INFN Istituto Nazionale di Fisica Nucleare

MUonE analysis status

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https://agenda.infn.it/event/28089/

Introduction

- **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 puzzle

- Letter-Of-Intent SPSC-I-252 submitted to CERN in June 2019

- Web pages with links to documents (papers, conferences, theses)
  - https://web.infn.it/MUonE/

Outline

- Fit Method recap
- Prospects for the 2022 TestRun
- Pair background
- Summary

Analysis: method recap

- NLO MC: 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
- $\Delta\alpha_{had}(t)$ from F.Jegerlehner's code(hadr5n12.f)→ $a_\mu^{HLO} = 688.6 \times 10^{-10}$
- Detector resolution effects parametrized (including multiple scattering and intrinsic resolution)
- 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.

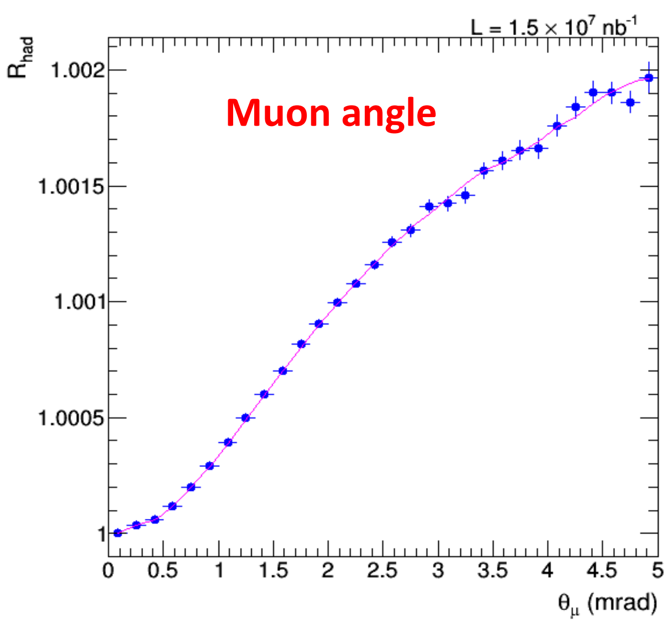
Hadronic running of α

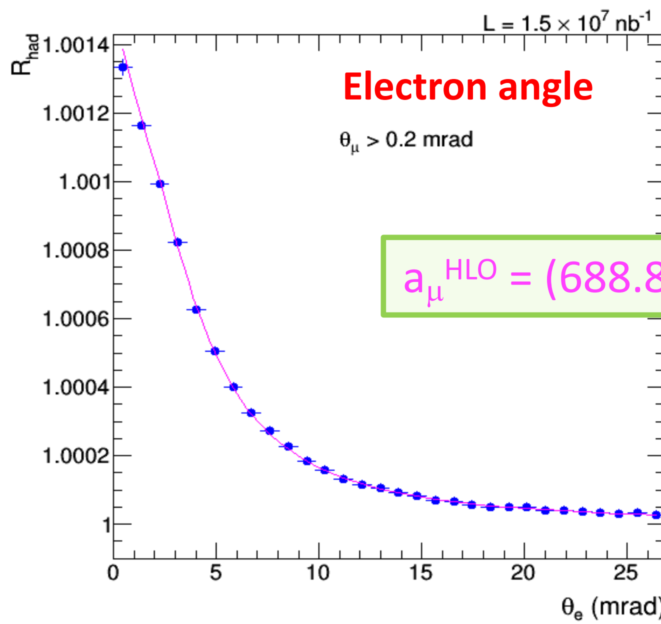
Most easily displayed by taking ratios of the MC predicted angular distributions (pseudodata) and the predictions obtained from the same MC sample reweighting $\alpha(t)$ to correspond to only the leptonic running.

- In this way most of the pure MC statistical fluctuations are cancelled.
- (of course, this trick is applicable only to pseudodata analysis. With real data we will need to match the MC statistics to the data size)

Observable effect ~ 10^{-3} / wanted precision ~10^{-2} → required precision ~10^{-5}

The expected distributions are obtained from the nominal integrated luminosity $L = 1.5 \times 10^{7}\ nb^{-1}$ (corresponding to 3-year run)





Example toy experiment

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

↓

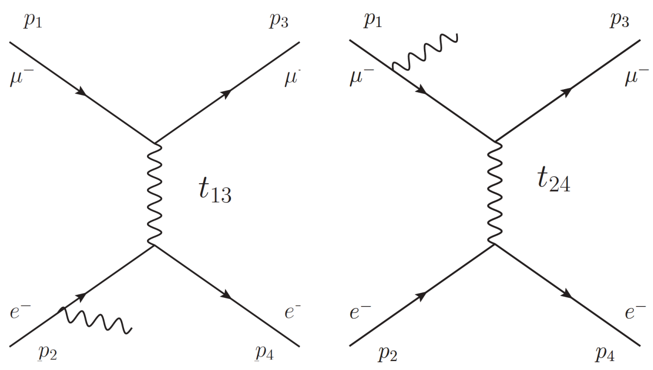
Stat.err. 0.35%

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



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

$\Delta\alpha_{had}$ parameterization

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

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

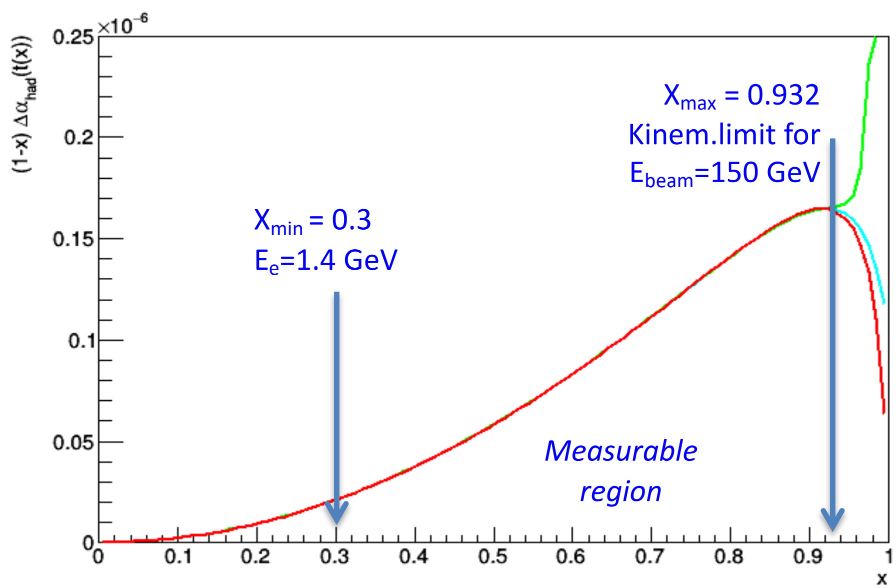
M with dimension of mass squared, related to the mass of the fermion in the vacuum polarization loop
k depending on the coupling $\alpha(0)$, the electric charge and the colour charge of the fermion

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

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

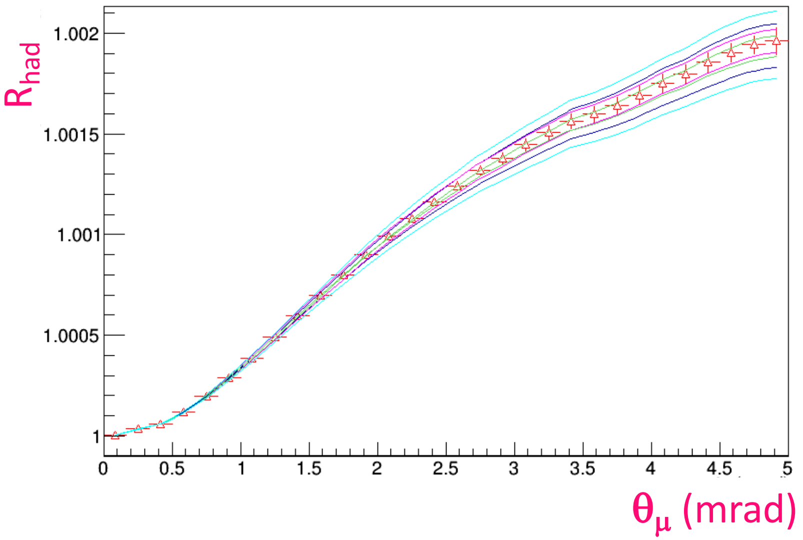
a_μ^{HLO} calculable from the master integral in the FULL phase space with this parameterization.

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



Template fit

- 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 $\Delta\chi^2=1$.

a_μ^{HLO}

- 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%

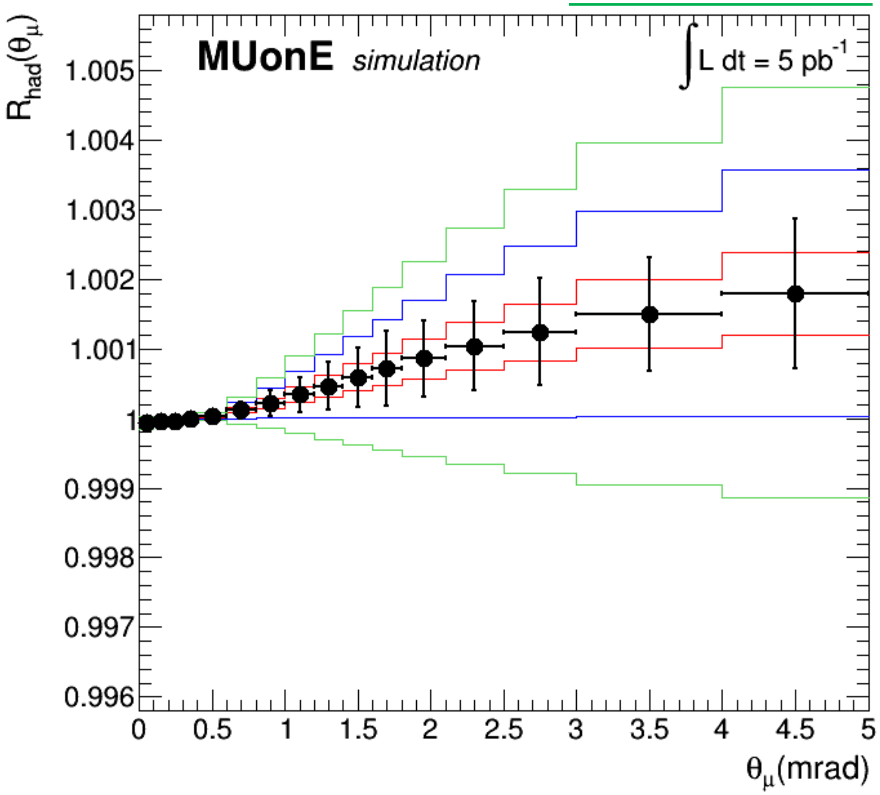
- The expectation from the used Jegerlehner's parameterization is: $a_\mu^{HLO} = 688.6 \times 10^{-10}$
  - difference from our fit is 0.2×10^{-10}, negligible w.r.t. the statistical uncertainty

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



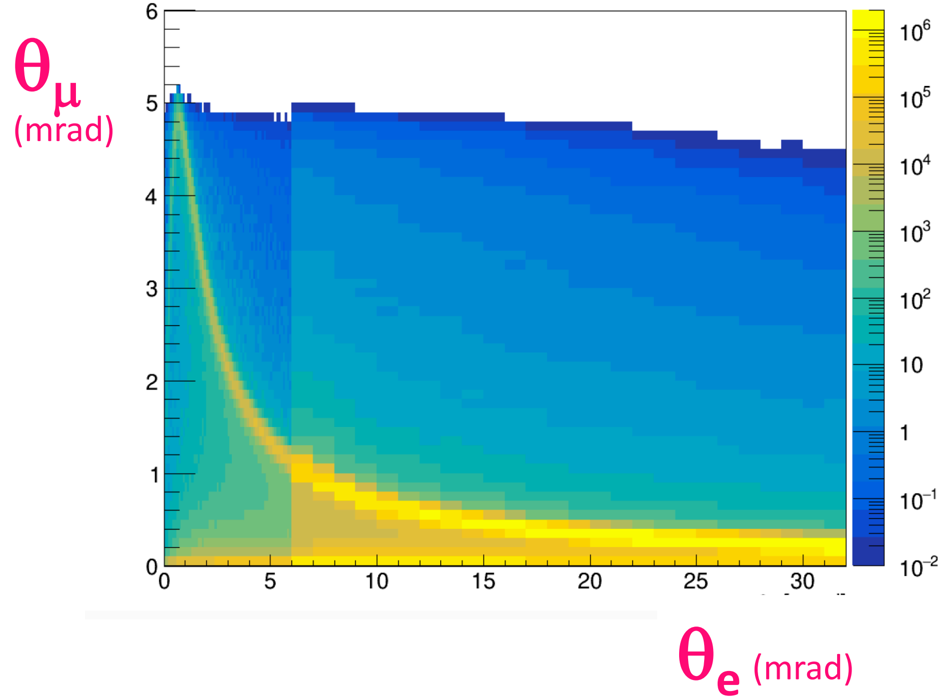
Initial sensitivity to the hadronic running of α.

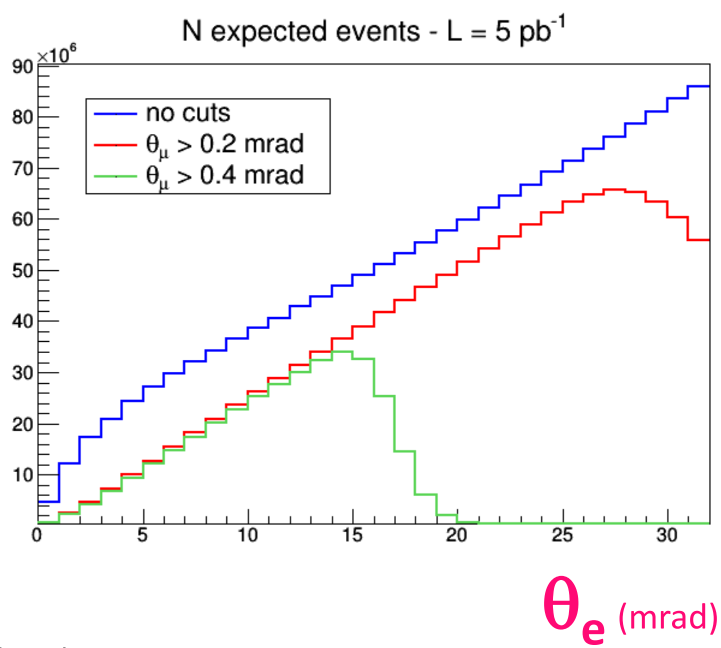
Pure statistical level: 5.2σ
2D (θ_μ,θ_e) K=0.136 ± 0.026

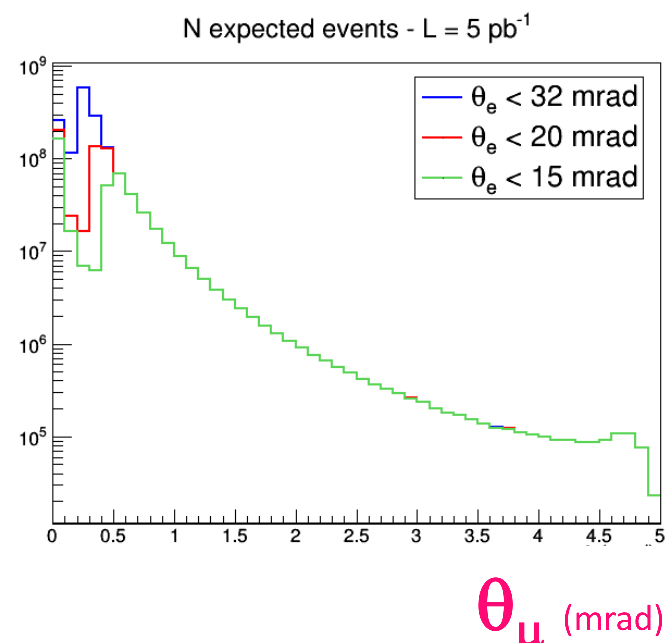
Definitely we will have sensitivity to the leptonic running (ten times larger)

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

Event kinematics

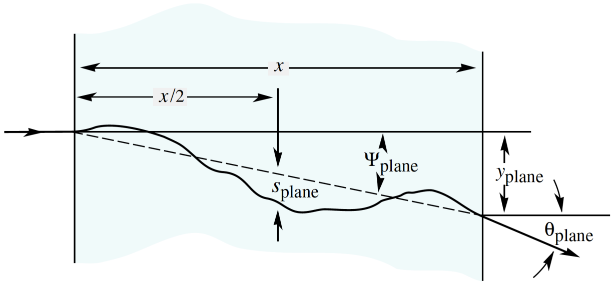






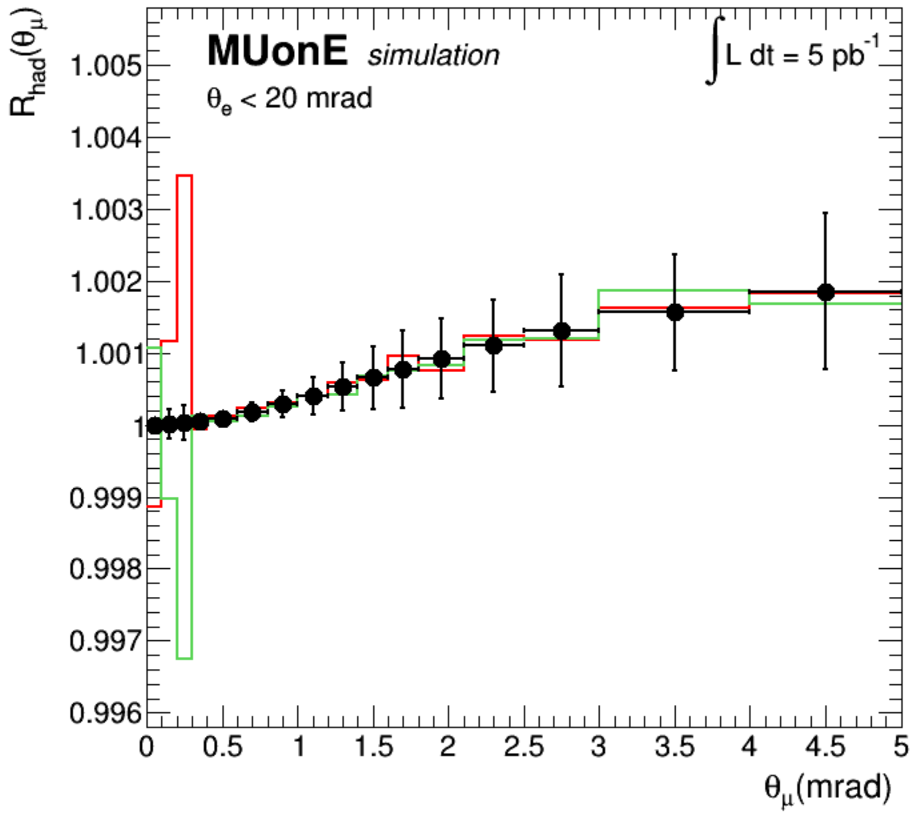
Systematic Effects: Multiple Coulomb Scattering

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

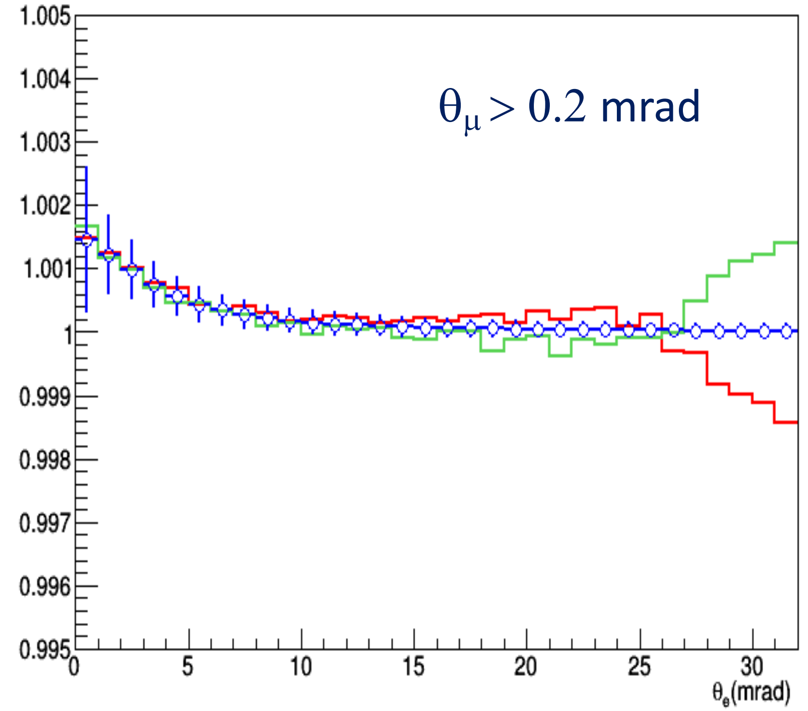


on the θ_μ distribution

arXiv:2012.07016



on the θ_e distribution



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

Fit of systematics

- First results using the CMS Combine tool, doing likelihood fits with systematics included as nuisance parameters
  - https://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/

- Currently 2 nuisance parameters introduced:
  - ν: normalization (Luminosity) $$N \rightarrow N\left(1 + \frac{\sigma(N)}{N}\right)^{\nu}$$

    $\sigma(N)/N=10^{-3}$ guess-estimated uncertainty on the luminosity

  - μ: shape (core width of Multiple Coulomb Scattering)

    $\sigma_{MCS} \rightarrow \sigma_{MCS}(1+\mu)$

- For each value of the signal parameter K, Combine is run to fit the nuisance parameters

- Best fit value of K is found by parabolic interpolation over the grid points

Fit of systematics: Test Run including Multiple Coulomb Scattering systematic

$$N \to N\left(1+\frac{\sigma(N)}{N}\right)^{\nu}$$

$\sigma_{MCS} \rightarrow \sigma_{MCS}(1+\mu)$

Pseudodata generated with μ=0.5%

Cuts	Fit results using (θ_e, θ_μ) distribution		
$\theta_\mu \geq 0.4\,\text{mrad}$ $\theta_e \leq 32\,\text{mrad}$	$K = (0.137 \pm 0.032)$	$\nu = 0.046 \pm 0.054$	$\mu = 0.510 \pm 0.020$
$\theta_\mu \geq 0.4\,\text{mrad}$ $\theta_e \leq 20\,\text{mrad}$	$K = (0.137 \pm 0.032)$	$\nu = 0.028 \pm 0.054$	$\mu = 0.515 \pm 0.022$
$\theta_\mu \geq 0.2\,\text{mrad}$ $\theta_e \leq 32\,\text{mrad}$	$K = (0.136 \pm 0.028)$	$\nu = -0.075 \pm 0.029$	$\mu = 0.509 \pm 0.012$
$\theta_\mu \geq 0.2\,\text{mrad}$ $\theta_e \leq 20\,\text{mrad}$	$K = (0.137 \pm 0.031)$	$\nu = 0.060 \pm 0.045$	$\mu = 0.514 \pm 0.018$

- Combine fit successfully determining the MCS nuisance to better than 5%
- No degradation on the signal parameter K
  - K and μ affects different kinematical regions

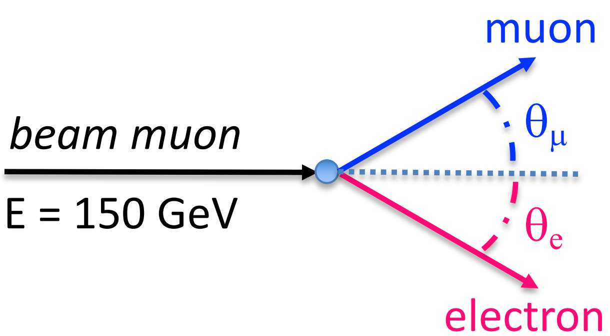
Systematic Effects: Beam Energy scale

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

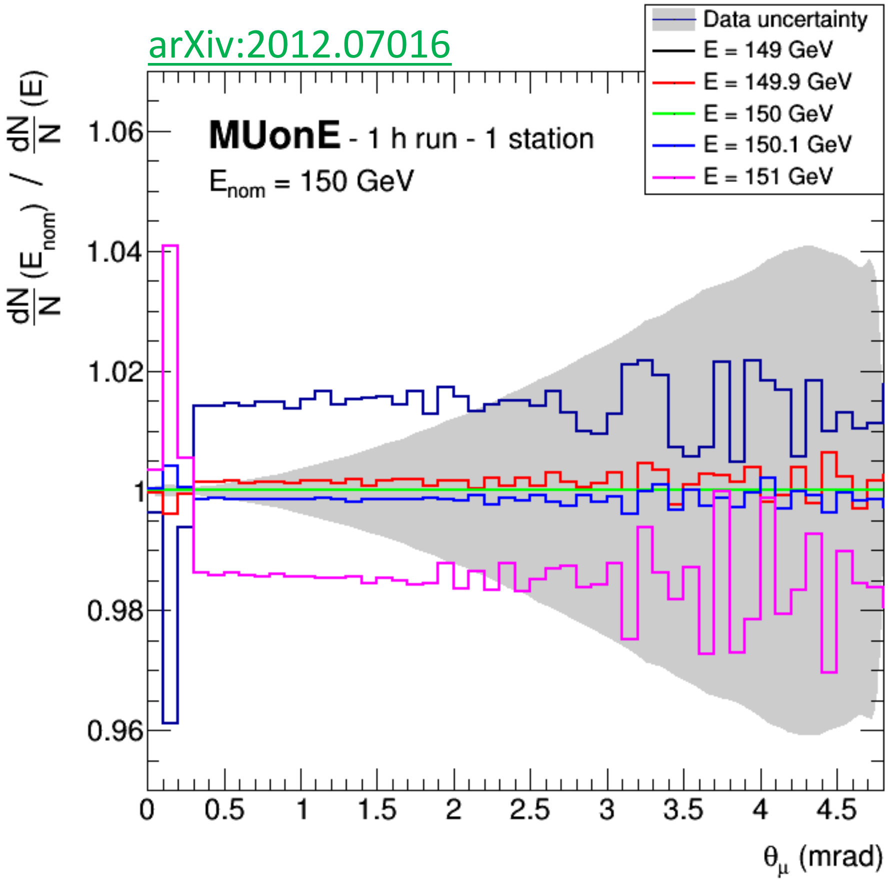


For equal angles:
$\theta_\mu = \theta_e \equiv \theta$

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

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

Background

- The main background in MUonE is the pair production from nuclear interactions: $\mu X \rightarrow \mu e^{+}e^{-} X'$

- The current (new) model implemented in GEANT4, is an approximation introduced for us in v.10.7, based on:

  A.G.Bogdanov et al, «*Geant4 simulation of production and interaction of muons*», IEEE Trans.Nucl.Sci. 53(2006)513

  http://cds.cern.ch/record/1020037

  - N.B.: previous versions completely neglected the angular distribution of e+e- pairs: the pair was produced as two collinear particles
  - A standalone generator for this process would be useful for the analysis, which needs fast tools
  - Also, it would be good to check/improve the model itself

- With real data the normalization and shape of this background will be checked directly in control regions and the model will be tested and tuned. In the end the model will be used to predict the residual contamination in the signal region. Therefore it has to be precise.

Summary

- MUonE analysis is based on a template fit of the angular distributions, using reweighting of the effective QED coupling with a convenient parameterisation (one-loop QED, *Lepton-Like*, with only 2 parameters). The expected statistical accuracy achievable on a_{μ}^{HLO} for the nominal integrated luminosity is 0.35%. The systematic error of the fit method is found to be negligible.

- Prospects for the 2022 TestRun with 3 stations have been assessed
  - Initial sensitivity to the hadronic running, measurement of the leptonic running

- Systematic effects have been studied which can be controlled mostly from data itself
  - E.g. Systematic error of ~1% on the core width of multiple scattering can be easily fitted from data

- Impact of the background from pair production in the material to be studied quantitatively. Need a standalone MC generator.

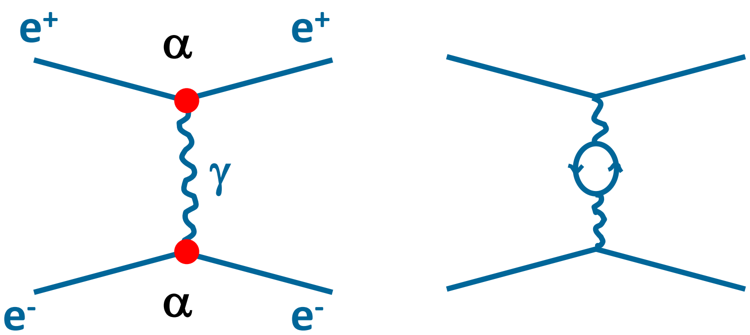
BACKUP

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

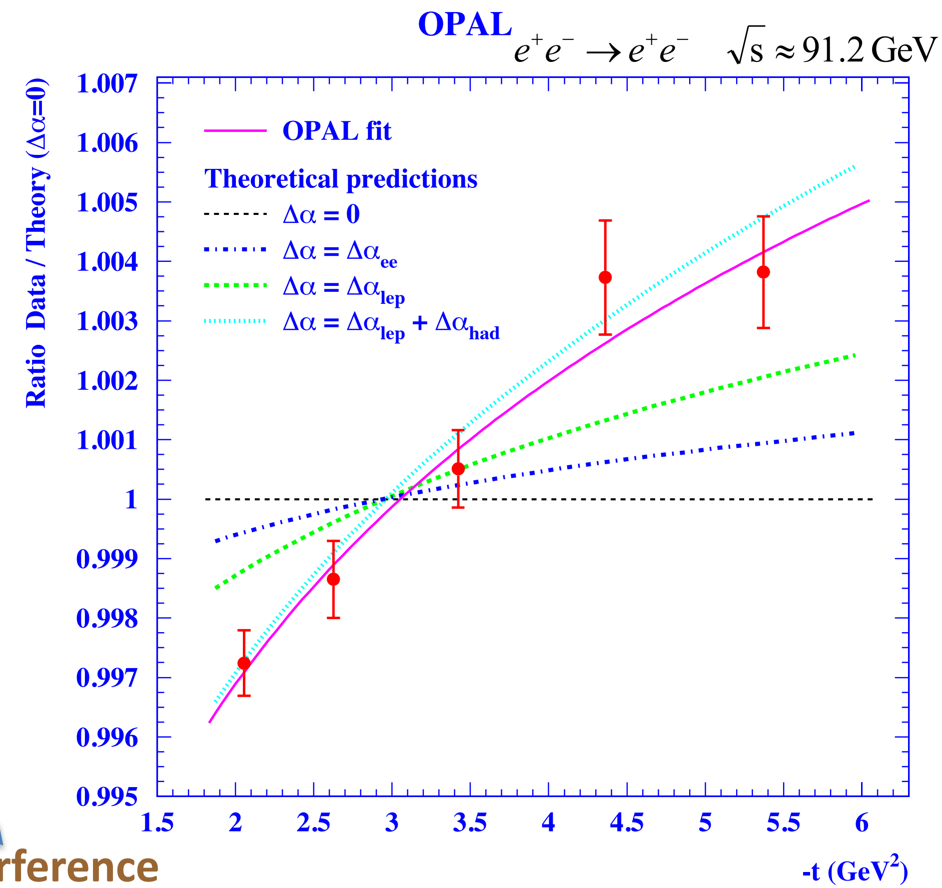
$$\left(\frac{1}{1-\Delta\alpha(t)}\right)^2$$

Effective coupling factorized

Photonic radiative corrections

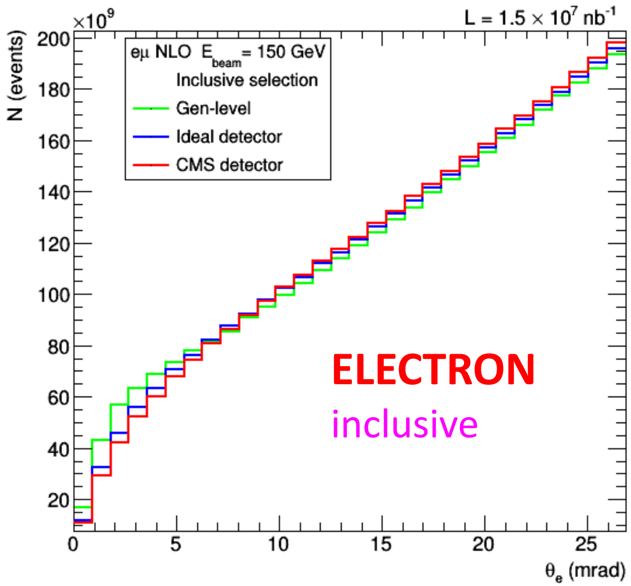
s-channel γ exchange correction

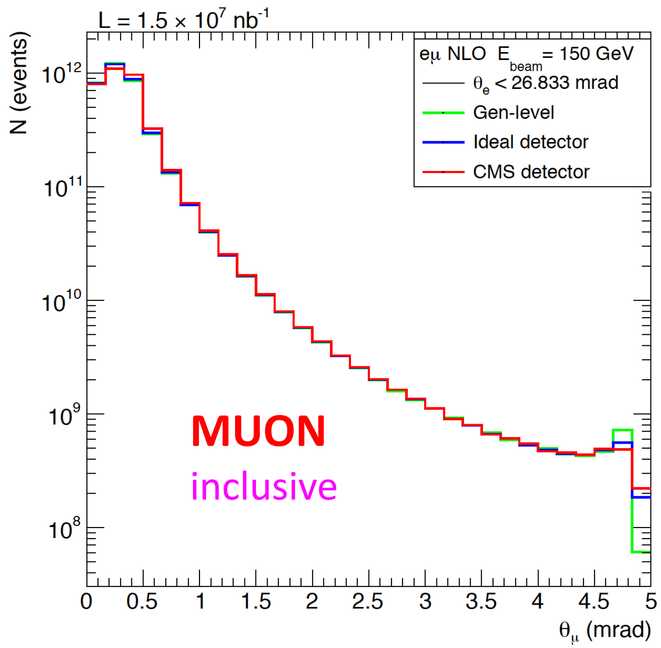
Z interference correction

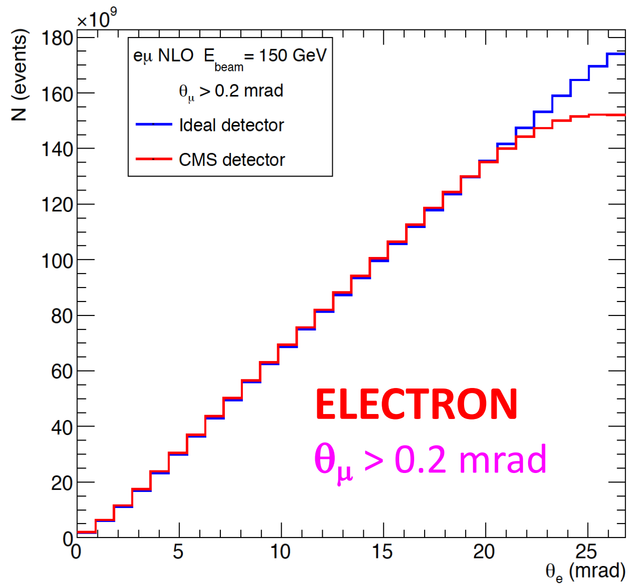


Other measurements in the space-like region by L3, VENUS

NLO eμ Angular distributions

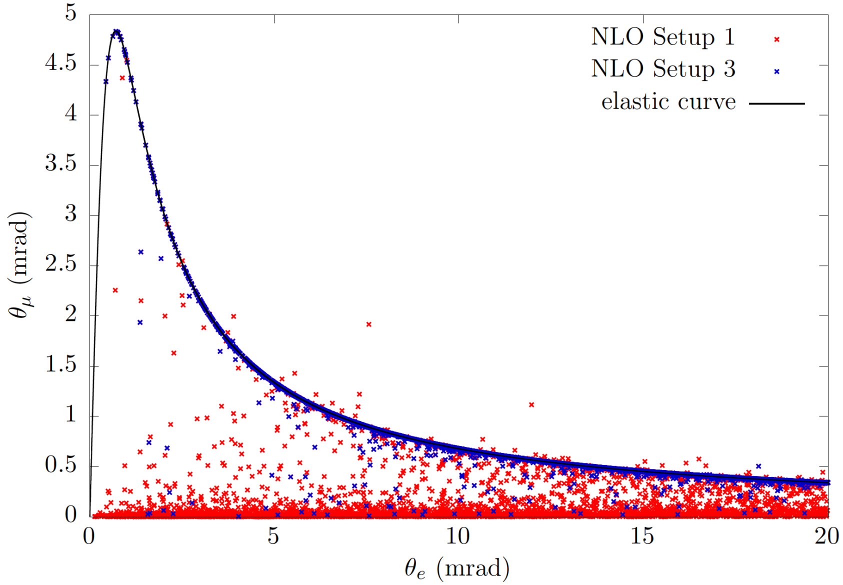






Event yield ~10^{12} (Ee>1 GeV) for the nominal integrated Luminosity $L = 1.5 \times 10^7$ nb^{-1}

Radiative events and elastic selection



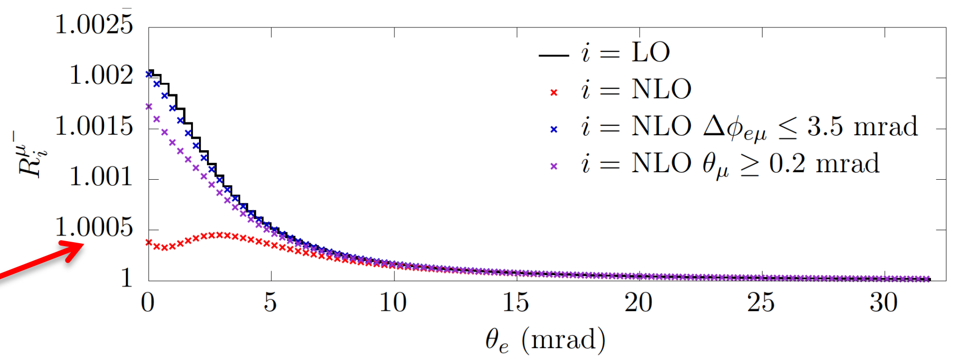
M.Alacevich et al, JHEP02(2019)155

NLO:

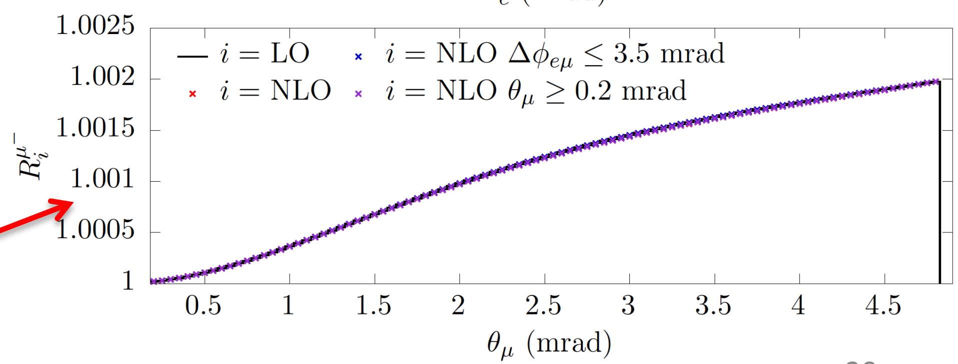
Setup 1 is the inclusive selection (no cuts)

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

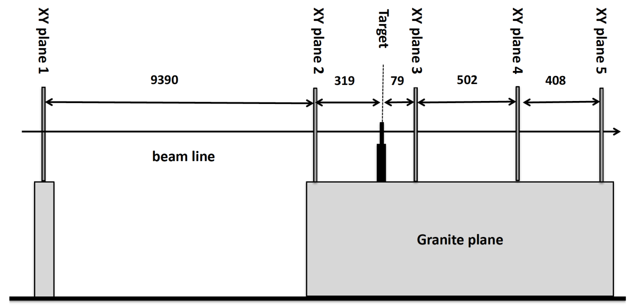


Instead the muon angle is a robust observable, stable w.r.t. radiative corrections -> it can be used with an inclusive selection (theoretically advantageous)



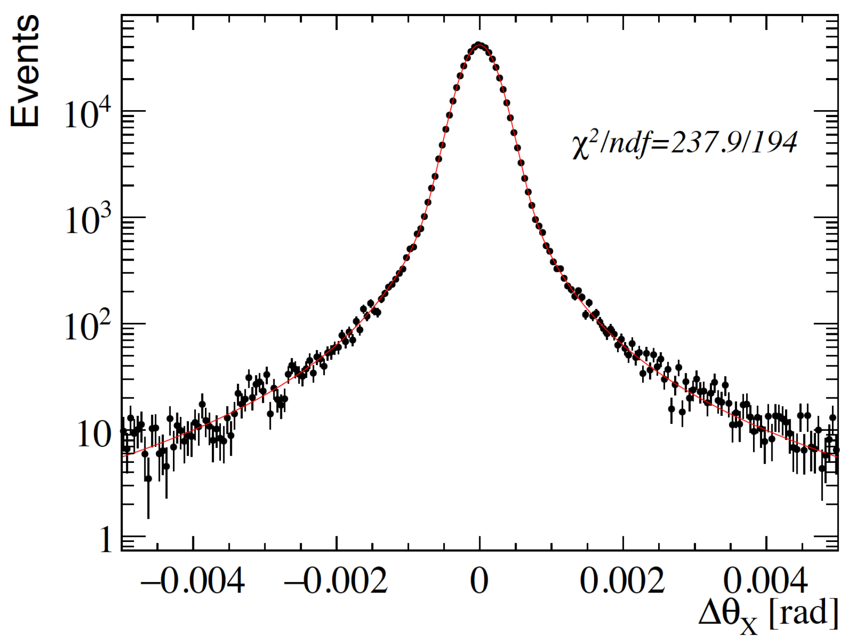
2017 Beam Test: Multiple Coulomb scattering

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

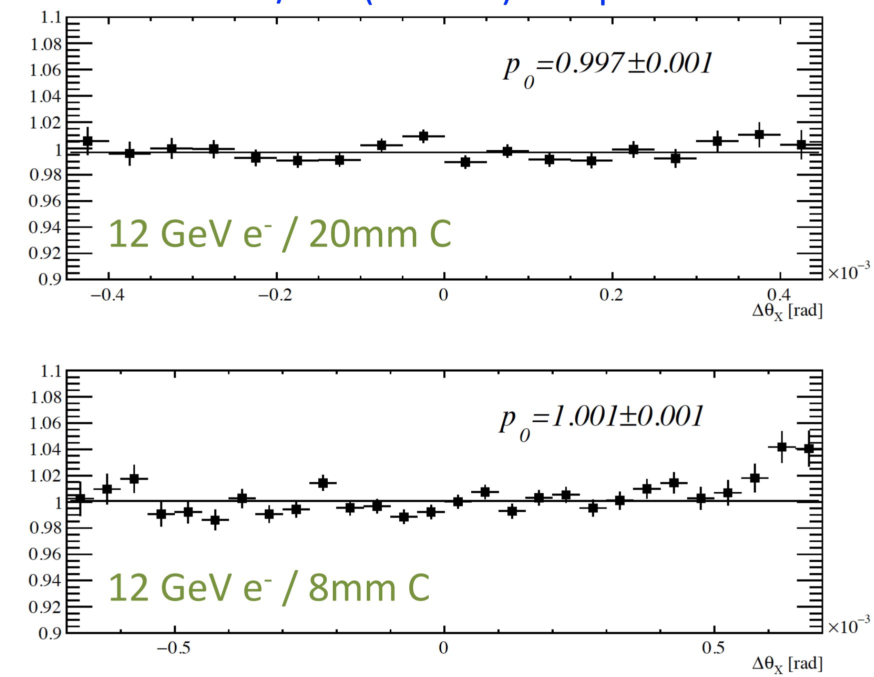


Adapted UA9 detector at CERN H8 Beam Line

DATA 12 GeV e- / 8mm C



DATA/MC (Geant4) comparison

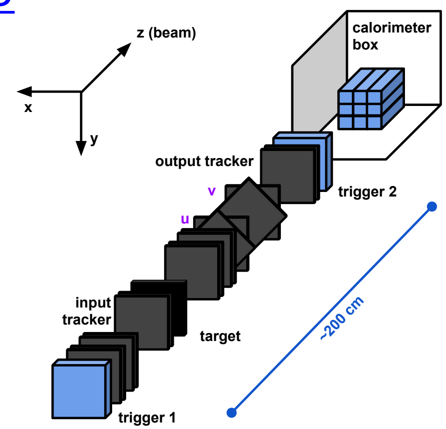


- Good description of data with a fit.
- Distribution core within 1-few % from GEANT.

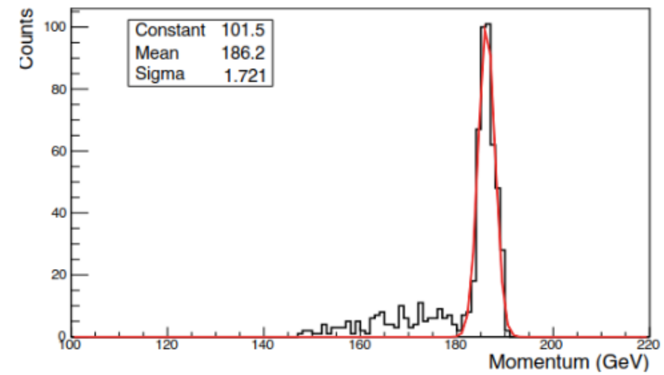
2018 Beam Test: μe elastic scattering

JINST 16 (2021) P06005

CERN North Area, downstream COMPASS
8mm C target
Si strip tracking (sensors from AGILE, with worse resolution than MUonE)
Small BGO ECAL

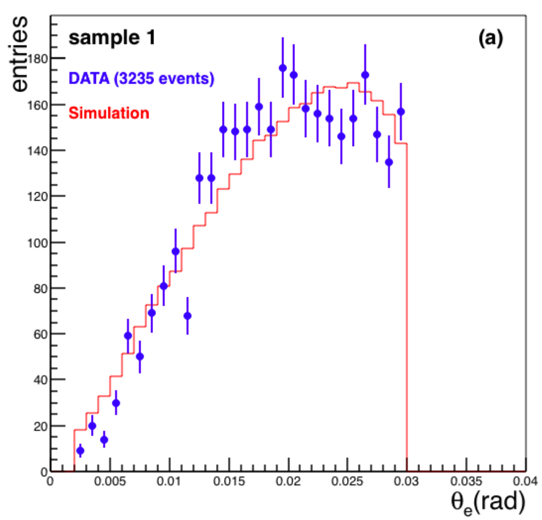


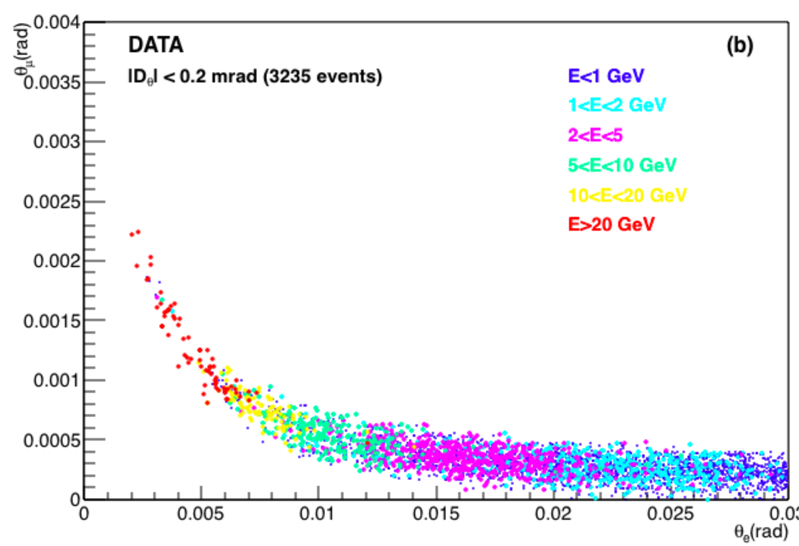
μ spectrum peaked at 187 GeV
From decays of 190 GeV beam π
1m W dump absorbing all surviving π



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

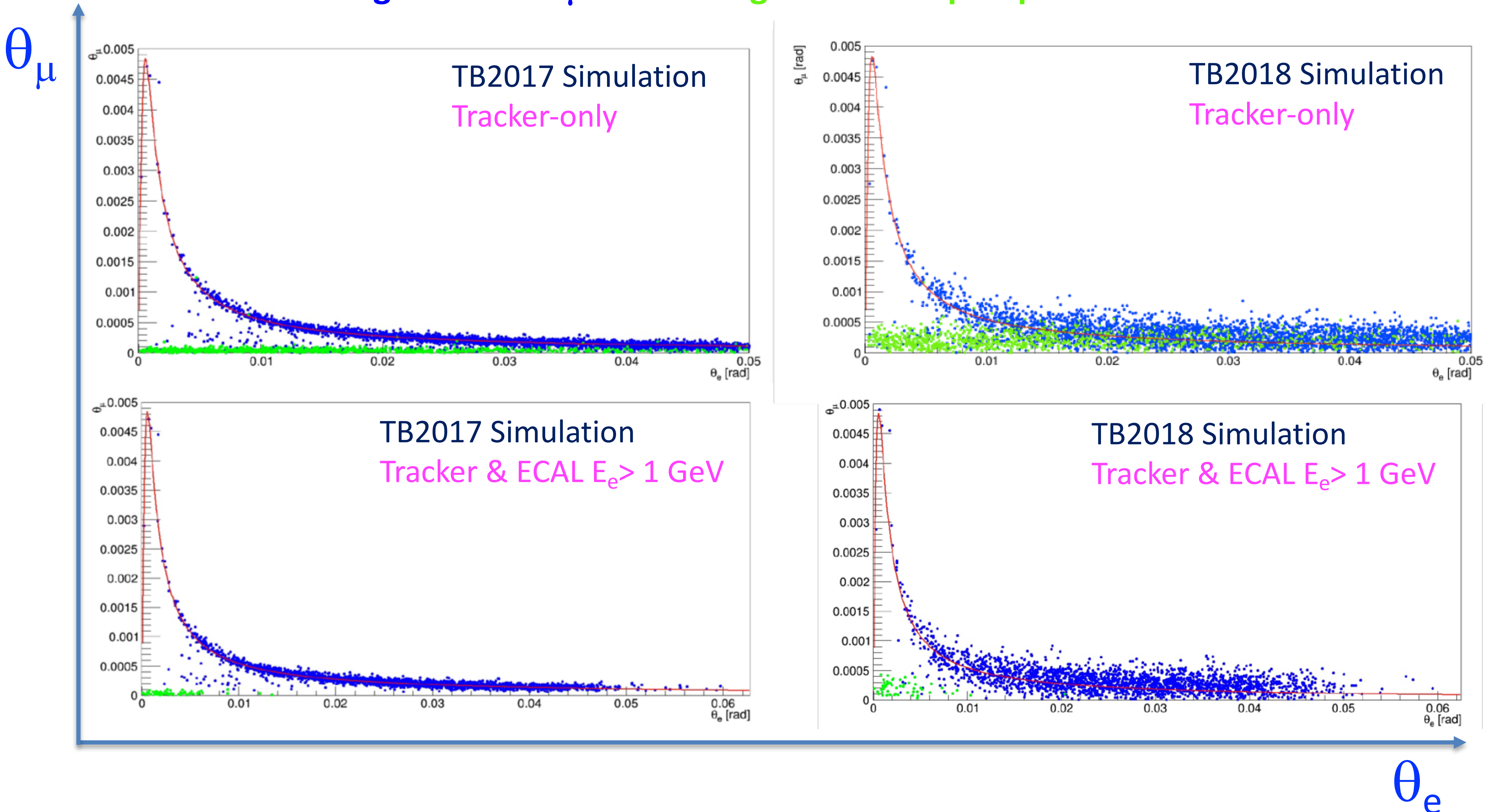
New GEANT4 version 10.7 (validation ongoing)

GEANT4 simulations

Effect of the position resolution on θ_μ vs θ_e distribution:

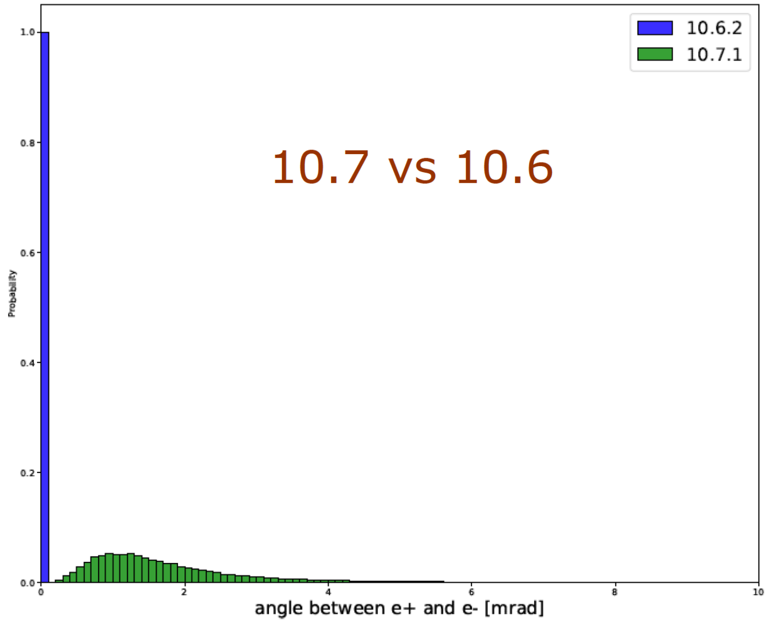
(Left) TB2017: UA9 resolution 7μm ; (Right) TB2018: resolution ~35-40μm

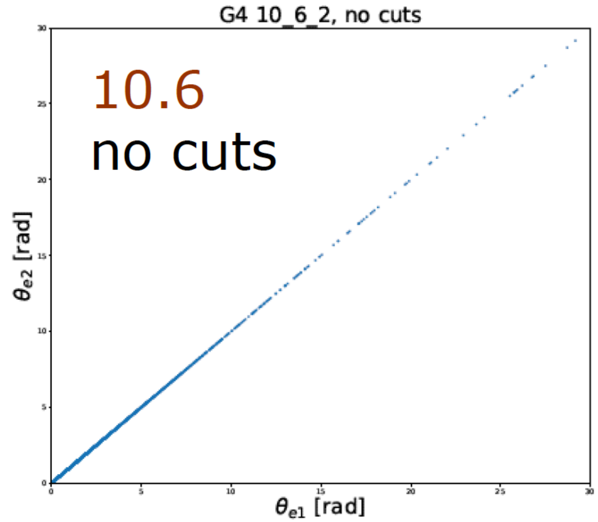
Signal: elastic μe **Background: e^+e^- pair production**

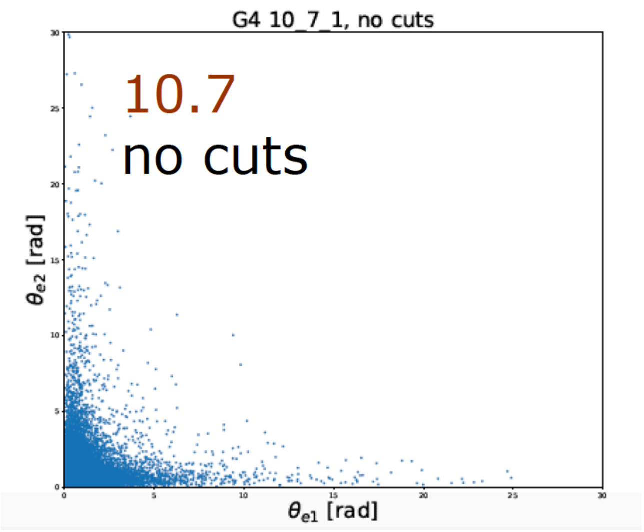


Background: Validation of new GEANT4 version

$\mu X \rightarrow \mu e^+e^- X'$ (X is a nucleus)
our main background







Unreliable simulation in the old version, no attempt to simulate the angular distribution of the electron-positron pair

Ongoing validation and background studies