Status of the MUonE project

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(INFN Bologna)

Colloquium — INPP, NCSR Demokritos - 25 May 2021

Outline

- Introduction on muon g-2
  - Experiment: the new FNAL measurement
  - Standard Model calculations: data-driven and ab initio (Lattice QCD)
  - Status of the data-theory comparison

- The MUonE project
  - The idea
  - Proposed detector
  - Studies on MC simulations
  - Results from Beam Tests 2017-2018
  - Status of theoretical calculations
  - Status and plans for the first Test Run

- Summary

Muon anomalous magnetic moment

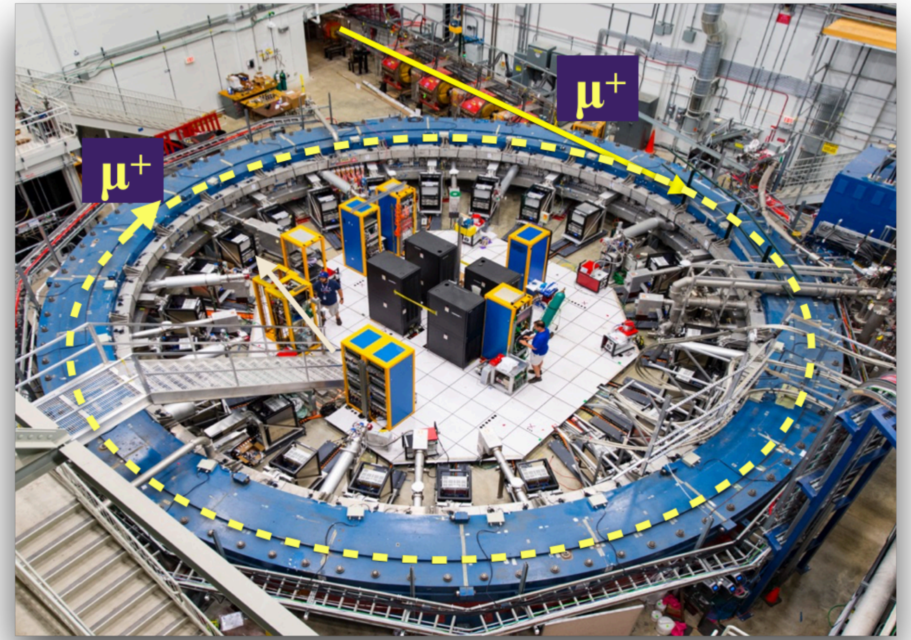
$$\vec{M}_l = g_l \frac{e}{2m_l}\vec{S}$$

Dirac equation : $g_l = 2$

Quantum corrections → the anomaly

$$\boxed{a_l \equiv \frac{g_l - 2}{2}}$$

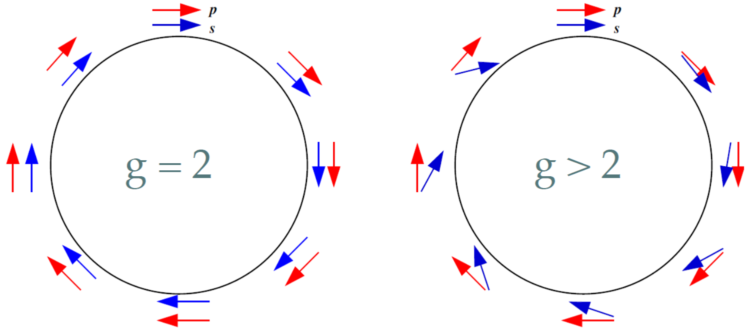
This observable can be both precisely measured experimentally and predicted in the Standard Model, providing a stringent test of the SM.



Anomalous precession frequency in a magnetic storage ring

(ideal case: perfectly uniform field and orthogonal motion)

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{m}$$

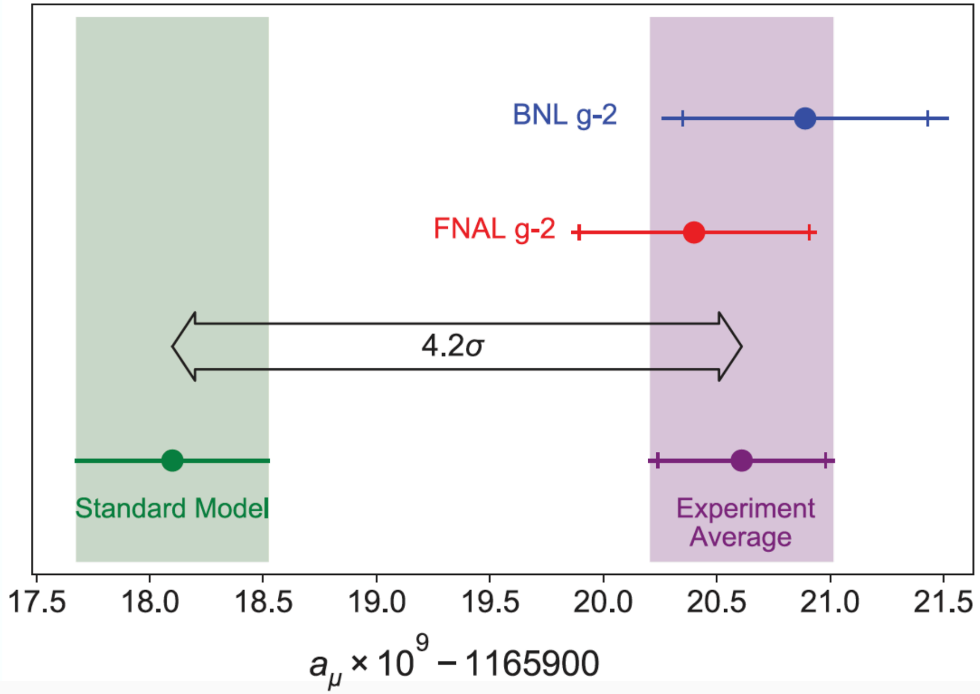


Muon g-2 measurements

Phys.Rev.Lett. 126 (2021) 141801

FNAL confirmed BNL: the experimental result is robust

SM: Muon g-2 Theory Initiative



3.7 σ

3.3 σ

4.2 σ

BNL E821	$(116592089 \pm 63)\times10^{-11}$
FNAL E989 Run 1	$(116592040 \pm 54)\times10^{-11}$
Weighted Average	$(116592061 \pm 41)\times10^{-11}$

Dominant Statistical uncertainties

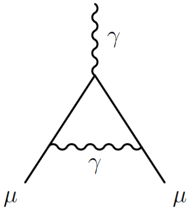
0.35 ppm

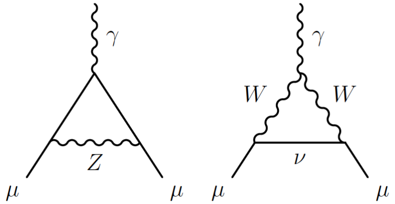
Expected improvements: factor 2 from FNAL Run 2+3; more from Run 4+5

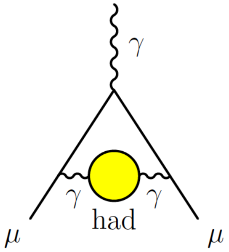
Muon anomalous magnetic moment

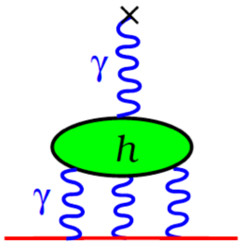
Currently accepted Standard Model prediction:
White Paper of the Muon g-2 Theory Initiative
Aoyama et al., Phys.Rept.887(2020)1

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









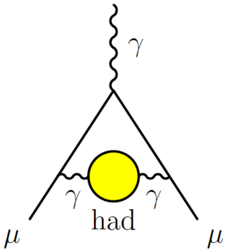
	QED	EWK	HADRONIC: VP	HADRONIC: Light-By-Light
Order	$\mathcal{O}(\alpha)$	$\mathcal{O}\left(G_F m_\mu^2\right) = \mathcal{O}\left(\frac{\alpha}{s_W^2}\frac{m_\mu^2}{M_W^2}\right)$	$\mathcal{O}(\alpha^2)$	$\mathcal{O}(\alpha^3)$
SIZE	10^{-3}	10^{-9}	7×10^{-8}	10^{-9}
Uncertainty	10^{-12}	10^{-11}	$\mathbf{4\times10^{-10}}$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

QED LO term (Schwinger) = α/2π ~ 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:

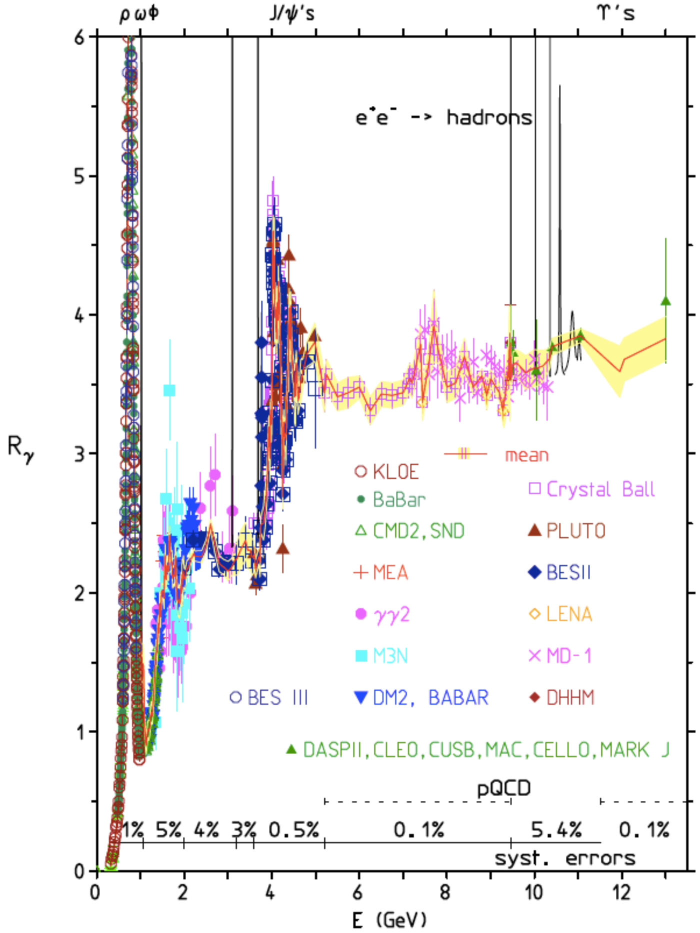
$$a_\mu^{HVP,LO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_\pi^2}^{\infty} \frac{\widehat{K}(s)R(s)}{s^2} ds$$

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

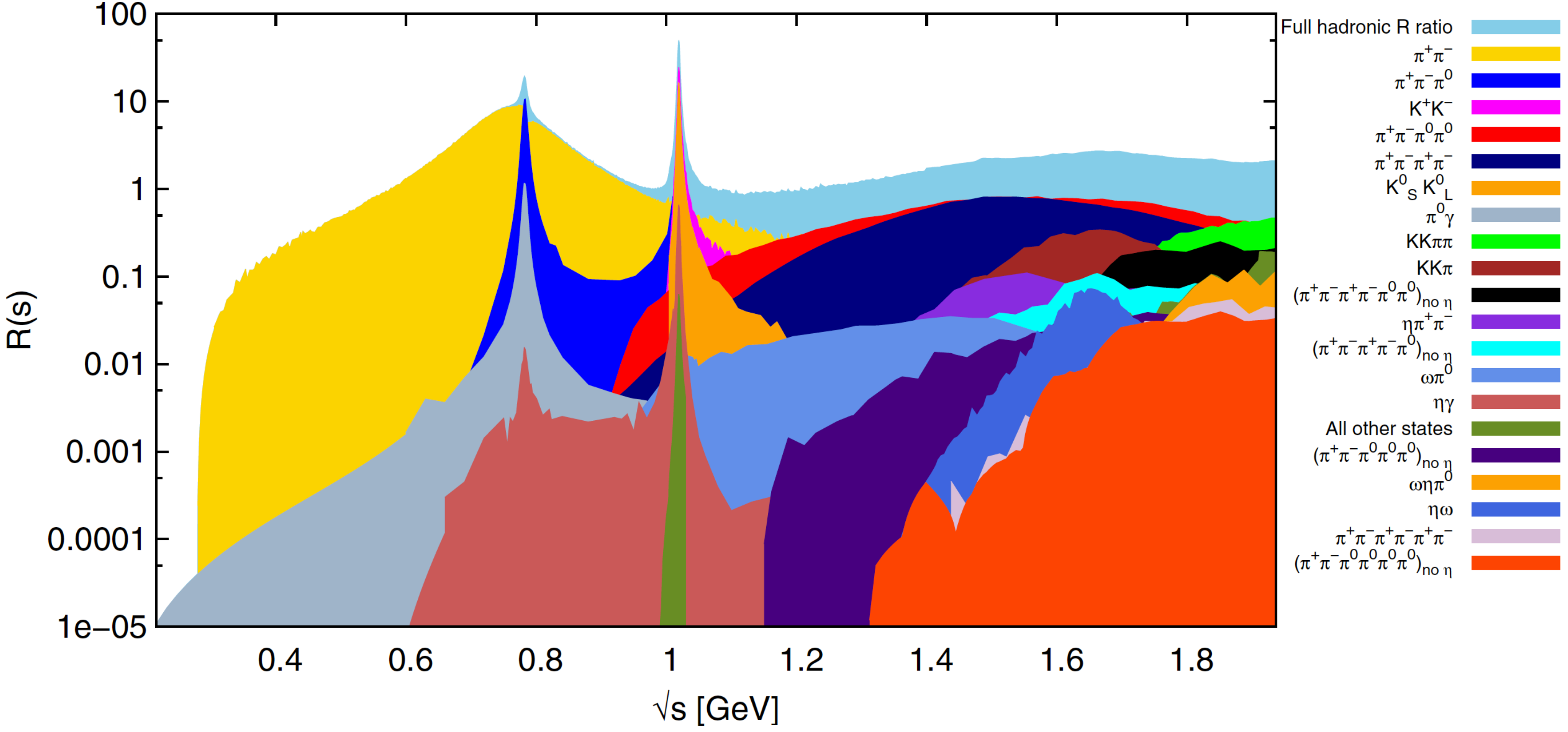
Radiative corrections to $R(s)$ crucial



F.Jegerlehner, EPJ Web Conf. 118 (2016) 01016

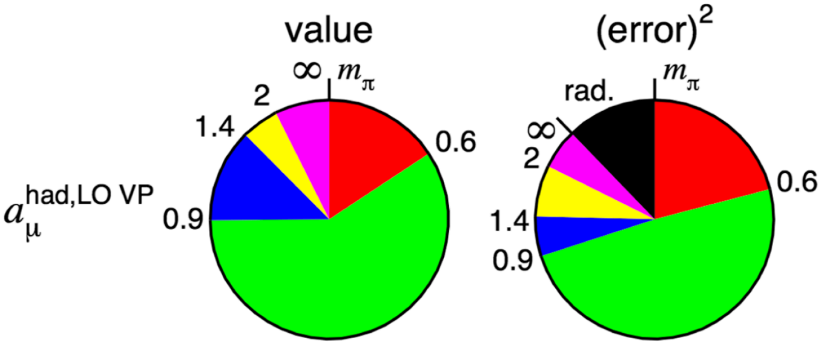
Low-energy hadronic cross section

Keshavarzi, Nomura, Teubner, Phys.Rev. D 97 (2018) 114025



Region around ρ – ω is the most important for the a_μ calculation

WP20: $a_\mu^{HVP,LO} = (6931 \pm 40)\times 10^{-11}$



New Lattice QCD result for $a_\mu^{HVP,LO}$

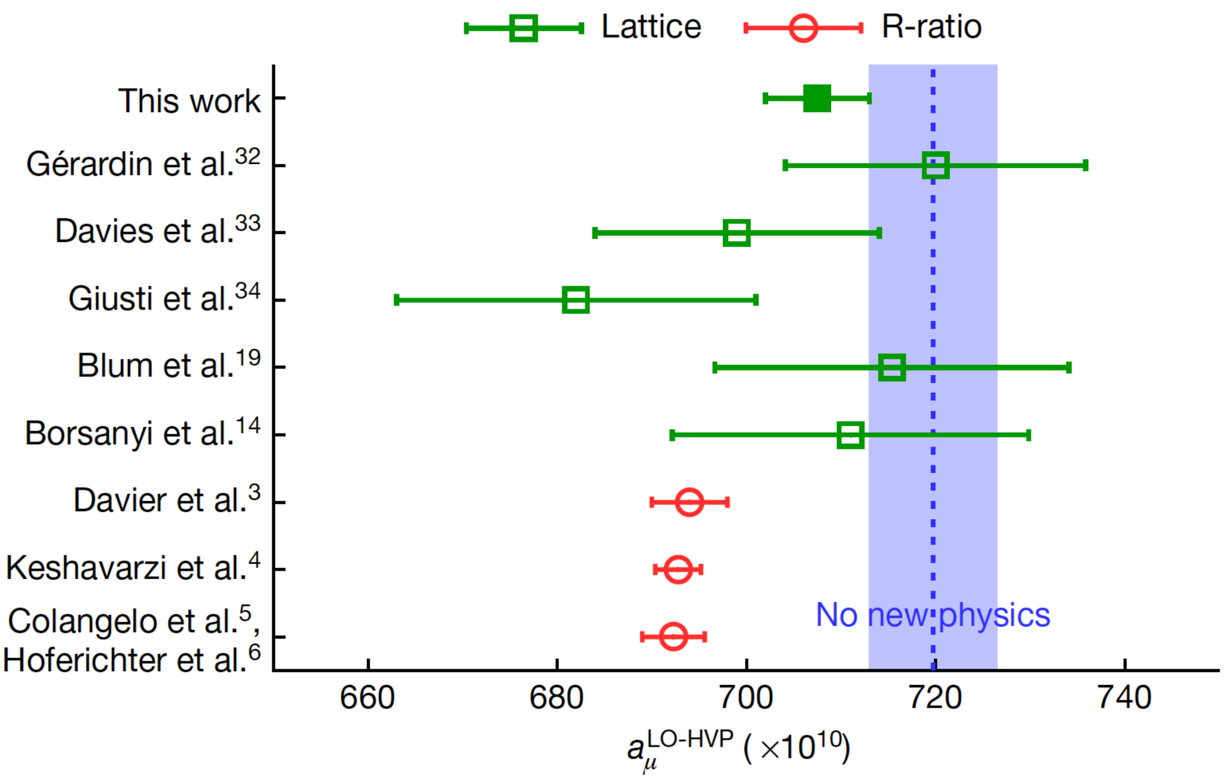
Great progress: the BMW collaboration reached 0.8% precision

It weakens the discrepancy with the measurement

tension ~2σ with the standard dispersive approach

Should be checked by other independent calculations

Borsanyi et al., Nature 593 (2021)



BMW(Lattice QCD): $a_\mu^{HVP,LO} = (7075 \pm 55)\times 10^{-11}$

WP20(R-ratio): $a_\mu^{HVP,LO} = (6931 \pm 40)\times 10^{-11}$

New physics ?

Taking the WP20 SM calculation, the difference with the experiments is:

$$\Delta a_\mu = a_\mu^{EXP} - a_\mu^{SM} = (251 \pm 59)\times 10^{-11}$$ **4.2σ**

If this is due to New Physics it could be:

- **NP at the weak scale and weakly coupled to SM particles**
- **NP very heavy and strongly coupled to SM particles**
- **NP very light ($\Lambda \lesssim 1$ GeV) and feebly coupled to SM particles**

What about the electron g-2 ?

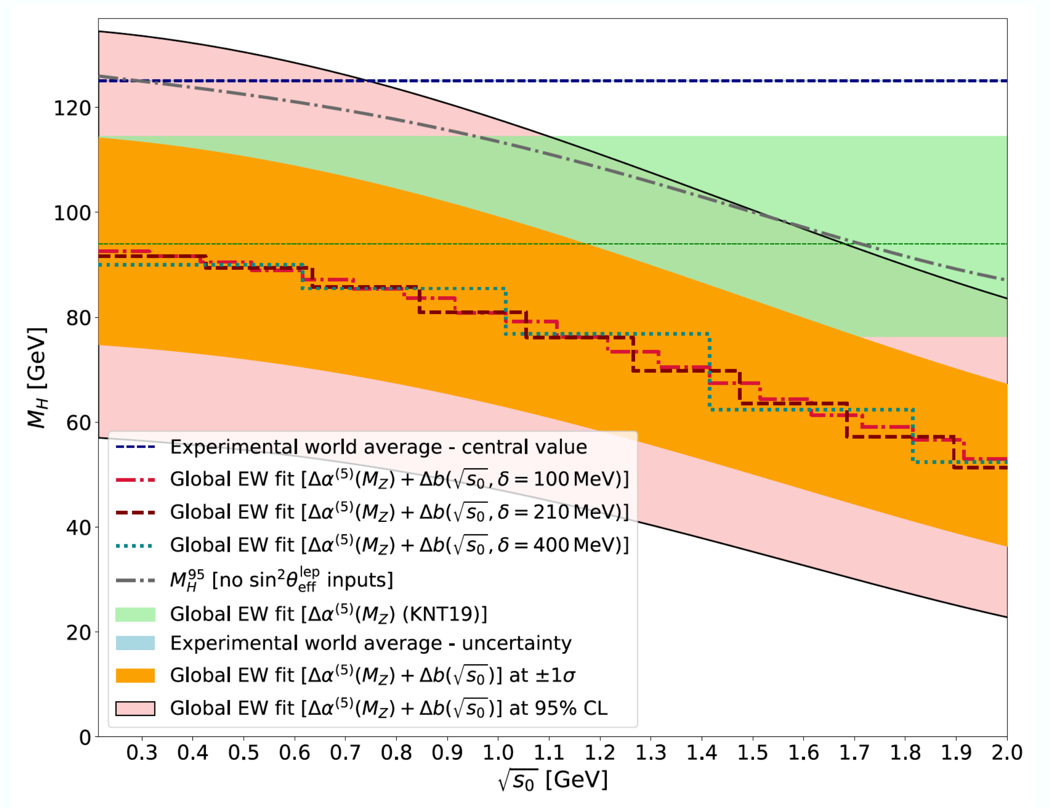
Naïve scaling for BSM physics: $\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} = 2.5\times 10^{-5} \rightarrow \Delta a_e = 0.6\times 10^{-13}$

Experimental error on the electron g-2: 2.8×10^{-13} not yet precise enough, although future is promising here (new super-precise measurements of α …)

Connection $a_\mu \rightarrow \Delta\alpha^{(5)}_{had}(M_Z^2) \rightarrow M_H$

Can Δa_μ be due to missing contributions in the hadronic σ(s) ?

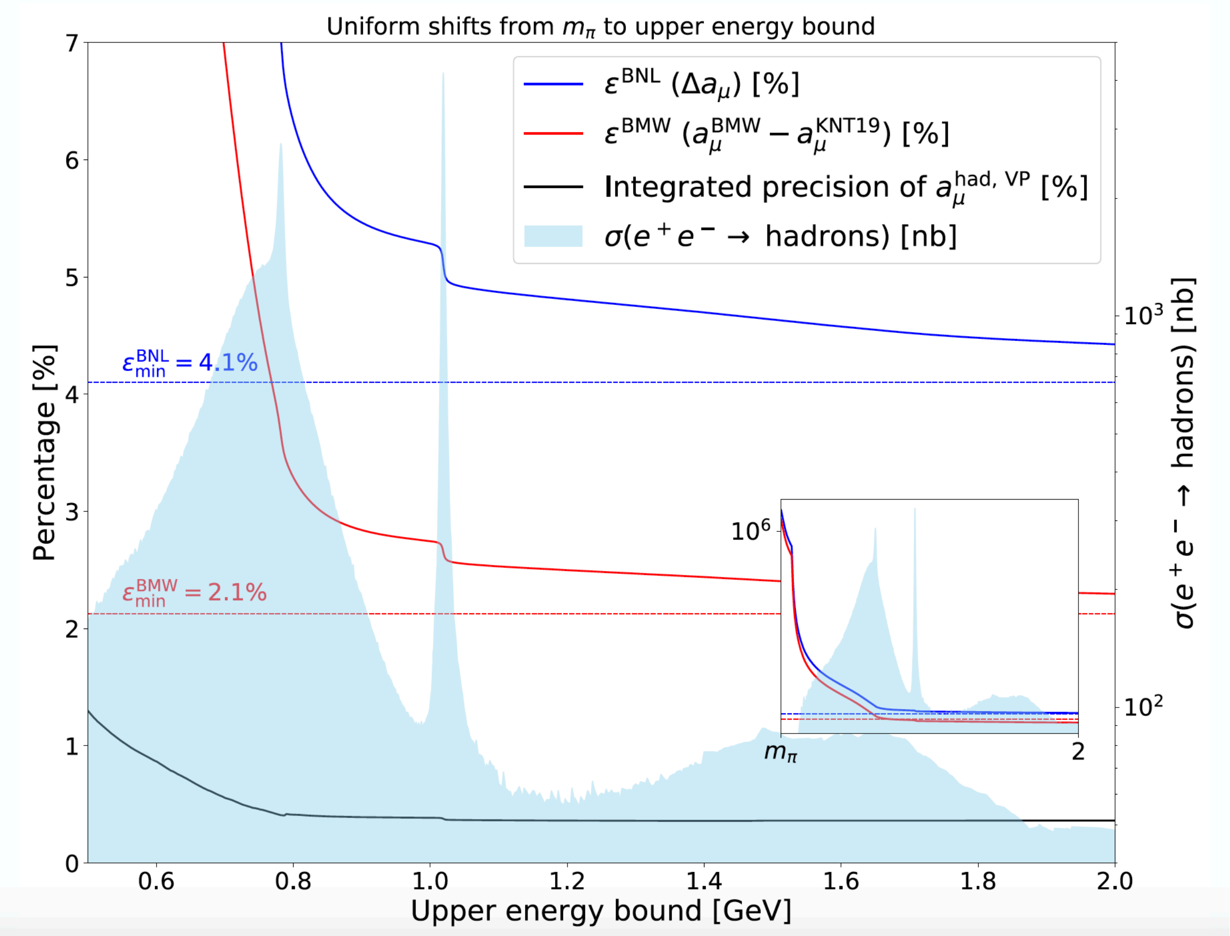
Keshavarzi, Passera, Marciano, Sirlin, Phys.Rev.D102(2020)033002



- An upward shift of σ(s) also induces an increase of $\Delta\alpha^{(5)}_{had}(M_Z^2)$
- Shifts Δσ(s) to fix Δa_μ are possible, but conflict with the EW fit if they occur above ~1 GeV
  - ❖ They would require new physics affecting the EW-fit

Required shifts in $\sigma_{had}(s)$

Keshavarzi, Passera, Marciano, Sirlin, Phys.Rev.D102(2020)033002



Shifts below ~1 GeV conflict with the quoted experimental precision of $\sigma_{had}(s)$

$a_\mu^{HVP,LO}$ determinations

- Standard data-driven (timelike R-ratio)
- Lattice QCD (ab initio)

- NEW proposal: data-driven spacelike (scattering)

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

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

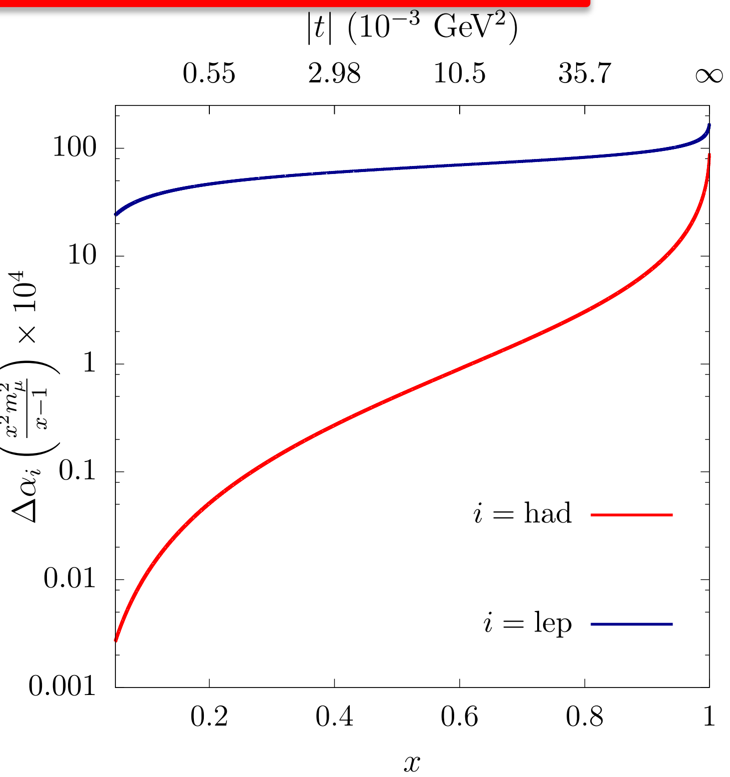
$$\boxed{a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]}$$

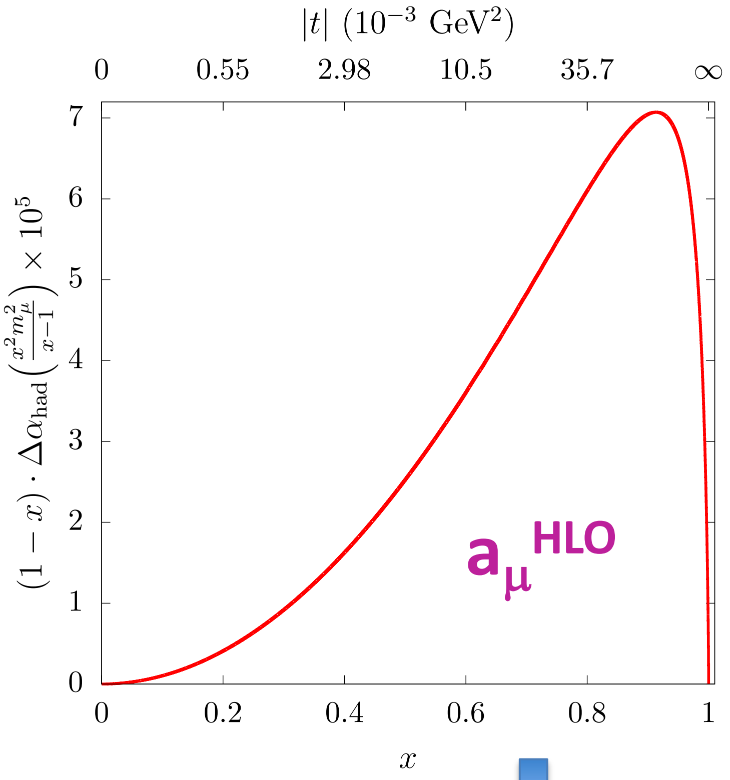
$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad 0 \le -t < \infty \qquad 0 \le x < 1$$

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

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

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





Integrand function smooth: no resonances

Low-energy enhancement:

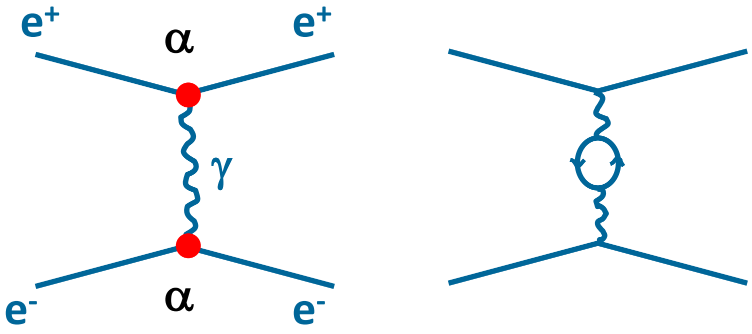
peak of the integrand at x ≅ 0.9 → $t = -0.11$ GeV^2 → $\Delta\alpha_{had} \sim 10^{-3}$

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

Eur.Phys.J.C45(2006)1

OPAL measurement: Bhabha scattering at small angle, with $1.8 < -t < 6.1$ GeV^2

about 10^7 events
precision at the per mille level



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

Born term for t-channel single γ exchange

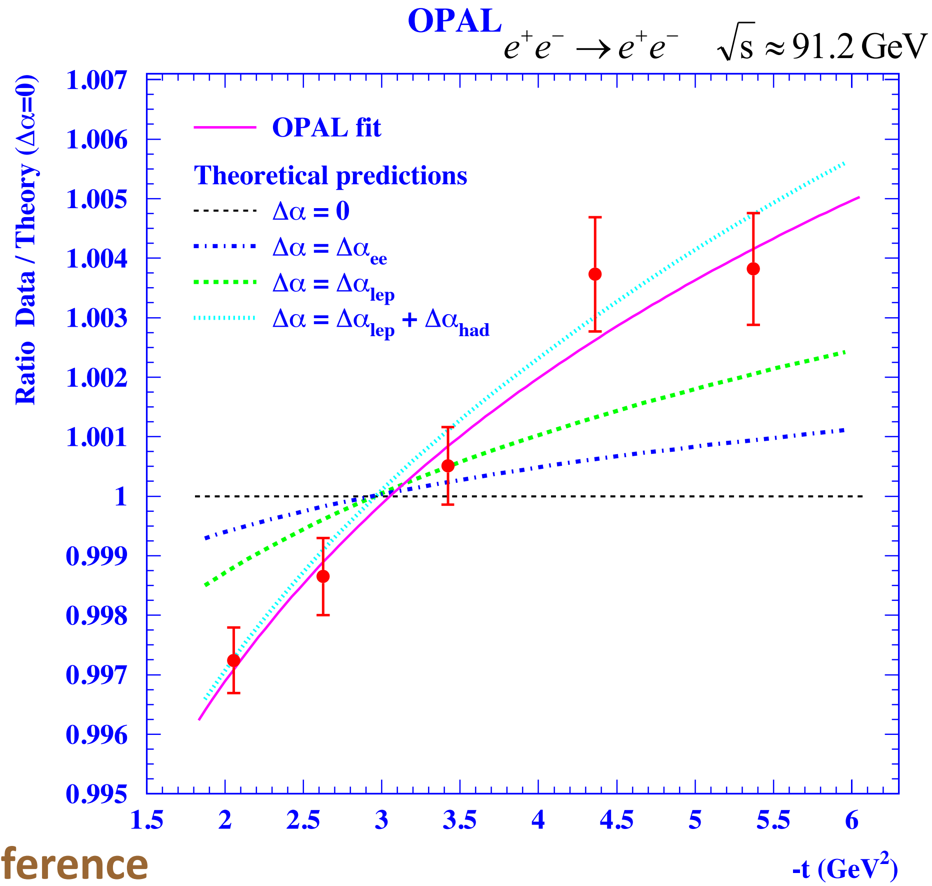
$$\boxed{\left(\frac{1}{1-\Delta\alpha(t)}\right)^2}$$

Effective coupling factorized

Photonic radiative corrections

s-channel γ exchange correction

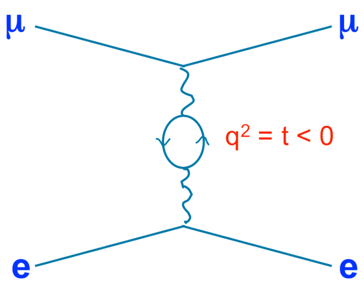
Z interference correction



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

MUonE experiment idea

Eur.Phys.J.C77(2017)139



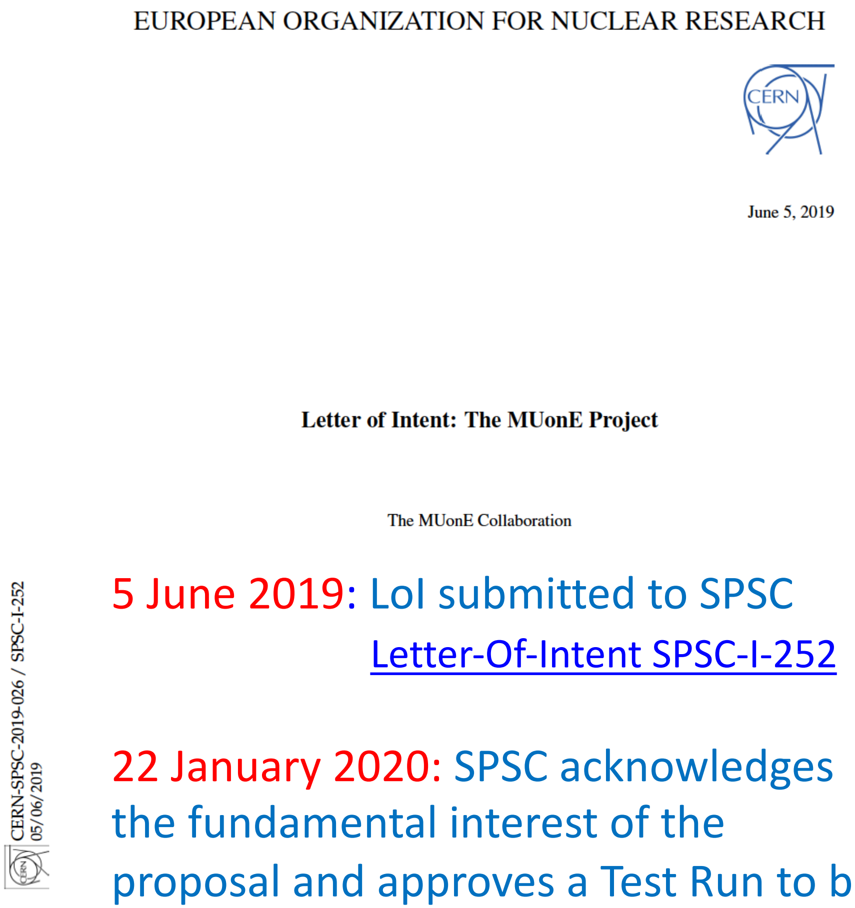
Very precise measurement of the running of α_{QED} from the shape of the differential cross section of elastic scattering of μ(150-160GeV) on atomic electrons of a fixed target with low Z (Be or C)
→ CERN SPS

$$\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \approx \underbrace{\frac{d\sigma_0}{dt}\left|\frac{1}{1-\Delta\alpha(t)}\right|^2}_{\text{running of }\alpha} \Rightarrow \Delta\alpha(t) = \underbrace{\Delta\alpha_{lep}(t)}_{\text{known from QED}} + \underbrace{\Delta\alpha_{had}(t)}_{\text{to be measured}}$$

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

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

MUonE experiment proposal



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

June 5, 2019

Letter of Intent: The MUonE Project

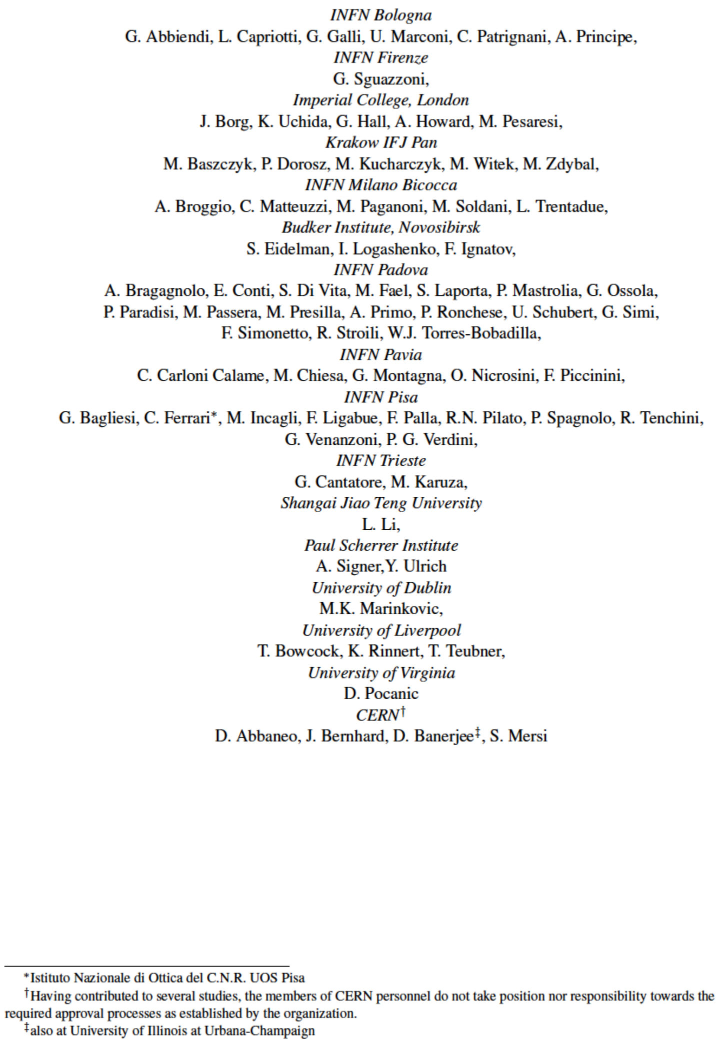
The MUonE Collaboration

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

5 June 2019: LoI submitted to SPSC
Letter-Of-Intent SPSC-I-252

22 January 2020: SPSC acknowledges the fundamental interest of the proposal and approves a Test Run to be held in 2021

(Covid19) Test Run will be completed in 2022 (schedule to be rediscussed)



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[*] Istituto Nazionale di Ottica del C.N.R. UOS Pisa

[†] Having contributed to several studies, the members of CERN personnel do not take position nor responsibility towards the required approval processes as established by the organization.

[‡] also at University of Illinois at Urbana-Champaign

still growing up

The MUonE Collaboration

CERN
Exp

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

Imperial College (London), Liverpool U. ***Exp-Th***

Krakow IFJ Pan
Exp

Northwestern U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) ***Exp-Th***

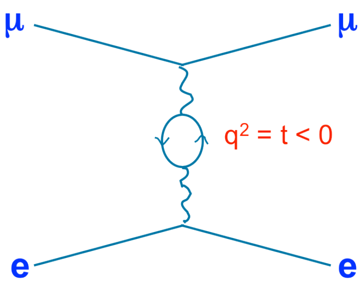
Shanghai Jiao Tong U.
Exp

LMU München
Th

PSI (Villigen), U.Zürich
Th

+ other involved theorists from: LAPTH/Annecy (F), U.Valencia (E), KIT/Karlsruhe (D), New York City Tech (USA)

μ-e elastic scattering



At LO

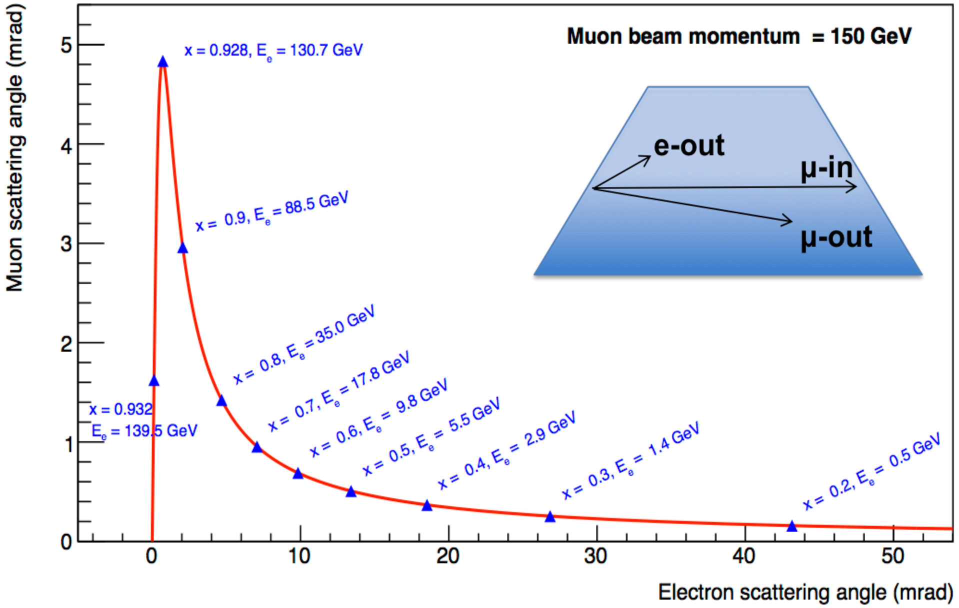
$$\frac{d\sigma}{dt} = \frac{4\pi\alpha^2}{\lambda(s, m_e^2, m_\mu^2)}\left[\frac{(s - m_e^2 - m_\mu^2)^2}{t^2} + \frac{s}{t} + \frac{1}{2}\right]$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)} \qquad \Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$$

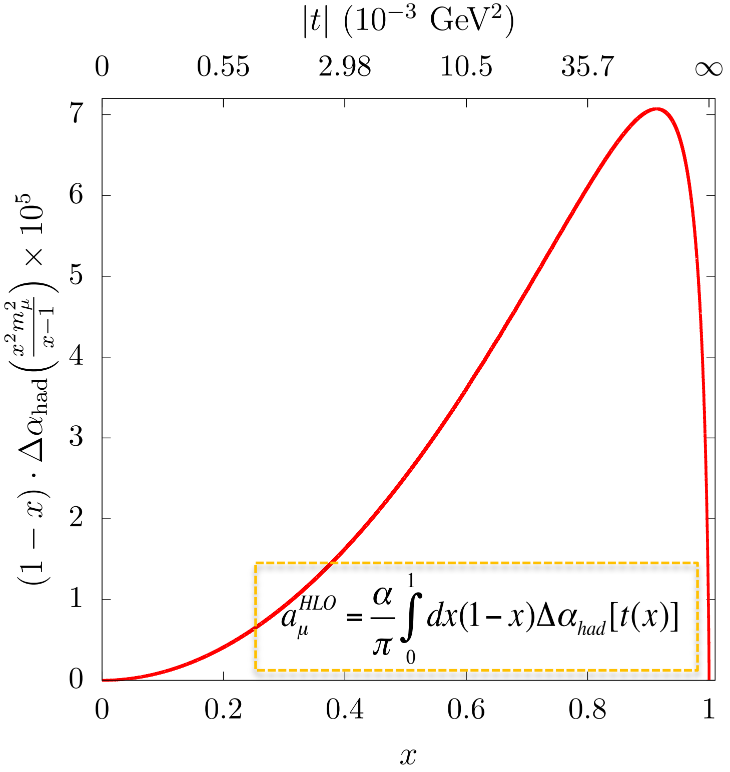
- **Elastic scattering: simple kinematics**
  - $t \cong -2\, m_e E_e$ E_e can be determined from the scattering angle θ_e and the beam energy

- Scattering angles θ_e and θ_μ correlated (helps selection: rejection of radiative/inelastic events)

- Elastic events are planar



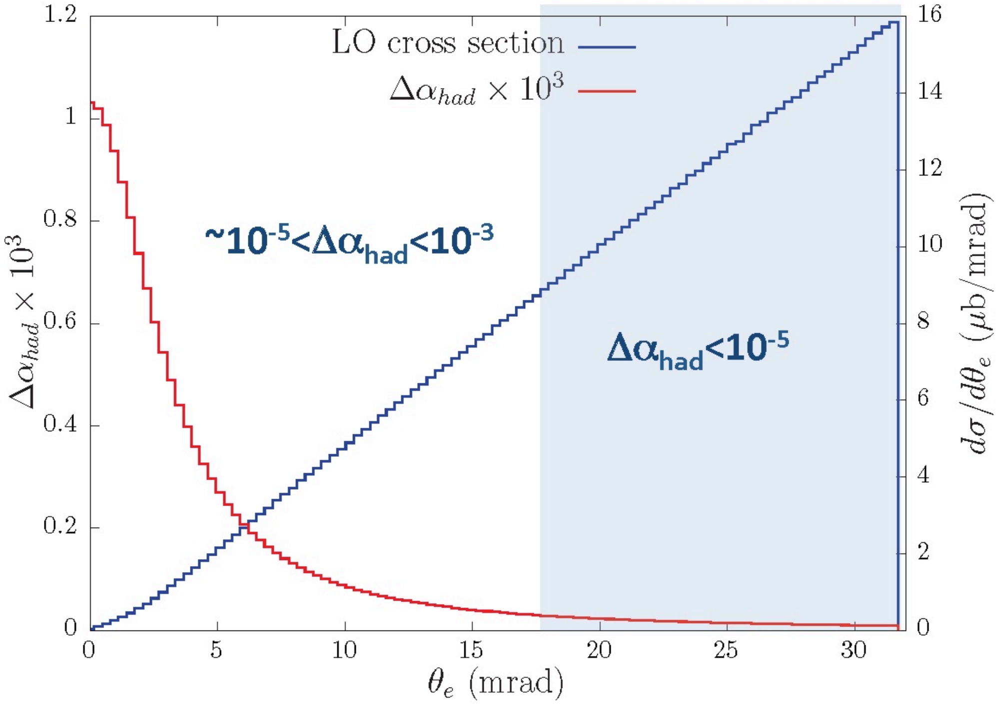
μ-e elastic scattering (2)



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

For E(beam)=150 GeV the phase space covers 87% of the a_μ^{HLO} integral.

Smooth extrapolation to the full integral with a proper fit model



THIS IS CHALLENGING:

Observable effect ~ 10^{-3}

wanted accuracy ~10^{-2}

→ Required precision ~10^{-5} on the shape of dσ/dt

MUonE Detector Layout

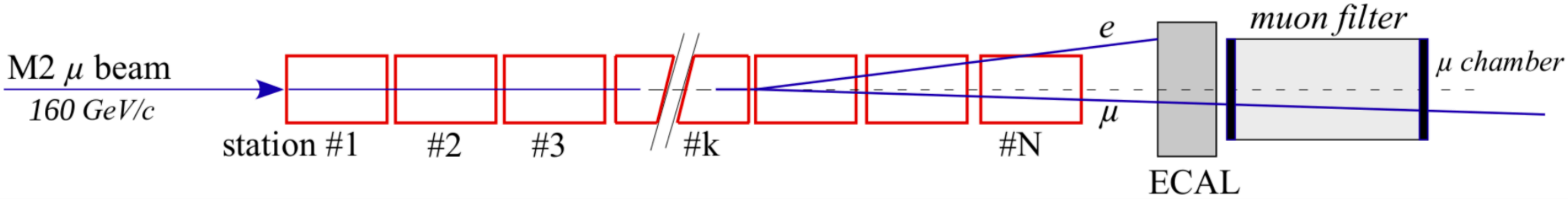
Letter-Of-Intent SPSC-I-252

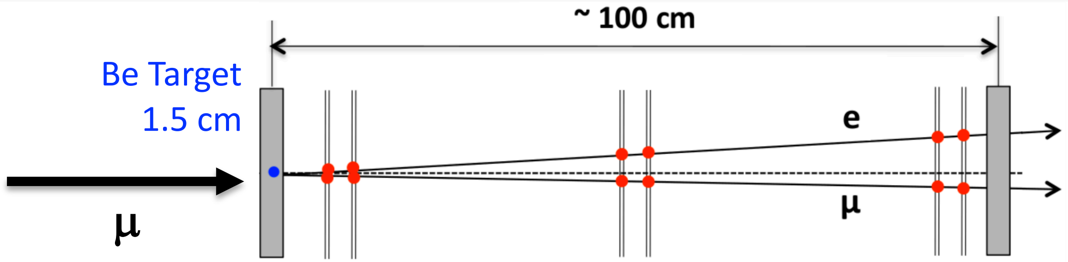
The detector concept is simple, the challenge is to keep the systematics at the same level as the statistical error .

- 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

➢ 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





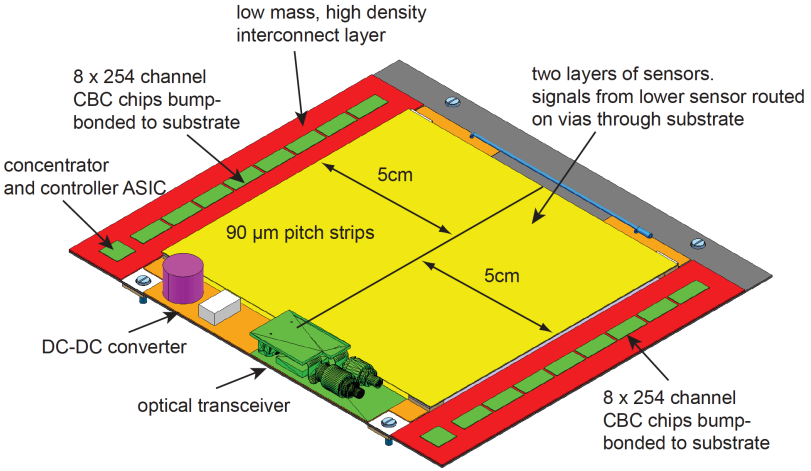
incoming μ direction measured by the previous module

Tracking: 3 pairs of Si layers with orthogonal strips

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

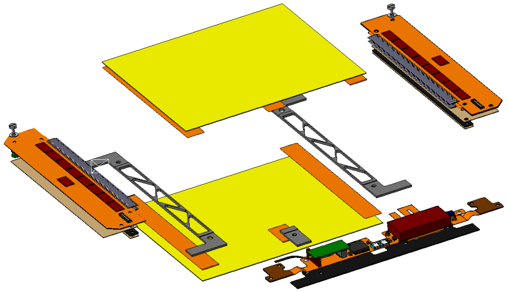
Detector choice: CMS-upgrade Outer Tracker 2S

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

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

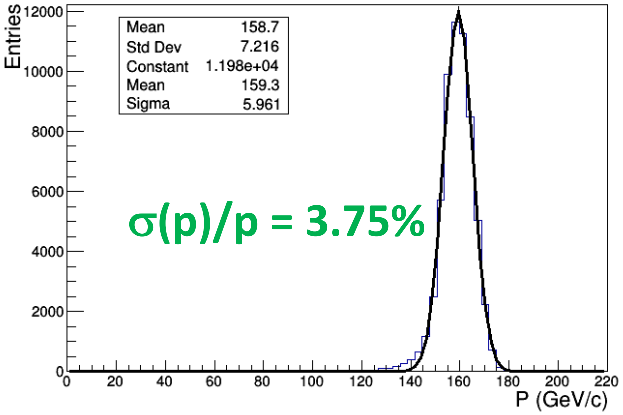
MAIN Difference w.r.t. LHC operation: signal is asynchronous while sampling has fixed clock at 40MHz -> can be overcome with a specific configuration of the FE

Location @ CERN & M2 beam parameters

MUonE Letter-Of-Intent SPSC-I-252

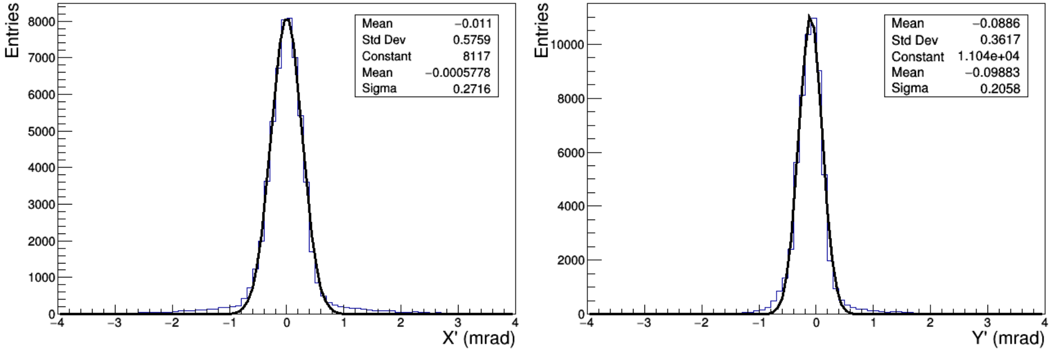
Upstream of the COMPASS detector, after its Beam Momentum Station (BMS), on the M2 beam line : available ~ 40 m

Beam Momentum

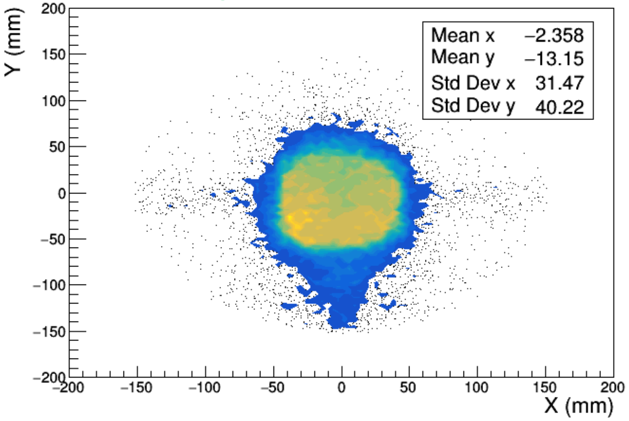


$\sigma(p)/p = 3.75\%$

Very small divergence ~0.2-0.3 mrad



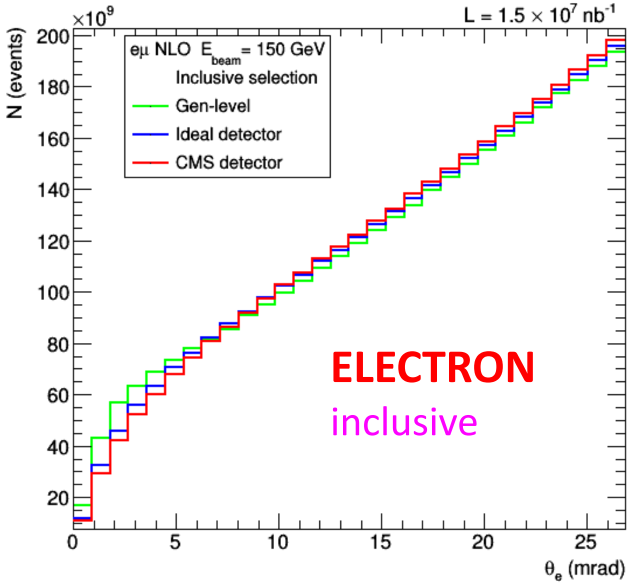
Beam spot size $\sigma_X \sim \sigma_Y \sim 3$cm

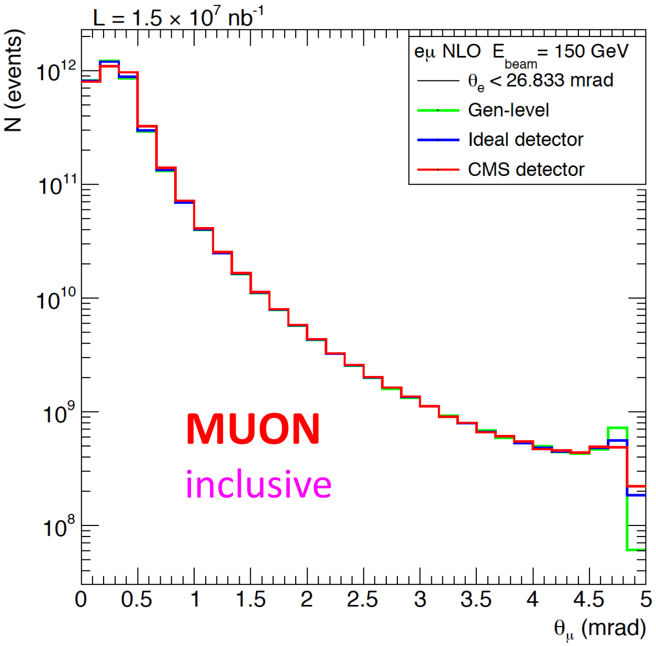


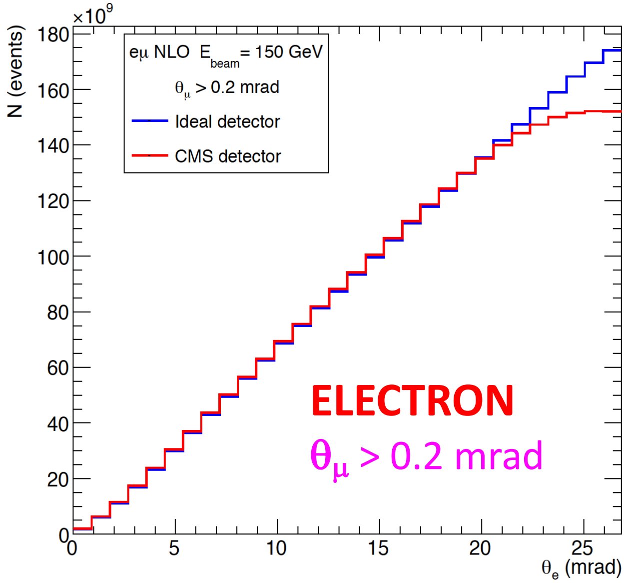
M2 beam typical max intensity: 5×10^7 μ/s

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

NLO Angular distributions

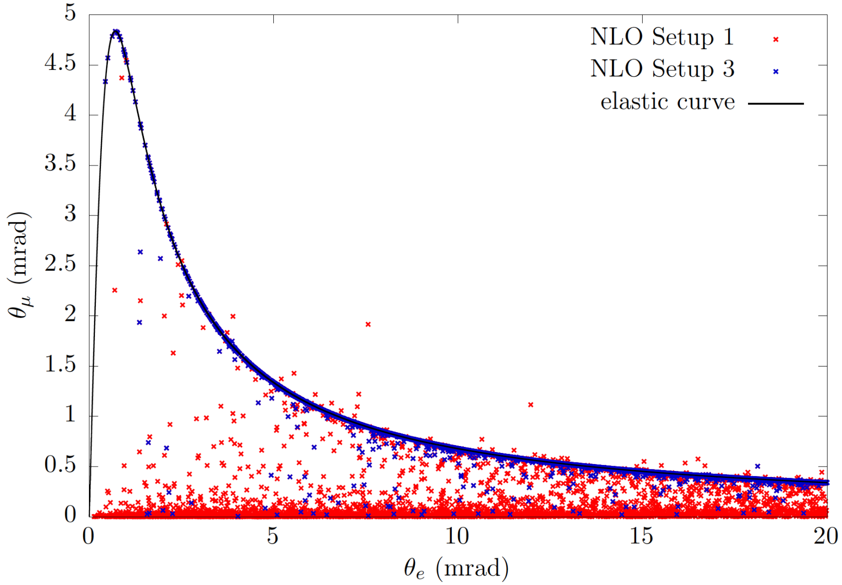






Event yield ~10^{12} (Ee>1 GeV) for the nominal integrated Luminosity L = 1.5 x 10^7 nb^{-1}

NLO MC and elastic selection



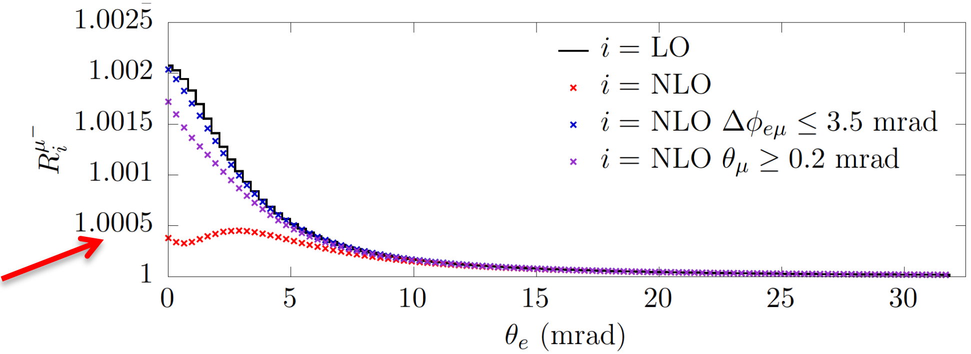
[M.Alacevich et al, JHEP02(2019)155](#)

NLO:

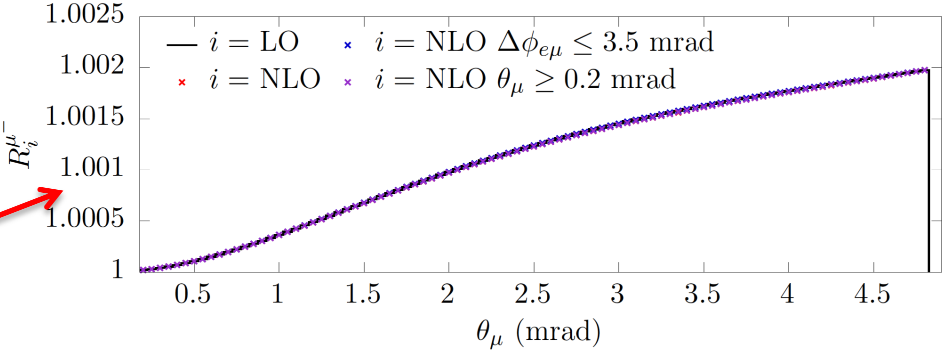
Setup 1 is the inclusive selection (no cuts)

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)



$\Delta\alpha_{had}$ parameterization

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

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

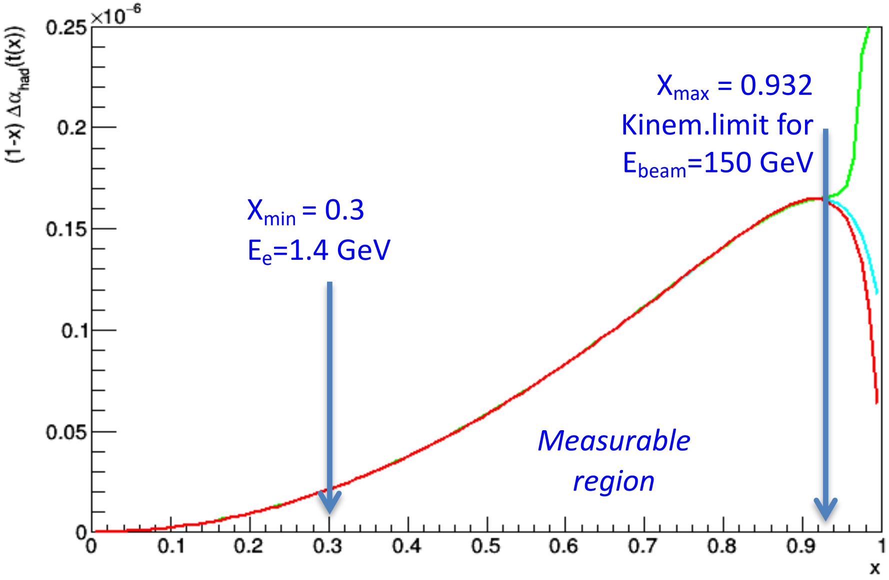
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

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

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

a_μ^{HLO} calculable from the master integral in the FULL phase space with this parameterization.

Instead simple polinomials diverge for x->1 (green is a cubic polinomial in t)



X_{max} = 0.932
Kinem.limit for
E_{beam}=150 GeV

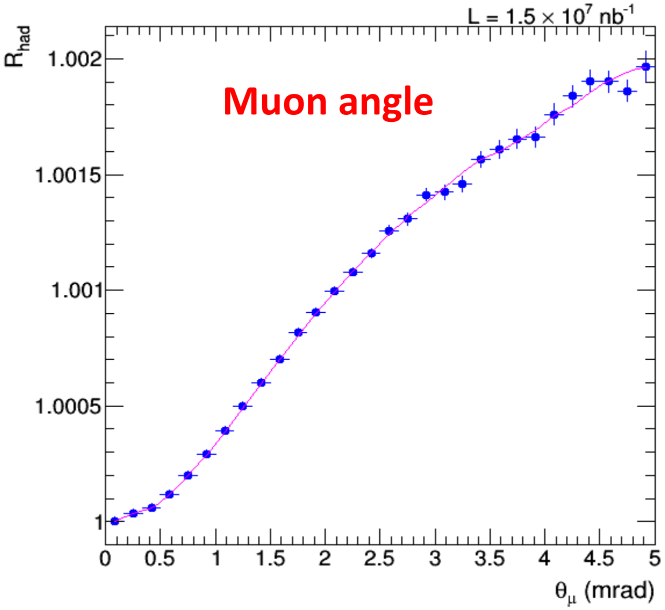
X_{min} = 0.3
E_e=1.4 GeV

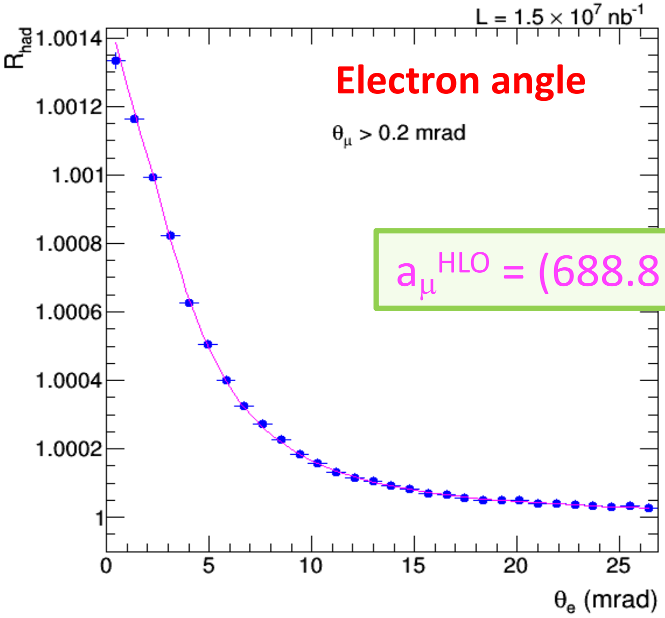
Measurable region

Extraction of the hadronic running of α

Most easily displayed by taking ratios of the observed angular distributions and the theory predictions evaluated for $\alpha(t)$ corresponding to only the leptonic running.
Observable effect ~ 10^{-3} / wanted precision ~10^{-2} → required precision ~10^{-5}

Example toy experiment shown with statistics corresponding to the nominal integrated Luminosity L = 1.5×10^{7} nb^{-1} (corresponding to 3-year run)





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

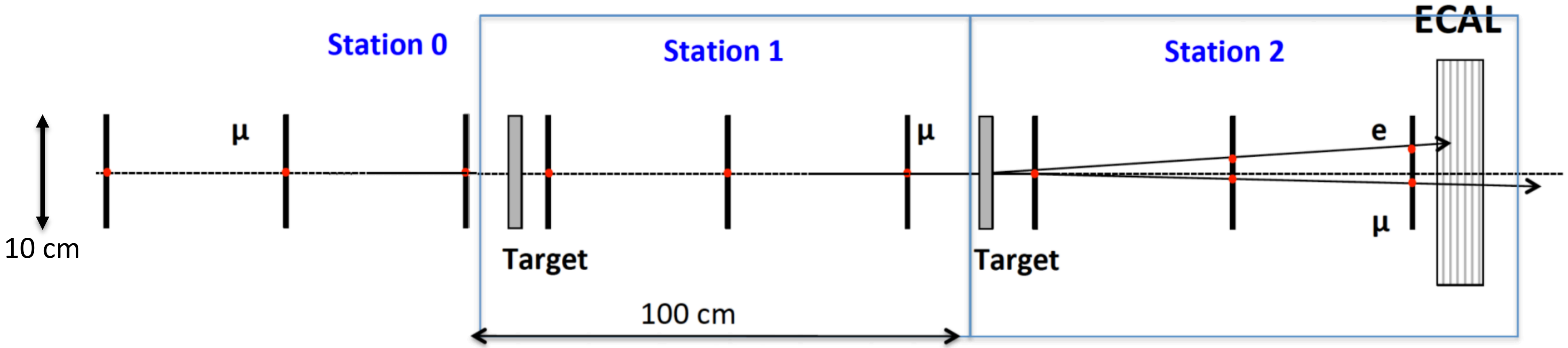
Stat.err.
0.35%

Template fit to the 2D angular distribution from NLO MC generator with parameterised detector resolution.
$\Delta\alpha_{had}(t)$ parameterised according to the "Lepton-Like" form. Shape-only χ^2 fit.

Test Run setup

To be held at CERN in 2022: 3 weeks allocated with full intensity μ beam

Location: M2 beam line, upstream of the COMPASS detector, after its BMS (available ~40 m)

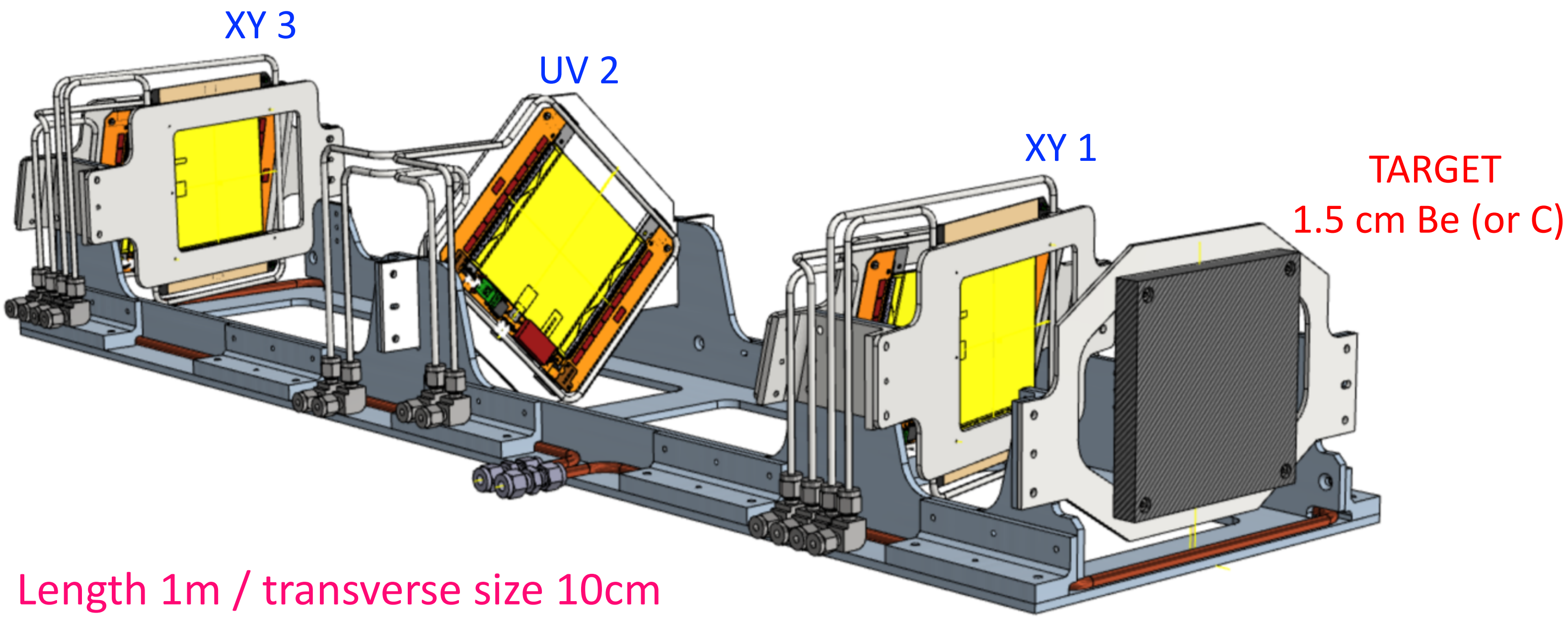


Main objectives:

- Confirm the system engineering
- Check mechanical and thermal stability.
- Test the alignment procedure
- Assess the detector counting rate capability.
- Check the DAQ system.
- Validate the trigger strategy (FPGA real-time processing to identify and reconstruct μ−e events).
- Assess the systematic errors
- After commissioning, take data to measure the leptonic contribution to the running of $\alpha(q^2)$.

If the results are satisfactory proceed to full-scale experiment to be deployed during LHC Run3

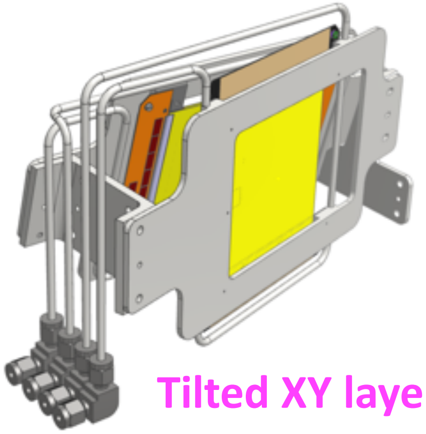
MUonE tracking station



Length 1m / transverse size 10cm
Target followed by 3 tracking layers:
each one is a pair of close-by 2S modules
with orthogonal strips, tilted by 233mrad

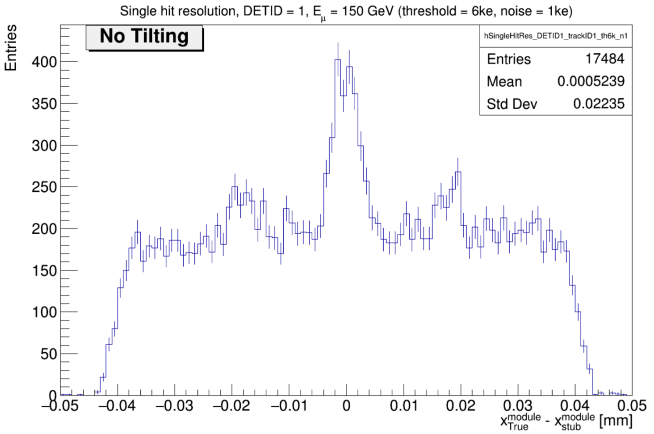
Stringent request: relative positions within the station stable to better than 10μm

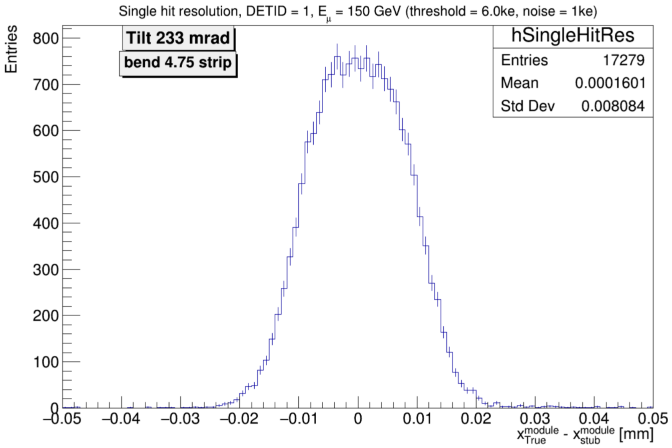
Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni)
Cooling system, tracker enclosure, Room temperature stabilized within 1-2 °C



Tilted XY layers

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

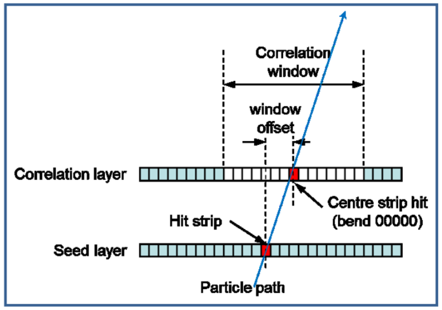
Further improvement: a small tilt of 25mrad is equivalent to an half-strip staggering of the two sensor layers of a 2S module

Final resolution:

22 μm → 8-11 μm

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

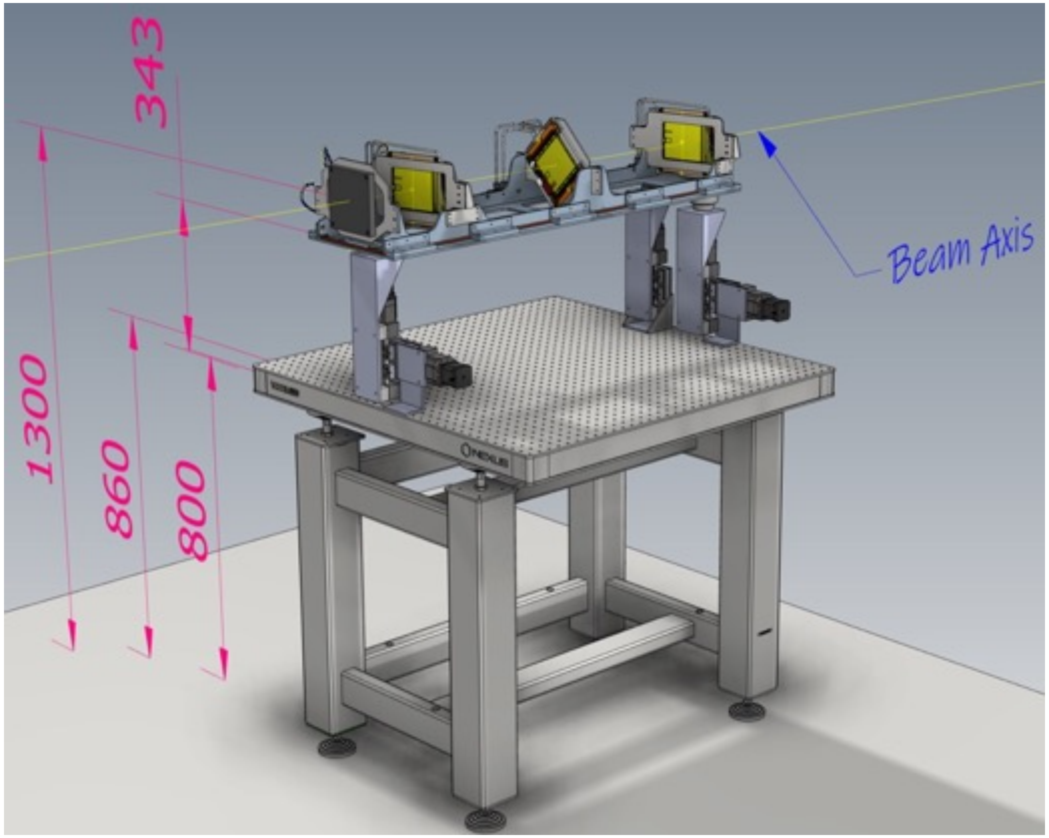
measured coordinate (x) determined by hit position on one layer and direction of the track stub



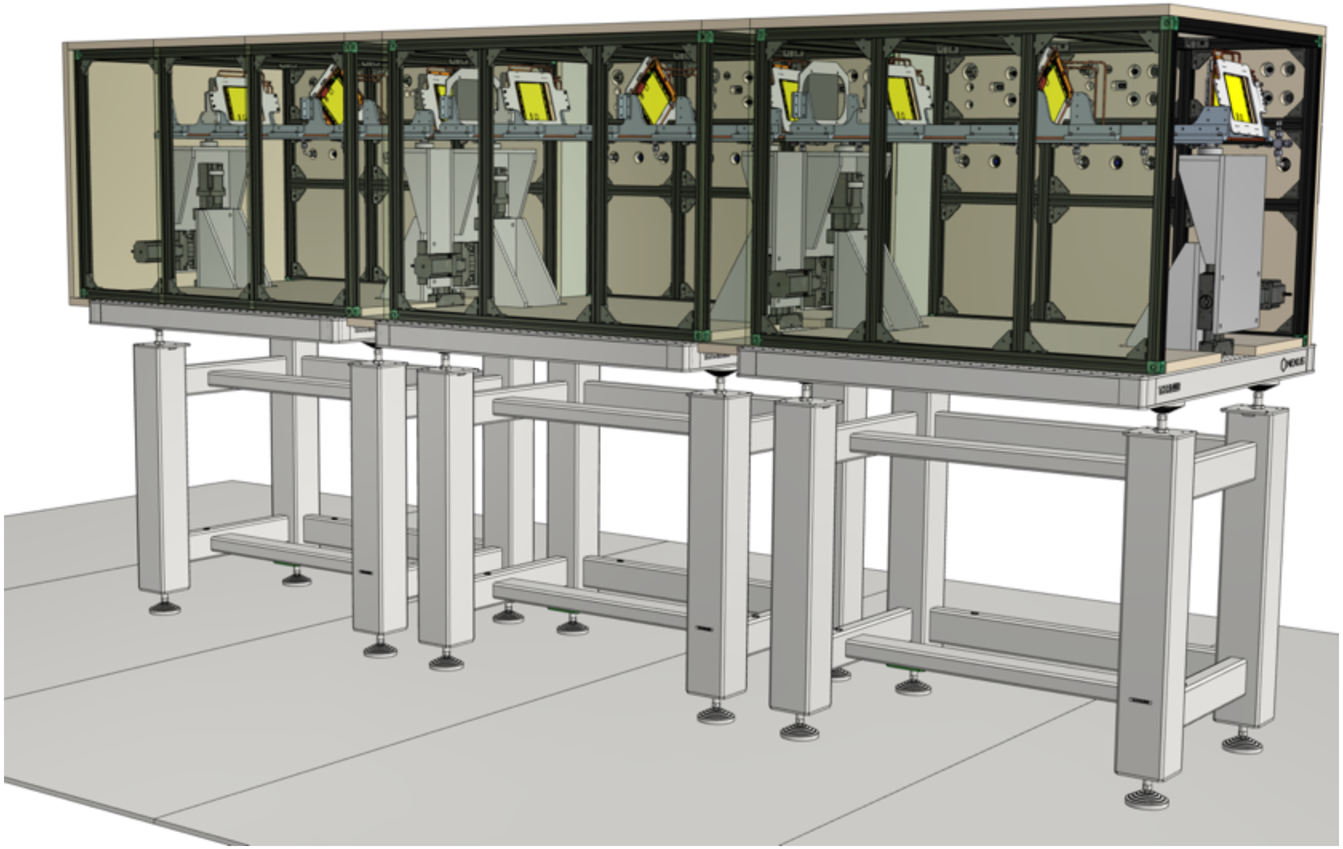
Tracker mechanics

Two aluminium mockups have been built: test mounting of dummy stations, planarity, alignment, cooling system, precision movement system and holographic system

Each station's position/orientation will be precisely adjustable with 3 motorized linear stages allowing to shift on X, Y axes by up to 3cm in steps of 5 μm (by kinematic coupling)



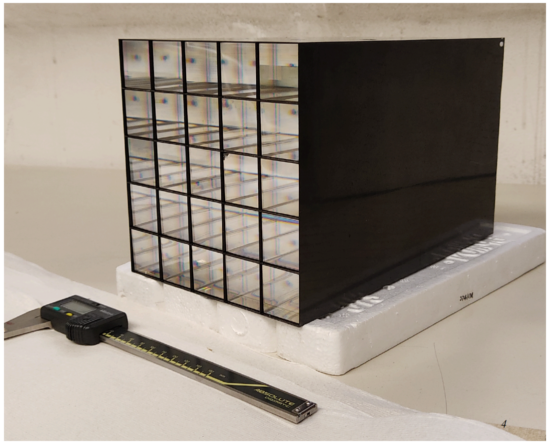
Tracker mechanics (2)



- Tracker enclosure shielding from light and to stabilise thermally
- Electrical, optical and hydraulic connections on the top, removable side panels
- Further complemented by a surrounding tent containing also the calorimeter, with chiller stabilising the room temperature

Calorimeter

PbWO4 crystals used by the CMS ECAL
Small 5x5 array, size 14x14 cm^2, length 22cm (24.7 X_0)



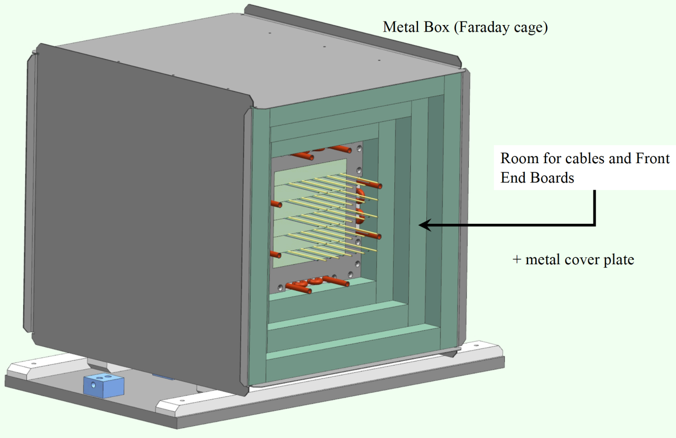
Mechanics: Carbon fiber alveolar structure with

- cooling system
- thermal insulation by polyurethane rigid foam panels and temperature control (ΔT <~ 0.1 °C)
    - Both crystal light yield and APD gain depend on temperature: (≈ −2%/◦C for the crystals, and ≈ −4%/◦C for the APDs)
- all cables and fibers on the back face
- movable with mm precision in the two axes perpendicular to beam

Hamamatsu APD sensor (1 cm^2)

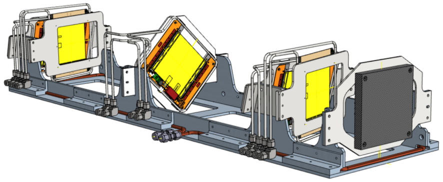
FE electronics linking with Serenity board for DAQ

Laser calibration /monitoring system for APD and FEE gain



DAQ

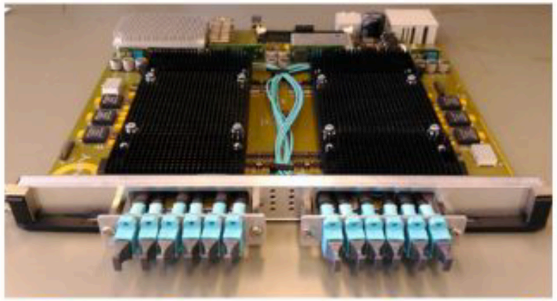
Tracker: event size ~1kb



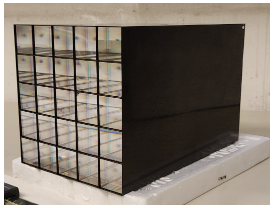
35 Gbps total

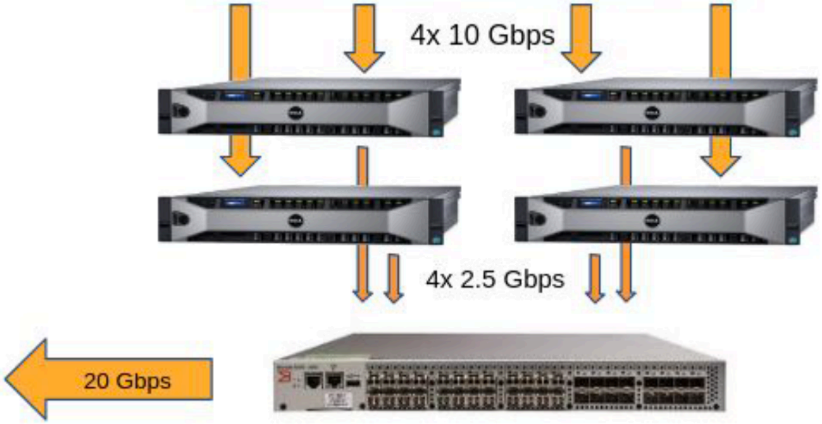
in-spill

DAQ heart: SERENITY board



ECAL (safe factor 2)





SPS Duty cycle ~0.25

Test Run:
~0.5 PB of data

Plan for the Test Run: **NO online selection, read out all data (3 stations)**

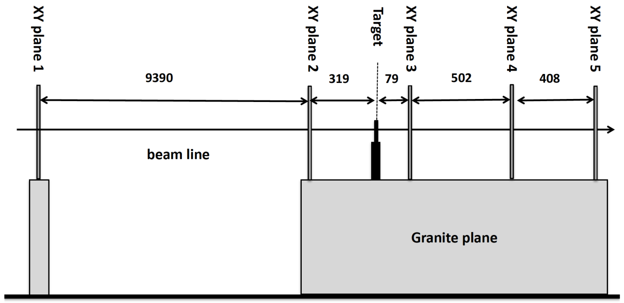
FPGA algos will be run online just to tag events and replayed offline for detailed studies

Data taking for ~two weeks, SPS efficiency ~2/3 → **~0.5 PB of data**

The Test Run will be a proof of concept for the MUonE DAQ

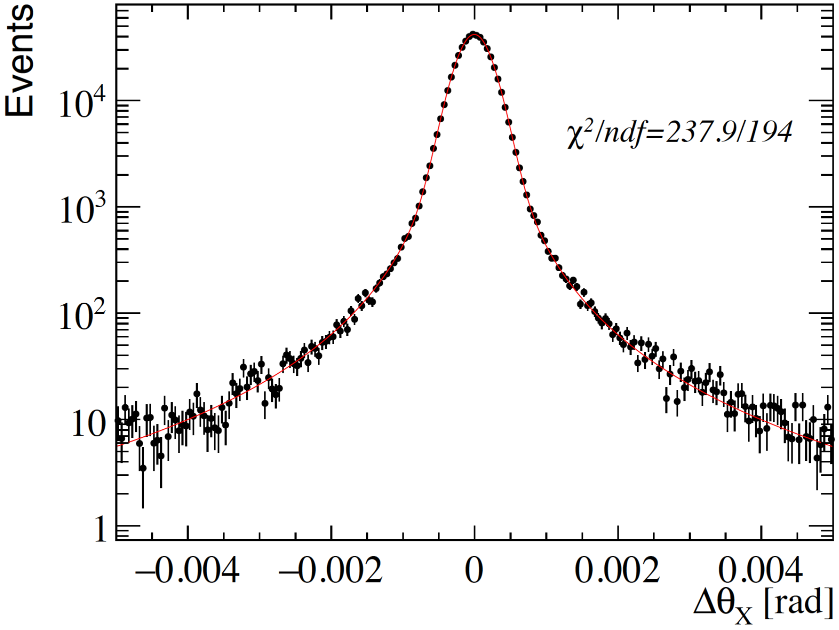
2017 Beam Test: Multiple Coulomb scattering

Studied in a Beam Test in 2017:
[JINST 15 (2020) P01017]()
12–20 GeV electrons
on 8-20 mm C targets

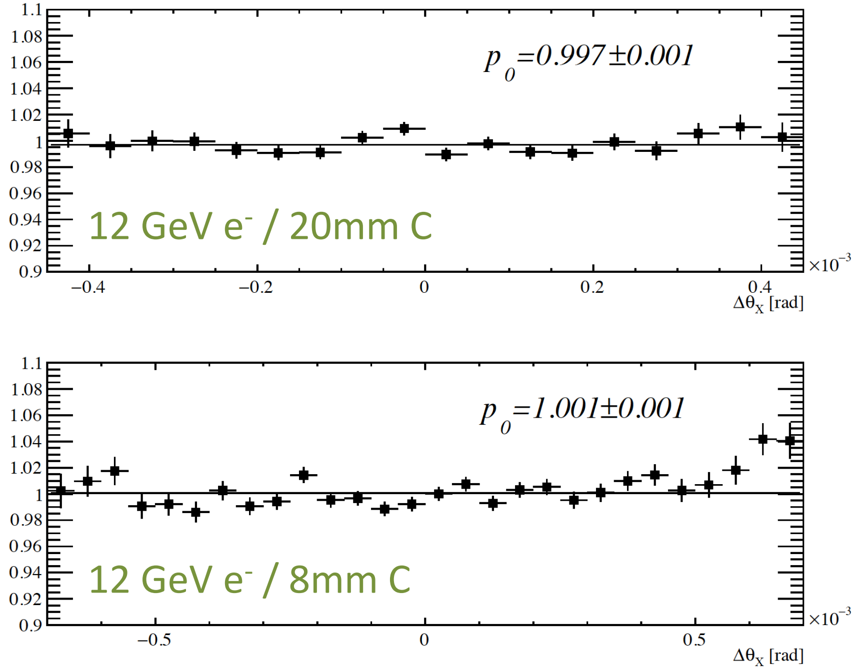


Adapted UA9
detector at CERN
H8 Beam Line

DATA 12 GeV e- / 8mm C



DATA/MC (Geant4) comparison



- Good description of data with a fit.
- Distribution core within 1-few % from GEANT.

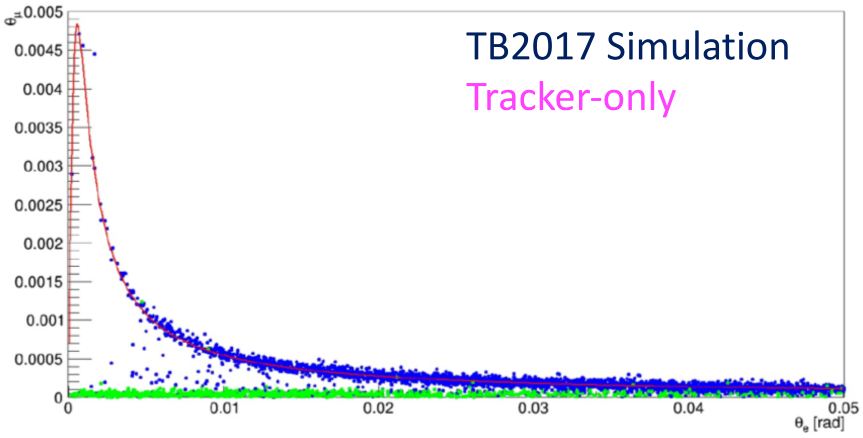
GEANT4 simulations

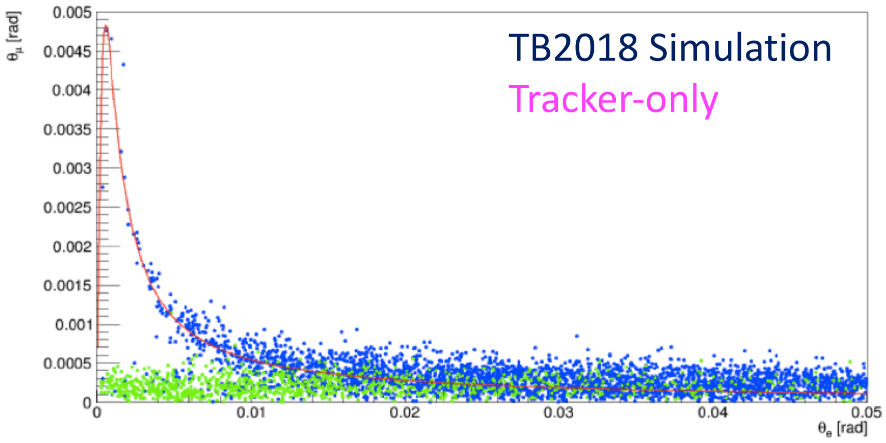
Effect of the tracker position resolution on θ_μ vs θ_e distribution:

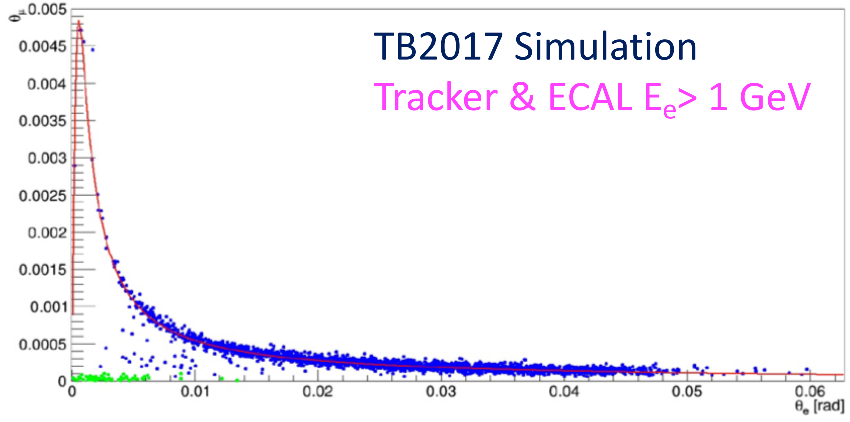
(Left) TB2017: UA9 resolution 7μm ; (Right) TB2018: resolution ~35-40μm

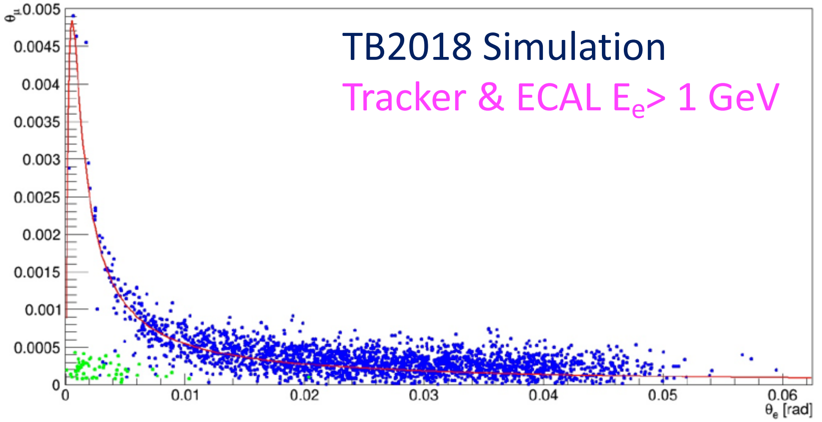
Signal: elastic μe

Background: e^+e^- pair production









2018 Beam Test: μe elastic scattering

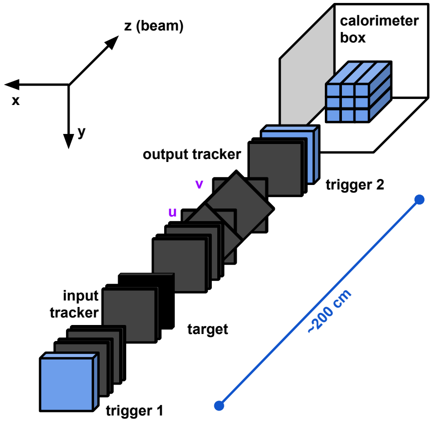
arXiv:2102.11111

CERN North Area, downstream COMPASS

8mm C target

Si strip tracking (sensors from AGILE, with worse resolution than MUonE)

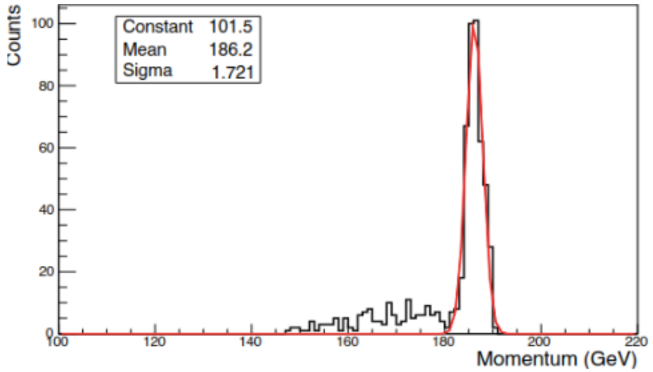
Small BGO ECAL



μ spectrum peaked at 187 GeV

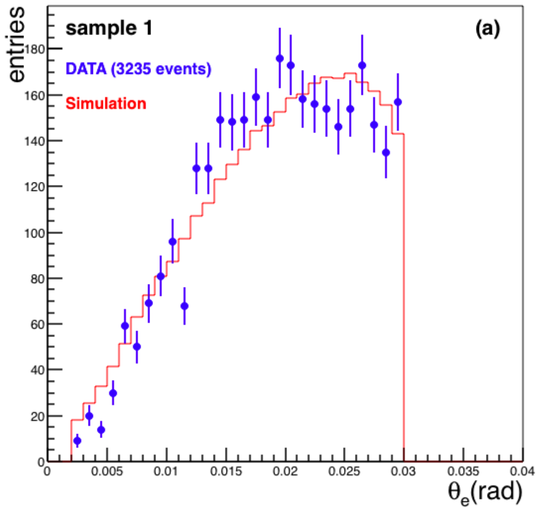
From decays of 190 GeV beam π

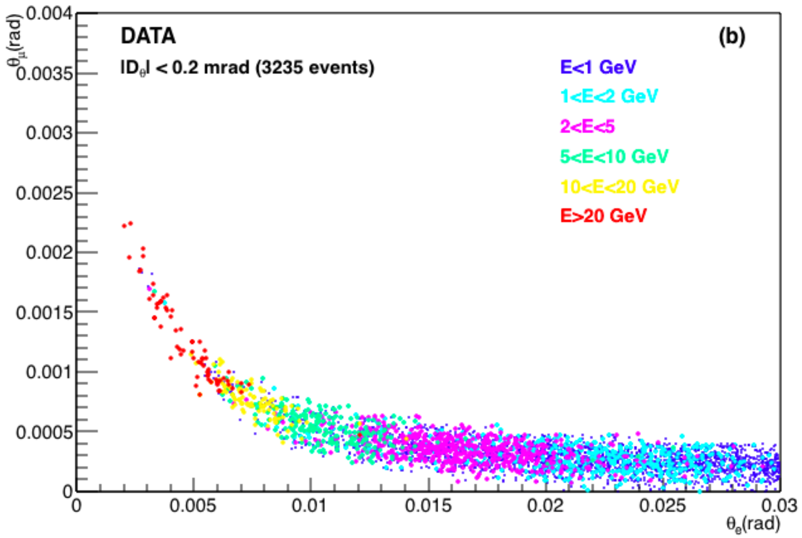
1m W dump absorbing all surviving π



Setup with lower performance than MUonE (σ_X~35μm)

Selection of a clean sample of elastic events





Important: Simulation of Background processes in part. e^+e^- pair production

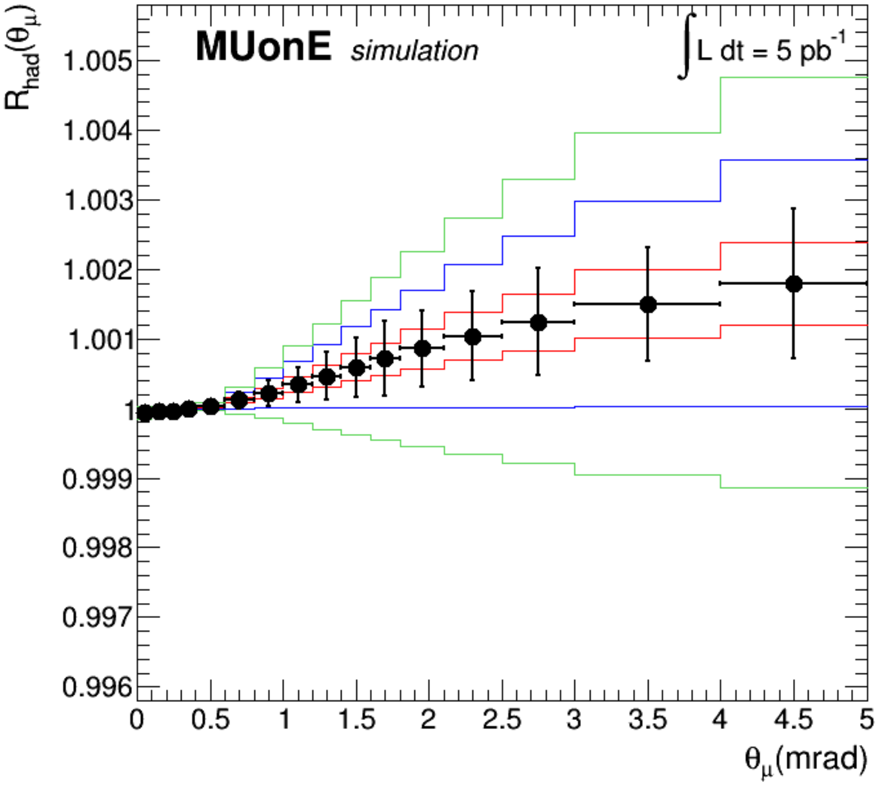
New GEANT4 version 10.7 (validation ongoing)

Expected sensitivity of a First Physics Run

Expected integrated Luminosity with the Test Run setup with full beam intensity & detector efficiency ~ $1 pb^{-1}$/day

In one week ~$5pb^{-1}$ → ~10^9 μe scattering events with $E_e > 1$ GeV ($\theta_e < 30$ mrad)

arXiv:2012.07016



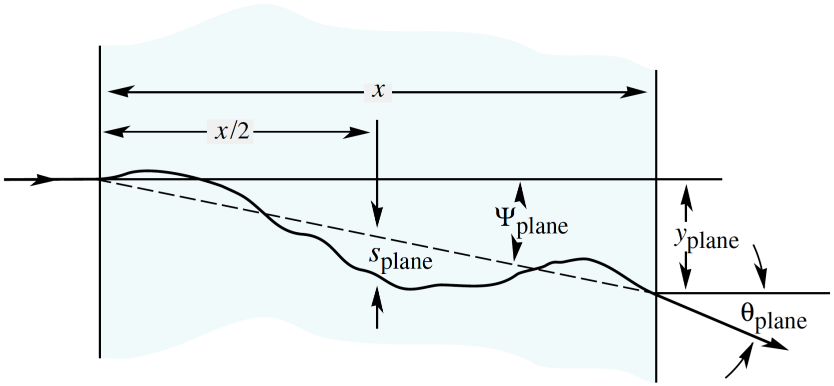
Initial sensitivity to the hadronic running of α.

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)

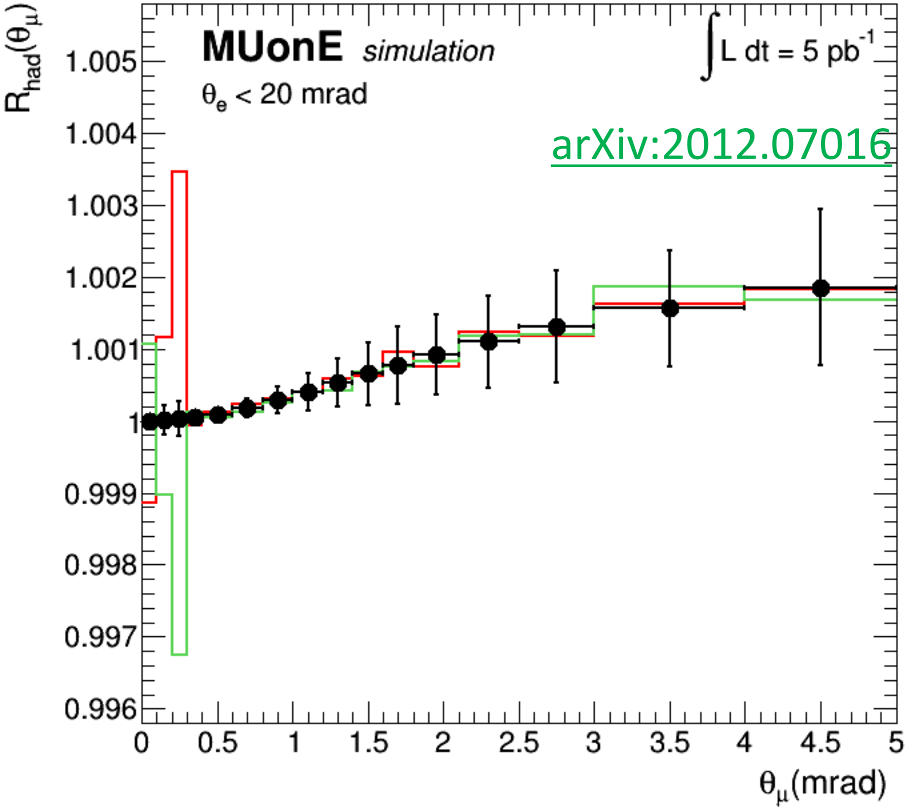
Template fit with just one fit parameter K= k/M in the $\Delta\alpha_{had}$ parameterization.
The other parameter fixed at its expected value: M = 0.0525 GeV^2

Systematic Effects: Multiple Coulomb Scattering



Particle trajectories disturbed: especially low-energy electrons

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



arXiv:2012.07016

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

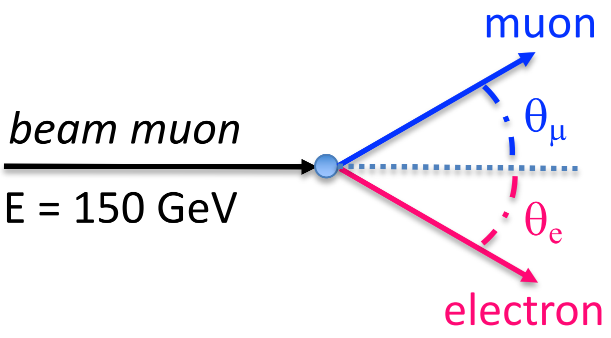
Systematic Effects: Beam Energy scale

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:

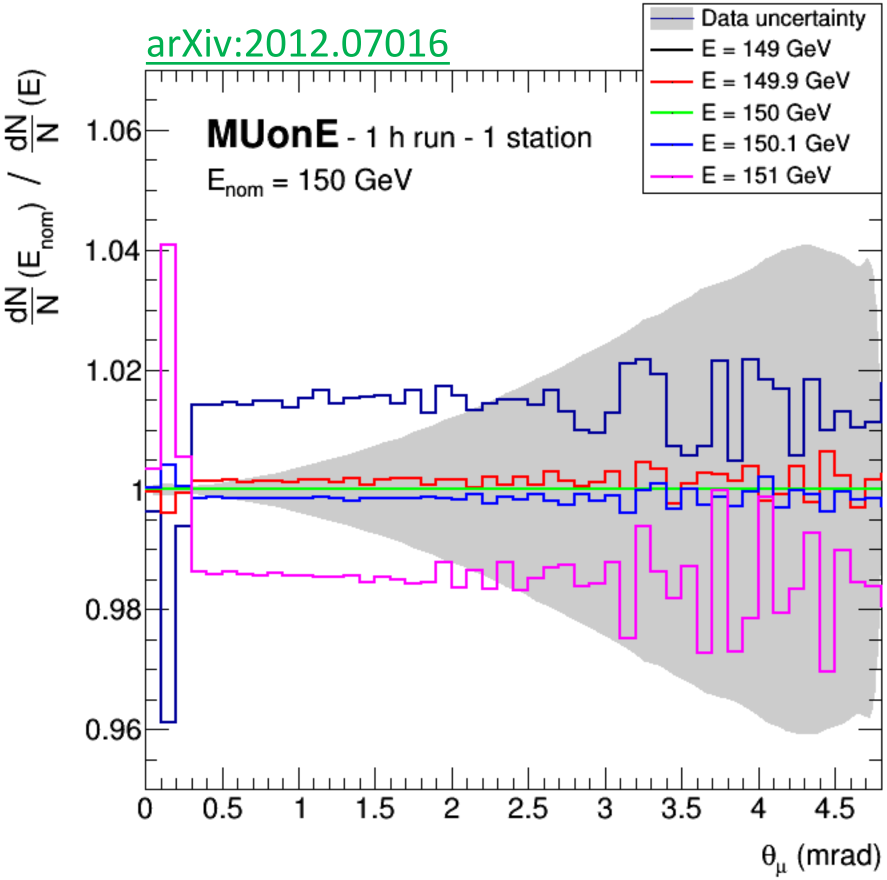
$\theta_\mu = \theta_e \equiv \theta$

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

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

From SPS E scale ~1% : 1.5 GeV

arXiv:2012.07016



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

Theory

Impressive progress

STATUS: report of the **MUonE theory initiative**

"Theory for muon-electron scattering @ 10ppm", P.Banerjee et al, Eur.Phys.J.C80(2020)591

NLO exact calculation including masses (m_μ, m_e) and EWK corrections in a fully differential MC code
M.Alacevich et al, JHEP02(2019)155 cross-checked with independent calculation by Fael & Passera

Full NNLO not yet available

- Two-loop master integrals ($m_e=0$, $m_\mu\neq0$)
  planar P.Mastrolia et al, JHEP11(2017)198 and non-planar S.Di Vita et al, JHEP09(2018)016
- NNLO hadronic corrections: M.Fael,M.Passera, Phys.Rev.Lett.122(2019)192001; M.Fael, JHEP02(2019)027
- Framework to recover leading m_e terms at NNLO from amplitudes calculated with massless electrons:
  T.Engel et al., JHEP02(2019)118, JHEP01(2020)085
- Two independent fully exclusive NNLO MC codes, featuring the exact NNLO photonic corrections on the leptonic legs, including all mass terms: C.Carloni Calame et al., JHEP11(2020)028; P.Banerjee et al, SciPostPhys.9(2020)027

VERY GOOD AGREEMENT between the two codes

Resummations (Parton shower and YFS) matched to (N)NLO fixed order under way

Study of possible contaminations from NEW physics on MUonE:
A.Masiero, P.Paradisi and M.Passera, Phys.Rev.D102(2020)075013
P.S.Bhupal Dev et al., JHEP05(2020)53

→ **MUonE is NOT vulnerable !**

Status / plans for the Test Run

- **Tracker:** delays (few months) in the procurement of the 2S modules (bottleneck: hybrids' production) due to Covid-19
  - Unlikely to have more than one MUonE tracking station fully integrated and ready for beam test in Fall 2021
  - Situation still subject to unpredictable changes
- **Calorimeter**: tight schedule but original plan still feasible
- **DAQ**: good progress, but partly related to the availability of tracker modules

MUonE plans to start the beam tests at the end of 2021 even with a partial setup

- *In this case with reduced objectives, mainly detector commissioning in real conditions of beam and environment*
- *The Test Run will be completed in 2022*

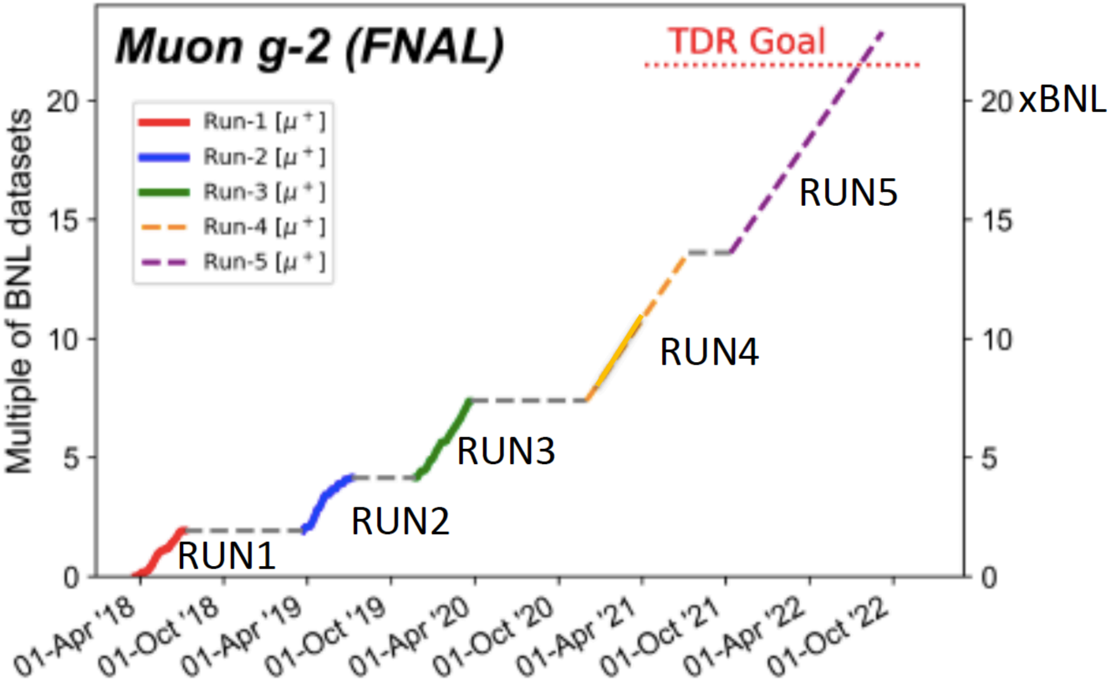
Summary

- **Long-standing puzzle of muon g-2:**
  - Experiment-Theory(SM) discrepancy 4.2σ
  - sensitive to BSM physics
  - Ongoing/future experiments will reduce the exp.error by a factor of ~4
  - Theory error dominated by the LO Hadronic vacuum polarization contribution $a_\mu^{HVP,LO}$
  - A new Lattice QCD calculation weakens the discrepancy but is in tension with the current SM prediction
- **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 Eur.Phys.J.C77(2017)139
  - 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 puzzle
- Letter-Of-Intent SPSC-I-252 submitted to CERN in June 2019
- **CERN has recognized the fundamental interest** and **approved a Test Run (to be held in 2021-22), which should verify the detector design and assess the potential to achieve a competitive measurement, as a condition to move on towards the full-scale experiment.**
  - Main challenge: control of systematic effects at the level of the statistical precision
- Full-scale experiment foreseen during LHC Run3 (2022-2024) if results of the Test Run are satisfactory

BACKUP

Future @FNAL

- RUN1 is only 6% of the final dataset
- Analysis of RUN2/3 (expect an improvement of a factor ~2 in precision)
- RUN4 (November 2020-July 2021) is expected to bring the statistics to ~13 BNL
- RUN5 in 2021-2022 should allow to achieve the x20 BNL project goal



Electron g-2

- Naïve scaling for BSM physics: $\frac{\Delta a_e}{\Delta a_\mu} = \frac{m_e^2}{m_\mu^2} = 2.5\times10^{-5} \rightarrow \Delta a_e = 0.6\times10^{-13}$
- Experimental error on the electron g-2: 2.8×10^{-13}
- Theory prediction much less affected by hadronic contributions, currently insensitive to shifts to the low energy cross sections
- Theory error on electron g-2 dominated by precision of α
  - in fact the $(g\text{-}2)_e$ was used to determine α
  - Recently two direct measurements of α based of atomic interferometry (Cs, Rb) have become more precise (**Rb: 81 ppt** !)
  - Unfortunately they differ by more than 5σ
  - $\Delta a_e = a_e^{EXP} - a_e^{TH}(Cs) = (-8.9 \pm 3.6)\times10^{-13}$ $\rightarrow -2.5\sigma$
  - $\Delta a_e = a_e^{EXP} - a_e^{TH}(Rb) = (+4.7 \pm 3.0)\times10^{-13}$ $\rightarrow +1.6\sigma$
- Future: expected improvements to the measurements of a_e and α

New measurement of α at 81ppt

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Article

Determination of the fine-structure constant with an accuracy of 81 parts per trillion

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The standard model of particle physics is remarkably successful because it is consistent with (almost) all experimental results. However, it fails to explain dark matter, dark energy and the imbalance between matter and antimatter in the Universe. Because discrepancies between standard-model predictions and experimental observations may provide evidence of new physics, an accurate evaluation of these predictions requires highly precise values of the fundamental physical constants. Among them, the fine-structure constant α is of particular importance because it sets the strength of the electromagnetic interaction between light and charged elementary particles, such as the electron and the muon. Here we use matter-wave interferometry to measure the recoil velocity of a rubidium atom that absorbs a photon, and determine the fine-structure constant $\alpha^{-1} = 137.035999206(11)$ with a relative accuracy of 81 parts per trillion. The accuracy of eleven digits in α leads to an electron g factor[1,2]—the most precise prediction of the standard model—that has a greatly reduced uncertainty. Our value of the fine-structure constant differs by more than 5 standard deviations from the best available result from caesium recoil measurements[3]. Our result modifies the constraints on possible candidate dark-matter particles proposed to explain the anomalous decays of excited states of ^{8}Be nuclei[4] and paves the way for testing the discrepancy observed in the magnetic moment anomaly of the muon[5] in the electron sector[6].

α and a_e

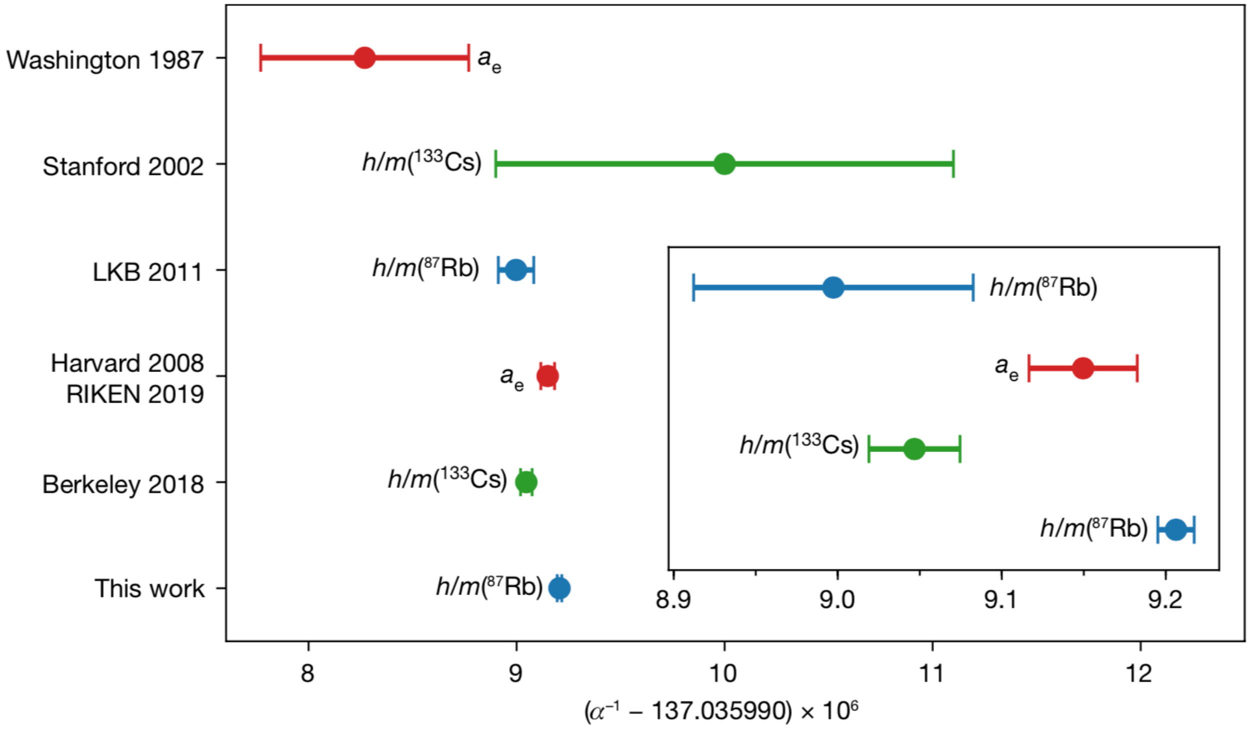
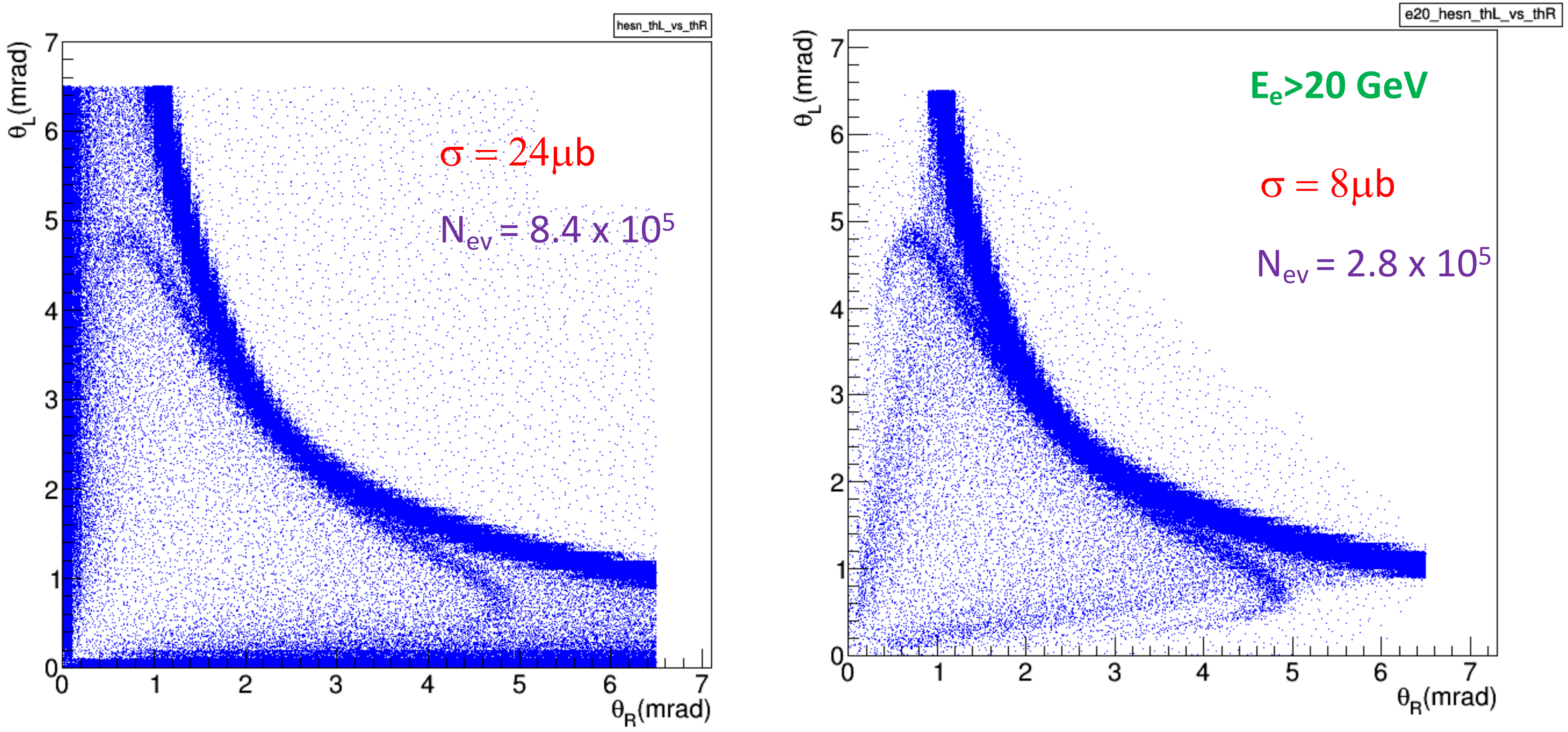


Fig. 1 | Precision measurements of the fine-structure constant. Comparison of most precise determinations of the fine-structure constant so far. The red points are from $g_e - 2$ measurements and QED calculations, and the green and blue points are obtained from measurements of caesium and rubidium atomic recoils, respectively. Errors bars correspond to $\pm 1\sigma$ uncertainty. Previous data are from ref. [34] (Washington 1987), ref. [10] (Stanford 2002), ref. [18] (LKB 2011), ref. [9] (Harvard 2008), ref. [2] (RIKEN 2019) and ref. [3] (Berkeley 2018). Inset, magnification of the most accurate values of the fine-structure constant.

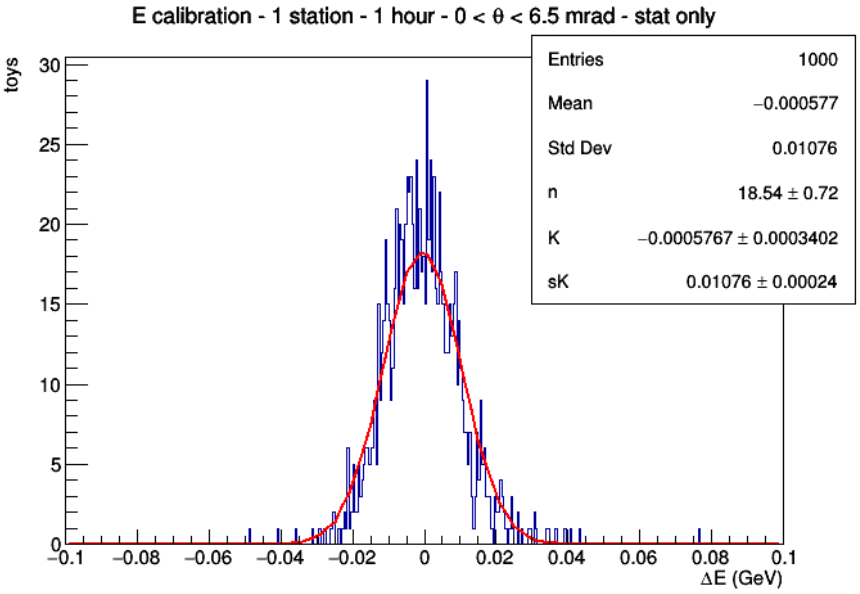
2D angular selection

- θ_L, θ_R < 6.5 mrad
  - Additionally a possible calorimeter cut E_e>20 GeV

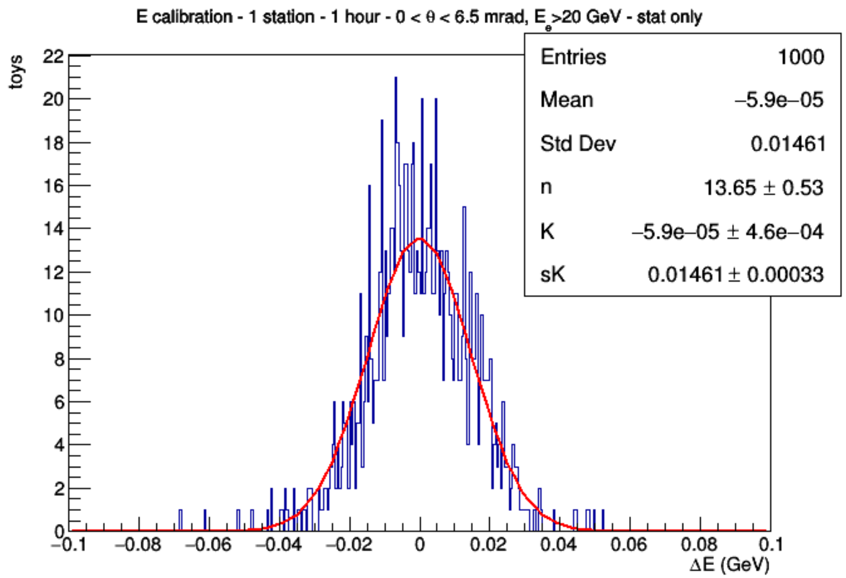


Beam Energy scale: statistical accuracy

- Template fit of (θ_L, θ_R) with Beam energy as fit parameter in the range 150 GeV ±100 MeV.
- Considering 1 hour run time in one station (1.5cm Be) → ~35nb^{-1}
- Angular selection: 0<(θ_L, θ_R)<6.5mrad → 24μb
  - With additional CALO E_e>20 GeV → 8μb
- 1000 toys (each one with 8.4x10^5 / 2.8x10^5 events)



With additional CALO E_e>20 GeV



$\sigma \simeq$ 10.8 MeV Bias ~ 0 $\sigma \simeq$ 14.6 MeV

Beam energy spread

- The beam energy profile has to be known. The M2 energy spread is ~3.75%. Assuming to have the integrated profile corresponding to a given run from the BMS spectrometer. A (very) conservative assumption σ_{BMS}=(1.0±0.5)% gives 19 MeV uncertainty on a 1-hour run on one station and a bias +16 / -5 MeV.
- The assumed BMS uncertainty is pessimistic, so this can certainly be better.
- If the event-by-event energy measurement would be available the impact of the energy spread could be effectively reduced by cutting the tails of the energy distribution, selecting only the central core.

Beam energy calibration (1hour-1station)

Preliminary summary of statistical and systematic uncertainties and biases from different sources (educated guess), estimated for a 1-hour run on one station. Increasing the running time all the uncertainties scale with statistics. Biases stay constant.

		ANGULAR SELECTION θ_L, $\theta_R < 6.5$ mrad		**ANGULAR SELECTION and CALO $E_e > 20$ GeV**	
		Bias (MeV)	Uncertainty (MeV)	Bias (MeV)	Uncertainty (MeV)
STATISTICAL	1hour / 1station	**-**	**11**	**-**	**15**
Longitudinal size	+10μm	**+3**	**-**		
	-10μm	**-3**	**-**		
Intrinsic Angular Resolution	+5%	**-3**	**8**		
	-5%	**+2**	**6**		
Beam Energy spread	BMS resolution +50%	**+16**	**14**		
	BMS resolution -50%	**-5**	**19**		
Multiple Coulomb Scattering	Target thickness +2%	**+7**	**15**	**+1**	**7**
	Target thickness -2%	**-3**	**13**	**0**	**5**
TOTAL		**+28 / -14**	**28**	**+22/-11**	**26**

Beam energy calibration (4days-1station)

Preliminary summary of statistical and systematic uncertainties and biases from different sources (educated guess), estimated for 4-days (100 h) run on one station.

		ANGULAR SELECTION θ_L, θ_R < 6.5 mrad		**ANGULAR SELECTION and CALO E_e>20 GeV**	
		Bias (MeV)	Uncertainty (MeV)	Bias (MeV)	Uncertainty (MeV)
STATISTICAL	1hour / 1station	**-**	**1.1**	**-**	**1.5**
Longitudinal size	+10µm	**+3**	**-**		
	-10µm	**-3**	**-**		
Intrinsic Angular Resolution	+5%	**-3**	**0.8**		
	-5%	**+2**	**0.6**		
Beam Energy spread	BMS resolution +50%	**+16**	**1.4**		
	BMS resolution -50%	**-5**	**1.9**		
Multiple Coulomb Scattering	Target thickness +2%	**+7**	**1.5**	**+1**	**0.7**
	Target thickness -2%	**-3**	**1.3**	**0**	**0.5**
TOTAL		**+28/-14**	**2.8**	**+22/-11**	**2.6**

Acoplanarity

There are several possible quantities related to the deviation of a given event from perfect coplanarity. They have different properties and numerically are very different.

Let $\mathbf{i}$, $\mathbf{m}$, $\mathbf{e}$ be unit vectors respectively along the directions of the incoming muon, the outgoing muon and the outgoing electron.

1) Triple product $T = \mathbf{i} \cdot \mathbf{m} \times \mathbf{e}$

(used by NA7; geometrically the volume of the parallelepiped defined by the three vectors)

2) Angle between the incoming muon and the plane of the outgoing particles $(\mathbf{m}, \mathbf{e})$

$$\mathrm{A} = \frac{\pi}{2} - \cos^{-1}\left(\frac{\mathbf{i} \cdot \mathbf{m} \times \mathbf{e}}{|\mathbf{m} \times \mathbf{e}|}\right)$$

3) Angle between the scattering planes formed by the outgoing particles with the incoming muon

$$\mathrm{A}_{\Phi} = \pm\left[\pi - \cos^{-1}\left(\frac{(\mathbf{i} \times \mathbf{m}) \cdot (\mathbf{i} \times \mathbf{e})}{|\mathbf{i} \times \mathbf{m}|\,|\mathbf{i} \times \mathbf{e}|}\right)\right] \text{ for } \begin{bmatrix} \mathrm{T} > 0 \\ \mathrm{T} < 0 \end{bmatrix}$$

Notice: A_{Φ} tests also that the outgoing electron and muon are directed on opposite sides in the transverse plane, while T and A do not depend on this.

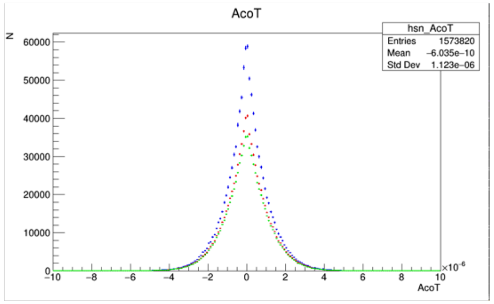
- ➢ this can provide significantly different power in suppressing the backgrounds, in particular also the pair production

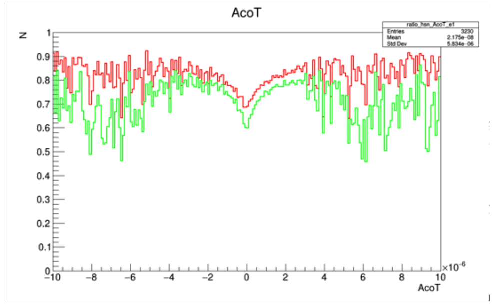
Acoplanarity

Blue: All Events
Red: Electron E>1 GeV
Green: Electron E> 2 GeV

Ratios: E>X / All

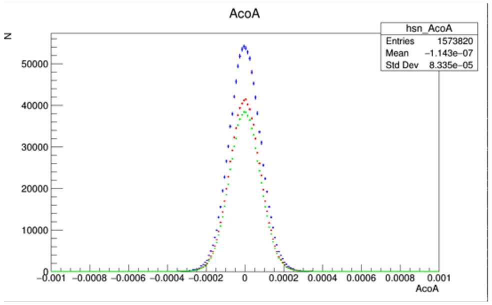
T

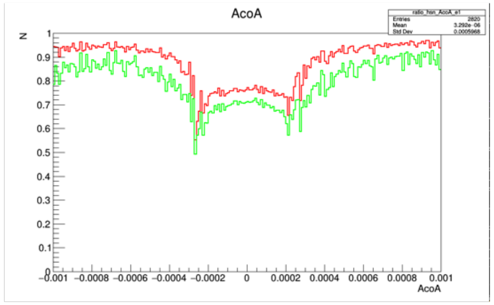




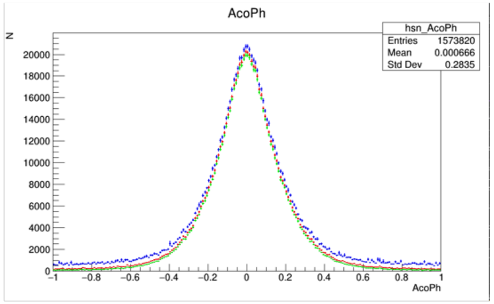
Energy cuts give unwanted pathological effects on T and A

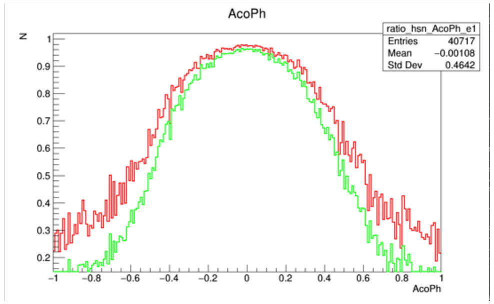
A





A_Φ



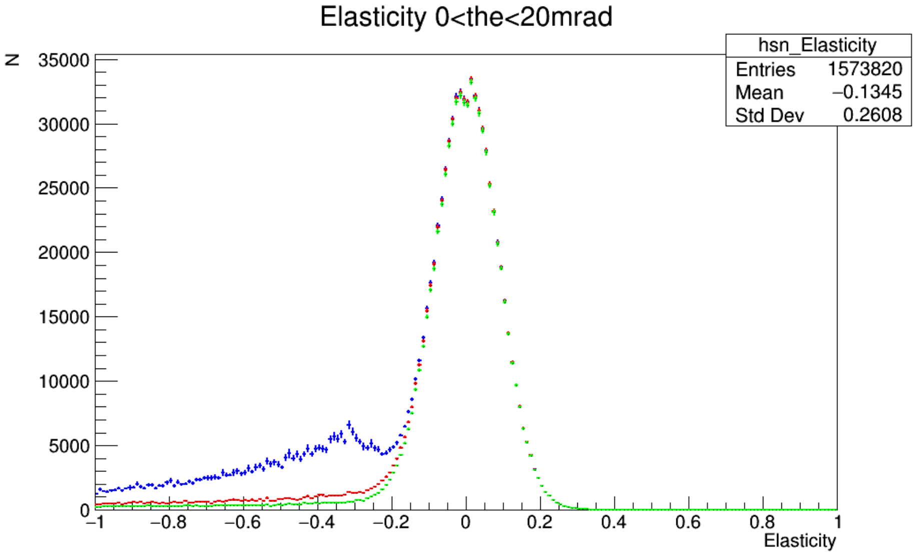


Good behaviour

Elasticity

The angular distance of a given event defined by the two angles P=(θ_e,θ_μ) from the nearest point C on the curve corresponding to the elastic scattering (at a given c.m.s. energy) can be taken as a measurement of the elasticity of the event

- ideally for perfect elasticity D=0



Blue: All Events

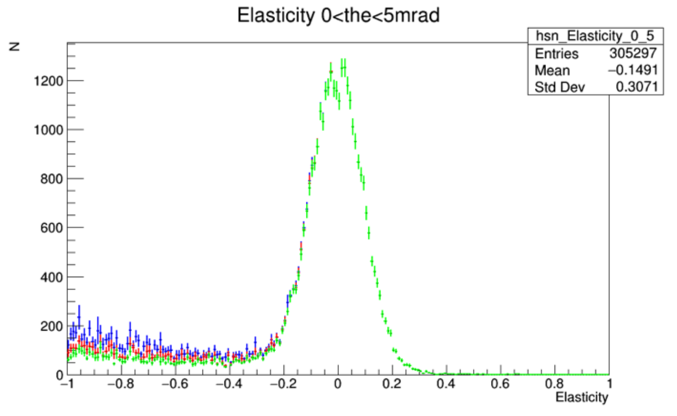
Red: Electron E>1 GeV

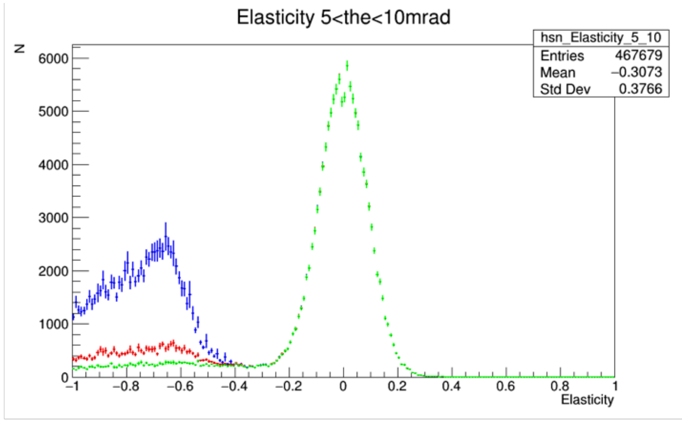
Green: Electron E> 2 GeV

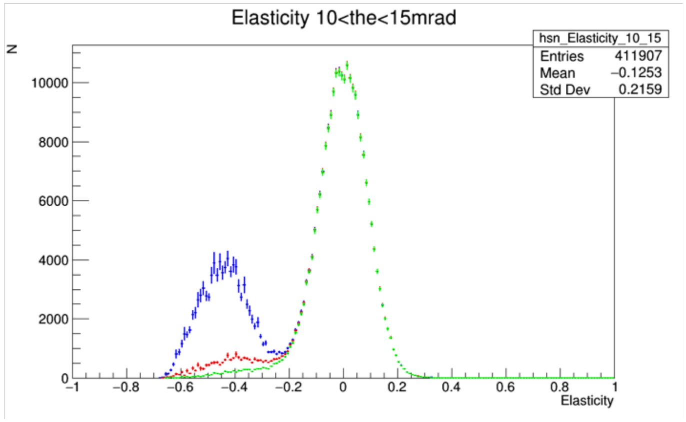
The left tail from radiative and detector smearing effects is effectively removed by energy cuts

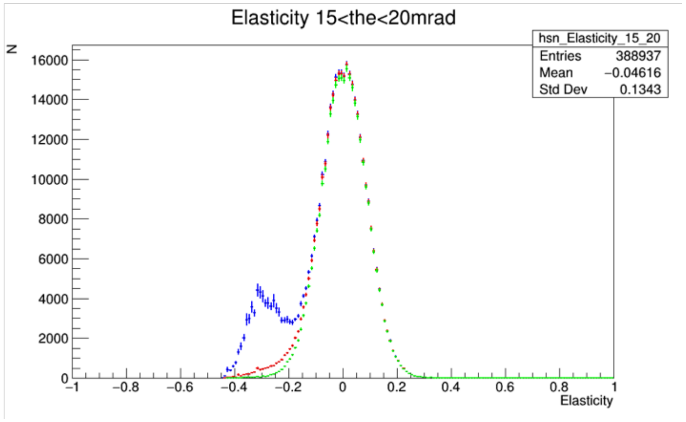
Elasticity - angular regions

Blue: All Events
Red: Electron E>1 GeV
Green: Electron E> 2 GeV









The left tail appears differently in different angular regions but is always effectively suppressed by energy cuts