The MUonE experiment

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(INFN Bologna)

NePSi 23, Pisa, 15-17 Feb 2023

https://agenda.infn.it/event/32931/

The MUonE project

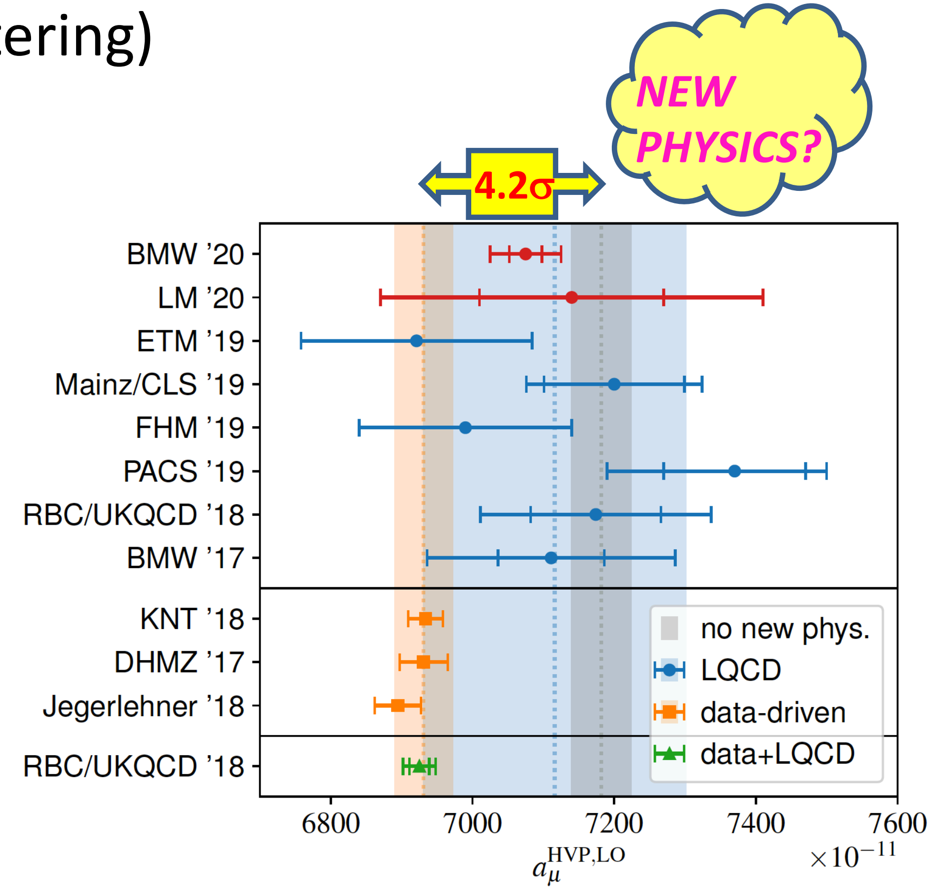
(MUon ON Electron elastic scattering)

Three possible methods to determine a_μ^{HLO} (leading hadronic contribution to the muon anomalous magnetic moment):

- Pure theory (Lattice QCD)
- Data-driven, from R-ratio measurements (timelike)

- Data-driven in spacelike domain (MUonE)

The MUonE experiment aims at an independent and precise determination of the leading hadronic contribution to the muon anomalous magnetic moment $a_\mu=(g_\mu-2)/2$, based on an alternative method, complementary to the existing ones.

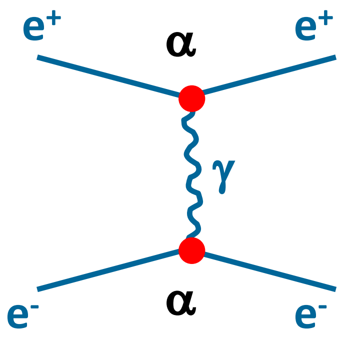


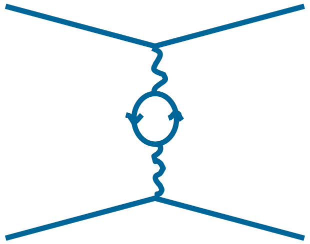
from M.Ce' [talk at Mainz (2022)]

Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

OPAL measurement: Eur.Phys.J.C45(2006)1
Bhabha scattering at small angle, with $1.8 < -t < 6.1$ GeV^2

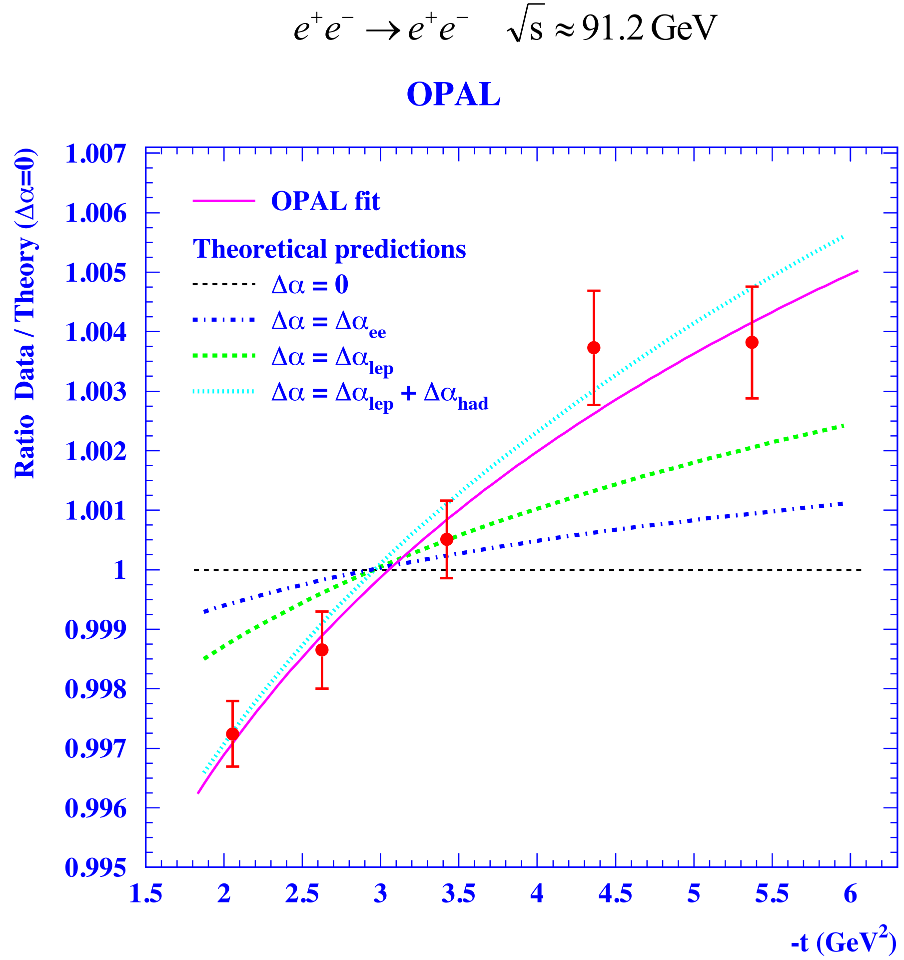
about 10^7 events, precision at the per mille level





$$\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt}\left[\frac{\alpha(t)}{\alpha_0}\right]^2 (1+\varepsilon)(1+\delta_\gamma) + \delta_Z$$

- $\frac{d\sigma^{(0)}}{dt}$: Born term for t-channel single γ exchange
- $\left[\frac{\alpha(t)}{\alpha_0}\right]^2 = \left(\frac{1}{1-\Delta\alpha(t)}\right)^2$: Effective coupling factorized
- $(1+\varepsilon)$: Photonic radiative corrections
- $(1+\delta_\gamma)$: s-channel γ exchange correction
- δ_Z: Z interference correction



Other measurements in the space-like region by L3, VENUS

a_μ^{HLO}: the MUonE approach (space-like data)

B. E. Lautrup, A. Peterman and E. de Rafael, Phys. Rept. 3 (1972) 193

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

C.M. Carloni Calame, M. Passera, L. Trentadue, G. Venanzoni, Phys.Lett.B746(2015)325 :

propose to determine a_μ^{HLO} from the measurement of the running of α in Bhabha scattering

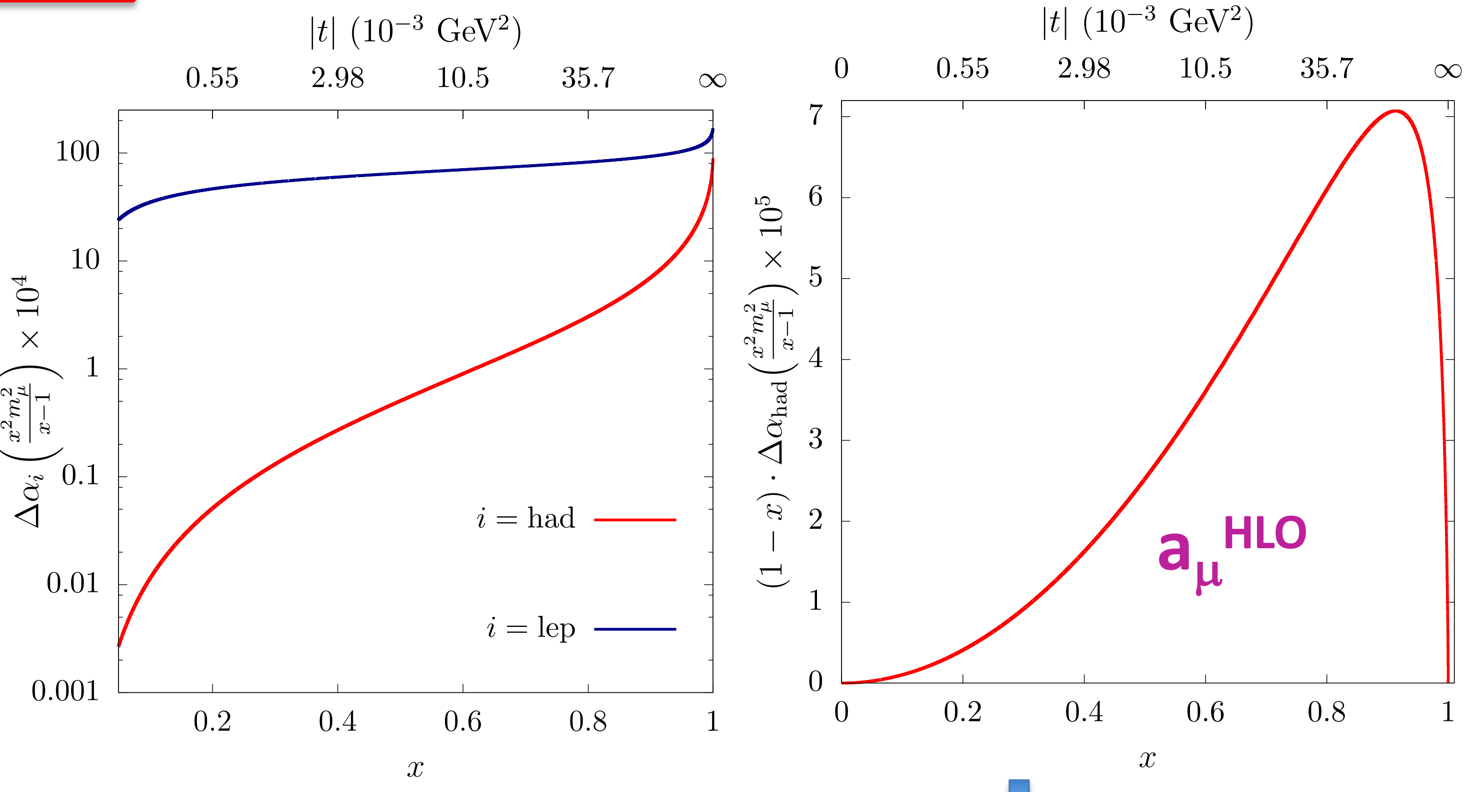
$\Delta\alpha_{had}$ is the hadronic contribution to the running of α in the space-like region (t<0):

$$\alpha(t) = \frac{\alpha}{1-\Delta\alpha(t)}$$

$$\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{had}$$

$$0 \le -t < \infty \qquad 0 \le x < 1$$

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



Integrand function smooth: no resonances

Low-energy enhancement:

peak of the integrand at $x \cong 0.9$ → $t = -0.11$ GeV^2 → $\Delta\alpha_{had} \sim 10^{-3}$

MUonE experiment idea

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

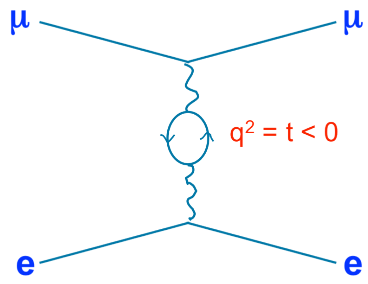
Measuring the leading hadronic contribution to the muon *g*-2 via *μe* scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,f], M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]

Eur.Phys.J.C77(2017)139

Very precise measurement of the running of α_{QED} from the shape of the differential cross section of elastic scattering of μ(150-160GeV) on atomic electrons of a fixed target with low Z (Be or C)

→ **CERN SPS**



$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

running of α

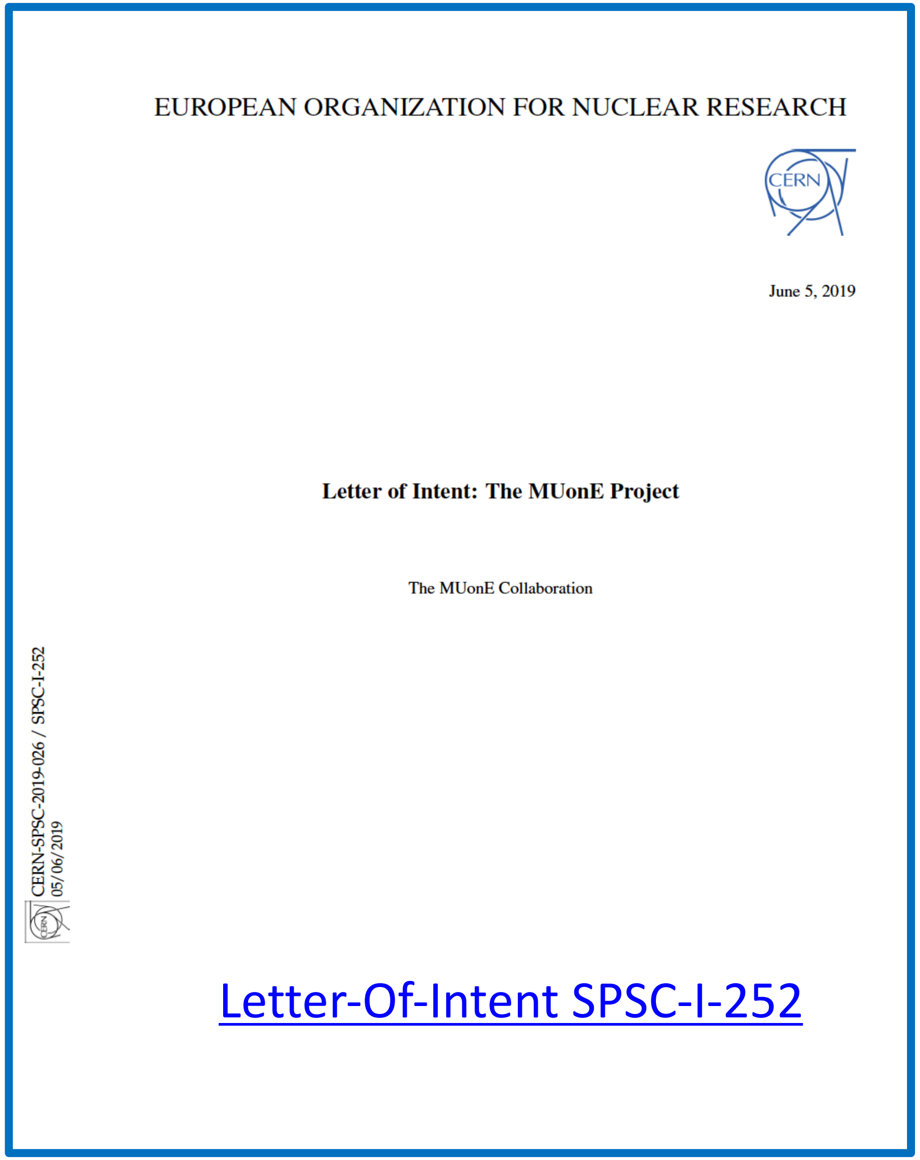
$$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

known from QED — to be measured

From $\Delta\alpha_{had}(t)$ determine a_μ^{HLO} by the space-like approach: Phys.Lett.B746(2015)325

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

MUonE experiment proposal



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

June 5, 2019

Letter of Intent: The MUonE Project

The MUonE Collaboration

CERN-SPSC-2019-026 / SPSC-I-252
05/06/2019

Letter-Of-Intent SPSC-I-252

5 June 2019: LoI submitted to SPSC

22 January 2020: SPSC acknowledges the fundamental interest of the proposal and approves a Test Run, which should verify the detector design and the potential outcomes

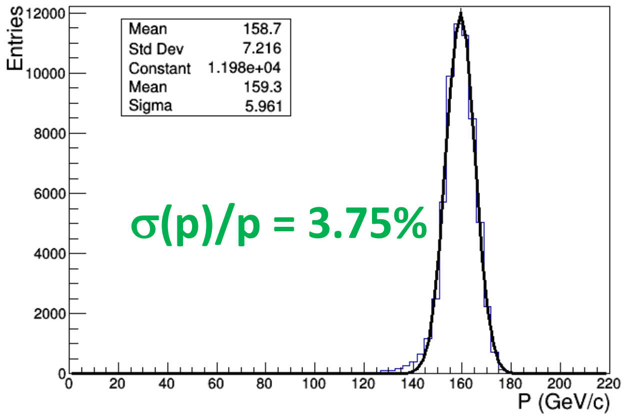
Test Run to be completed in 2023

Location @ CERN & M2 beam parameters

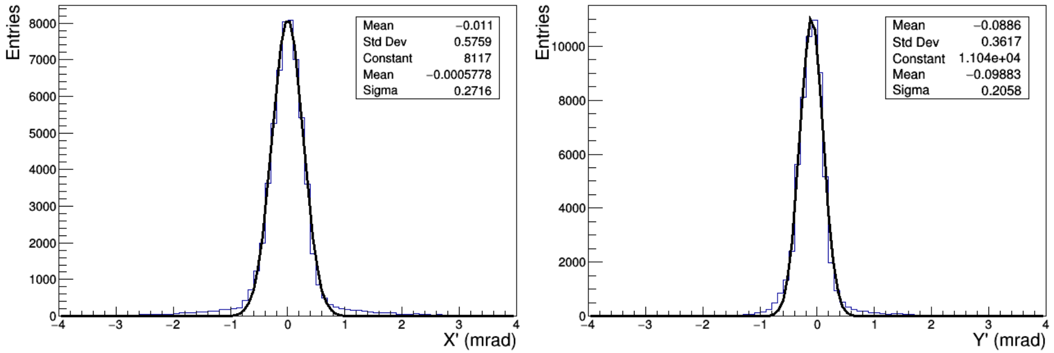
MUonE Letter-Of-Intent SPSC-I-252

Upstream of the COMPASS detector, after its Beam Momentum Station (BMS), on the M2 beam line : available ~ 40 m

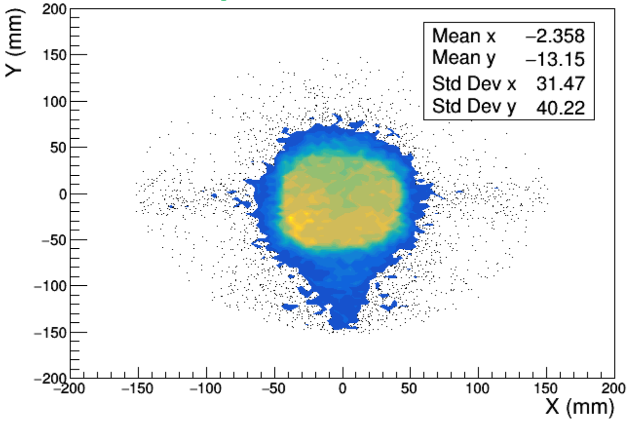
Beam Momentum



Very small divergence ~0.2-0.3 mrad



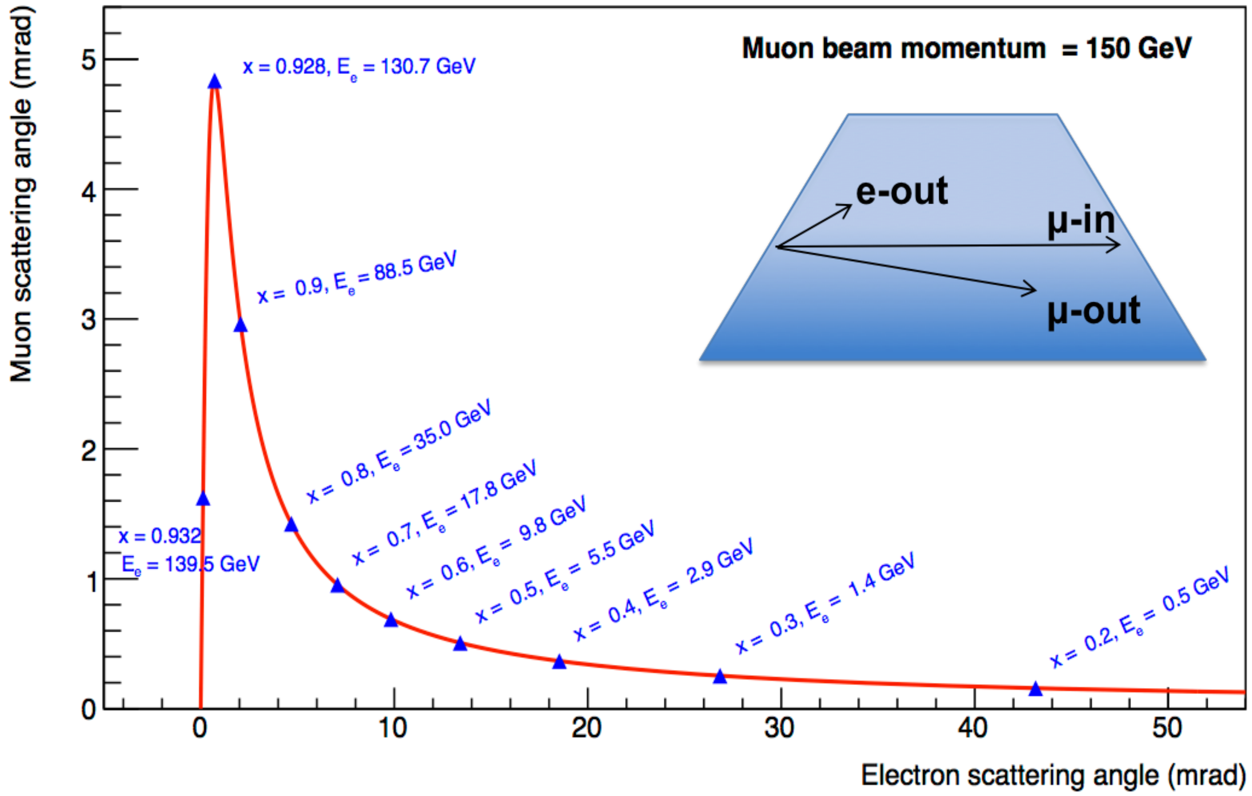
Beam spot size σ_X~σ_Y~3cm



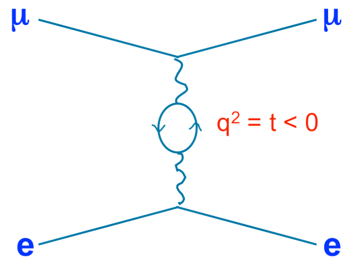
M2 beam typical max intensity: 5×10^7 μ/s

SPS Fixed Target cycle ~15-20 s / Spill duration ~ 5s

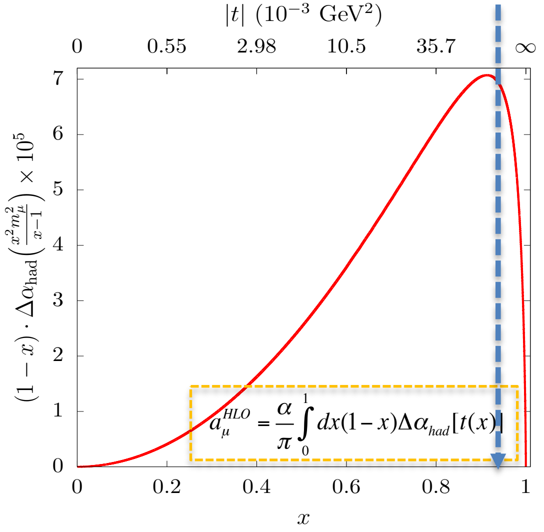
μ-e Elastic scattering: pros



- **Simple kinematics:** $t \cong -2\, m_e E_e$
  E_e can be determined from the scattering angle θ_e and the beam energy
- Scattering angles θ_e and θ_μ are correlated
- Events are planar



Kin.Limit: x~0.93



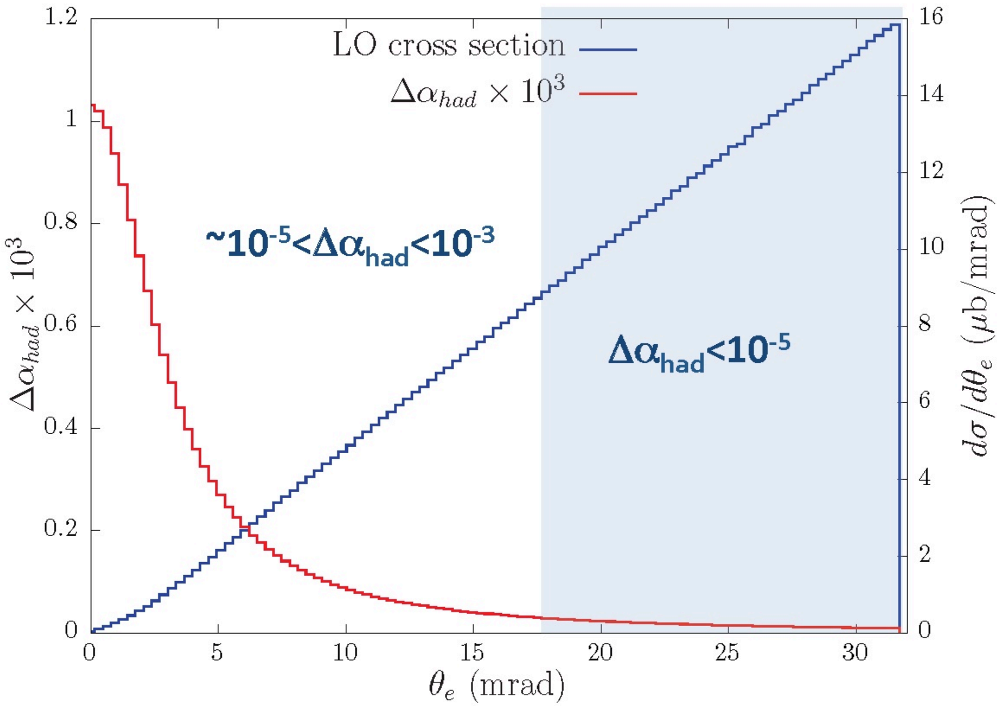
- For E(beam)=160 GeV the phase space covers 88% of the a_μ^{HLO} integral
  - Smooth extrapolation to the full integral with a proper fit model

μ-e elastic scattering: challenges

Observable effect **~ 10^{-3}**

wanted accuracy **~10^{-2}**

Required precision **~10^{-5}** on the shape of $d\sigma/dt$



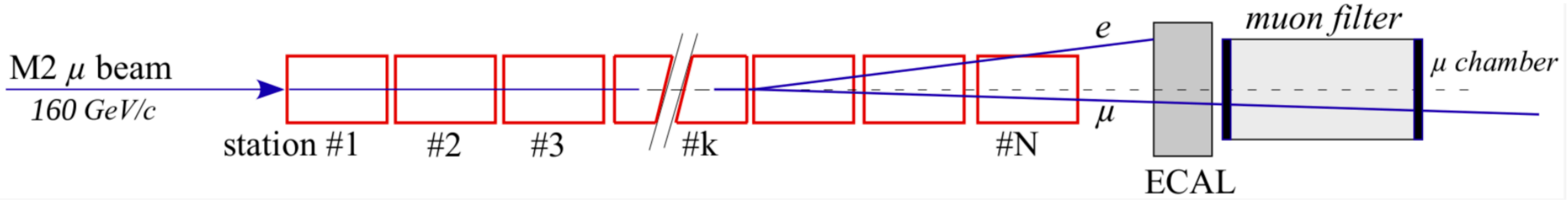
- Large statistics to reach the necessary sensitivity
- Minimal distortions of the outgoing e/μ trajectories within the target material and small rate of radiative events

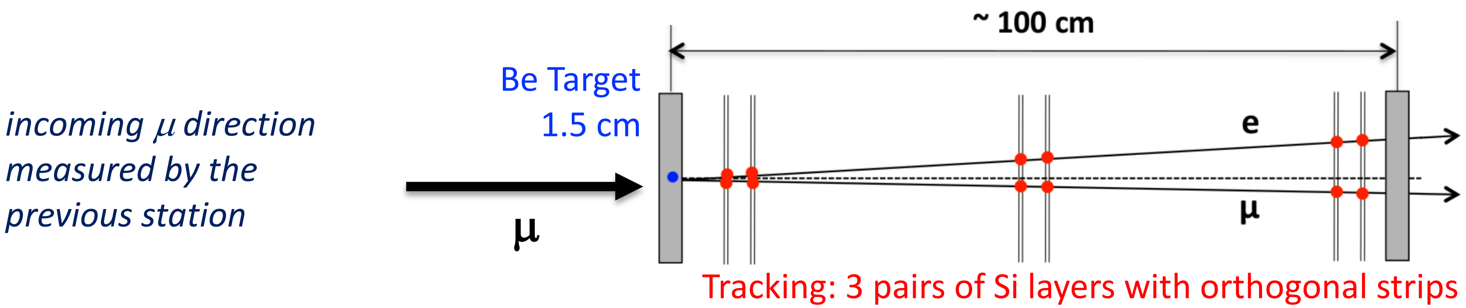
MUonE Detector Layout

Letter-Of-Intent SPSC-I-252

The detector concept is simple, the challenge is to keep the systematics at the same level as the statistical error .

- Modular structure of 40 independent and precise tracking stations, with split light targets equivalent to 60cm Be
- ECAL and Muon filter after the last station, to help the ID and background rejection

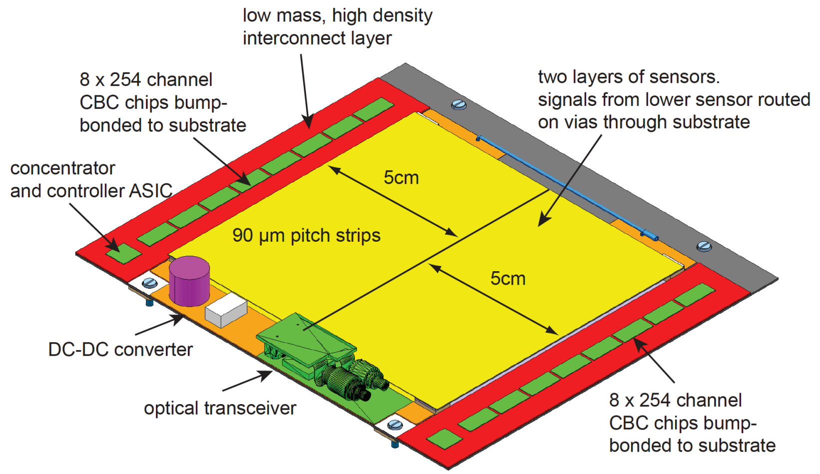




- Boosted kinematics: θ_e<32mrad (for E_e>1 GeV), θ_μ<5mrad:
  - the whole acceptance can be covered with a 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

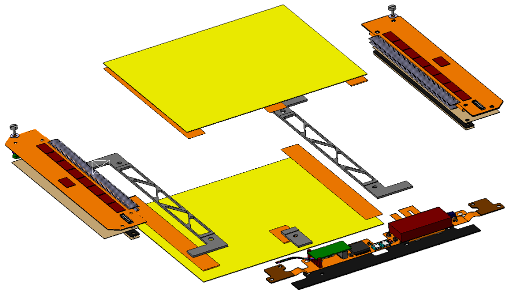
Detector choice: CMS-upgrade Outer Tracker 2S

MUonE Letter-Of-Intent SPSC-I-252   Details: see CMS Tracker Upgrade TDR



Two close-by planes of strips reading the same coordinate, providing track elements (**stubs)**

suppression of background from single-layer hits or large-angle tracks

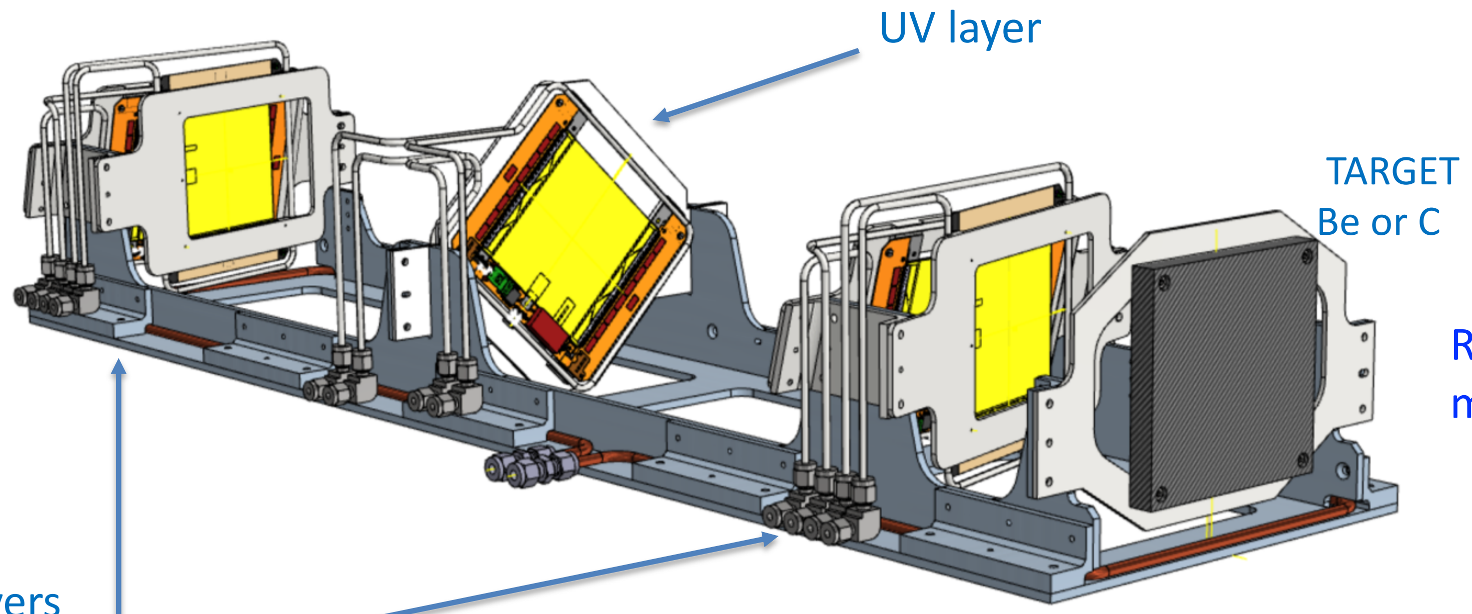


- Large active area 10x10 cm^2
  -> complete/uniform angular coverage with a single sensor

- Position resolution ~20μm
  -> improvable to ~10μm with a 15^o-20^o tilt around the strip axis and/or with effective staggering of the planes (with a microrotation)

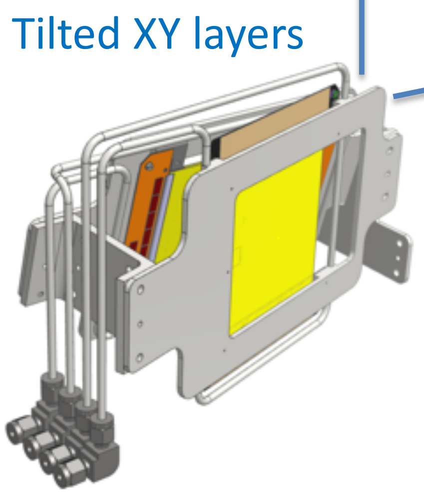
MAIN Difference w.r.t. LHC operation: signal is asynchronous while sampling has fixed clock at 40MHz -> can be overcome with a specific configuration of the FE

MUonE tracking station



Length 1m
Transverse size 10cm

Relative positions of modules must be stable within 10μm



Tilted X and Y modules to improve the resolution

U, V modules to solve reconstruction ambiguities

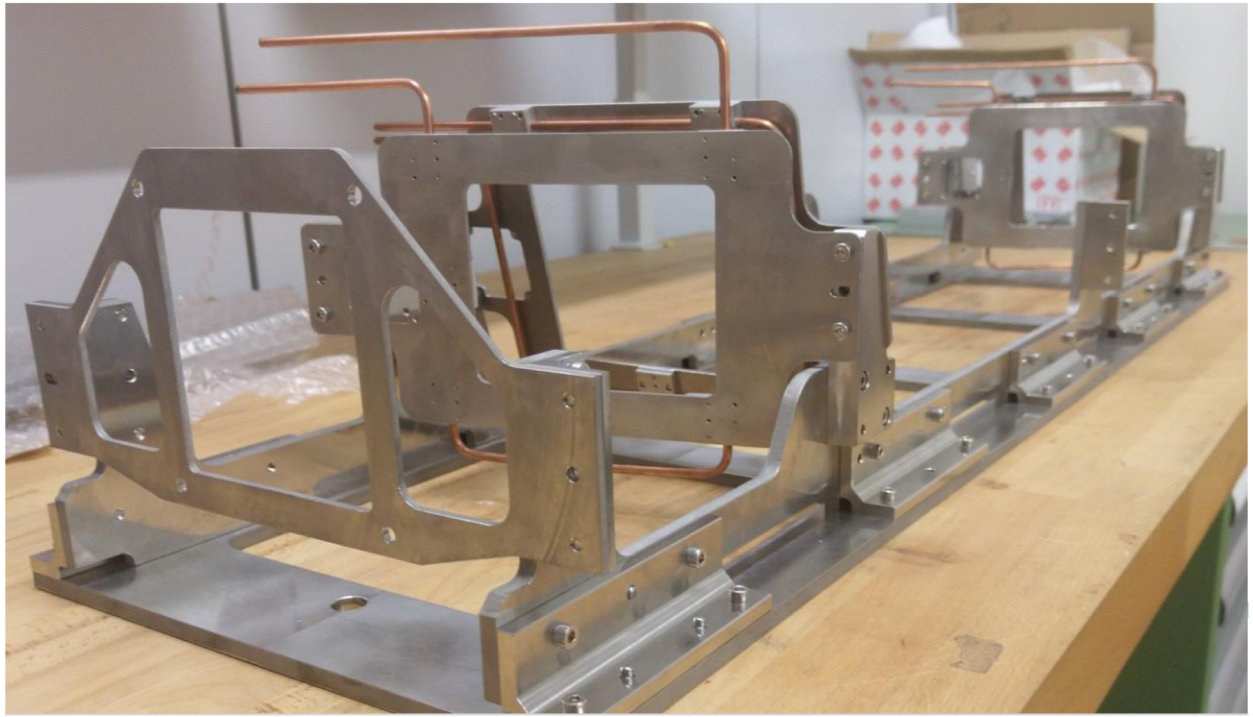
Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni)

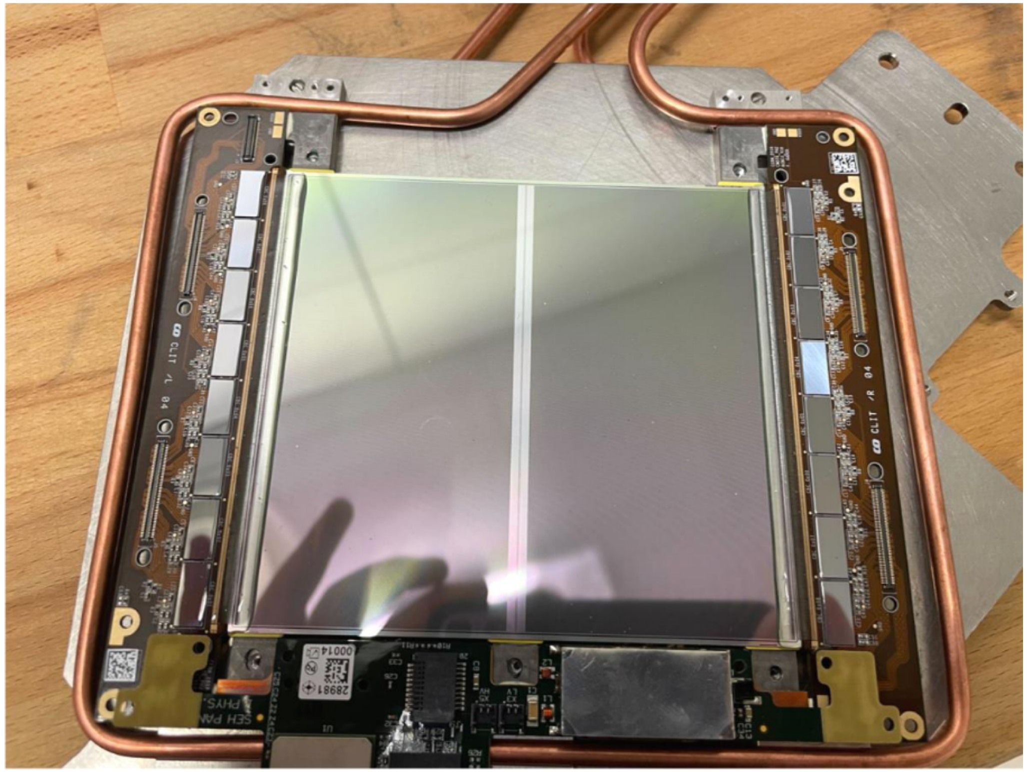
Cooling system, tracker enclosure,
Room temperature stabilized within 1-2 ^{o}C

Laser holographic system to monitor the stability

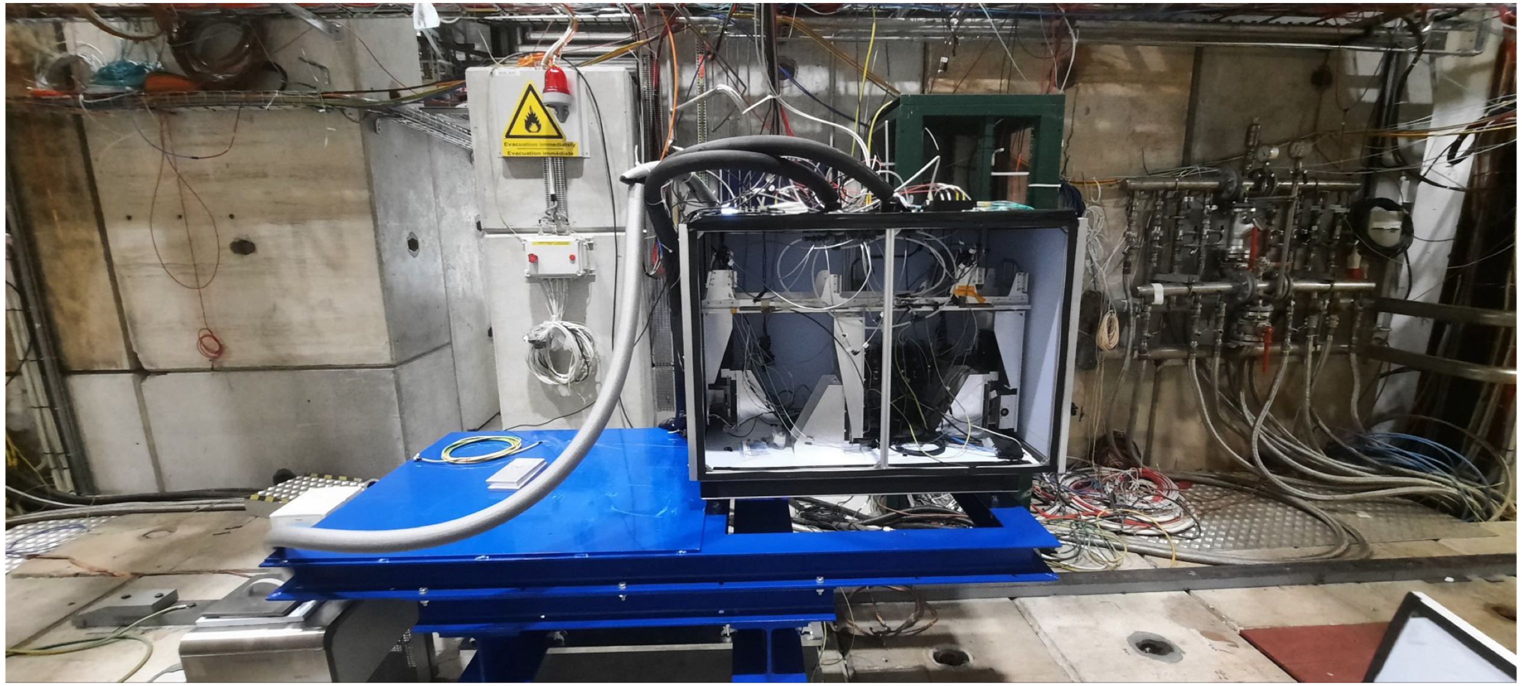
Support structure and 2S module on its frame

The support structure in INVAR





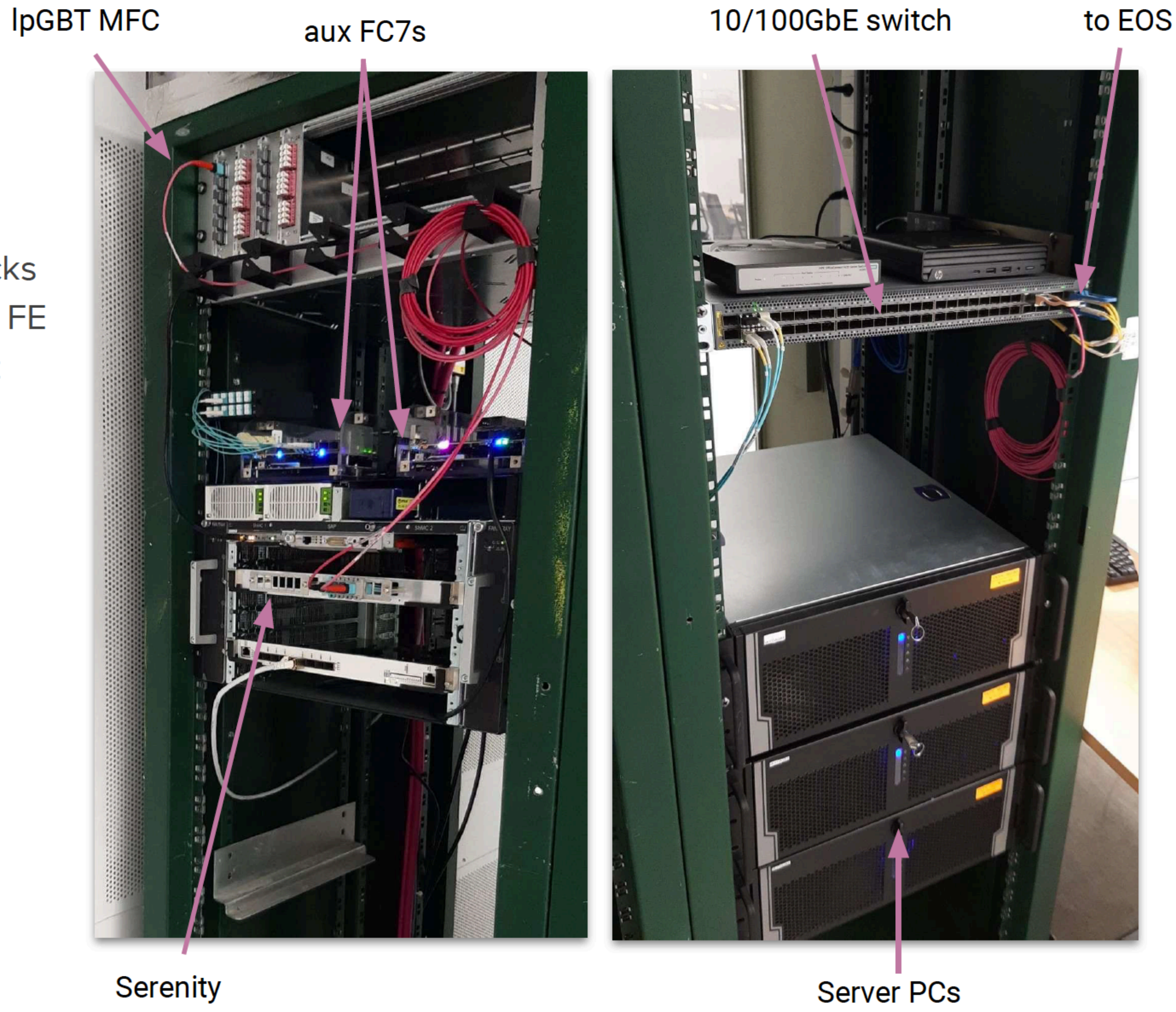
Tracker beam test setup



- Joint tests with CMS-Tracker in 2021-2022
- In 2022 the MUonE setup was placed on rails to allow easy movements in and out the M2 beam

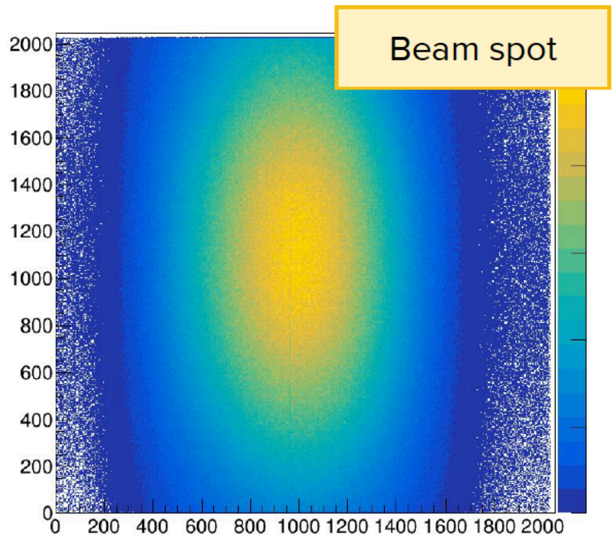
Readout & DAQ

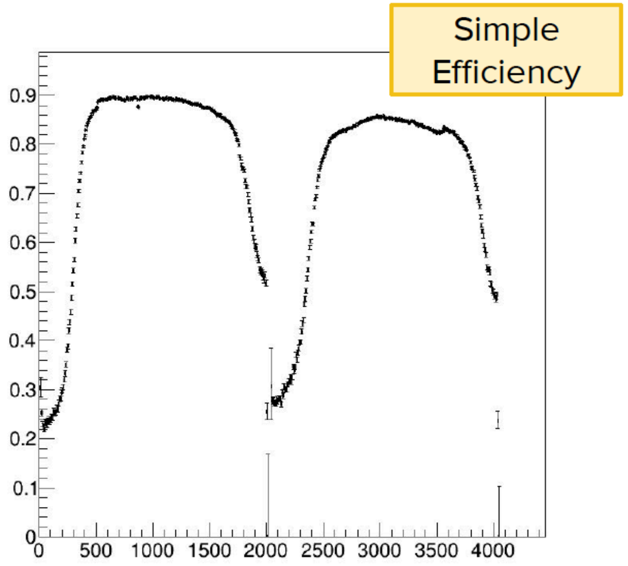
- Station is read out optically (lpGBT)
  - ~60m optical fibre from detector to barracks
  - Serenity implements lpGBT serial link and FE decoding, stub data processing at 40MHz and optionally event filtering
  - Packaged events transmitted over 10GbE links to servers
- Servers receive 10GbE data
  - Ryzen 9 5900X server PCs
  - 128GB RAM, 1TB NVMe SSD, 40TB RAID
  - Buffering, packaging, DQM, ship to EOS
- 10/100GbE switch
  - Direct 100GbE connection to B513/EOS
- FC7s for aux functions

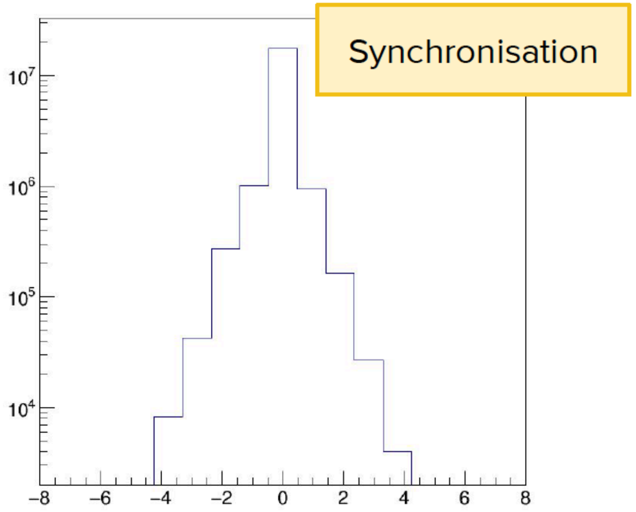


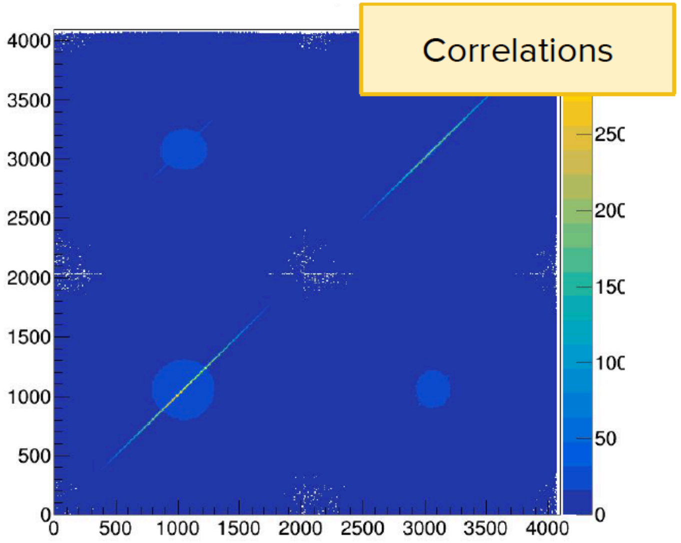
Online DQM

- Data stored on EOS for current data-taking run is sampled
    - Plots displayed on webUI
- Performed more complex calculations on data:
    - Synchronisation between modules
    - System alignment
    - Beam spot
    - Stub efficiency
- Many previous analyses have now become part of the DQM!



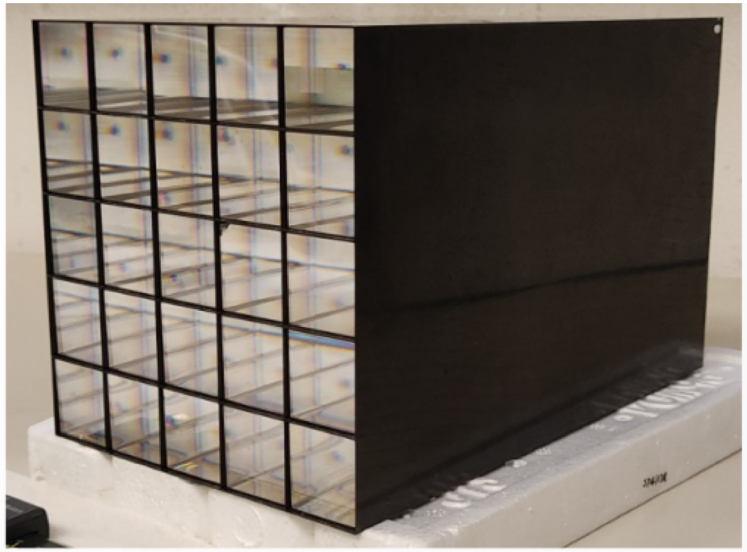






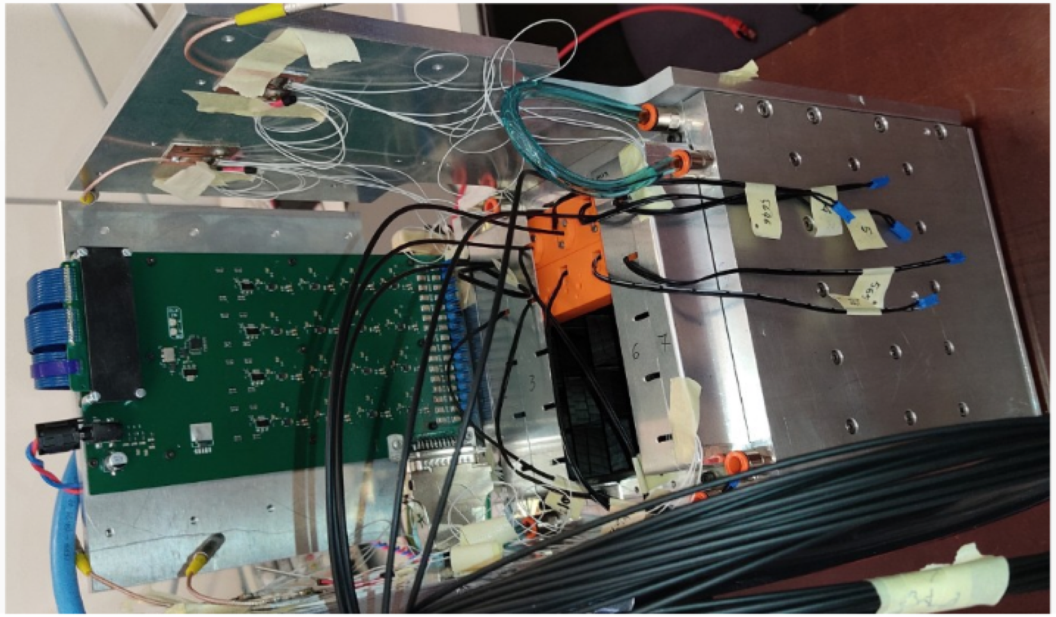
ECAL

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



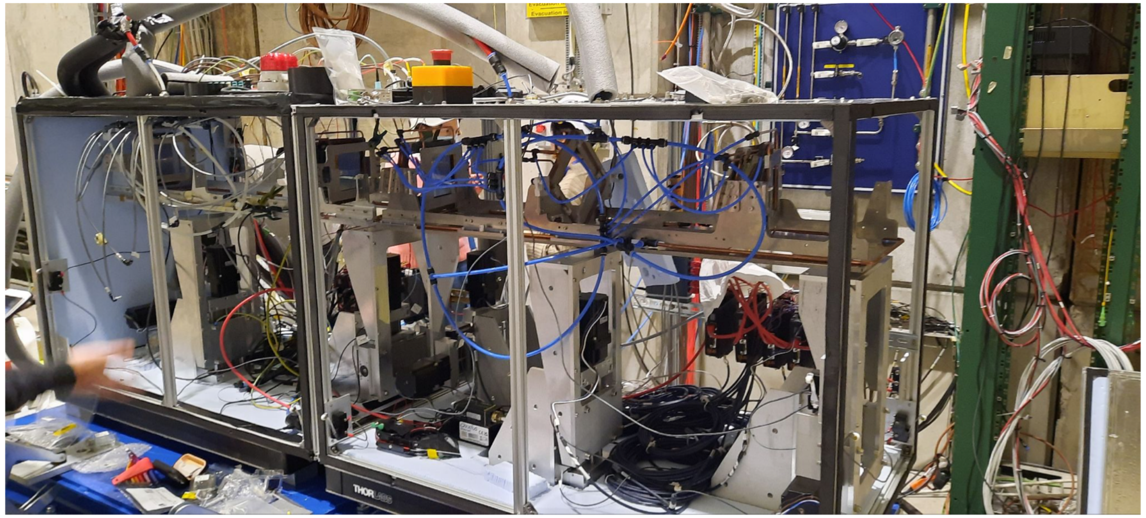
Beam Test: 20-27 July 2022, CERN East Area.

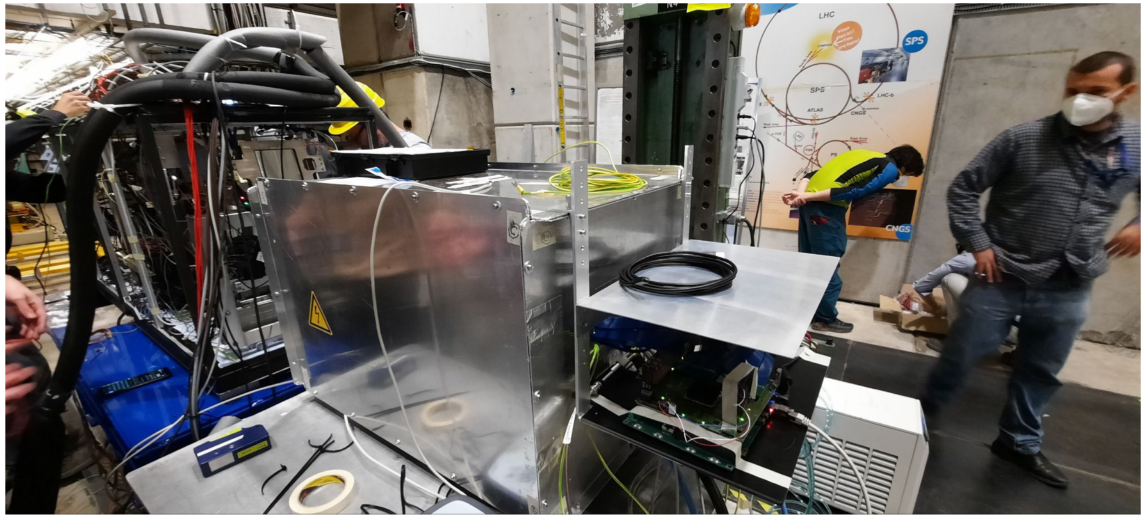
- Electrons in range 1-4 GeV.
- Overall debug of detector, DAQ.
- Absolute energy calibration, energy resolution.
- Calorimeter being installed downstream of the tracking station at the M2 beam line.



Test with a full station and a calorimeter (October ’22)

- A fully equipped tracking station and the calorimeter
- One week of test in M2 as main users performed the last October
- High intensity, asynchronous muon beam (160 GeV), up to 2×10^8 muon/spill, for the first time
  - or low intensity 40 GeV electrons
- Tracker system always on, DAQ reliable throughout
- Some 100TB of stub data collected



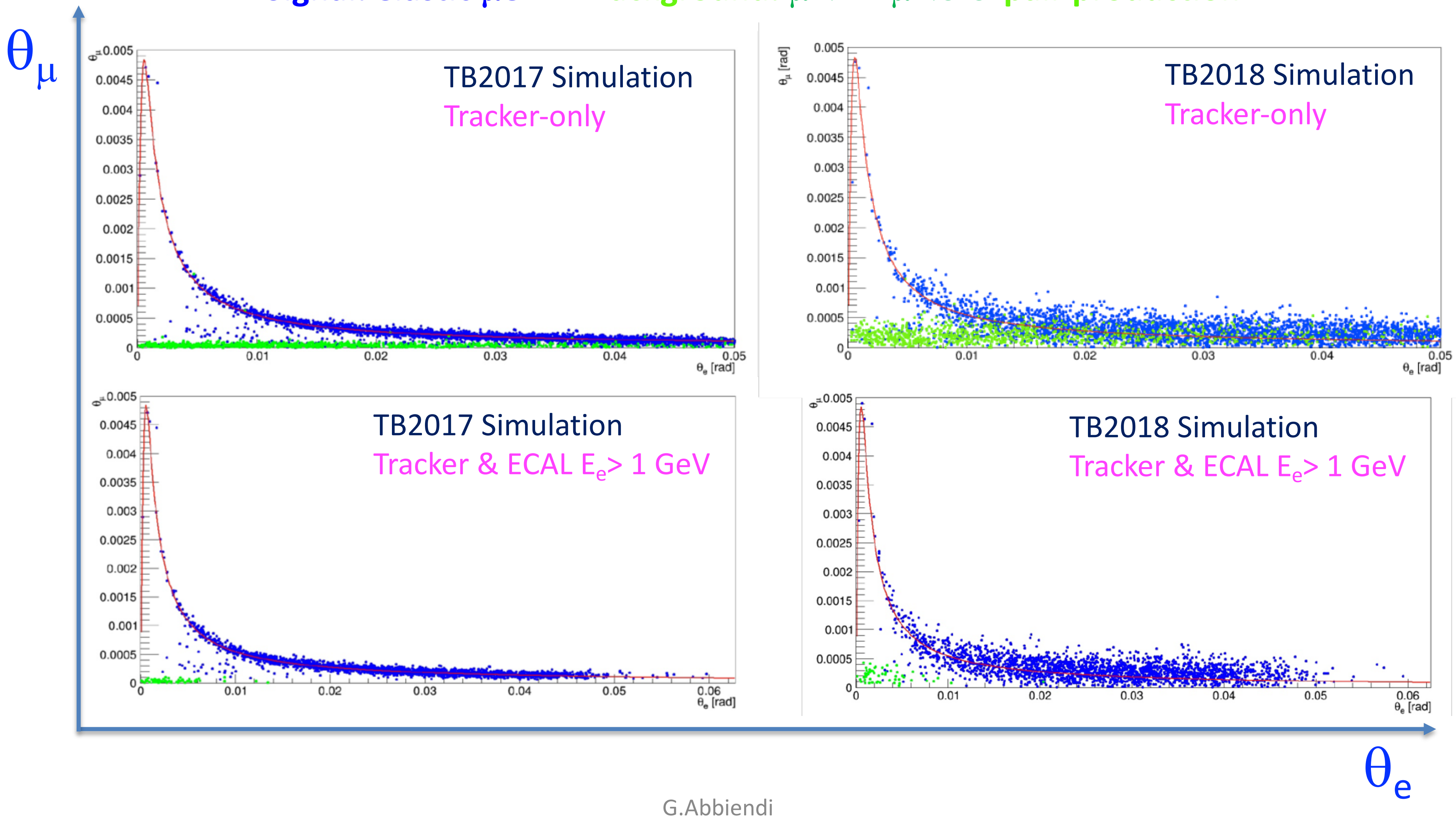


GEANT4 simulations

Effect of the position resolution on θ_μ vs θ_e distribution:

(Left) TB2017: UA9 resolution 7μm ; (Right) TB2018: resolution ~35-40μm

Signal: elastic μe **Background: $\mu N \rightarrow \mu N e^+ e^-$ pair production**



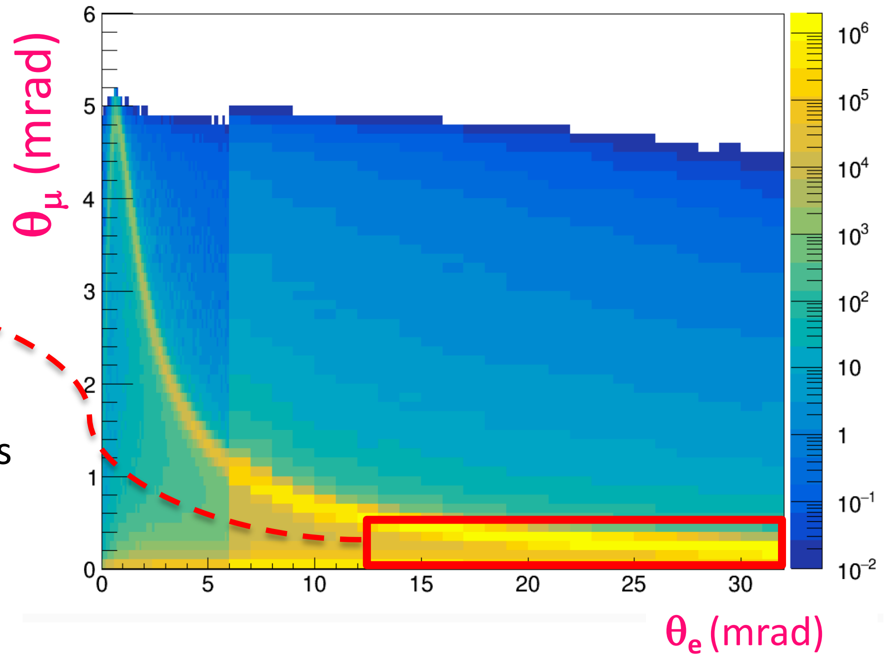
Event kinematics

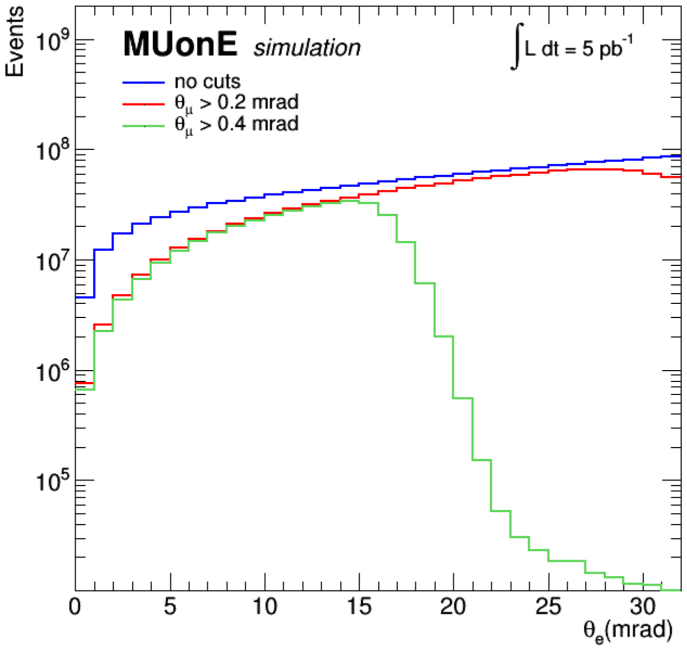
Normalisation region

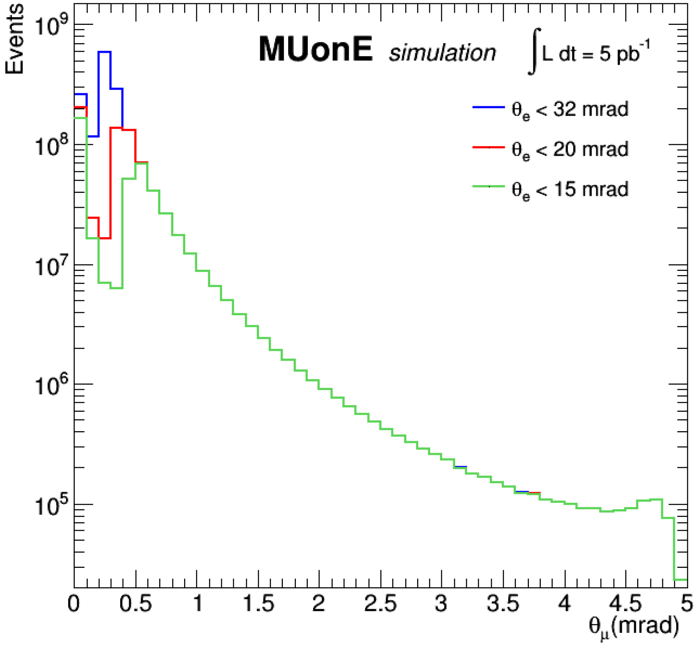
huge statistics

vanishing signal ($\Delta\alpha_{had}$)

convenient for studies of systematics







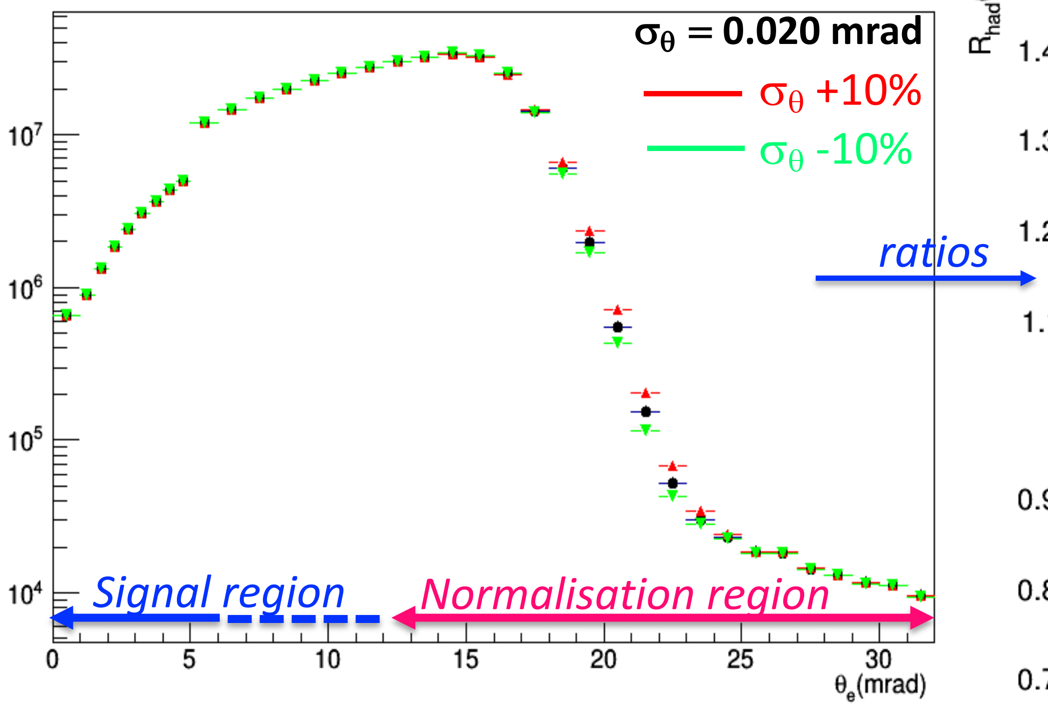
Probing systematics in the normalisation region

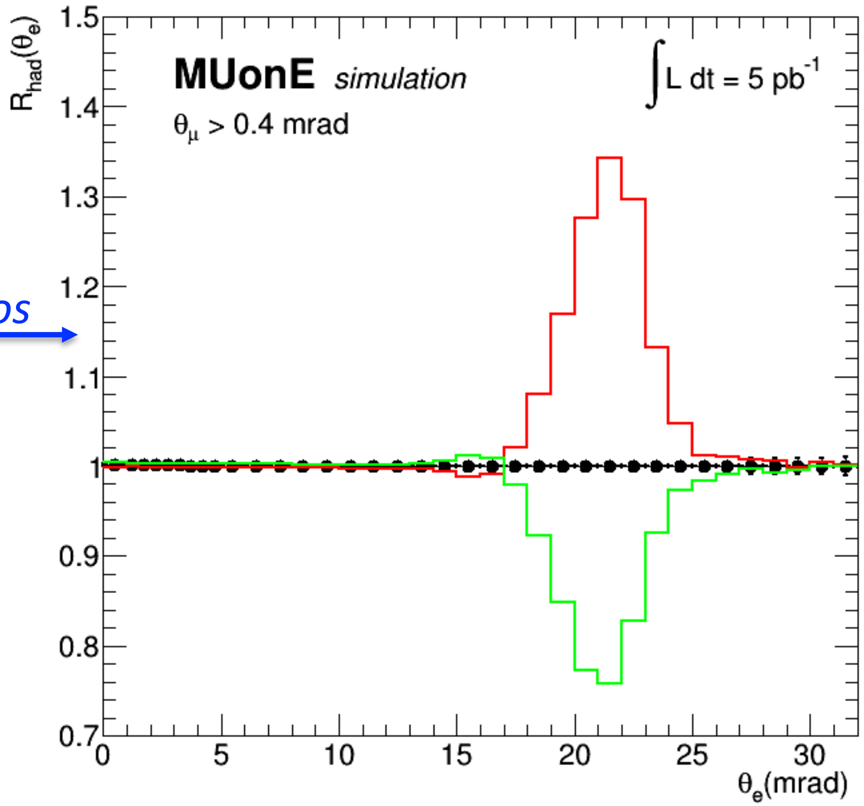
The **intrinsic angular resolution** can be probed by looking at the θ_e distribution after a cut on θ_μ distribution, e.g. cutting at $\theta_\mu > 0.4$ mrad

→ Effect of a ±10% error w.r.t. the nominal σ_θ = **0.020 mrad**

Huge distortion of 20-30% around electron angles of 20 mrad

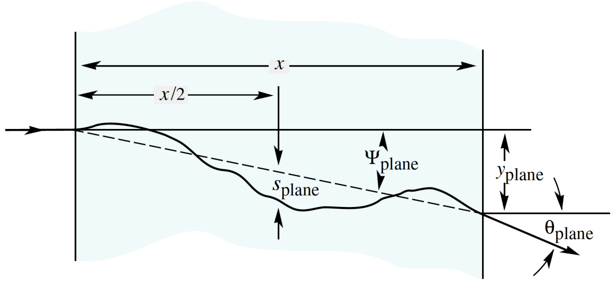
No effect in the signal region

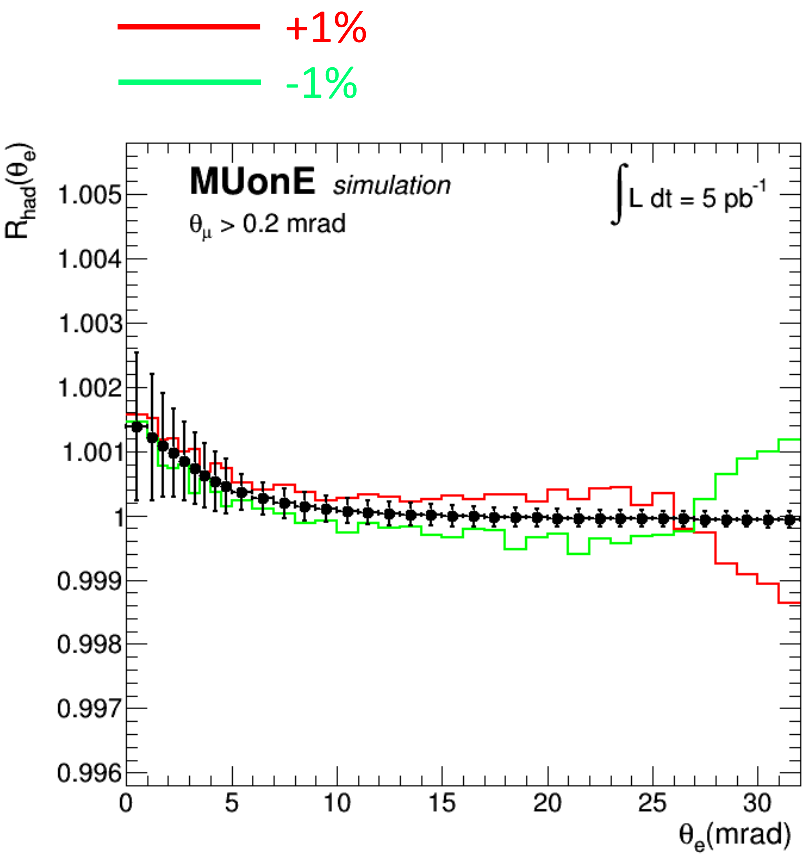


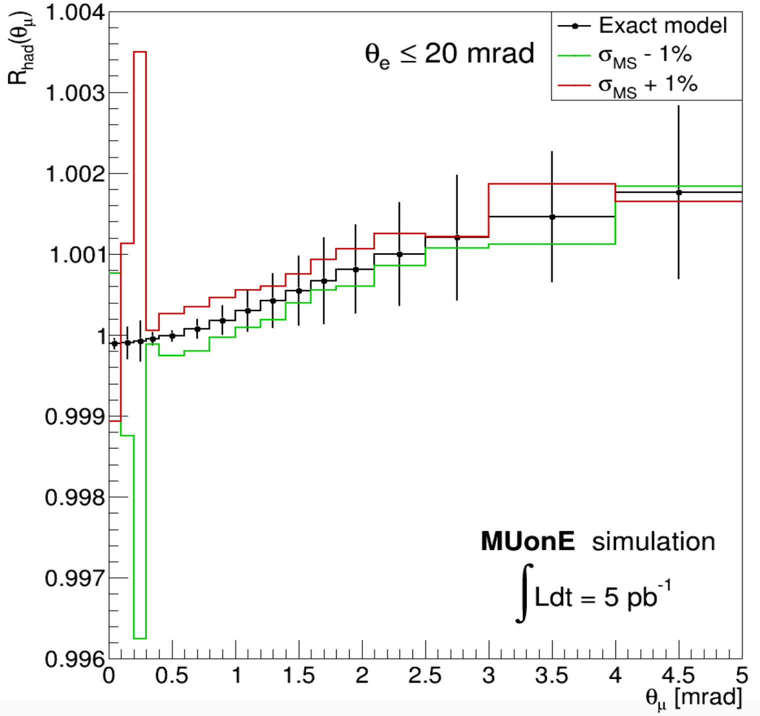


Systematics: Multiple Coulomb Scattering

Effect of a flat error of ±1% on the core width of multiple scattering







Multiple scattering previously studied in a Beam Test in 2017: JINST 15 (2020) P01017 with 12–20 GeV electrons on 8-20 mm C targets

$\Delta\alpha_{had}$ parameterisation

Physics-inspired from the calculable contribution of lepton-pairs and top quarks at t<0

$q^2 = t < 0$

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

M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop

k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

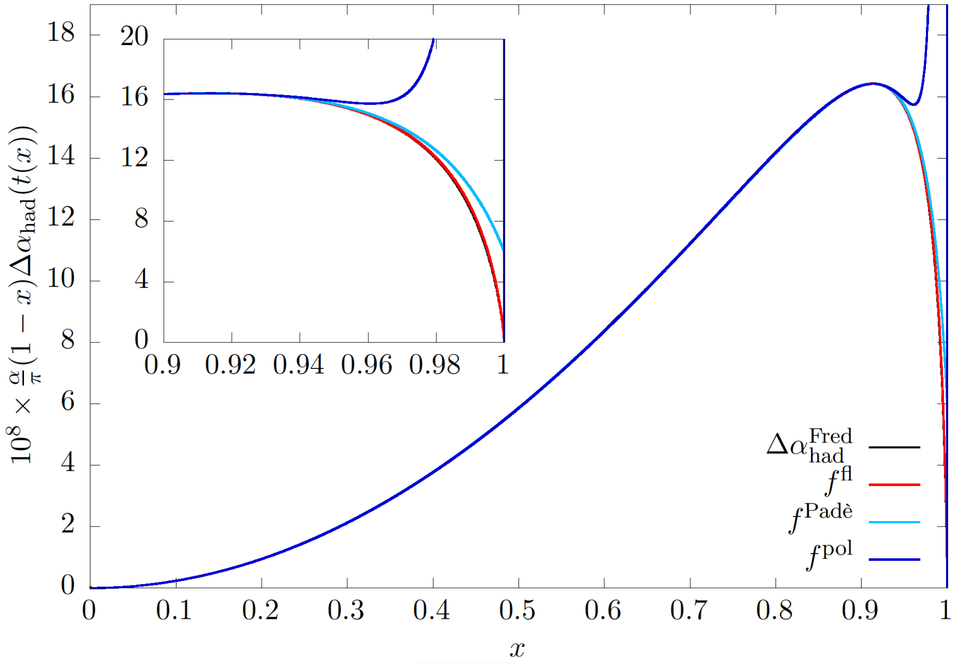
Low-|t| behavior dominant in the MUonE kinematical range:

$$\Delta\alpha_{had}(t) = -\frac{1}{15}\frac{k}{M}t$$

for $t \to -0$

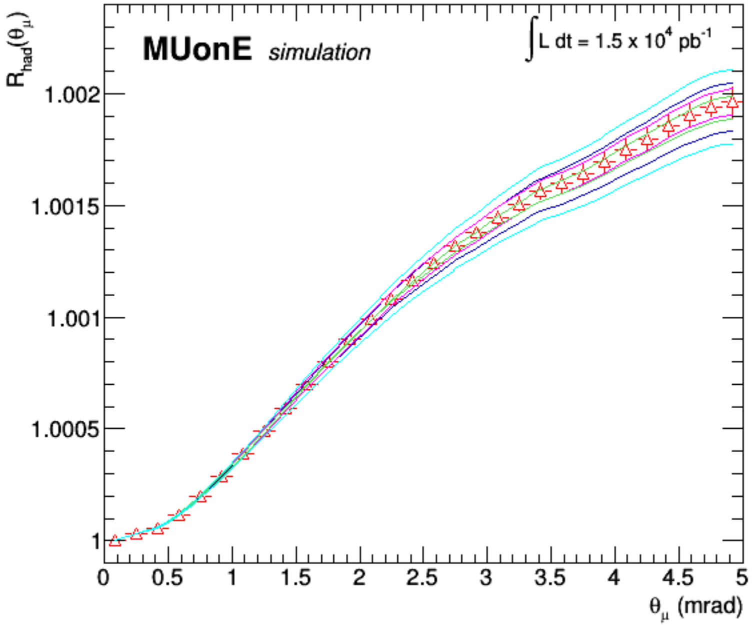
$$\Delta\alpha_{had}(t) = \frac{k}{3}\left(\log\frac{|t|}{M} - \frac{5}{3}\right)$$

for $t \to -\infty$



Template fit

Full description in:
Phys. Scripta 97 (2022) 054007 [arXiv:2201.13177]



Define a grid of points (K,M) in the parameter space covering a region of ±5σ around the expected values (with σ the expected uncertainty). Step size taken to be 0.5σ. This defines 21x21 = 441 templates for the relevant distributions.

For every template in the grid calculate the χ^2 obtained with the pseudodata distribution:

$$\chi^2(K,M) = \sum_i^{bins} \frac{R_i^{data} - R_i^{(K,M)}}{\sigma_i^{data}}$$

– Neglect the statistical errors of the templates as in the ratios they are vanishingly small.

Minimise the χ^2 interpolating across the grid by parabolic approximation.
Final errors correspond to $\Delta\chi^2=1$.

Hadronic running of α

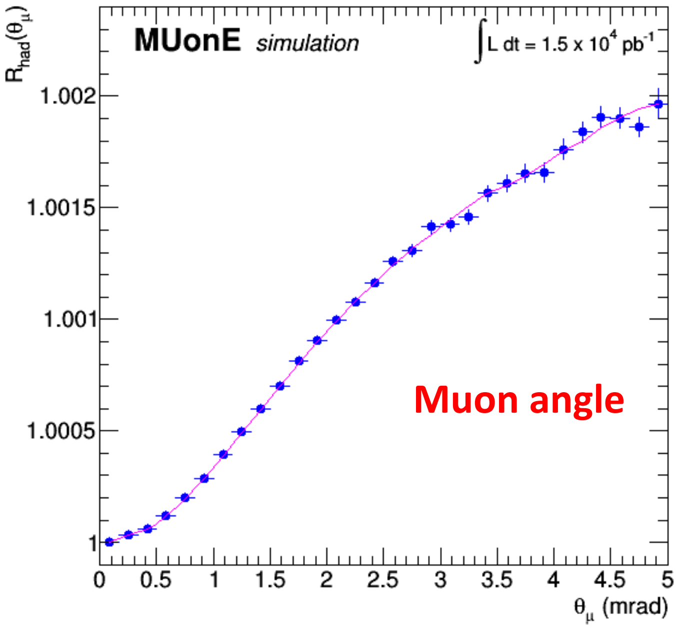
Most easily displayed by taking ratios of the MC predicted angular distributions (pseudodata) and the predictions obtained from the same MC sample reweighting α(t) to correspond to only the leptonic running:

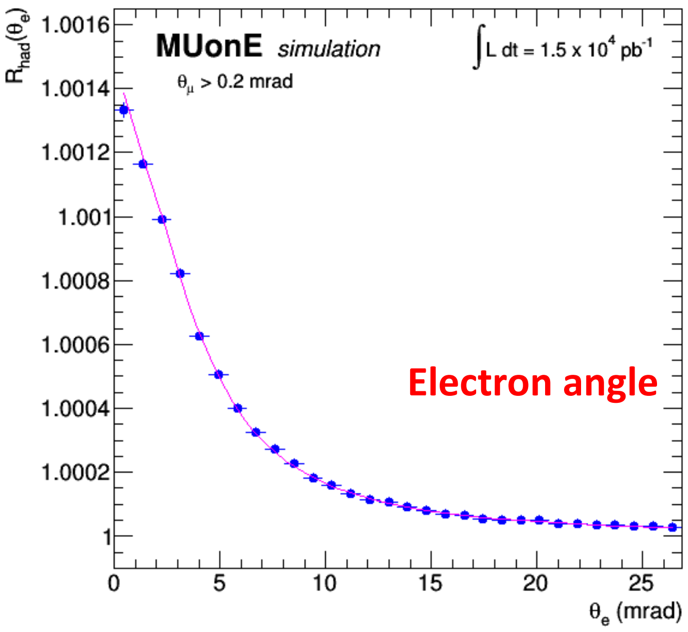
$$R_{had}(\theta) = \frac{d\sigma(\theta, \Delta\alpha_{had})}{d\sigma(\theta, \Delta\alpha_{had}=0)}$$

Observable effect ~ 10^{-3}
wanted precision ~10^{-2}

→ required precision ~10^{-5}

Example toy experiment: the expected distributions are obtained from the nominal integrated luminosity, corresponding to 3-year run



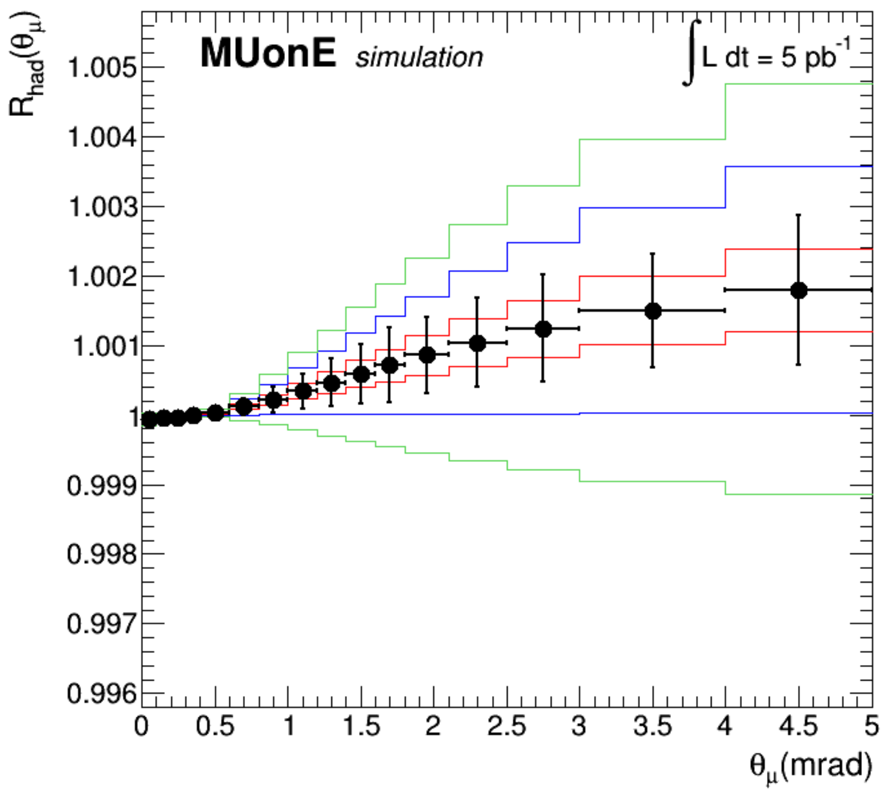


Expected Fit result $a_\mu^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$ → Stat.err. 0.35%

Closure test ok:
expected from the used input parameterization (Jegerlehner's) $a_\mu^{HLO} = 688.6 \times 10^{-10}$
→Negligible error from the fit method: 0.2×10^{-10}

Expected sensitivity of a First Physics Run

Expected integrated Luminosity with the Test Run setup:
assuming full beam intensity and full detector efficiency ~1pb^{-1}/day,
in one week ~5pb^{-1} → ~10^9 μe scattering events with E_e > 1 GeV (θ_e < 30 mrad)



Template fit with just one fit parameter K= k/M in the $\Delta\alpha_{had}$ parameterization. The other parameter fixed at its expected value: M = 0.0525 GeV^2

Initial sensitivity to the hadronic running of α.

Pure statistical level: 5.2σ
2D (θ_μ,θ_e) K=0.136 ± 0.026

Definitely we will have sensitivity to the leptonic running (ten times larger)

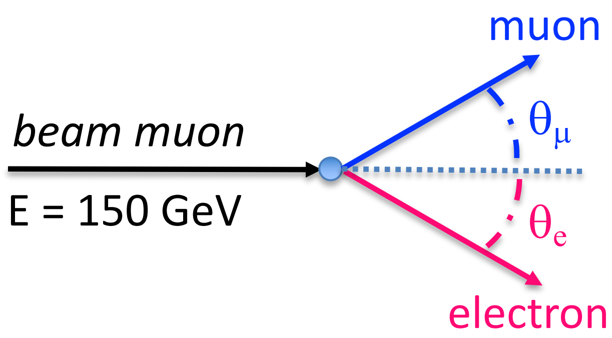
Systematics: Beam Energy scale

Time dependency of the beam energy profile has to be continuously monitored during the run:

- SPS monitor
- COMPASS BMS

} needed external infos

However, the absolute beam energy scale has to be calibrated by a physics process: kinematical method on elastic μe events



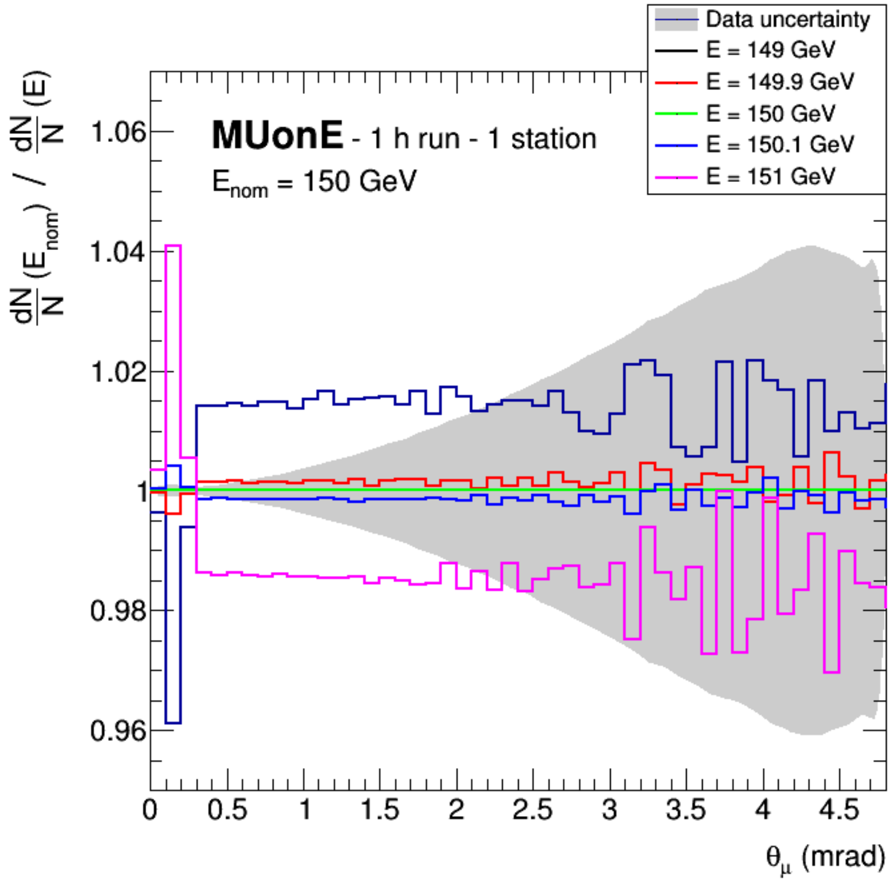
For equal angles: $\theta_\mu = \theta_e \equiv \theta$

$$\theta \simeq \sqrt{\frac{2m_e}{E}}$$

Can reach <3 MeV uncertainty in a single station in less than one week

From SPS E scale ~1% : 1.5 GeV

Effect of a syst shift of the average beam energy on the θ_μ distribution: 1h run / 1 station



Simultaneous fit of signal and nuisances

Full description in Riccardo Pilato's PhD thesis

- Template fit using CMS Combine tool
  - Likelihood fit with systematics included as nuisance parameters, simultaneously extracted along with the signal parameters
    https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/

- Currently including 4 nuisance parameters, related to:
  - Normalisation (uncertainty in the integrated luminosity)
  - Average beam energy
  - Intrinsic angular resolution
  - Multiple Coulomb Scattering (core width)

- Recent improvement: two-step workflow suited to the Test Run luminosity
  1. fit the main systematic effects (nuisance parameters) in the normalisation region (where signal is ~0). Use a short run of ~1h time station-by-station (~35/nb) assuming SM for the hadronic running.
  2. fit signal + nuisance parameters using as starting values and prior uncertainties for the nuisances the values determined in (1). Use the full Test Run statistics (~5/pb).

Example Fit results

From Riccardo Pilato's PhD thesis

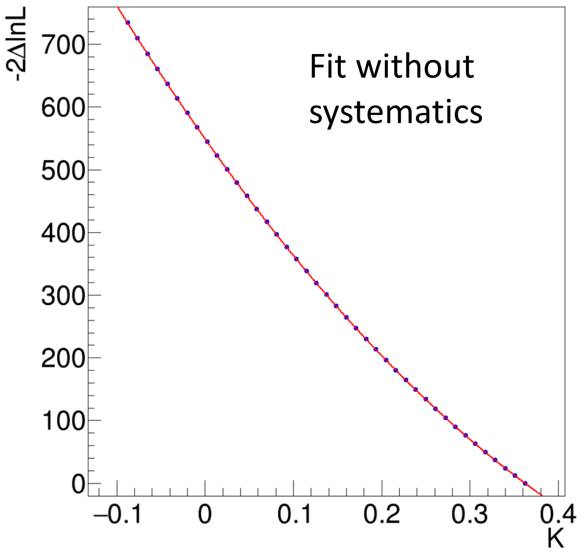
Pseudodata with statistics equivalent to the Test Run (5/pb). Input Signal parameter: K=0.136.
Normalisation nuisance ν=0. Distorted by the following 3 simultaneous shape systematics:

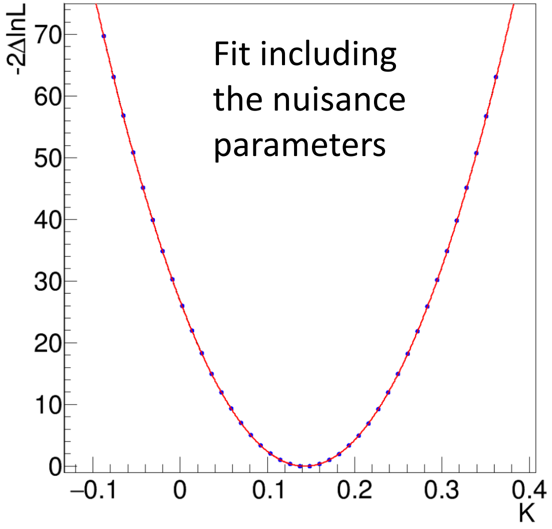
	Nominal configuration	Shift in the pseudo-data
Beam energy scale	$E_{beam} = (150 \pm 1)$ GeV	+ 6 MeV
Multiple scattering	$\sqrt{x/X_0} = 0.1458 \pm 1\%$	+ 0.5%
Angular intrinsic resolution	$\sigma_{Intr} = 0.02\,\mathrm{mrad} \pm 10\%$	+ 5%

Results:

Selection cuts	Fit results	
$\theta_e \leq 32$ mrad, $\theta_\mu \geq 0.2$ mrad	$K = 0.133 \pm 0.028$	$\mu_{MS} = (0.47 \pm 0.03)\%$ $\mu_{Intr} = (5.02 \pm 0.02)\%$ $\mu_{E_{Beam}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$
$\theta_e \leq 20$ mrad, $\theta_\mu \geq 0.4$ mrad	$K = 0.133 \pm 0.033$	$\mu_{MS} = (0.46 \pm 0.04)\%$ $\mu_{Intr} = (5.02 \pm 0.03)\%$ $\mu_{E_{Beam}} = (6.5 \pm 0.6)$ MeV $\nu = -0.008 \pm 0.007$
$\theta_e \leq 32$mrad, $\theta_\mu \geq 0.4$ mrad	$K = 0.133 \pm 0.033$	$\mu_{MS} = (0.46 \pm 0.04)\%$ $\mu_{Intr} = (5.03 \pm 0.03)\%$ $\mu_{E_{Beam}} = (6.5 \pm 0.6)$ MeV $\nu = -0.009 \pm 0.007$
$\theta_e \leq 20$ mrad, $\theta_\mu \geq 0.2$ mrad	$K = 0.133 \pm 0.031$	$\mu_{MS} = (0.47 \pm 0.03)\%$ $\mu_{Intr} = (5.02 \pm 0.03)\%$ $\mu_{E_{Beam}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.006$
$\theta_{L,R} \in [0.2, 32]$ mrad	$K = 0.132 \pm 0.029$	$\mu_{MS} = (0.45 \pm 0.02)\%$ $\mu_{Intr} = (5.04 \pm 0.02)\%$ $\mu_{E_{Beam}} = (6.9 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$
$\theta_{L,R} \in [0.4, 20]$ mrad	$K = 0.133 \pm 0.034$	$\mu_{MS} = (0.43 \pm 0.03)\%$ $\mu_{Intr} = (5.05 \pm 0.03)\%$ $\mu_{E_{Beam}} = (6.8 \pm 0.6)$ MeV $\nu = -0.008 \pm 0.007$

Fit Results are in excellent agreement with the input values for all the selections, both with and without particle identification





Conclusions & Plans

- **MUonE** experiment proposal: measuring the running of α_{QED} from the shape of the differential cross section for elastic scattering of μ(160GeV) on atomic electrons at the CERN SPS
  - Getting a_μ^{HLO} with a novel method integrating over the space-like region
  - Independent and complementary to the standard method integrating over the time-like region and to lattice QCD calculations
  - Competitive precision ~0.35-0.5% on a_μ^{HLO} allowing to better constrain the theory prediction, will help to solve the muon g-2 puzzle
- Impressive progress on the needed theoretical calculations and tools
  - (see talks by E.Budassi and C.L.Del Pio)
- Successful beam tests in 2021-22 with one tracking station
  - Stable operation under very high intensity
  - Good quality data collected (analysis ongoing)
- Test Run 2023: prove the feasibility of the method
  - 2 or 3 tracking stations (minimum: one before / one after the target)
  - Integration of the ECAL readout with the full DAQ
  - Implementation of online (in-FPGA) event selection
    - Simple track and vertex reconstruction
    - Selection of two-track events
  - Study backgrounds
  - Study the alignment in test beams
  - Study the beam energy calibration and validate our method
- Write the experimental proposal
- Move to the experiment with 10 stations to get a first measurement before LS3

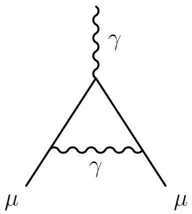
More infos:
papers, conferences, theses see:
https://web.infn.it/MUonE/

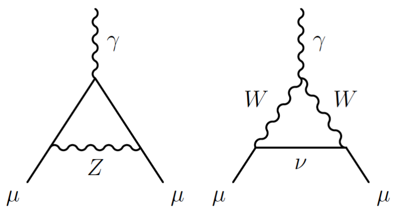
BACKUP

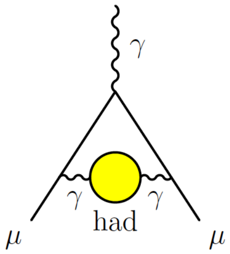
Muon g-2 Theory prediction

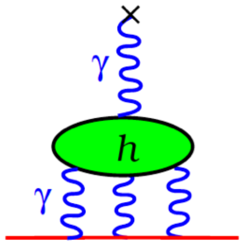
Currently accepted Standard Model prediction:
White Paper of the Muon g-2 Theory Initiative
[Aoyama et al., Phys.Rept.887(2020)1]()

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had}$$









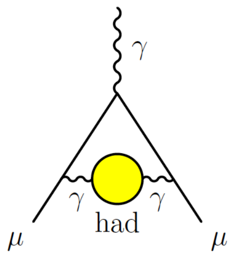
	QED	EWK	HADRONIC: VP	HADRONIC: Light-By-Light
Order	$\mathcal{O}(\alpha)$	$\mathcal{O}(G_F m_\mu^2) = \mathcal{O}(\frac{\alpha}{s_W^2}\frac{m_\mu^2}{M_W^2})$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha^3)$
SIZE	10^{-3}	10^{-9}	7×10^{-8}	10^{-9}
Uncertainty	10^{-12}	10^{-11}	$\mathbf{4\times10^{-10}}$	2×10^{-10}

QED LO term (Schwinger) = $\alpha/2\pi$ ~ 0.00116
QED corrections known up to 5 loops,
uncertainty related to missing 6 loops!

Hadronic contributions
-not calculable by pQCD-

➡ **Dominant Theoretical uncertainty**
LO Hadronic Vacuum Polarization
Relative uncertainty: 0.6%

$a_\mu^{HVP,LO}$: standard data-driven approach (time-like)



Dispersion relations, optical theorem:

$$a_\mu^{HVP,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{\hat{K}(s) R(s)}{s^2} ds$$

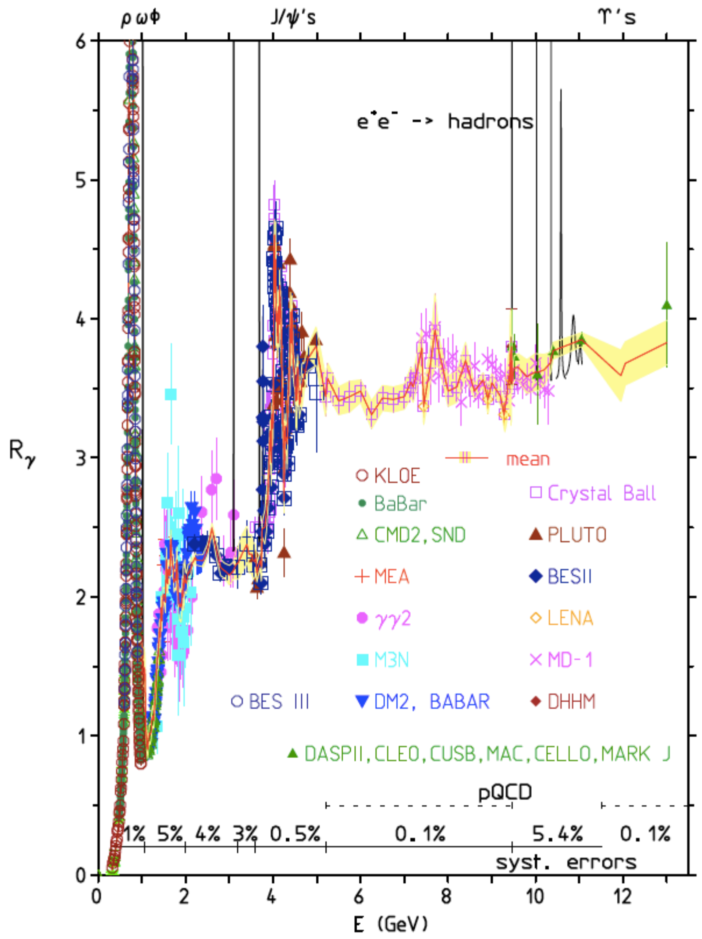
$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$\hat{K}$ smooth

Traditionally the integral is calculated by using the experimental measurements up to an energy cutoff, beyond which perturbative QCD can be applied.

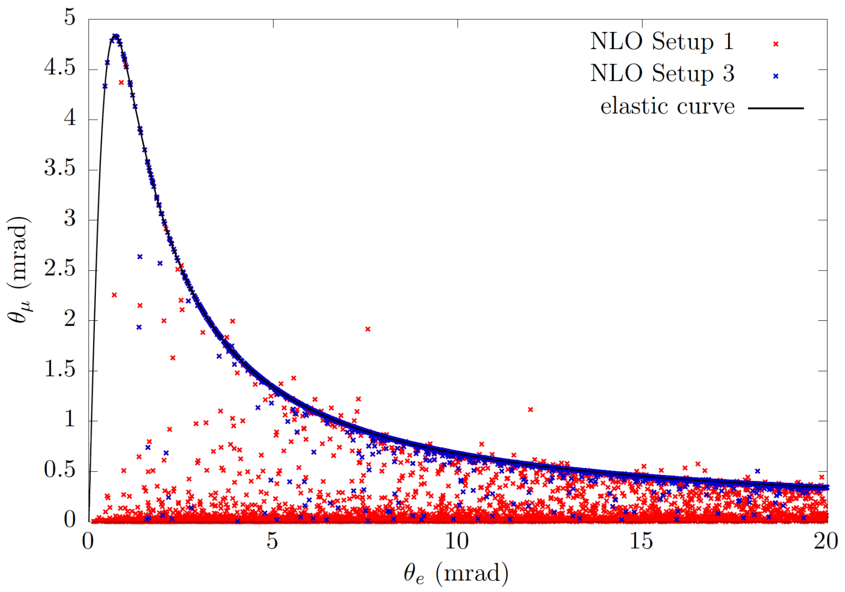
Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

Radiative corrections to $R(s)$ crucial



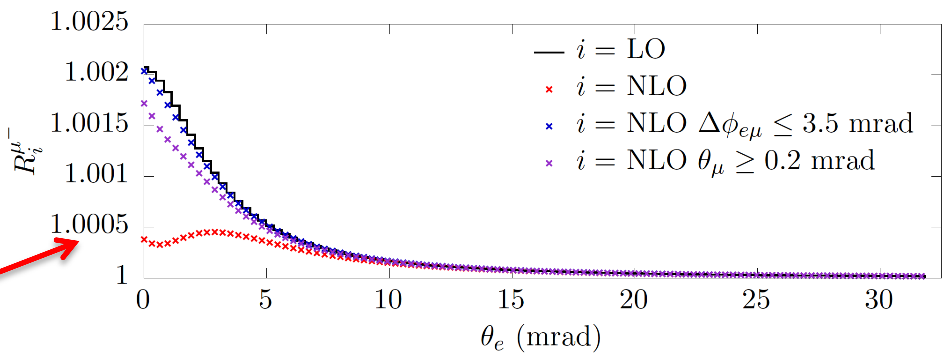
F.Jegerlehner, EPJ Web Conf. 1c18 (2016) 01016

Radiative events and elastic selection

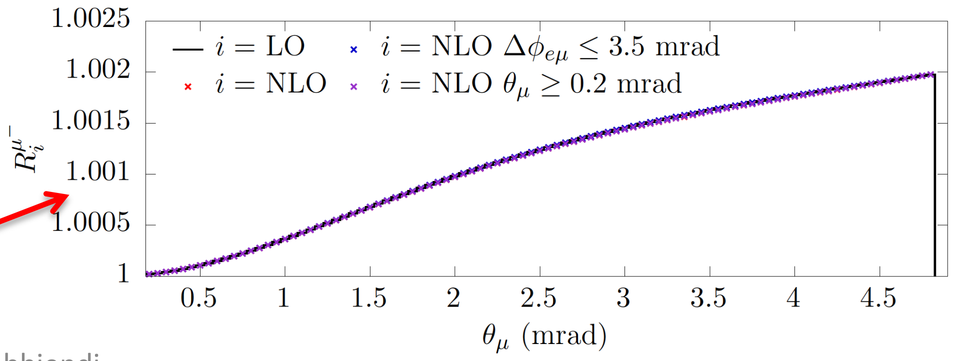


[M.Alacevich et al, JHEP02(2019)155](#)

NLO:
Setup 1 is the inclusive selection (no cuts)
Setup 3 has an acoplanarity cut $|\pi-(\phi_e-\phi_\mu)|<3.5$ mrad



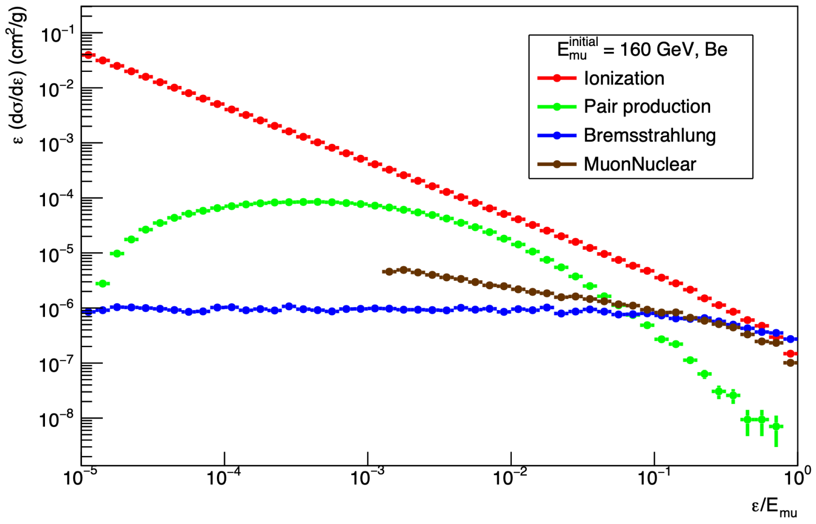
Without any selection the signal sensitivity of the electron angle is destroyed -> necessary to implement an “elastic” selection



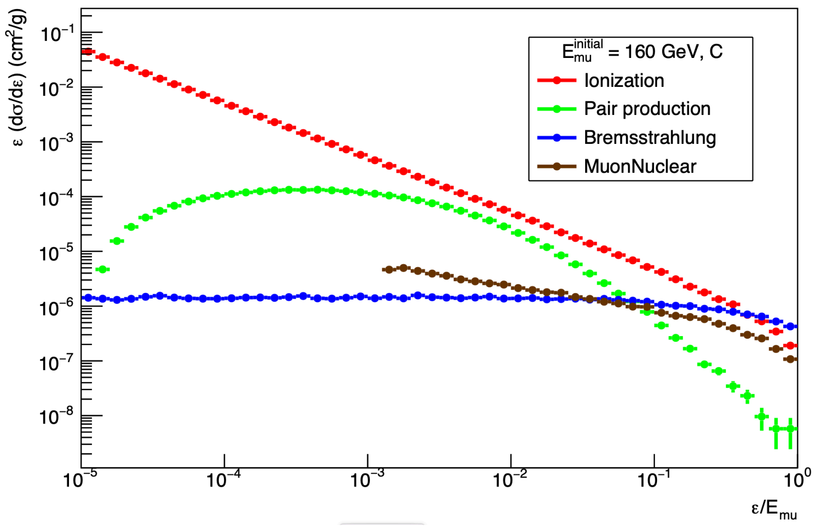
Instead the muon angle is a robust observable, stable w.r.t. radiative corrections -> it can be used with an inclusive selection (theoretically advantageous)

GEANT4: μ interaction cross sections

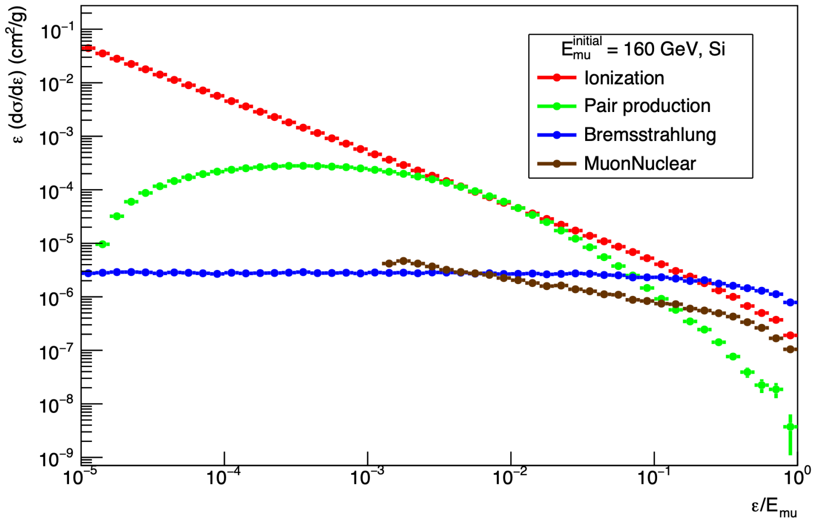
Differential macroscopic cross section: beryllium



Differential macroscopic cross section: carbon



Differential macroscopic cross section: silicon



GEANT4 simulation

ε Muon Energy loss fraction

σ Macroscopic cross section

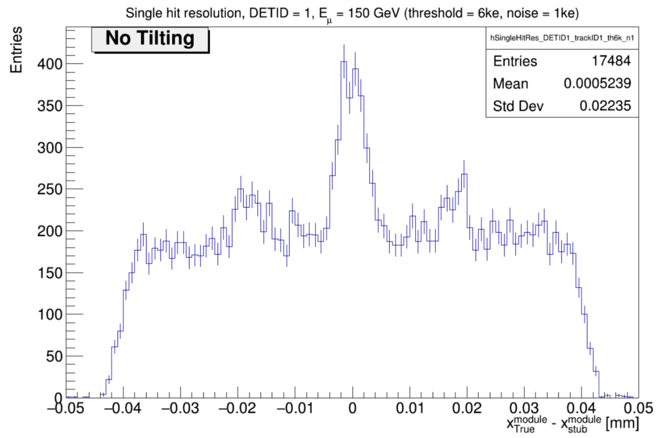
$\sigma = \sigma_A \, n_A/\rho_A$

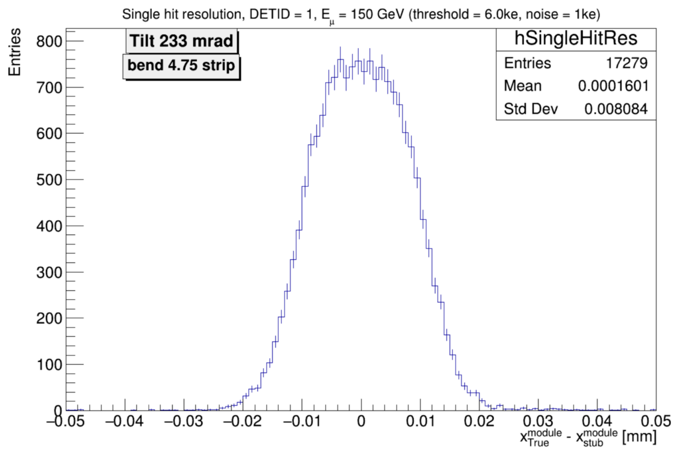
σ_A Atomic cross section

n_A density of atoms per unit volume

ρ_A material density in g/cm³

Simulation: Intrinsic Resolution – Tilted geometry





Strip digital readout: with 90μm pitch the expected resolution is 90/sqrt(12)≅26μm on a single sensor layer for single-strip clusters

Tilting a sensor around an axis parallel to the strips → Charge sharing between adjacent strips, improving the resolution

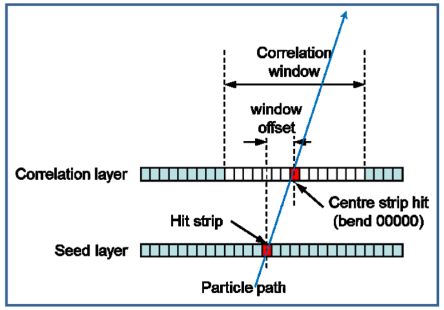
The best is obtained when <cluster width>~1.5 (same number of clusters made of 1 or 2 strips) for a tilt angle ~15 degrees

Further improvement: a small tilt of 25mrad is equivalent to an half-strip staggering of the two sensor layers of a 2S module

Final resolution:

22 μm → 8-11 μm

measured coordinate (x) determined by hit position on one layer and direction of the track stub



Tilt angle [mrad]	<bend> [strips]	threshold [σ]	resolution [μm]	<cluster width> [strips]
210	4.25	5	7.8	1.51
221	4.5	5.5	11.5	1.51
233	4.75	6	8.0	1.50
245	5	6.5	11.2	1.51
257	5.25	7	8.7	1.50
268	5.5	7.5	11.0	1.49

FastSim analysis strategy

- NLO MESMER MC
- $\Delta\alpha_{had}(t)$ from F.Jegerlehner's code(hadr5n12.f)→ $a_{\mu}^{HLO} = 688.6 \times 10^{-10}$
- Detector resolution effects parametrized in a simplified way (including only: multiple scattering on 1.5cm Be target and intrinsic resolution σ_{θ}=0.02 mrad)
  - Neglecting: scattering on the Si planes, non-Gaussian tails, residual backgrounds
  - Neglecting: detailed track simulation and reconstruction
- Fit is done directly on the angular distributions of scattered μ and e
  - No attempt to estimate t (or x) event by event
  - $\theta_e < 32$ mrad (geometric acceptance)
  - $\theta_{\mu} > 0.2$ mrad (remove most of the background)
  - Both 1D and 2D distributions fitted. 2D is the most robust.
  - Ideally there is no need to identify the outgoing muon and electron, provided the event is a signal one. In this case we simply label the two angles as θ_L, θ_R ("Left" and "Right" w.r.t. an arbitrary axis)
- Shape-only fit: the absolute normalization shall not count.

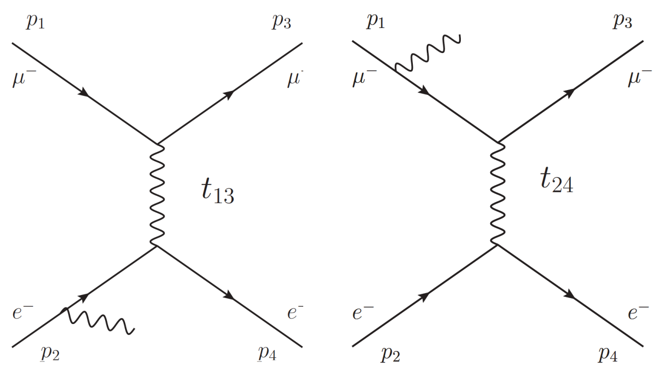
Template Fit technique

- MC templates for any useful distribution are built by reweighting the events to correspond to a given functional form of $\Delta\alpha_{had}(t)$
- $\Delta\alpha_{had}(t)$ is conveniently parameterised with the “Lepton-Like” form, one-loop QED calculation.

The 2->3 matrix element for one-photon emission at NLO can be split in 3 parts (radiation from mu or e leg and their interference), each one with a different running coupling factor → **3 coefficients**

NOTE: at NNLO one needs **11 coefficients**

By saving the relevant coefficients at generation time we can easily reweight the events according to the chosen parameters in the $\Delta\alpha_{had}(t)$



Determination of a_μ^{HLO} by the Master Integral

- From the fitted (K,M) values the hadronic contribution to $\Delta\alpha_{had}(t)$ is determined from the Lepton-Like parameterisation:

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

- Then, by using the master integral, we have the result in the full phase space:

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

- The result for the nominal luminosity is $a_\mu^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$
  - statistical uncertainty of 0.35%

- The expectation from the used Jegerlehner's parameterization is: $a_\mu^{HLO} = 688.6 \times 10^{-10}$
  - difference from our fit is 0.2×10^{-10}, negligible w.r.t. the statistical uncertainty