MUonE experiment at SPS

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Zakład XVII

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Outline

- Muon *g*-2
- a_μ in Standard Model
- How to measure a_μ
- Over 40 years of muon *g*-2 measurements
- Future experiments precision and theoretical errors
- How to measure hadronic contribution to a_μ
- MUonE experiment at SPS
- Kraków group contribution

Magnetic moment of the muon

Interaction of particle with static magnetic field

$$V(\vec{x}) \;=\; -\vec{\mu}\cdot\vec{B}_{\text{ext}}$$

The magnetic moment $\vec{\mu}$ is proportional to its spin *($c = \hbar = 1$)*

$$\vec{\mu} \;=\; g\left(\frac{e}{2m}\right)\vec{S}$$

The Landé *g*-factor is predicted from the Dirac equation to be

$$g \;=\; 2$$

g - gyromagnetic ratio

for elementary *(pointlike)* fermions

In reality: $g > 2 \;\rightarrow$ anomalous magnetic moment

$$a_\mu = \frac{g-2}{2}$$

Muon *g-2*

Additional effects from QED, electroweak theory and hadronic factors move SM prediction of *g* away from 2 $\rightarrow$ we measure difference *g-2*

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}$$

If a discrepancy with SM value is found, beyond SM contributions to *g-2* could come from SUSY, dark photons, extra dimensions or other new physics *(NP)*

- QED:
  - known to 5-loop
  - 99.99% of a_μ^{SM}
  - ~0.001% of $\delta a_\mu^{\mathrm{SM}}$
- EW:
  - known to 2-loop
  - 0.0001% of a_μ^{SM}
  - 0.2% of $\delta a_\mu^{\mathrm{SM}}$
- Hadron:
  - 0.006% of a_μ^{SM}
  - ~99.8% of $\delta a_\mu^{\mathrm{SM}}$

- able to reduce QED and EW uncertainties to $O(10^{-11})$
- QCD contribution: *pQCD* cannot be employed

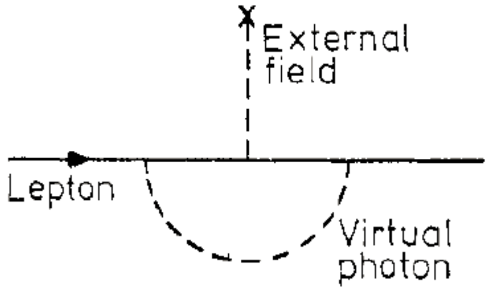
a_μ in Standard Model - **QED**

[Ann. Rev. 62, 237–264 (2012)]

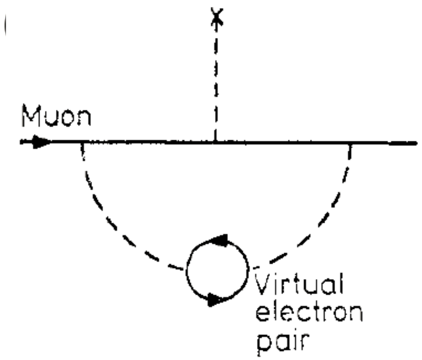
QED treats $a_\mu \neq 0$ by correcting it for self-interaction processes

- quantum fluctuations associated with emission and absorption of virtual photons
- polarization of the vacuum by these photons into virtual particle-antiparticle pairs

lowest-order



second lowest-order



$$a_\mu^{\rm QED} = \frac{\alpha}{2\pi} + 0.765\,857\,425(17)\left(\frac{\alpha}{\pi}\right)^2 + 24.050\,509\,96(32)\left(\frac{\alpha}{\pi}\right)^3 + 130.879\,6(6\,3)\left(\frac{\alpha}{\pi}\right)^4 + 753.3(1.0)\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

$$\boxed{a_\mu^{\rm QED} = 116\,584\,718.95(0.08) \times 10^{-11}}$$

- recent calculations to 5th order in α reduce QED uncertainty to ~10^{-13}

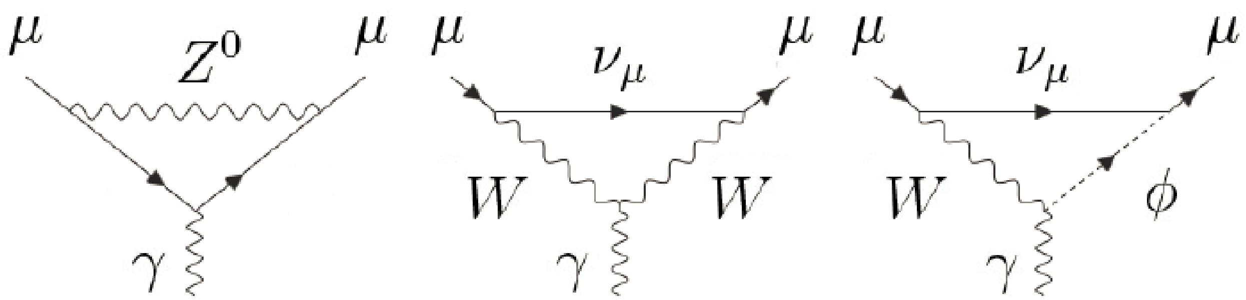
a_μ in Standard Model - **EW**

[Ann. Rev. 62, 237–264 (2012)]

EW term of a_μ groups all the loop contributions that involve W, Z, Higgs bosons and neutrinos

- such processes are suppressed by at least $(\alpha_0\, m_\mu / \pi\, M_W)^2 \sim 4 \times 10^{-9}$ wrt QED

EW lowest-order self-interaction processes

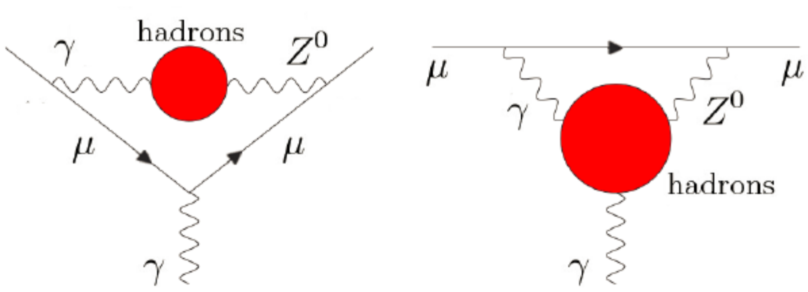


$$a_\mu^{\mathrm{EW}}[\text{1-loop}] = 194.8 \times 10^{-11}$$

$$a_\mu^{\mathrm{EW}}[\text{2-loop}] = -41.2(1.0) \times 10^{-11}$$

$$\boxed{a_\mu^{\mathrm{EW}} = 153.6(1.0) \times 10^{-11}}$$

Hadronic loops



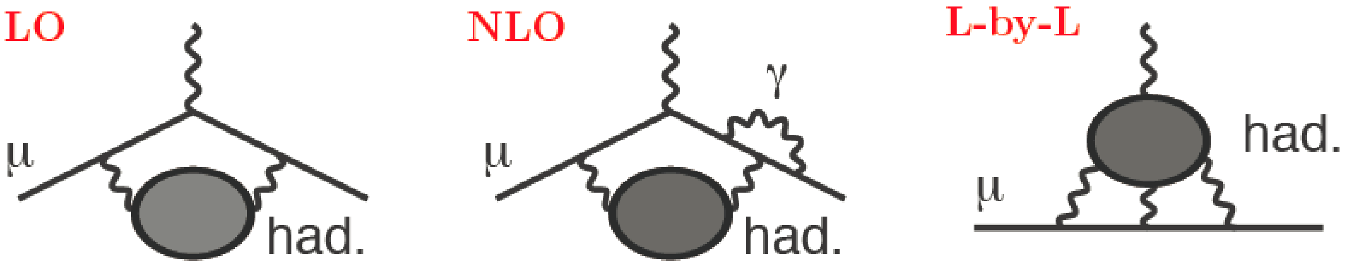
- measurement of Higgs mass reduces electroweak error from 2×10^{-11} to 1×10^{-11}

a_μ in Standard Model - **QCD**

Most of the $a_\mu(SM)$ uncertainty comes from self-interaction processes with hadronic loops

- contributions of these effects cannot be computed from first principles
- predominant correction comes from the hadronic leading-order contribution
  - $\rightarrow$ *lowest-order hadronic loop vacuum polarization process*
  - $\rightarrow$ *it involves long-distance interactions for which pQCD cannot be employed*

$$a_\mu^{\mathrm{had}} = a_\mu^{\mathrm{had,VP\ LO}} + a_\mu^{\mathrm{had,VP\ NLO}} + a_\mu^{\mathrm{had,Light-by-Light}}$$



LBL model-dependent calculations, improvement expected from lattice calculations

HVP based on the hadronic cross-section e^+e^-data, efforts to get with lattice

LO hadronic contribution

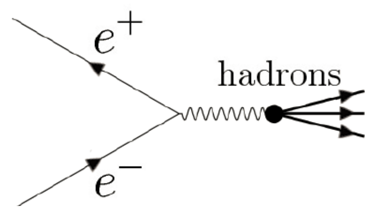
[Ann. Rev. 62, 237–264 (2012)]

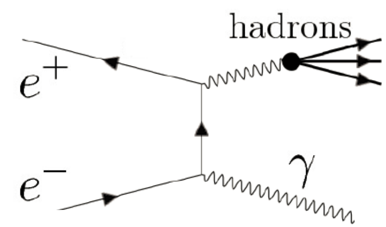
Hadronic vacuum polarization contribution determined from e^+e^- → *hadrons* measurements at BESIII, CMD3, BaBar, KLOE, VEPP-2000

- dispersion relation + experimental cross-section e^+e^- *(and τ)→ hadrons*

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha_0^2}{3\pi^2}\int_{4m_\pi^2c^4}^{\infty} ds K(s)\sigma^{(0)}(s)$$

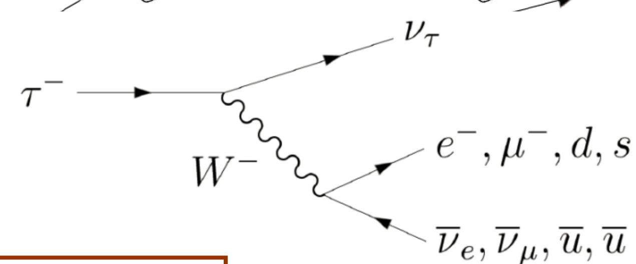
$\sigma^{(0)}$ → total x-section e^+e^-→ *hadrons*
kernel function *K(s) ~ 1/s*





- σ from experiments & subtracted from ISR and vacuum polarization corrections

- improved by integrating e^+e^- data with spectra of hadronic τ decays *(isospin-breaking corrections)*



$$\boxed{a_\mu^{\mathrm{had,LO}} = \begin{cases} 6963(62)(36)\times 10^{-11} & e^+e^- \\ 7110(50)(8)(28)\times 10^{-11} & \tau \end{cases}}$$

$$a_\mu^{\mathrm{h,HO}} = -100(6)\times 10^{-11}$$

$$a_\mu^{\mathrm{LbL}} = 86(35)\times 10^{-11}$$

- lattice also tried *(not so precise)*

All approaches to determine LO hadronic correction heavily model-dependent

Discrepancy wrt SM

Adding predictions and combining errors in quadrature → overall SM prediction

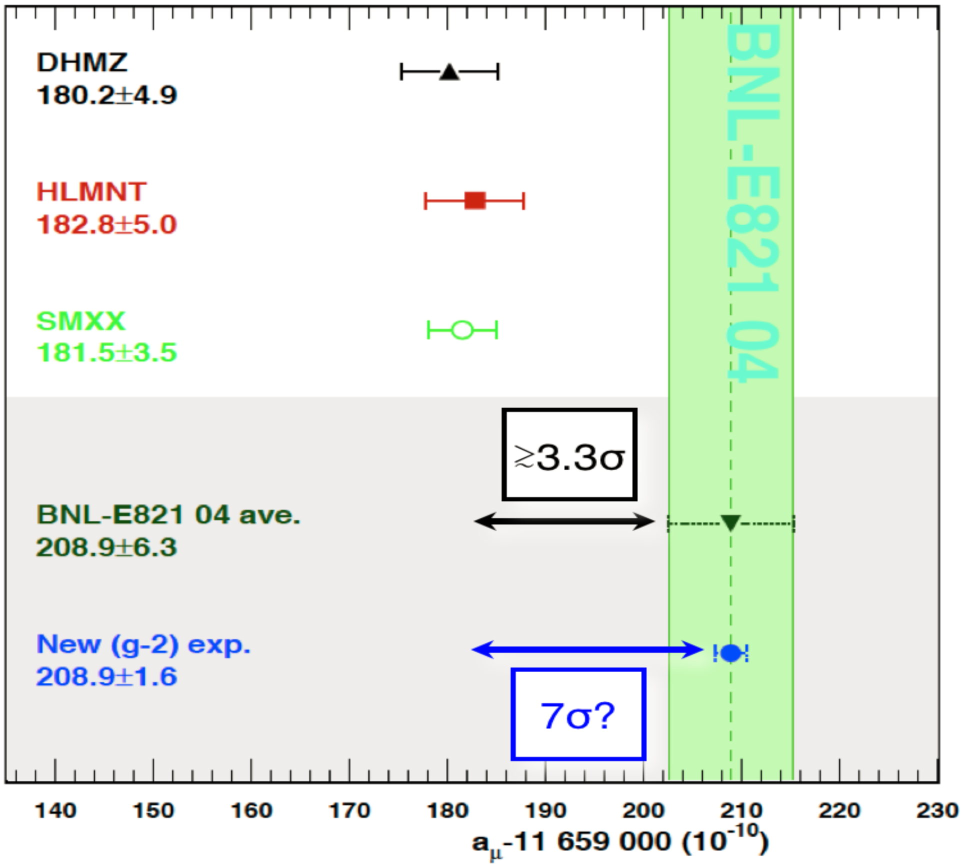
$$a_\mu^{\rm SM} = 116591803(49) \times 10^{-11} \qquad a_\mu^{\rm exp} = 116592091(54)(33) \times 10^{-11}$$

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = 288(80) \times 10^{-11}$$

- this gives **3.7σ** discrepancy between SM and measurements
- many contributions to SM prediction model- and dataset-dependent

  → *most of independent calculations leads to discrepancies at 3-4σ level*

New experiments will lower exp. error from 0.5 ppm to ~0.14 ppm in few years

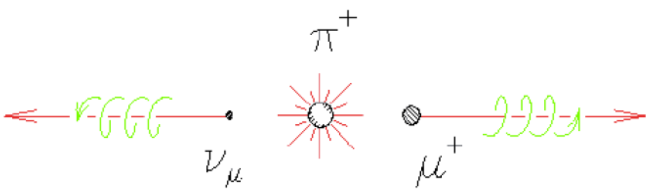


How to measure a_μ ?

Parity violation in $\pi \to \mu \to e$ decay chain $\to$ *way to measure muon mag. moment*

- muon from spin-0 positive *(negative)* pion decay at rest
  - $\to$ pion with zero final orbital angular momentum *(short range of the weak force)*
  - $\to$ as neutrino *(antineutrino)* is left *(right)* handed *(helicity -1 (+1))*
  - $\to$ muon 100% polarized to conserve angular momentum *(helicity -1 (+1) - born longitudinally polarized in the pion rest frame)*

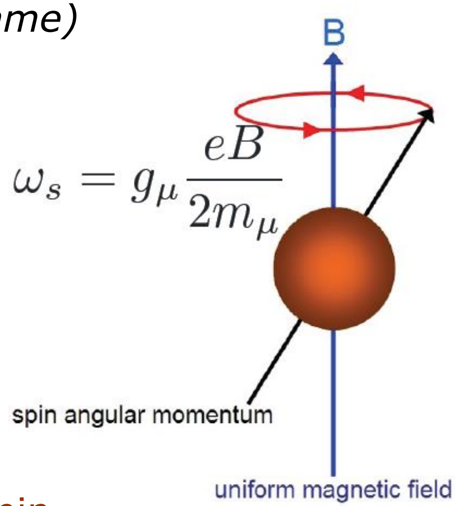
$$\pi^+ \to \mu^+ \nu_\mu$$



- beam of pions
  - $\to$ very forward / very backward muons are highly polarized

Polarized muon spin at rest in a magnetic field will precess

$$\omega_s = g_\mu \frac{eB}{2m_\mu}$$

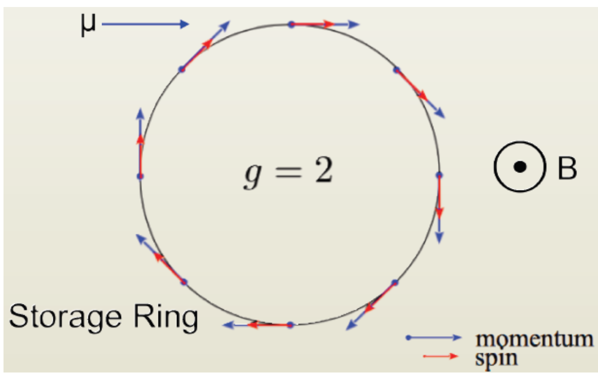


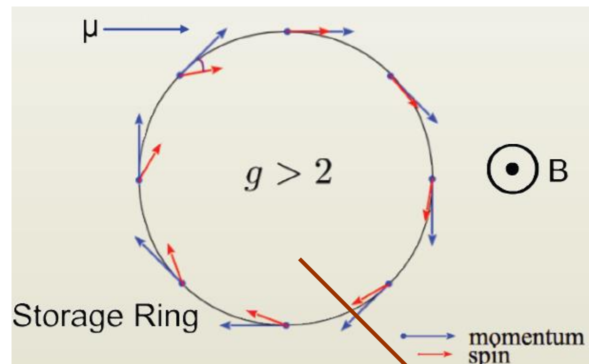
- if $a_\mu \neq 0$ there is a precession between momentum and spin vectors
- weak interaction provides information where muon spin was initially
  - $\to$ in the decay, highest energy electrons are correlated with muon spin
  - $\to$ in parity violating decay $\mu^- \to \nu_\mu e^- \overline{\nu}_e$ positron is preferentially emitted in the muon spin direction

Experimentally: how to measure ?

- put (polarized) muons in a magnetic field and measure spin precession f.q.
- get muon spin direction from decayed electrons
- a_μ ~ difference between spin precession frequency and cyclotron frequency
  - $\rightarrow$ if $g_\mu = 2$: spin always aligns with momentum
  - $\rightarrow$ if $g_\mu \neq 2$: spin beats against momentum, oscillating radially

$$\omega_c = \frac{eB}{mc}$$

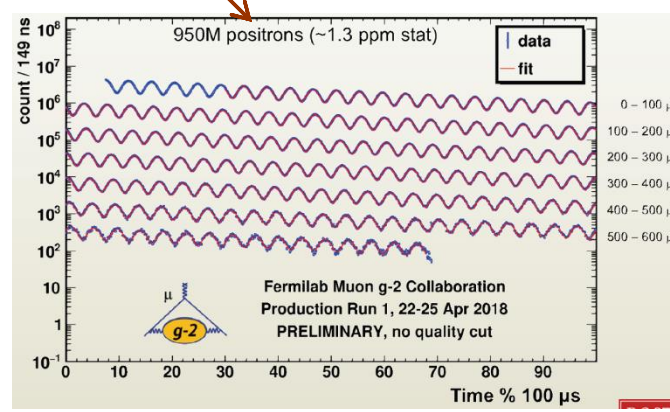




$$\omega_s = g\frac{eB}{2mc}$$

$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = a_\mu \frac{eB}{mc}$$



Measurements of ω_a and B field provide a_μ

Real world considerations

With the presence of both electric and magnetic fields

$$\omega_a = -\frac{Qe}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

Anomalous magnetic moment independent of the electric field

- larger γ, longer muon lifetime, more *g*-2 circles observed $\rightarrow$ OK

Problem: particles are not stored in the uniform magnetic field

Solution: introduce gradient with electric field to build a trap

But not all muons are at magic momentum *(Δp = 0.5%)*, i.e. the term is not completely vanished

- vertical motion of the beam can be corrected for by measuring beam profile
  $\rightarrow$ *using scintillating fiber tracker and straw tube trackers*

A precise map of the field is needed in order to achieve highly precise results
$\rightarrow$ *field measurements are often based on proton NMR*

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Penning Trap

$$\gamma = \sqrt{1 + 1/a}$$

$$p = m\sqrt{\gamma^2 - 1}$$

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Problem: particles are not stored in the uniform magnetic field

Solution: introduce gradient with electric field to build a trap

$\gamma_{\text{magic}} = 29.3$

$p_{\text{magic}} = 3.09$ GeV/c

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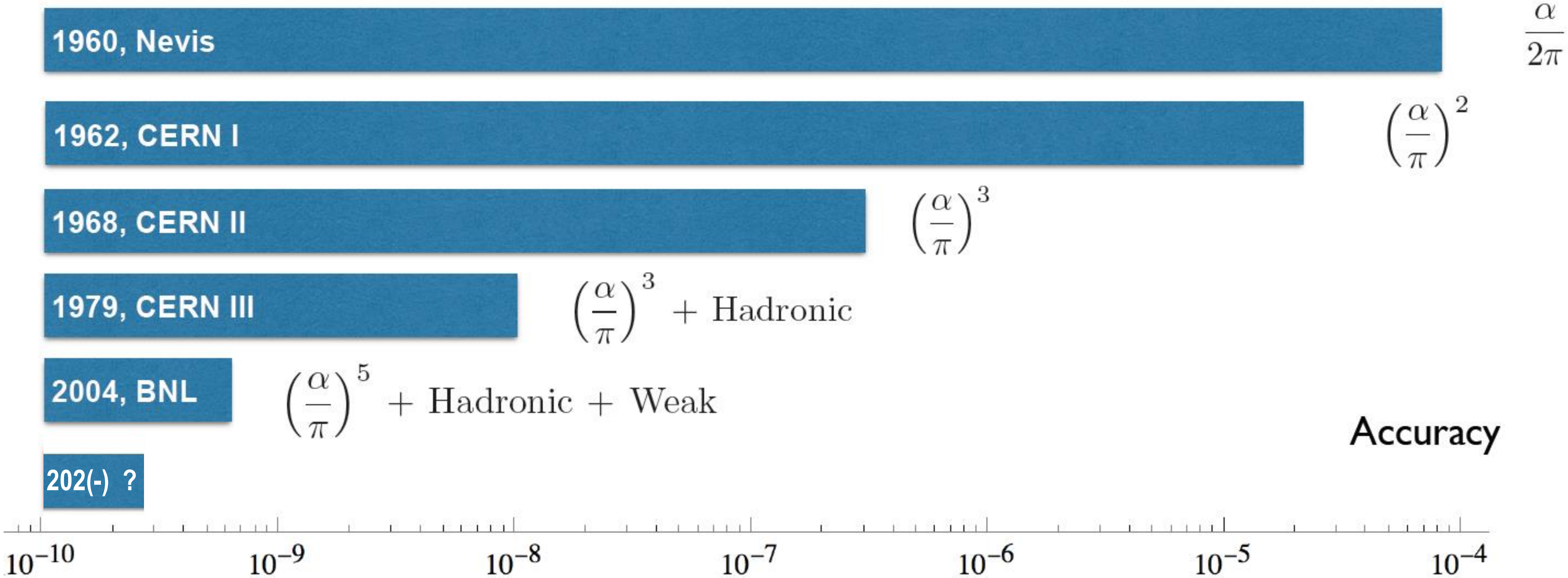
Over 40 years of muon g-2

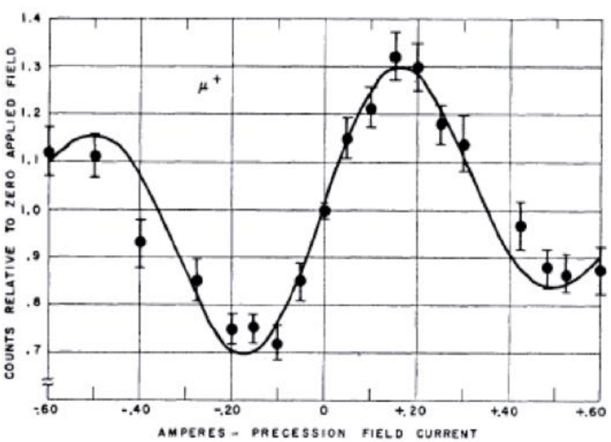


First muon spin rotation experiment at Nevis cyclotron

- mixed beam of π^+ and μ^+ of ~100 MeV
- muons stopped in a carbon target, placed in magnetic field
- scintillator telescope measured $\mu^+ \to e^+ \nu_\mu \bar{\nu}_e$ decay
- mag. field varied, higher causing more spin precession before decay

muon g-2 measured with ~10% precision, a_μ with ~35%

number of counts wrt magnetic field

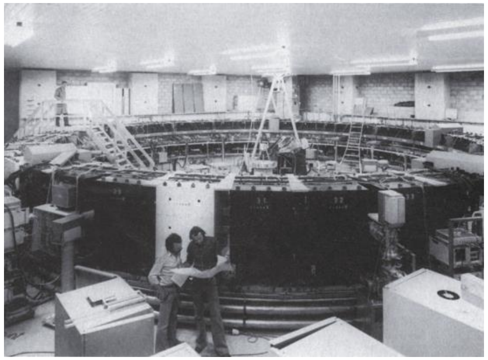


Over 40 years of muon *g*-2

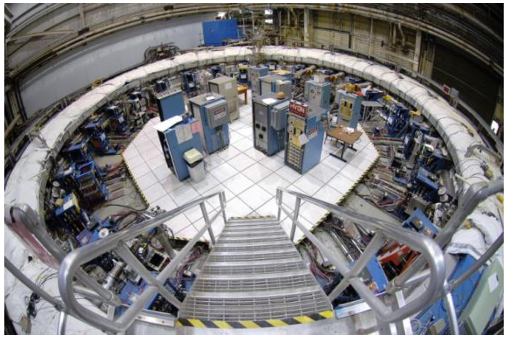
- CERN I (1958-1962)
  - → ~150 MeV positive muons from the pion in-flight decays in synchro-cyclotron
  - → first measurements, (*g*-2) to 0.4%
- CERN II (1962-1968)
  - → first muon storage ring (MSR), magnetic focusing
  - → (*g*-2) to 270 ppm
- CERN III (1969-1976)
  - → second MSR, electric field focusing, γ_m = 29.3, p_μ = 3.09 GeV
  - → vertical electric focusing did not affect measured a_μ because of magic γ *(Penning Trap)*
  - → (*g*-2) to 7 ppm
- **BNL E821 (1990-2003)**
  - → superferric magnet, high intensity beam, muon injection
  - → (*g*-2) to 0.5 ppm
- **FNAL, J-PARC (202(-))**
  - → improvements in all aspects
  - → **(*g*-2) to 0.14 ppm**

CERN synchro-cyclotron

CERN second MSR



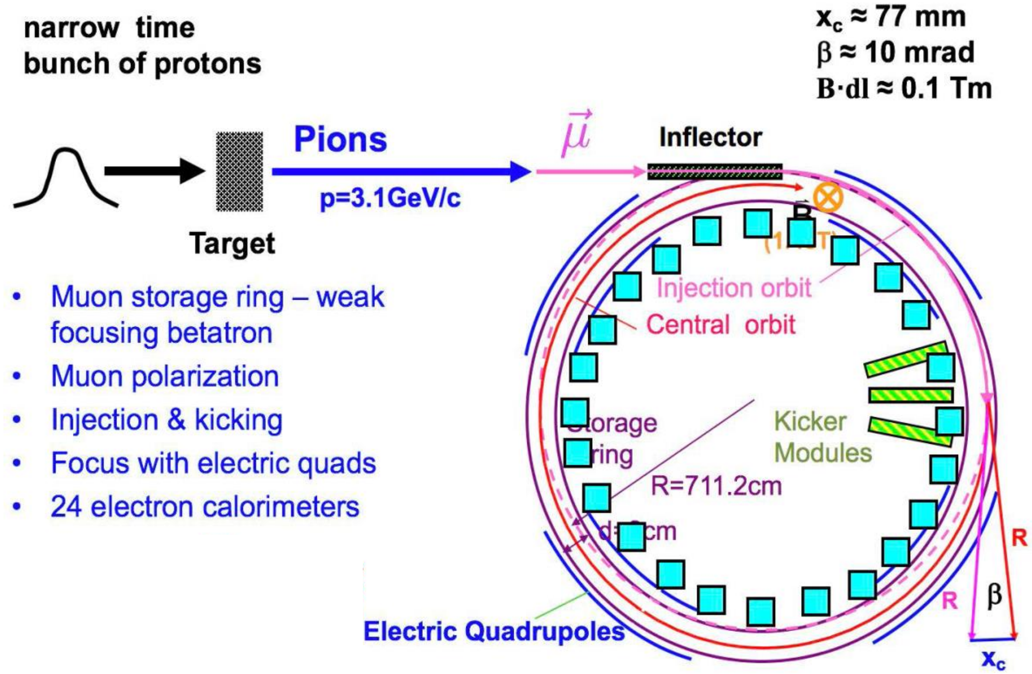
E821 MSR



Future experiments: E989 at Fermilab

- plan to collect 21 × BNL statistics
  - reduce stat. error by a factor of 4
  - more rapid rate of filling (12 Hz)
  - increased nr of muons per fill
    (5-10) × 10^4 / fill
- re-usage of E821 storage ring
  - pure muon beam with no hadronic component
  - reduce beam power, p_μ closer to p_{magic}
  - increase injection efficiency
- error on ω_a reduced from 0.18 ppm in E821 to 0.07 ppm in E989
  - improved laser calibration
  - segmented calorimeter
  - better collimator in the ring
  - improved tracker
- error on ω_p reduced to 0.07 ppm

- uniformity and monitoring of mag. field
- fixed NMR probes measure time variations of the field during data taking
- better temperature stability of magnet



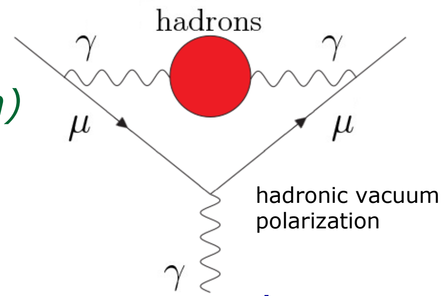
Data taking started in 2019

Goal: **improvement in precision to 0.14 ppm**

Hadronic terms: novel experimental approach

If results from new generation *g*-2 experiments at Fermilab and J-PARC reach their asymptotic precision *(to ~0.10-0.14 ppm)*

→ **hadronic contributions to a_μ(SM) will be a main limitation on muon anomaly!**



Now: hadronic leading-order contribution evaluated via dispersion integral

- relies on experimental e^+e^- hadronic cross sections *(accuracy ~0.6%)*
- at low energy experimental results heavily fluctuate

  → *hadronic resonances and particle production threshold effects*

A novel method exploits space-like processes

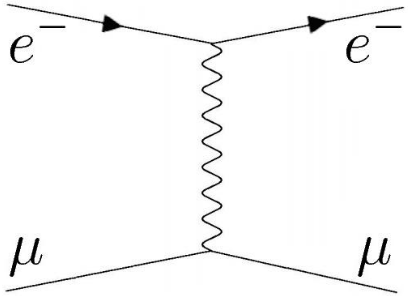
- determination of a_μ^{HLO} from scattering μ-*e* data

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

$t(x) = q^2(x) = x^2 m_\mu^2 c^4/(x-1)$ is the squared 4-momentum transfer

$\Delta\alpha_{\mathrm{had}}(t)$ is the hadronic contribution to the running of $\alpha(t)$

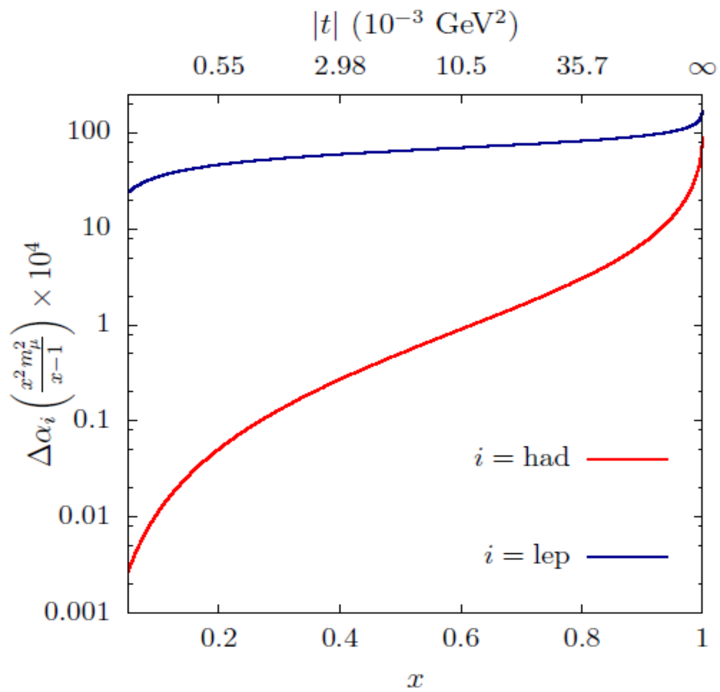
$\alpha_0 = e^2/\hbar c$ is the fine structure (or Sommerfeld's) constant



lowest-order contribution to μ-*e* elastic scattering

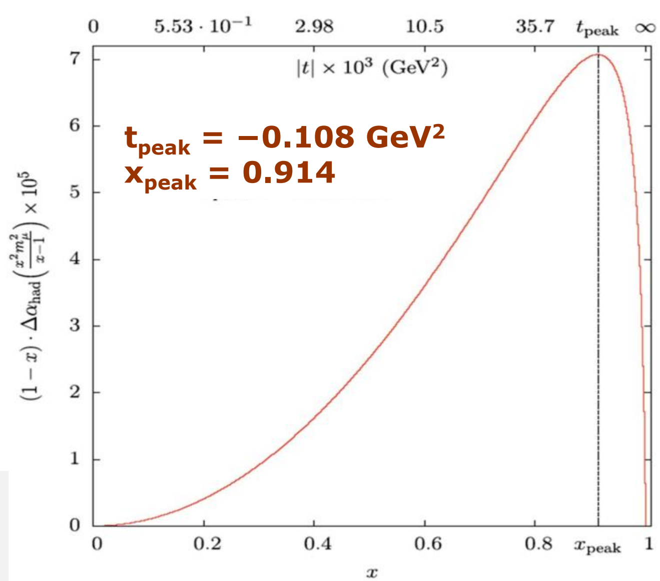
Hadronic terms: novel experimental approach

Hadronic and leptonic contribution to running fine-structure constant



$$\alpha(t) = \frac{\alpha_0}{1 - (\Delta\alpha_{\mathrm{lep}}(t) + \Delta\alpha_{\mathrm{had}}(t))}$$

- hadronic contribution $\Delta\alpha_{had}(t)$ extracted from $\alpha(t)$
  - in the space-like region *($x \in (0\text{-}1)$ and $t(x) < 0$)*
- leptonic contribution well known from perturbative calculations
- a_μ^{HLO} evaluated via sum rule in eq. on slide 15



- integrand of a_μ^{HLO} smooth and free of resonances
- experimental data on *t*-channel processes needed:
  - → space-like contribution to Bhabha scattering
  - → **fully space-like *μ-e* elastic scattering**

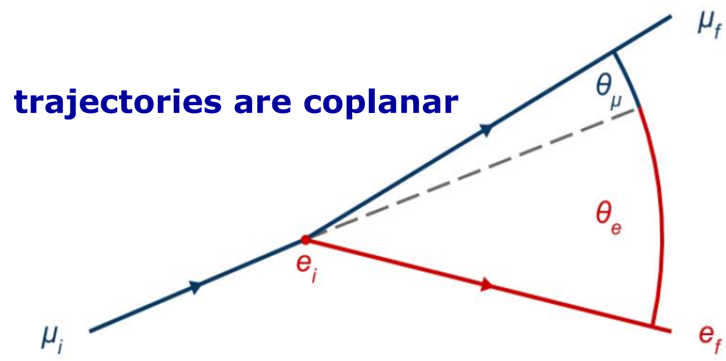
Measure differential cross-section as a function of t on a range which spans the t_{peak} value

a_μ^{HLO} via muon-electron scattering

Elastic scattering of high-energy muons on the atomic electrons in a low-Z target

- running of fine-structure constant can be extracted from differential x-section for μ-e elastic scattering

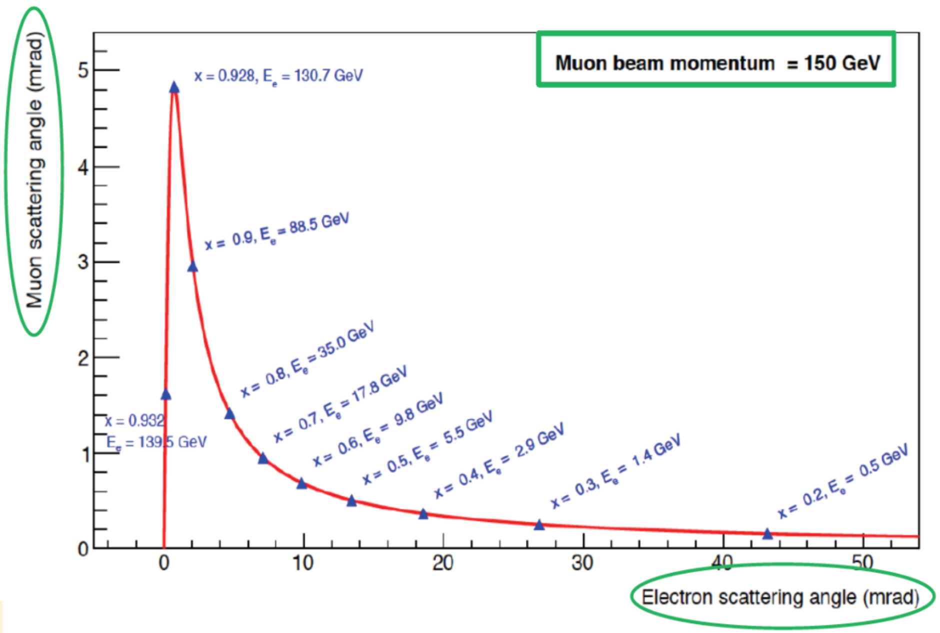
$$\boxed{\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha(0)}\right|^2}$$



- $d\sigma_0/dt$ - effective Born cross section
  - including virtual and soft photons
  - well known in SM
- $\alpha(t)/\alpha(0)$
  - include vacuum polarization effect
  - higher-order radiative corrections must be included for higher precision

For incoming muon energy E_i^μ in a fixed target experiment t variable is related to energy of scattered electron E_e^f or θ_e^f

$$\boxed{E_e^f = m_e\frac{1+r^2c_e^2}{1-r^2c_e^2} \qquad \theta_e^f = \arccos\left(\frac{1}{r}\sqrt{\frac{E_e^f - m_e}{E_e^f + m_e}}\right)}$$



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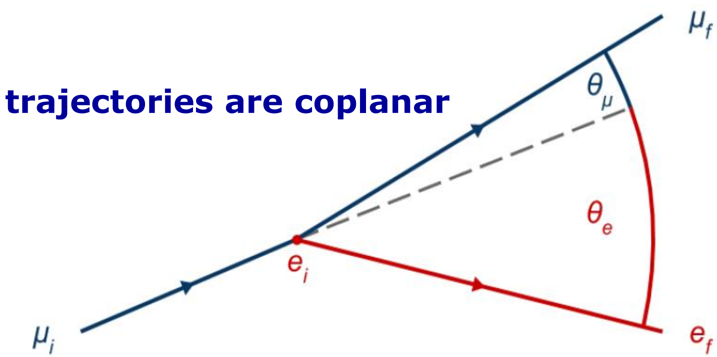

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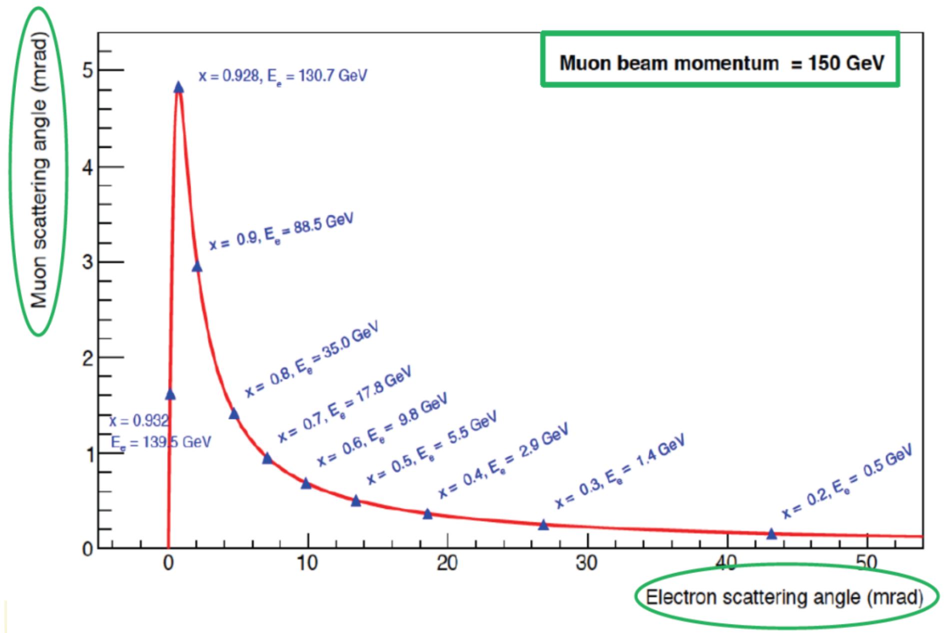
For incoming muon energy E_i^μ in a fixed target experiment *t* variable is related to energy of scattered electron E_e^f or θ_e^f

$$r \equiv \frac{\sqrt{(E_\mu^i)^2 - m_\mu^2}}{E_\mu^i + m_e}, \quad c_e \equiv \cos\theta_e^f$$



MUonE experiment at SPS

CERN-SPSC-2019-026 / SPSC-I-252 (2019)

Statistics:

- CERN's 160 GeV muon beam M2 (1.3×10^7 μ/s)
- incident on *Be* layers *(total thickness 60cm)*
  → target made of a low-Z material to minimize MCS, pair production and Bremsstrahlung
- 2 years of data taking (2×10^7 s/yr) → integrated luminosity $L_{int} \sim 1.5 \times 10^7$ nb^{-1}

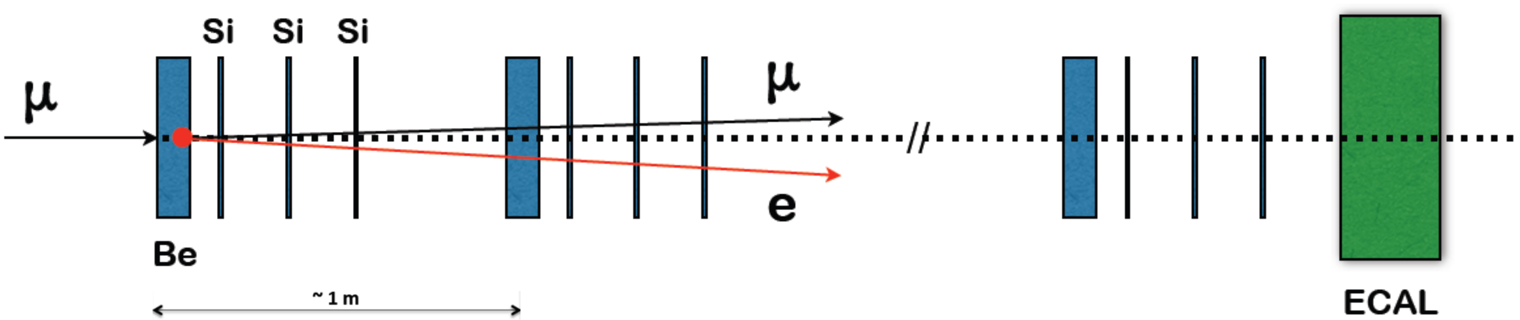
Highly boosted final state:

$0 < -t < 0.161$ GeV^2 $0 < x < 0.93$

For a 160 GeV muon beam scan region extends to x=0.932, i.e. beyond the peak!

Systematics: systematic effects must be known at: $\lesssim$ **10ppm**

Theory: to extract $\Delta\alpha_{had}(t)$ from this measurement, ratio of SM cross sections in the signal and normalisation regions must be known at $\lesssim$ **10ppm**

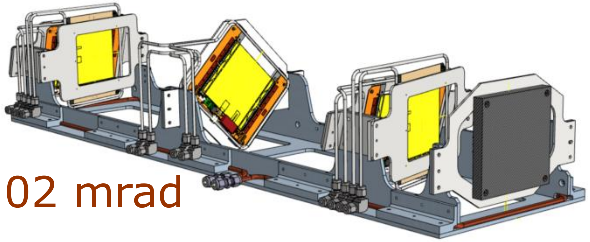


MUonE experiment at SPS

CERN-SPSC-2019-026 / SPSC-I-252 (2019)

The detector setup *(under study and optimization)*

- modular structure made by *up to 40* layers of *Be (or C) 1.5 cm* thick
  - → interleaved with 6 layers of *Si* tracking planes
    (410μm thick, pitch 240μm, active area 9.5 × 9.5 cm²)
  - → **CMS upgrade *Si* trackers**
  - → hit resolution ~10 μm
  - → expected angular resolution ~ 10 μm / 0.5 m = 0.02 mrad



- need to measure very precisely the angles of outcoming electron and muon
  - → to exploit kinematical correlation of the *μ-e* collision
- need to measure direction (and energy) of the incoming muon
  - → a la COMPASS
- PID crucial for low angle particles
  - → EM calorimeter (lead tungstate ($PbWO_4$) crystals, 14 × 14 cm², 22 cm long, 25 X_0)

This is an experiment where the main issue is to control the systematic error at the same level as the statistical one

Muon beam M2 at CERN

MUonE will be located between Beam Momentum Station and COMPASS

~ 50 MHz

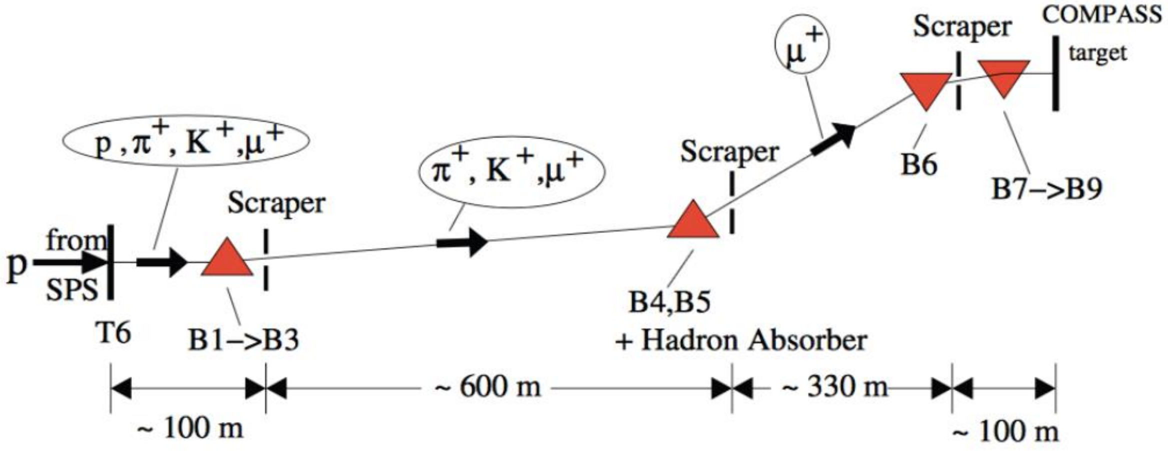


Table 3
Parameters and performance of the 160 GeV/c muon beam.

Beam parameters	Measured
Beam momentum $(p_\mu)/(p_\pi)$	$(160\,\mathrm{GeV}/c)/(172\,\mathrm{GeV}/c)$
Proton flux on T6 per SPS cycle	$1.2 \cdot 10^{13}$
Focussed muon flux per SPS cycle	$2 \cdot 10^{8}$
Beam polarisation	$(-80 \pm 4)\%$
Spot size at COMPASS target $(\sigma_x \times \sigma_y)$	$8 \times 8\,\mathrm{mm}^2$
Divergence at COMPASS target $(\sigma_x \times \sigma_y)$	$0.4 \times 0.8\,\mathrm{mrad}$
Muon halo within 15 cm from beam axis	16%
Halo in experiment $(3.2 \times 2.5\,\mathrm{m}^2)$ at $\|x, y\| > 15\,\mathrm{cm}$	7%

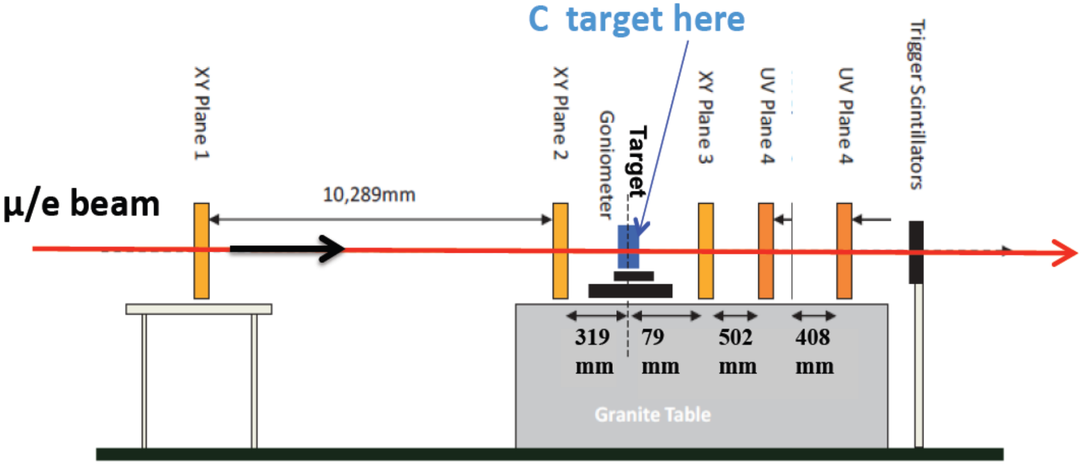
https://arxiv.org/pdf/hep-ex/0703049.pdf

Test beam 2017 *(27 Sep - 3 Oct)*

- used existing UA9 setup in H8-128
  - → 5 *Si* strip planes: 2 before *(upstream)* and 3 after the target, 3.8×3.8 cm^2
- data taken with electron and muon beams
  - → beam energy: *e-* of 12/20 GeV; *μ* of 160 GeV
  - → 10^7 events with *C* targets of different thickness *(2,4,8,20mm)*

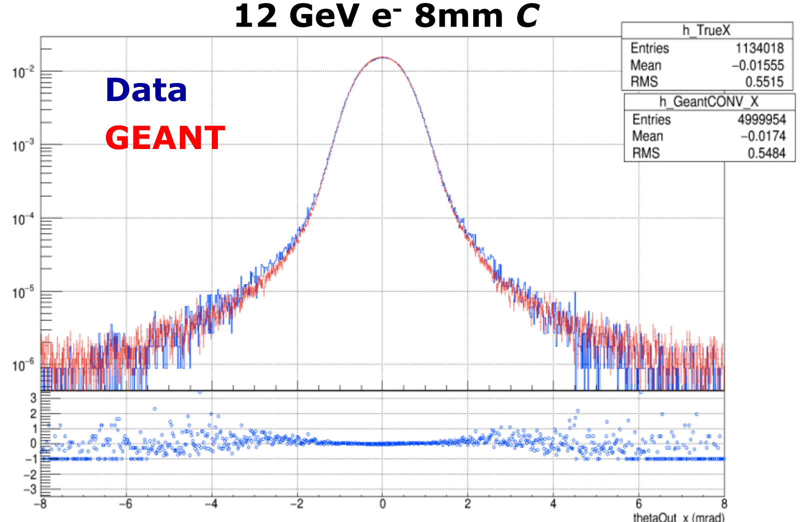
Goal: measure multiple scattering tails for *e* → *e* through material to compare with GEANT 4 model

- with muon data
  - → identify *μ* and *e* from elastic scattering in the final state
  - → measure multiplicity of particles from the target to evaluate background



Adapted UA9 apparatus

12 GeV e^- 8mm *C*

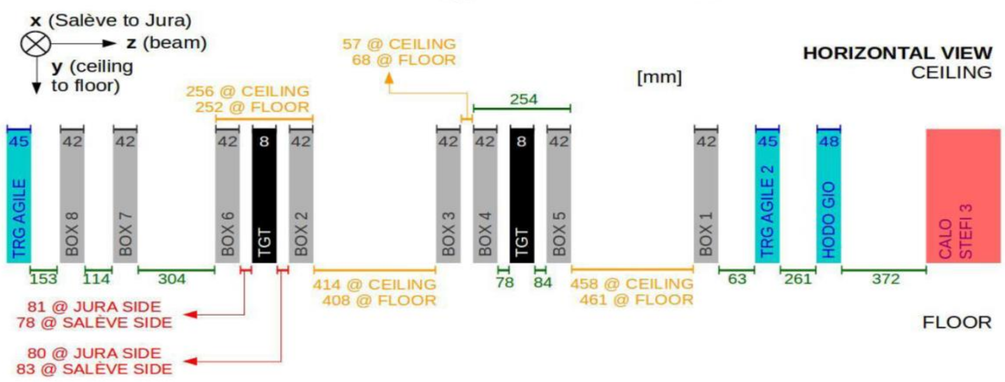


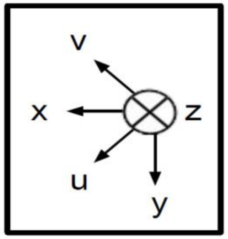
Output angle [mrad]

Test beam 2018 *(Apr 1st to Nov 12th)*

- the setup has been located downstream COMPASS
- aim of the measurement campaign
  → muon-electron elastic scattering with high statistics
- using muons from pions decays *(hadron beam)*
  → estimated beam momentum p_{beam} = (187±7) GeV
- to measure the correlation between the scattering angles
  → muon angle vs the electron angle
- electron energy vs the electron angle correlation and PID
- detector → tracking system: 16 stations equipped with the AGILE silicon strip sensors
  400 micron thick, single sided, about 40 micron intrinsic hit resolution
  → electromagnetic calorimeter: 3x3 cell matrix, BGO-PMT crystals, ~8×8 cm^2

MUonE configuration @ 02/05





Test beam 2018

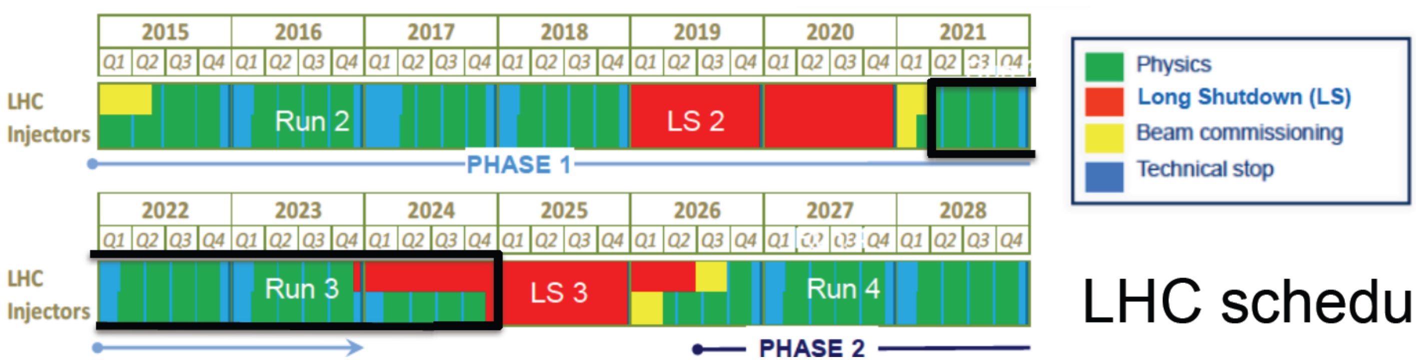
MUonE status and plans

IFJ PAN group involved in all the stages listed below

Letter of Intent accepted by SPSC CERN in 2020

CERN-SPSC-2019-026 / SPSC-I-252 (2019)

- test beam performed in 2017 and 2018 *(arXiv:2102.11111v1, submitted to JINST)*
- 2019
  - → finalization the LoI, accepted by SPSC
  - → setting up the Collaboration
- 2020 → detector design and analysis strategy optimization
- 2021 → final feasibility studies with a detector prototype (Pilot Run)
- 2022–2024 → start data taking after LS2



LHC schedule

Pilot Run in 2021

Requests 3 weeks of the M2 beam, at the end of the running period of 2021

- upstream COMPASS

Prototype of the final setup

- 2 stations, each consists of a thin Be target and 6 CMS tracking layers
- 6 other tracking layers upstream detector for tracking the incoming muons

Goal

- confirm the system engineering, i.e. assembly, mounting and cooling
- assess the detector counting rate capability
- check the signal integrity in the process of data transfer for DAQ
- prove the validity of the trigger-less operation mode
- evaluate the FPGA real-time processing
- test the procedure for the alignment of the sensors
- estimate the systematics

Collaboration

1st MUonE Collaboration Meeting 25-26 Mar 2019, CERN

→ *first IB meeting*

20 institutes from 9 countries, ~40 people

- **CERN**
- University of Siegen - **DE**
- Trinity College Dublin - **IR**
- Bologna, Ferrara, Milano Bicocca, Padova, Parma, Pavia, Pisa, Trieste **- IT**
- **Institute of Nuclear Physics PAN** - **PL**
- Shangai - **PRC**
- Budker Institute of Nuclear Physics Novosibirsk - **RU**
- JINR - **RU**
- University of Liverpool - **UK**
- Imperial College London - **UK**
- University Illinois Urbana Champaign - **USA**
- University of Virginia - **USA**

Kraków MUonE Group

IFJ PAN MUonE Group

Marcin Kucharczyk *(group leader)*	IFJ PAN		
Mariusz Witek	IFJ PAN		
Mateusz Goncerz *(PhD)*	IFJ PAN	Piotr Dorosz *(electroics)*	WIEiT AGH
Miłosz Zdybał *(PhD)*	IFJ PAN	Mateusz Baszczyk *(electronics)*	WIEiT AGH

RESPONSIBILITIES

Detector simulation / software / data analysis

- **full responsibility for detector simulation, event reconstruction and software environment *(FairRoot)* implementation and maintenance** *(for testbeam, pilot run and for final detector)*
- involvement in physics analyses
- involved in LoI

Dominant role in the simulation, software alignment, event reconstru-ction and final data analysis of testbeam data 2018

(paper submitted to JINST, arXiv:2102.11111v1)

Hardware

- involvement in FPGA based trigger and DAQ
- cover the costs of the high and low voltage equipment for trackers in Pilot Run

Krakow group - chosen activities

- Implementation and maintenance of the software framework

  - FairRoot

- Test beam 2018

  - detector simulation, software alignment, event reconstruction, data analysis

- Detector simulation, event reconstruction and data analysis

  - Pilot Run

  - Final MUonE detector

- Deep learning techniques for the event reconstruction

Software environment - FairRoot

FairRoot framework based on ROOT (*https://fairroot.gsi.de/*)

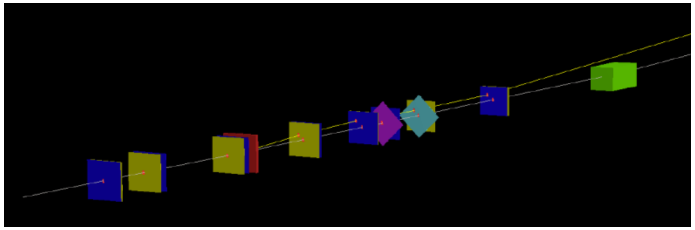
MUonE experiment

FairRoot framework for implementation of detector geometry, event generation, simulation, event model and data analysis

FairRoot framework

- object oriented simulation, reconstruction and data analysis framework for the FAIR experiments at GSI Darmstadt
- enables users to design and/or construct their detectors and/or analysis tasks in a simple way
- it is a useful framework with all components ready:
  - detector simulation → *convenient interface to GEANT*
  - event reconstruction
  - event displaying
  - generators easily interfaced
  - both fast and full simulation available, etc.

Test beam 2018 MC event



- succesfully used by PANDA and SHIP projects & now TestBeam 2018 MUonE

FairMUonE package used for testbeam 2018, foreseen to be software environment for the final experiment

Implementation and maintenance by Krakow group

Software environment - FairRoot

Light weight simulation, reconstruction and analysis framework

- Geometry
  - → create the shape and define the media, creating and positioning of the volume, active and passive volumes, magnetic field, …
- MC generators
  - → MUonE dedicated generators can be easily added
- Configuration
  - → easy and straightforward setup
  - → basic functionality extended with custom classes
  - → python for configuring of C++ objects, execution of non-CPU critical algo's
  - → user friendly
- Execution
  - → main code is compiled only once
  - → all the stages from detector geometry / Geant parameters up to event generation and reconstruction is handled via ROOT macros
  - → easy to run on processing farms / GRID
  - → data processing via chains of tasks

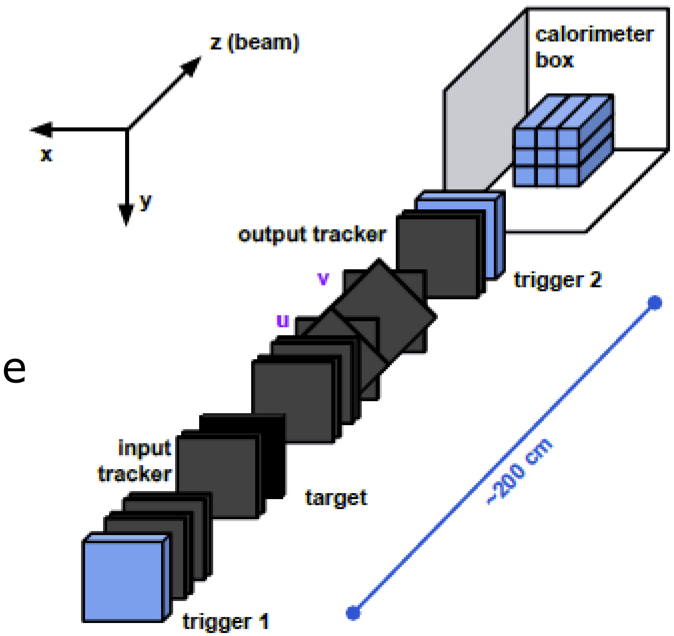
Analysis of testbeam data 2018

At COMPASS site from April 1st to November 12th

- muons from pions decays
  - → estimated p_{beam} = (187±7) GeV
- detector
  - → tracking system: 16 stations equipped with the AGILE silicon strip sensors

    400μm thick, single sided, ~40μm resolution
  - → EMCal: 3x3 cell matrix, BGO-PMT, ~8×8 cm²

    resolution not enough to perform PID



Data sample:

- collected during test beam run in 2018
- single target
- about 500'000'000 events
- total calo deposit above 1 GeV

Signal MC (elastic scattering) sample:

- $E_{in} = 187$ GeV
- electron momentum cut at 1 GeV
- total calo deposit above 1 GeV
- 500'000 events
- flat beam profile, ± 4.6 cm, $\theta = 0$

no background simulation - angular distr. of electron pair to be improved in Geant 10.7

Dominant contribution from Krakow group

Introduction - tracking for testbeam 2018

- relatively simple topology of μ-e scattering

  $\rightarrow$ 3 tracks to be reconstructed:

  - incoming muon before target

  - outgoing electron and muon after target

- detector setup assumes rather clean physics environment

  $\rightarrow$ low detector occupancy

  $\rightarrow$ no hardware-based trigger

- boosted kinematics of the collision $\rightarrow$ *cover large part of acceptance*

- time structure of the beam $\rightarrow$ *keep the background at low level*

- in practice no CPU time limit

  $\rightarrow$ track reconstruction can be treated as offline-like

  $\rightarrow$ quality of the track reconstruction can be maximized

  $\rightarrow$ it can boost much the reconstruction efficiency and precision

Pattern recognition

GOAL $\rightarrow$ maximum possible track reconstruction efficiency!

- first stage - performed in the *x-z* and *y-z* projections

  $\rightarrow$ *constructing pairs from all the combinations of hits in x, y and stereo layers separately*

- two-dimensional lines in *x-z* or *y-z* projections for each pair of hits
- for each 2D line collect all the hits within a certain window
- at least 3 hits to accept 2D track candidate
- no unique combinations of hits forming two-dimensional lines imposed
- use robust fit to the selected 2D lines in *x-z* or *y-z* projections

  $\rightarrow$ *reconstruct 2D tracks*

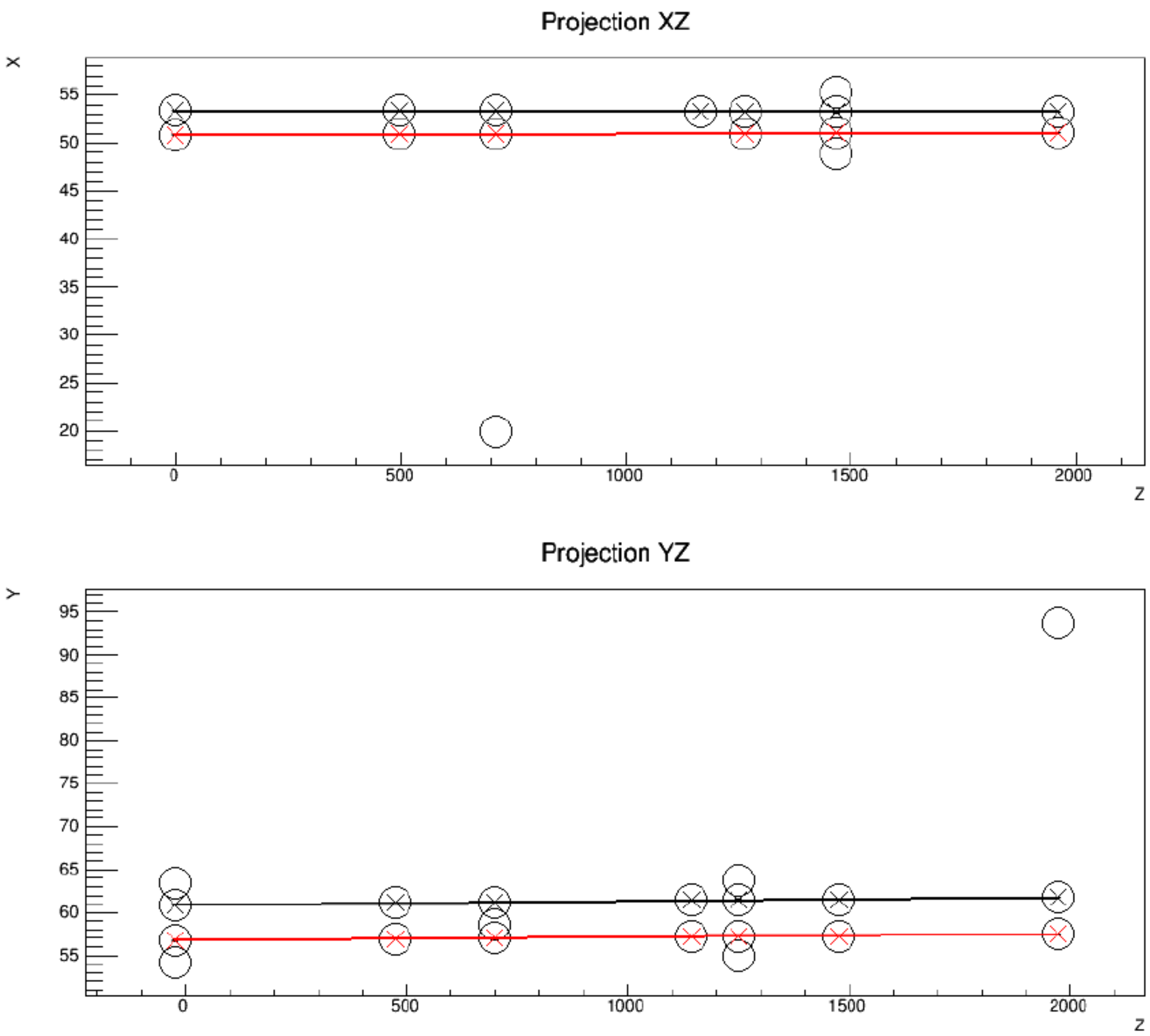
- fast fitting procedure with removal of outlier hits

  $\rightarrow$ *assumed uncertainties of the x and y hit positions as in detector layout*

- all fitted *x-z* and *y-z* lines will be paired to create 3D lines
- all 3D lines fitted using least square method

  $\rightarrow$ *using all hits collected within a certain window wrt initial 3D line*

Efficient reconstruction of close tracks



Track reconstruction

- all combinations of 2D line segments combined into 3D track candidates

  → no prior requirements on quality of such combinations
  (to maximize reconstruction efficiency)

- for each 3D track candidate initial parameters of 3D line determined from corresponding 2D lines

  → seed for track fitting

- iterative fitting procedure using a least square method

  → all hits along initial trajectory collected within a certain window

  → after each iteration outlier hits will be removed and the fit are repeated until no outlier is found

  → at least 3 hits in x-z and 3 hits in y-z projections to accept the track

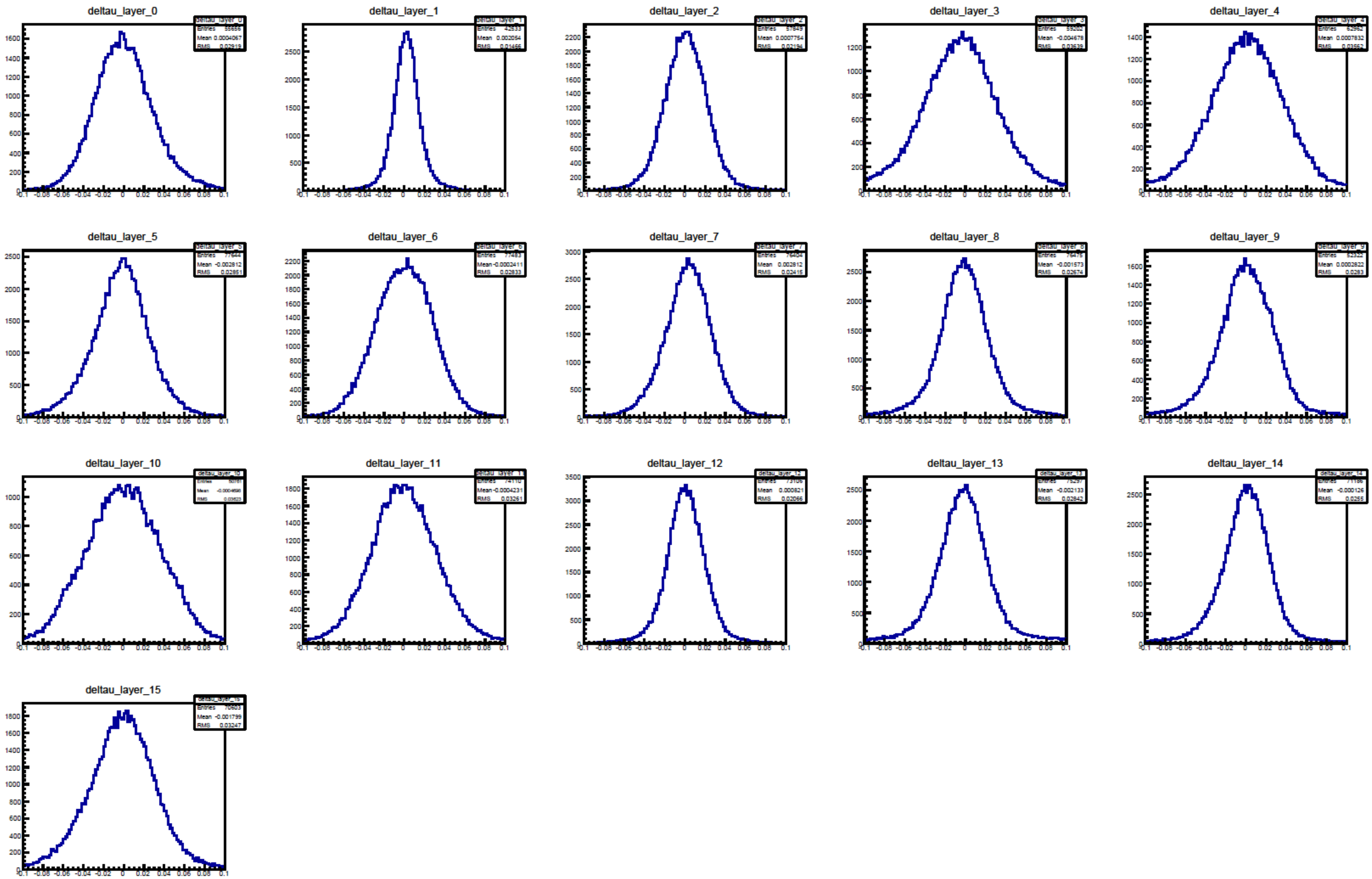
- clone removal procedure

  → tracks with largest number of hits accepted first

  → *(if same nr of hits)* minimum χ^2/ndf

- after accepting a track hits used by this track will be marked as used

Resolutions (mm): **σ = 20-35 μm**



Alignment

Starting with hardware-base pre-alignment

$\rightarrow$ data sample with preliminary alignment

$\rightarrow$ **looks reasonable but *u,v* layers not aligned!**

$\rightarrow$ we aligned first *u* and *v* and then re-aligned all the layers

- reference point taken as the bottom edge of the first box

$\rightarrow$ taken for all *x, y, u, v* layers

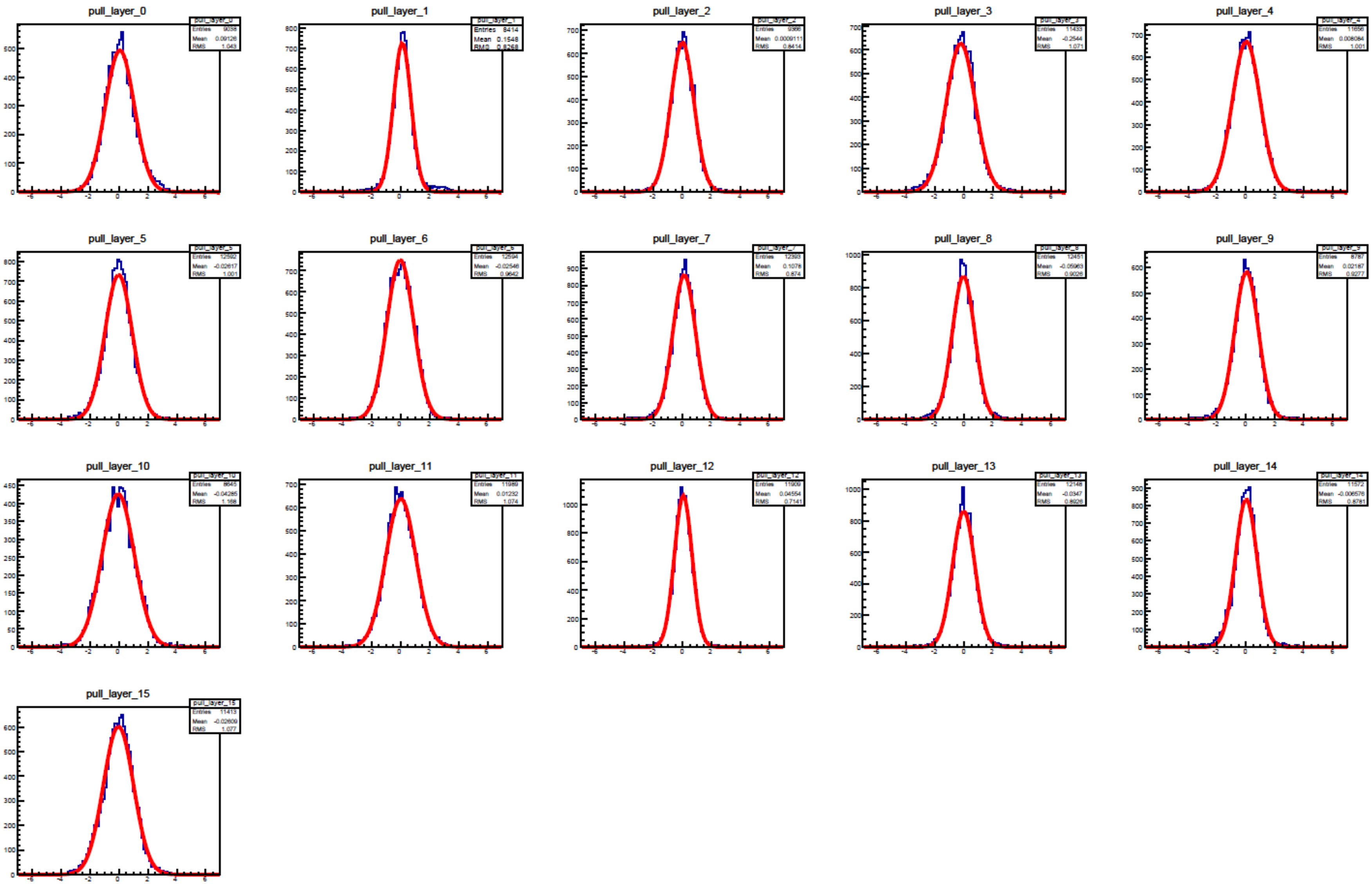
RE-ALIGNMENT (after *u,v* alignment)

1. collect good quality tracks (at least 10 hits)
2. minimize residuals of every station on-by-one

   $\rightarrow$ loop over all the good quality tracks and minimize the sum of residuals (χ^2)
3. iterative procedure using MINUIT
4. align stations one-by-one

pull distributions fitted with a single Gaussian on the next slide

Alignment: pull distributions



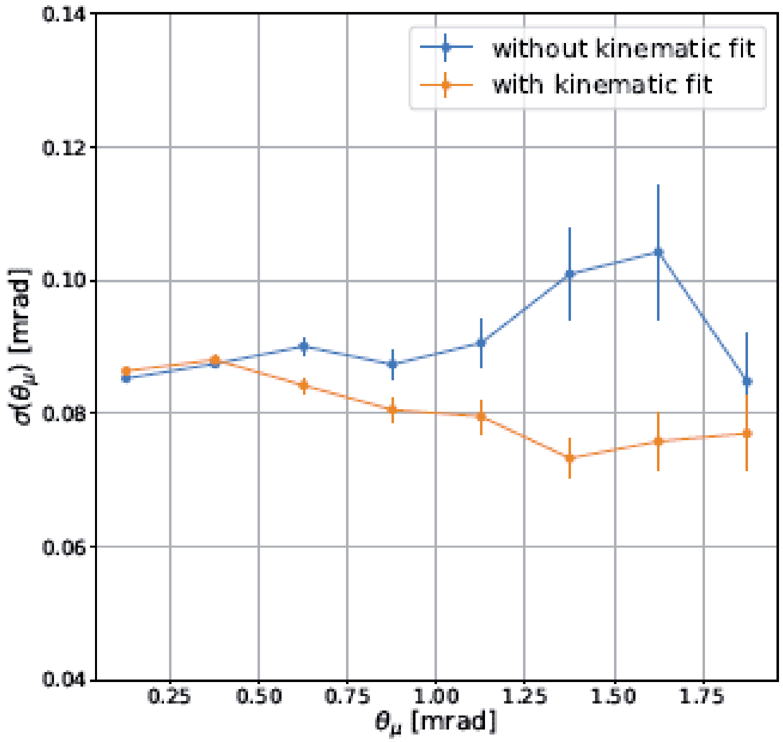
Reconstruct *μ-e* elastic scattering event

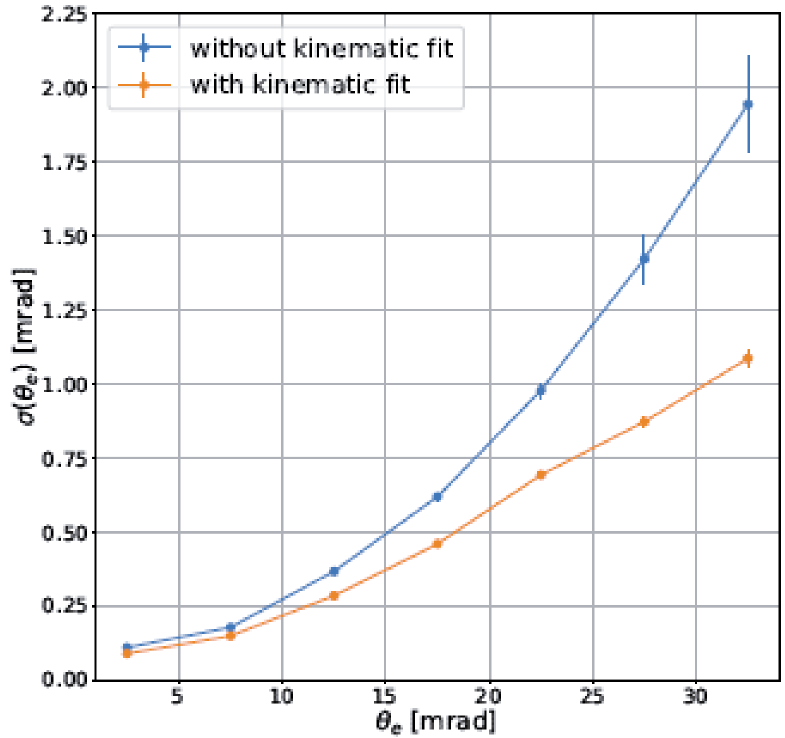
Kinematic fit for incoming muon track and two outgoing muon and electron tracks originating from the target position

- identify tracks based on their theta angle wrt incoming muon
  (no PID from EMCal)
  - $\rightarrow$ larger angle – electron
  - $\rightarrow$ smaller angle – muon
- account for electron multiple scattering by introducing additional sigma term to its χ^2 using approximate momentum to calculate error
- minimize vertex χ^2 (sum of χ^2's of tracks constrained to go through the vertex position) by varying its *x* and *y* position at target *z*
- recalculate track slopes and theta angles wrt incoming muon
- use the sum of χ^2 of tracks as event quality variable

Angular resolution

Angular resolution as a function of the scattering angle for muons and electrons with and without kinematic fit

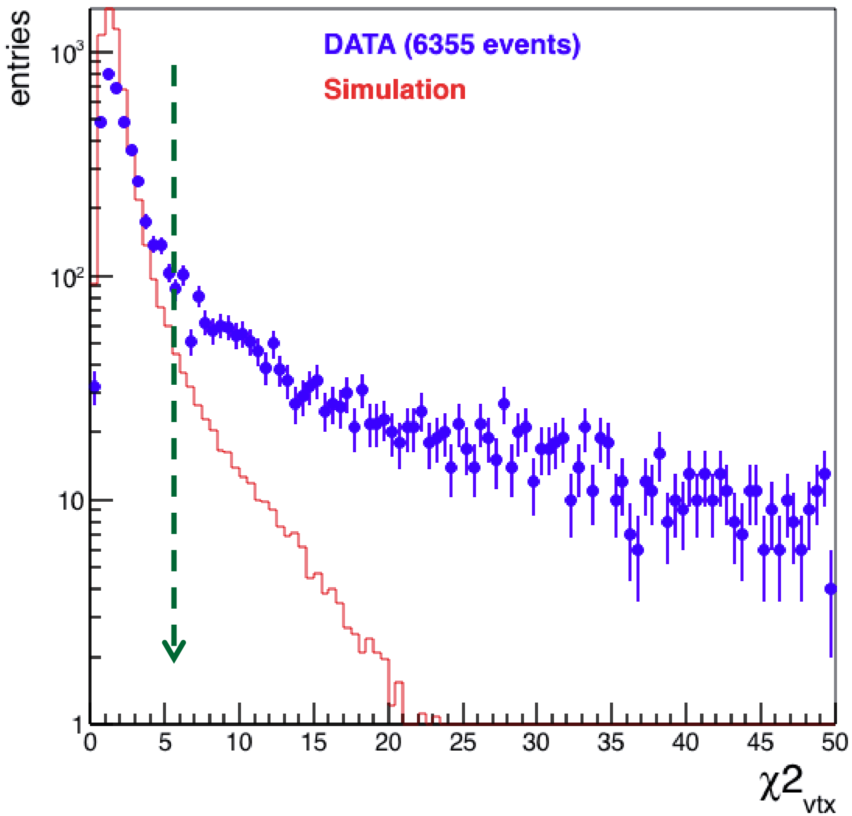




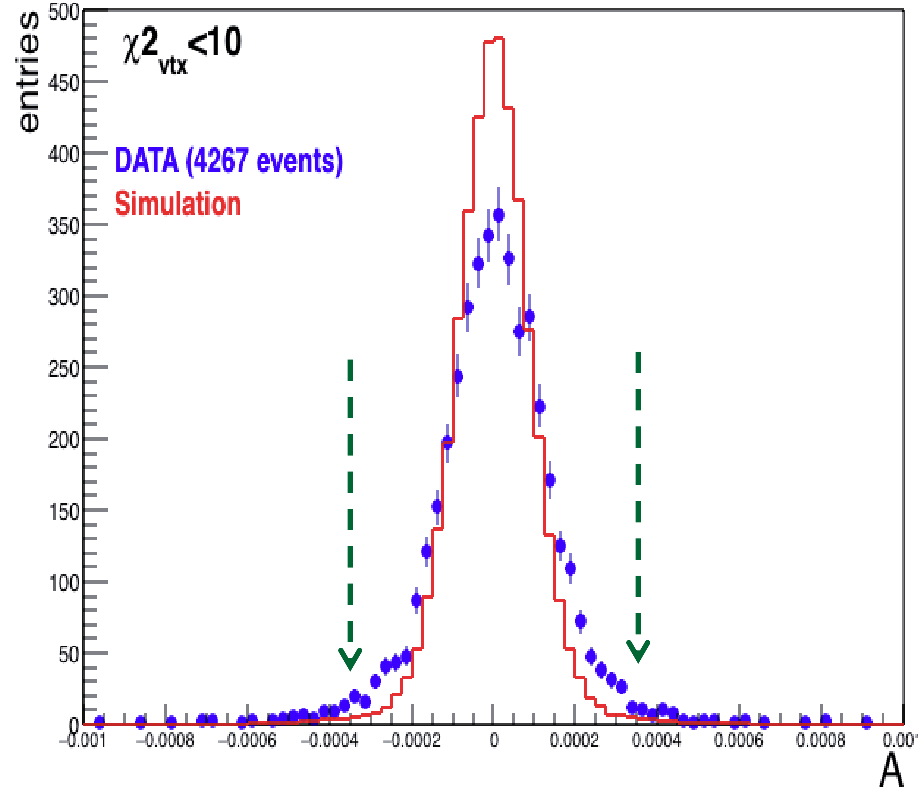
varies mainly due to multiple scattering

Variables used in selection

vertex χ^2/ndf



acoplanarity $= \frac{\pi}{2} - \measuredangle\left(\vec{P_{in}}, \vec{P_{out1}} \times \vec{P_{out2}}\right)$

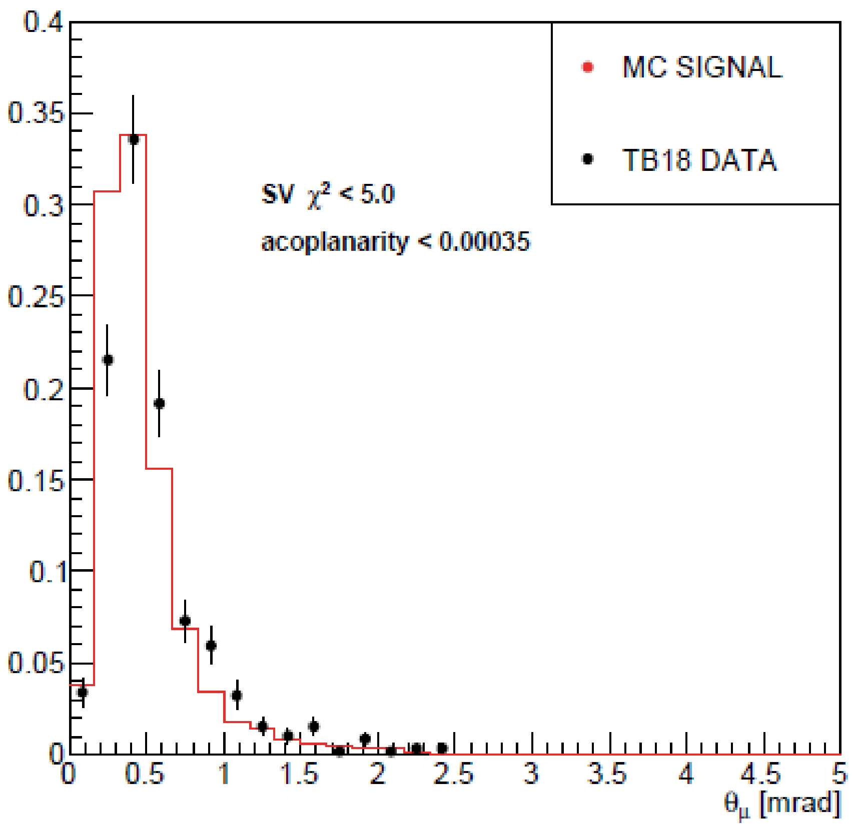


no background simulated

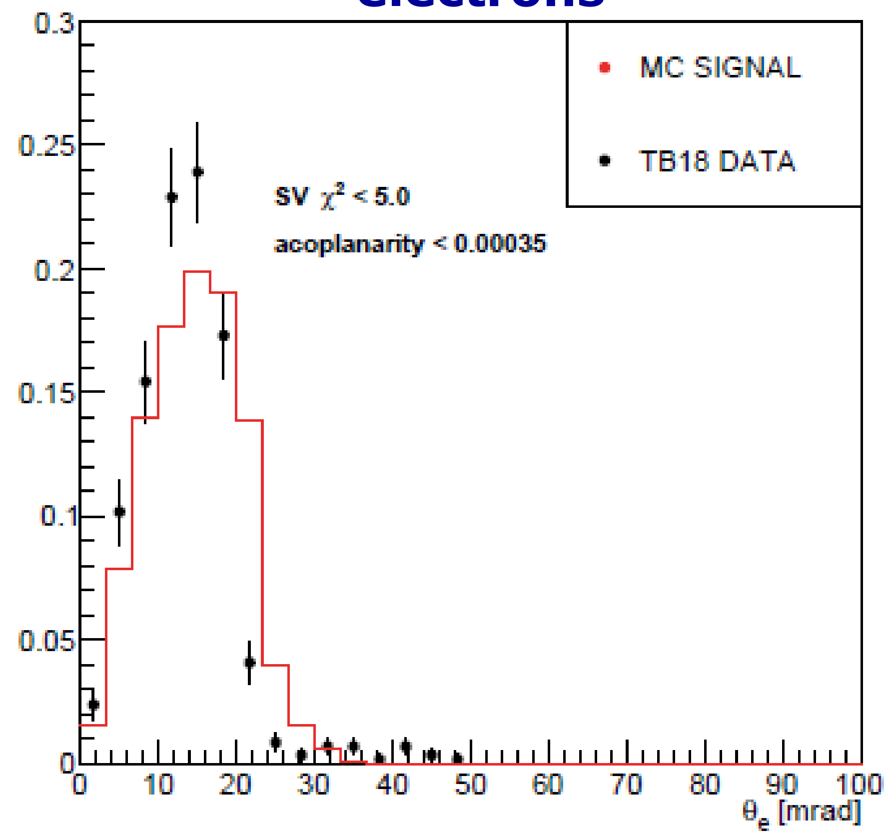
Scattering angles

Selection: |acoplanarity| < 0.00035, χ^2_{vtx} < 5.0

muons



electrons

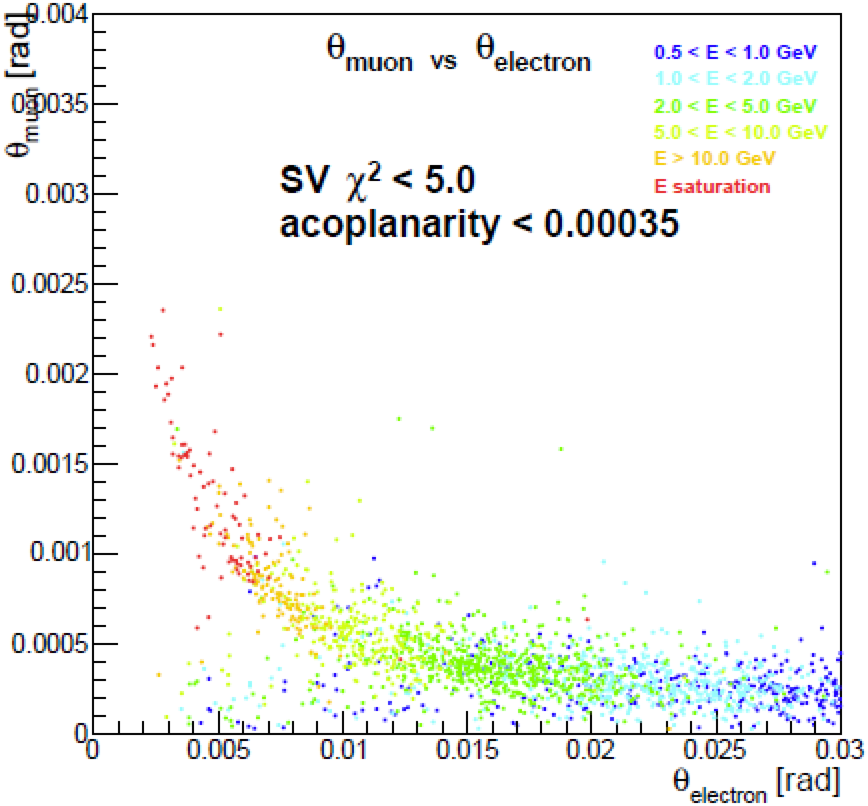


no background simulated

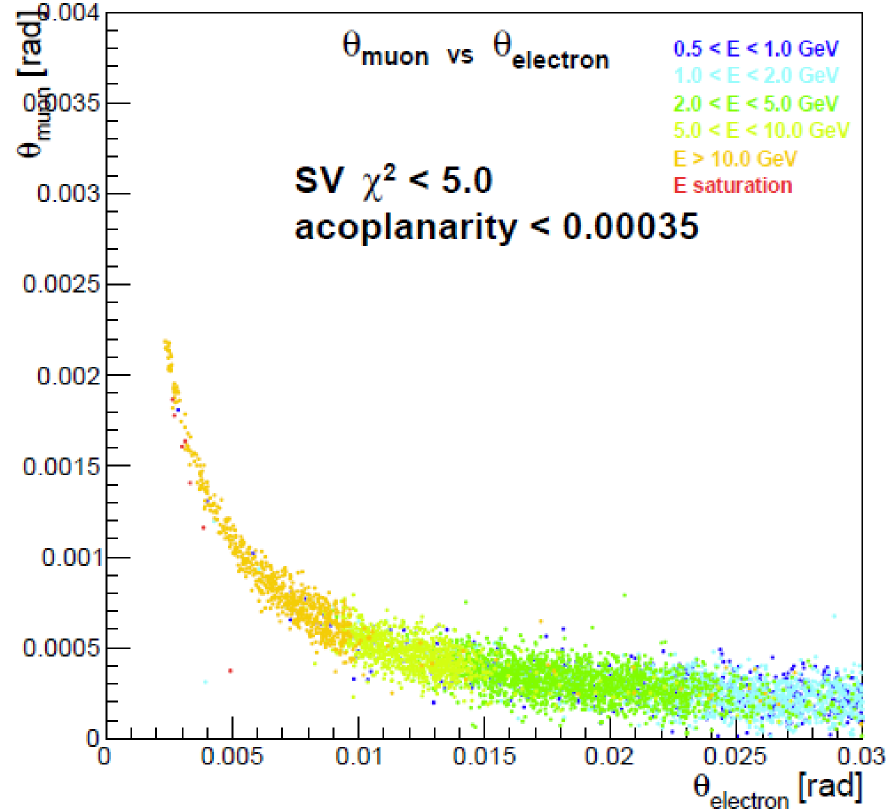
Correlations between scattering angles

Selection: |acoplanarity| < 0.00035, $\chi^2_{vtx} < 5.0$

TB18 DATA



MC signal, normalized



colors represent the energy deposited in the calorimeter

no background simulated

Testbeam 2018 analysis - conclusions

- Aimed mainly to explore the ability to select a clean sample of elastic scattering events in view of designing the final experiment

  → able to select clean sample even if the resolution worse than the one planned to be used in MUonE

  → first results of this kind

- Importance of an adequate calorimeter

  → understand the electrons emitted in the range of a few GeV

  → determine the behaviour of the background

- Important upgrade of Geant4

  → accurate angular distribution of the electrons of the pair has to be implemented

  → Geant4 version 10.7 *(under tests now, to be in FairRoot in March)*

Results in: arXiv:2102.11111v1, submitted to JINST

Deep machine learning

Potential use of deep machine learning in MUonE

Deep Neural Networks (DNN)

$\rightarrow$ very fast

$\rightarrow$ parallel

$\rightarrow$ in principle do pattern recognition 'at once' - without looping over hits

High occupancy expected in the final MUonE experiment

$\rightarrow$ higher precision with DNN

$\rightarrow$ higher efficiency with DNN

Consultations with HEPTrkx group working on tracking for HEP experiments

https://heptrkx.github.io/

Deep machine learing - first results

Initial studies in collaboration with **Marcin Wolter**

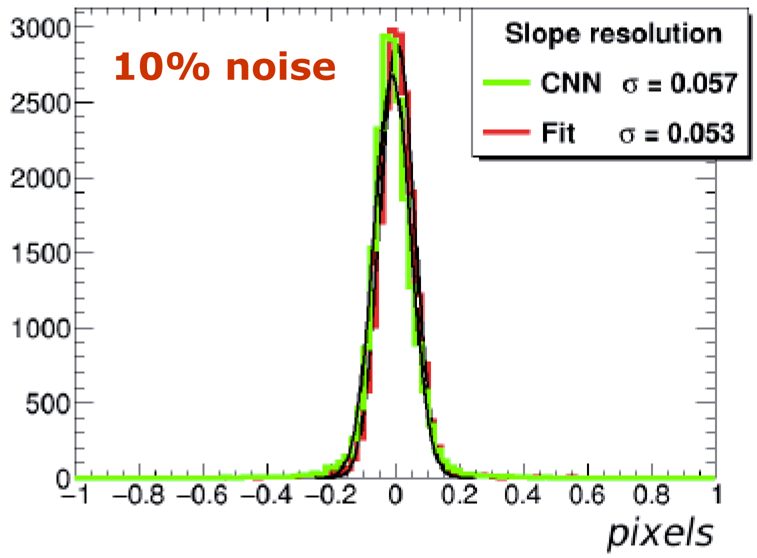
Toy model of track finding using Deep Neural Networks

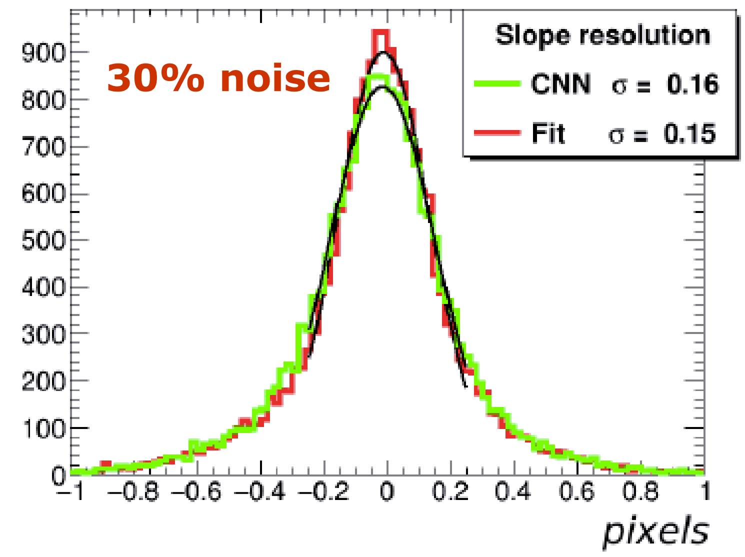
→ 2-dimensional data to reduce the training time

→ straight line tracks *(no magnetic field)* on the 28×28 pixel plane

→ finite hit efficiency and random noise

3 tracks
- 70% hit efficiency
- 10-30% random noise





Results published in: Computer Science 20(4) (2019) 477-493

Deep machine learing - 2D tracks with GNN

Summer student’s work supervised by Marcin Wolter

GNN - Graph Neural Network

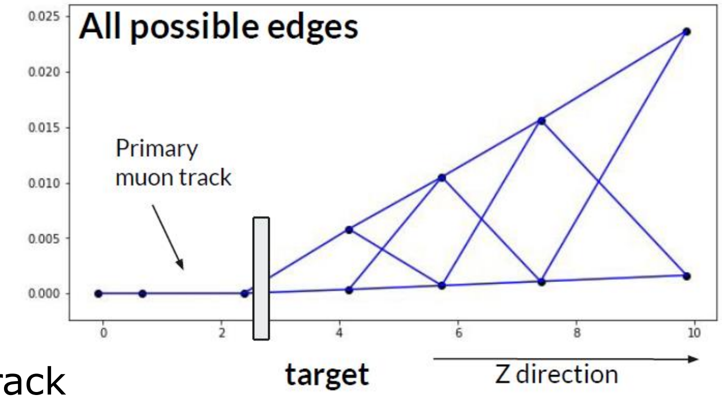
MC tracks for MUonE TB2018 used

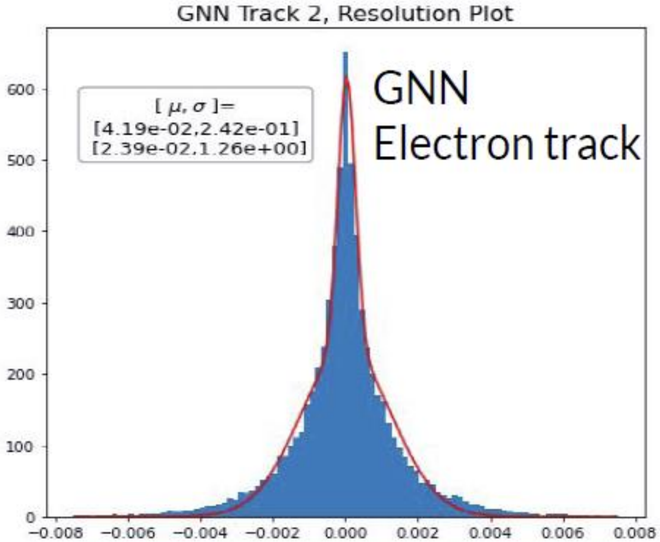
Input data - graph, instead of vectors or matrices

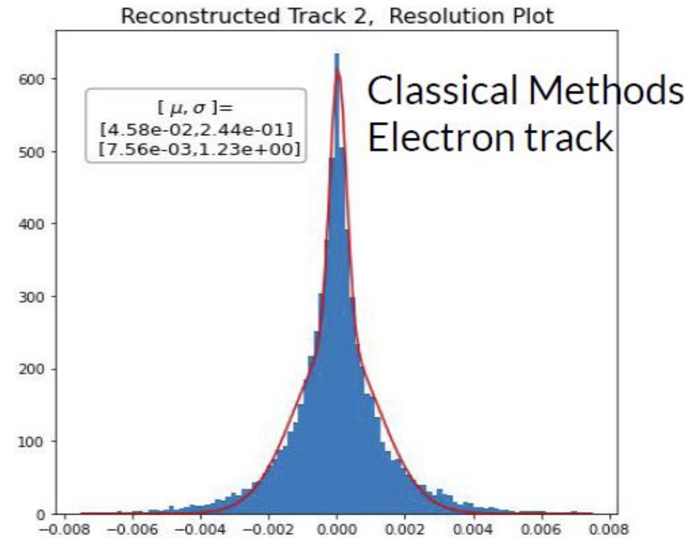
$\rightarrow$ in this case, hit positions - nodes

Output data - graph with edges, connecting hit points

$\rightarrow$ each edge has a weight - probability to belong to track







Miłosz Zdybał is recently working on application of DNN for 3D tracking

Conclusions

Exciting times for the muon *g*-2

- precise determinations of a_μ at Fermilab and JPARC

HLO corrections are essential

- space-like approach (MUonE) allows to reach the precision below 5 ppm

Successful test beams at CERN in 2017 and 2018 *(we see elastic μ-e events!)*

Letter of intent accepted by SPSC

Valuable solutions for the tracker exist *(not require R&D for new technologies)*

- final detector prototype will be tested in Pilot Run in 2021

Theoretical calculations

- MC at NLO available, and NNLO progressing successfully

Important involvement of IFJ PAN group
- implementation and maintenance of the software framework
- responsibility for detector simulation and event reconstruction
- optimization of detector layout (LOI)
- analysis of test beam data *(paper sent to JINST)*
- contribution to DAQ development
- participation in the costs of detector construction for Pilot Run