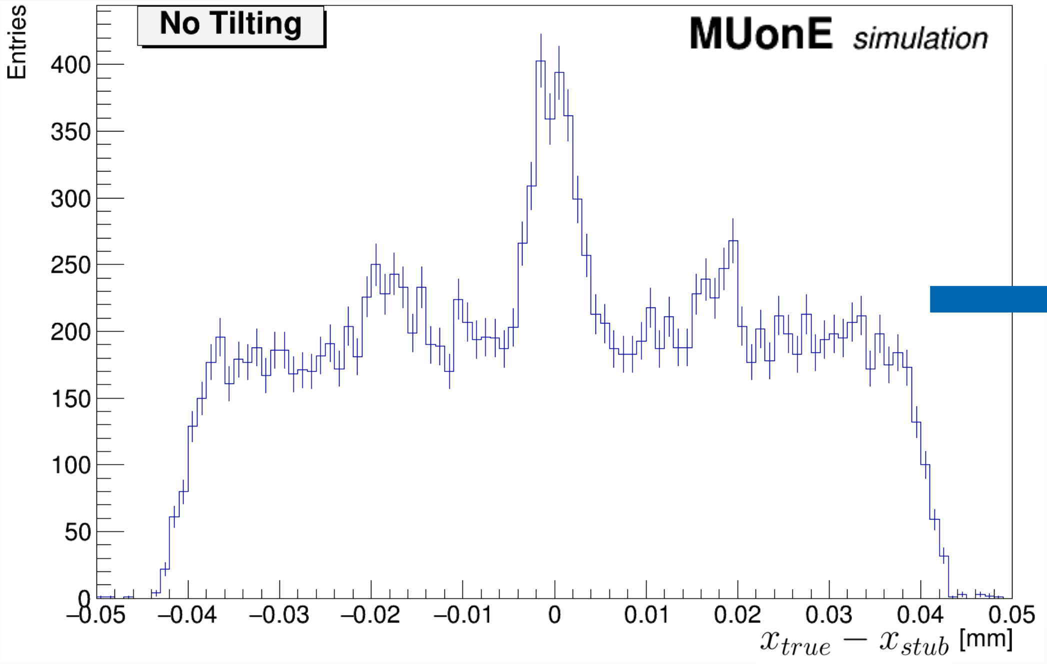
⬇

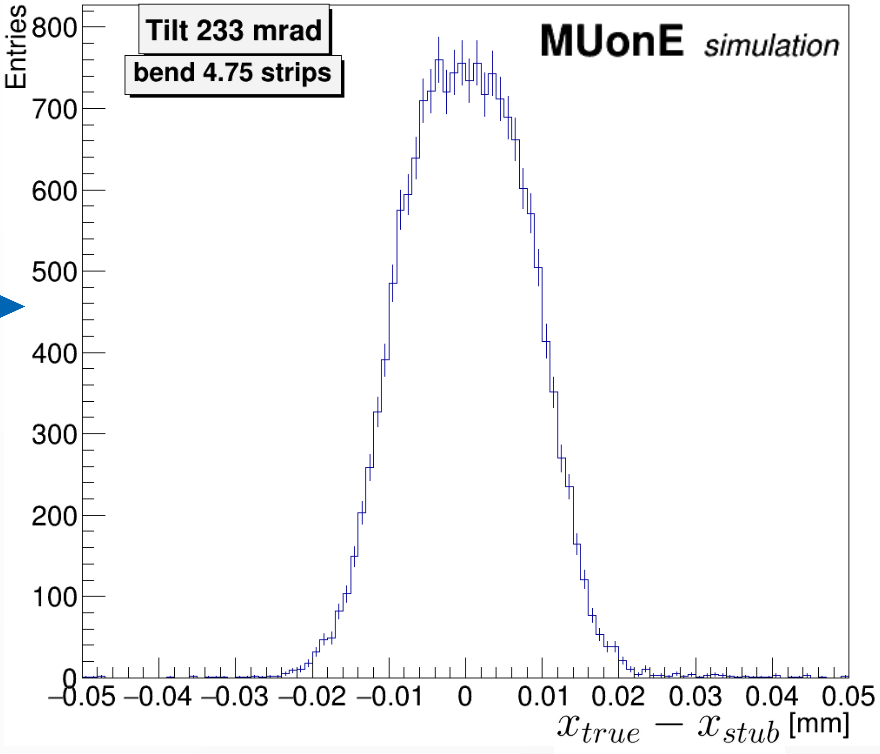
Low CTE material:
INVAR (CTE ~ 1.2×10^{-6} K^{-1})

Laser holographic system
to monitor stability.

- (x, y) layers tilted by 233 mrad: improve spatial resolution.
  - Simulations: ~22µm → ~10 µm.
- (u, v) layers to solve reconstruction ambiguities.

MUonE simulations: Improving resolution - tilted geometry



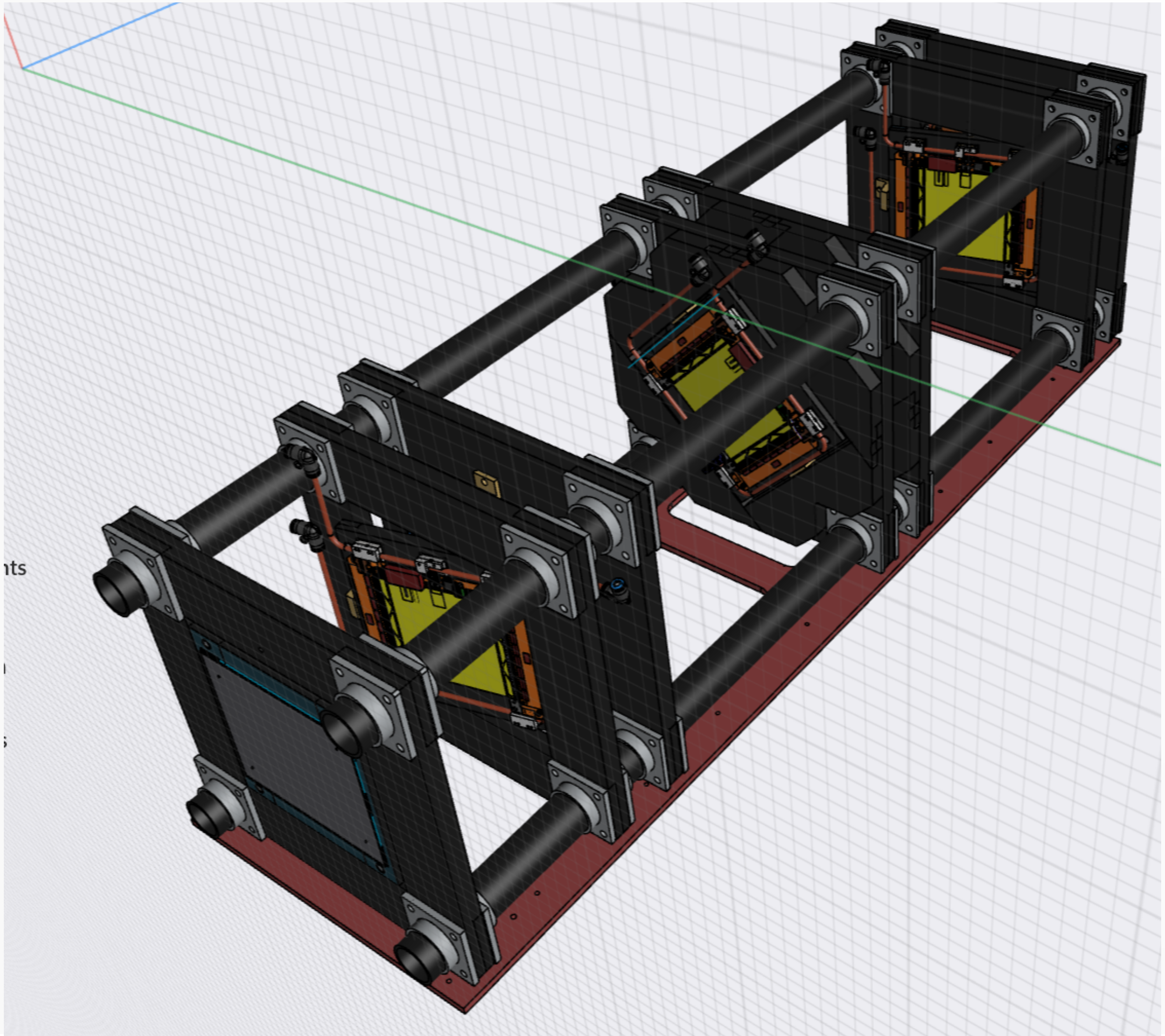


- Improvement mainly due to charge sharing between adjacent strips
- Tune the tilt angle and the digitization threshold to equalize the number of hits composed of 1 or 2 strips.

Final resolution

22 µm → ~10 µm

Tracking station



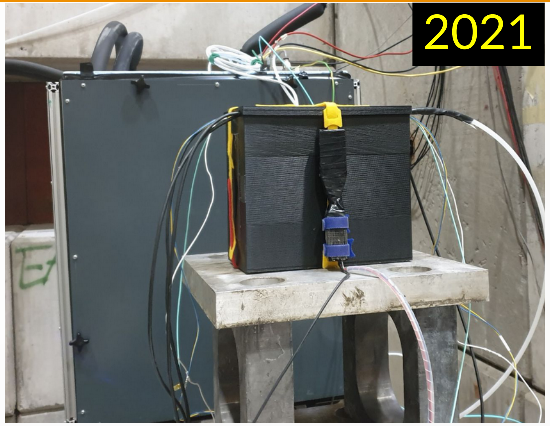
A new design under development at Liverpool.

Carbon Fiber tubes for the mechanical structure: (sub ppm) 0 CTE along the longitudinal direction.

First prototype to be assembled in the next weeks.

Beam Test 2021-2022

- Fall 2021: parasitic beam test.
  - Low beam rate (~10kHz).
  - 2 modules in the MUonE station + 2 modules in an external box.
- Summer 2022: intermittent beam test at the final MUonE location.
  - 4 modules in the MUonE station.
- October 2022: 1 week beam test as main users.
  - Fully equipped tracking station.


2021


2022

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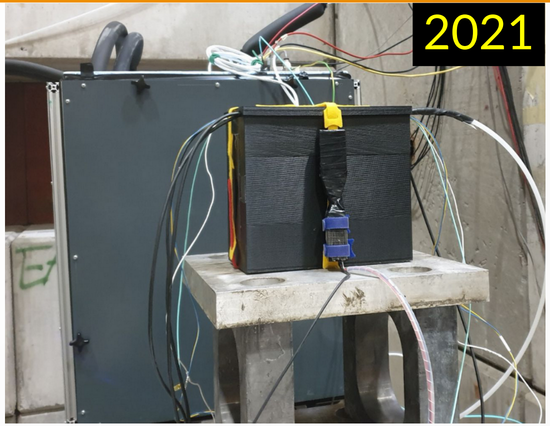
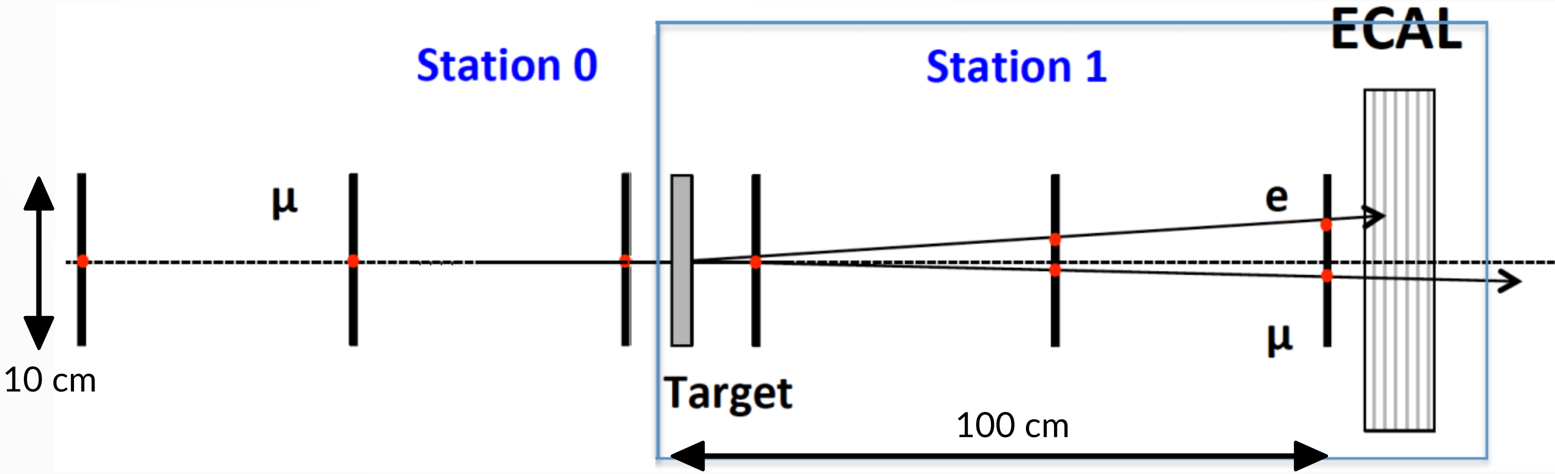
Positive results on the thermal stability of the tracking system and the 2S modules synchronization.



Test Run 2023

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.
- Monitor mechanical and thermal stability.
- Test the detector performance.
- Assess the strategy for the systematic errors.
- Measure $\Delta\alpha_{\rm lep}(t)$ with a few % precision.

MUonE activity in Liverpool

- Hardware:
  - Mechanical structure made of Carbon Fiber (0 CTE in the longitudinal direction).
- Simulation & Analysis:
  - Upgrade of the Beam Magnet Spectrometer (BMS) at the M2 beamline → precise determination of the beam energy profile.
  - Signal contamination due to pair production background.
  - Development of the final analysis strategy to extract $\Delta\alpha_{\mathrm{had}}$.

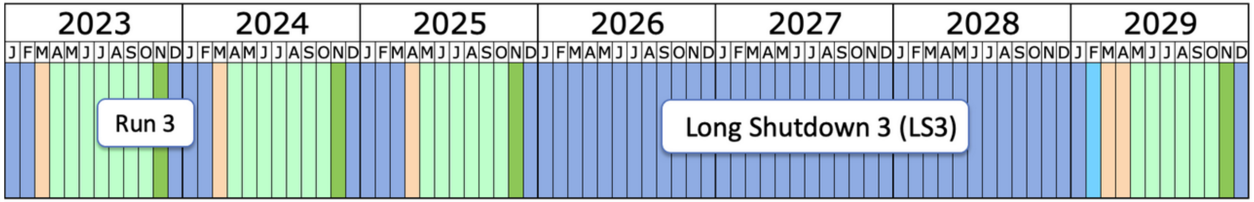
MUonE group:

T. Bowcock, J. Carroll, G. Casse, S. Charity, K. Ferraby, K. Hennessy, F. Ignatov, T. Jones, R. Pilato, J. Price, K. Rinnert, T. Smith, T. Teubner, G. Venanzoni, J. Vossebeld, C. Zhang.

Conclusions

MUonE
web site

- The new method proposed by MUonE to measure a_μ^{HLO} is independent and competitive with the latest evaluations.
- Intense Beam Test activities in 2021-2022:
  first experience with detector in real beam conditions.
- 3 weeks Test Run in 2023:
  proof of concept of the experimental proposal
  using 1 tracking station + ECAL.
- Towards the full experiment: 5-10 stations before LS3 (2026).
  2-4 months data taking: first measurement (few % precision) of a_μ^{HLO}.
- New collaborators are welcome!



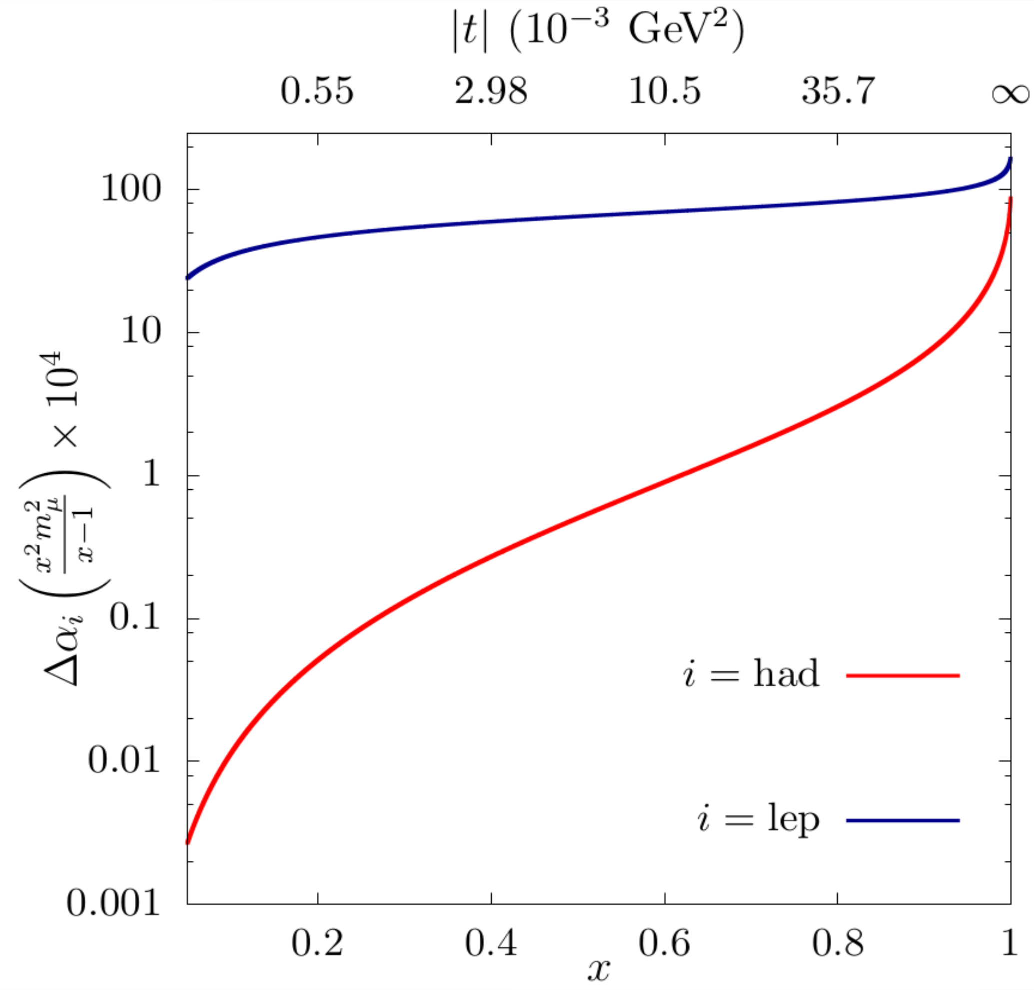
BACKUP

- 160 GeV muon beam on atomic electrons.

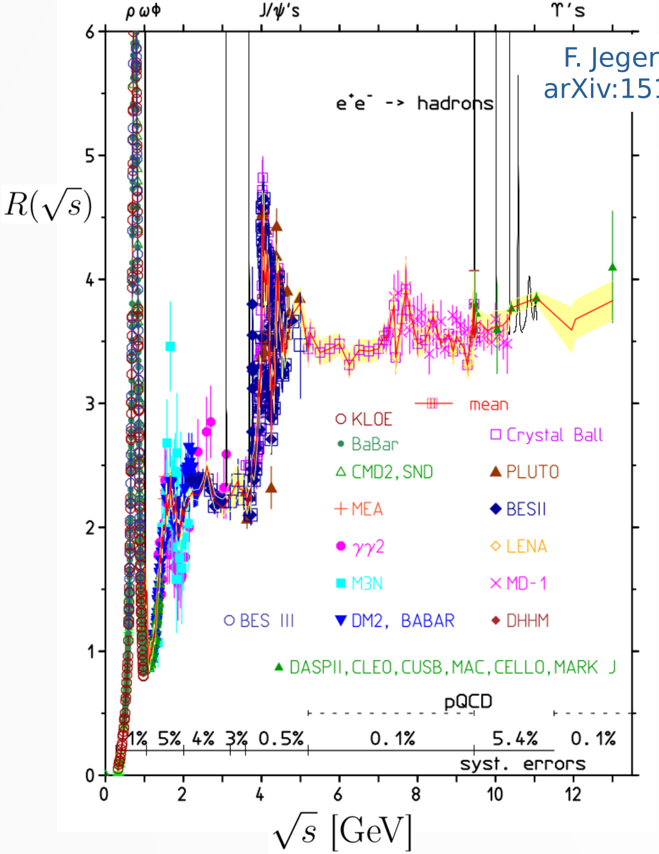
$$\sqrt{s} \sim 420\,\mathrm{MeV}$$

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

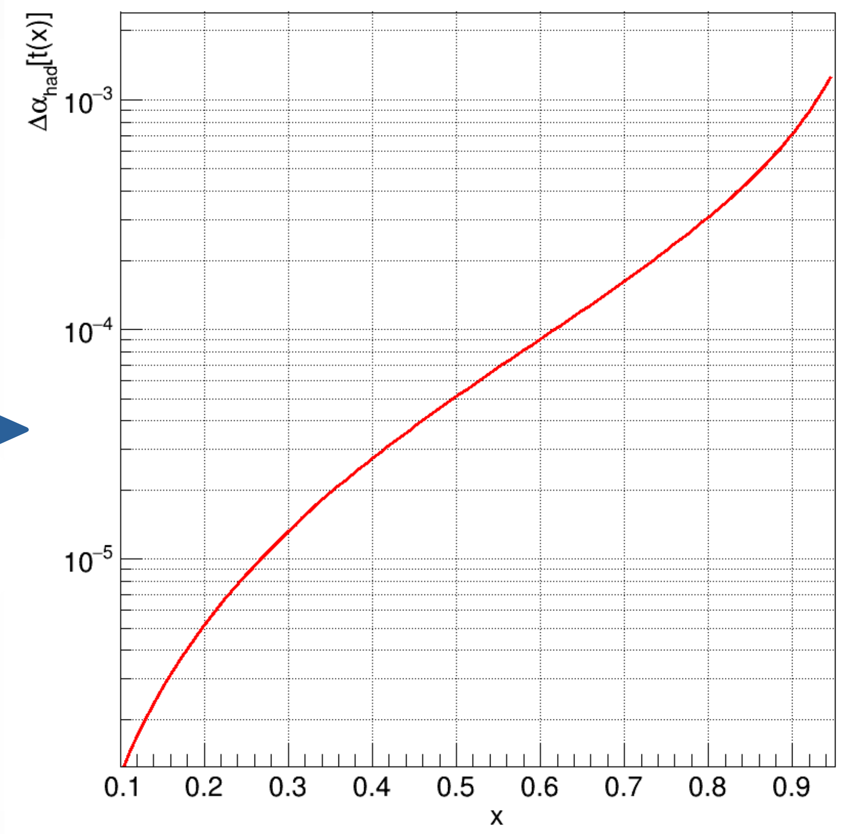
$$\Delta\alpha_{had}(t) \lesssim 10^{-3}$$



From time-like to space-like



F. Jegerlehner, arXiv:1511.04473

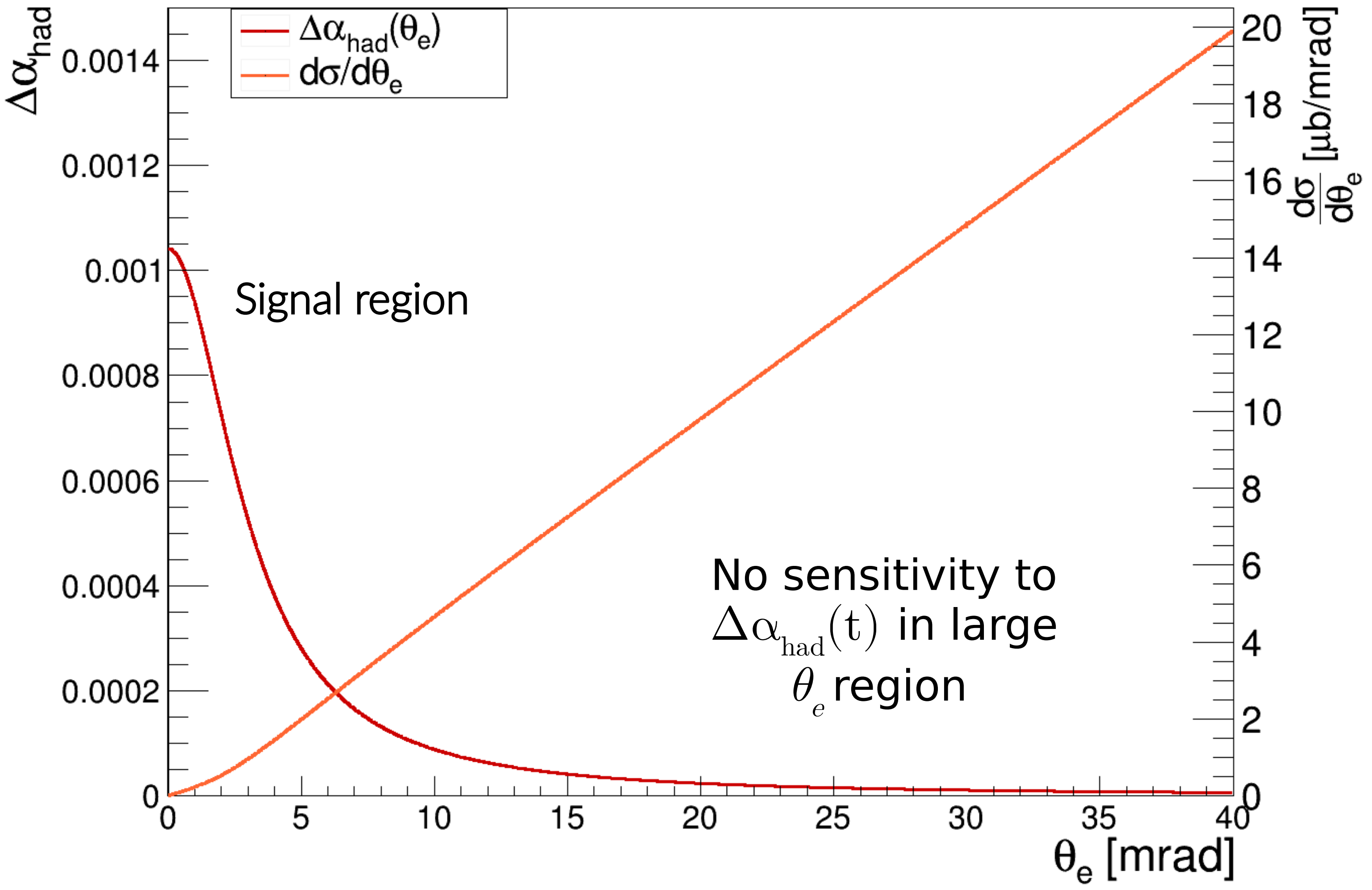


$$a_\mu^{HLO} = \frac{\alpha_0^2}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

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

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

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



Signal region

No sensitivity to $\Delta\alpha_{\mathrm{had}}(t)$ in large θ_e region

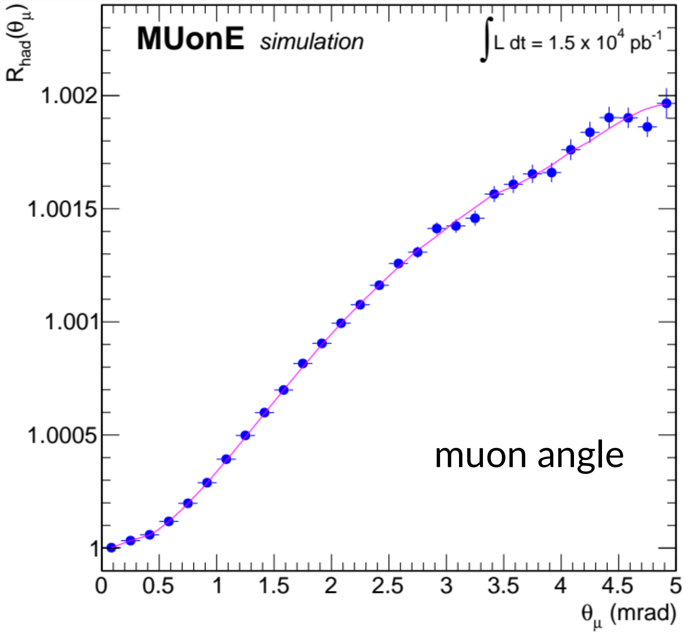
Extraction of a_μ^{HLO}

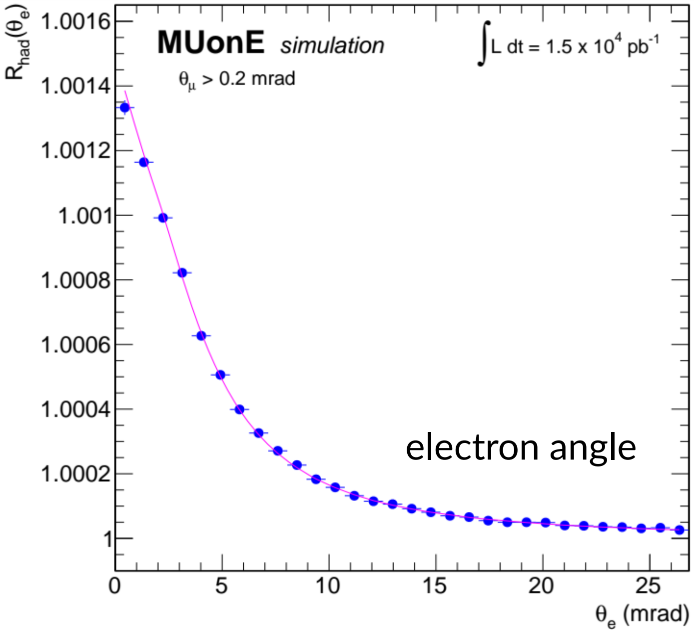
$\Delta\alpha_{had}(t)$ parameterization: inspired from the 1 loop QED contribution of lepton pairs and top quark at *t* < 0

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

2 parameters:
K, M

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





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

Results from simulation:

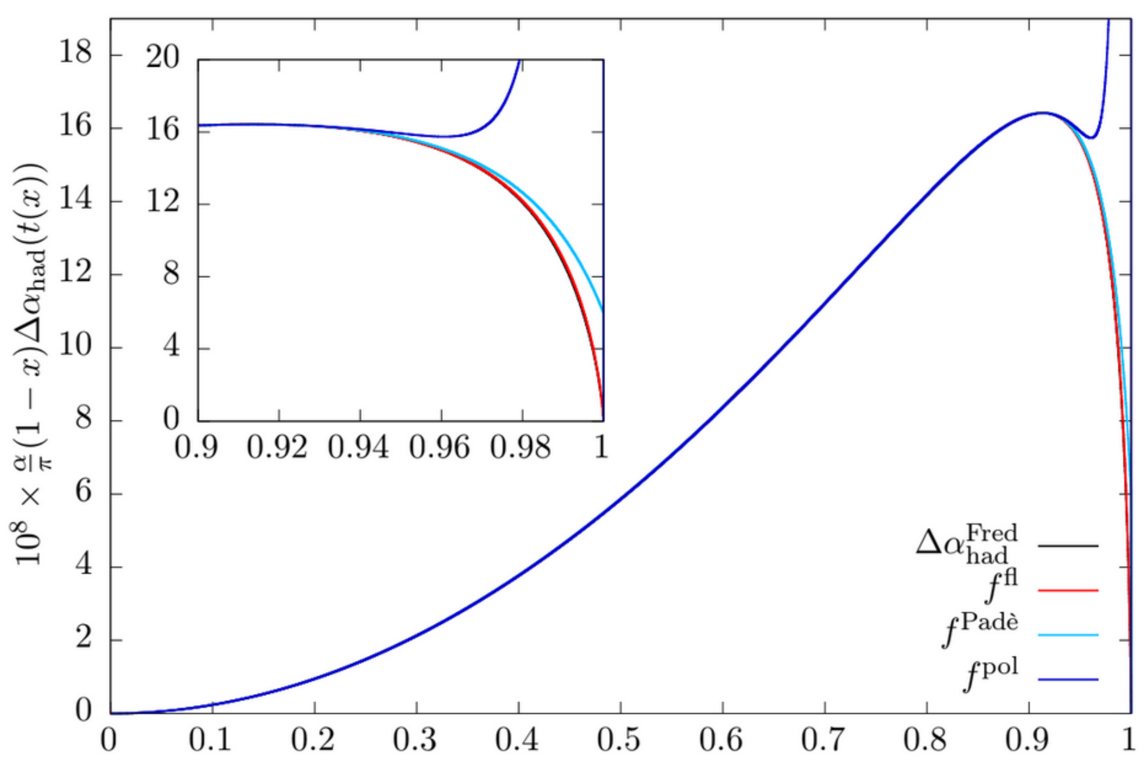
$$a_\mu^{HLO} = (688.8 \pm 2.4)\ 10^{-10}$$

Input value:

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

“Lepton-like” parameterization

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

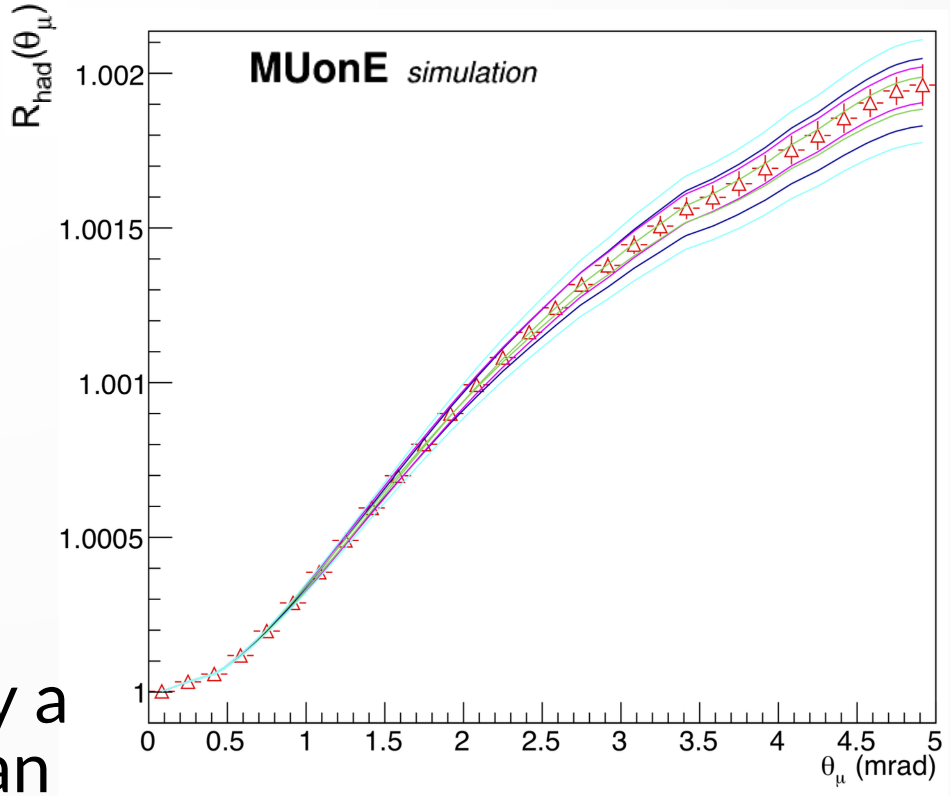


K = related to α_0 and the electric charge of the lepton in the loop (and also colour charge for quarks)

M = related to the squared mass of the particle in the loop

It allows to extrapolate $\Delta\alpha_{had}(t)$ also in the region which is not accessible by kinematics ($x > 0.93$).

Template fit



1. Define a grid of points (K, M)
   in the parameters space,
   in order to cover a region
   ±5σ around the expected values
   (σ = expected uncertainty).
   Step size: σ/4 or σ/2.

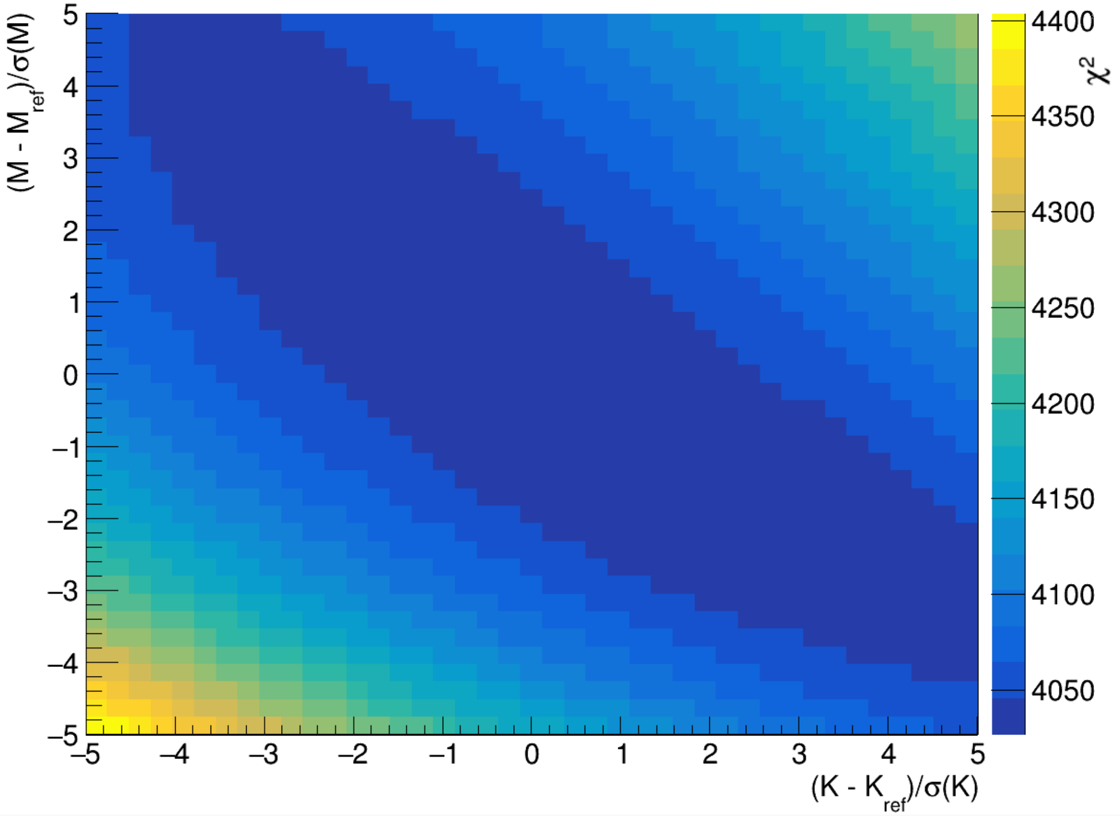
2. Generate a MC sample and apply a reweighting procedure to make an ensemble of template distributions.
   Each template distribution corresponds to a (K, M) point in the grid.

Template fit

3. Make a χ^2 (or likelihood) comparison between the data and each template distribution.

4. Perform a parabolic interpolation across the grid points to get the best fit parameters (K, M).

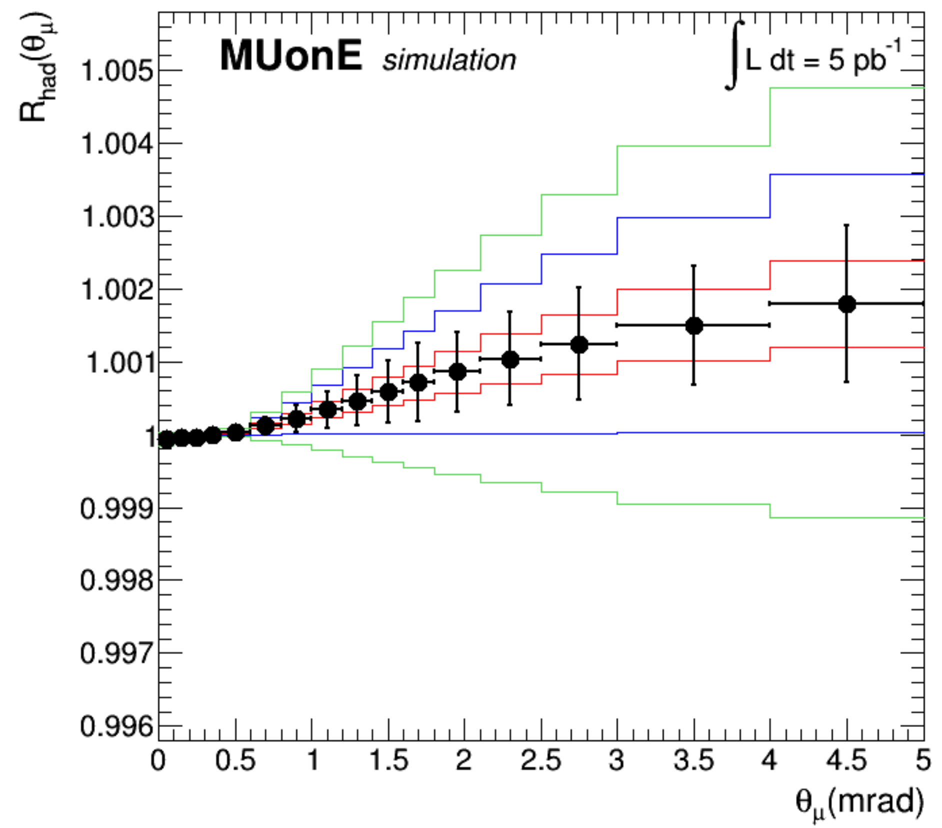
$$\chi^2 = \sum_i^{\text{bins}} \left(\frac{\text{data}_i - \text{templ}(K, M)_i}{\sigma_i^{\text{data}}} \right)^2$$



Test Run: expected sensitivity on $\Delta\alpha_{had}(t)$

Expected luminosity for the Test Run: L_{TR} = 5 pb^{-1} ⟷ ~10^9 events with E_e > 1 GeV (θ_e < 32 mrad)

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



We will be sensitive to the leptonic running ($\Delta\alpha_{lep}(t)$ < 10^{-2})

Low sensitivity to the hadronic running ($\Delta\alpha_{had}(t)$ < 10^{-3})

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

K = 0.136 ± 0.026
(20% stat error)

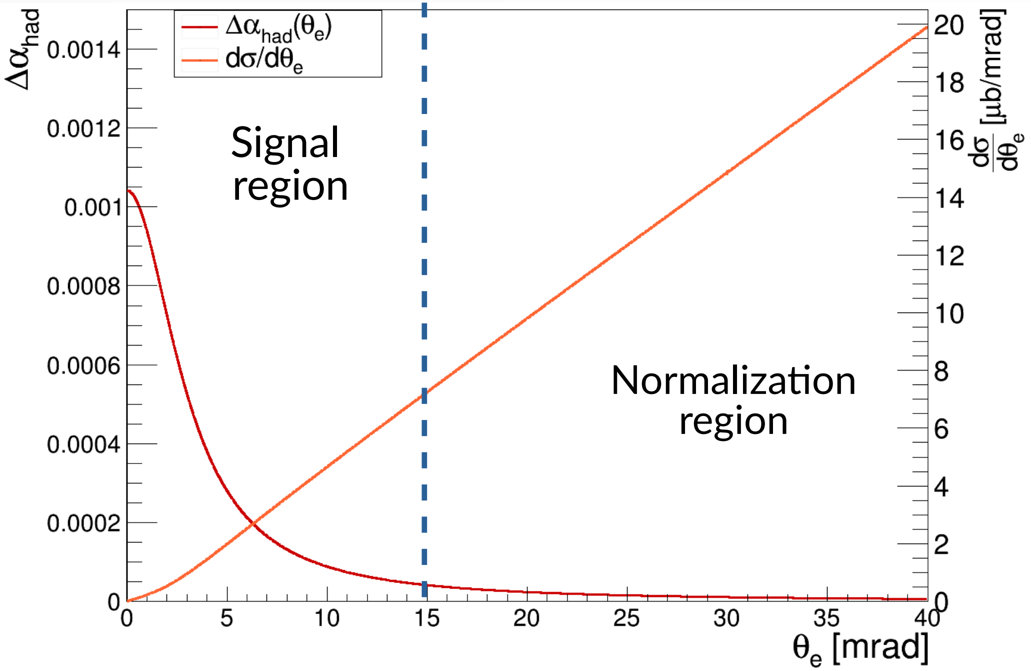
Strategy for the systematic effects

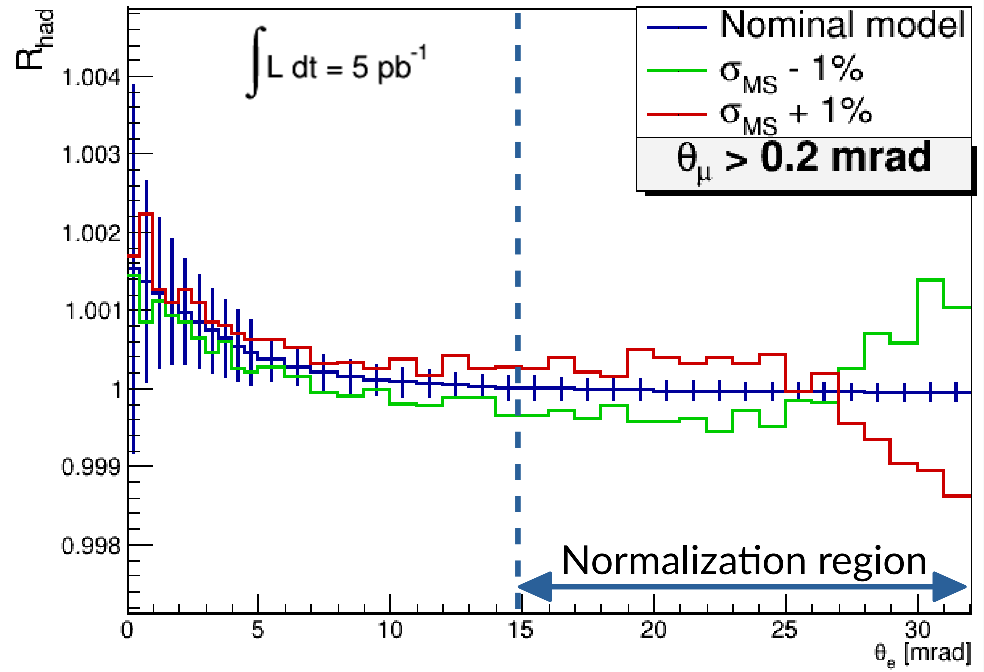
Main systematics have large effects in the normalization region.
(no sensitivity to $\Delta\alpha_{\mathrm{had}}$ here)

Example: modelization of multiple scattering effects.

Other systematics:

- Angular intrinsic resolution.
- Knowledge of the beam energy.

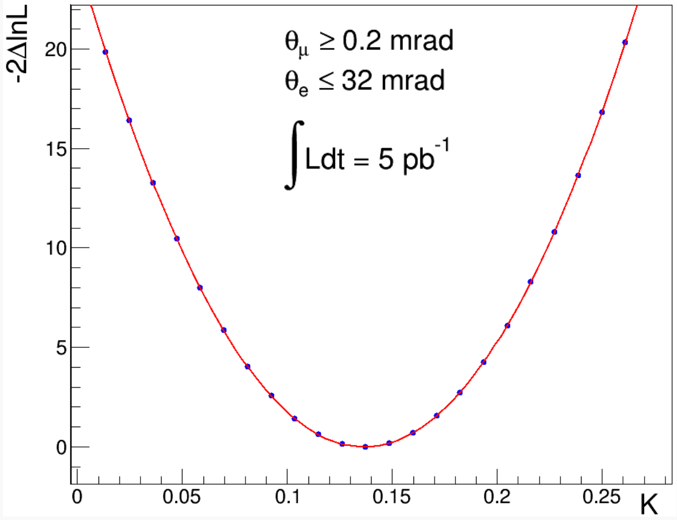




Strategy for the systematic effects

Promising strategy:

- Study the main systematics in the normalization region.
- Include residual systematics as nuisance parameters in a combined fit with signal.
- MESMER MC for the template fit + Combine tool to fit the nuisance parameters.



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

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

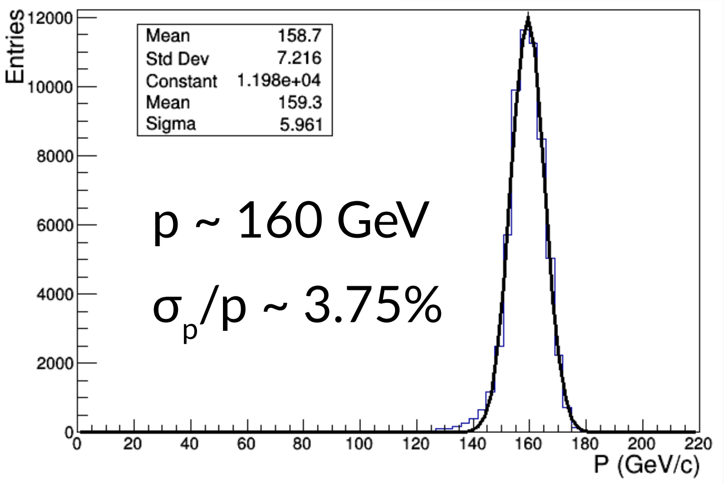
Further tests:

- Repeat the procedure using the Geant4 Simulation + Track Reconstruction.
- Final MuonE statistics.
- Improve the modelization of systematic effects.

Location: M2 beam line at CERN

- Location: upstream the COMPASS detector (CERN North Area).
- Low divergence muon beam: $\sigma_{x'} \sim \sigma_{y'} \sim 0.3$ mrad.
- Spill duration: 4.8 s. Duty cycle ~ 25%.
- Maximum rate: 50 MHz (~ 3×10^8 μ^+/spill).

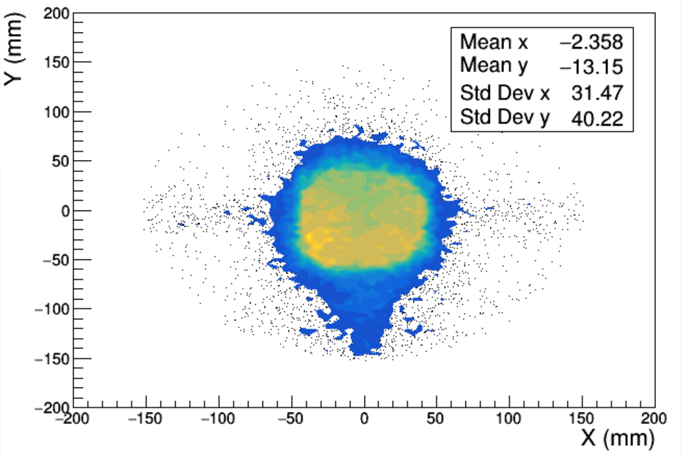
Beam momentum



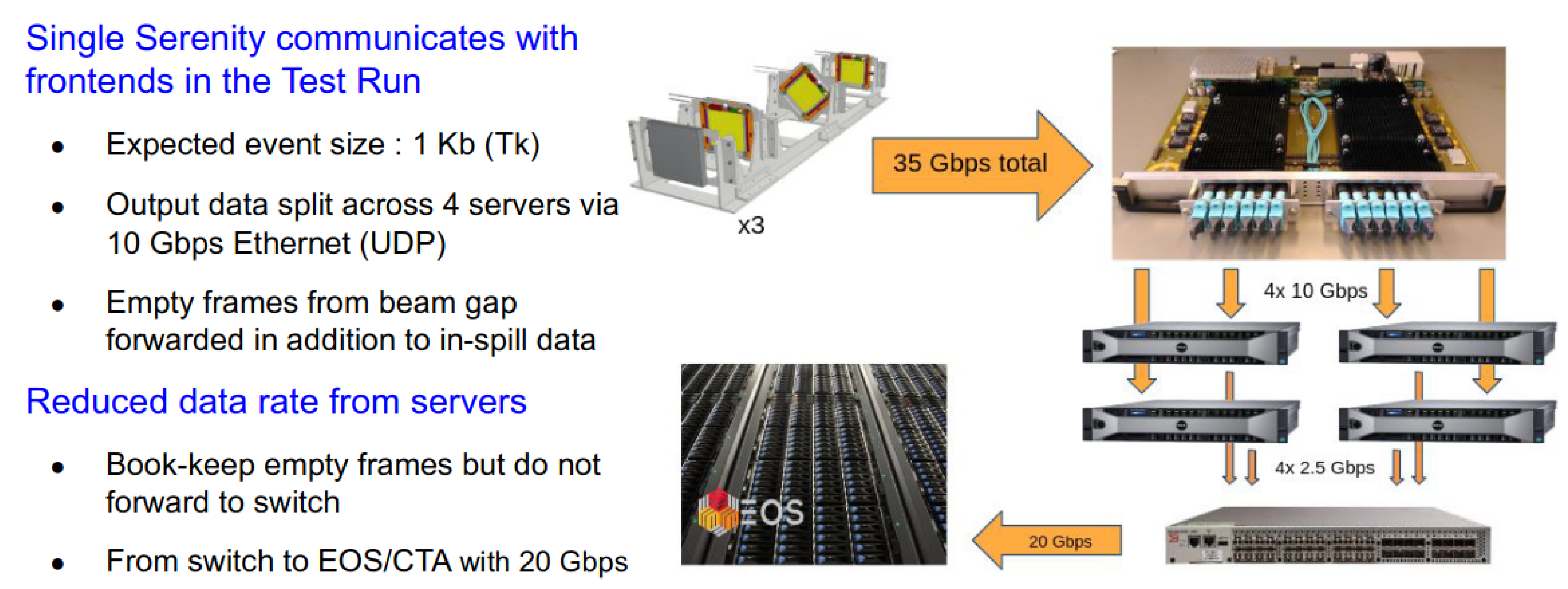
$p \sim 160$ GeV

$\sigma_p/p \sim 3.75\%$

Beam spot: $\sigma_x \sim \sigma_y \sim 2.7$ cm



BE-DAQ architecture



Single Serenity communicates with frontends in the Test Run

- Expected event size : 1 Kb (Tk)
- Output data split across 4 servers via 10 Gbps Ethernet (UDP)
- Empty frames from beam gap forwarded in addition to in-spill data

Reduced data rate from servers

- Book-keep empty frames but do not forward to switch
- From switch to EOS/CTA with 20 Gbps

- Test Run: read all data with no event selection.
- Information will be used to determine online selection algorithms to be used in the Full Run.

Tracker: CMS 2S modules

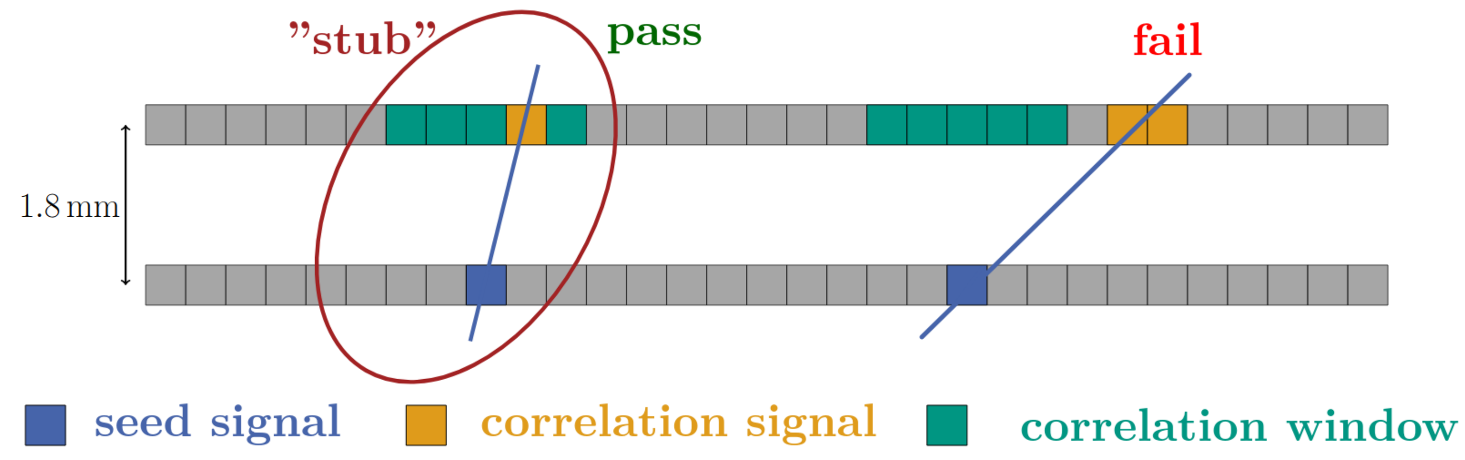
CMS Tracker Phase2 Upgrade - TDR

Two sensors reading the same coordinate:

- Background suppression from single-sensor hits.
- Rejection of large angle tracks.

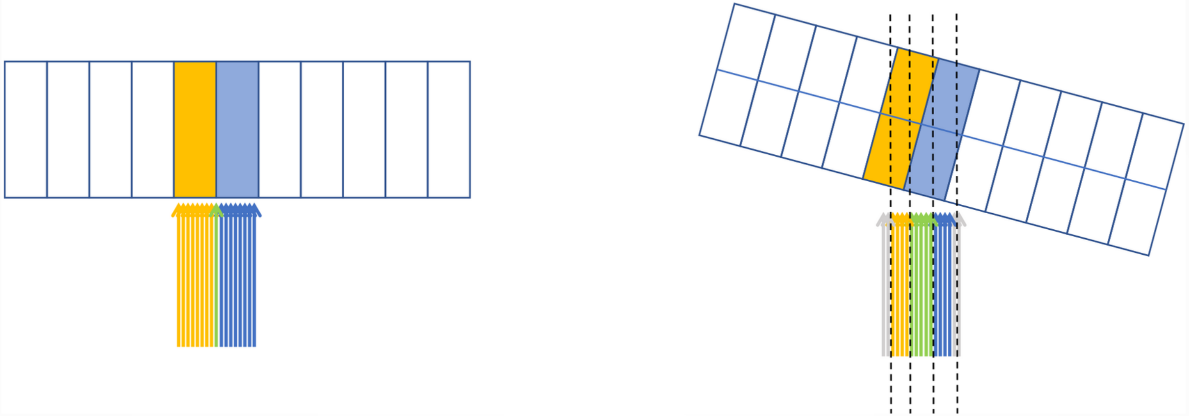
- x_{seed}
- bend = $x_{corr} - x_{seed}$

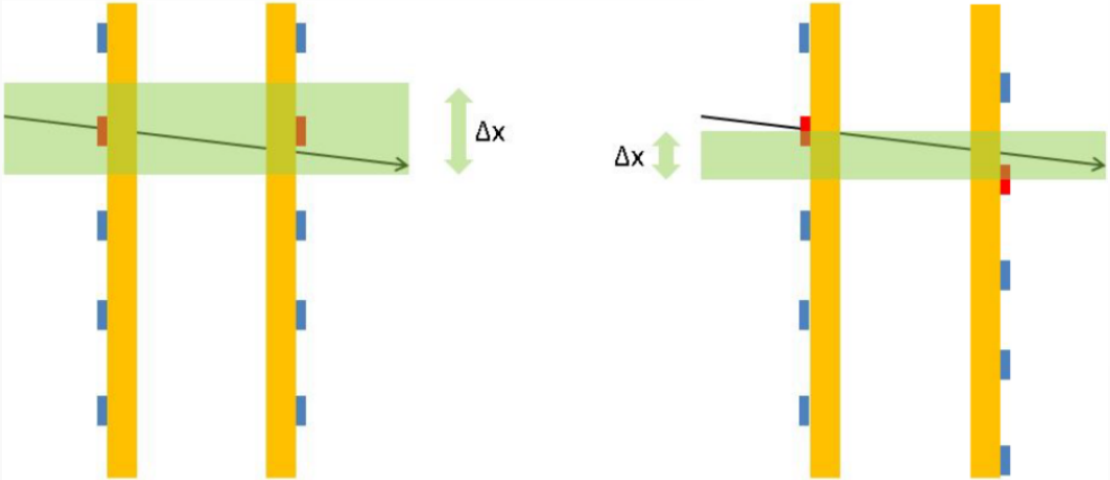
$$x_{stub} = x_{seed} + \frac{\text{bend}}{2}$$



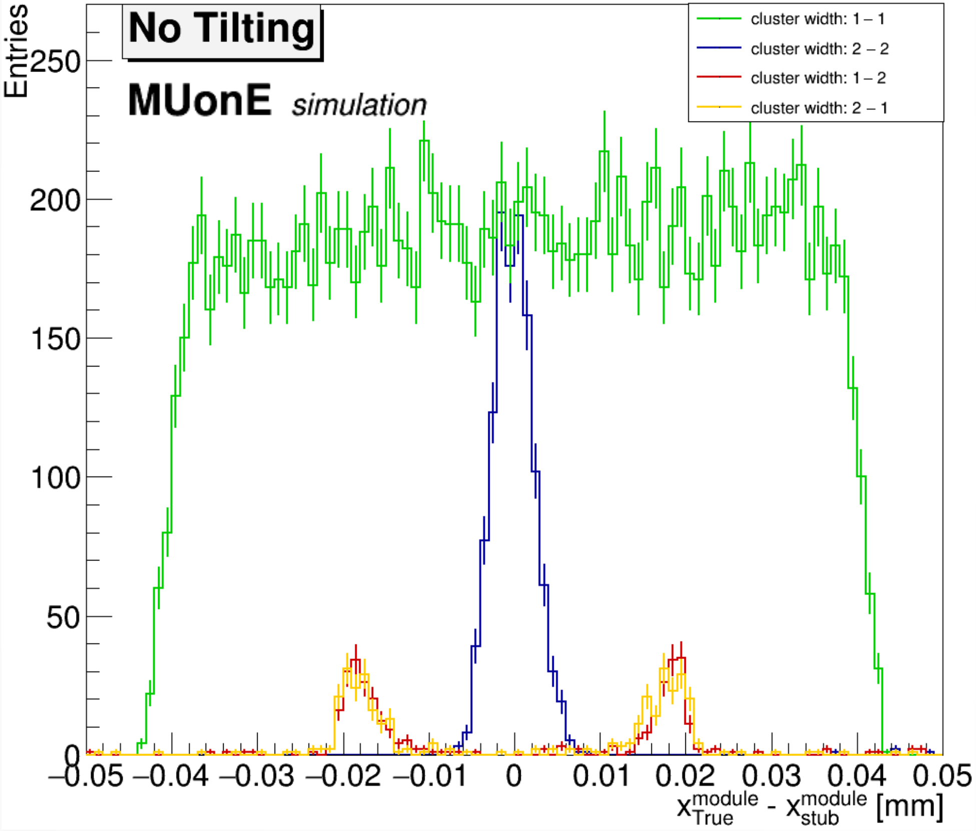
Stub information: position of the cluster in the seed layer + distance between position of correlation cluster and seed cluster (bend)

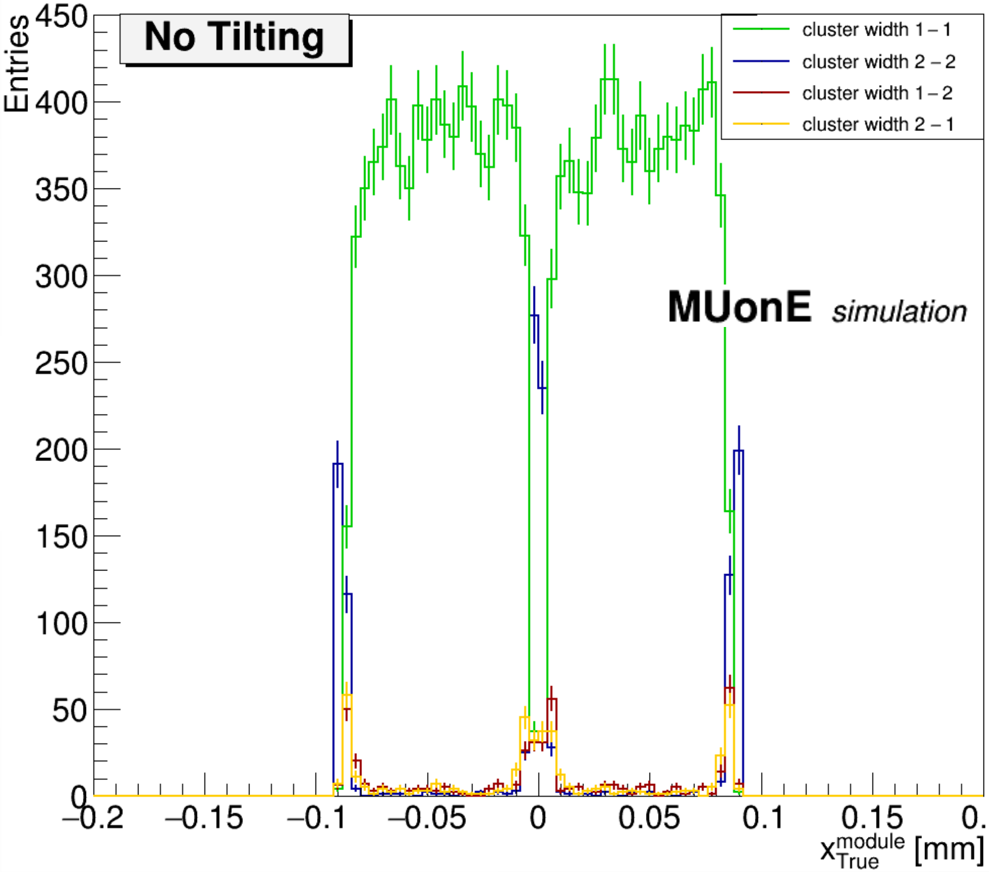
1) charge sharing: energy deposition of particles in the Si is shared among neighbouring strips





2) effective staggering: tilting a 2S module by 25 mrad is equivalent to stagger the two sensors by ½pitch


No Tilting
MUonE simulation
cluster width: 1 – 1
cluster width: 2 – 2
cluster width: 1 – 2
cluster width: 2 – 1
Entries
0
50
100
150
200
250
−0.05
−0.04
−0.03
−0.02
−0.01
0
0.01
0.02
0.03
0.04
0.05
x_{True}^{module} - x_{stub}^{module} [mm]

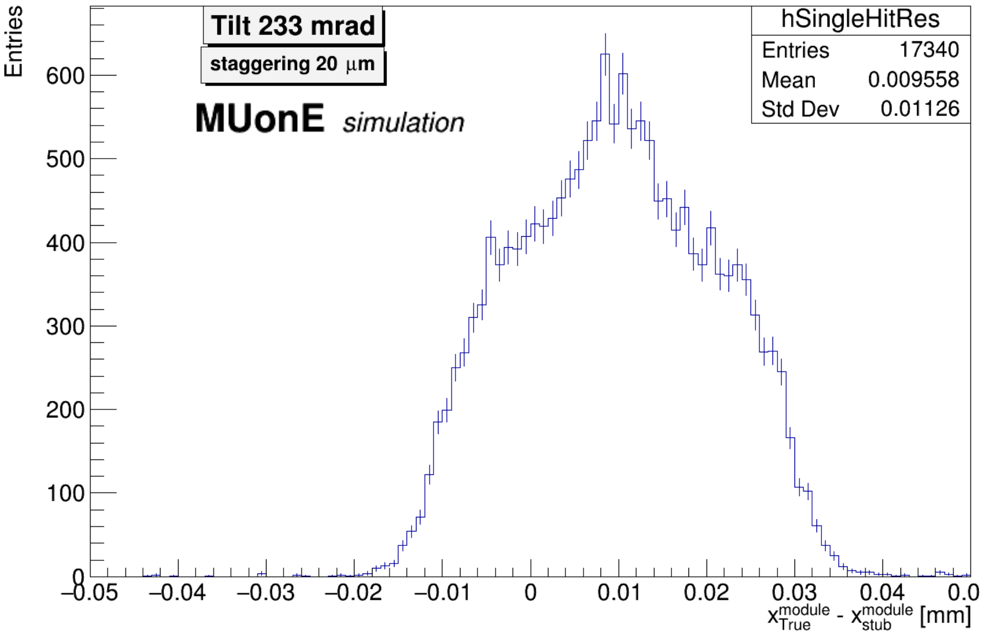

No Tilting
MUonE simulation
cluster width 1 – 1
cluster width 2 – 2
cluster width 1 – 2
cluster width 2 – 1
Entries
0
50
100
150
200
250
300
350
400
450
−0.2
−0.15
−0.1
−0.05
0
0.05
0.1
0.15
0.2
x_{True}^{module} [mm]

MUonE simulations:
Improving resolution - tilted geometry

Tilt angle [mrad]	<bend> [strips]	threshold [σ]	resolution [μm]
210	4.25	5	7.8
221	4.5	5.5	11.5
233	4.75	6	8.0
245	5	6.5	11.2
257	5.25	7	8.7
268	5.5	7.5	11.0

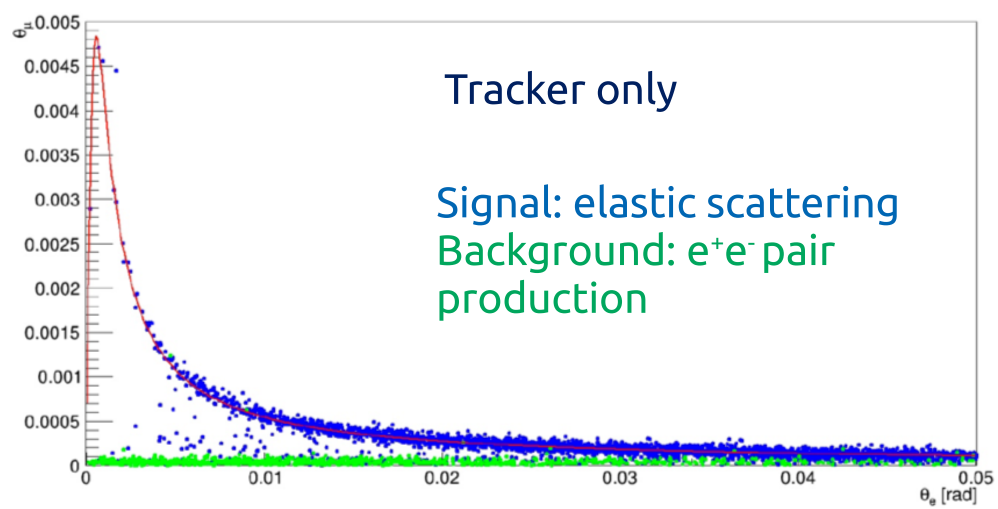
Effect of a staggering between the two sensors

Staggering [μm]	resolution [μm]	bias [μm]
0	8.0	0
5	8.4	2.4
10	9.4	4.9
15	10.4	7.3
20	11.3	9.6
25	11.2	12.1
30	10.4	14.5



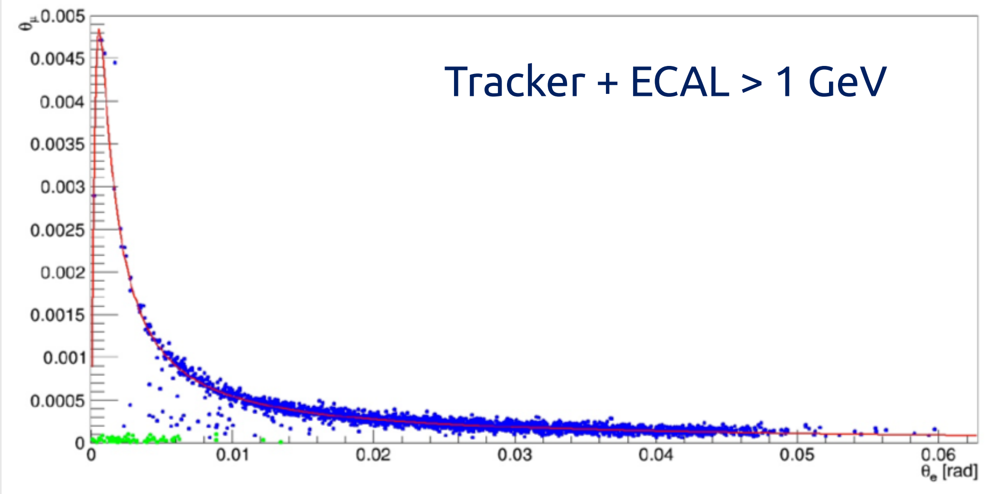
GEANT4 simulations

TB2017 (resolution ~7µm)



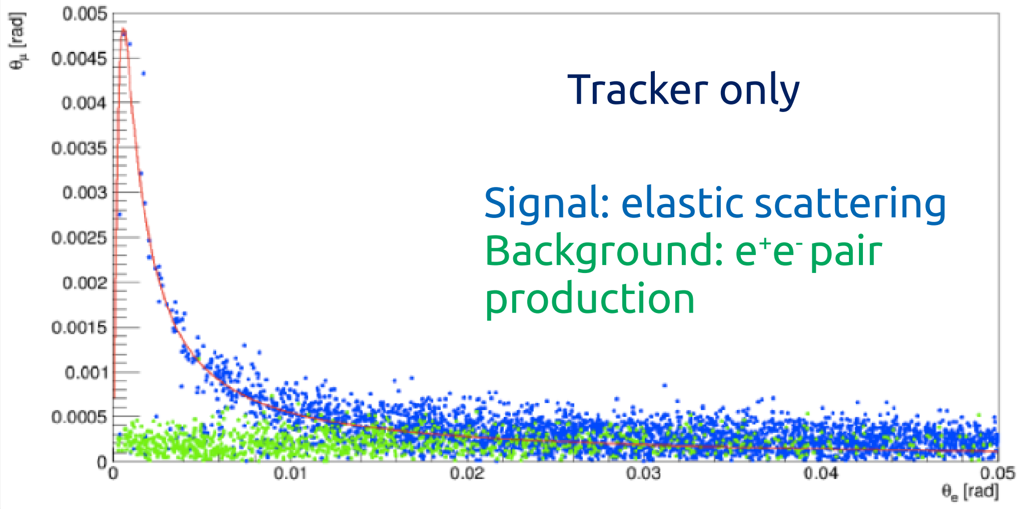
Tracker only

Signal: elastic scattering
Background: e^+e^- pair production



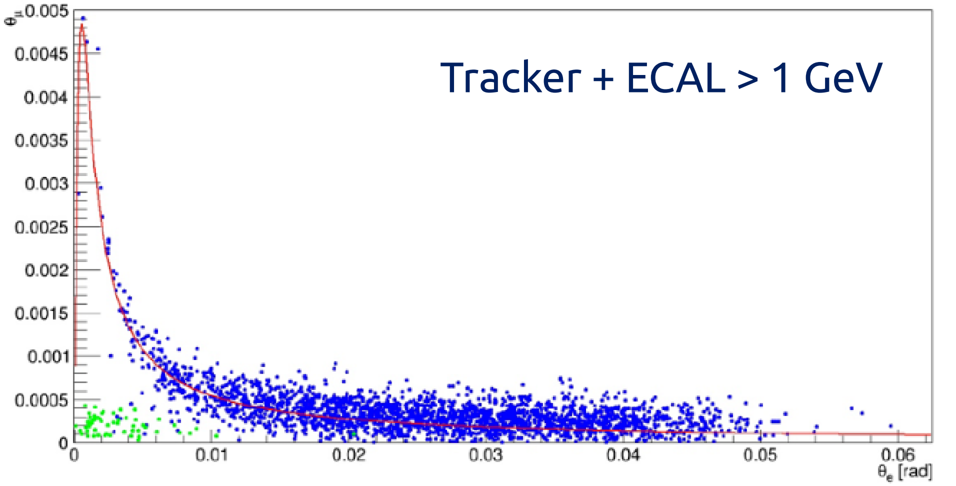
Tracker + ECAL > 1 GeV

TB2018 (resolution ~40µm)



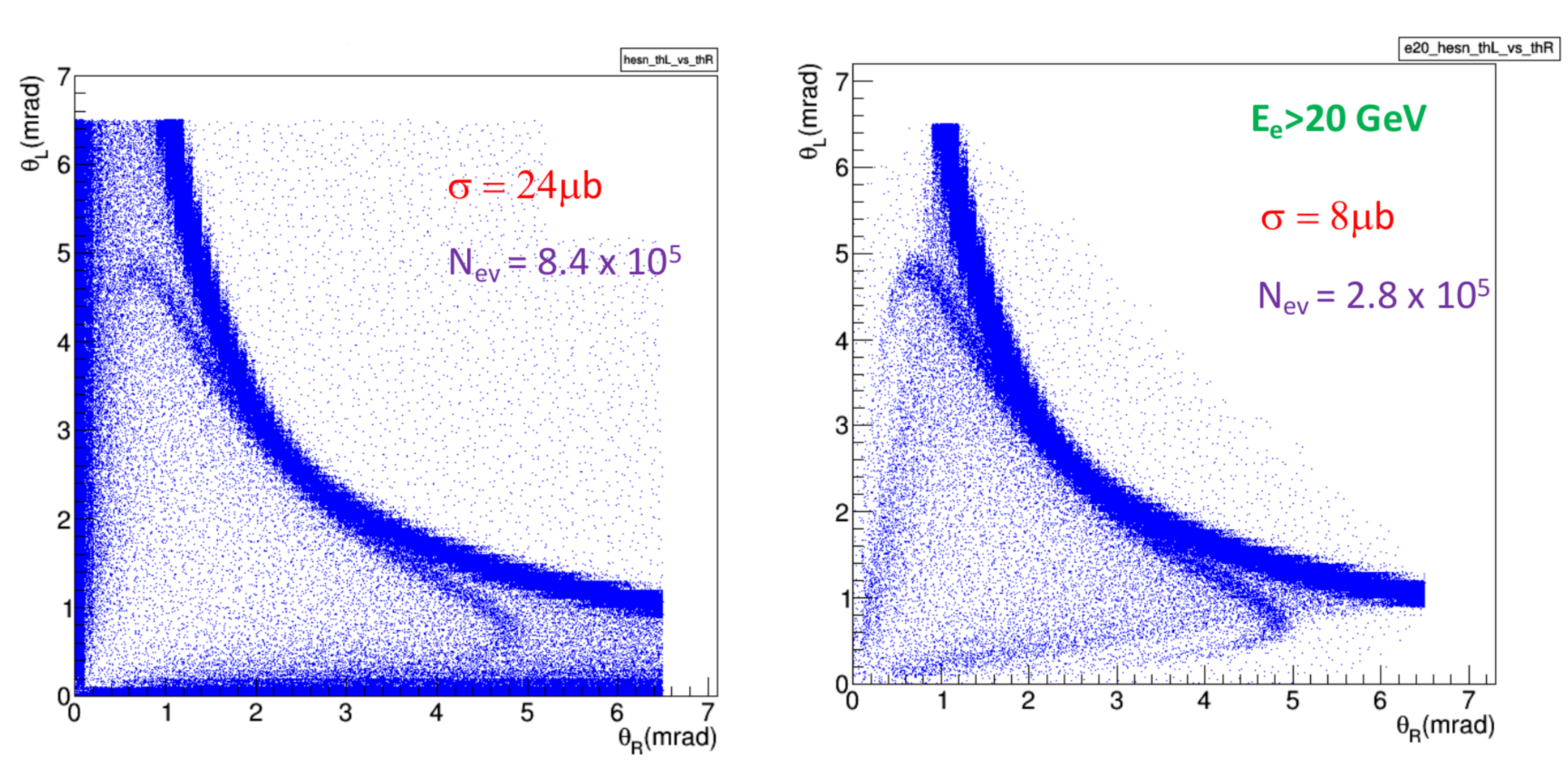
Tracker only

Signal: elastic scattering
Background: e^+e^- pair production



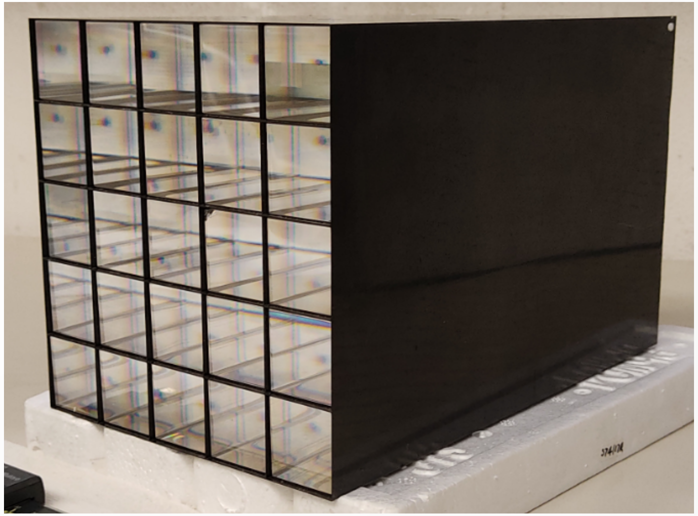
Tracker + ECAL > 1 GeV

Effect of energy selection using the calorimeter



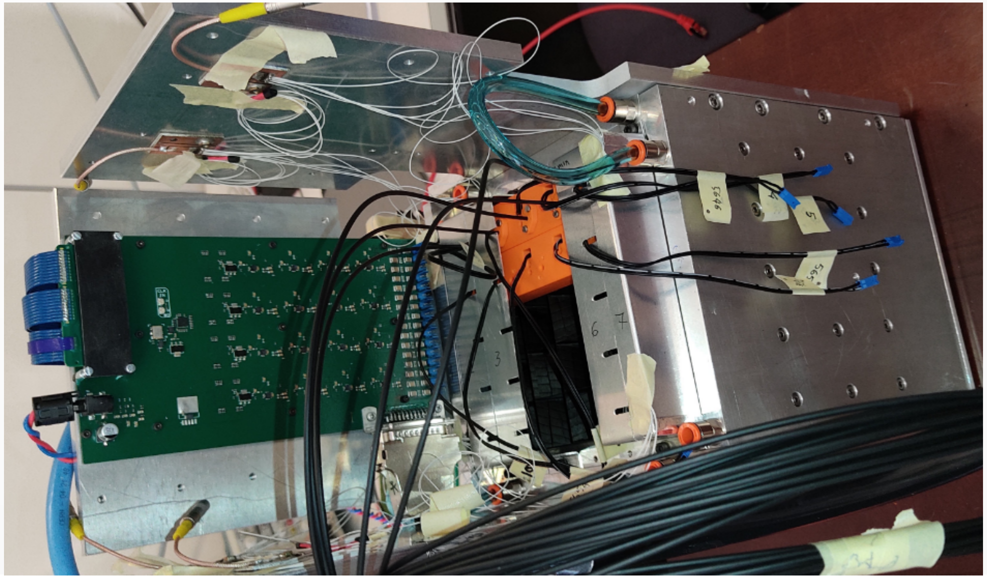
Calorimeter

- 5x5 $PbWO_4$ crystals:
  area: 2.85x2.85 cm^2 , length: 22cm (~25 X_0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors.



Beam Test: 20-27 July 2022,
CERN East Area.

- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter installed downstream the tracking station at M2 beam line in September.

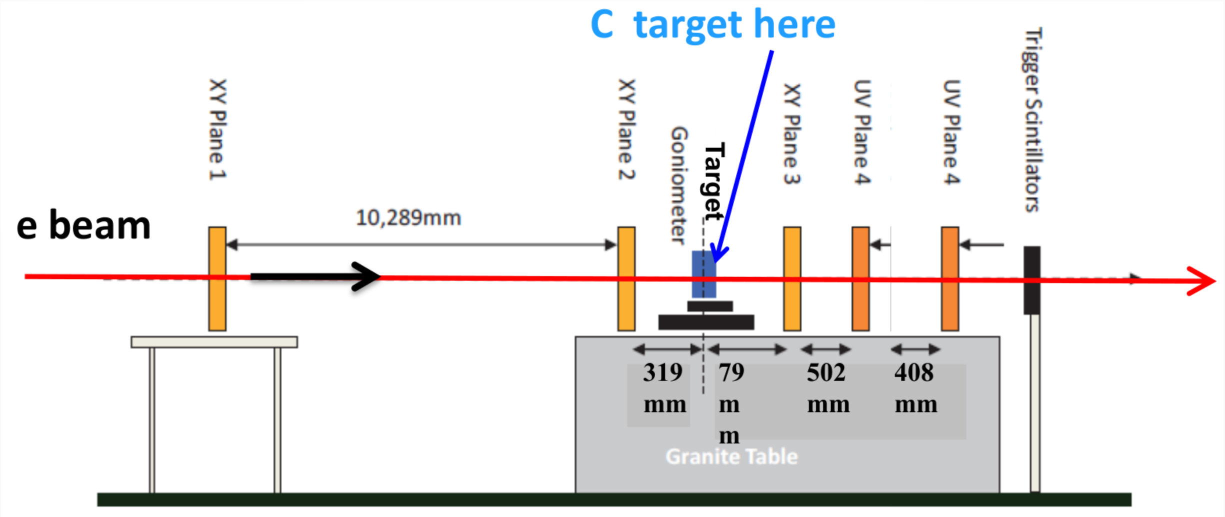


Multiple scattering: results from TB2017

Multiple scattering effects of electrons with 12 and 20 GeV on Carbon targets (8 and 20 mm)

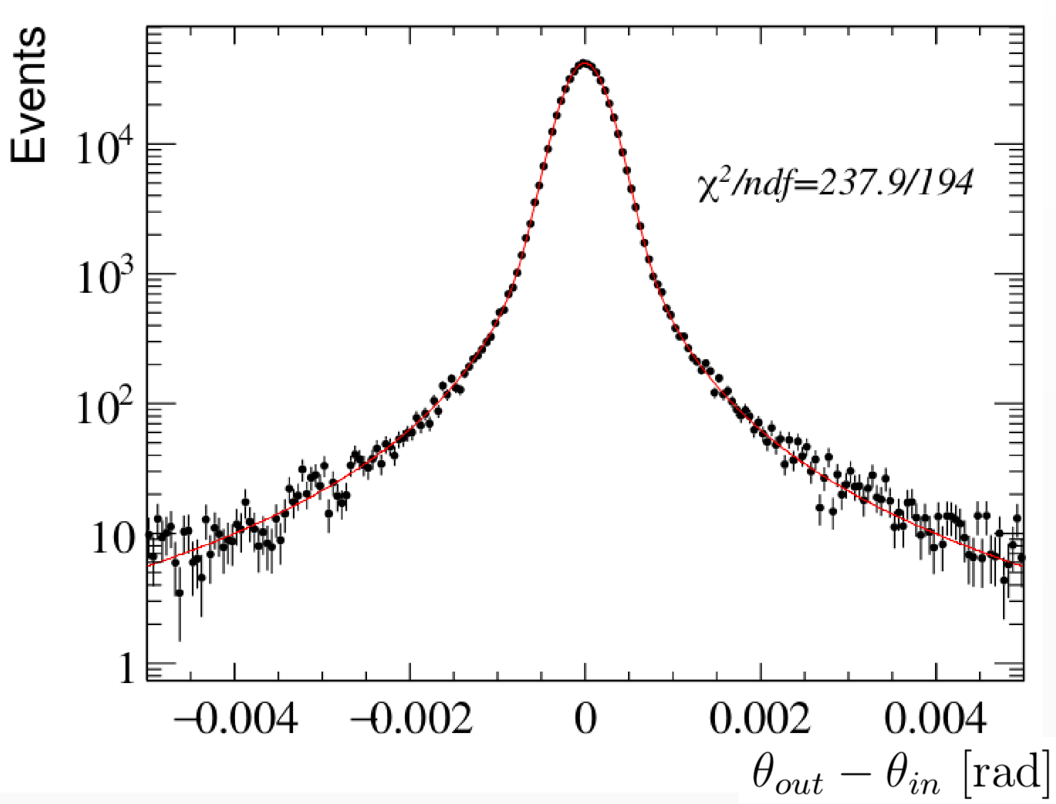
Main goals:

- to determine a parameterization able to describe also non Gaussian tails
- to compare data with a GEANT4 simulation of the apparatus



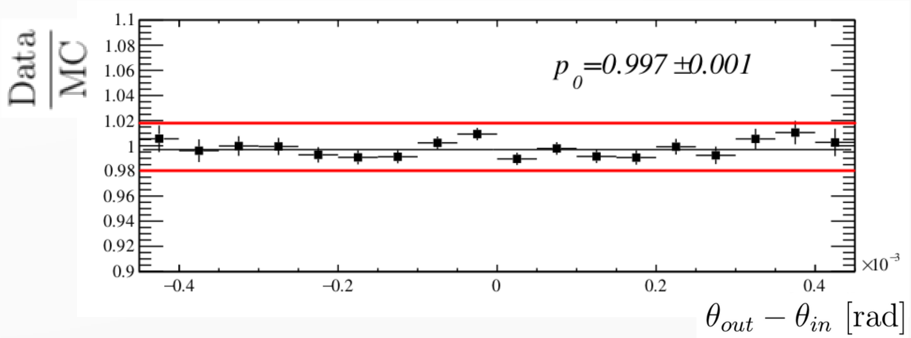
Multiple scattering: results from TB2017

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



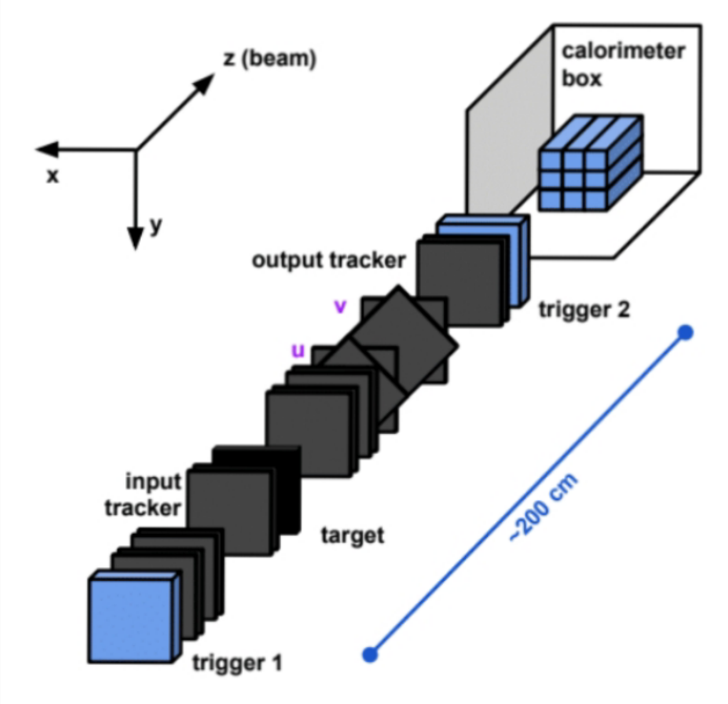
$$\vec{p} = [N,\ a,\ \mu,\ \sigma_G,\ \nu,\ \sigma_T]$$

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



Test Beam 2018

Abbiendi et al, JINST 16 (2021) P06005



First evidence of elastic scattering.

- Detector located downstream Compass.
  - 8 mm C target
  - Si strip sensors (AGILE) ~40μm intrinsic resolution
  - 3x3 BGO ECAL. 2.1x2.1cm^2, 23 cm length