Status of the MUonE experiment

Giovanni Abbiendi

(INFN Bologna)

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Muon anomalous magnetic moment

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

Dirac eq : $g_l = 2$
Quantum corrections → the anomaly

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

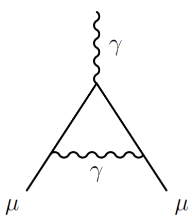
This observable can be both precisely measured experimentally and predicted in the Standard Model, providing a stringent test of the SM.

E821 experiment at BNL :
[Phys.Rev.D73 (2006) 072003]

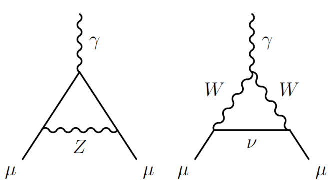
$$a_\mu^{E821} = 11659209.1(5.4)(3.3) \times 10^{-10}$$

0.54 ppm
Dominated by statistics

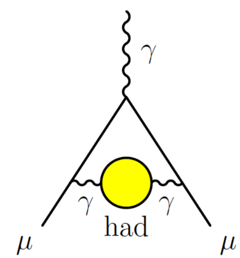
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EWK} + a_\mu^{had}$$



QED corrections known up to 5 loops, rel. precision ~7×10^{-10}
LO term (Schwinger) = $\alpha/2\pi$ ~ 0.00116



EWK corrections ~ 10^{-9}
rel. uncertainty <1%

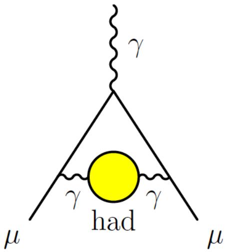


Hadronic contribution ~ 7×10^{-8}
-not calculable by pQCD-

Main contribution: LO Vacuum Polarization
estimated rel. uncertainty 0.35% - 0.6%

→ **Dominant Theoretical uncertainty**

a_μ^{HLO}: standard data-driven approach (time-like)



Dispersion relations, optical theorem:

$$a_\mu^{HLO} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{\hat{K}(s) R_{had}(s)}{s^2}$$

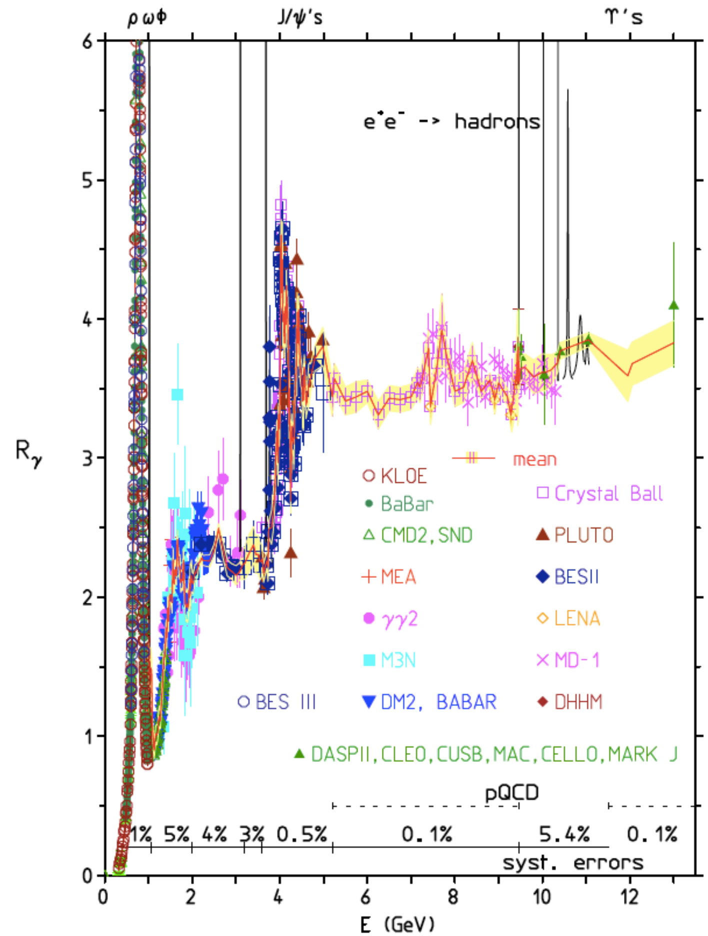
$R_{had}(s) = \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$

K smooth function

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

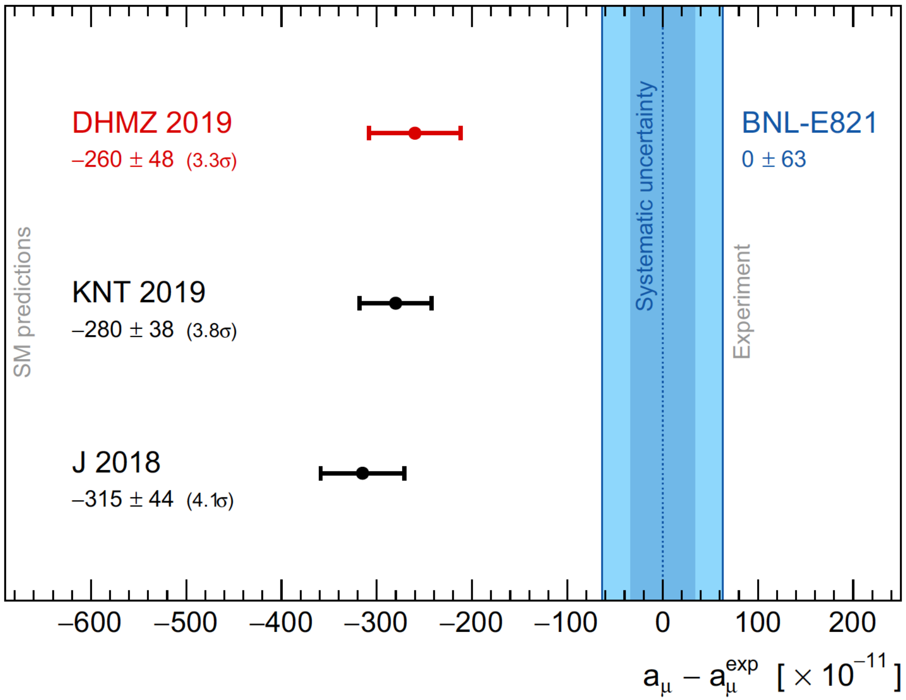
Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

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



Alternative: **Lattice QCD calculations**
continuously progressing, expected to become more and more competitive in the near future

a_μ measurement versus SM



Plot from: M.Davier et al, Eur.Phys.J.C 80 (2020) 241

3-4 σ discrepancy

new physics ?

A recent lattice QCD paper claims no discrepancy at all: Sz.Borsanyi et al., arXiv:2002.12347 [hep-lat]

New g-2 experiment on-going at Fermilab aims at **a reduction of the experimental error by a factor of 4**

Theoretical precision should be improved as well

MUonE experiment proposal

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

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

-Initially proposed for use with Bhabha scattering data from flavour factories-

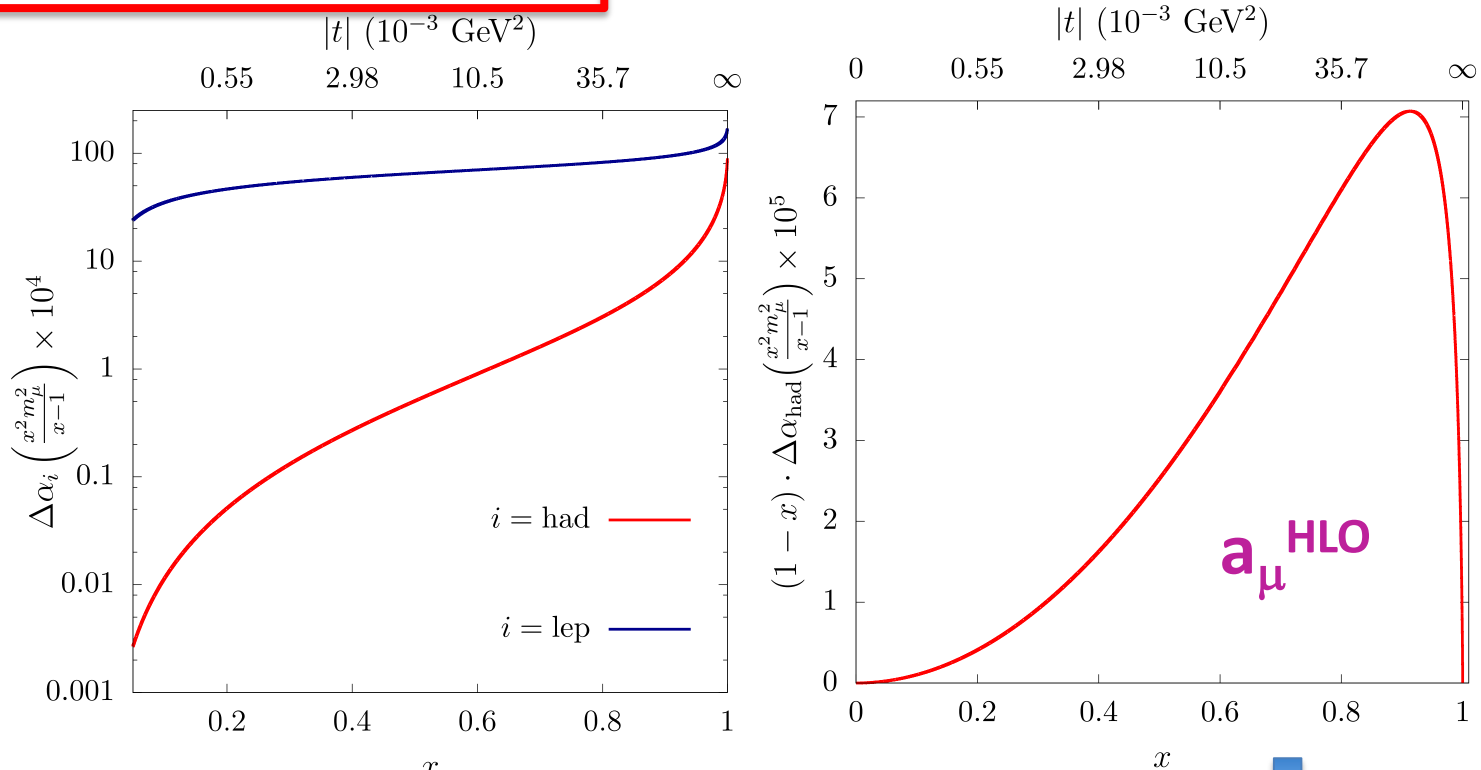
$$a_\mu^{HLO} = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

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

$\Delta\alpha_{had}$ 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:

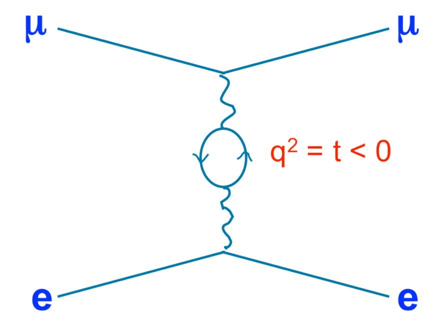
peak of the integrand at $x \cong 0.9$ → $t = -0.11$ GeV^2 → $\Delta\alpha_{had} \sim 10^{-3}$

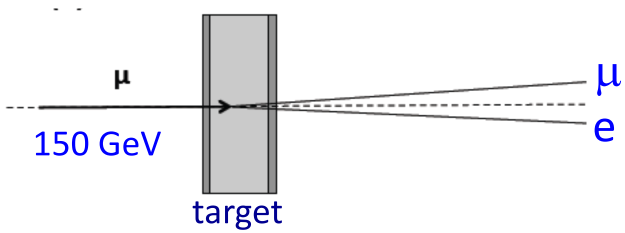
MuonE experimental Proposal

Eur.Phys.J.C77(2017)139

Elastic scattering $\mu e \rightarrow \mu e$ with a μ beam of E=150 GeV on atomic electrons of a fixed target with low Z (Be or C)

From the measured differential cross section determine $\Delta\alpha_{had}(t)$ and then a_μ^{HLO} by the space-like approach



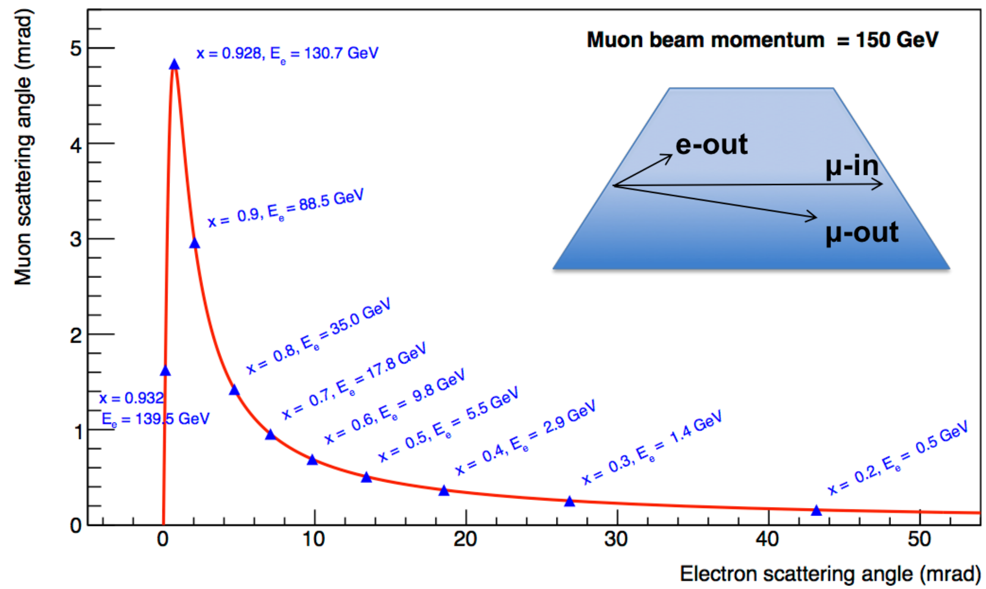


running of α

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

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

known from QED — to be measured !



- **Elastic scattering: simple kinematics.**
- Scattering angles θ_e and θ_μ correlated (helps selection: rejection of radiative/inelastic events)
- 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

MUonE Detector Layout

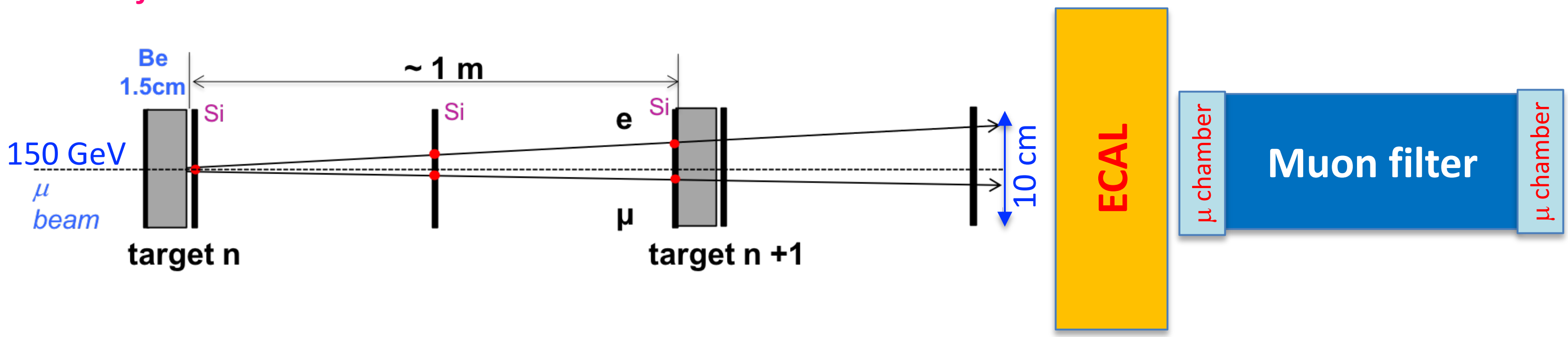
Letter-Of-Intent SPSC-I-252

The detector concept is simple, the challenge is the request 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



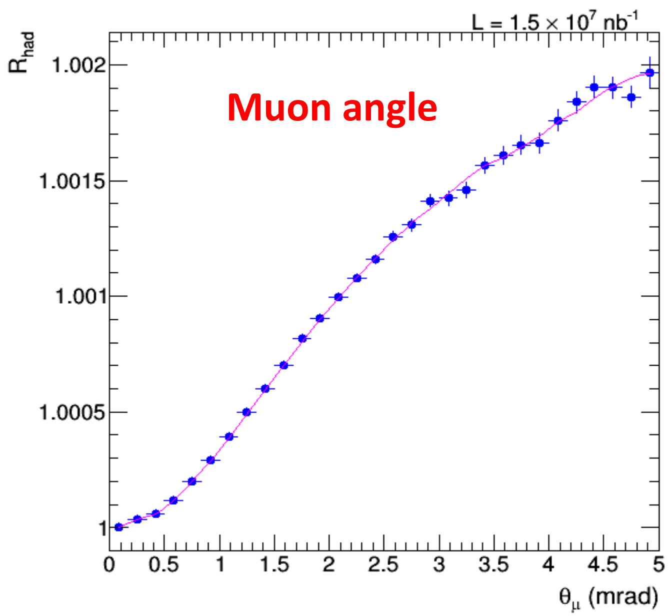
incoming muon direction measured by the previous module

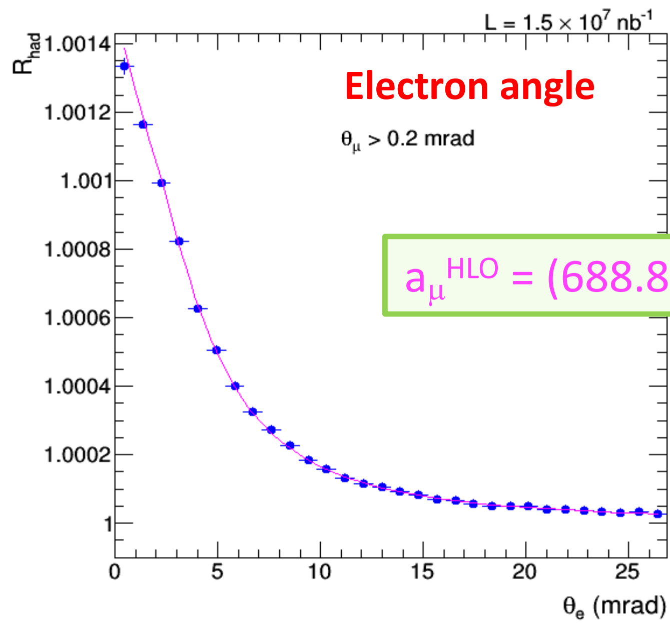
Boosted kinematics: θ_e<32mrad (for E_e>1 GeV), θ_μ<5mrad: the whole acceptance can be covered with a 10x10cm^2 silicon sensor at 1m distance from the target, reducing many systematic errors

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 x 10^7 nb^{-1} (corresponding to 3-year run)

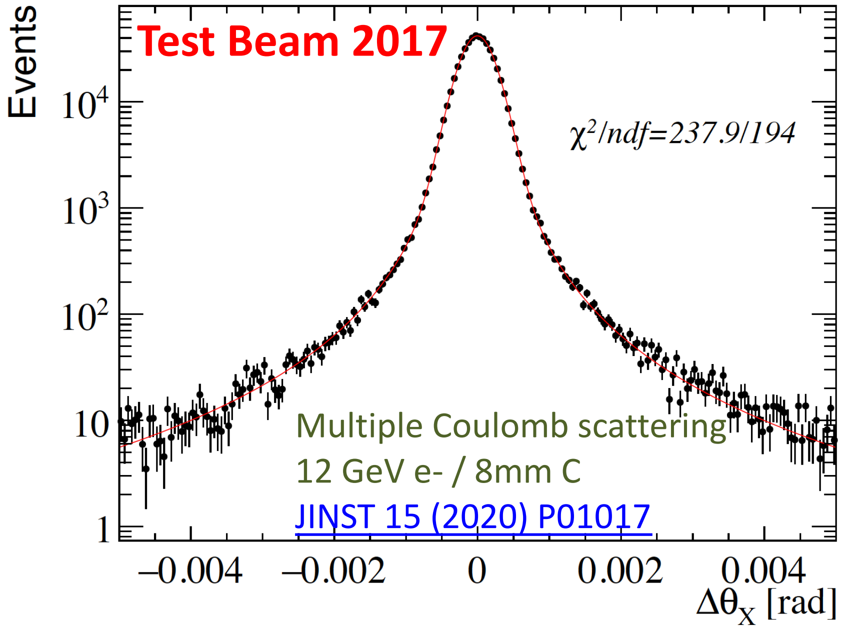


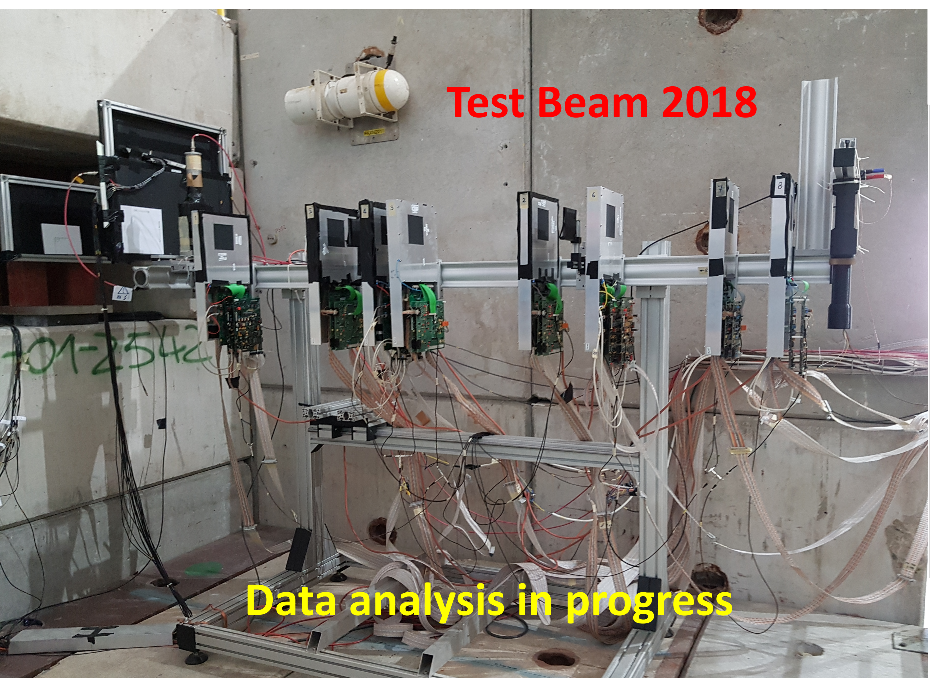


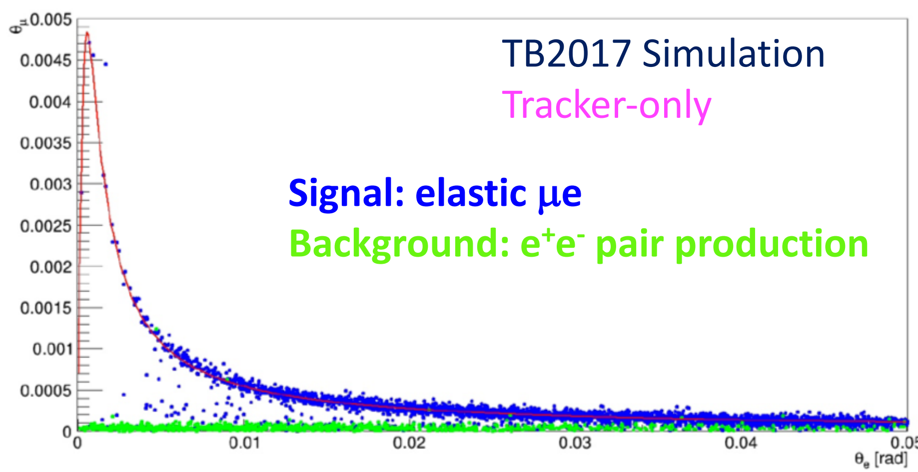
$a_\mu^{HLO} = (688.8 \pm 2.4) \times 10^{-10}$

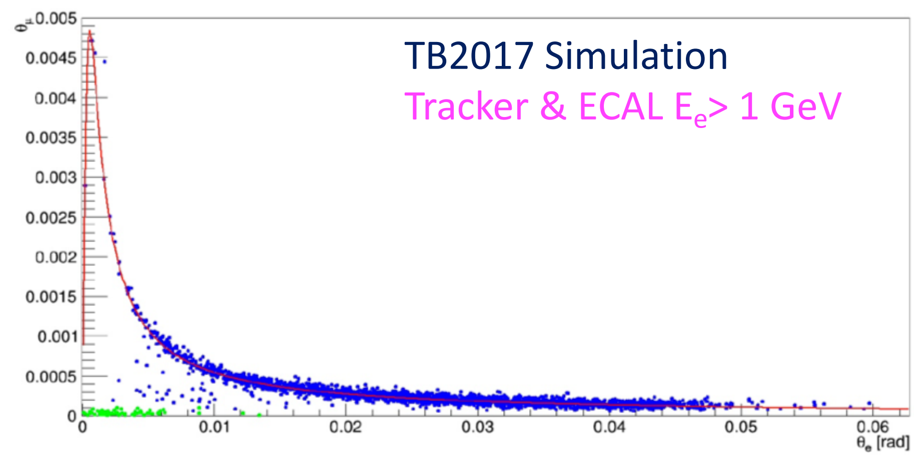
Template fit to the 2D angular distribution from NLO MC generator with parameterised detector resolution.
$\Delta\alpha_{had}(t)$ parameterised according to the "Lepton-Like" form. Shape-only χ^2 fit.

Beam tests @CERN & Simulations



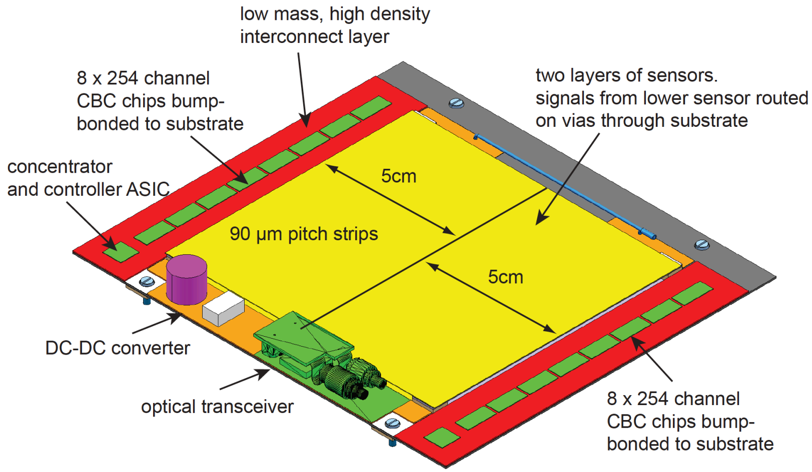






Detector choice: CMS-upgrade Outer Tracker 2S

MUonE Letter-Of-Intent SPSC-I-252



Two close-by planes of strips providing track elements (**stubs)** -> suppression of background from single-layer hits or large-angle tracks

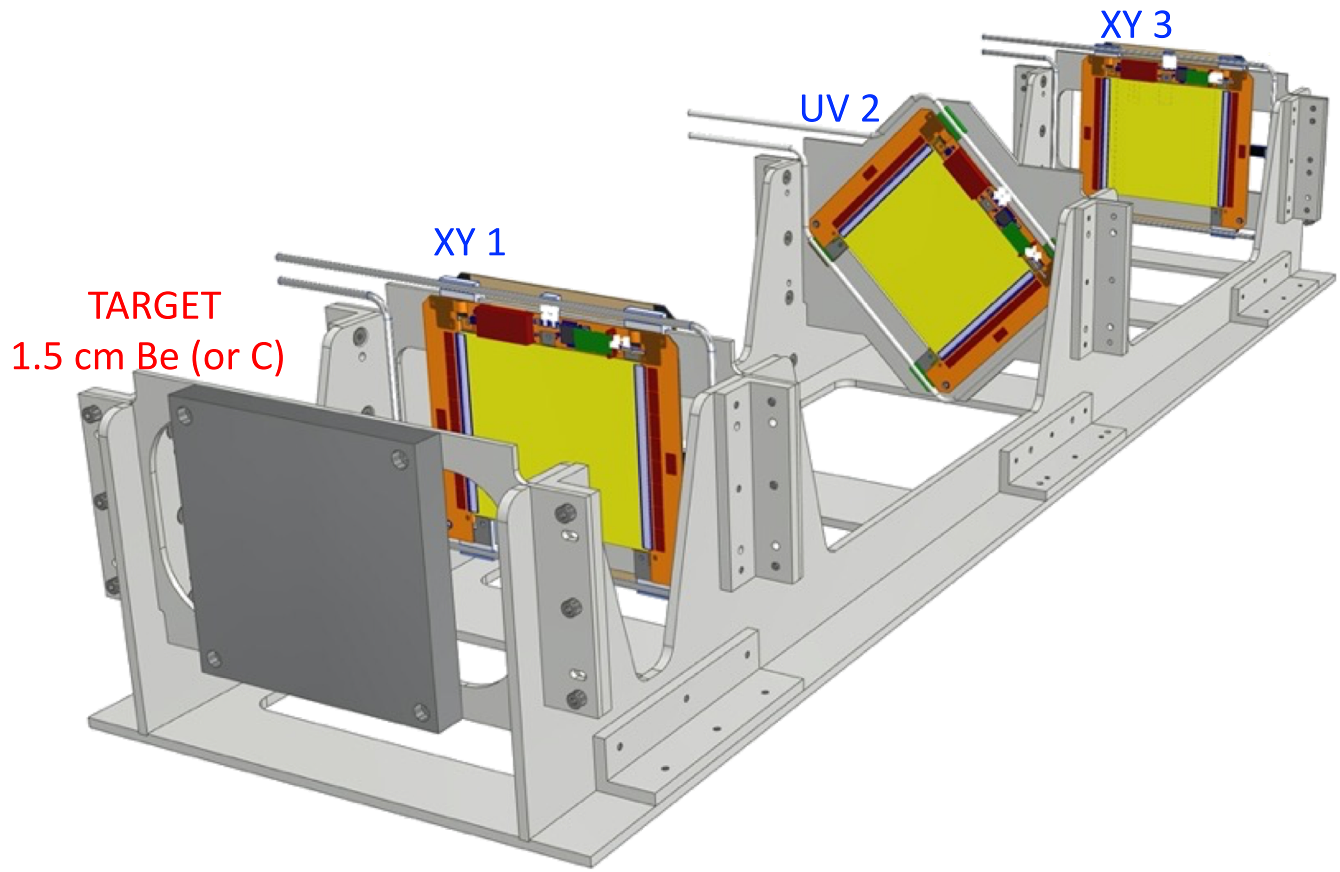
Details: see
CMS Tracker Upgrade TDR

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

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

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



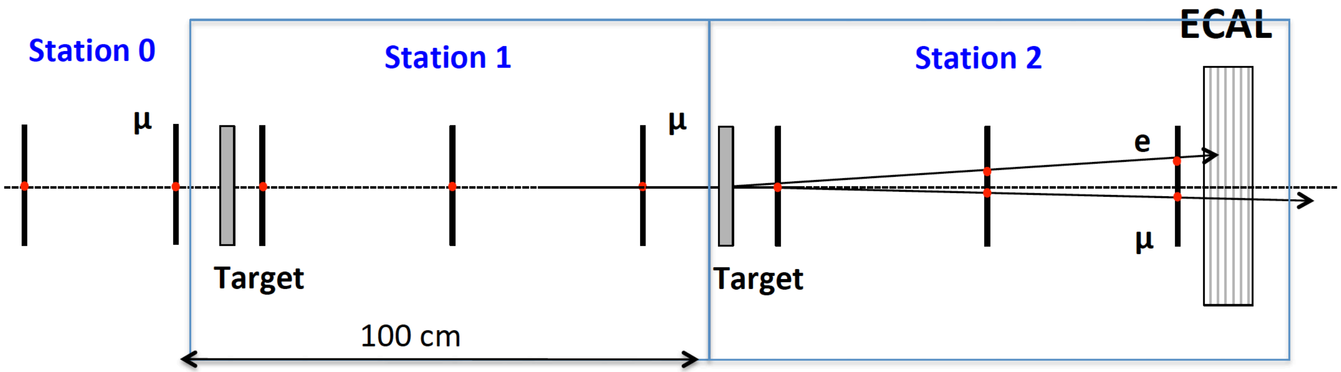
Length 1m
Target followed by
3 tracking layers:
each with a pair of close-by 2S modules with orthogonal strips.
Layer 1 and 3 with XY strips, Layer 2 with 45^{o} rotation to solve reconstruction ambiguities

Stringent request: relative positions within the station stable to better than 10µm
Low CTE support structure: INVAR (alloy of 65%Fe, 35%Ni), easier to machine and less expensive than carbon fiber.
Cooling system, tracker enclosure
Room temperature stabilized within 1-2 ^{o}C

Test Run 2021

To be held at CERN in Fall 2021: 3 weeks allocated with full intensity μ beam

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



Two MUonE tracking stations + ECAL + muon filter at the end

Station 0 without target, to track the incoming muons

Transverse size (not to scale) tracking modules 10x10 cm^2

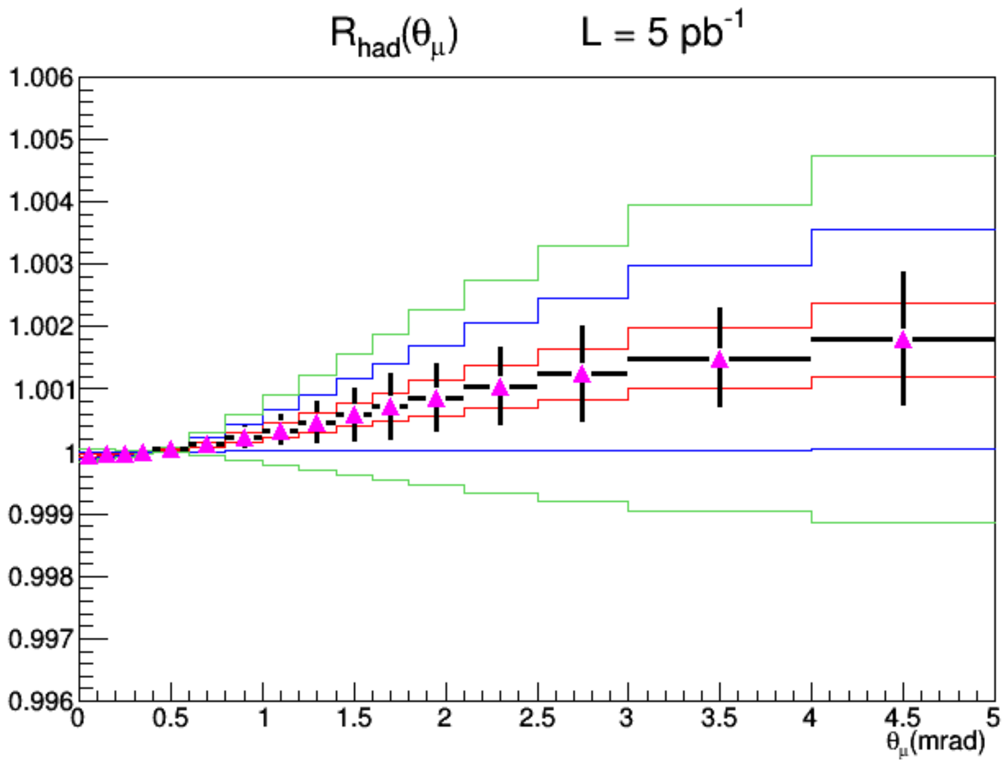
Main objectives:

- Confirm the system engineering: assembly, mounting and cooling.
- Monitoring/checking mechanical and thermal stability.
- Assessing the detector counting rate capability.
- Checking of the DAQ system.
- Validating the trigger strategy: FPGA real-time processing to identify and reconstruct μ−e events.
- Test the procedure for the alignment of the sensors.
- After commissioning, take data to measure the leptonic contribution to the running of $\alpha(q^2)$.

Expected sensitivity of the TR 2021

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

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



Initial sensitivity to the hadronic running of α.

Pure statistical level: 5.2σ

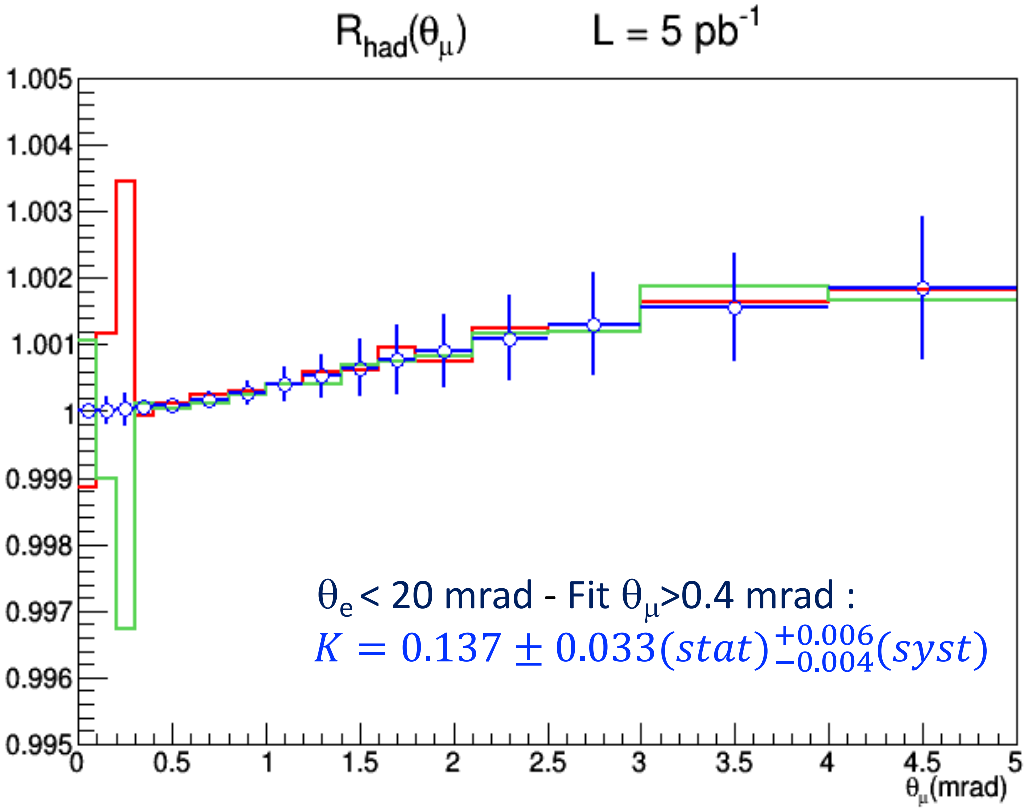
2D (θ_μ,θ_e) K=0.136 ± 0.026

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

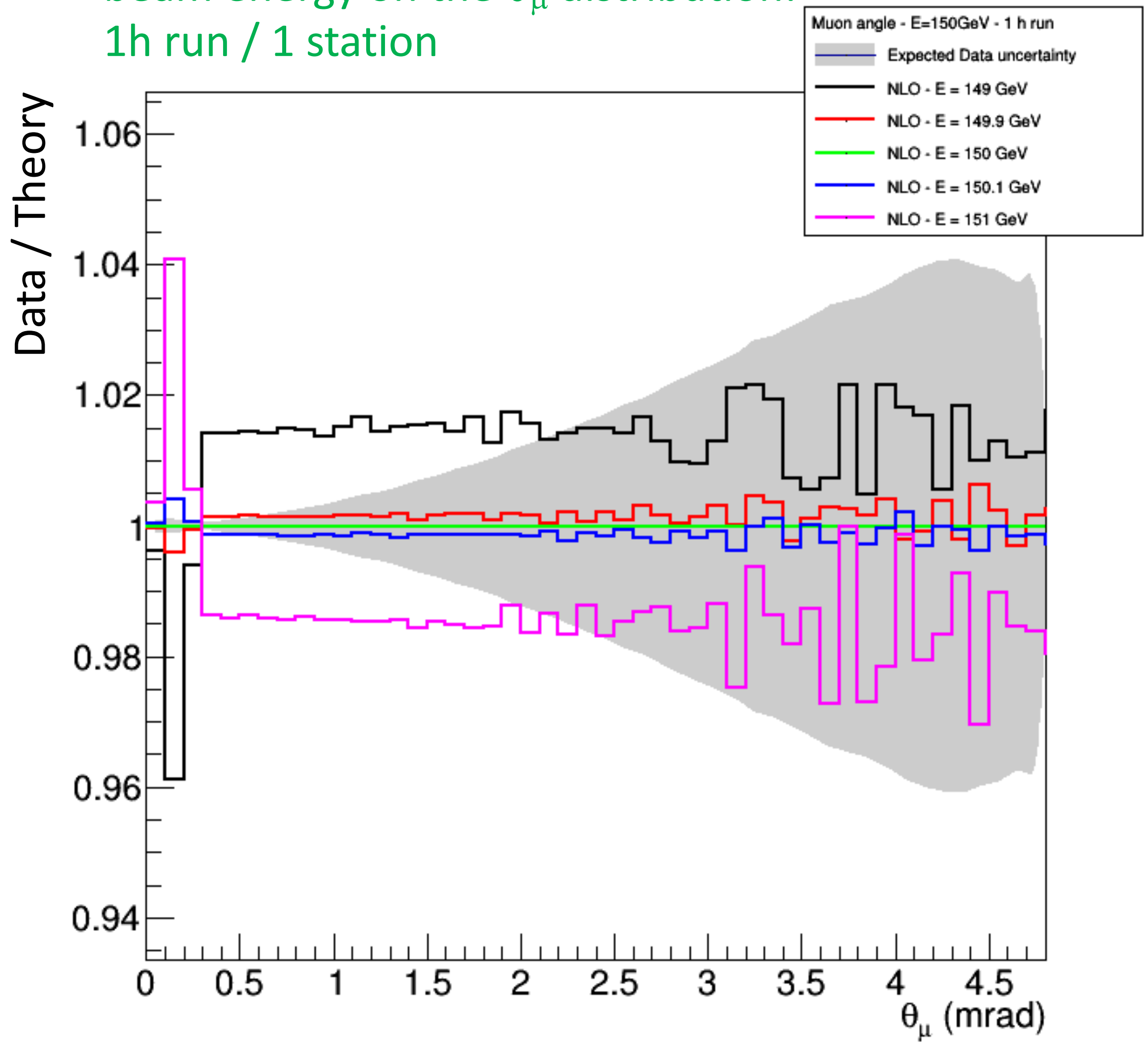
Effect of a flat error of 1% on the core width of multiple scattering



Systematic Effects: Beam Energy scale

- M2 beam average energy scale known at ~1%
- Beam muon momentum measured by the COMPASS BMS spectrometer with ~0.8% resolution
- Absolute energy scale has to be controlled by a physics process:
  - ❖ Inverse kinematic method on elastic μe events
  - ❖ Fit of the average angle distribution
- Can reach <3 MeV uncertainty in a single station in less than one week

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 ($m_e=0$, $m_\mu\neq 0$)
  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., arXiv:2007.01586; P.Banerjee et al, arXiv:2007.01654

➡ **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, arXiv:2002.05418
P.S.Bhupal Dev et al., JHEP05(2020)53

→ **MUonE is NOT vulnerable !**

Summary

- **Long-standing puzzle of muon g-2:**
  - Experiment-Theory(SM) discrepancy 3-4σ
  - sensitive to BSM physics
  - Ongoing/future experiments will reduce the exp.error by a factor of 4
  - Theory error dominated by the Leading Hadronic contribution a_μ^{HLO}
- **MUonE** experiment proposal: measuring the running of α_{QED} from the shape of the differential cross section for elastic scattering of μ(150GeV) 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
  - 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 carried out at the end of 2021, 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 in 2022-2024 if results of the Test Run are satisfactory

being formed, still growing up

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

The MUonE Collaboration

Northwestern U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) ***Exp***

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)

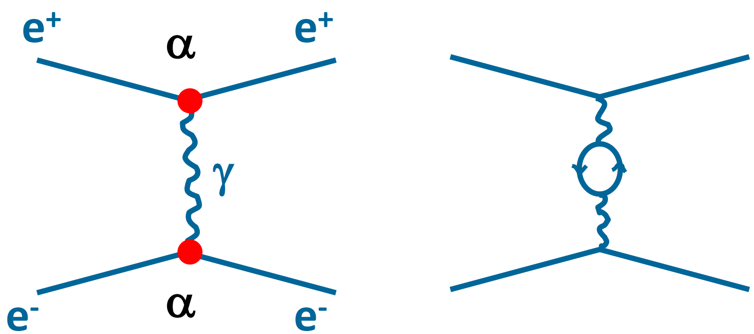
BACKUP

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

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

[Eur.Phys.J.C45(2006)1]

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

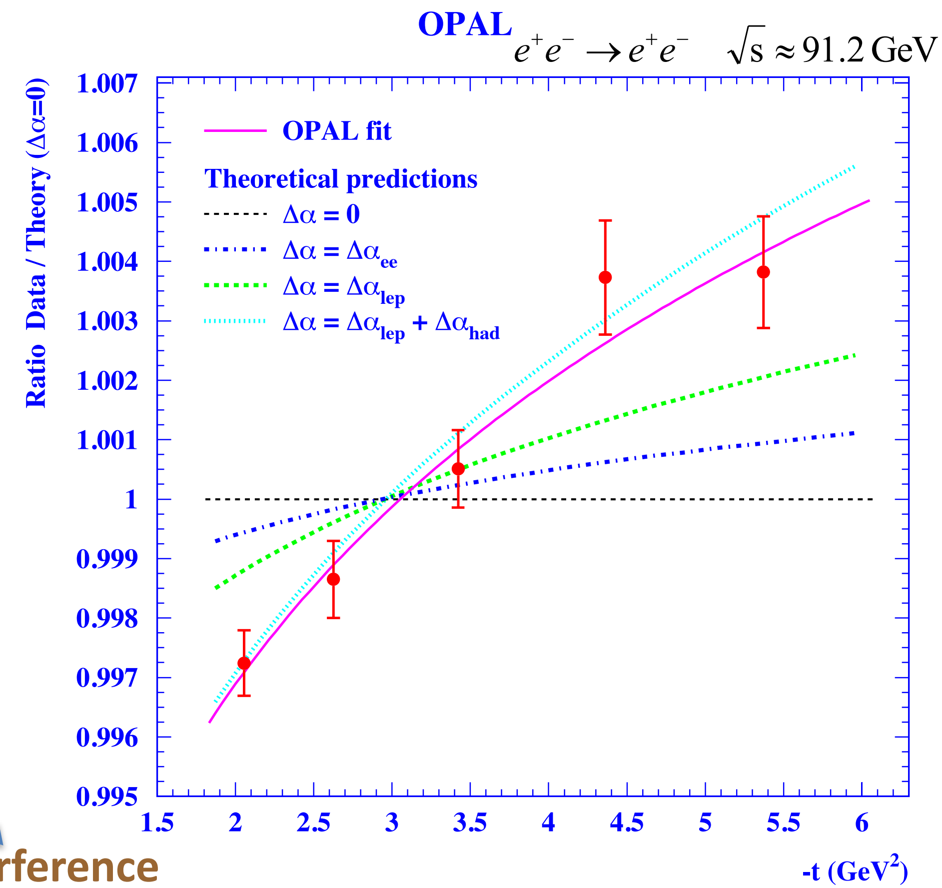
$$\left(\frac{1}{1-\Delta\alpha(t)}\right)^2$$

Effective coupling factorized

Photonic radiative corrections

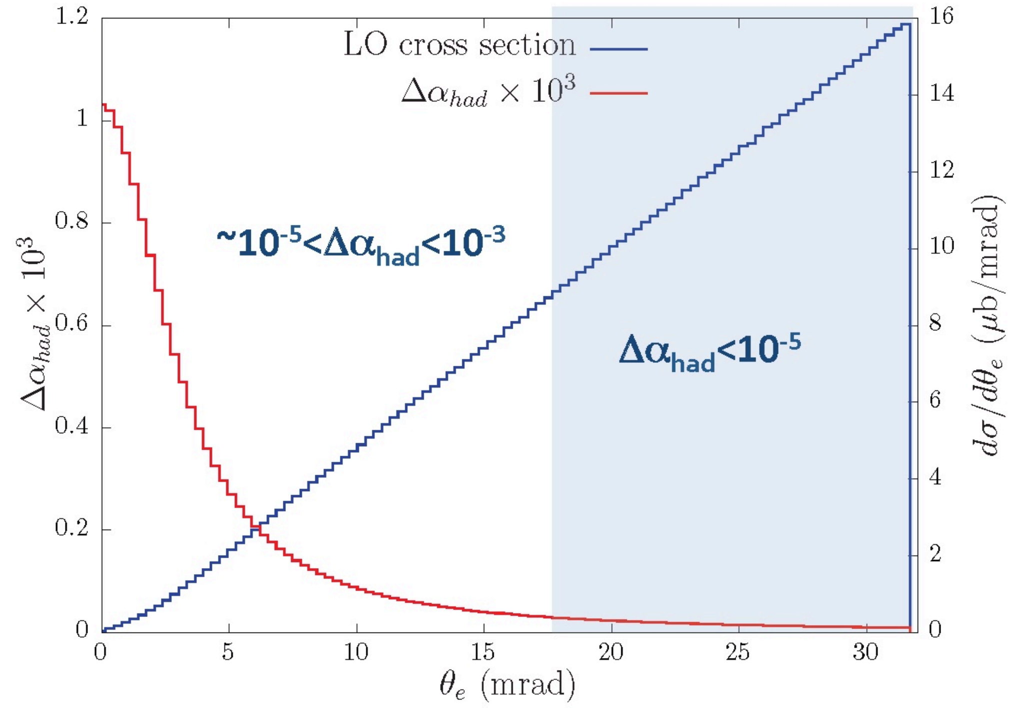
s-channel γ exchange correction

Z interference correction



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

LO μ-e elastic scattering



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

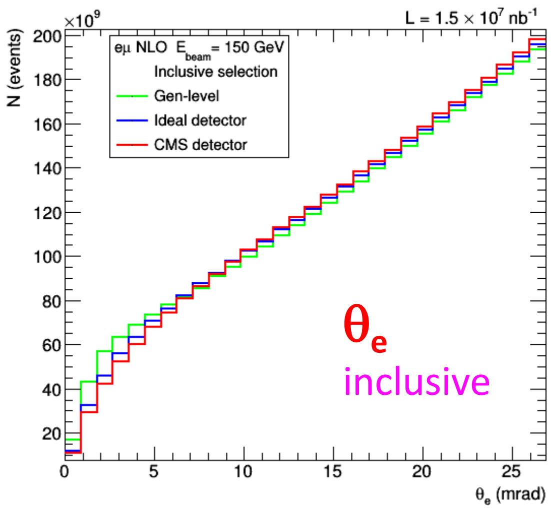
$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2 \qquad \alpha(t) = \frac{\alpha(0)}{1 - \Delta\alpha(t)}$$

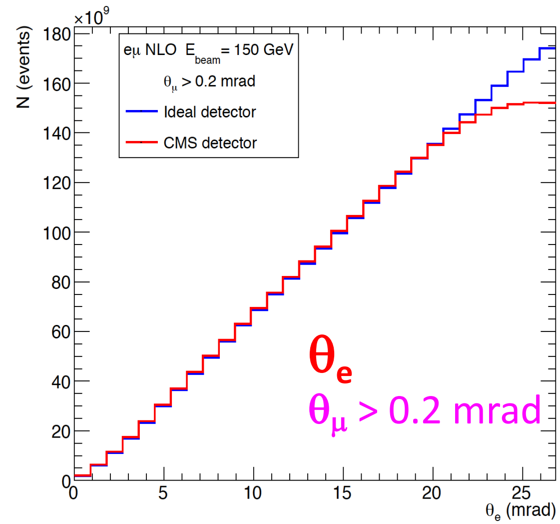
$\Delta\alpha(t) = \Delta\alpha_{lep}(t) + \Delta\alpha_{had}(t)$

Simple kinematics: $t \cong -2\, m_e E_e$

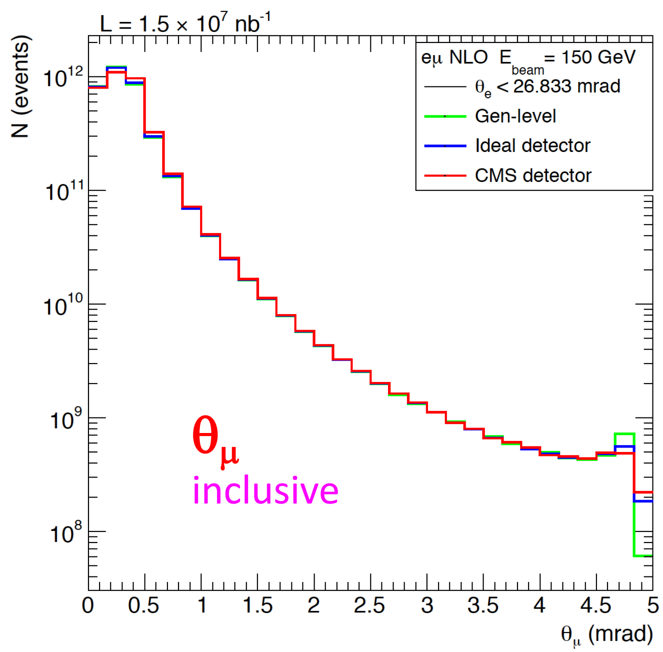
E_e can be determined from the scattering angle θ_e and the beam energy

Angular distributions





statistics corresponding to the nominal integrated Luminosity L = 1.5 x 10^7 nb^{-1}



$\Delta\alpha_{had}$ parameterization

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

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

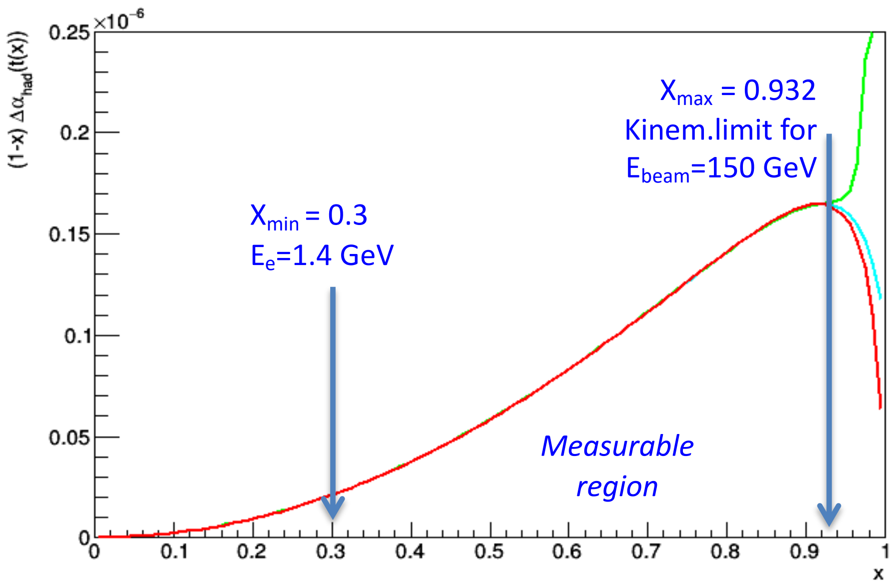
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

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

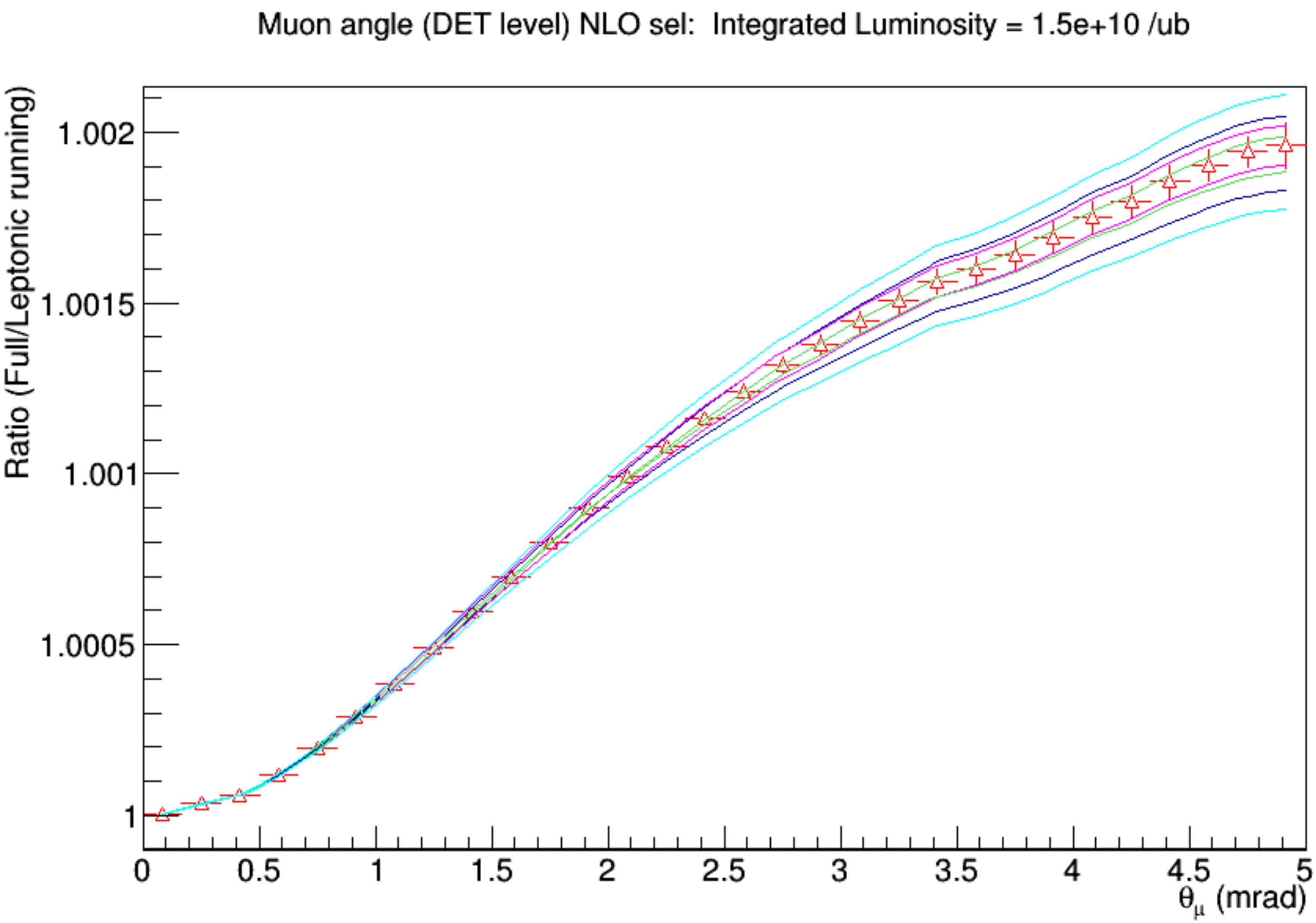
$$\Delta\alpha_{had}(t) \simeq -\frac{1}{15}\frac{k}{M}t$$

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

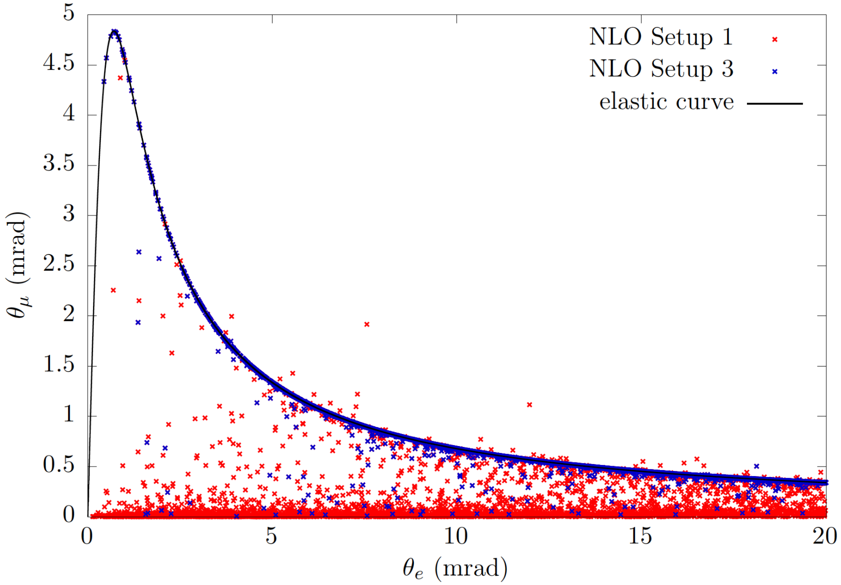
Instead simple polinomials diverge for x->1 (green is a cubic polinomial in t)



Template fit

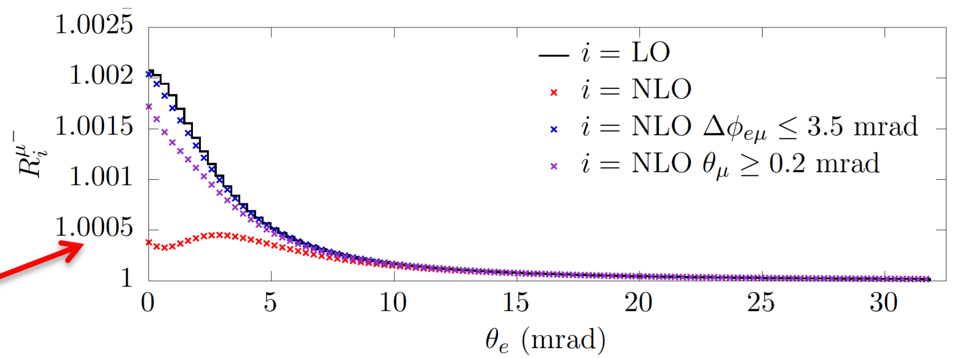


NLO MC and elastic selection

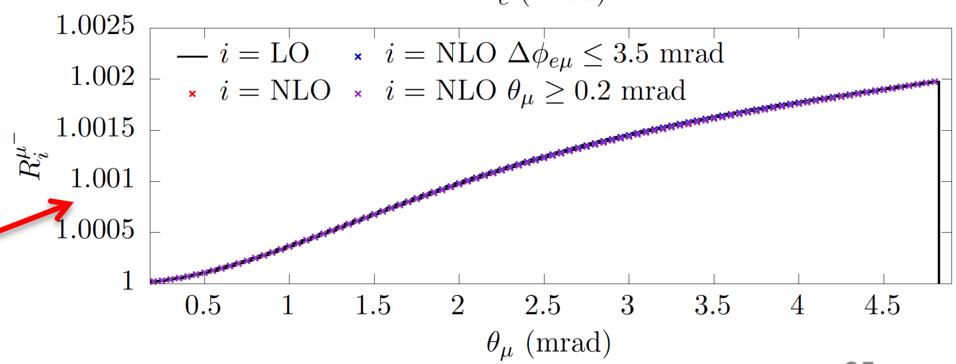


[M.Alacevich et al, JHEP02(2019)155](#)

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

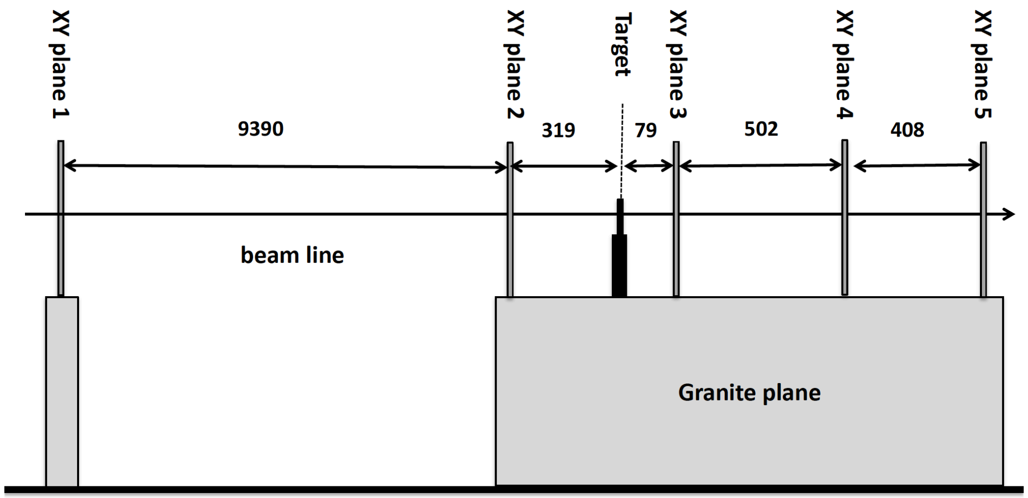


Without any selection the signal sensitivity of the electron angle is destroyed -> necessary to implement an "elastic" selection



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

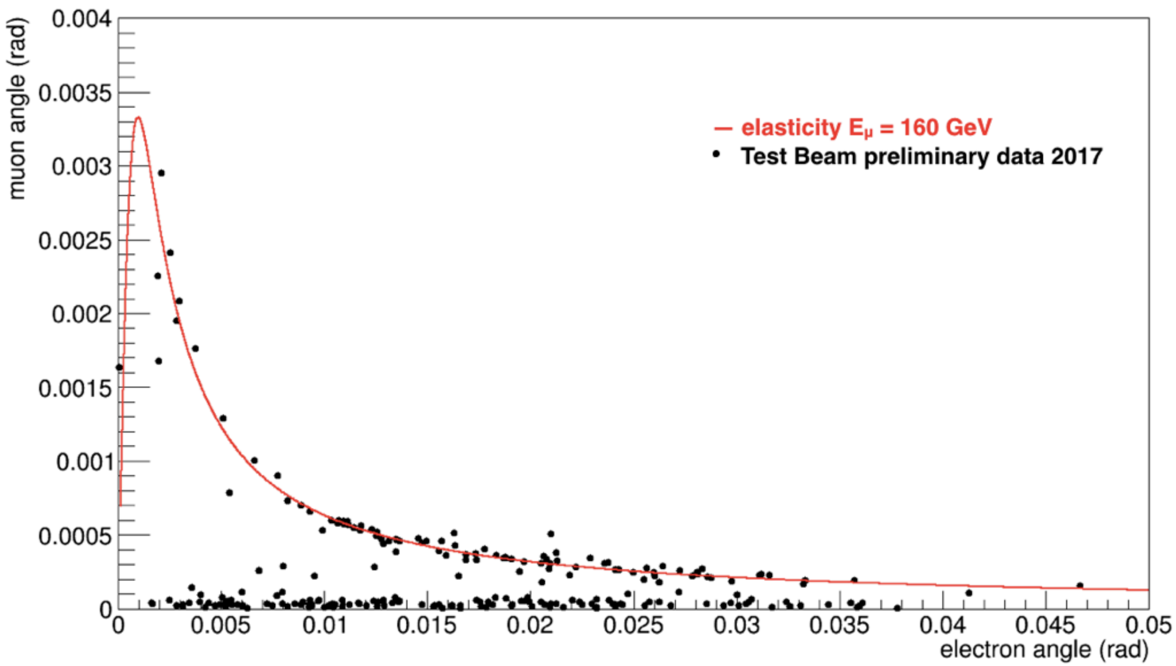
Test Beam 2017



[JINST 15 (2020) P01017](#)

Adapted UA9 detector at CERN H8 Beam Line

5 pairs of Si strips planes (measuring orthogonal coords), 2 before and 3 after the 8-20mm C target



Evidence for μe elastic scattering with μ beam with E=160 GeV

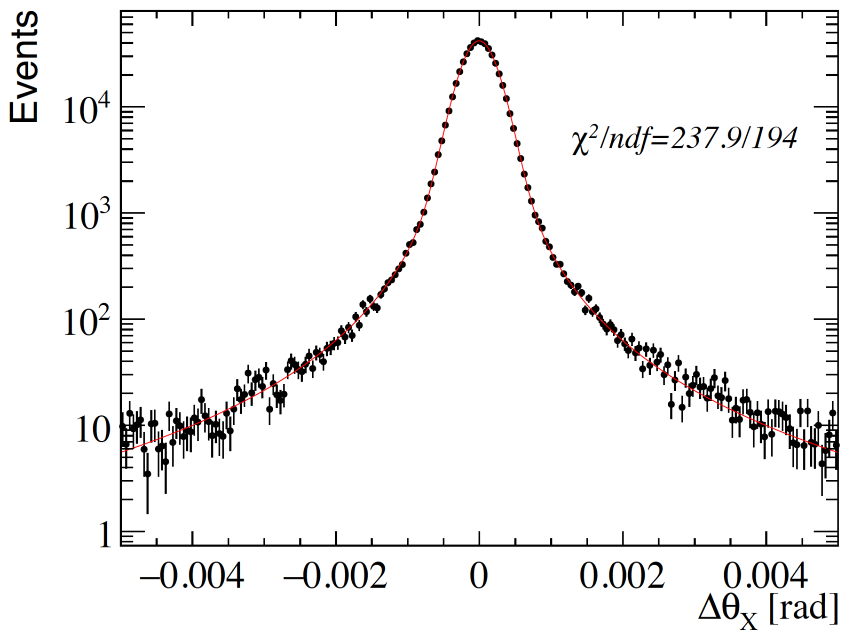
Golden Selection:
Single track in,
two tracks out

Multiple Coulomb scattering

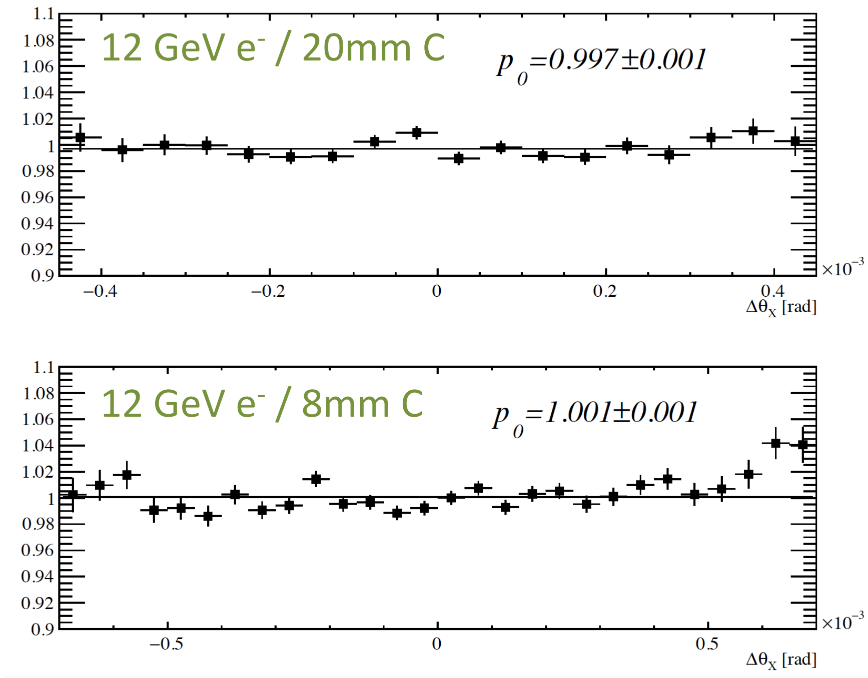
(One of the most important effects to be controlled among systematics)

Studied in the TB2017: [JINST 15 (2020) P01017]
12 – 20 GeV electrons on 8 – 20 mm C targets

DATA 12 GeV e- / 8mm C



DATA/MC (Geant4) comparison



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

Test Beam 2018

2 stations (target+Si-tracking) + ECAL,
on M2 beam behind Compass

Purpose:
study of signal and background events

Data analysis in progress

Nucl.Instrum.Meth.A 936(2019)636

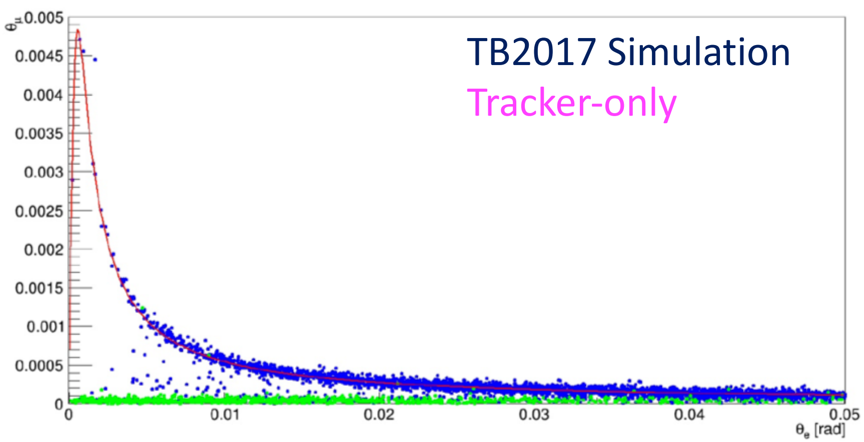
Geant4 simulations

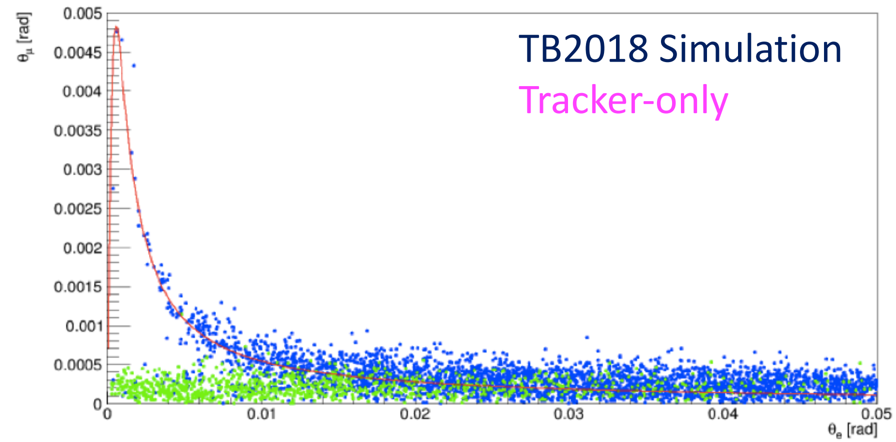
Effect of the tracker position resolution on θ_μ vs θ_e distribution:

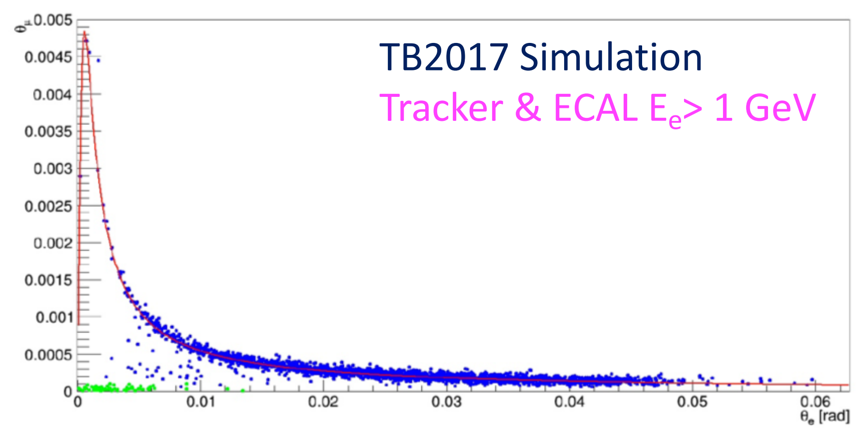
(Left) TB2017: UA9 resolution 7μm ; (Right) TB2018: resolution ~40μm

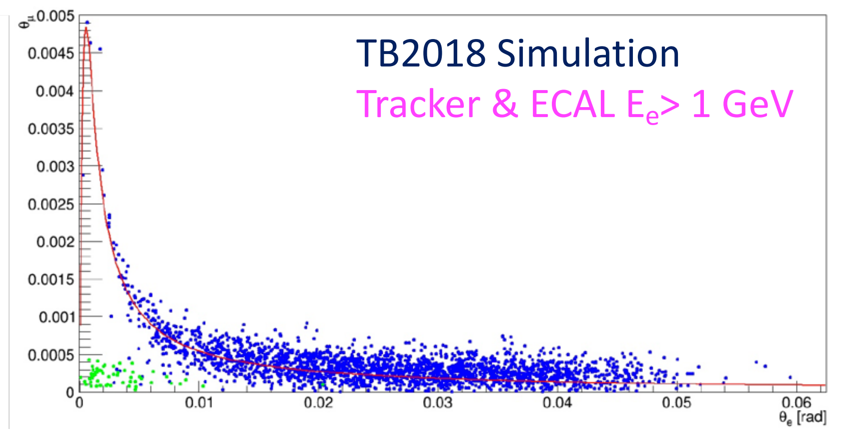
Signal: elastic μe

Background: e^+e^- pair production



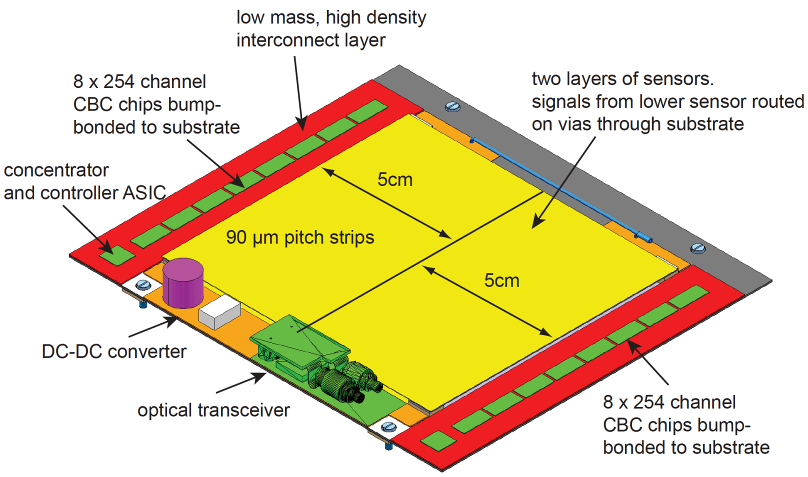


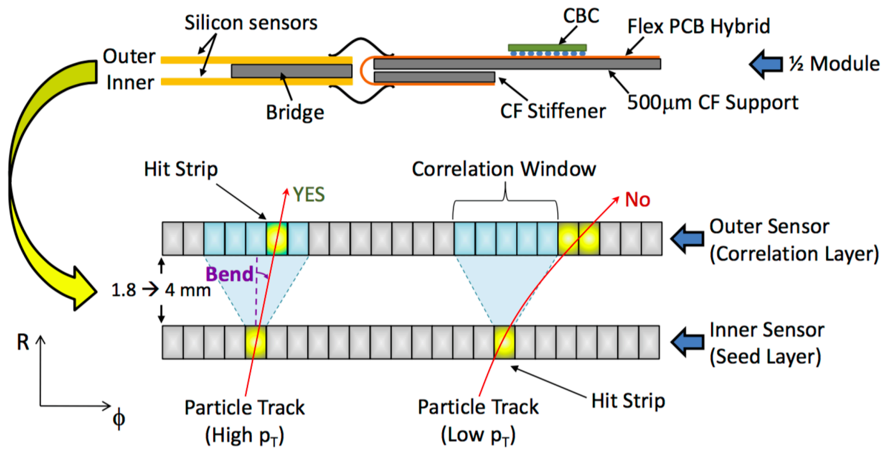




Detector choice: CMS-upgrade Outer Tracker 2S

[Letter-Of-Intent SPSC-I-252]

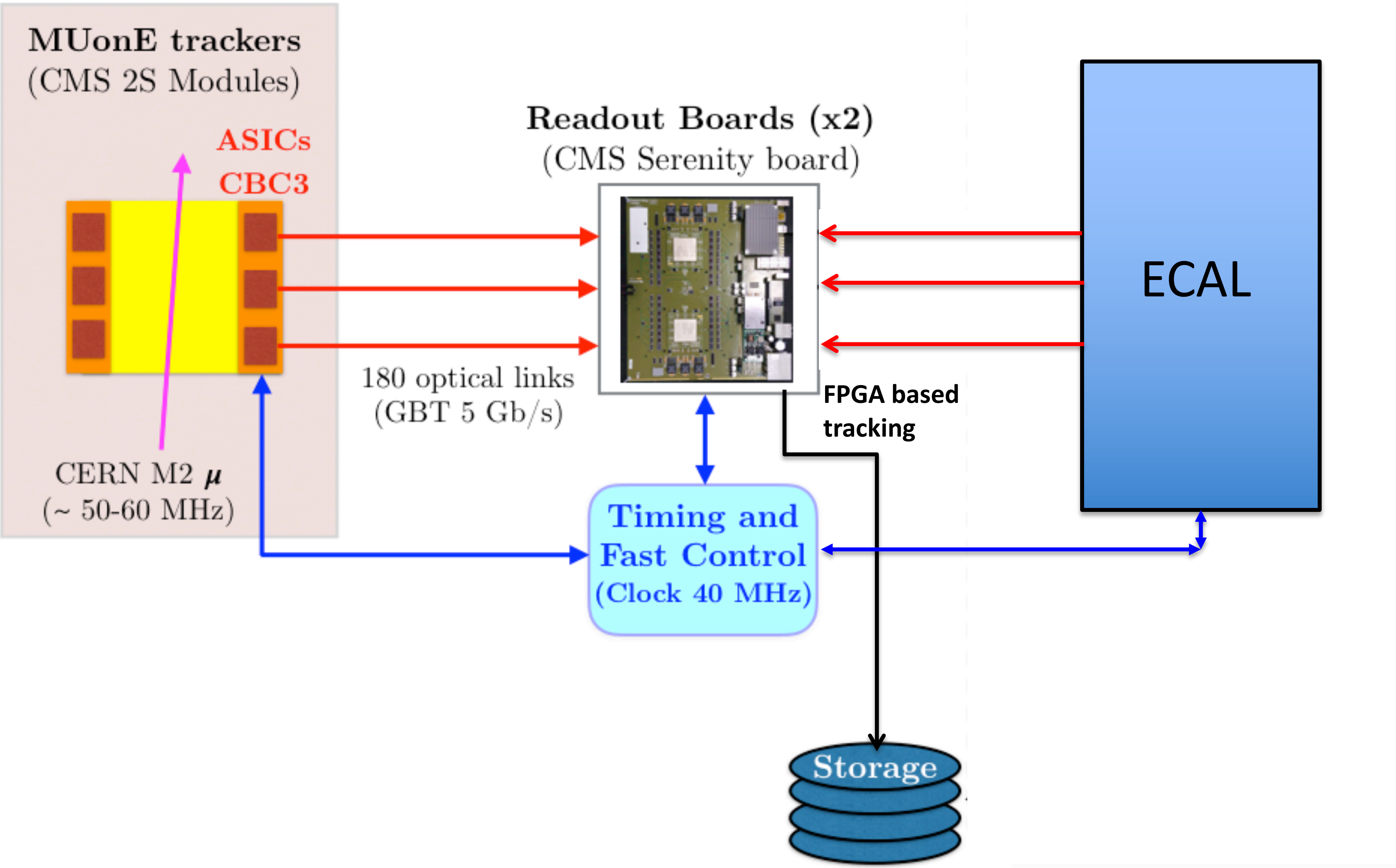




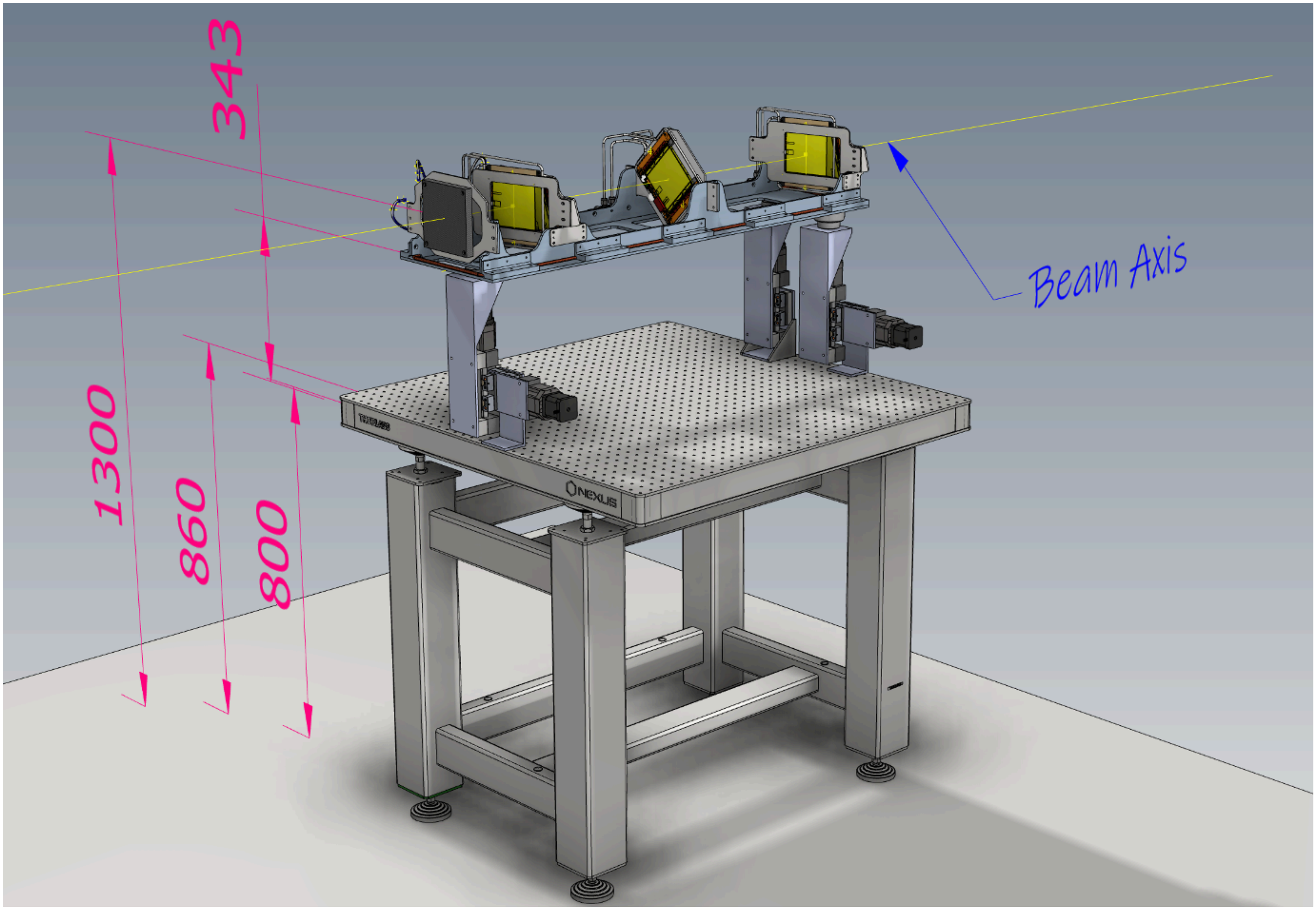
Details: see [CMS Tracker Upgrade TDR]

- Large active area 10x10 cm^2 -> complete/uniform angular coverage with a single sensor
- Two close-by planes of strips providing track elements (**stubs**) -> suppression of background from single-layer hits or large-angle tracks
- Good position resolution ~20μm -> further improvable with effective staggering of the planes and/or a 15^o-20^o tilt around the strip axis
- Fast response time
- Readout rate 40 MHz -> established CMS DAQ based on the Serenity platform can cope with the ~50 MHz intensity of the M2 muon beam
- Material budget: 320μm Si each sensor (2 in a module) -> not ideal but a fair compromise
- **DRAWBACK:** signal is asynchronous while sampling has fixed clock at 40MHz -> can be overcome with a specific configuration of the FE

The DAQ and trigger system



Precision alignment: motorized linear stages



Requirements in sensors positioning

- Systematics due to the uncertainty δz on the longitudinal position: $\Delta\theta/\theta = \delta z/L$
- $<E_\mu>$ measurable by reverting the kinematics

μe equal-angle related to the beam energy

$$\theta_{eq} \simeq \sqrt{\frac{2m_e}{P_{beam}}}$$

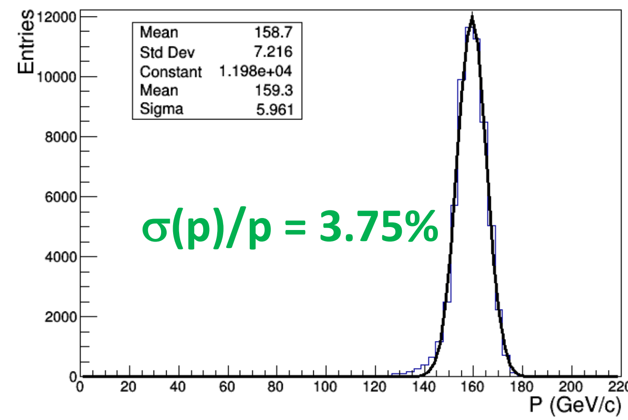
- It requires few hours of data taking to get the sample $\{(\theta_e, \theta_\mu) : |\theta_e - \theta_\mu| < 1$ mrad$\}$ of size $N \sim 10^6$
- $N \sim 10^6$ implies $\delta<\theta> \sim 0.02$ mrad/sqrt(10^6) $\sim 2\times10^{-5}$
- It sets the scale of the systematics: 10 μm/ 1m

Location @ CERN & M2 beam parameters

MUonE Letter-Of-Intent SPSC-I-252

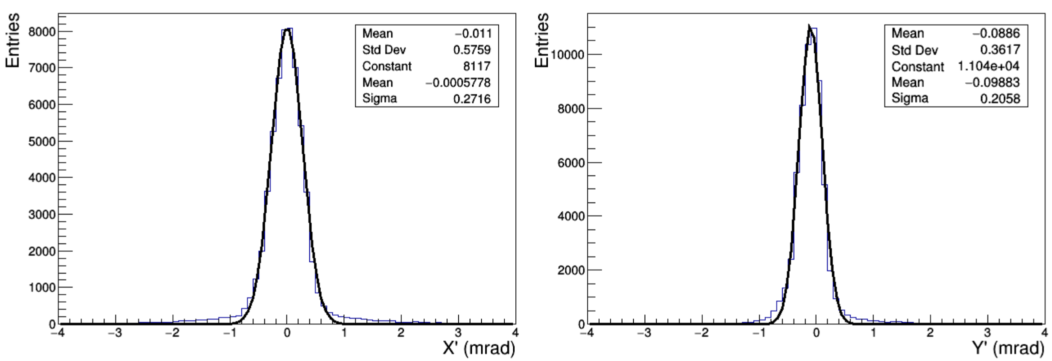
Upstream of the COMPASS detector, after its Beam Momentum Station (BMS), on the M2 beam line : available ~ 40 m

Beam Momentum

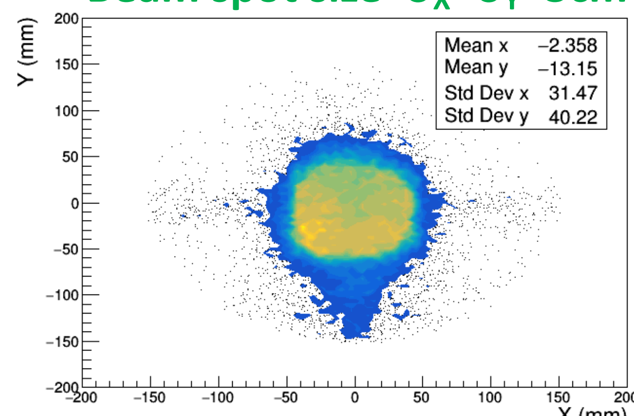


$\sigma(p)/p = 3.75\%$

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

Systematic Effects: Beam Energy scale

- M2 beam average energy scale known at ~1%
- Beam muon momentum measured by the COMPASS BMS spectrometer with ~0.8% resolution
- Absolute energy scale has to be controlled by a physics process:
  - ❖ Inverse kinematic method on elastic μe events
  - ❖ Fit of the average angle distribution
- Can reach <3 MeV uncertainty in a single station in less than one week

Effect of a syst shift of the average beam energy on the θ_μ distribution: 4h run / 1 station