The MUonE Experiment:
Understanding Muon $g-2$ Puzzle via $\mu-e$ Scattering

Ce Zhang

on behalf of the MUonE collaboration

MIP 2024

UNIVERSITY OF LIVERPOOL

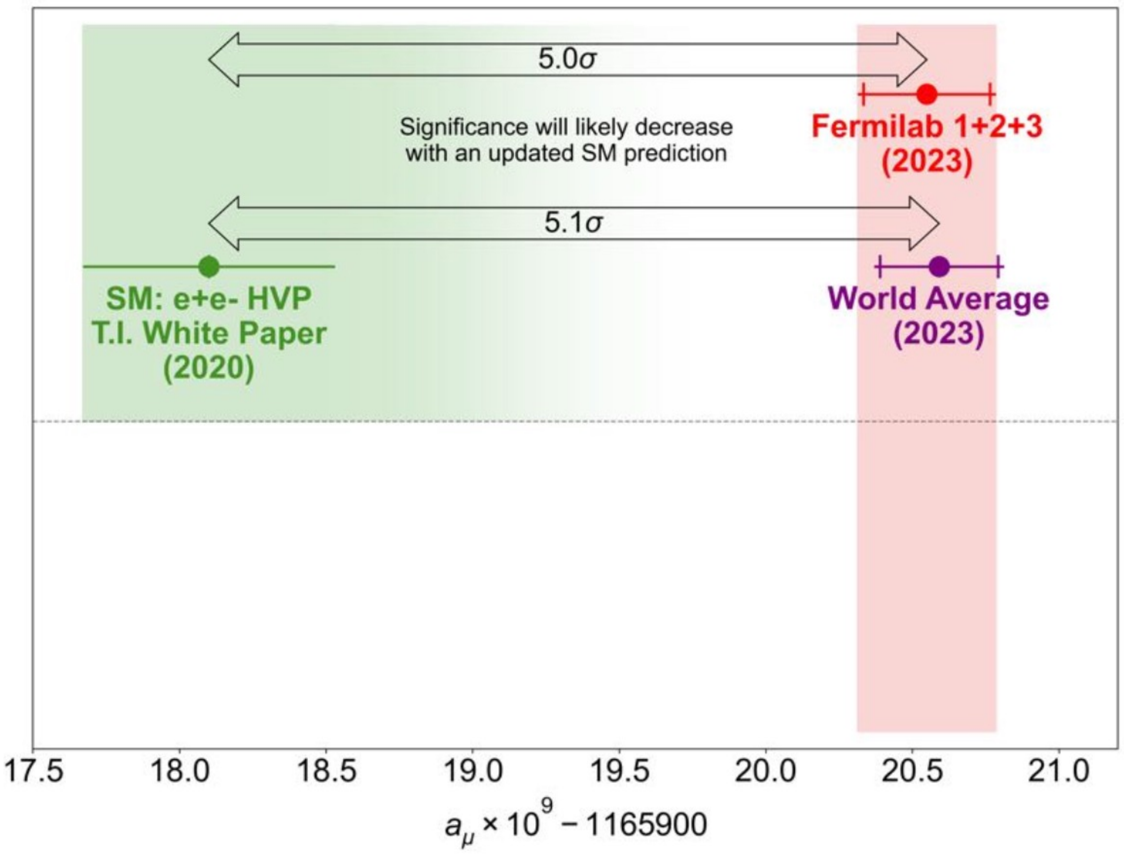
LEVERHULME TRUST

The MUonE Experiment:
Understanding Muon $g-2$ Puzzle via $\mu - e$ Scattering

- Muon $g-2$ Puzzle
- The MUonE Experiment
  - Principle
  - Setups
  - Test runs & first results
  - Timeline
- Summary

Muon $g - 2$ Puzzle

Discrepancy between experiments & theories



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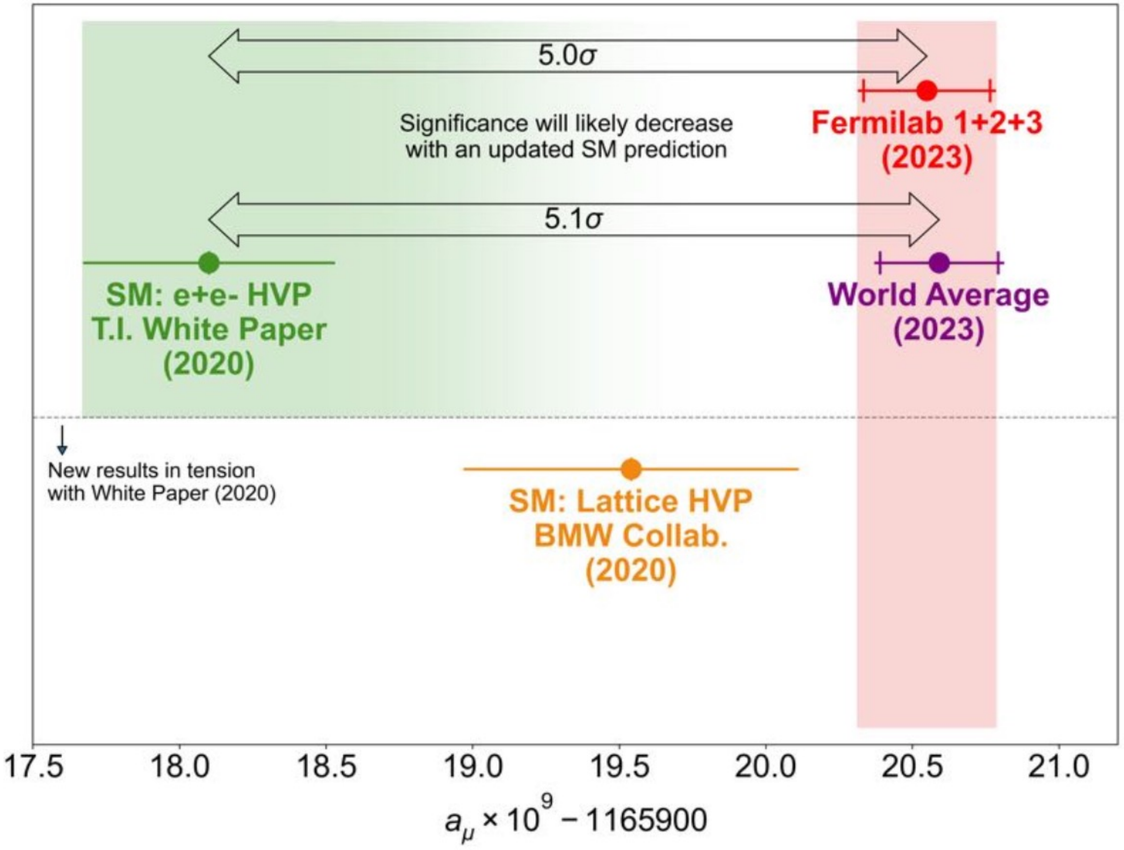

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- Since then, two important developments on SM prediction:
  - Lattice QCD from the BMW (2020)

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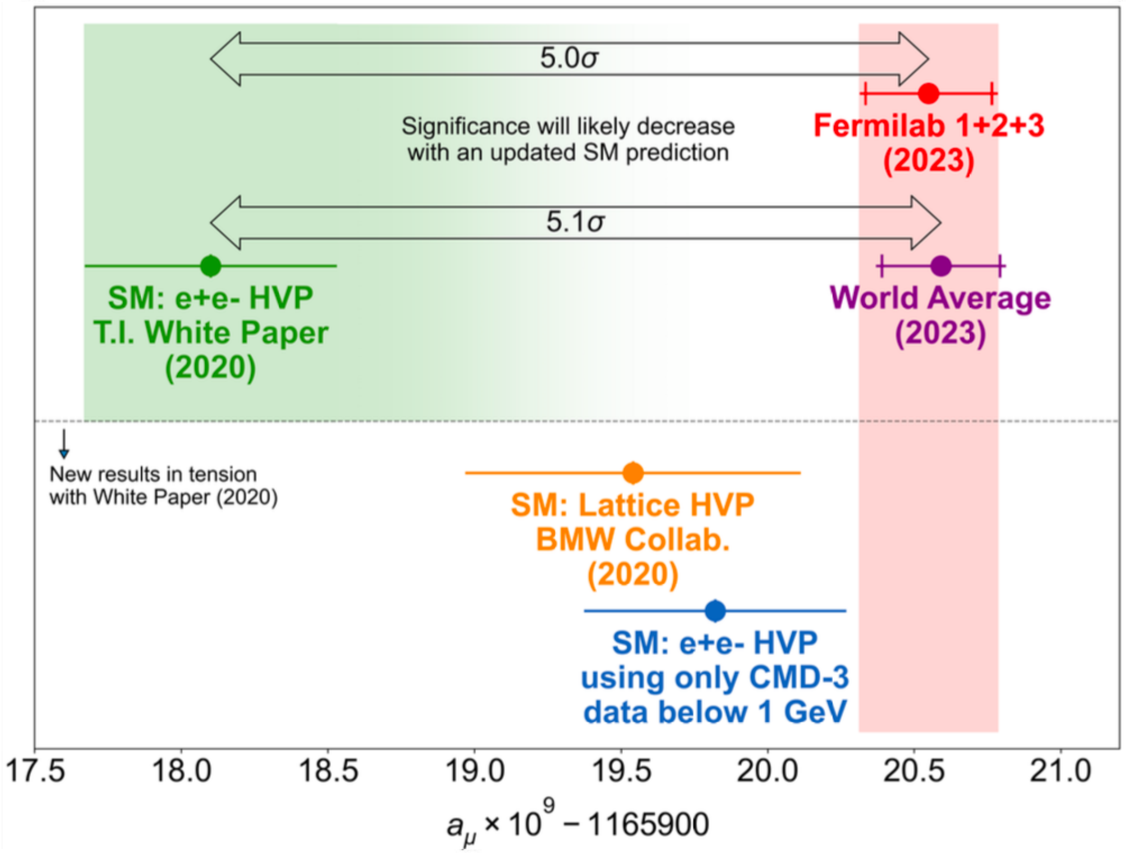


- New experimental average with SM prediction (WP-2020) gives > 5σ
- Since then, two important developments on SM prediction:
  - Lattice QCD from the BMW (2020)
  - New $e^+e^- \rightarrow \pi^+\pi^-$ cross section from CMD-3 (2023)

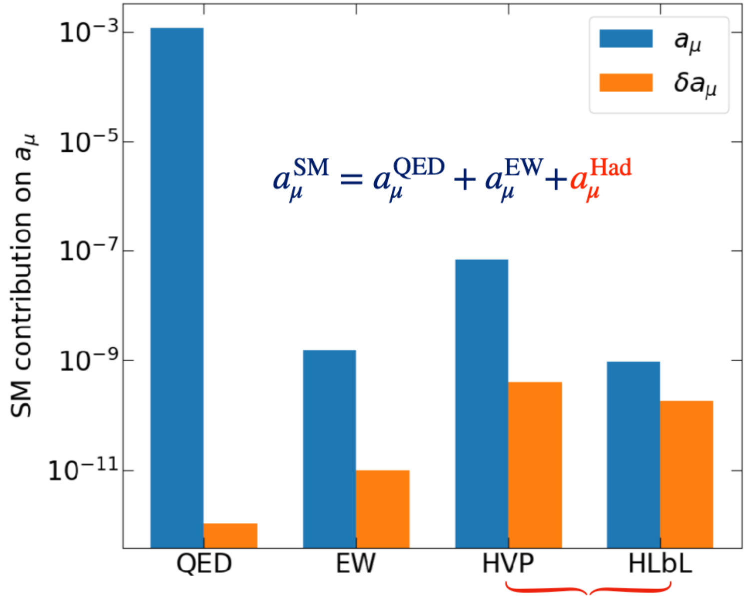
> **Disclaimer:**
> The CMD-3 point is a visual exercise. It is not a fully updated SM prediction!

- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

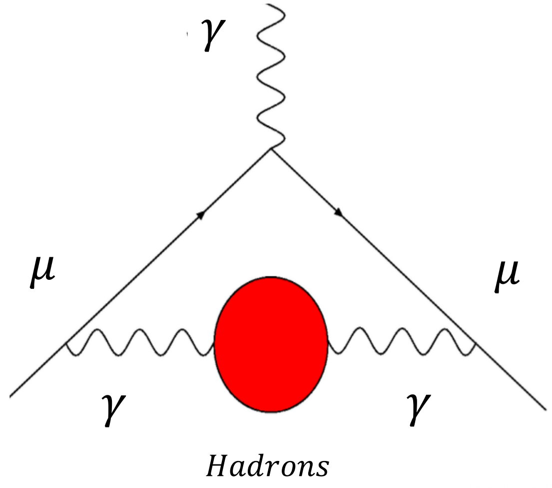
Muon $g-2$ Puzzle

Standard Model (SM) predictions

- The uncertainty in the SM prediction of a_μ is **entirely limited** by our knowledge of the hadronic leading order contribution $\boldsymbol{a_\mu^{\mathrm{HLO}}}$ $(\boldsymbol{a_\mu^{\mathrm{HVP},LO}})$



- **HVP**: **hadronic vacuum polarization →**
- **HLbL**: hardronic light-by-light



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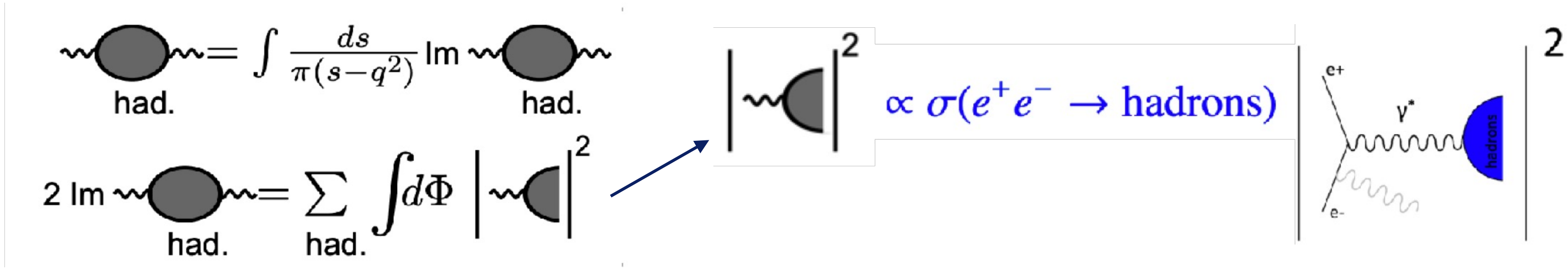
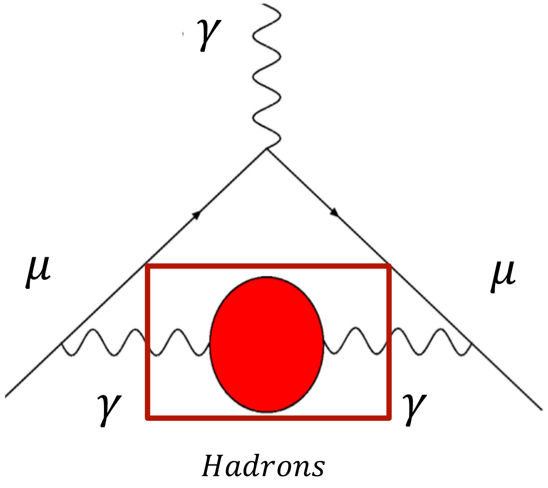
  2) Dispersive Method: using σ($e^+e^- \rightarrow$ hadrons) data





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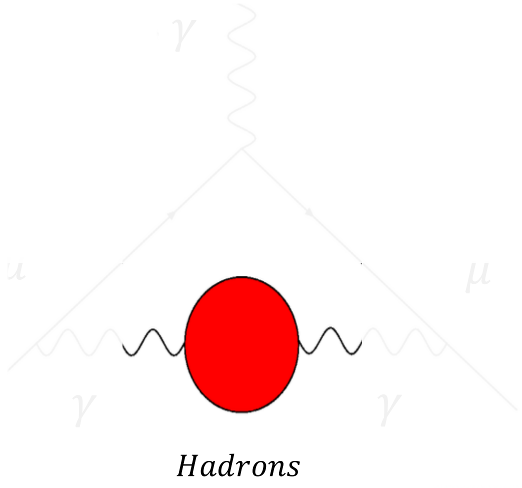
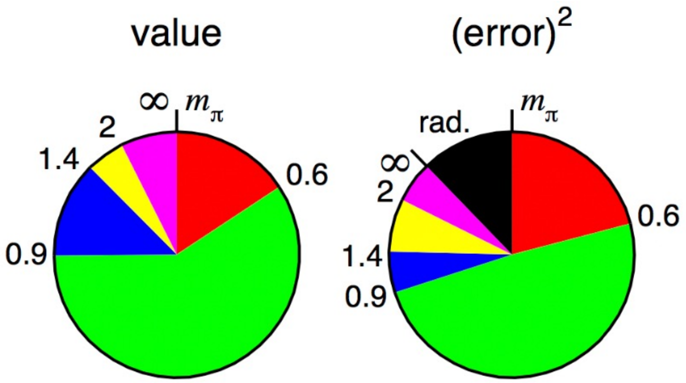
$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \, \frac{R_{\mathrm{had}}(s)\, K(s)}{s^2}, \quad R_{\mathrm{had}}(s) = \sigma(e^+e^- \rightarrow \text{hadrons}) \Big/ \frac{4\pi\alpha(s)}{(3s)}$$



Muon $g-2$ Puzzle

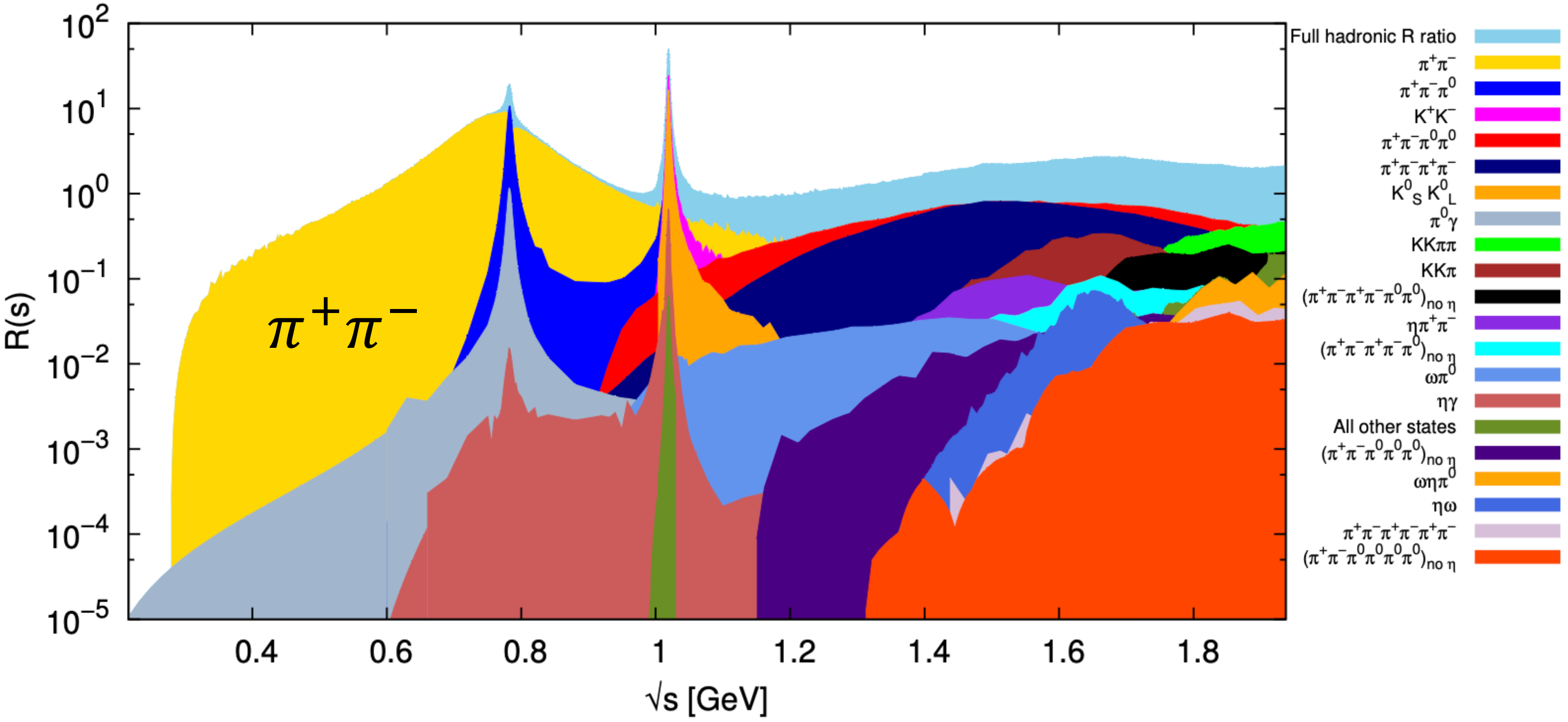
Chaotics in $e^+e^- \to \pi^+\pi^-$ for a_μ^{HVP}

- $e^+e^- \to \pi^+\pi^-$ **channel** is the major source of uncertainty in a_μ^{HVP}



Keshavarzi, Nomura, Teubner 2018

$\sigma(e^+e^- \to$ hadrons) contribution in the energy region



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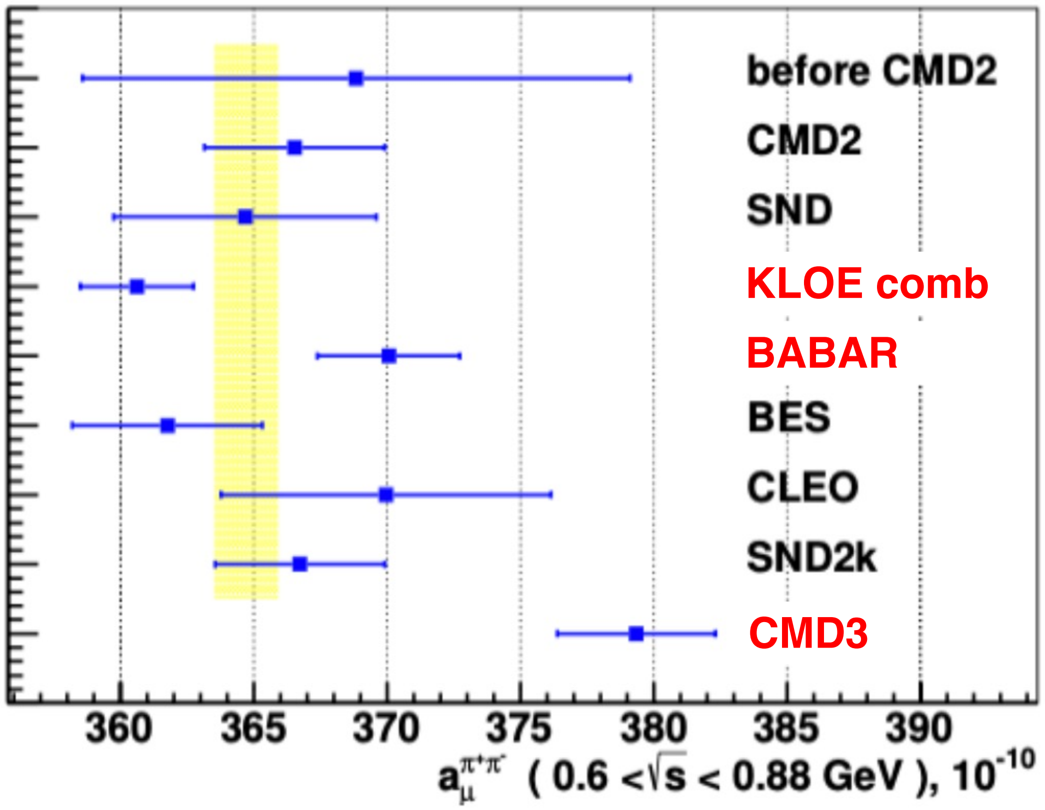

- Discrepancy between **KLOE** and **BABAR** result needs further investigation
- A recently published **CMD-3 result** was different from all the previous data!

Muon $g - 2$ Puzzle

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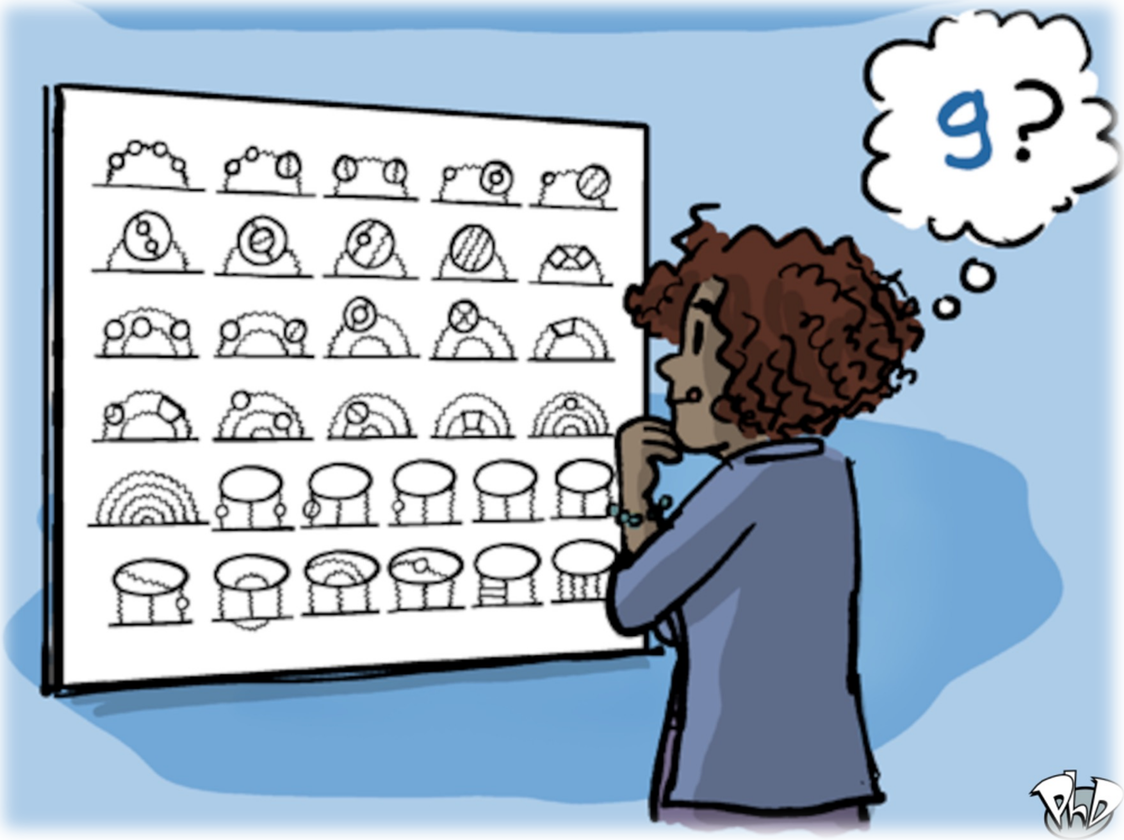
A quick summary on the muon g-2 theory puzzle:

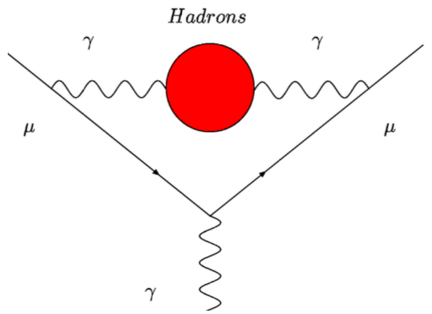
- a_μ^{HVP} represents a major uncertainty
- e^+e^- data-driven ⇔ Lattice conflict
- Conflicts in the data-driven method:
  - BABAR ⇔ KLOE
  - Latest CMD3 ⇔ all the previous data



MUonE Experiment

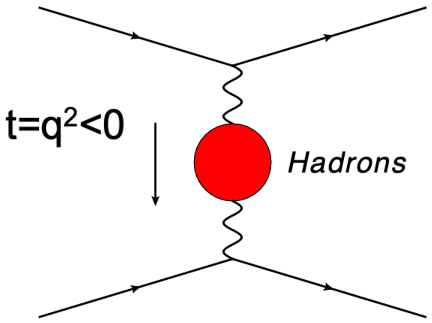
A new approach measuring $\boldsymbol{a_\mu^{\mathrm{HVP}}}$ with running of $\Delta\boldsymbol{\alpha}_{\mathbf{had}}$

- The dispersive approach to compute $a_\mu^{\mathrm{HVP,LO}}$ is via the **time-like** formula:



$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds\, \frac{R_{\mathrm{had}}(s)\boldsymbol{K(s)}}{s^2}, \quad K(s) = \int_0^1 dx\, \frac{x^2(1-x)}{x^2+(1-x)(s/m_\mu^2)}$$

- Alternatively, exchanging the x and s integrations → **space-like** formula:



$$a_\mu^{\mathrm{HVP}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\Delta\boldsymbol{\alpha}_{\mathbf{had}}[\boldsymbol{t(x)}], \quad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

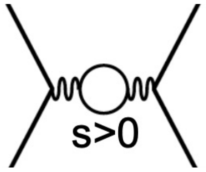
- $\Delta\boldsymbol{\alpha}_{\mathbf{had}}$ is the hadronic contribution to the **running α** (electromagnetic coupling constant)

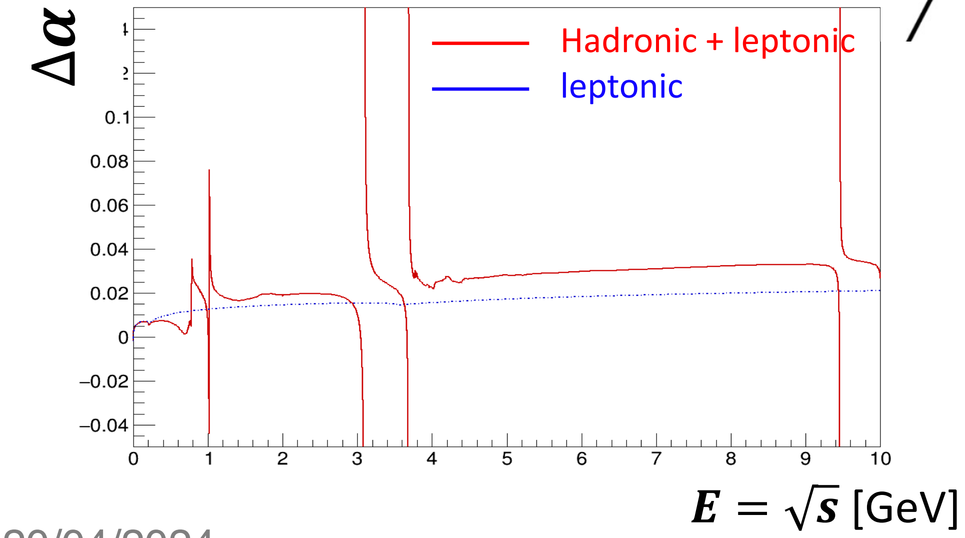
MUonE Experiment

Running of $\Delta\alpha_{\mathrm{had}}$: ‘Time-like’ vs ‘Space-like’

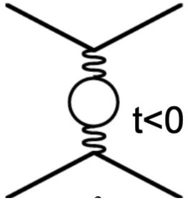
$$\Delta\alpha^{(5)}_{had}(q^2) = -\frac{\alpha}{3\pi}\, q^2 \int_{m^2_{\pi^0}}^{\infty} ds' \frac{R(s')}{s'(s'-q^2)}$$

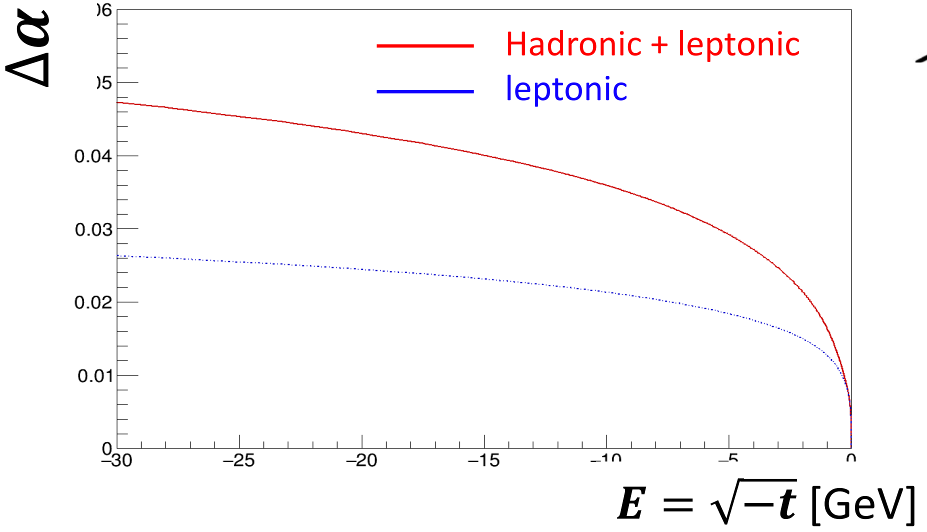
- **Time-like:** characterized by the opening of resonances





- **Space-like**: very smooth behaviour

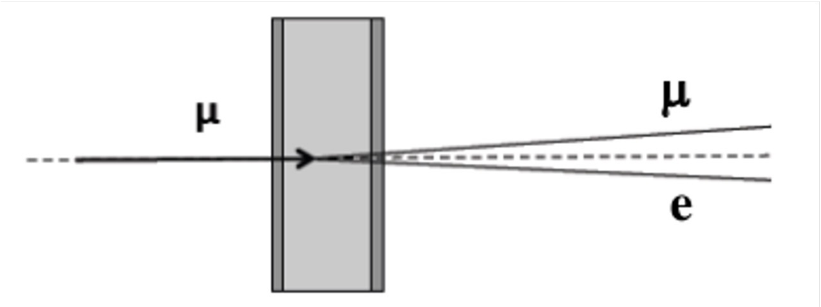




MUonE Experiment

$\Delta\alpha_{\text{had}}$ via Muon-electron scattering

- $\Delta\alpha_{\text{had}}[t(x)]$ can be extracted from the **shape** of the differential cross-section of **muon-electron scattering** $\mu^+e^- \rightarrow \mu^+e^-$



$$R_{\text{had}} = \frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}} = 0)} \sim 1 + \underline{2\Delta\alpha_{\text{had}}(t)}$$

To be determined in this experiment

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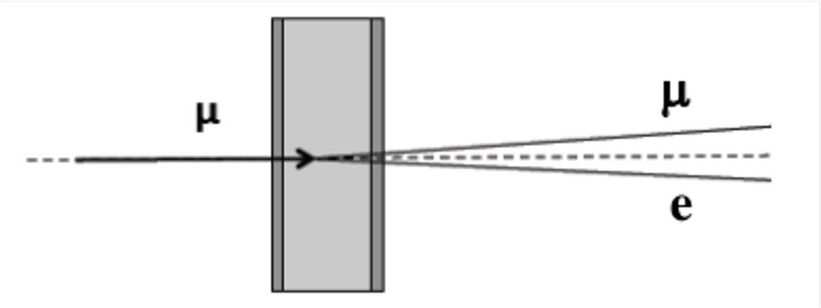

Shape of this is measured

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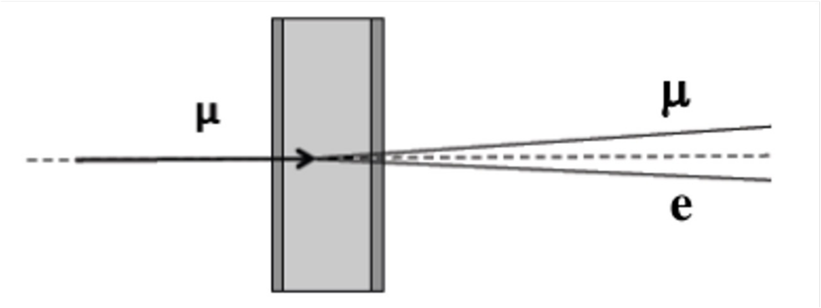

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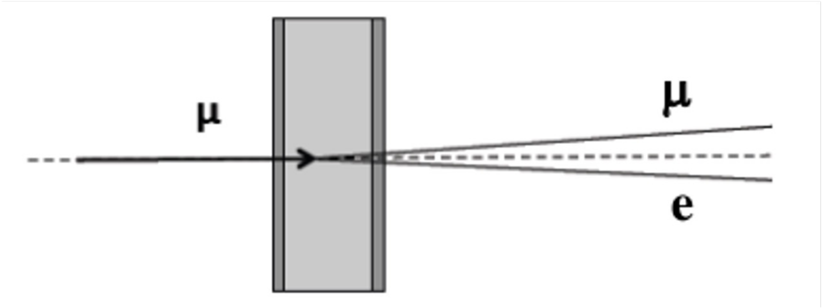

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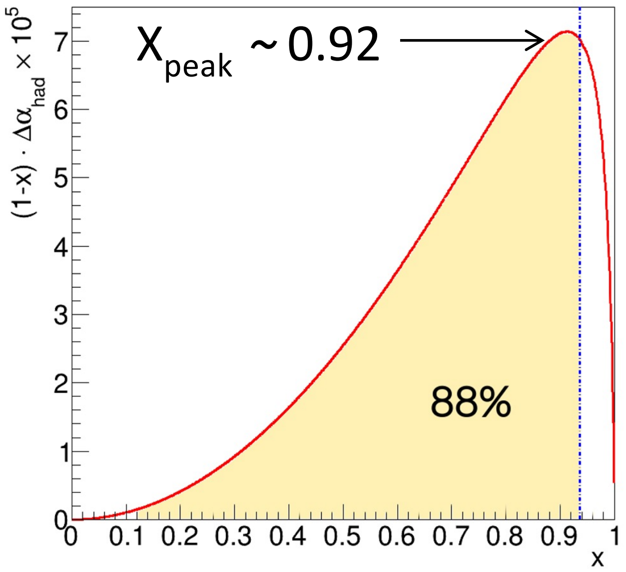
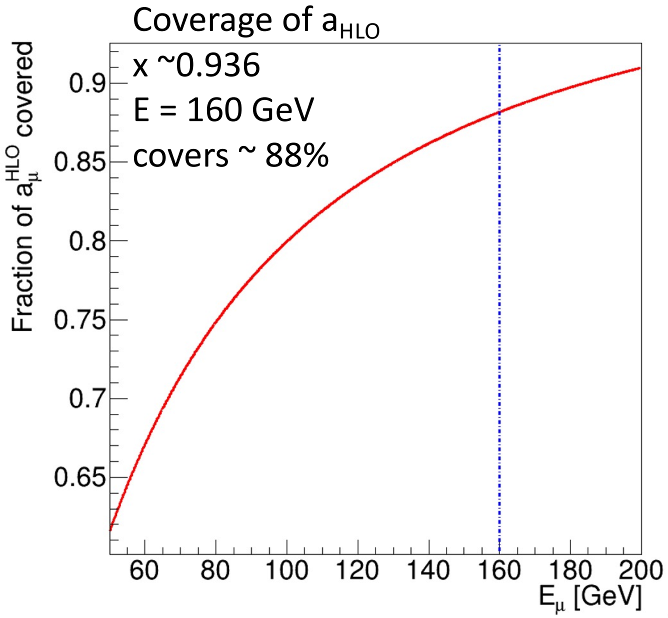
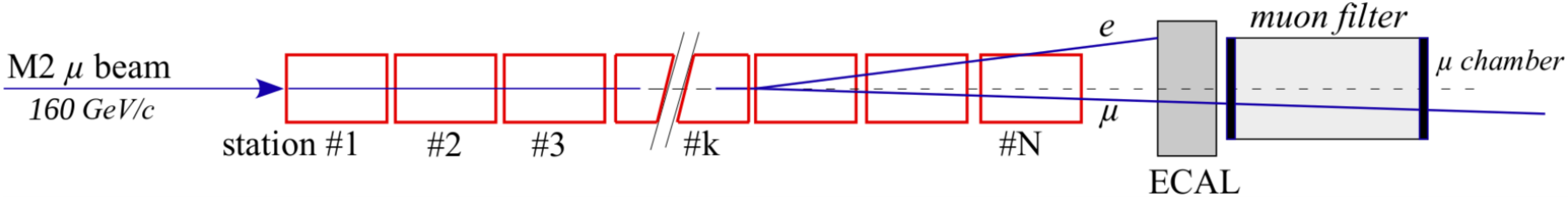




MUonE Experiment

Setup overview



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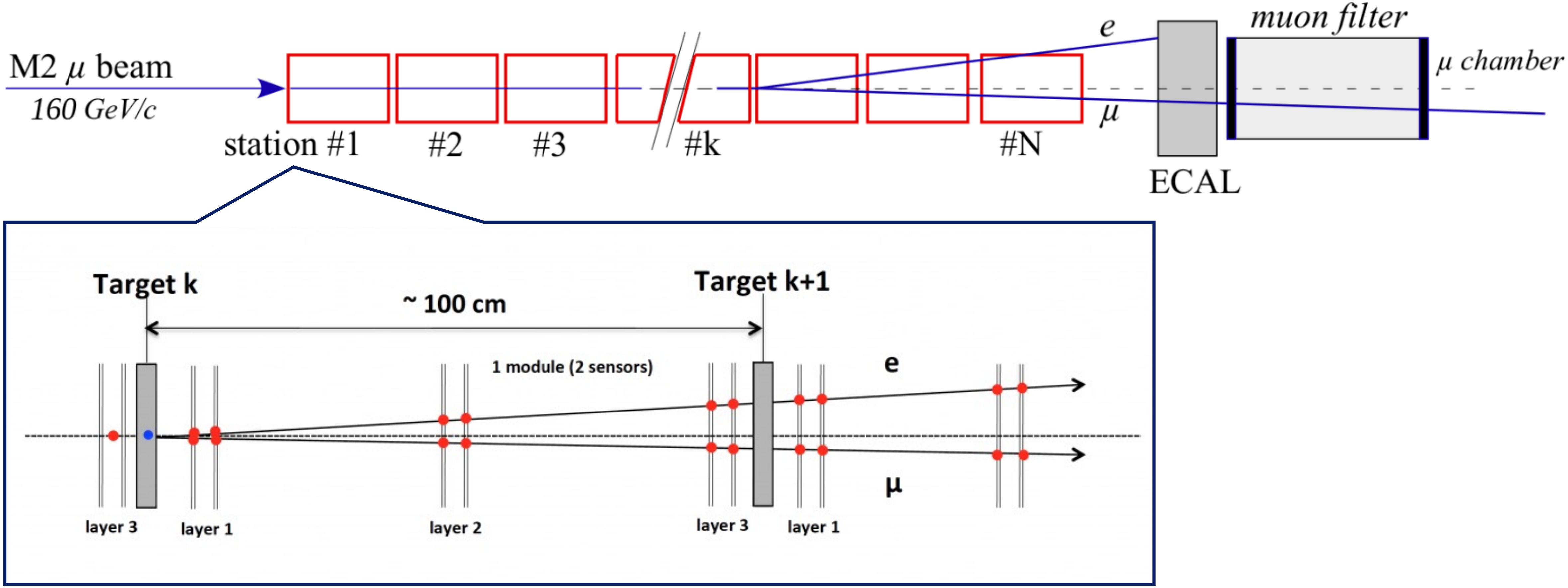

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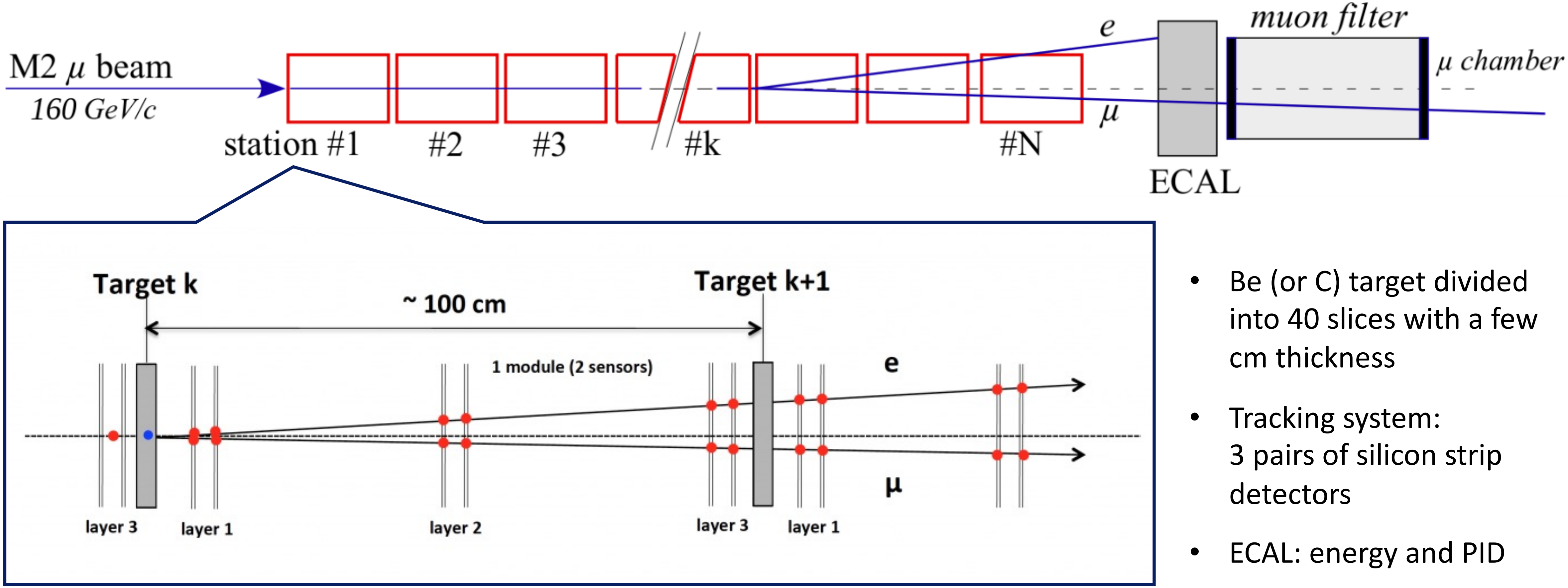

- Be (or C) target divided into 40 slices with a few cm thickness
- Tracking system: 3 pairs of silicon strip detectors
- ECAL: energy and PID

MUonE Experiment

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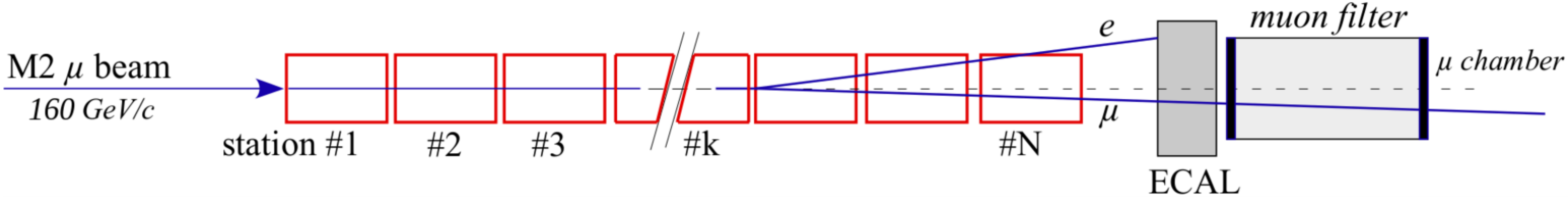
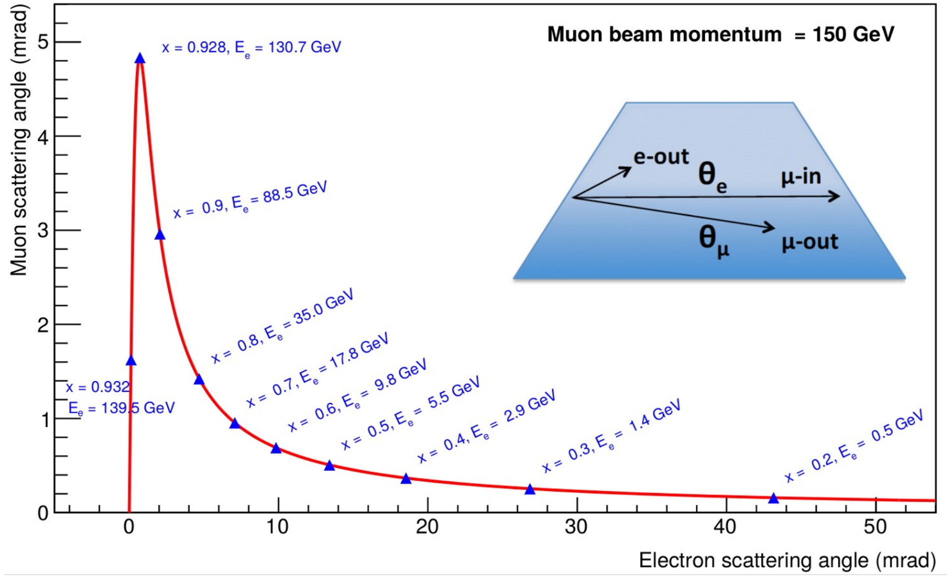
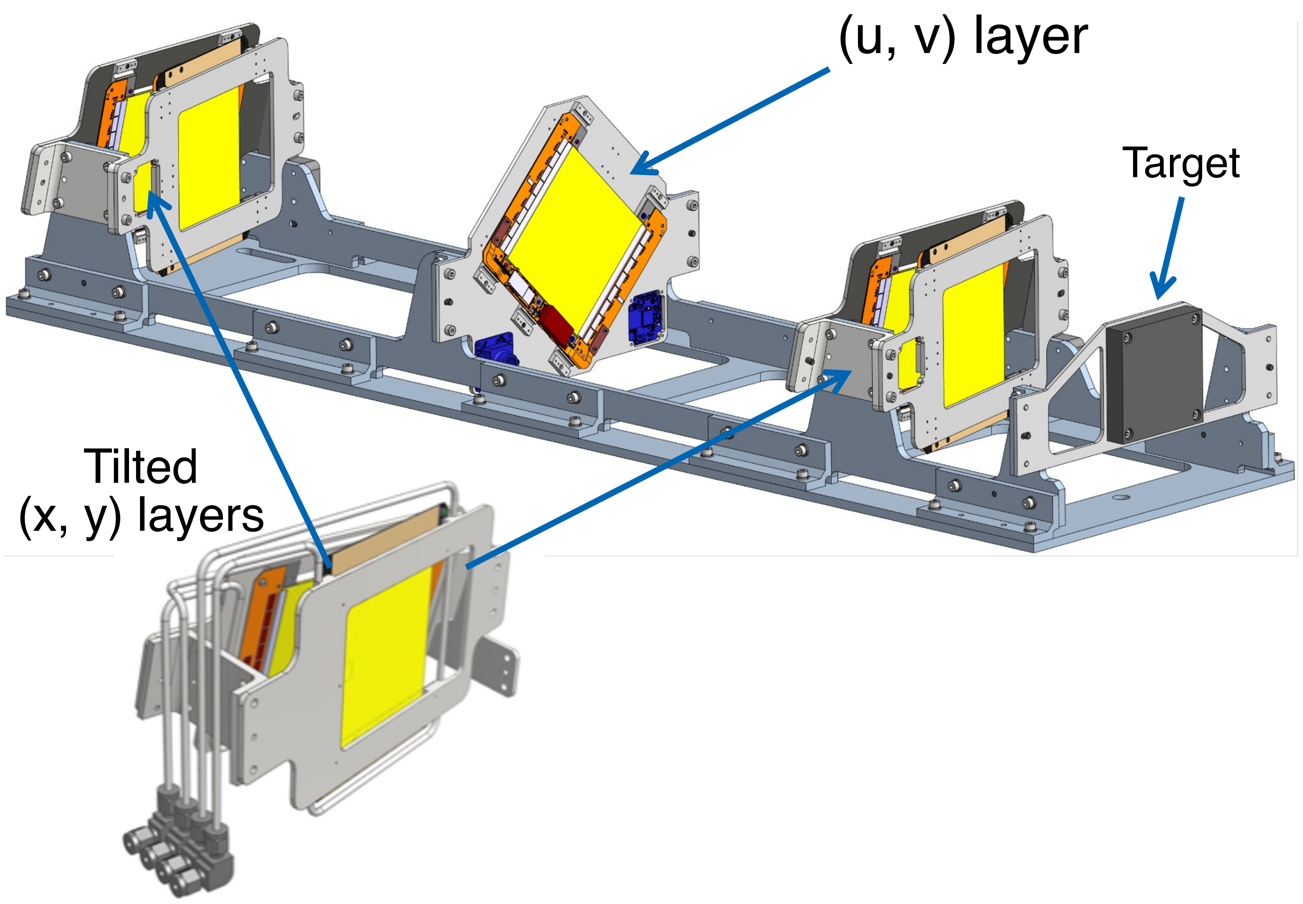


- **Angle correlation** between muon and electron allows to select elastic events and reject background ($\mu\ N \to \mu\ N\ e^+e^-$).
- Boosted kinematics:
  - Single detector to cover full acceptance
  - $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.



MUonE Experiment

Setup: the tracking station



- Two (x, y) layers and (u, v) layer
  - (x, y) layers tilted for better resolution
  - (u, v) layer rotated to solve reconstruction ambiguities.
- Relative position between stations must be stable at **10 μm** → **a super precise experiment!**
  - Low-CTE material (INVAR, carbon)
  - Well-controlled temperature
  - Laser system to monitor stability

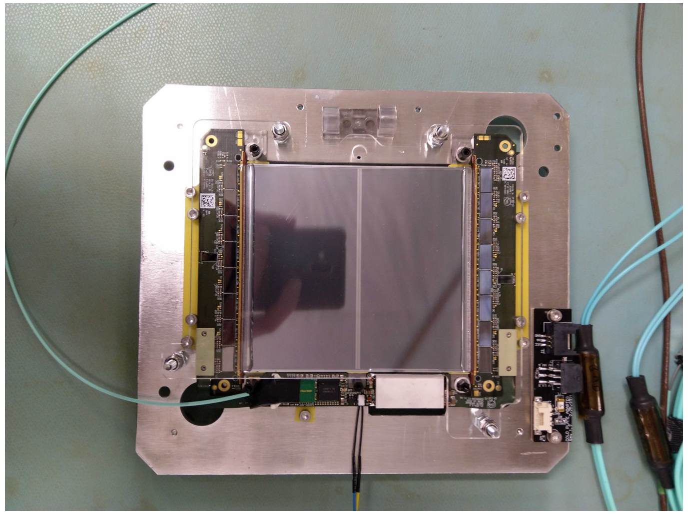
MUonE Experiment

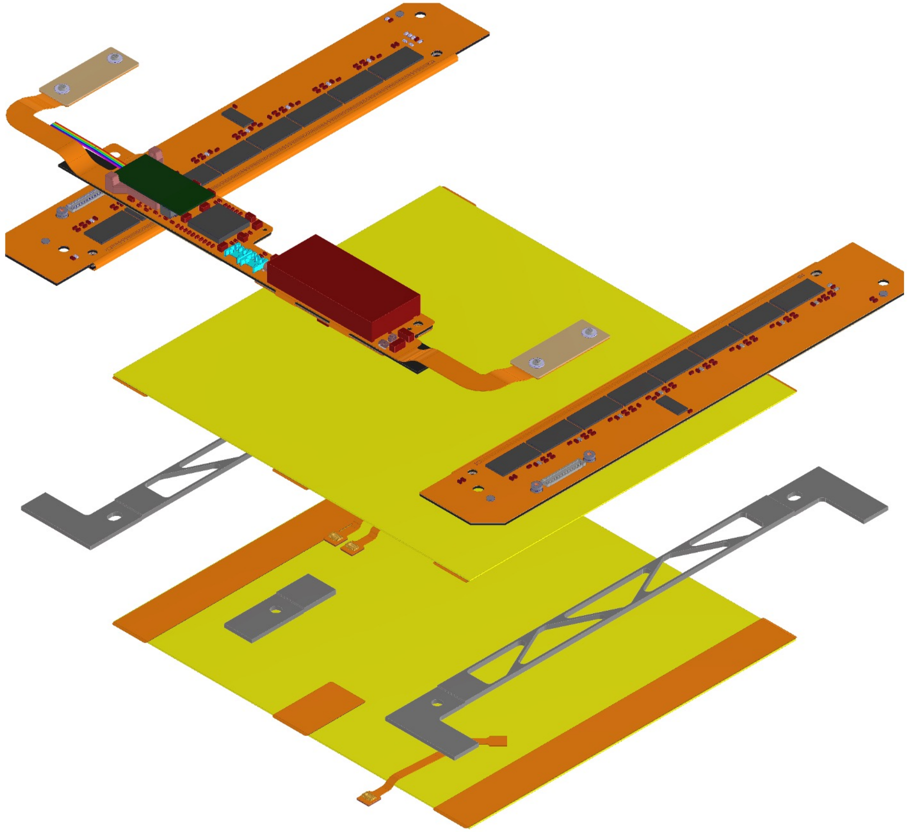
Setup: the tracker (CMS 2S Module)

- Silicon strip sensors currently in production for the CMS-Phase 2 upgrade (HL-LHC).
- Each module is divided in two independent halves.

A single half:

- 1016 strips
- 5 cm long
- Divided in 8 sectors
- Each sector has independent read-out





MUonE Experiment

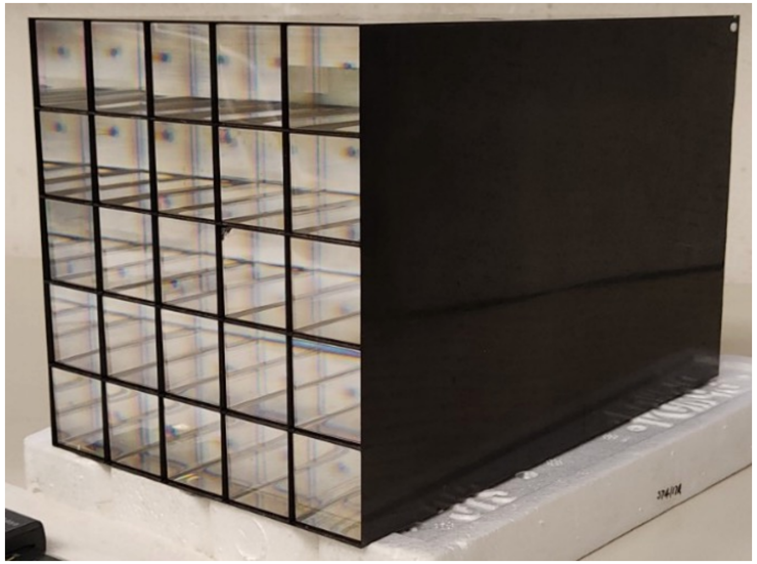
Setup: calorimeter

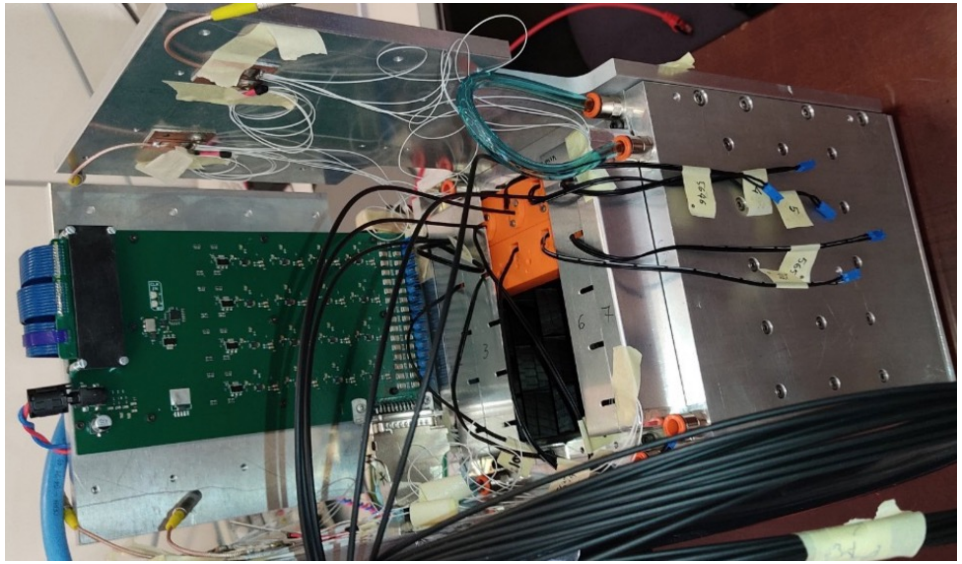
- A forward ECAL covering part of the total scattering acceptance
- Useful for **PID** & systematic study (an independent kinematic measurement)
- Support from FNAN muon g-2 ECAL

Transverse dim: ~ 1x1 m^2

5x5 $PbWO_4$ crystals:

- Area: 2.85x2.85 cm^2
- Length: 22 cm (~25 X0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors.





The experiment location

Muon (M2) beam-line at CERN Prévessin site

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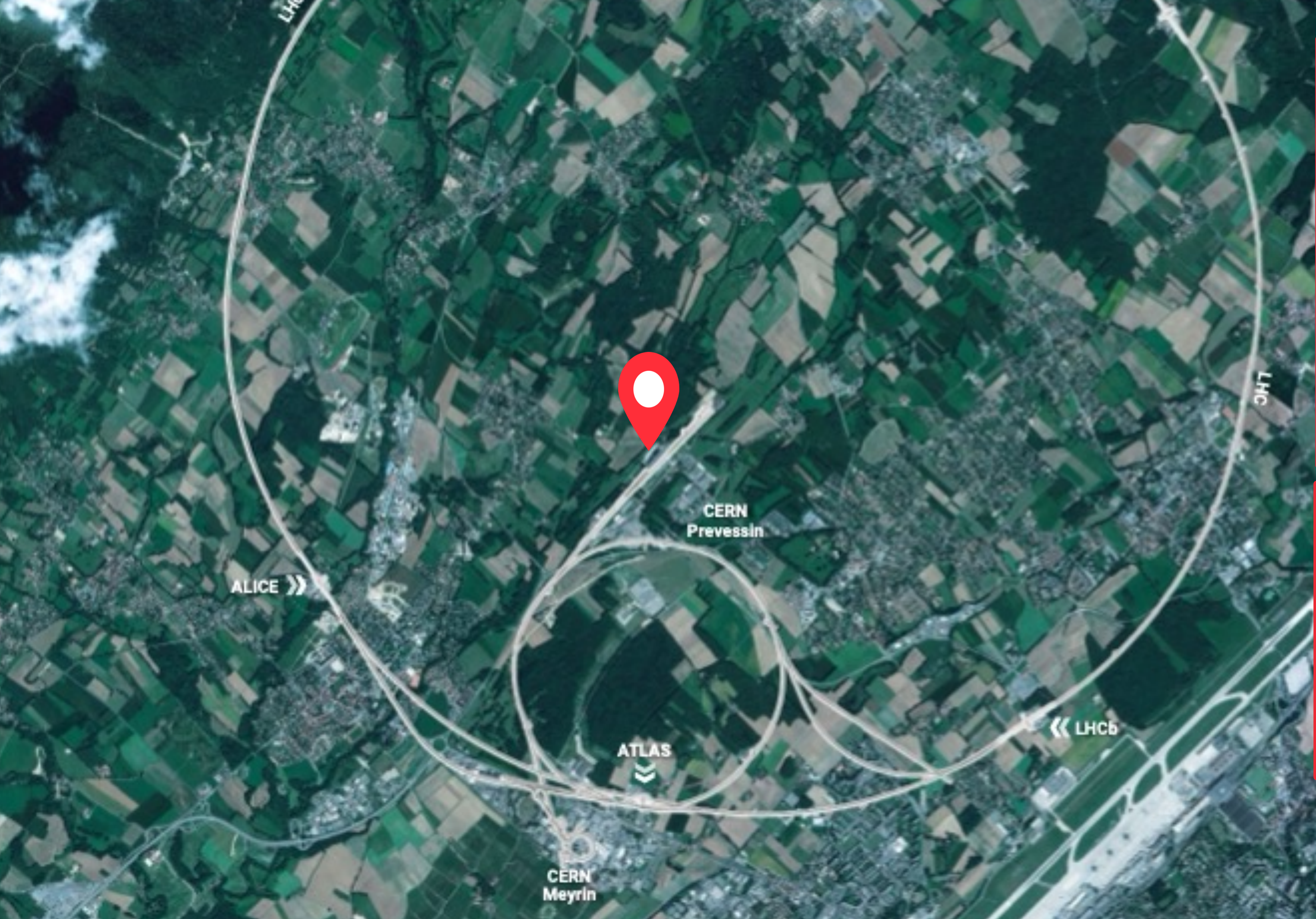

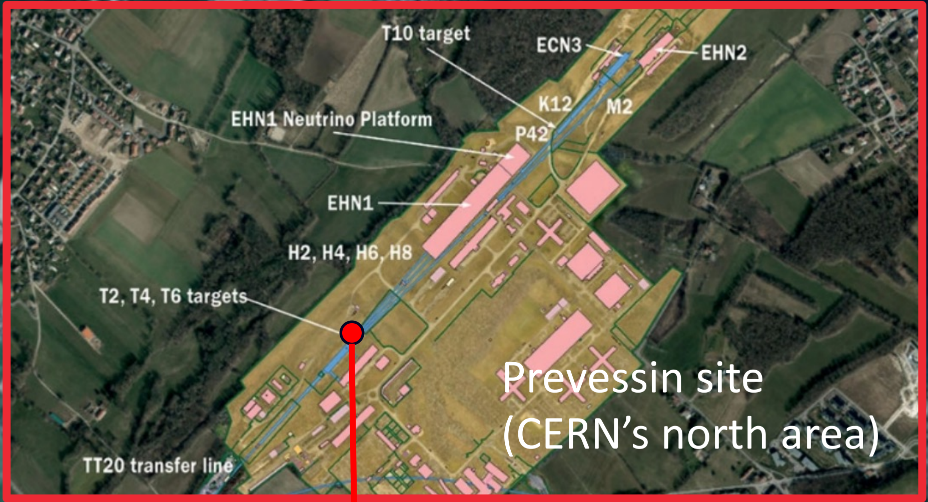

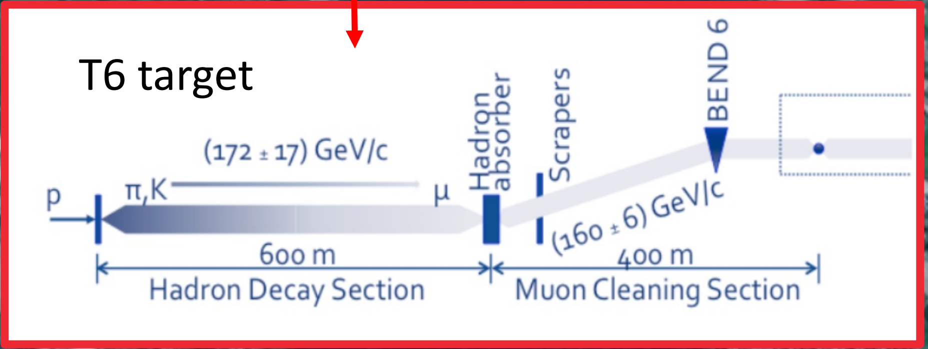

Test runs

Joint test with CMS tracker group from 2021 to 2023

Oct – Nov 2021
• First test of the 2S module with tracker DAQ system • Also confirmed thermal stability of the mechanical structure

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- Beam intensity and profile measured in the real beam conditions

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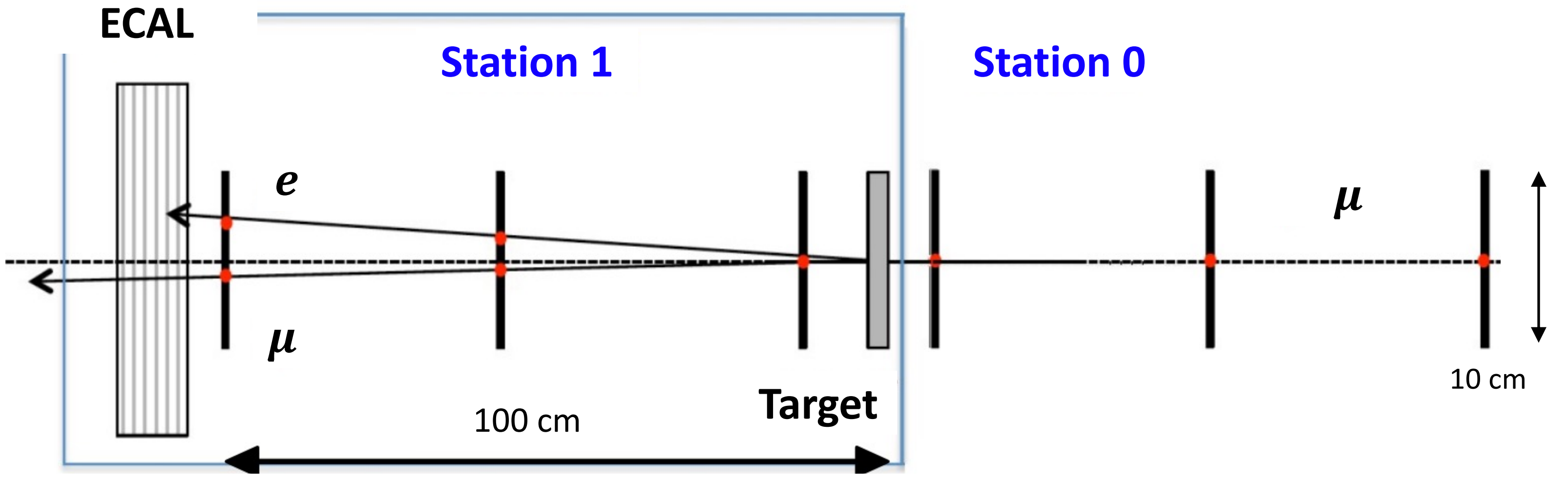
Aug – Sep 2023

- **First physics data taking to for the $\Delta\alpha_{\text{lep}}$ measurement**

Test run 2023

2 stations (pre-tracker + target + tracker) + ECAL

- Expected luminosity: ~ 1pb^{-1}
- $\sim 10^{12}$ μ accumulated on target with $\sim 2.5\times 10^{8}$ elastic events with $E_e > 1$ GeV
- Goal: demonstration measurement of $\Delta\alpha^{\text{LEP}}$ with a few % precision



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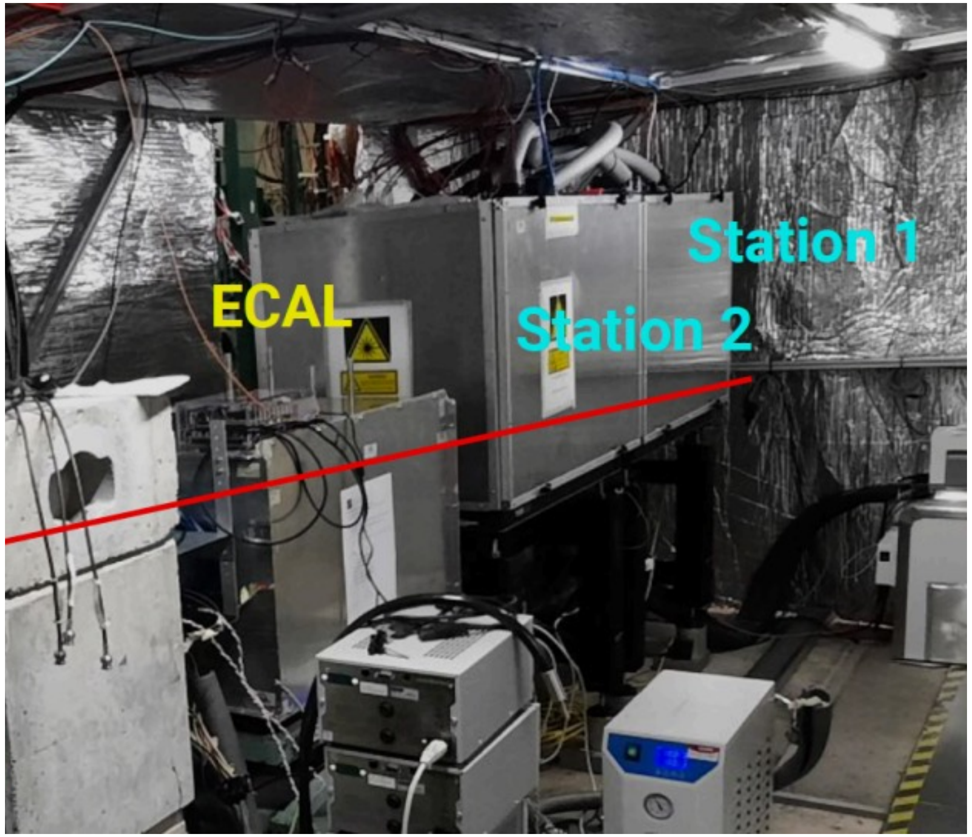


Test run 2023

Data sets under various configs

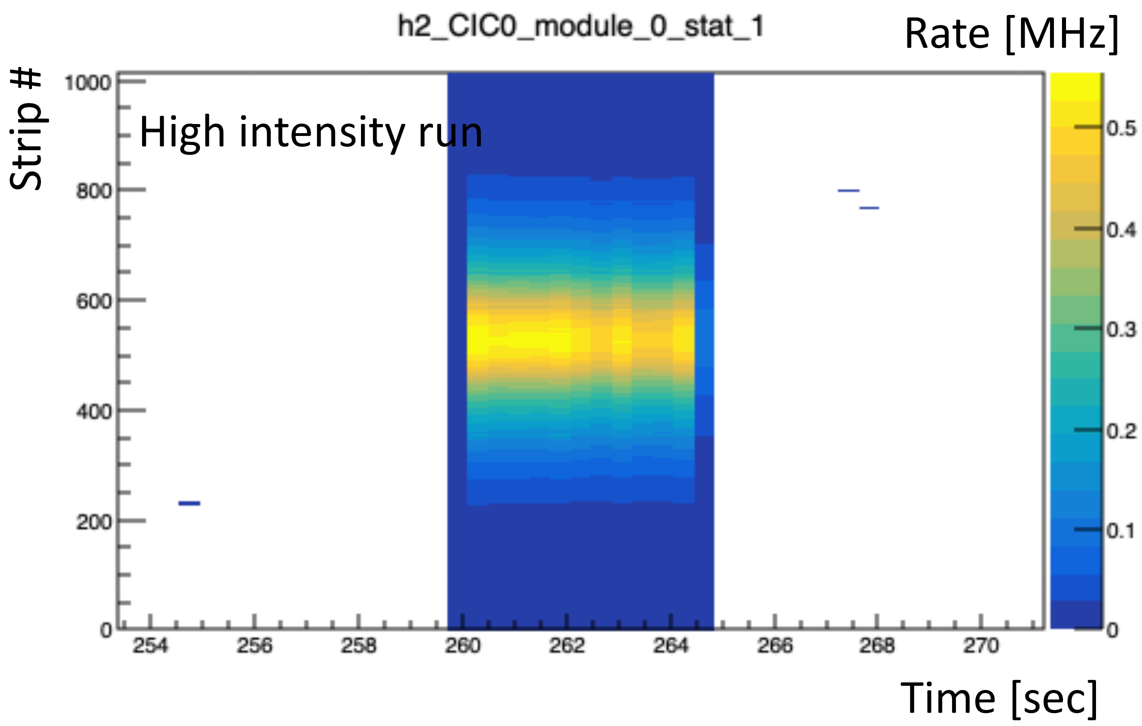
- 160 GeV muons with max asynchronous rate of 50 MHz (2E8/spill)

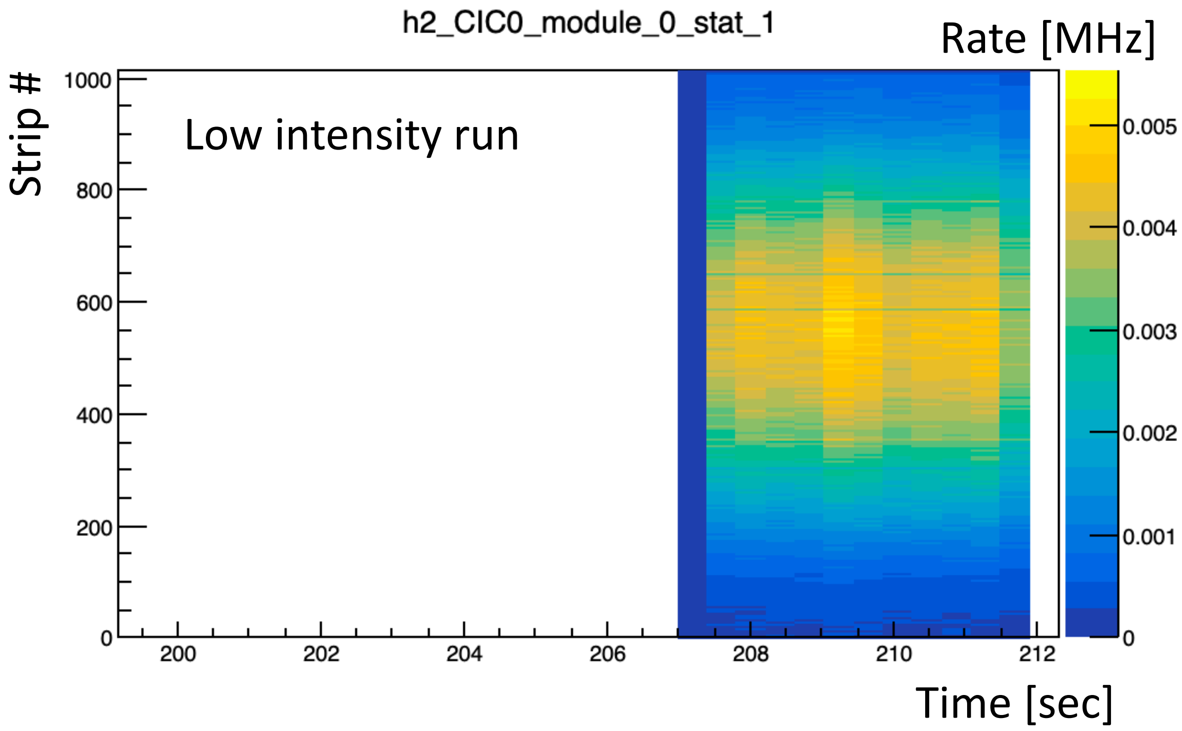
Beam intensity	Particle type	Target thickness	ECAL	Estimated muons
Low	Muon	2 cm	N	~1e9
High	Muon	2 cm	N	>300e9
High	Muon	3 cm	N	under production
High	Muon	2 cm	Y	under production
Low	Electron	2 cm	N	N/A

Test run 2023

Muon beam profile & intensity

- Silicon strip helps us 'see' the beam profile at the target position





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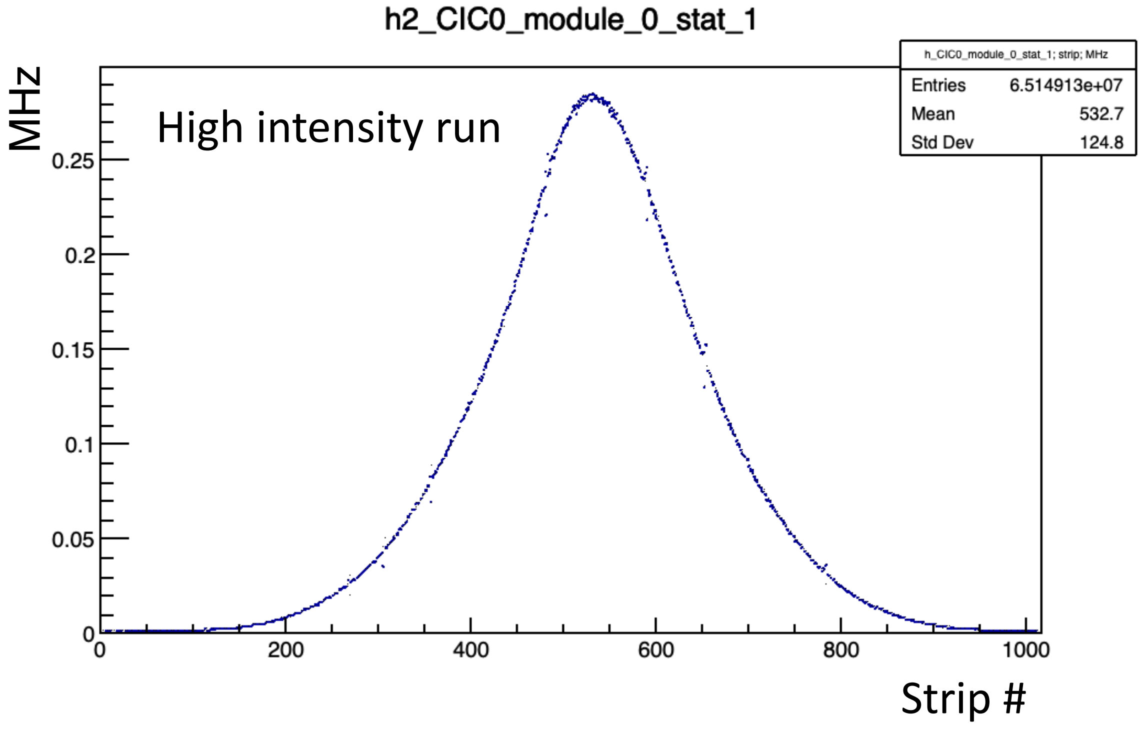

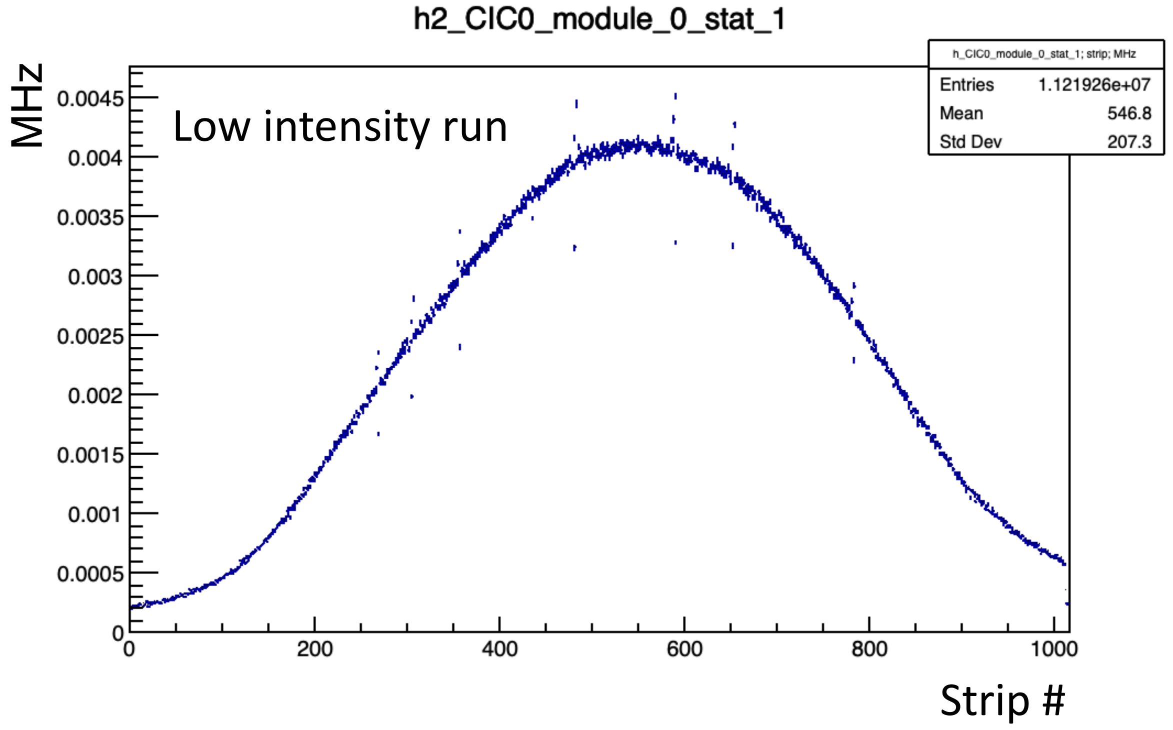

Test run 2023

Muon beam profile & intensity

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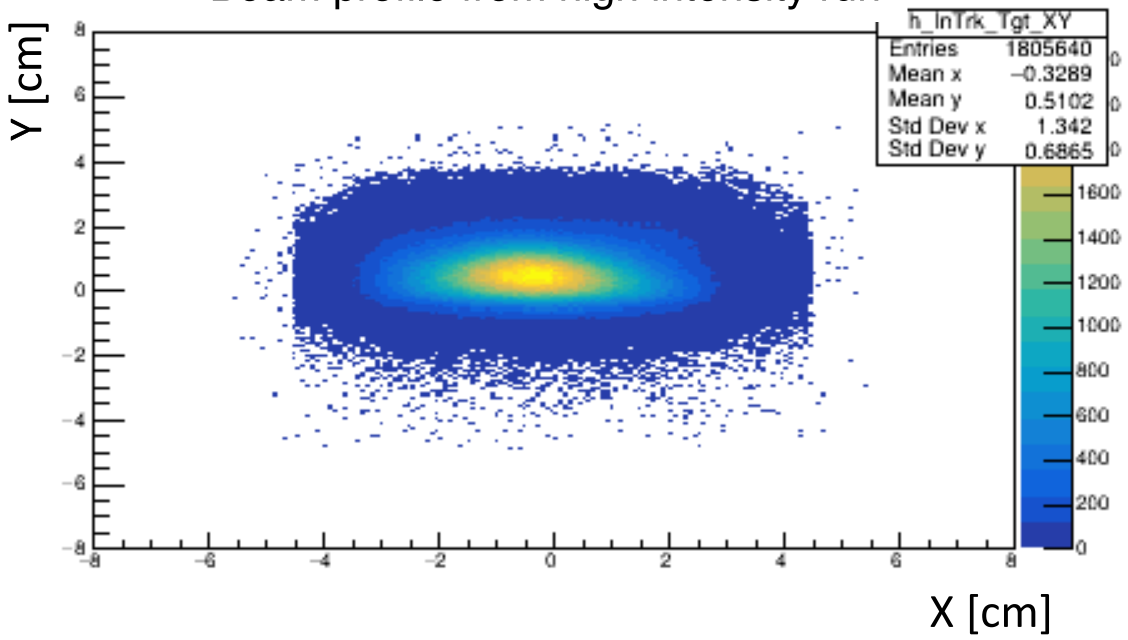
Beam profile from high intensity run



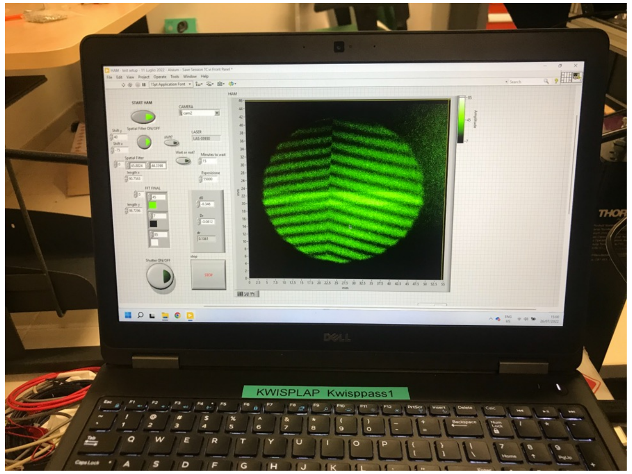
$\sigma_x = 1.34$ cm
$\sigma_y = 0.68$ cm

Confirmed the beam profile fits our detector dimensions

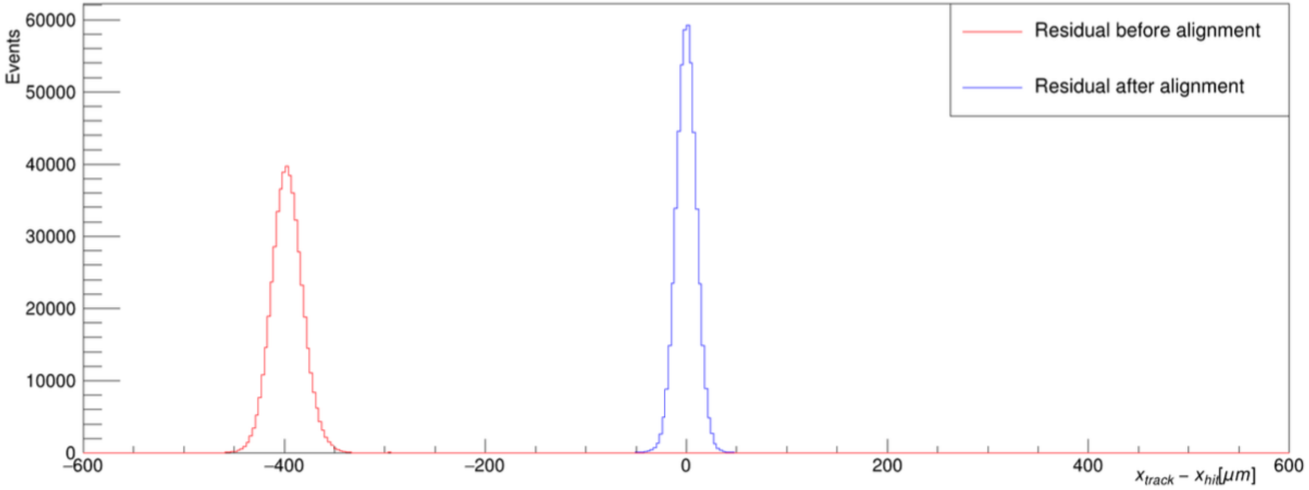
Test run 2023

Module alignment, resolution and efficiency

- It is extremely challenging for MUonE to achieve precise alignment of less than **1 um** transversely and **~10 μm** longitudinally for the modules and stations.
  - Hardware level: metrology measurements using **laser survey**
  - Software level: implemented with FairMUonE



a laser holographic system developed at INFN



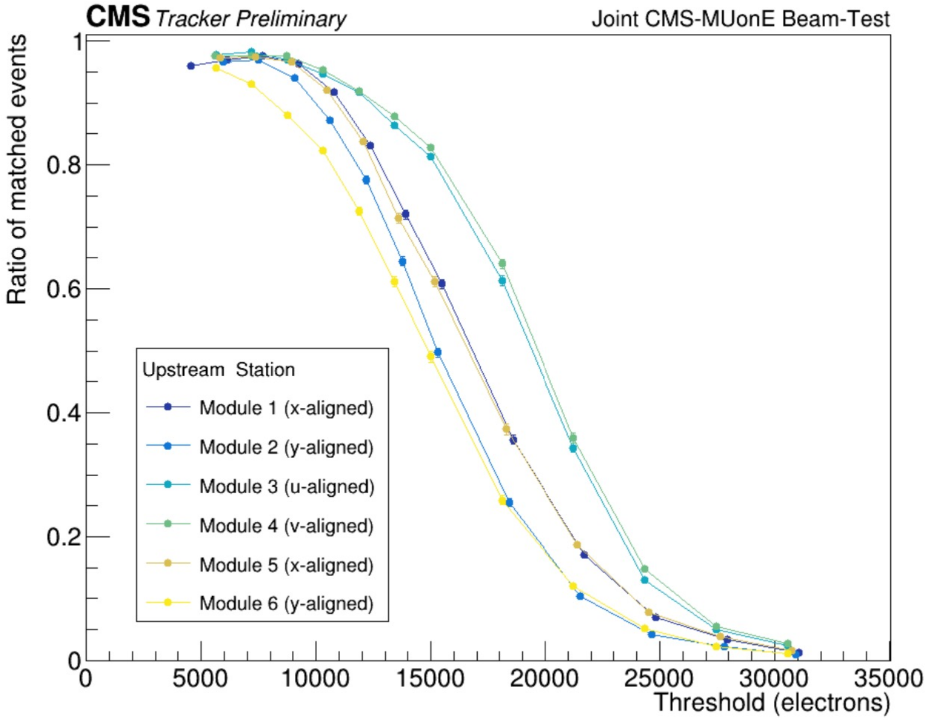
Test run 2023

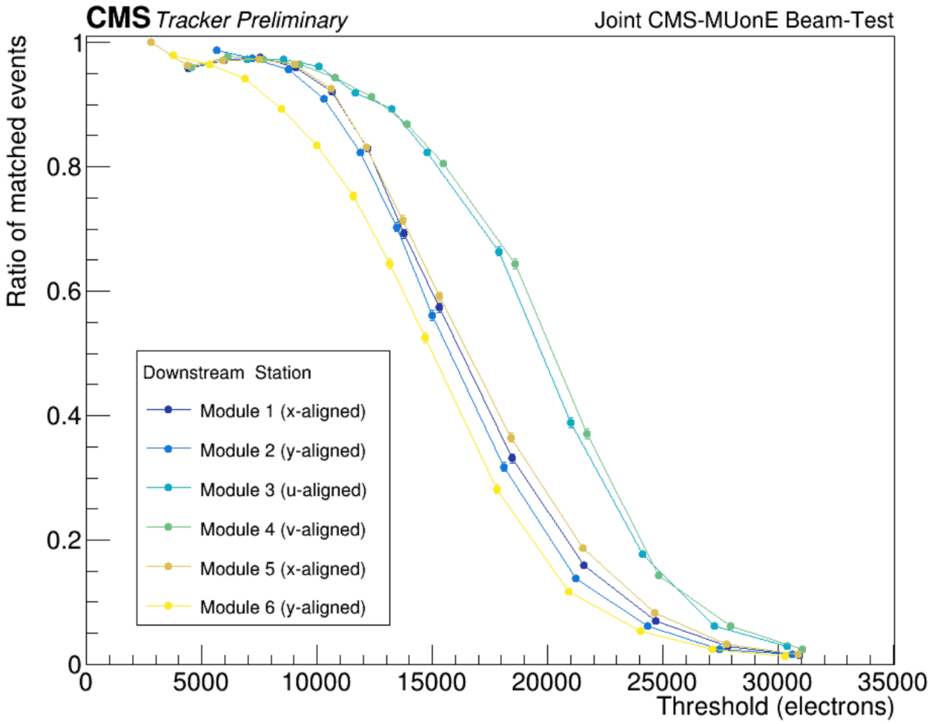
Module alignment, resolution and efficiency

- Module consistency check performed jointly with CMS tracker team

Ratio of events with at least a stub in a given module when all other modules have measured a single stub, as a function of comparator threshold

Plots approved by CMS

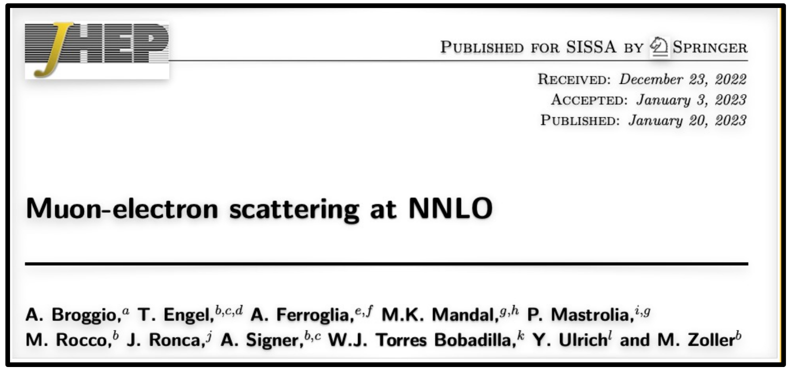




Analysis for test run 2023

Software framework

- **NNLO** Monte Carlo generator: **MESMER**
- ‘MuE’ fast simulation (Geant4-based)
  - (θ_e, θ_μ) up to the NLO generator
  - Limited detector effects (multiple scattering) included
- ‘FairMUonE’ dedicatedlty developed for this project
  - **Full detector effects** and **track reconstruction**
  - Event selection & **weighted (θ_e, θ_μ)** for template fits
- ‘Combine’ tool for analyzing systematic effects


JHEP

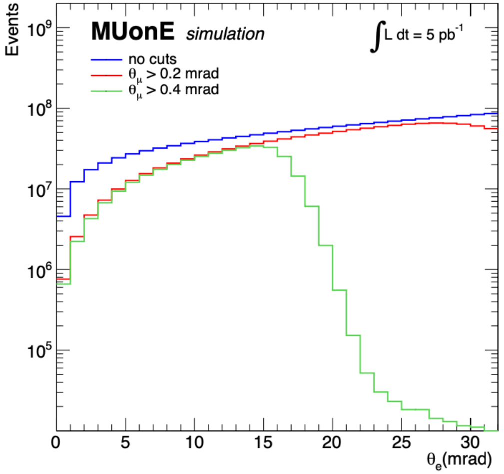
Published for SISSA by Springer

Received: *December 23, 2022*
Accepted: *January 3, 2023*
Published: *January 20, 2023*

Muon-electron scattering at NNLO

A. Broggio,[a] T. Engel,[b,c,d] A. Ferroglia,[e,f] M.K. Mandal,[g,h] P. Mastrolia,[i,g] M. Rocco,[b] J. Ronca,[j] A. Signer,[b,c] W.J. Torres Bobadilla,[k] Y. Ulrich[l] and M. Zoller[b]

First NNLO prediction!

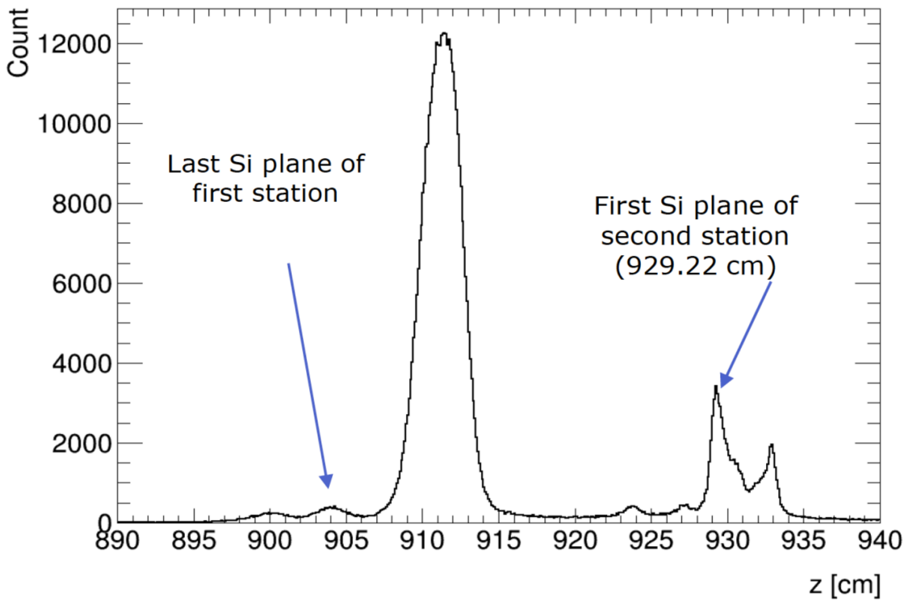


Analysis for test run 2023

Event reconstruction & selections

- Some basic criteria
  - Track candidate quality (χ^2)
  - Vertex position in the target
  - Acoplanarity
- Kinematic considerations
  - $E_{\mu(\text{beam})},\ \theta_\mu,\ \theta_e$:
    - θ_μ : tune background of e^+e^- pairs
    - θ_e : tune acceptance
    - $E_{\mu(\text{beam})}$ is in principle described by two angles
  - PID: muons can be distinguished from electrons using solely the angular information

Skimming + 2 outgoing tracks + (min, max) angular cuts



Analysis for test run 2023

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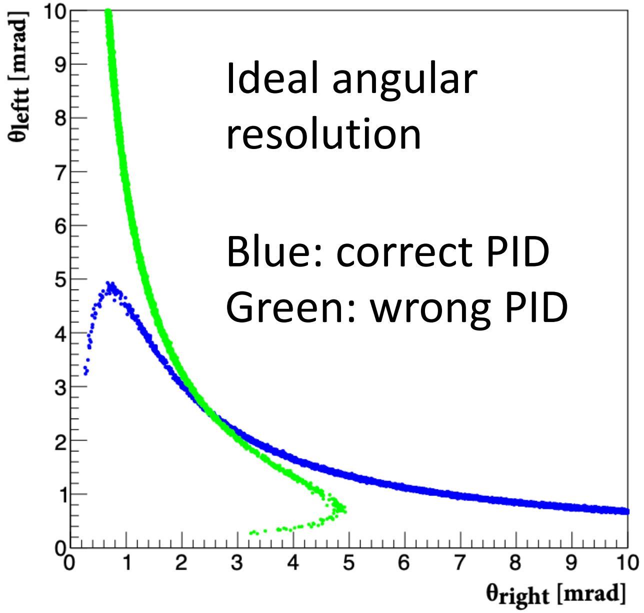
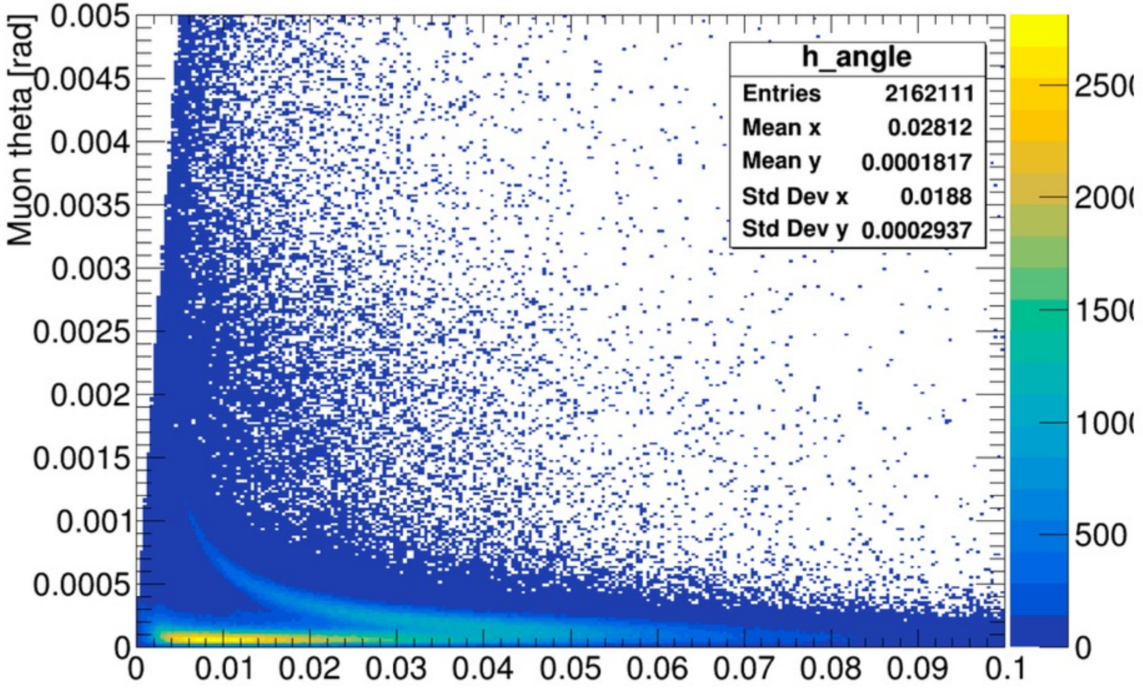


Test run 2023

First elastic scattering results

Angle distribution before selection



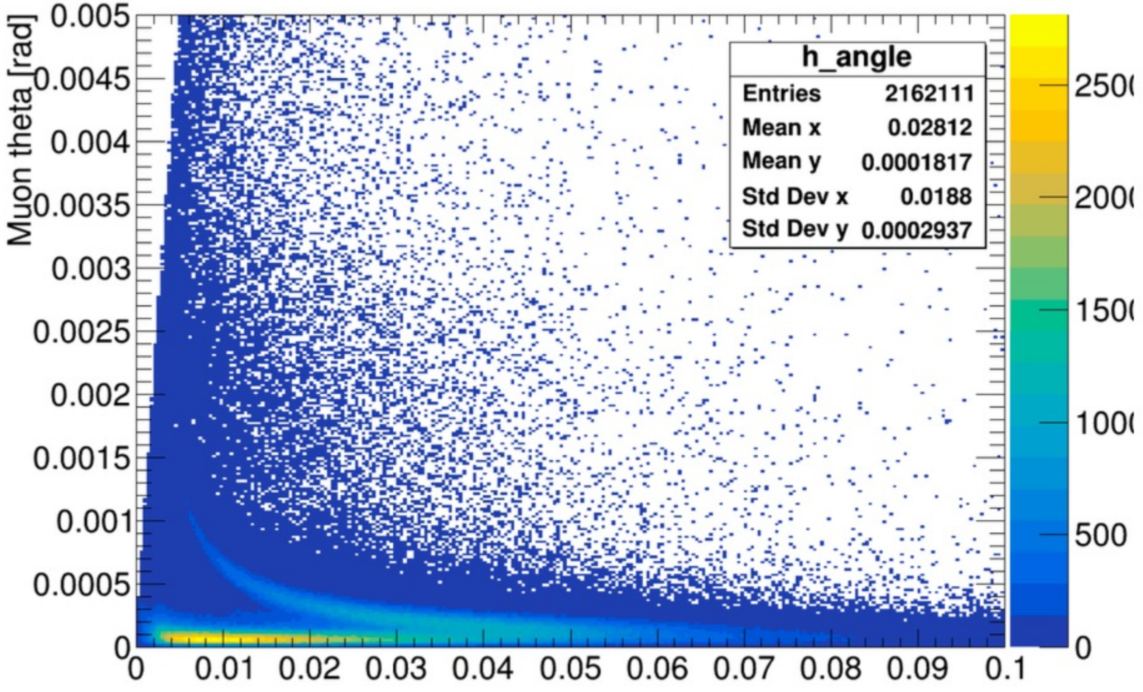
Selections:

- Angles from the best vertex fit in FairMUonE
- 3 tracks (1 incoming & 2 out)
- Acoplanarity cut (<=1)
- Vertex reconstructed +/- 1 cm of the target mean position
- **Angles: θ_μ> 0.2 mrad; θ_e < 32 mrad**

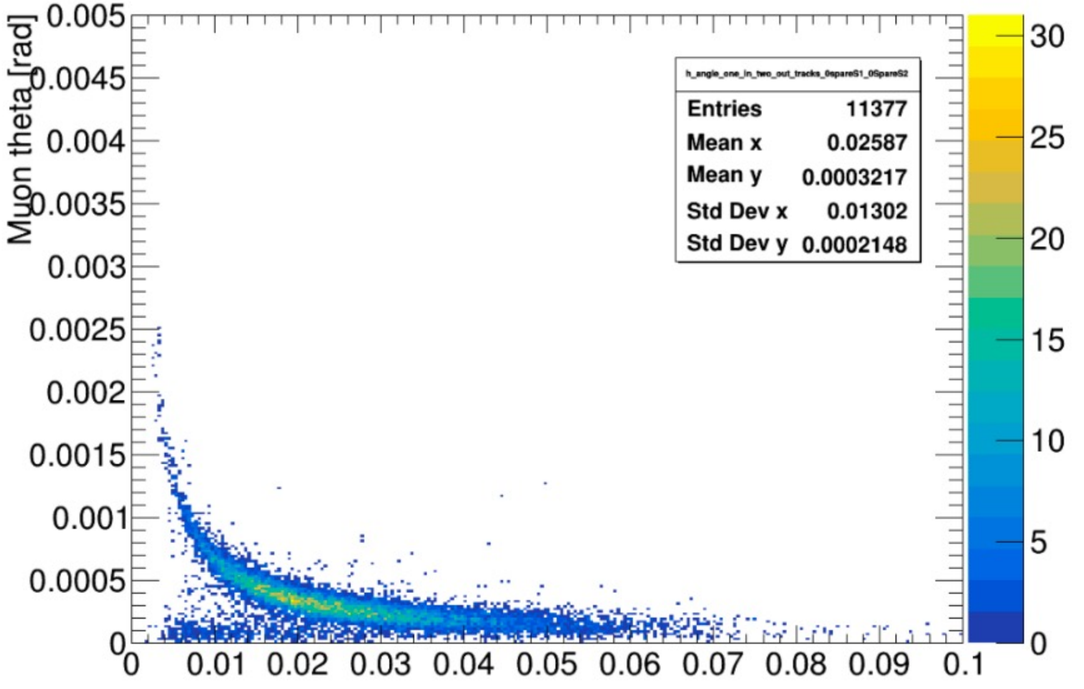
Test run 2023

First elastic scattering results

Angle distribution before selection



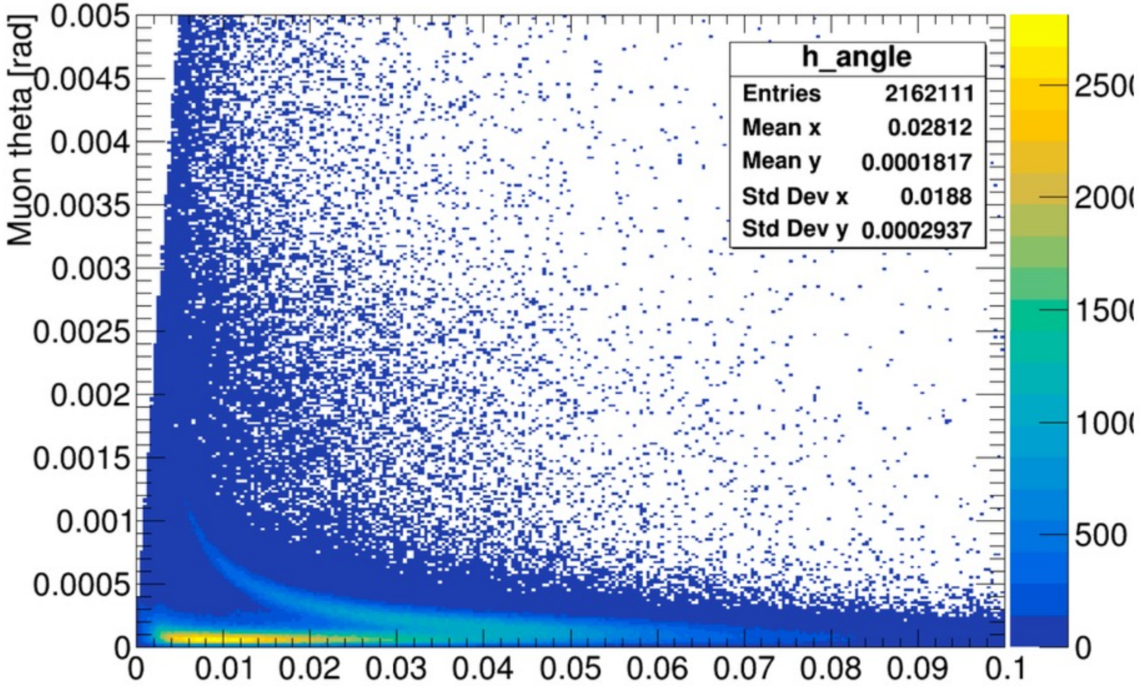
Angle distribution after selection



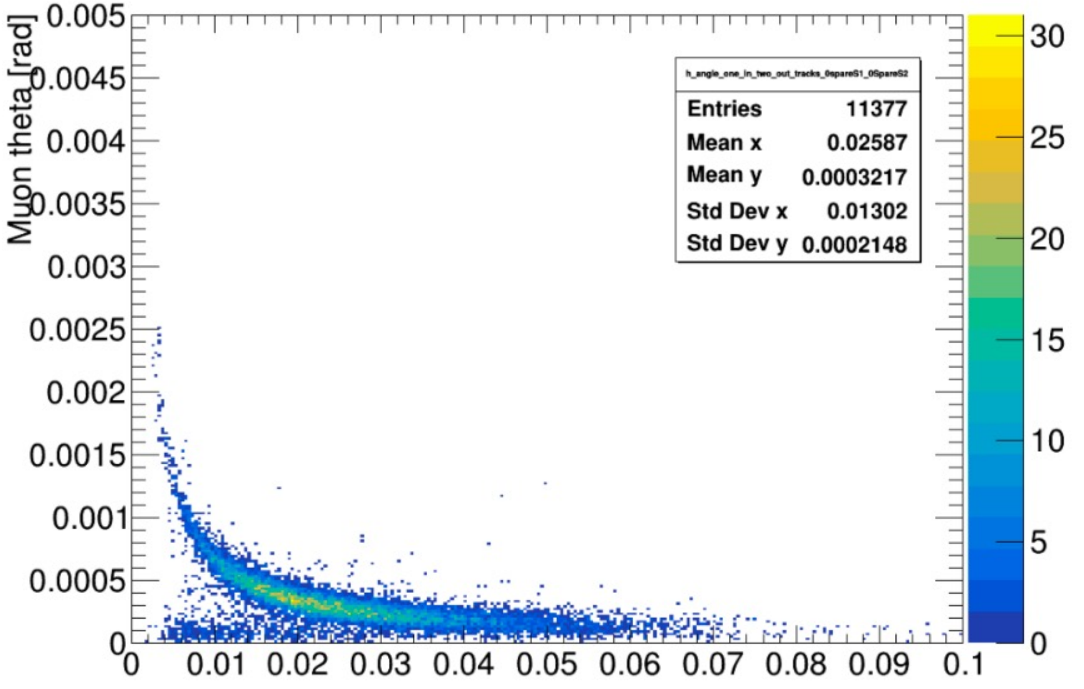
Test run 2023

First elastic scattering results

Angle distribution before selection

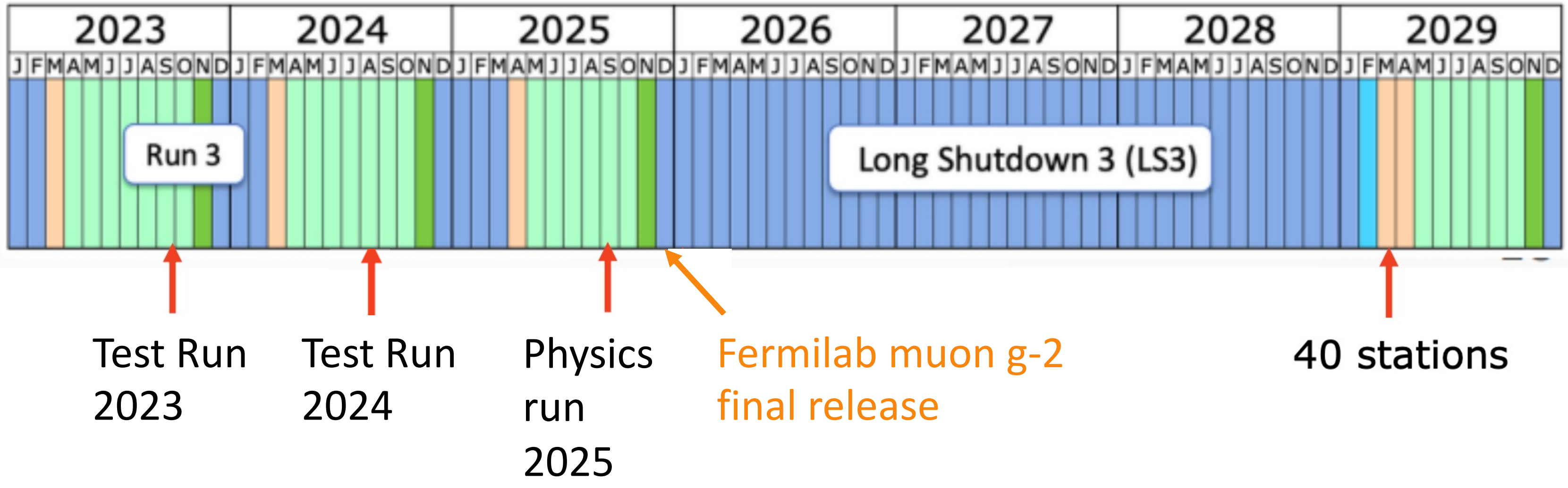


Angle distribution after selection



Timeline

- **Experimental proposal** to be submitted this year! (June 2024)
- **The first physics run in 2025** before LHC *Long Shutdown* (2026 - 2028)
  - **3** stations; 2- 4 months data-taking; **about 20% precision of a_μ^{HLO}**
- **Full run** with 40 stations after LS3 with final goal ~0.3% precision



Summary

- Muon $g-2$ puzzles:
  - Conflict between **Muon g-2 SM predictions** and experimental measurement
  - $\boldsymbol{a_\mu^{\mathrm{HVP,LO}}}$ represents a major uncertainty in the e^+e^- data-driven method for SM prediction
- MUonE: a new approach for $\boldsymbol{a_\mu^{\mathrm{HVP,LO}}}$ **via $\boldsymbol{\mu - e}$ scattering**
  - An **independent determination of $\boldsymbol{\Delta\alpha_{\mathrm{had}}}$ for the first time**
  - A **high-precision experiment;** lots of hardware & software developments
  - We are now analyzing 2023 data demonstrative for $\boldsymbol{\Delta\alpha_{\mathrm{lep}}}$
  - Promising test lead us to **the first physics run in 2025** and **full run for 2028+**

50+ people from over 9 countries

https://web.infn.it/MUonE/

The MUonE Collaboration

CERN
Exp-Th

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

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

Krakow IFJ Pan
Exp

Cornell U.,
Northwestern U.,
Regis U.,
Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) *Exp-Th*

Shanghai Jiao Tong U.
Exp

PSI (Villigen), U.Zürich, ETH Zürich
Th

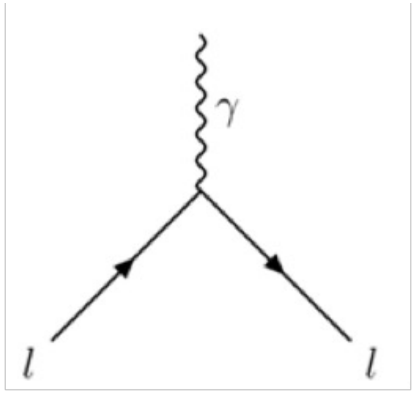
Mainz U., Max-Planck Inst.
Exp-Th

+ other involved theorists from: New York City Tech (USA), Vienna U. (A)

Backup

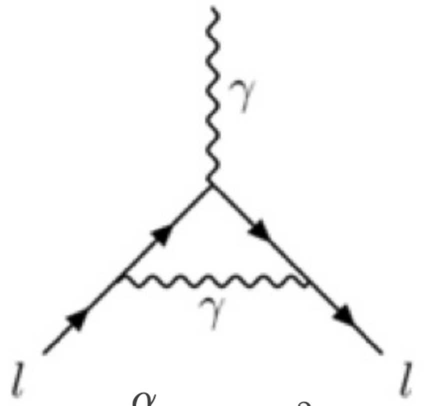
Muon $g-2$

- The anomalous magnetic moment of the muon:
  - Magnetic moments **precess** in a magnetic field $\vec{\mu} = g\frac{e}{2m}\vec{S}$
  - g - factor quantifies interaction strength



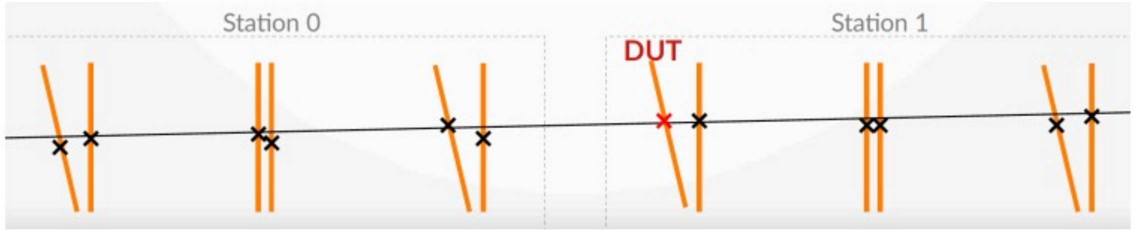
- Interactions with virtual particles cause g to deviate from 2 ($g > 2$). **Muon magnetic anomaly** is defined as:

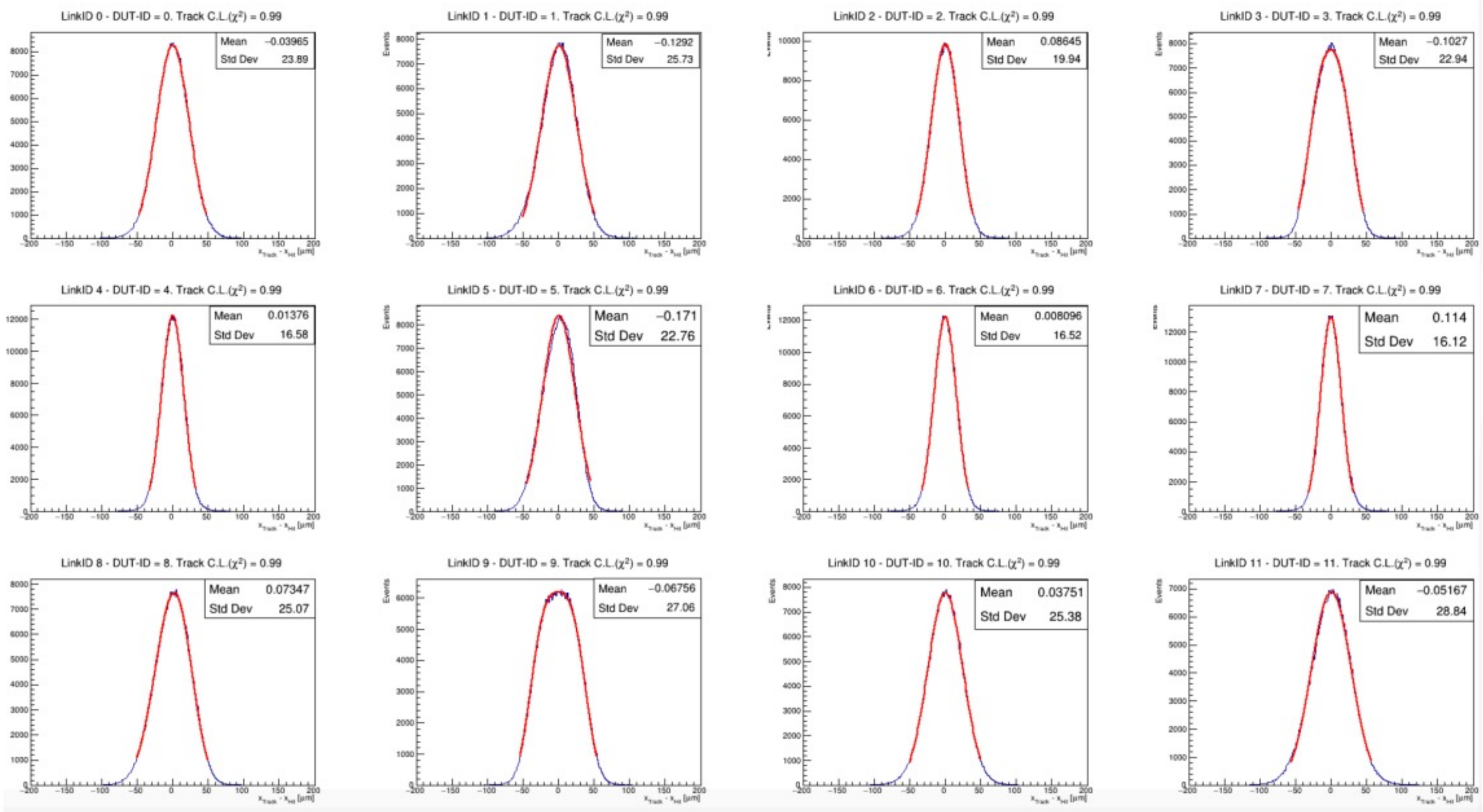
$$a_\mu = \frac{g-2}{2}$$



$\frac{\alpha}{2\pi} + O(\alpha^2)$

Real Data Alignment - Resolution





The tracker is aligned with passing beam muons leaving one hit in all the 12 detector modules

three coordinates aligned per each module:
Strip local position (local X)
Rotation angle around the Z axis
Orthogonal coordinate (local Y)

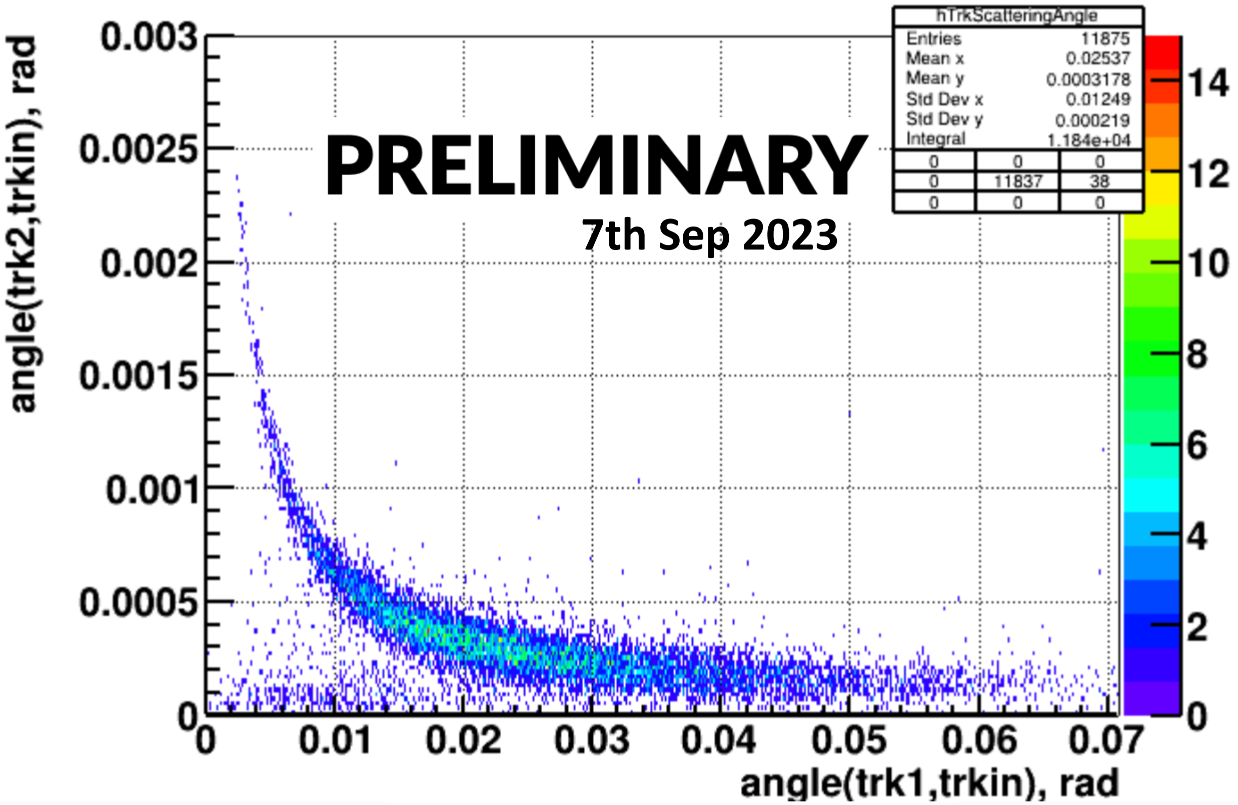
Unbiased residuals on the tracker modules after the alignment: RMS consistent with expected resolution

On-going development to include the metrology measurements as starting point

Results from test run 2023

Preliminary result on scattering events!

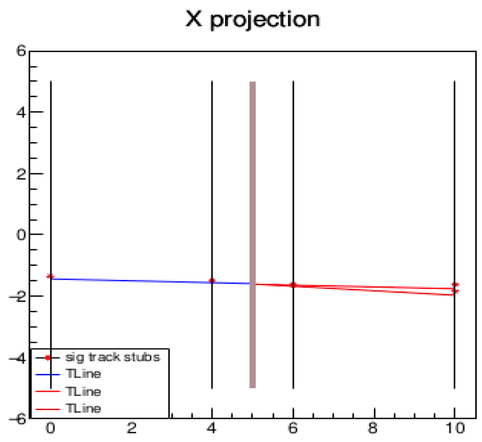
- Runs with a 3-cm target installed
- N single muons 2.9×10^{8} in used sample (assuming no hit loss and overlap)
- One track in the 1st station + 2 tracked in the 2nd station
- Chi2/ndf track cut<5
- Zvtx selection applied after selecting two outgoing tracks within the target position

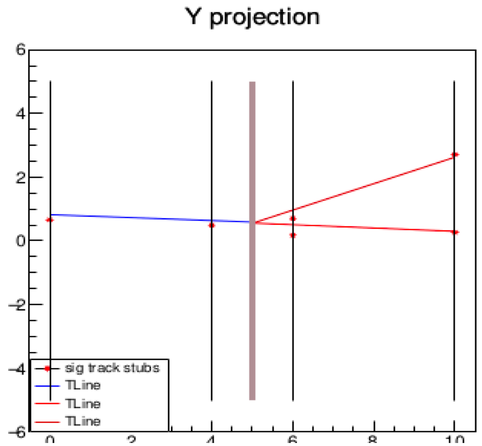


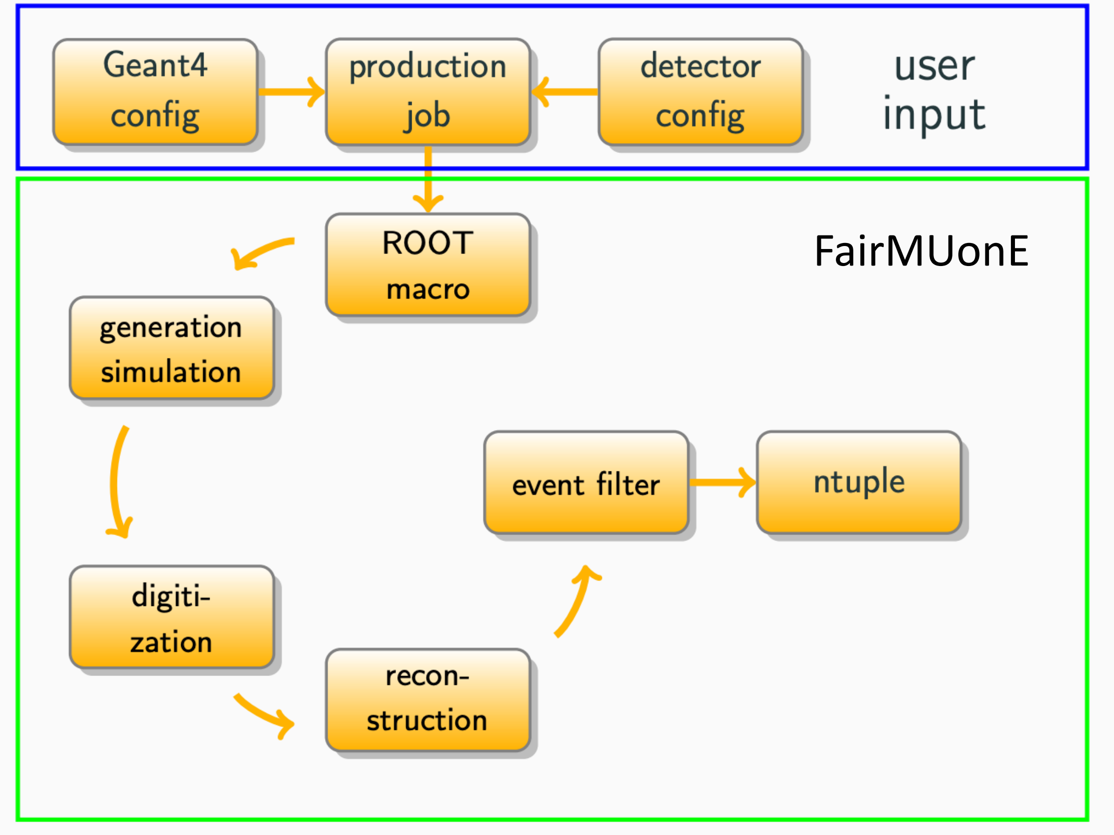
Elastic Scattering Analysis

‘FairMUonE’ Package

- The package developed dedicated to MUonE
- Both simulation and track reconstruction in the same package
- Digitization of tracker & calo are implemented







Elastic Scattering Analysis

Template Fit

- Extracting $\Delta\alpha_{had}(t)$ through **a template fit** to the (θ_e, θ_μ) distribution
- $\Delta\alpha_{had}$ parameterization **(K, M)**: $\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$
  - 'Lepton-like' parameterization
  - K: related to $\boldsymbol{\alpha_0}$ and the electric charge of the lepton in the loop (had: quarks colour charge)
  - M: related to the **squared mass of the particle** in the loop $(m_l^2, m_\mu^2, m_\tau^2)$
  - In the hadronic parameterization, K & M don't have real physical meaning

Elastic Scattering Analysis

Template Fit

- Extracting $\Delta\alpha_{had}(t)$ through **a template fit** to the (θ_e, θ_μ) distribution
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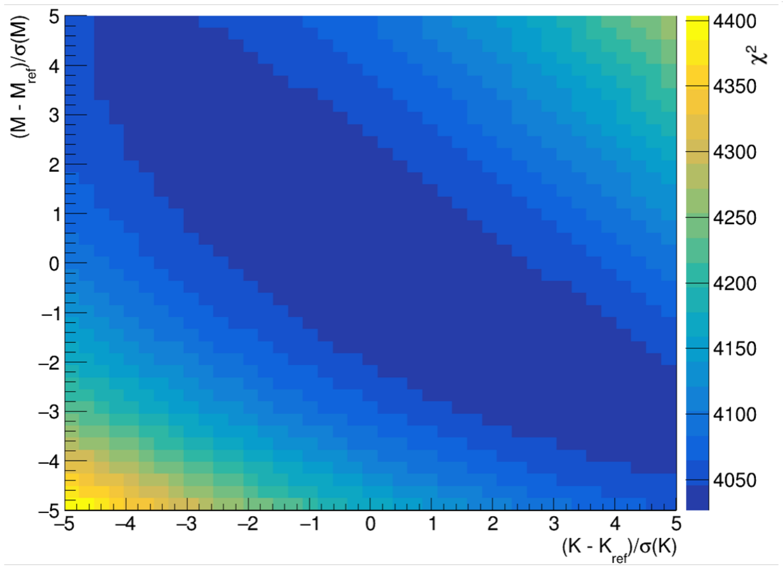
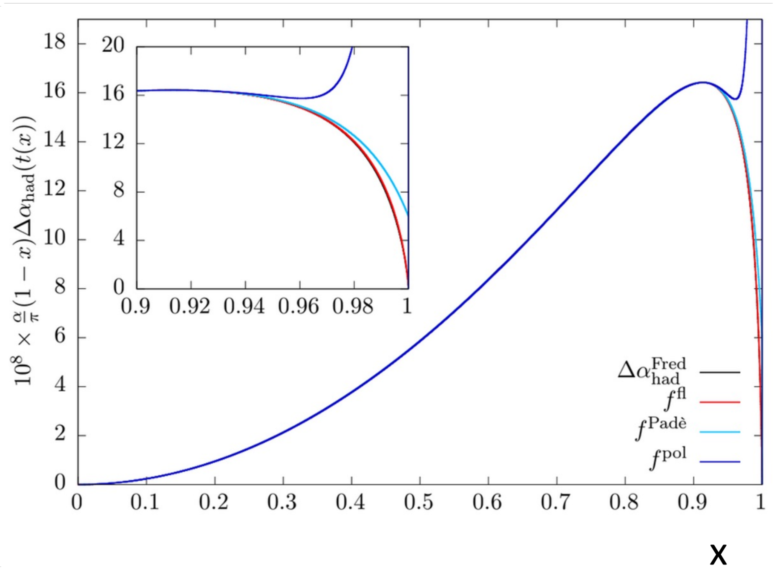


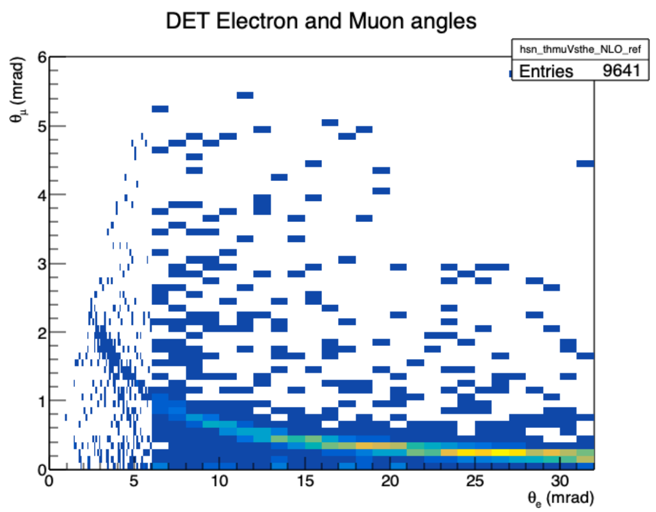


Preliminary template fit:

- Luminosity: 1.5×10^4 pb^{-1}
- 4×10^{12} elastic events with $E_e > 1$ GeV ($\theta_e < 32$ mrad)
- Input a_μ^{HLO}: **688.6×10^{-10}**
- Fitted a_μ^{HLO}: **$(688.8 \pm 2.4) \times 10^{-10}$**
- 0.35% statistical error

Test of template fit for $\Delta\alpha_{\mathrm{lep}}$

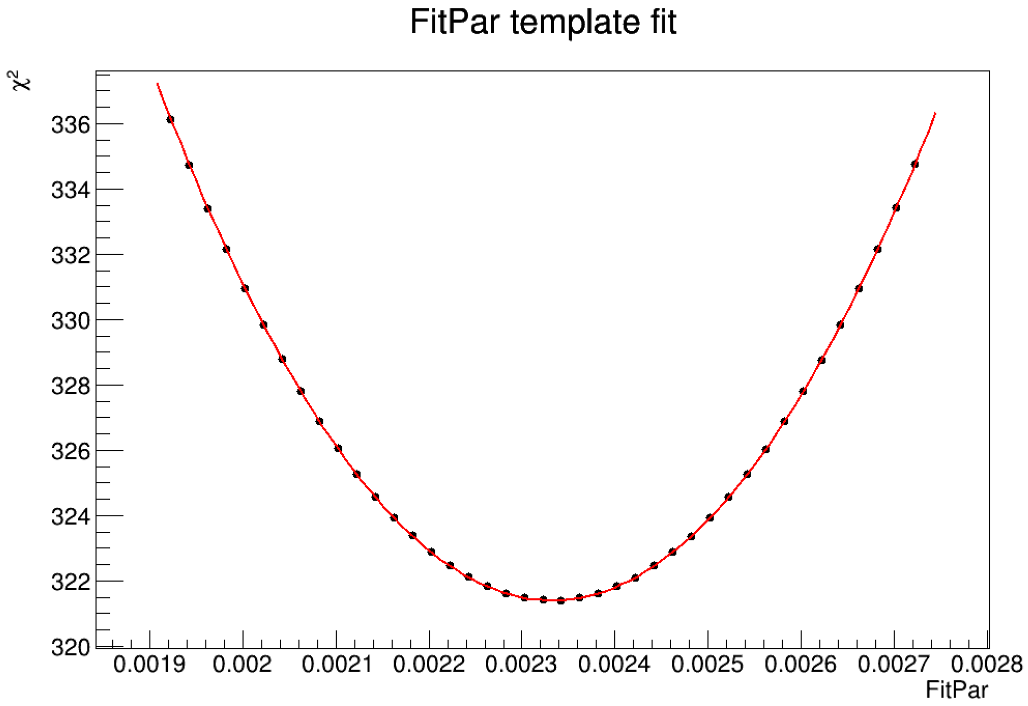
- Input about 1e4 MC events into the template fit
  - 3cm_HitSharing1_NoAlignment_Alpha2
  - Passing 'default_gold_angles_aco_zvtx' to fast simulation, do reweighting and generates 40 templates
  - Usual trick: use the **same MC set** for the pseudodata and the templates. Smear the pseudodata according to the expected statistics to make it independent of the templates

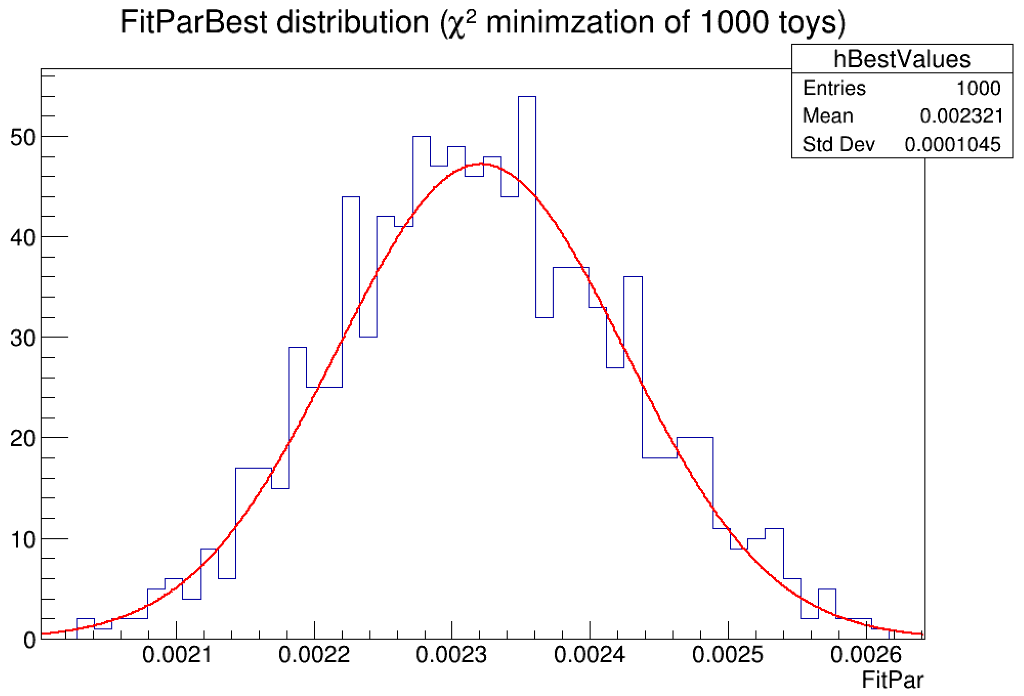


Template fit parameters:

- Kref = 0.0023223 +/- 8e-05
- Mref = 0.000511 +/- 0
- Sigma limit = 5
- Sigma step = 4
- Weights normalization: 1345.26 μb

Test of template fit for $\Delta\alpha_{\mathrm{lep}}$



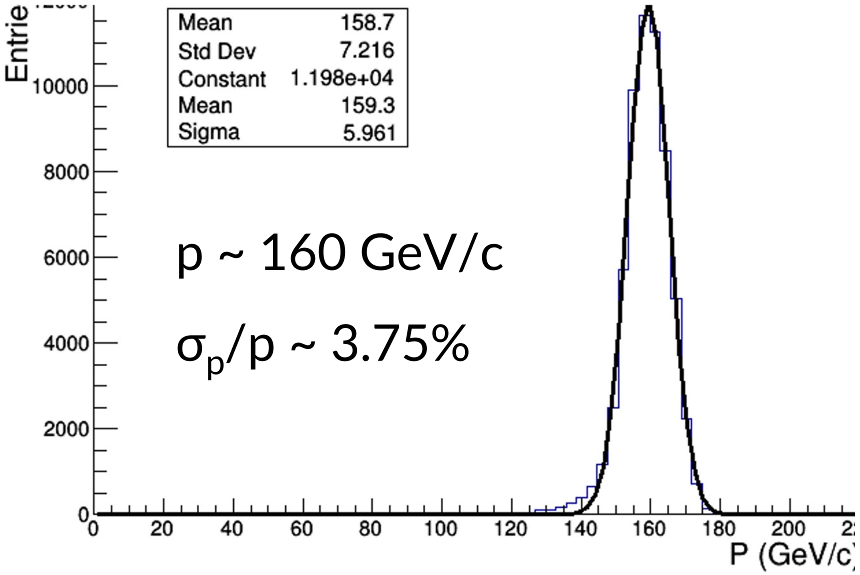


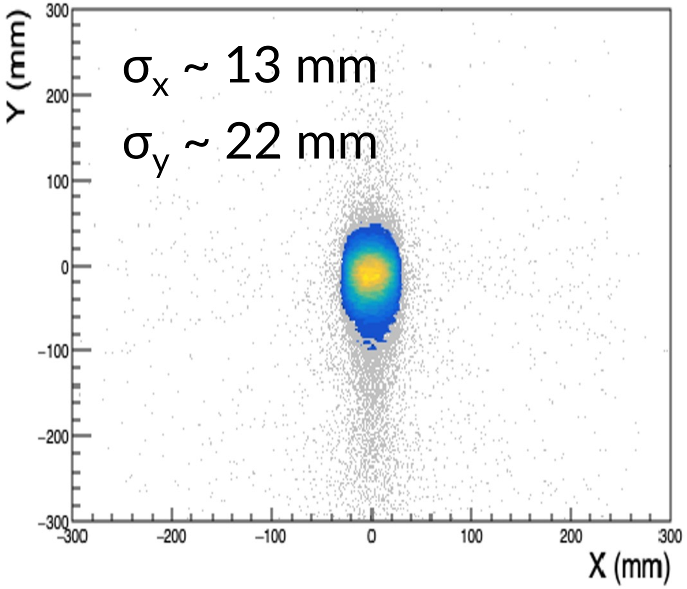
Fited best K = 0.00232086 +/- 0.000104678
(~4.4%, but it doesn't mean much!)

Test run 2023

Muon (M2) beam-line at CERN Prévessin site

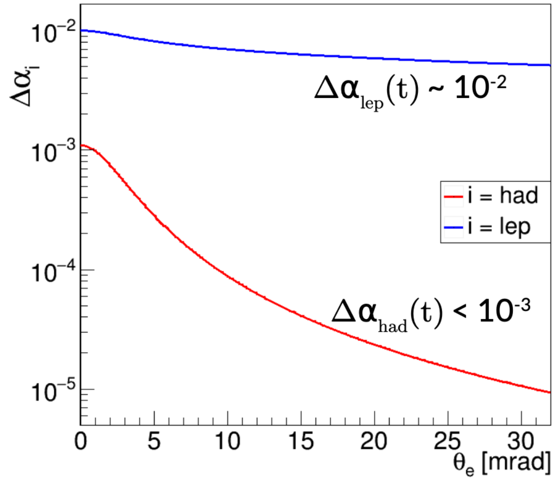
- CERN North Area M2: upstream of the COMPASS detector
  - Maximum 50 MHz (2-3×10^8 μ^+/spill) for 10^{12} 400 GeV/c incident protons



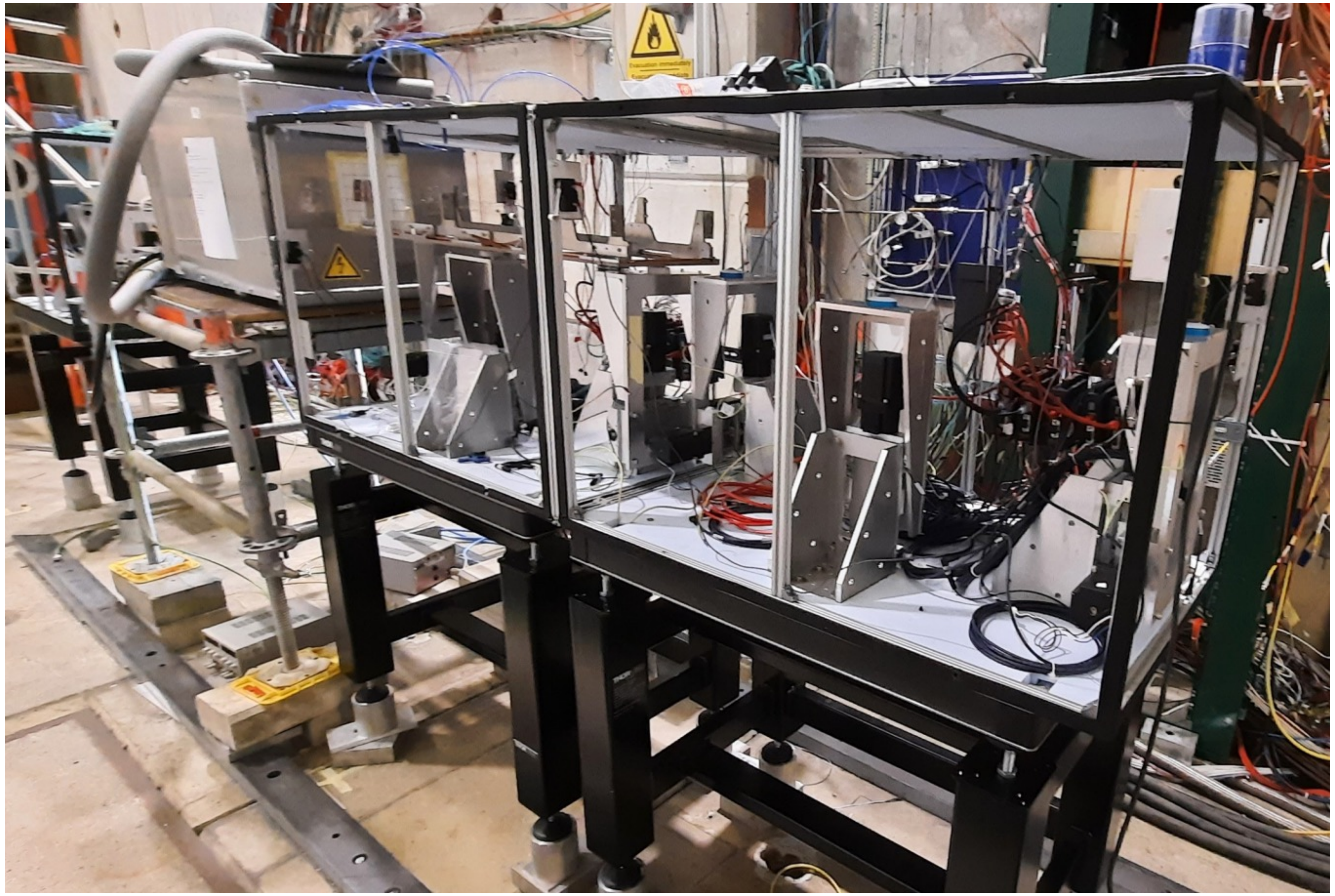


Test run 2023

- 21 Aug – 17 Sep
- 2 stations (pre-tracker + target + tracker) + ECAL
- Expected luminosity: ~ $1pb^{-1}$
  - $\sim 10^{12}$ μ accumulated on target with $\sim 2.5\times10^{8}$ elastic events $E_e > 1$ GeV
- **Goals**:
  - Engineering stability & detectors performance
  - Background study
  - Reconstruction & prompt analysis
  - Demonstration measurement of $\Delta\alpha^{\mathrm{LEP}}$ with a few % precision!

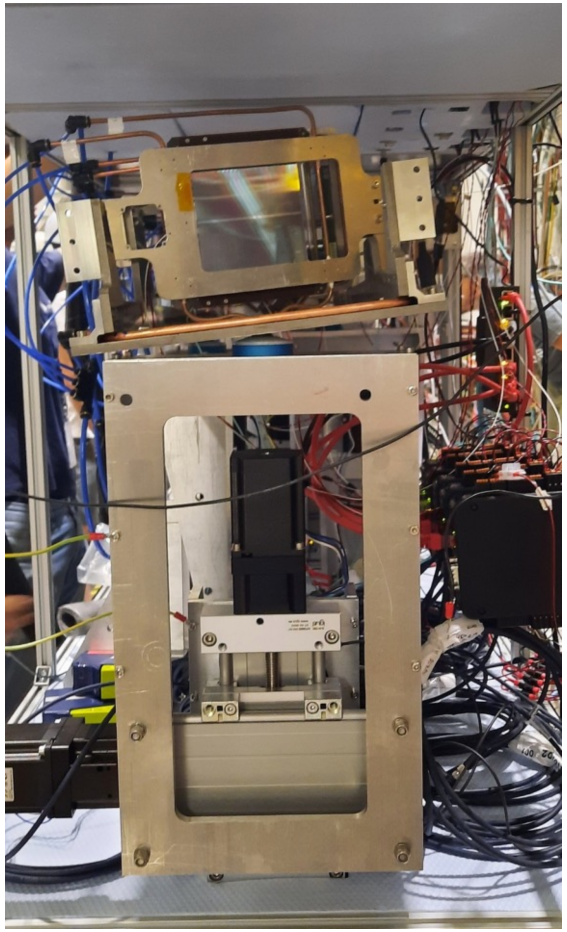


Test run 2023

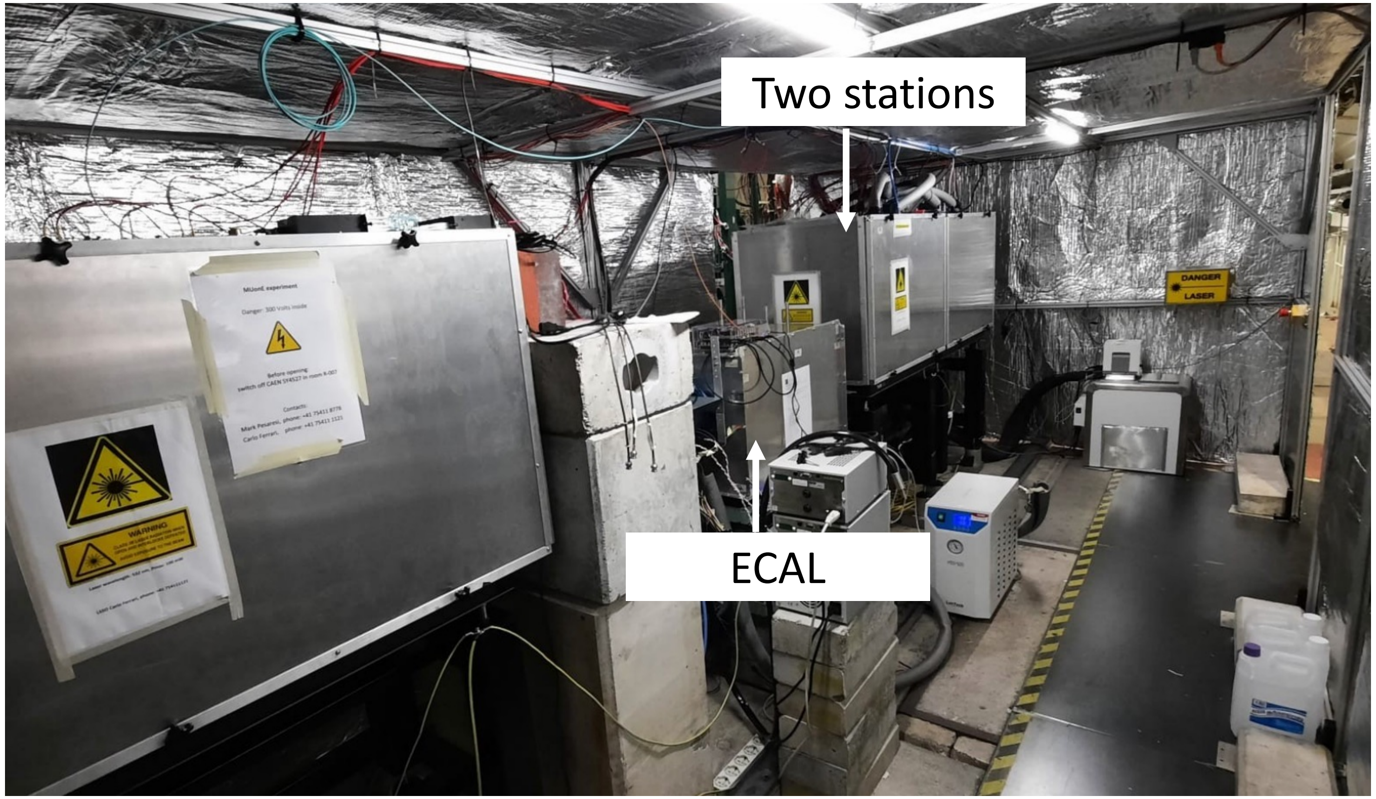


← Two stations

2S module →



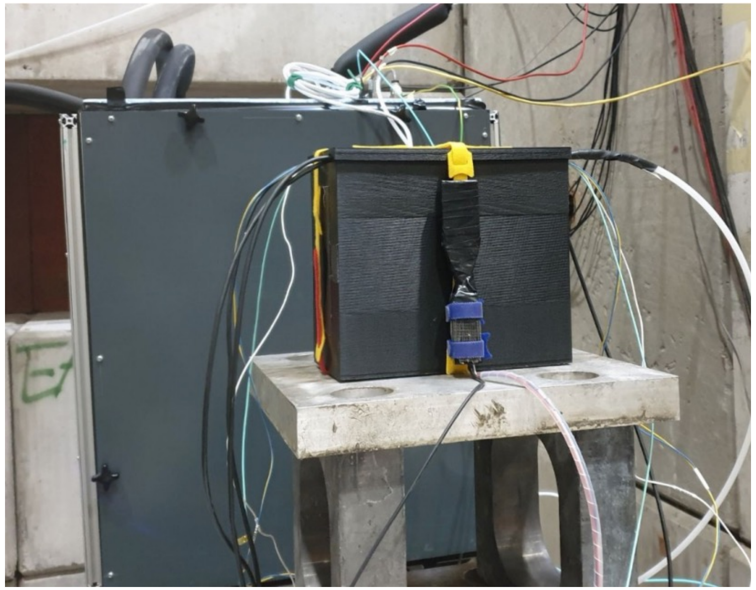
Test run 2023

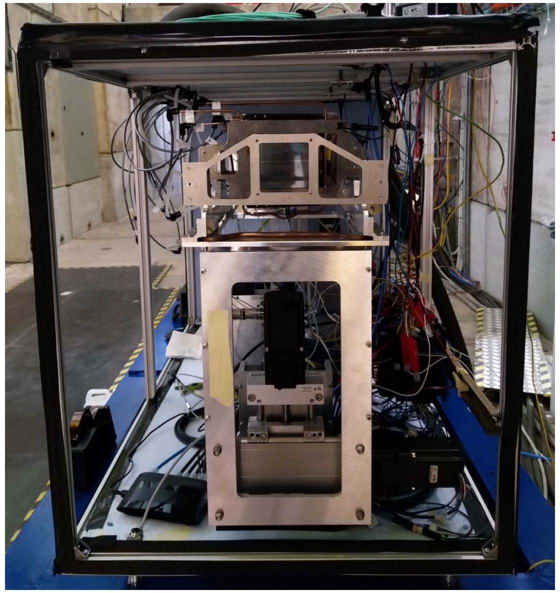


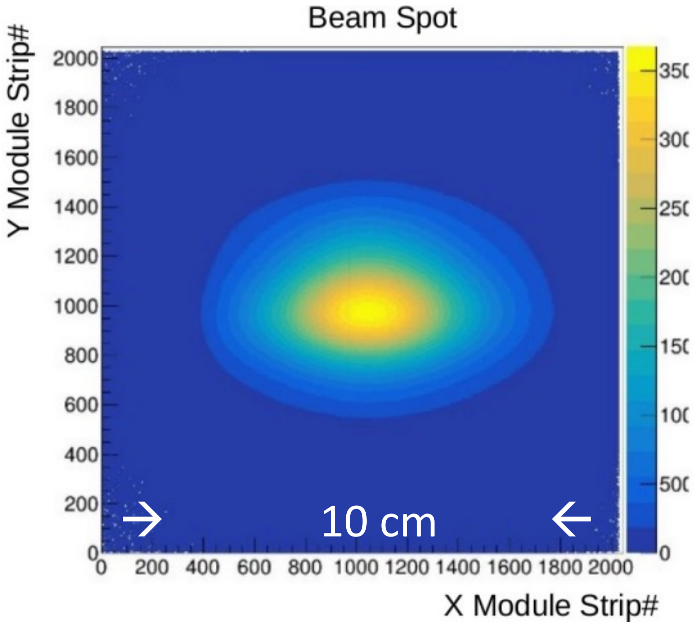
Test runs

2021, 2022 and 2023

- Intense Beam Test activities with detector in real beam conditions







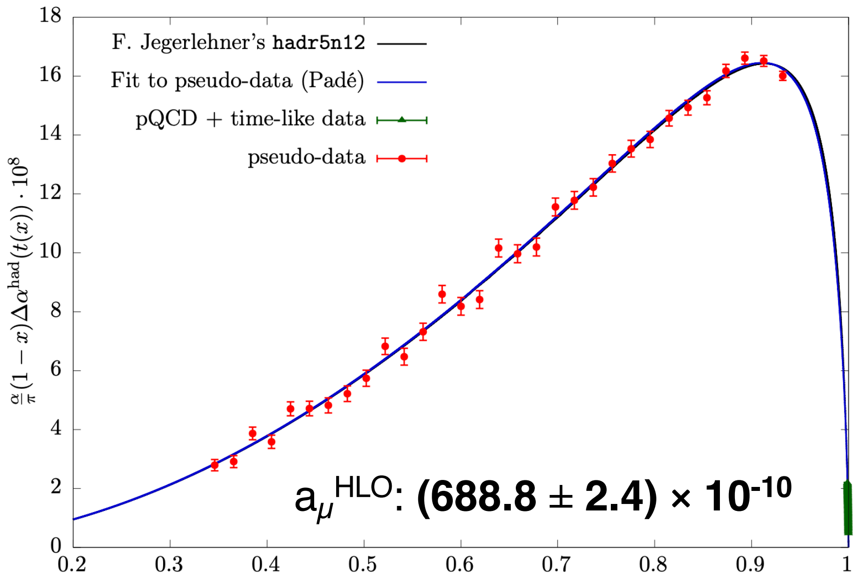
2S module firstly tested on Nov 2021

1 full station (6 modules) + ECAL in the proposed MUonE location, Oct 2022

Systematic Effects

General Considerations

- The main challenge of the MUonE is the control of systematic effects at the same level of the stat precision
  - **~0.3%** statistical accuracy on $a_\mu^{\text{HVP,LO}}$
  - Competitive with dispersive data-driven method
  - **3 years data-taking** with full stations → 4E12 events
  - Estimated **10 ppm** systematic uncertainty



Systematic Effects

General Considerations

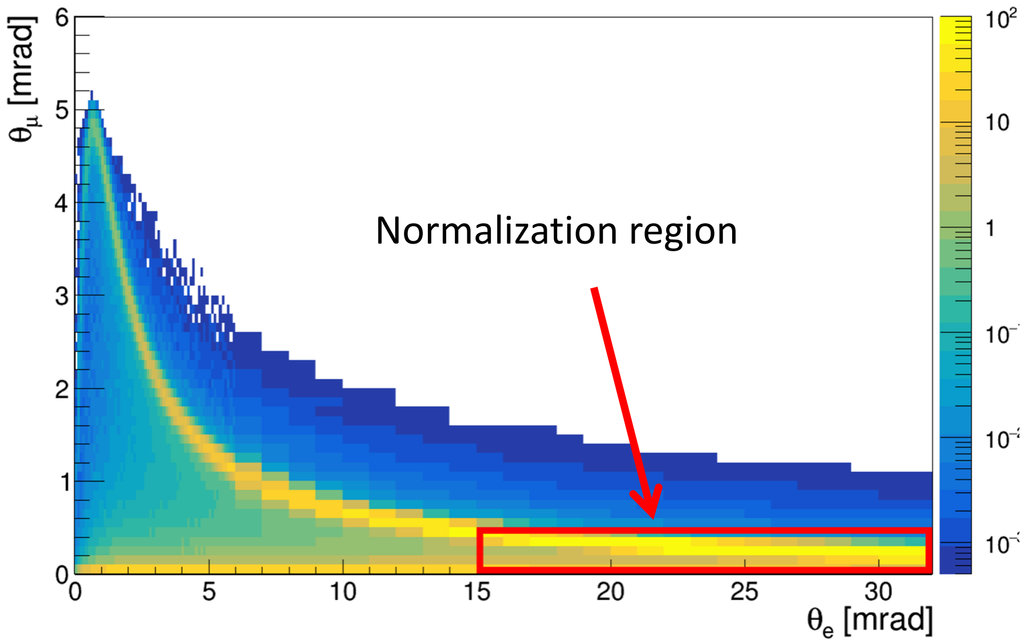
$$R_{\mathrm{had}} = \frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}} = 0)} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$

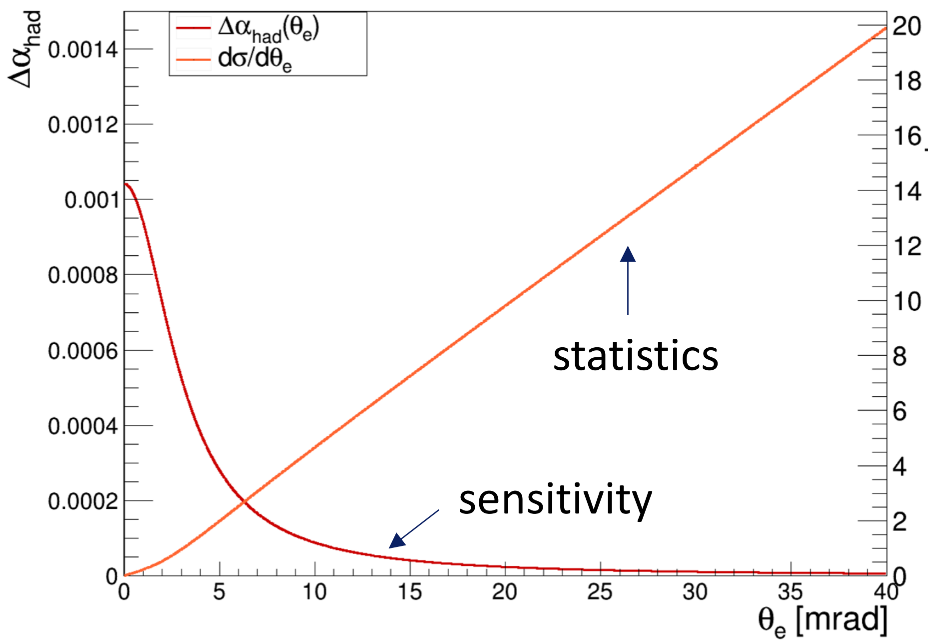
- Theory input: MC generator of radiative contributions at **NNLO** level
- Experimental requirements:
  - Uniform detection efficiency (modules, across all angular range)
  - Precise alignment (10 $\mu\mathrm{m}$ longitudinally)
  - Main sources:
    - **Multiple-scattering** (accuracy of 1%)
    - Angular resolution (a few %)
    - Beam energy
    - …

Systematic Effects

Strategy

- Main systematics have large effects in **the normalization region**.
- Large statistics but not sensitivity to Δa_{had}

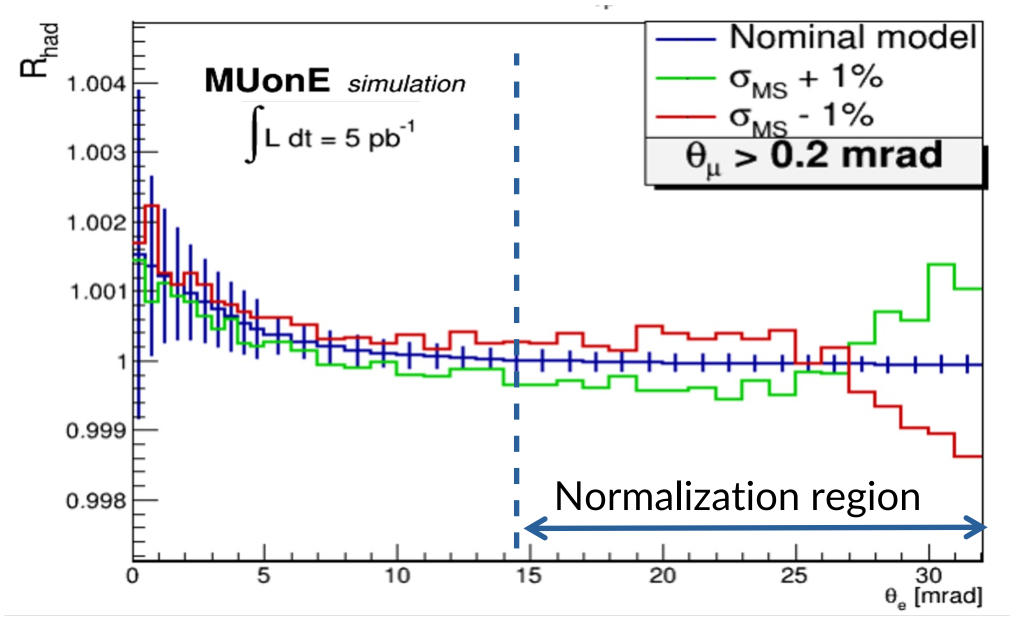


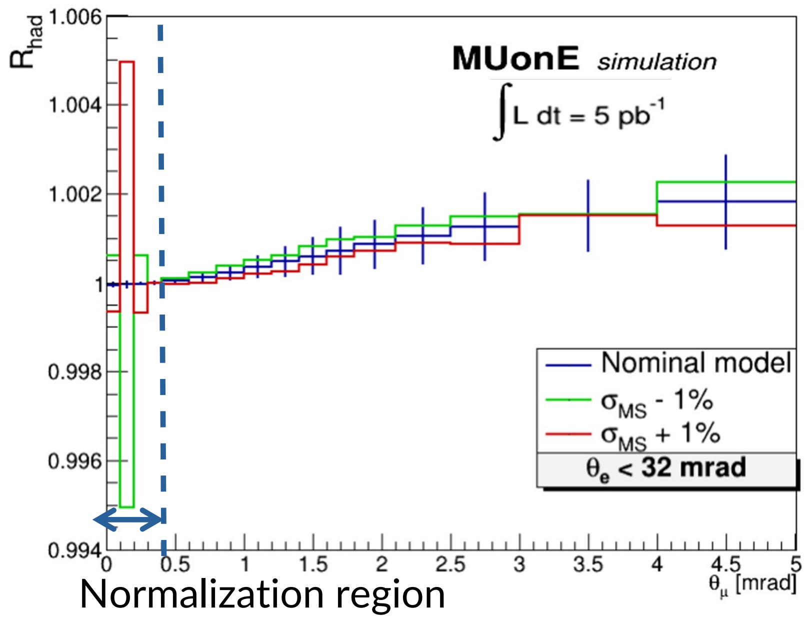


Systematic Effects

① Multiple Scattering

- Effect of $\alpha \pm 1\%$ error on the multiple scattering core width
- Previously studied in a Beam Test in 2017 with 12–20 GeV electrons on the 8-20 mm Carbon targets: G. Abbiendi et al JINST (2020) 15 P01017

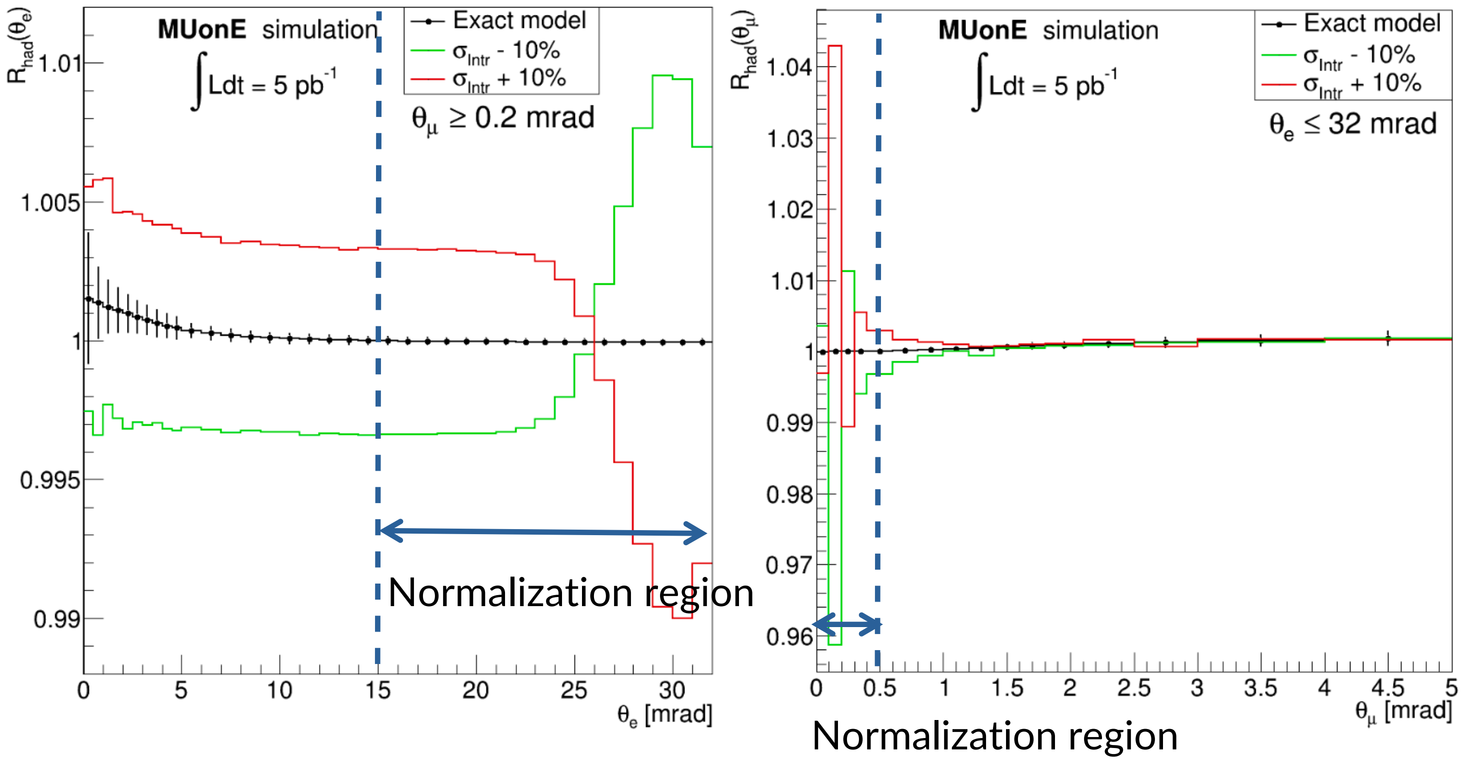




Systematic Effects

② Angular Intrinsic Resolution

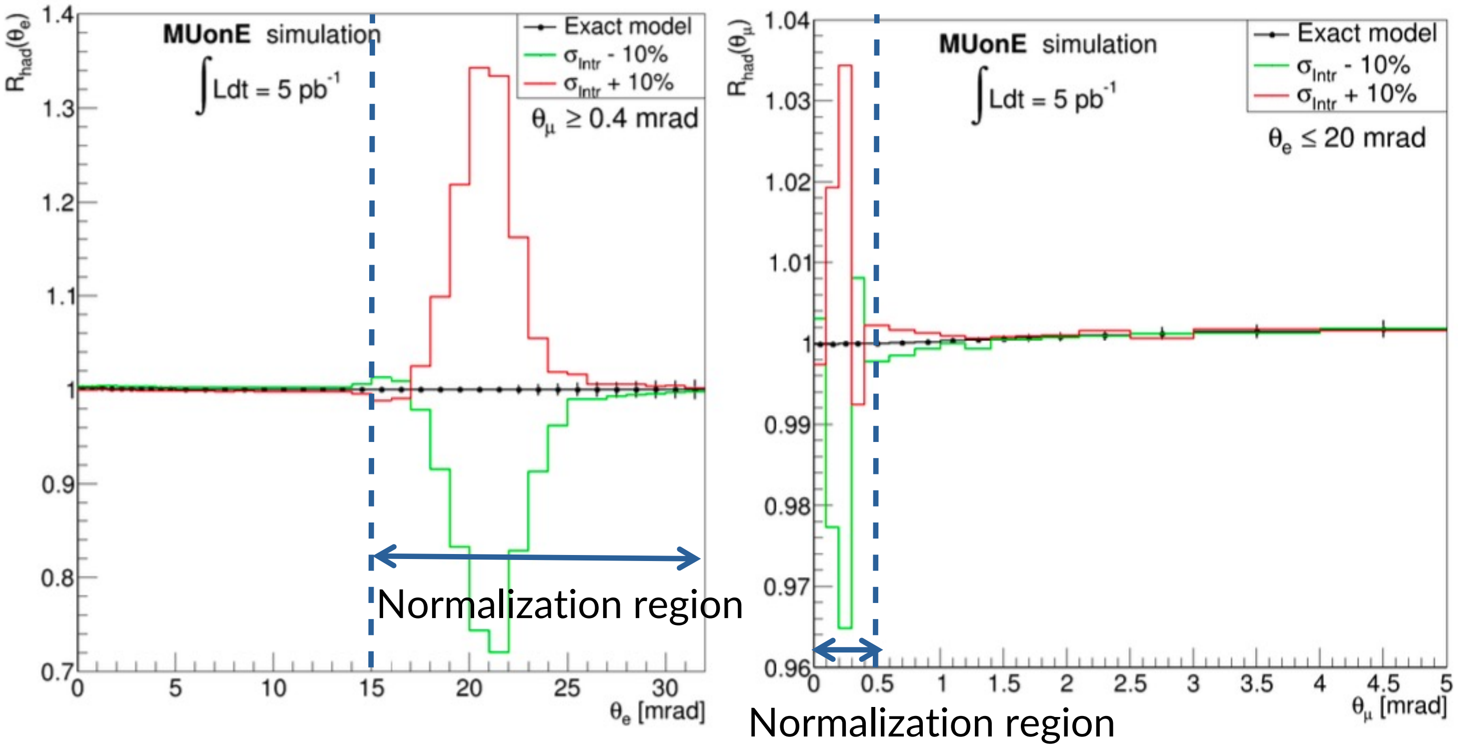
- 2S modules resolution (from beam test): 8-11μm
- An effect of a ±10% error on the angular intrinsic resolution



Systematic Effects

② Angular Intrinsic Resolution

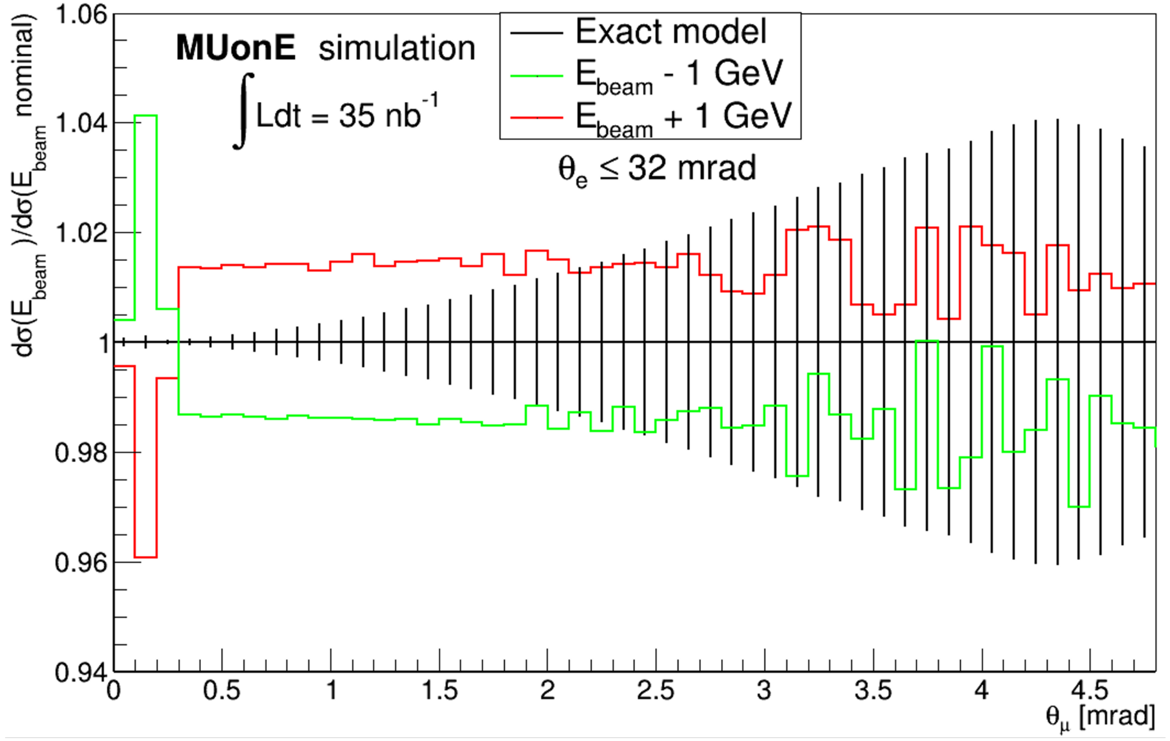
- 2S modules resolution (from beam test): 8-11μm
- An effect of a ±10% error on the angular intrinsic resolution
- $\theta_\mu > 0.4\ \mathrm{mrad}$ ($\theta_e < 20\ \mathrm{mrad}$) gives better normalization region



Systematic Effects

③ Muon Beam Energy

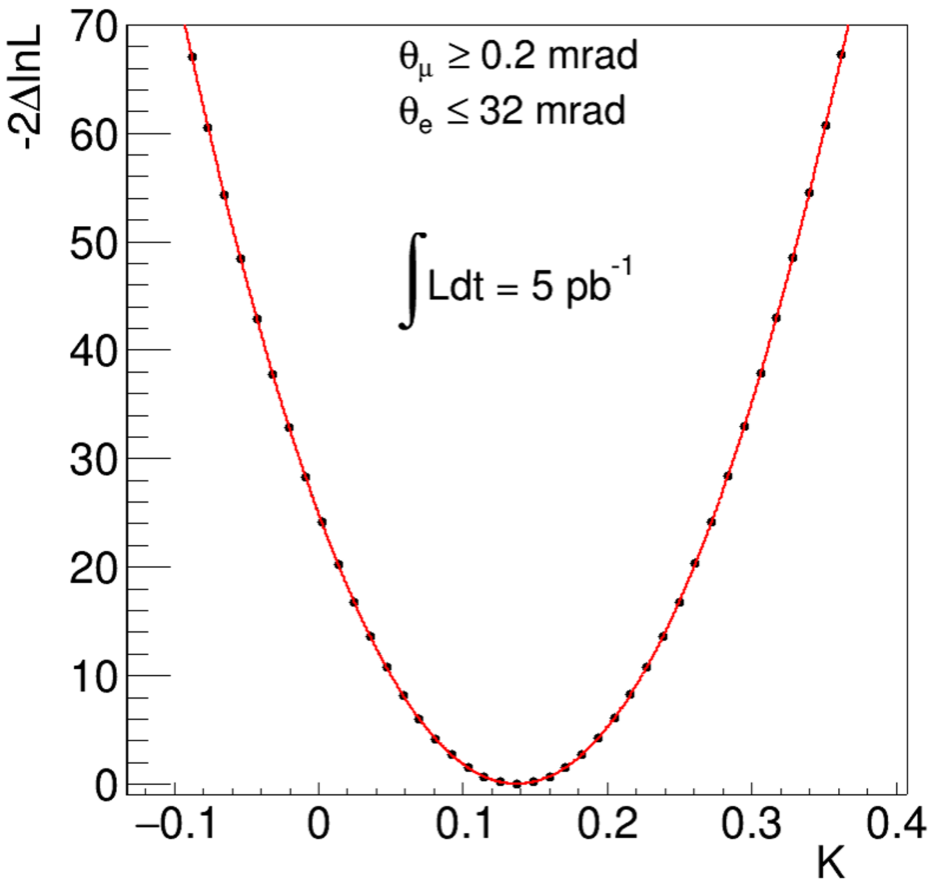
- Accelerator provides E_{beam} with O(1%) precision (~ 1 GeV) → goal of **10 ppm** in the differential cross section
- The effect can also be seen in a quick data taking (~hours) for calibration



Systematic Effects

④ Residual Systematics: the ‘Combine’ Tool

- Include **residual systematics as nuisance parameters** in a fit with signal.
- We can adjust the distortions in the shape of the differential cross section due to the residual systematics
  - Combine tool performs a likelihood fit to the nuisance parameters for each template
  - The profile likelihood as a function of K
  - Best fit value of K is determined by parabolic interpolation among the template points.
  - Nuisance parameters values for $K = K_{best\_fit}$



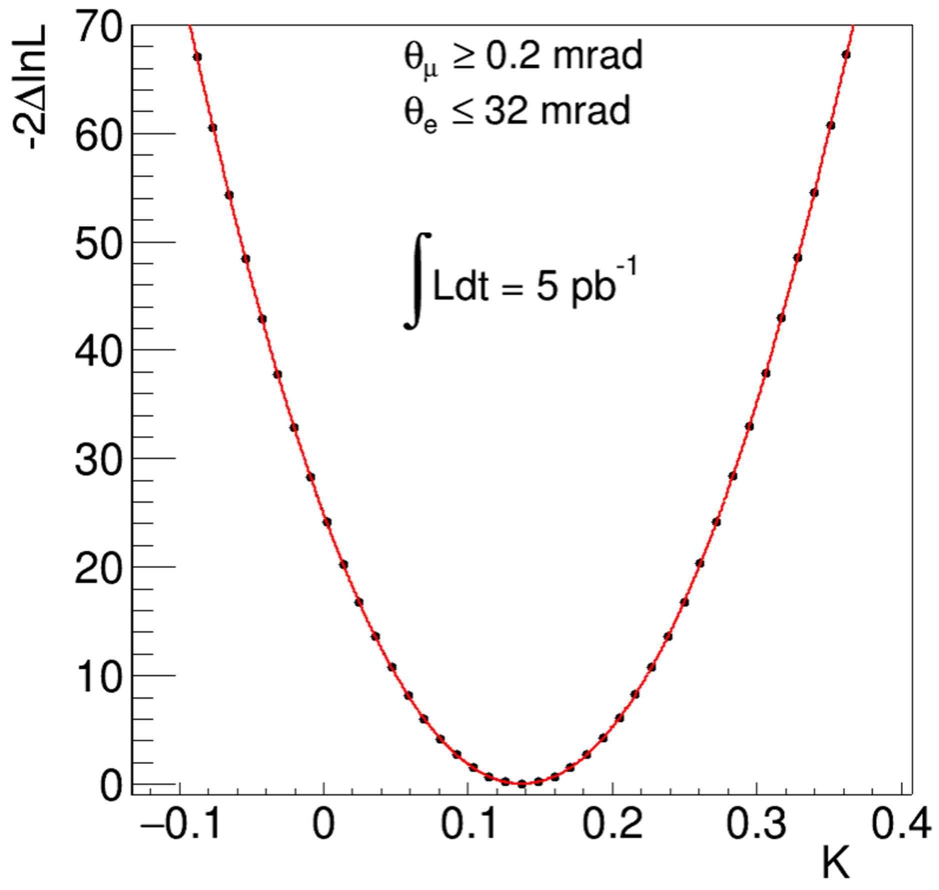
Systematic Effects

④ Residual Systematics: the 'Combine' Tool

- Include **residual systematics as nuisance parameters** in a fit with signal.
- We can adjust the distortions in the shape of the differential cross section due to the residual systematics

Selection cuts	Fit results
$\theta_e \leq 32\,\mathrm{mrad}$ $\theta_\mu \geq 0.2\,\mathrm{mrad}$	$K = 0.133 \pm 0.028$ $\mu_{\mathrm{MS}} = (0.47 \pm 0.03)\%$ $\mu_{\mathrm{Intr}} = (5.02 \pm 0.02)\%$ $\mu_{\mathrm{E_{Beam}}} = (6.5 \pm 0.5)$ MeV $\nu = -0.001 \pm 0.003$

(Input shifts identified correctly)



Open to new ideas!

- Tracker (2S module?), Calorimeter
  - Efficiency, pile-up, …
- Mechanics
- A new method to extract a_μ^{HLO} using the same MUonE data
- Software developments (systematic effects, prompt data analysis, computing…)
- …
- Working towards **TDR next year** → an important milestone
- New collaborators & ideas are welcome!

Alternative method to extract a_μ^{HLO}

a_μ^{HLO} can be written as the sum of 4 terms:

$$a_\mu^{\mathrm{HLO}} = a_\mu^{\mathrm{HLO}\,(I)} + a_\mu^{\mathrm{HLO}\,(II)} + a_\mu^{\mathrm{HLO}\,(III)} + a_\mu^{\mathrm{HLO}\,(IV)}$$

MUonE:

$$a_\mu^{\mathrm{HLO}\,(I)} = -\frac{\alpha}{\pi}\sum_{n=1}^{3}\frac{c_n}{n!}\frac{d^{(n)}}{dt^n}\Delta\alpha_{had}(t)\Big|_{t=0}$$

~99% of a_μ^{HLO}

Time-like data and pQCD:

$$a_\mu^{\mathrm{HLO}\,(II)} = \frac{\alpha}{\pi}\frac{1}{2\pi i}\oint_{|s|=s_0}\frac{ds}{s}c_0 s\,\Pi_{had}(s)\Big|_{\mathrm{pQCD}}$$

$$a_\mu^{\mathrm{HLO}\,(III)} = \frac{\alpha^2}{3\pi^2}\int_{s_{\mathrm{th}}}^{s_0}\frac{ds}{s}[K(s)-K_1(s)]R(s)$$

$$a_\mu^{\mathrm{HLO}\,(IV)} = \frac{\alpha^2}{3\pi^2}\int_{s_0}^{\infty}\frac{ds}{s}[K(s)-\tilde{K}_1(s)]R(s)$$

~1% of a_μ^{HLO}

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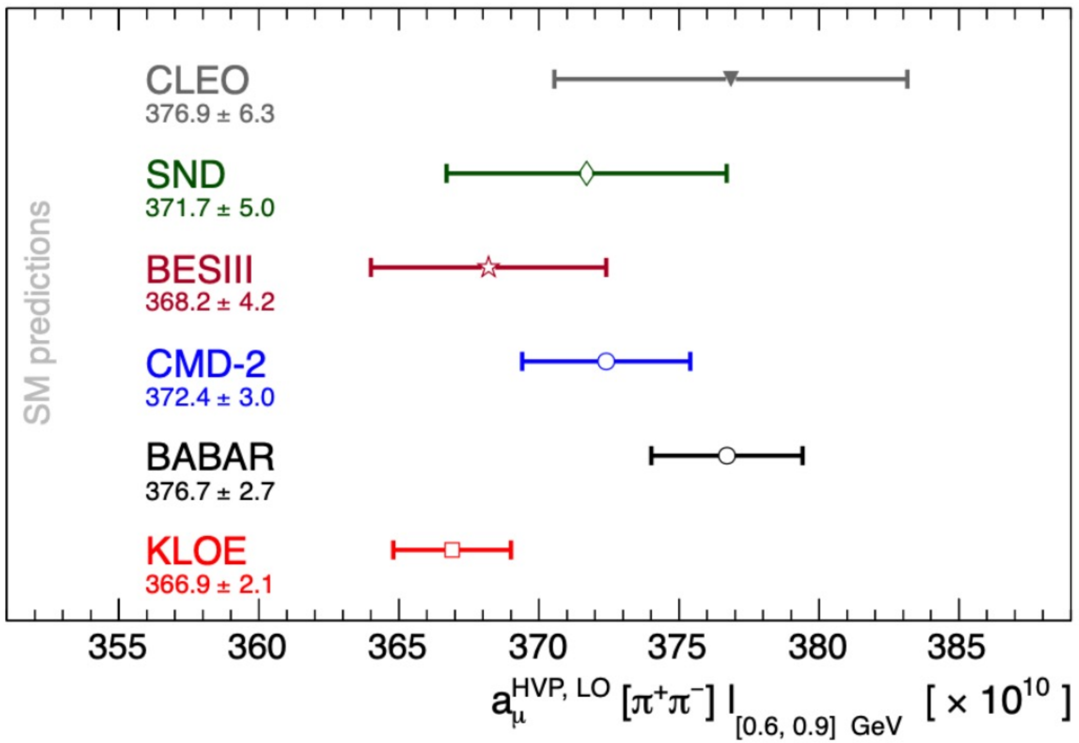
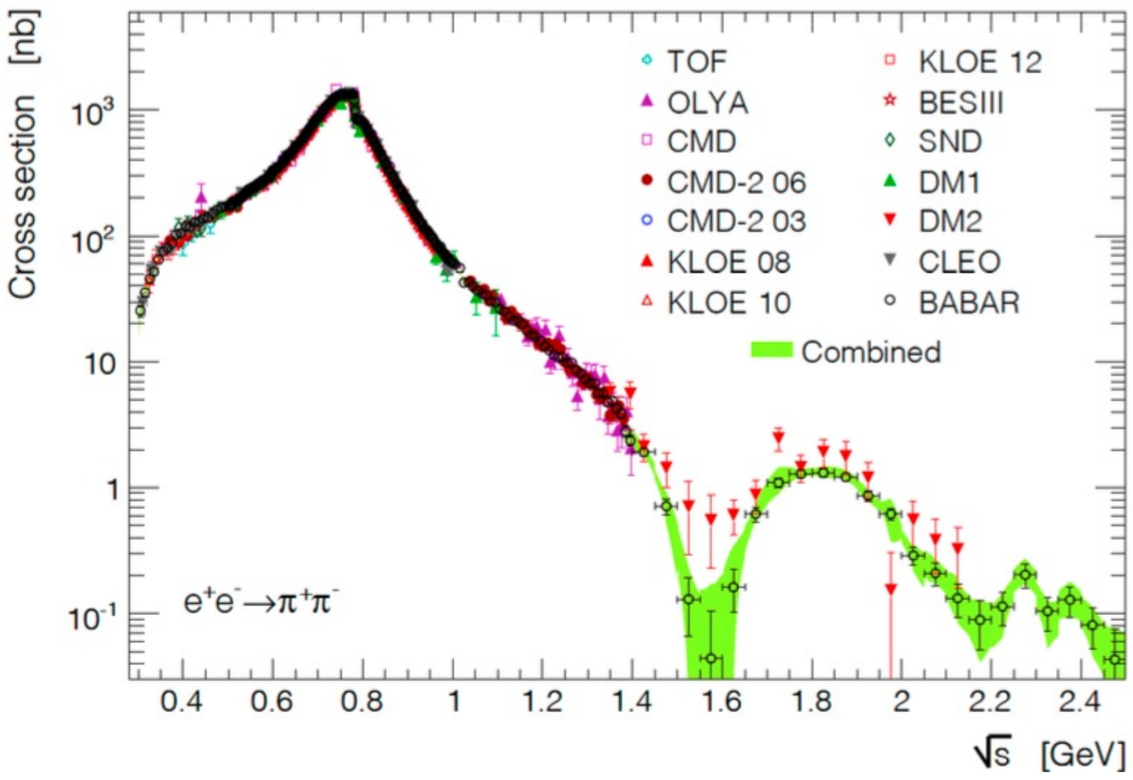
Talk at Bern, 8th Sep by GV

Muon $g-2$ Puzzle

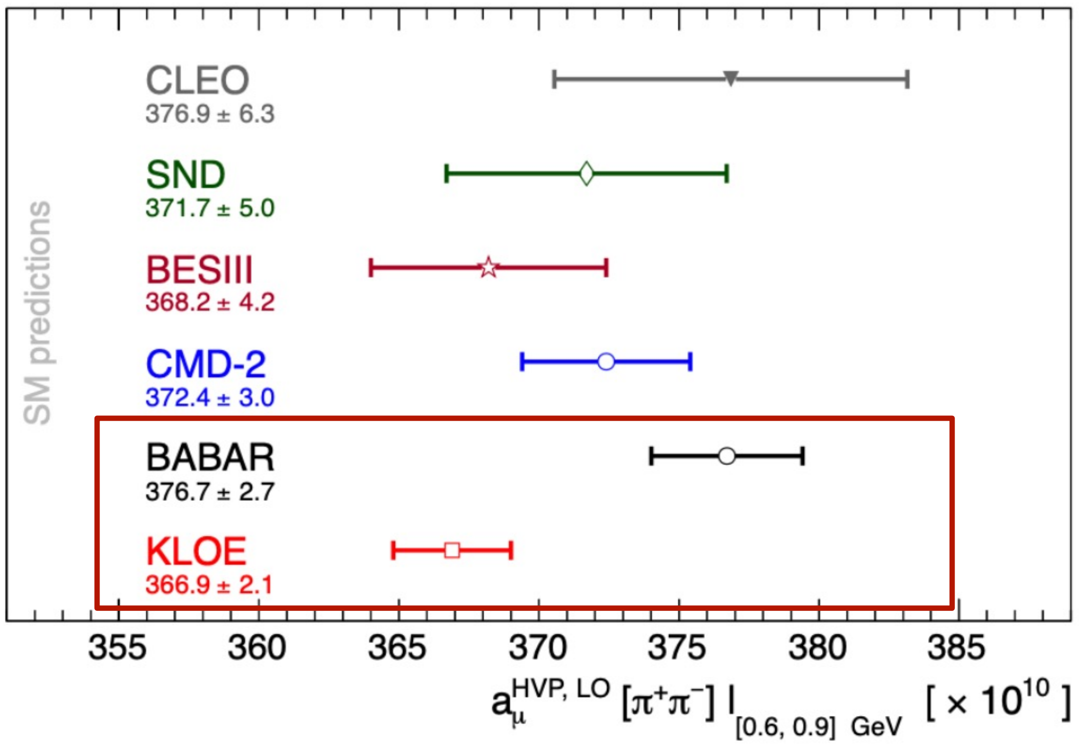
$e^+e^- \to \pi^+\pi^-$ Channel

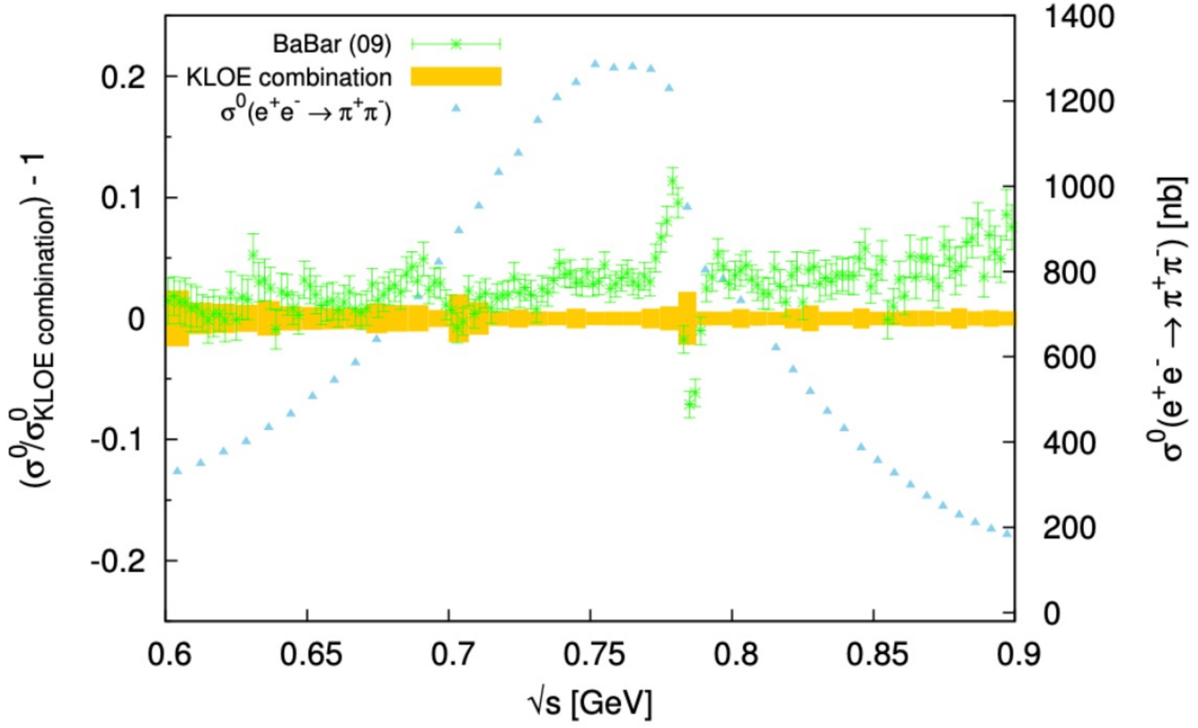




Muon $g-2$ Puzzle

$e^+e^- \to \pi^+\pi^-$ Channel





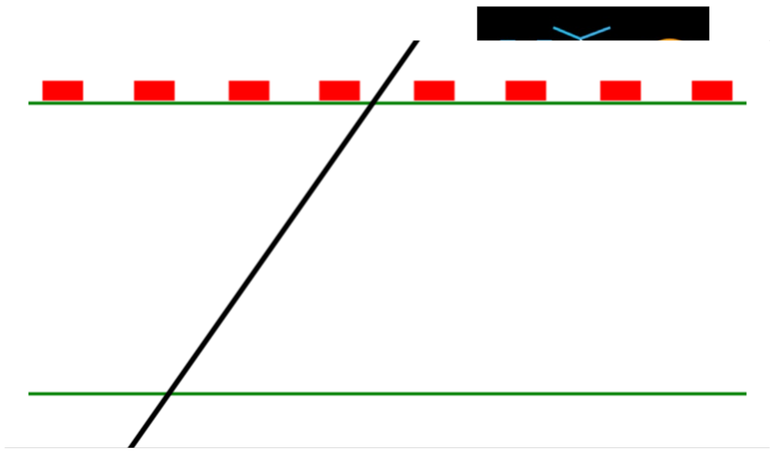
- The discrepancy between BABAR and KLOE needs to be understood

Track Reconstruction

Production loop – reconstruction – algorithm

- 2D tracks reconstructed in X and Y projections
  - seeding with hit pairs
  - additional hits assigned based on distance from track
  - track refitted until no new hits can be added
  - clones with same sets of hits removed
  - trivial hit pairing with intended detector setup
- 3D tracks reconstructed from all pairs of X and Y tracks
  - stereo hits assigned based on distance
  - tracks with no stereo hits must have at least 3 X and Y hits
  - only tracks with stereo hits allowed with intended detector setup
  - tracks fitted and sorted based on χ^2/ndf
  - shared hits removed from worse tracks
  - if adaptive fitter enabled, Kalman filter is ran on tracks
- linking based on deposited charge
  - full digitization $\rightarrow$ no direct matching
  - 3 tracks with highest deposits assigned to each stub, sorted
  - reconstructed track linked to track with highest weighted sum
- for each target, all possible vertices are reconstructed
  - if enabled, also adaptive vertices
- signal vertices
  - single incoming and two outgoing tracks required (fixed number)
  - z position fixed in the middle of the target
  - kinematic fit with tracks restricted to an interaction point
  - modifies track parameters $\rightarrow$ improved θ angle resolution
- adaptive fitter
  - implemented for alignment using pions
  - only outgoing tracks required (at least 2, variable)
  - seeding based on distance in target, window size to be optimized
  - doesn't modify tracks, assigns Tukey weights instead
  - fits vertex position, including z

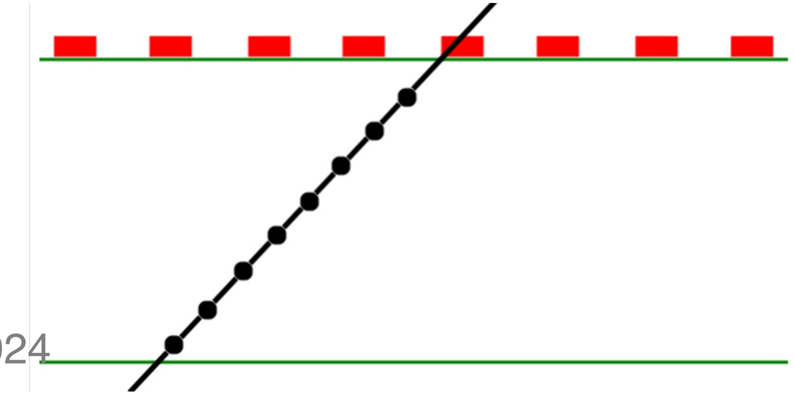
The digitization algorithm



1) Primary ionization

- Start from the trajectory of a particle in a Si sensor + energy deposit.

- The trajectory is sampled into ionization points (10 µm steps). An even fraction of the total energy deposit is associated to each point.

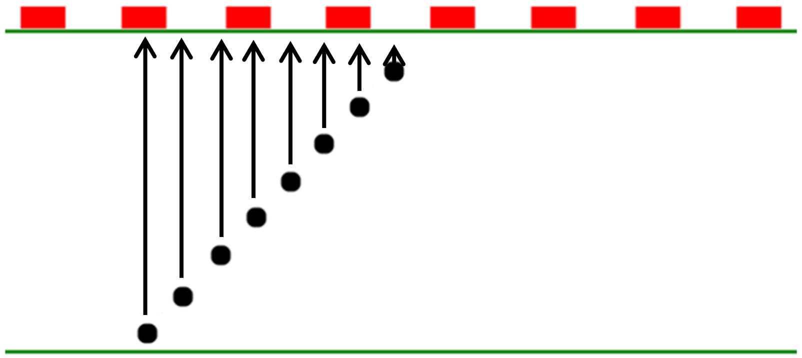


- The fraction of energy deposit is converted into a charge ($Q = E_{dep}/3.6$ eV).

The digitization algorithm

2) Drift

- The ionization points are drifted on the sensitive surface of the Si.
- A Gaussian charge diffusion model is applied to the ionization points.

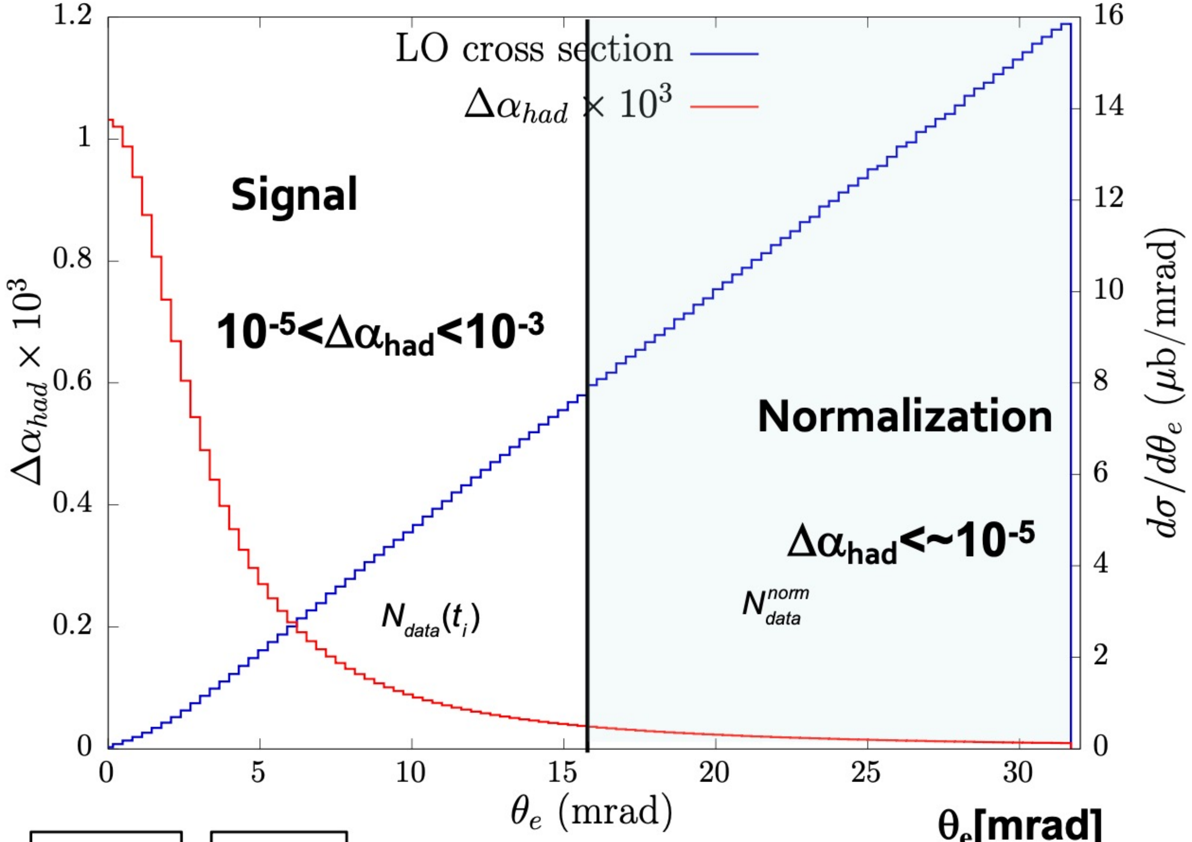


$$\sigma_{drift} \propto \sqrt{\text{drift distance}}$$

3) Induce signal

- The inonization point is expanded to a 2D cloud. The dimension depend on the drift distance.
- The total amount of charge in each strip is obtained by adding contribution from all the particles.

MUonE : signal/normalization region



$$\frac{N_{data}(t_i)}{N^0_{MC}(t_i)} = \boxed{\frac{N_{data}(t_i)}{N^{norm}_{data}}} \times \boxed{\frac{\sigma^{0,norm}_{MC}}{\sigma^0_{MC}(t_i)}} \sim 1-2(\Delta\alpha_{lep}(t_i)+\Delta\alpha_{had}(t_i))$$

Ratio of the theoretical cross section (with no VP)

Ratio of data $N_{signal}(t)/N_{normalization}$

a_μ^{HLO} at 0.3% → These two ratios should be known at 10^{-5}

G. Venanzoni, PSI Colloquium, 28 March 2019