The MUonE Experiment:

Understanding Muon $g-2$ Puzzle via $\mu - e$ Scattering

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INPAC/SJTU Seminar

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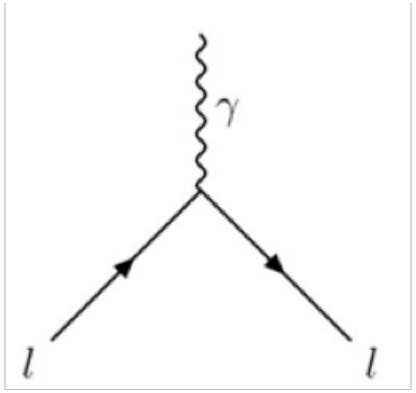
The MUonE Experiment:
Understanding Muon $g-2$ Puzzle via $\mu-e$ Scattering

- Muon $g-2$ Puzzle
- MUonE Experiment
  - Principle
  - Apparatus (tracker, calo, muon beam…)
  - Simulation, Analysis & Systematics Effects
  - Test Runs
  - Current Status (the collaboration, schedule…)

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
  - Dirac predicted $\boldsymbol{g} = \mathbf{2}$ for spin-1/2 fermions



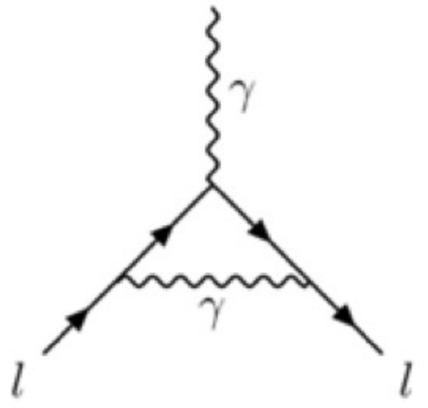
- Interactions with virtual particles cause g to deviate from 2 ($g > 2$). **Muon magnetic anomaly** is defined as:

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

First order QED correction by Schwinger:

$$a_l = \frac{g_l - 2}{2} = \frac{\alpha}{2\pi} + \mathrm{O}(\alpha^2)$$

$$= 0.001\,161\,40\,.$$



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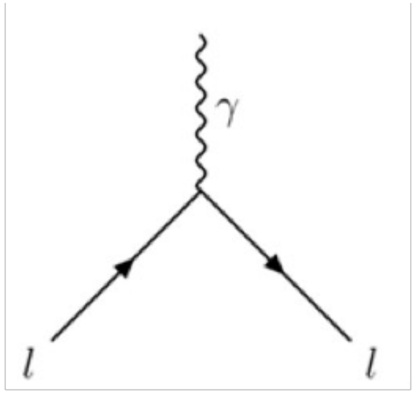

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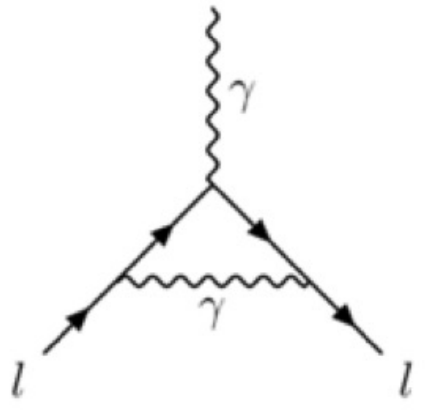
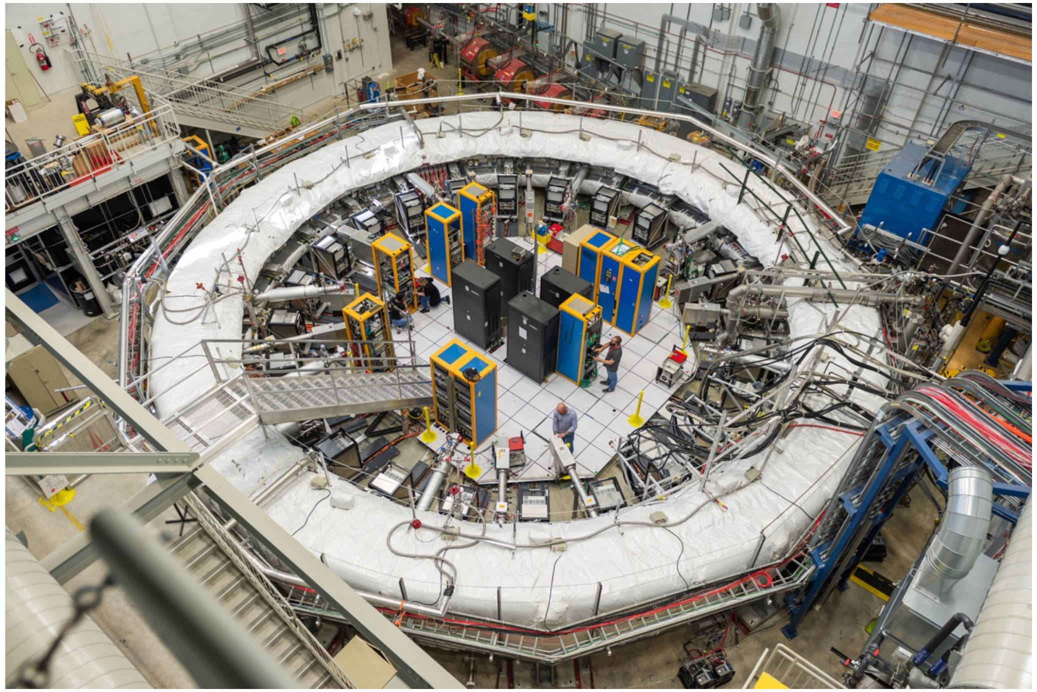
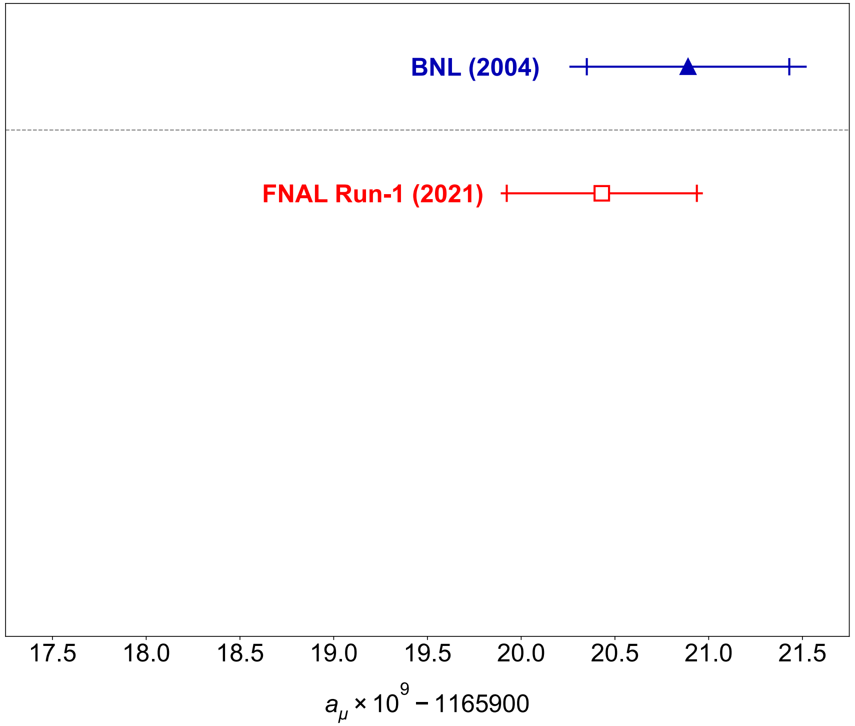


Muon $g-2$

Experiment at Fermilab

- Latest result announced at Fermilab on Aug. 10, 2023





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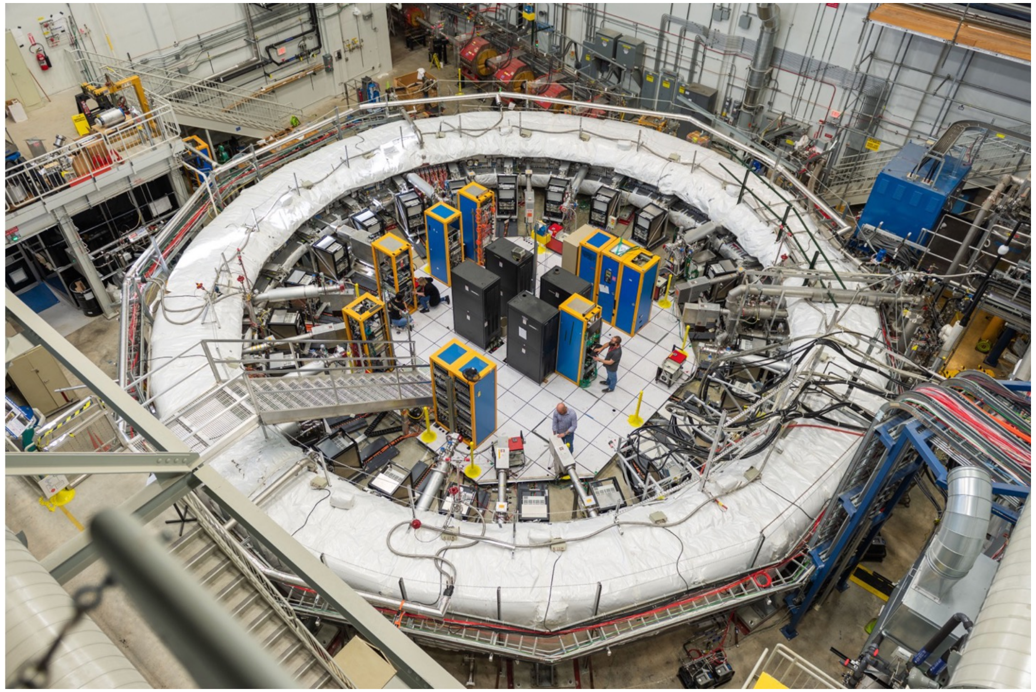

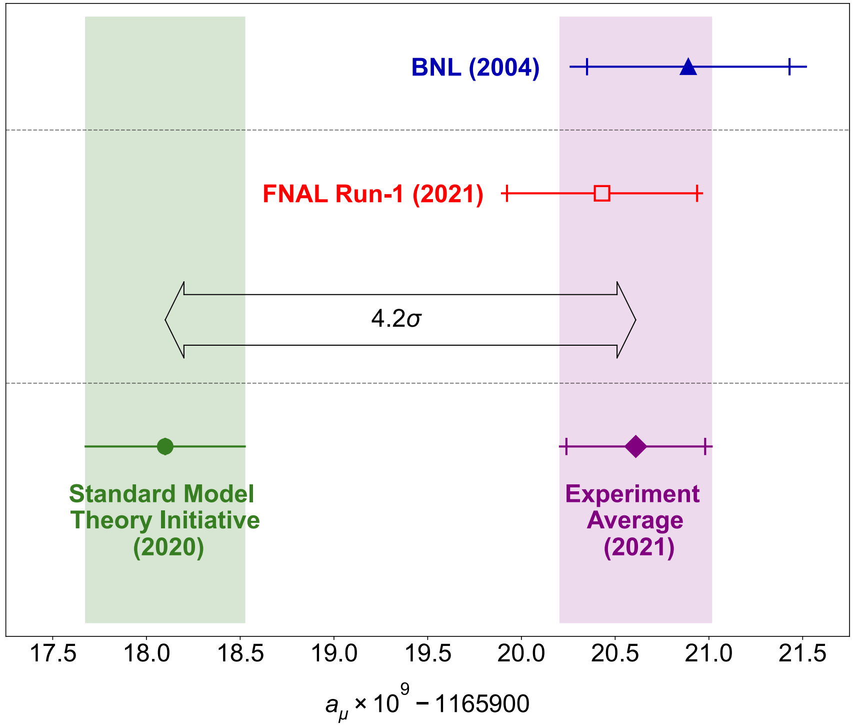

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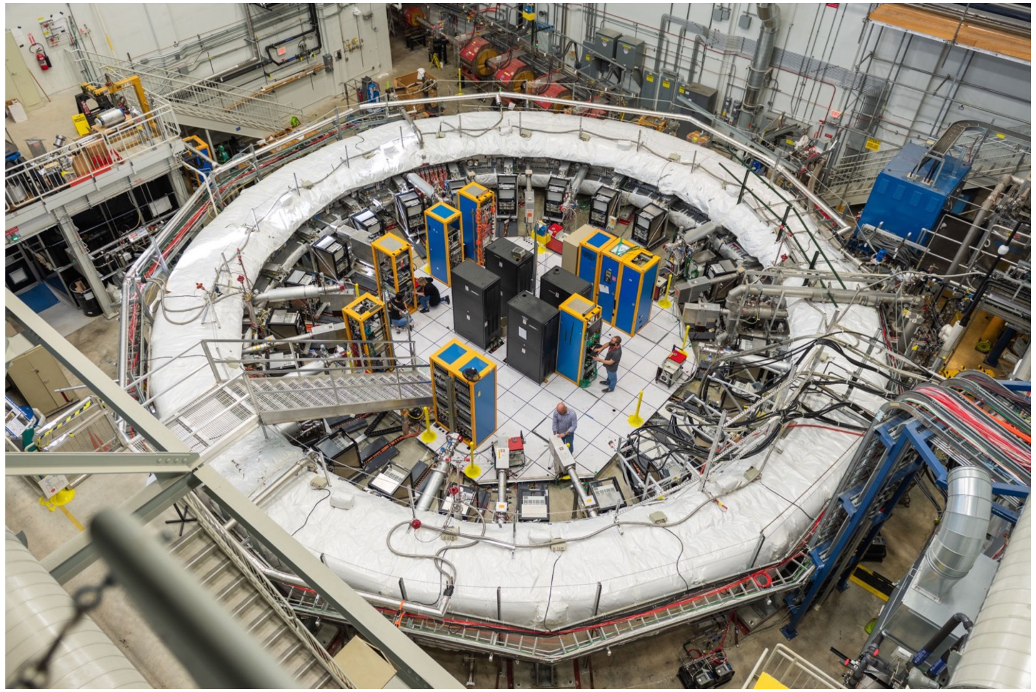

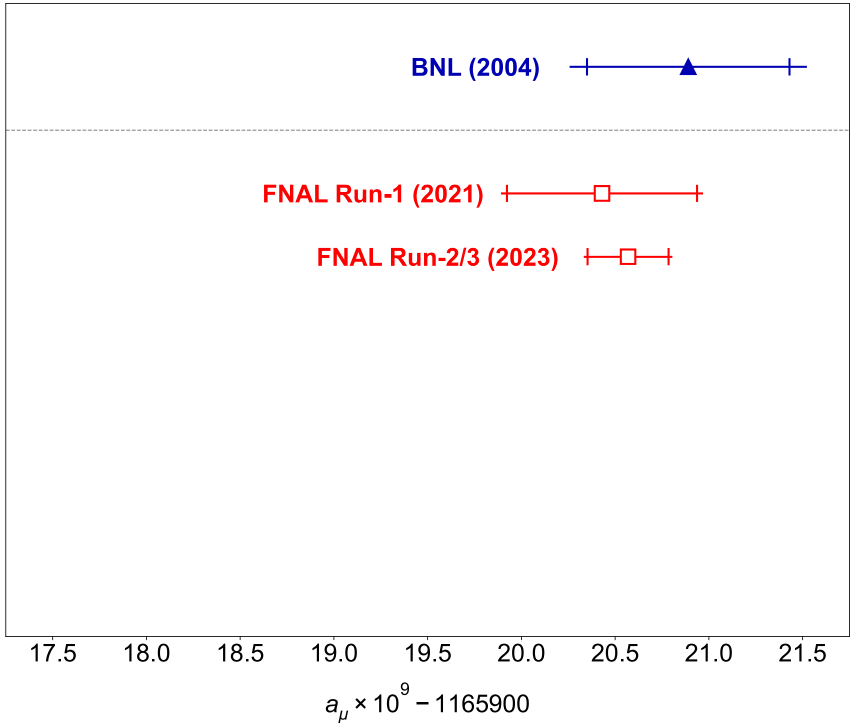

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- FNAL (2021) + BNL average in tension with Theory Initiative White Paper (2020) at $4.2\ \sigma$
- FNAL (2023): **Excellent agreement** with BNL and Run-1; Uncertainty more than halved to **215 ppb**

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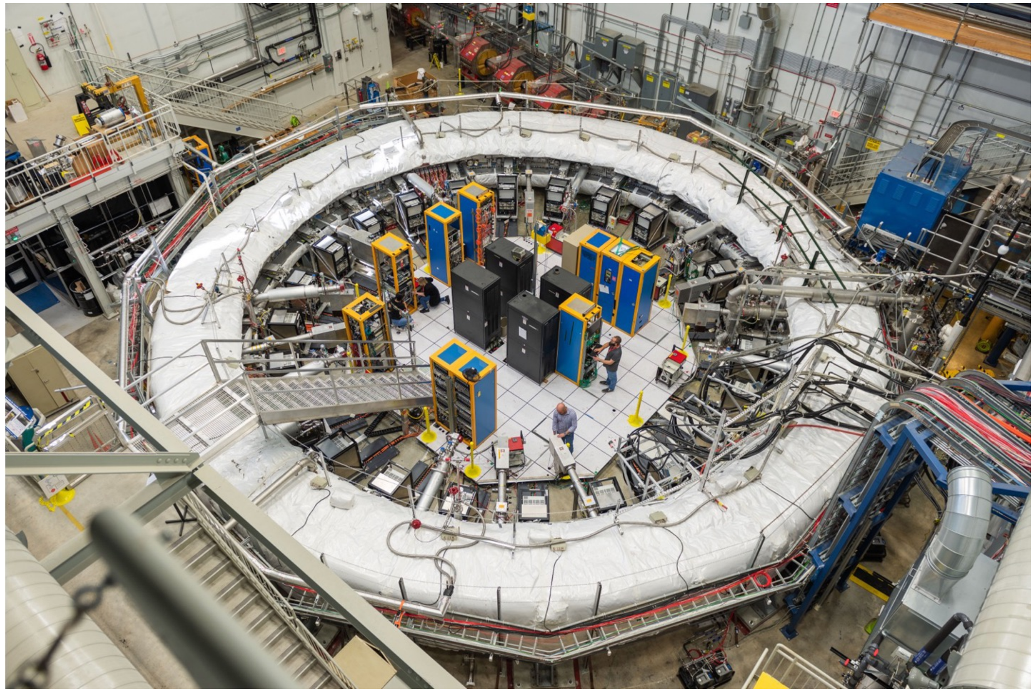
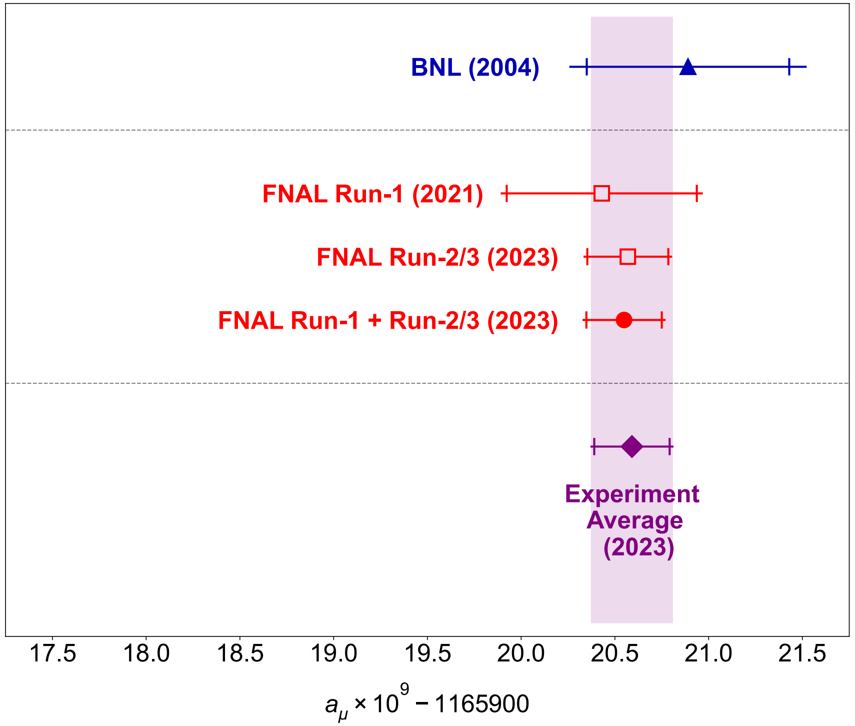
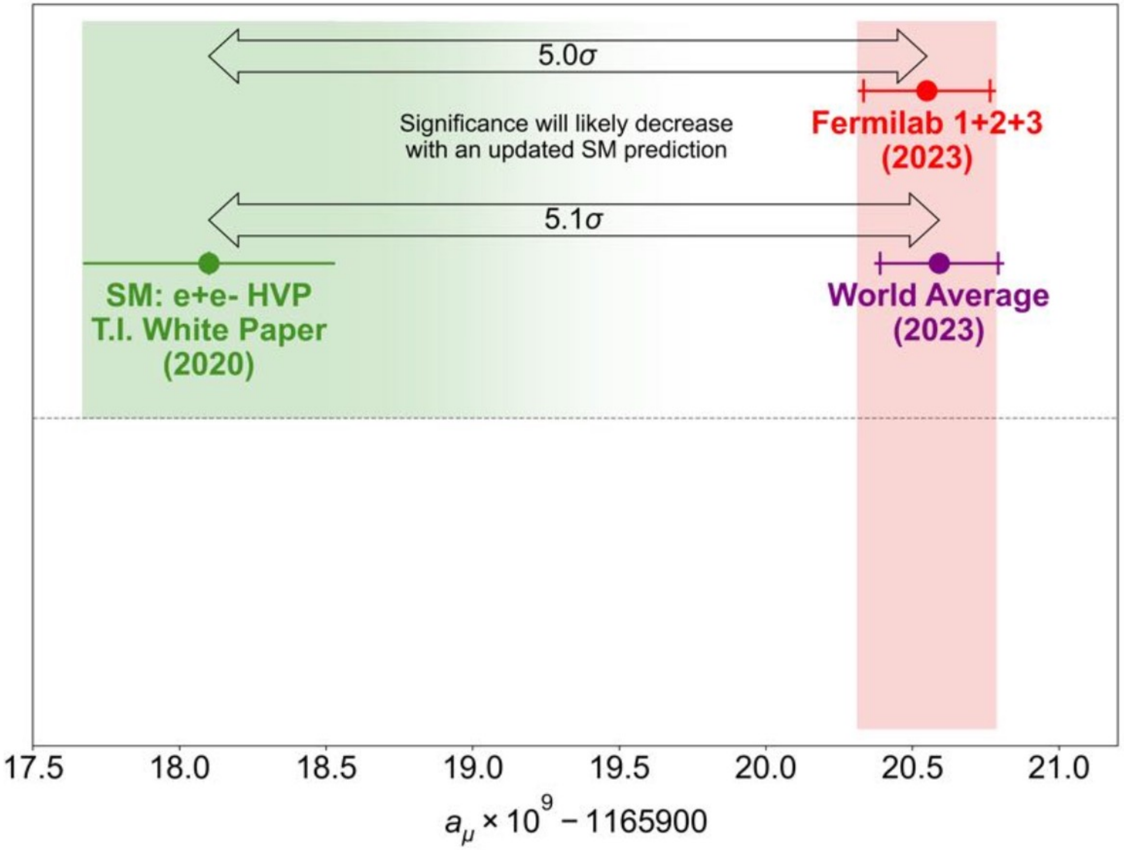




- Combined FNAL result uncertainty: **203 ppb**
- Combined world average uncertainty is **190 ppb**
- Average is **dominated by FNAL** value

Muon $g-2$ Puzzle

Discrepancy between Experiments & Theories



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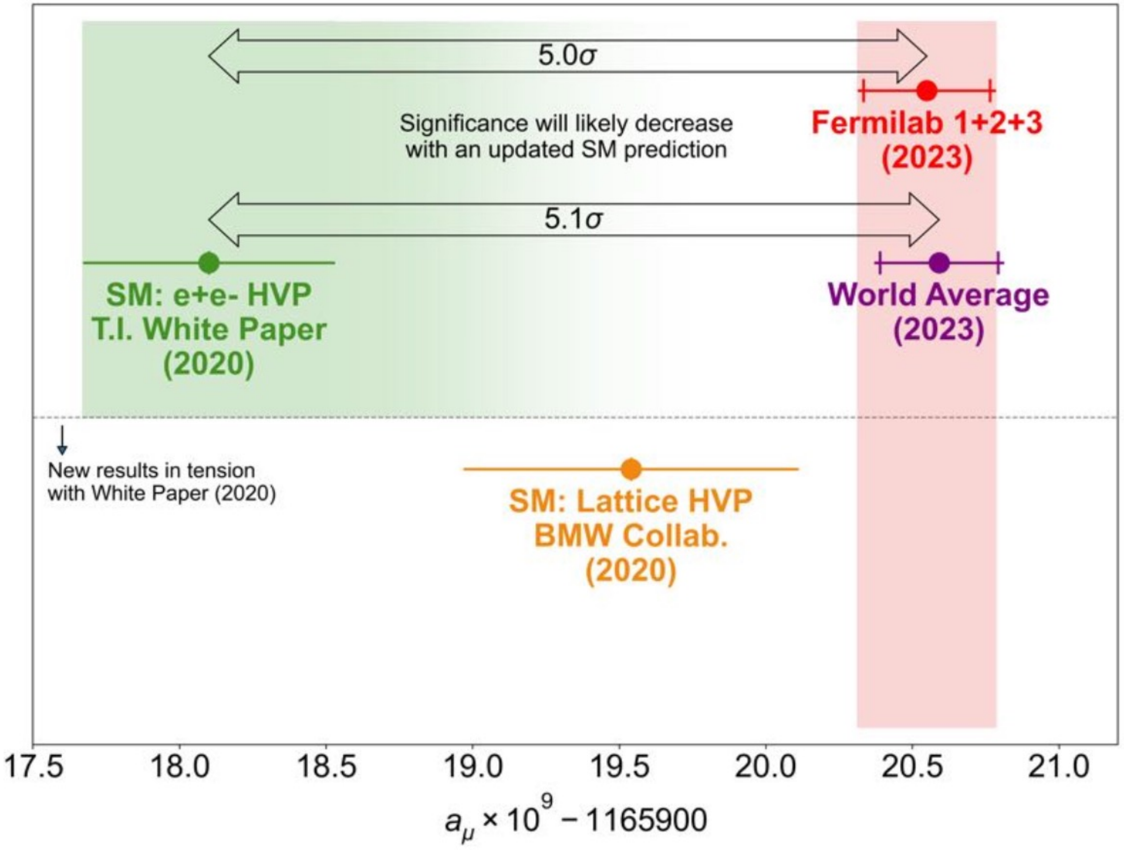

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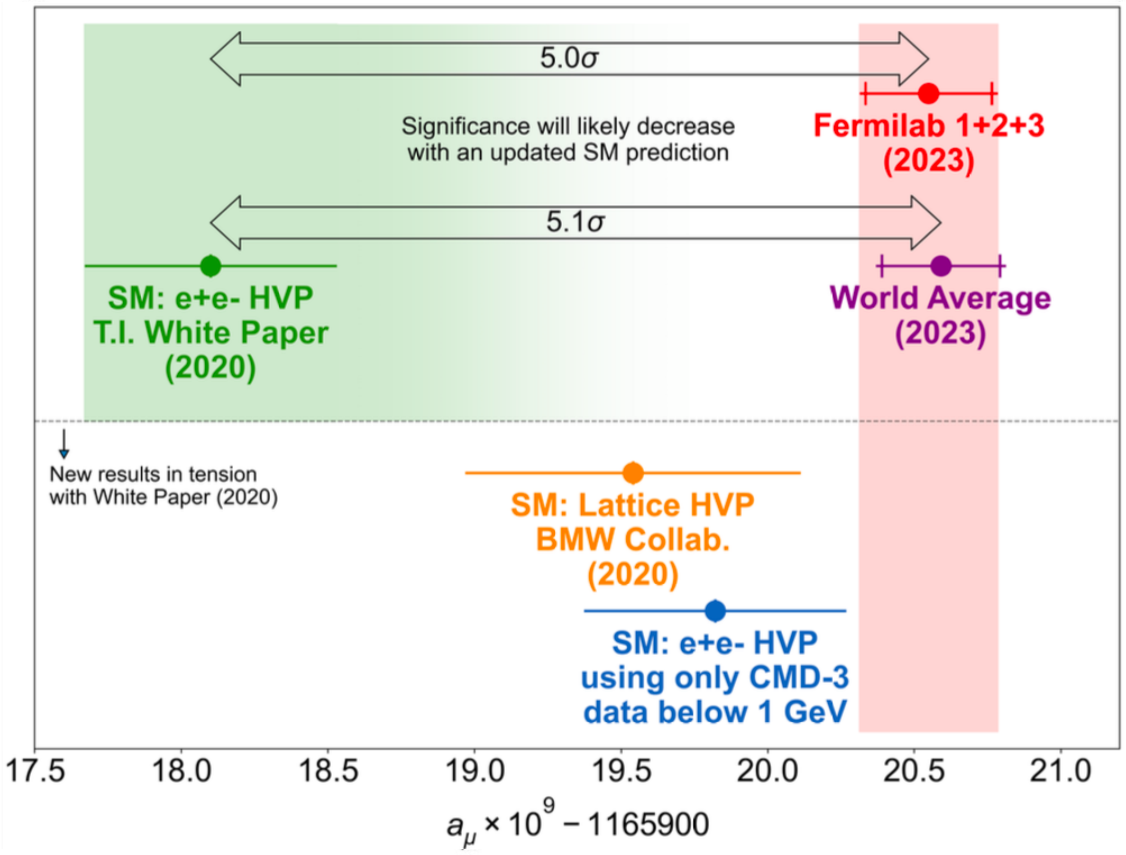

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  - New $e^+e^- \to \pi^+\pi^-$ cross section from CMD-3 (2023)

> **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

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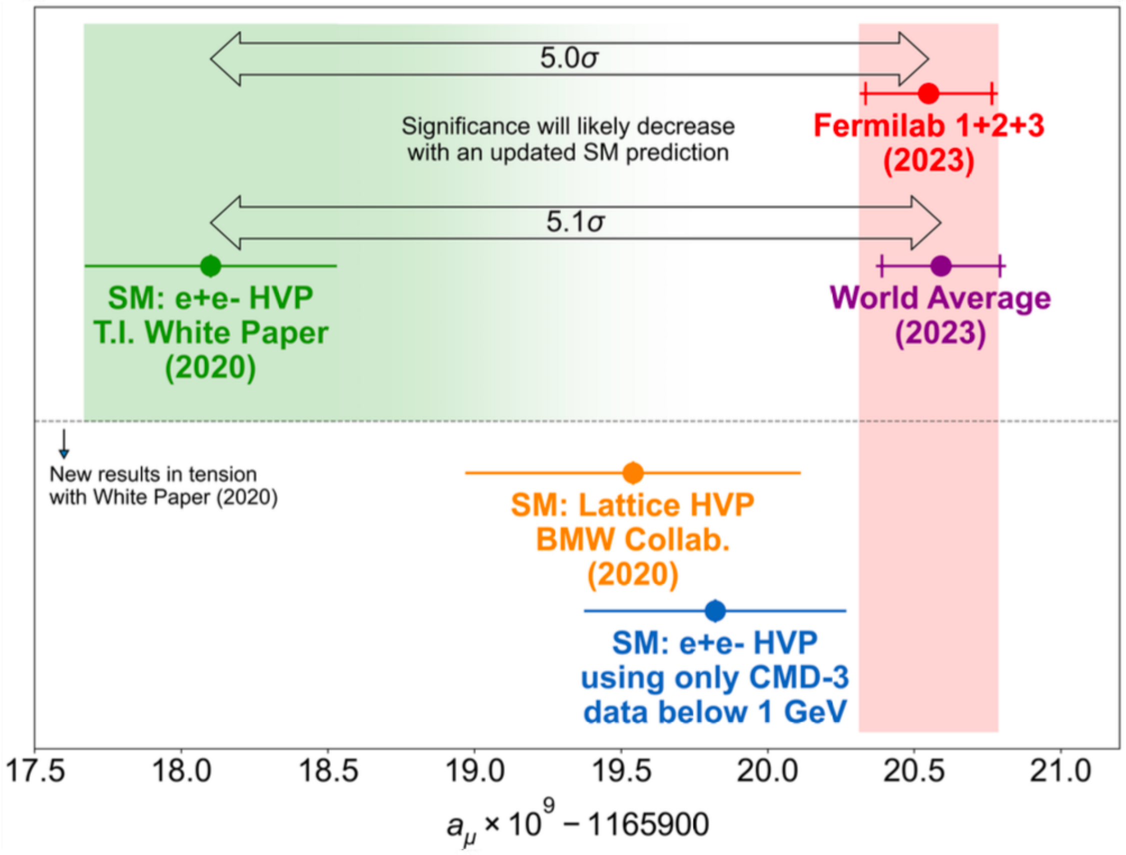

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- Since then, two important developments on SM prediction:
  - Lattice QCD from the BMW (2020)
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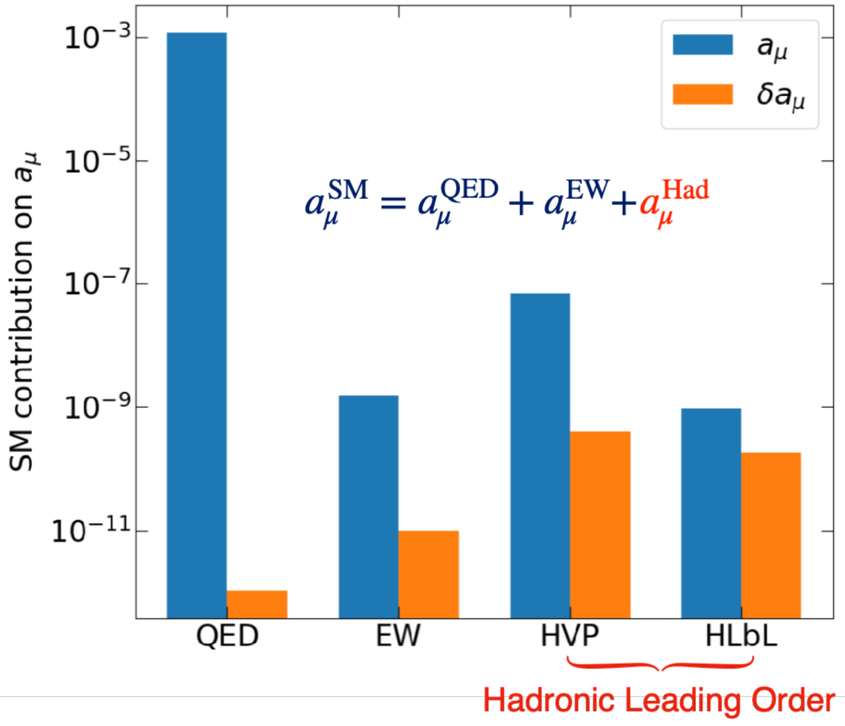
- Future experimental progress:
  - Fermilab (final) Run 4/5/6 (~ 2 yrs)
  - New approach at J-PARC (2028 -)

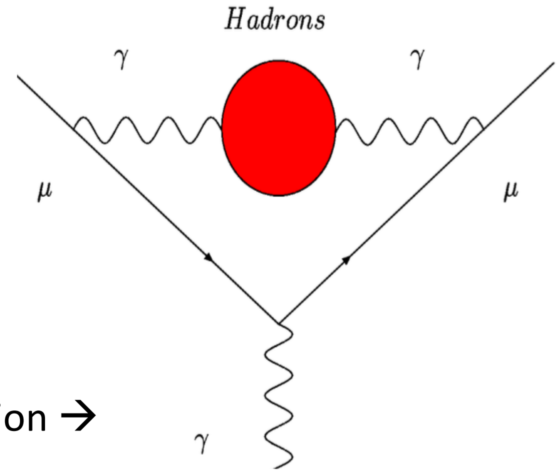
Muon $g-2$ Puzzle

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 a_μ^{HLO} $(a_\mu^{\mathrm{HVP,LO}})$



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



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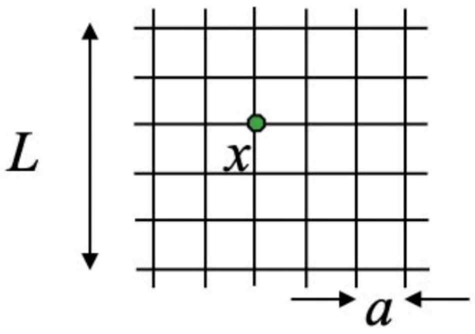

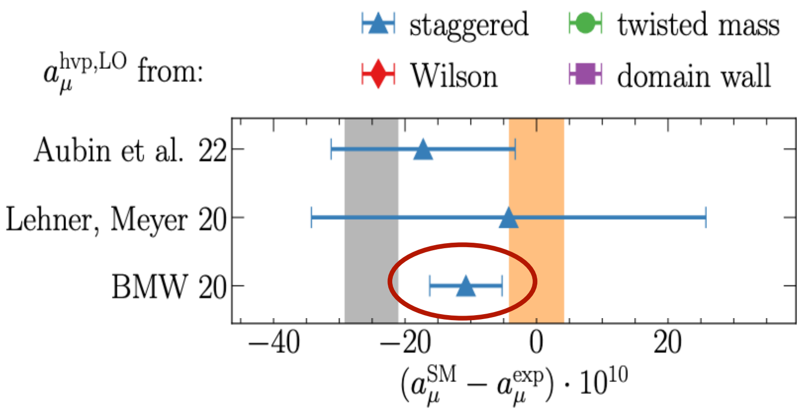

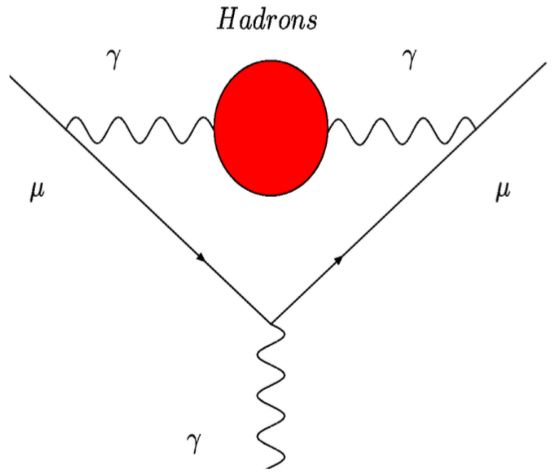

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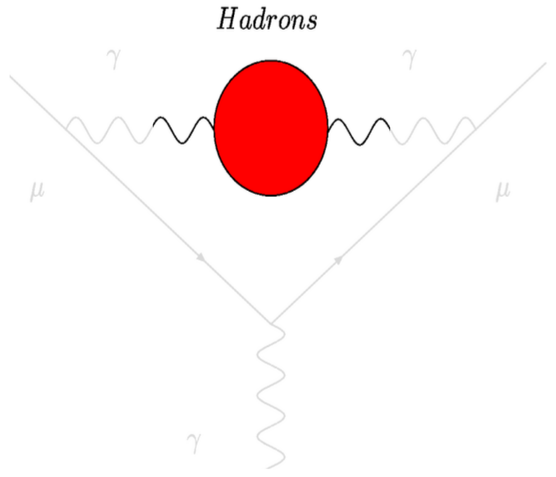

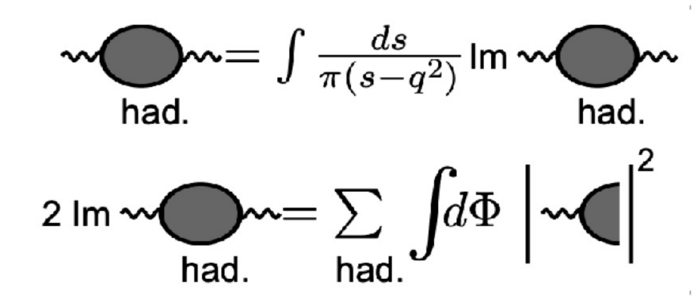

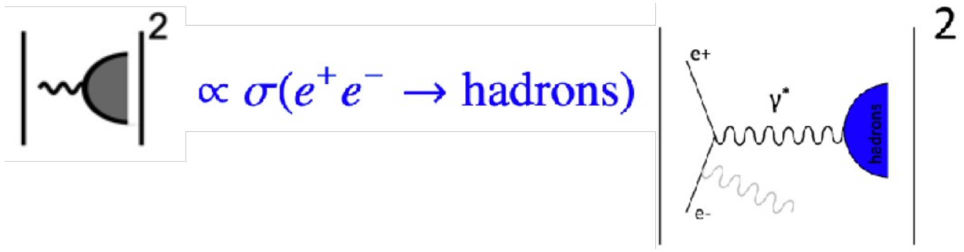

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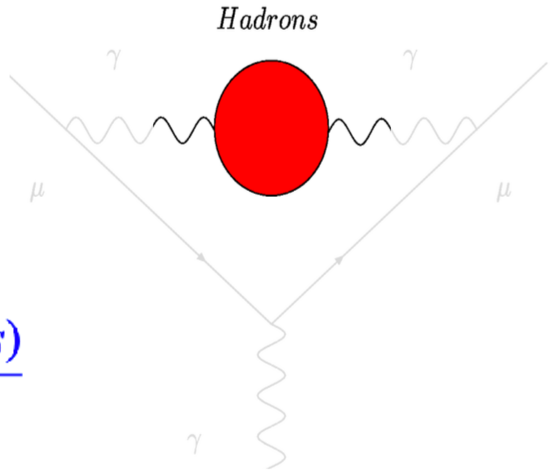
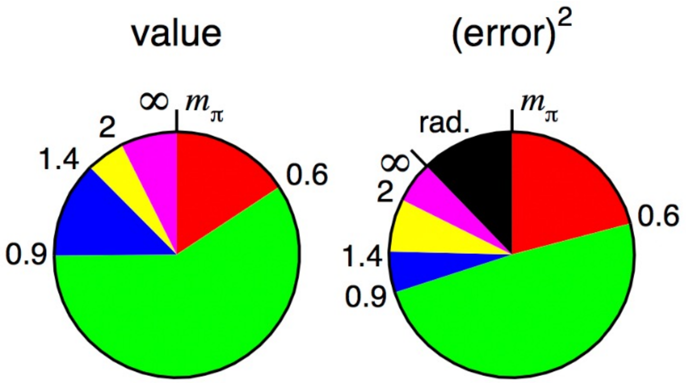


$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds\, \frac{R_{\mathrm{had}}(s)\, K(s)}{s^2}, \quad R_{\mathrm{had}}(s) = \sigma(e^+e^- \to \text{hadrons}) \Big/ \frac{4\pi\,\alpha(s)}{(3s)}$$

Muon $g-2$ Puzzle

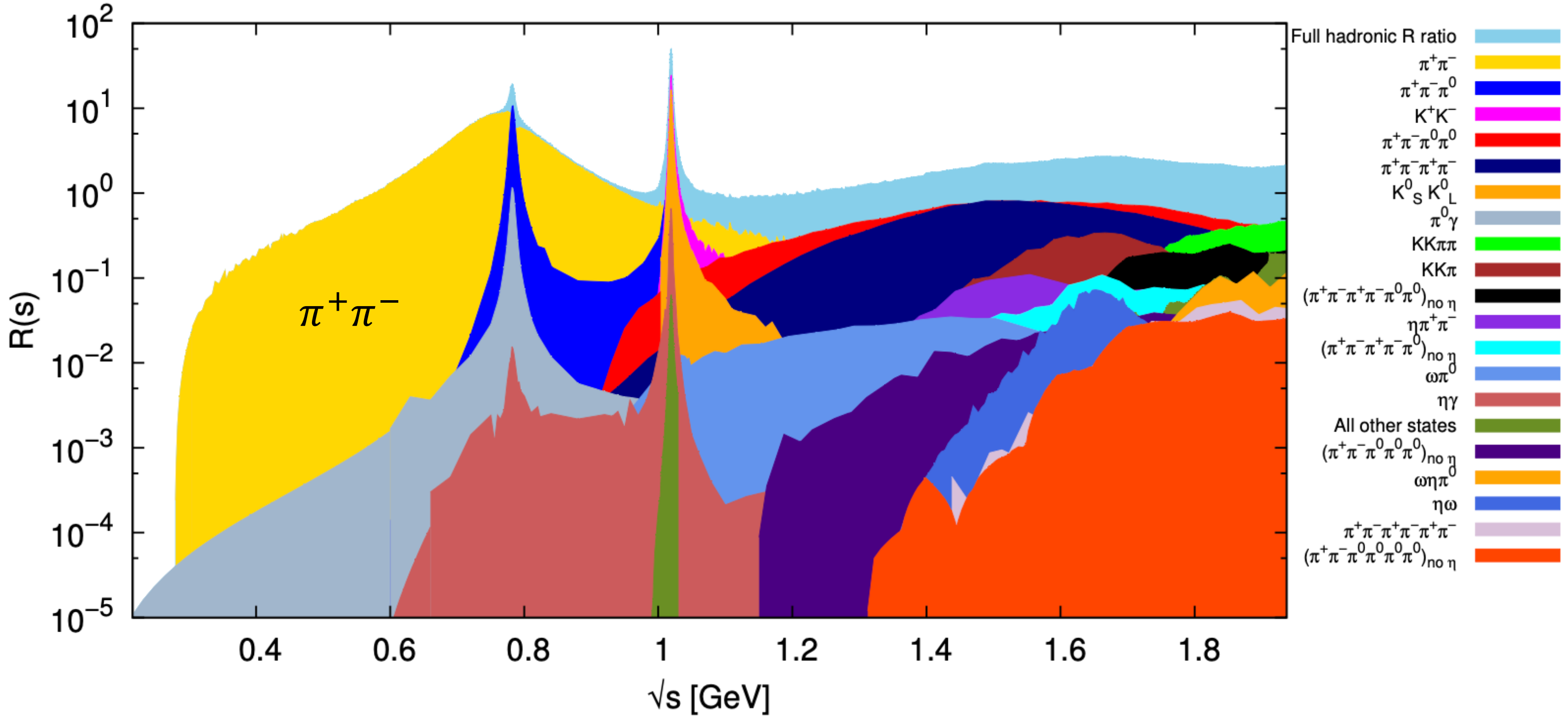
Dispersive Method Using Collider Data

- $e^+e^- \to \pi^+\pi^-$ **channel** is the major source of uncertainty



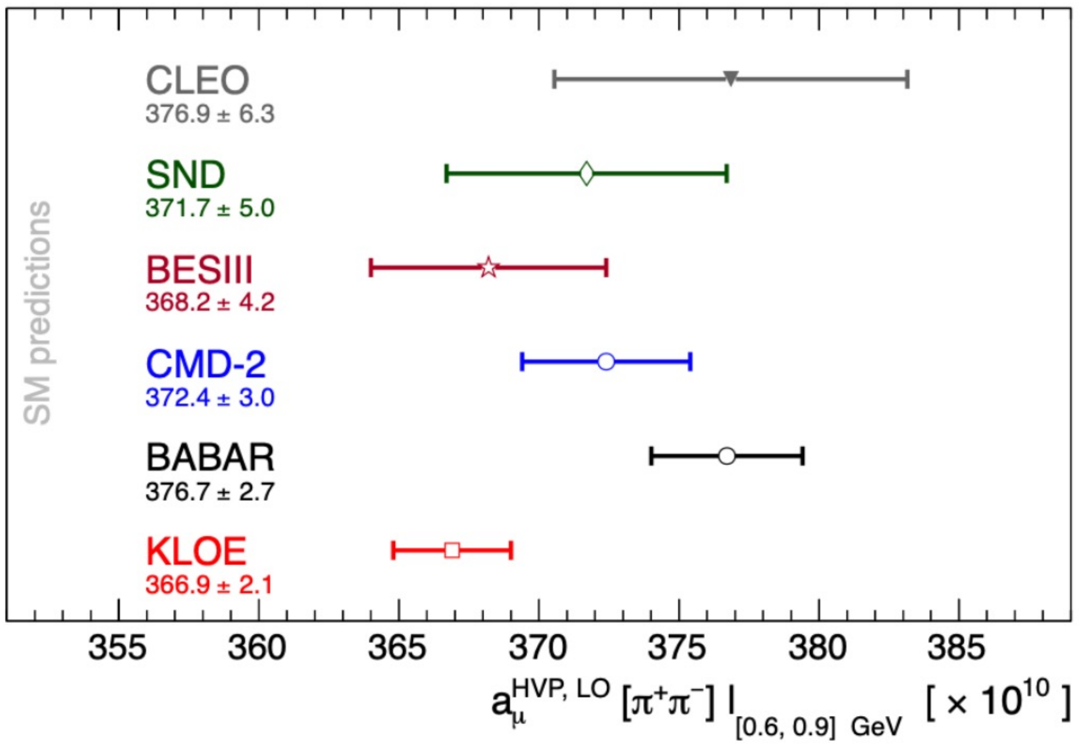
Keshavarzi, Nomura, Teubner 2018

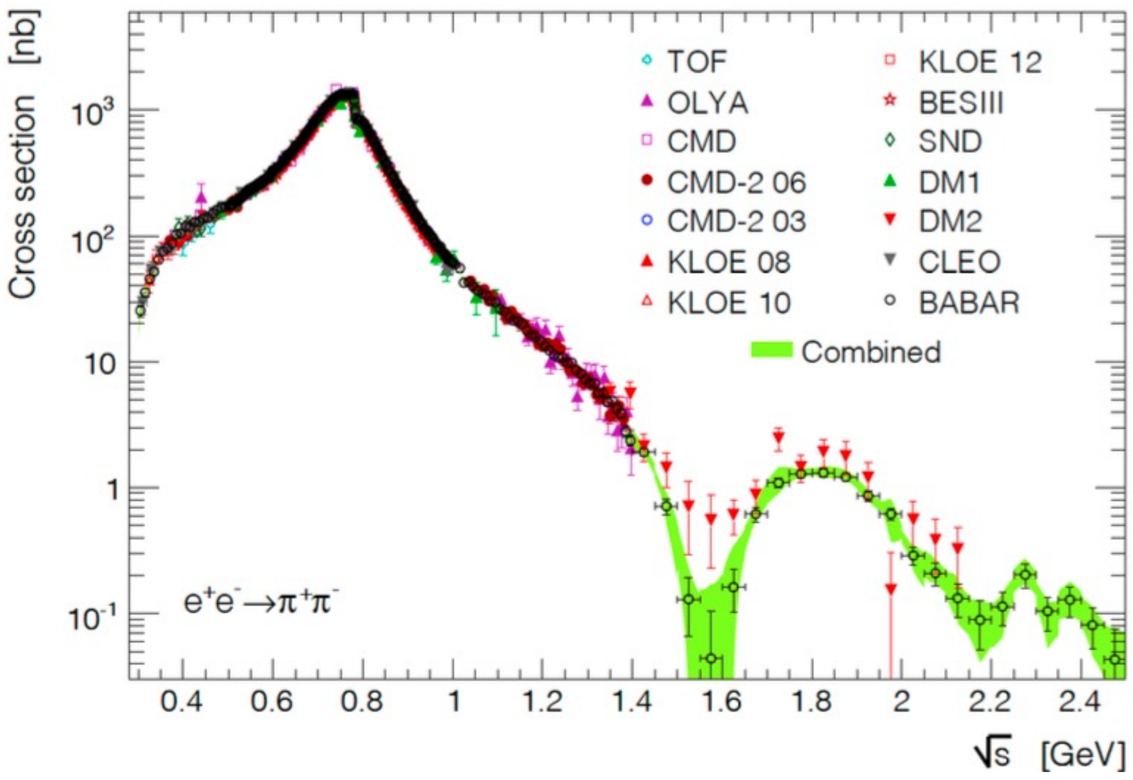
σ(e⁺e⁻→ hadrons) contribution in the energy region



Muon $g-2$ Puzzle

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





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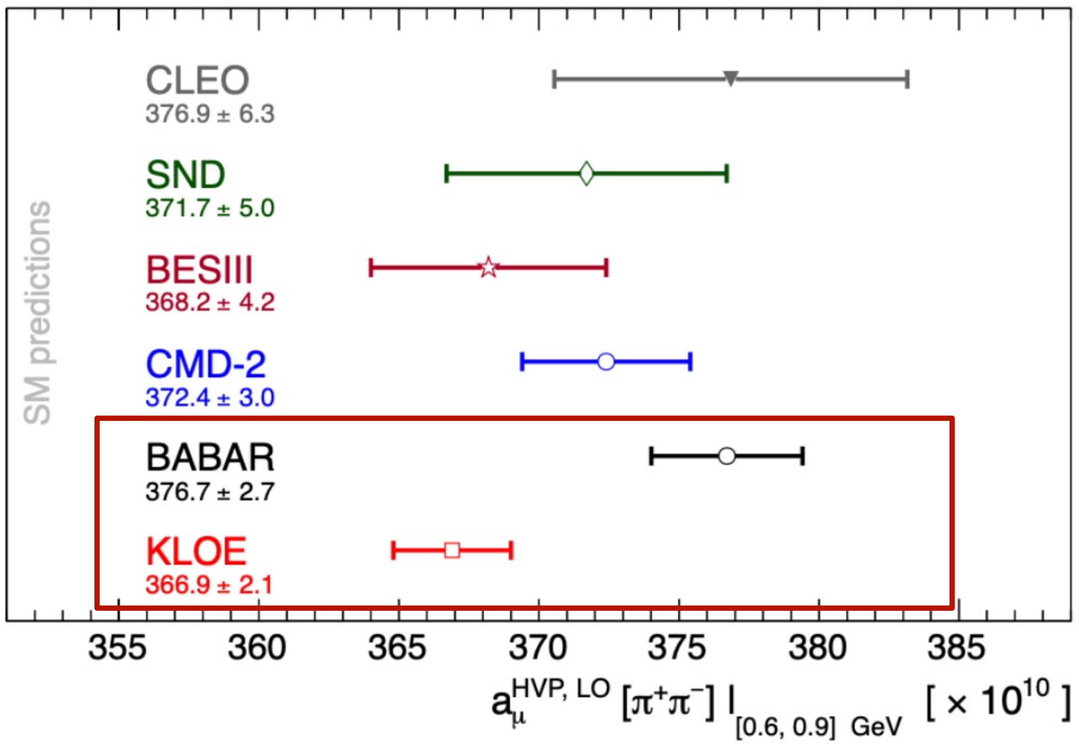
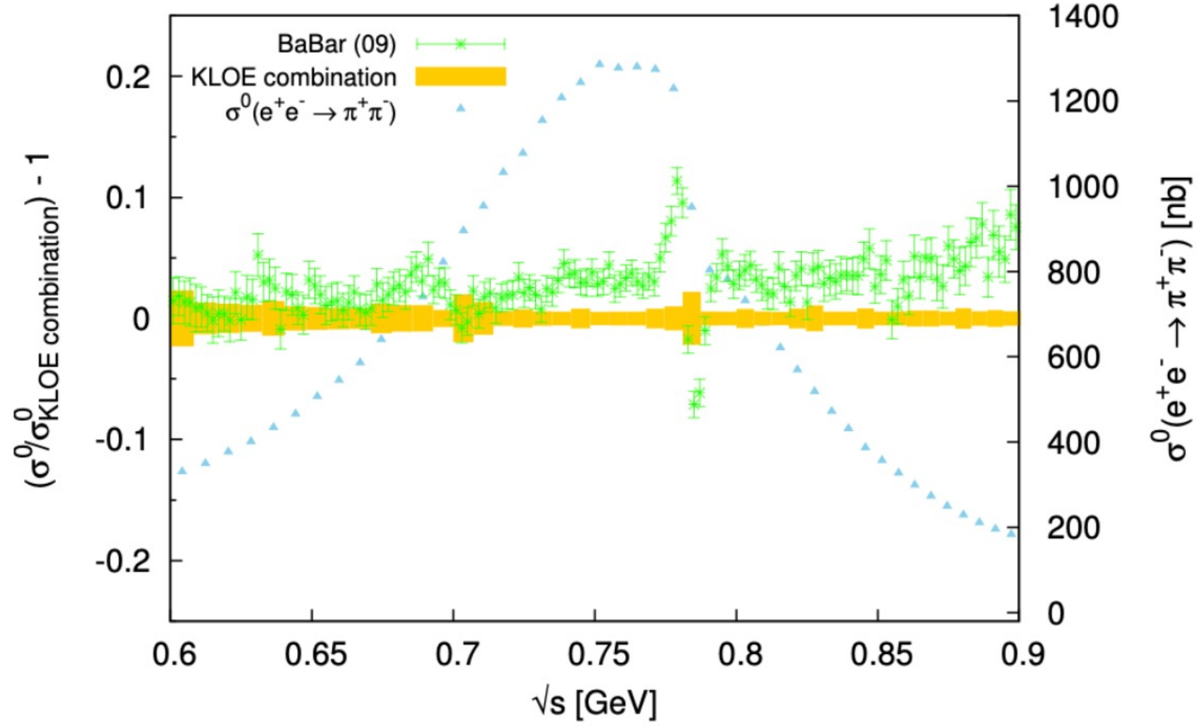
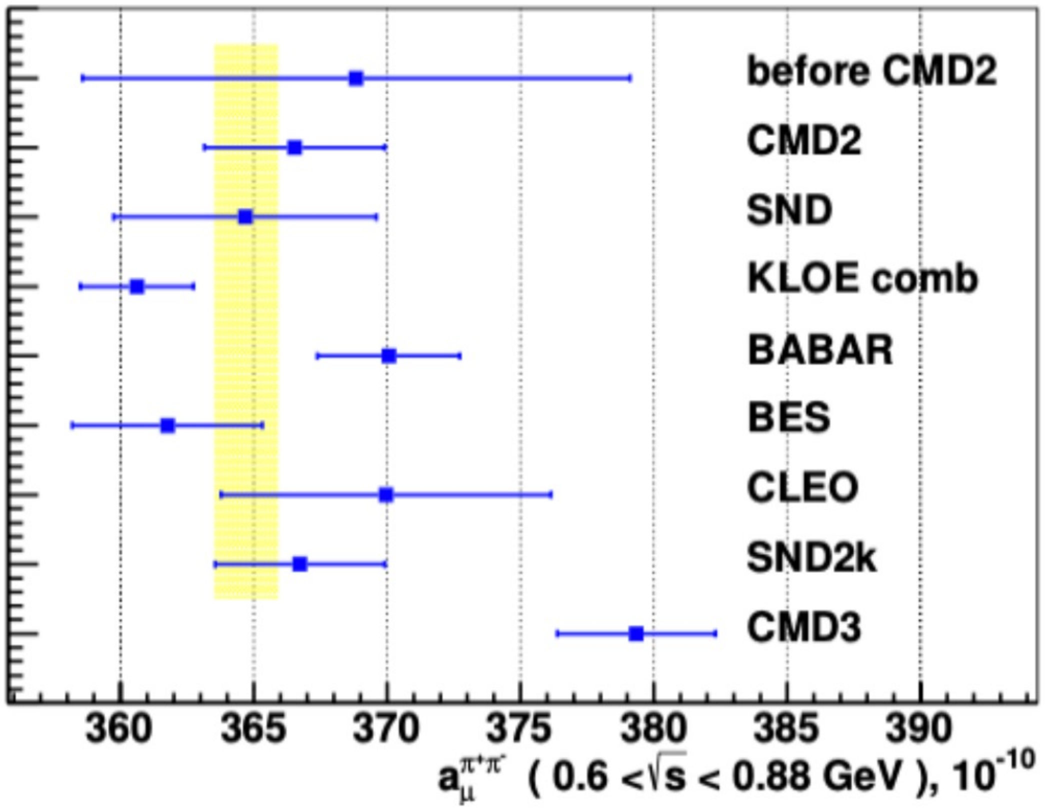




- The discrepancy between BABAR and KLOE needs to be understood

Muon $g-2$ Puzzle

CMD-3 Result on $e^+e^- \to \pi^+\pi^-$ Channel



- A recent CMD-3 result is different from all the previous data → more chaotic!

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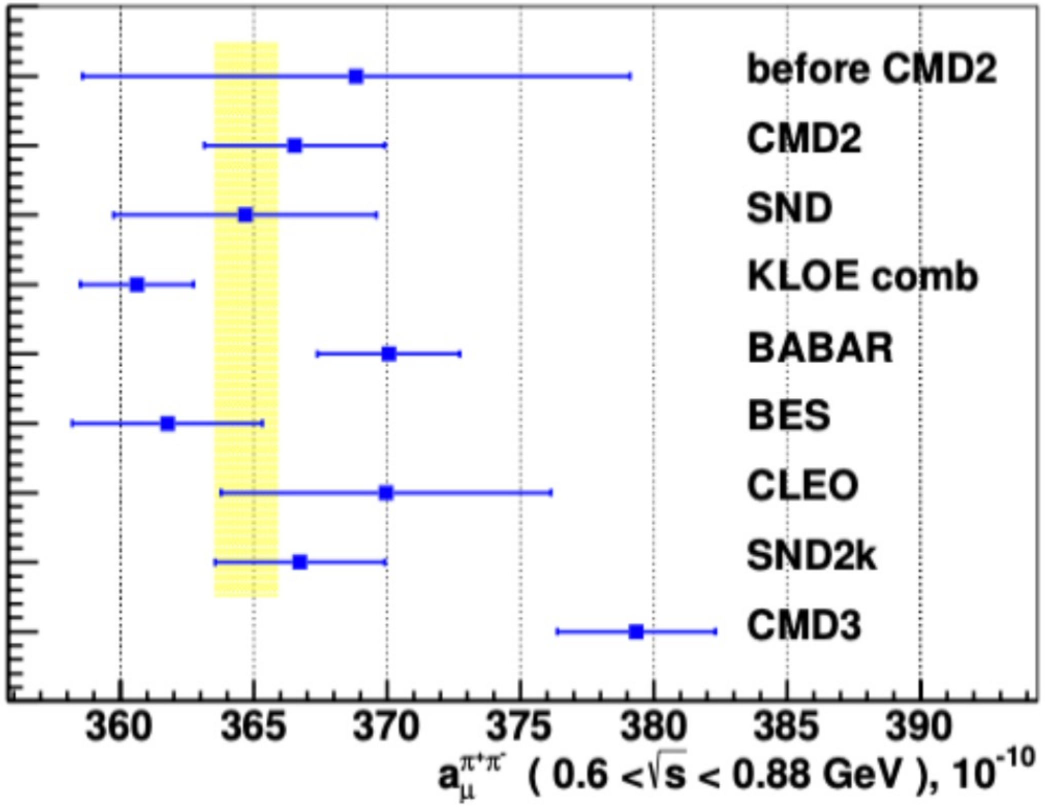
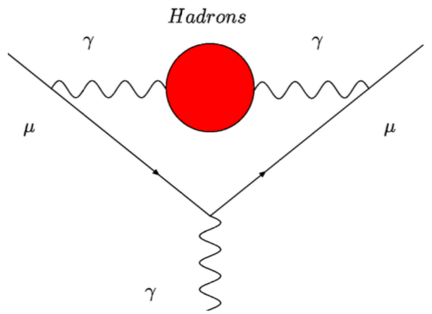


- A recent CMD-3 result is different from all the previous data → more chaotic!
- **A quick summary on the puzzle:**
  - a_μ^{HVP} represents a major uncertainty
  - e^+e^- data-driven dispersive ⇔ Lattice (BMW)
  - Within the data-driven method:
    - Babar ⇔ KLOE (recently, some clues on MC generator…)
    - Latest CMD3 ⇔ all the previous data

MUonE Experiment

A New Approach towards a_μ^{HVP} with running of $\Delta\alpha_{\mathbf{had}}$

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



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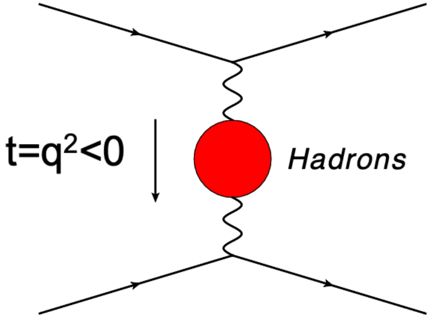
- Alternatively, exchanging the x and s integrations → **space-like** formula:



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

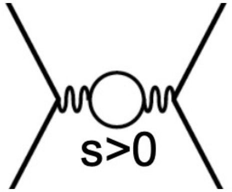
  - $\Delta\alpha_{\mathbf{had}}$ is the hadronic contribution to the **running α** (electromagnetic coupling constant)

MUonE Experiment

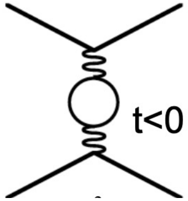
Running of $\Delta\alpha_{\text{had}}$: Time-like vs Space-like

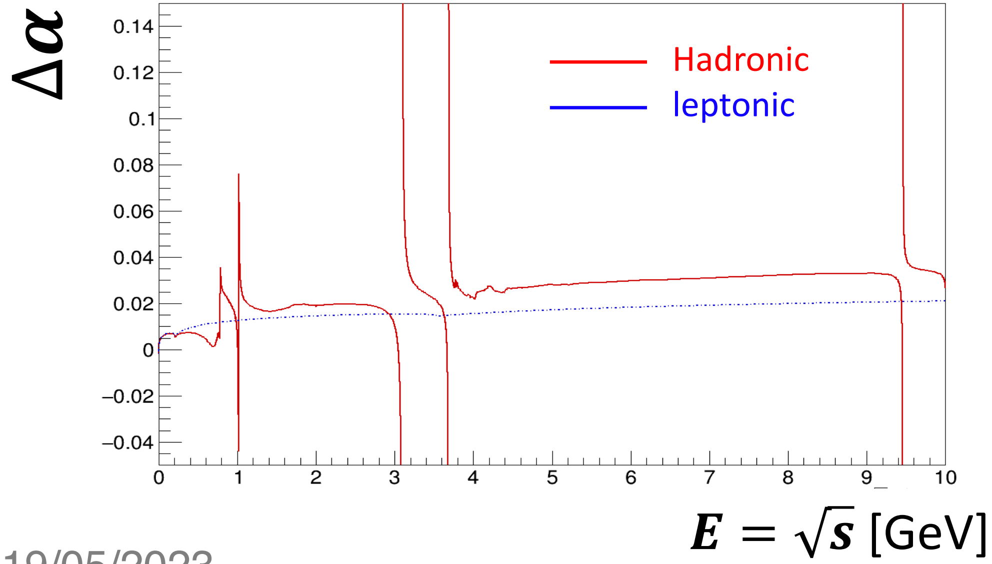
$$\Delta\alpha^{(5)}_{had}(q^2) = -\frac{\alpha}{3\pi}\, q^2 \int_{m^2_{\pi^0}}^{\infty} ds' \frac{R(s')}{s'(s'-q^2)}$$

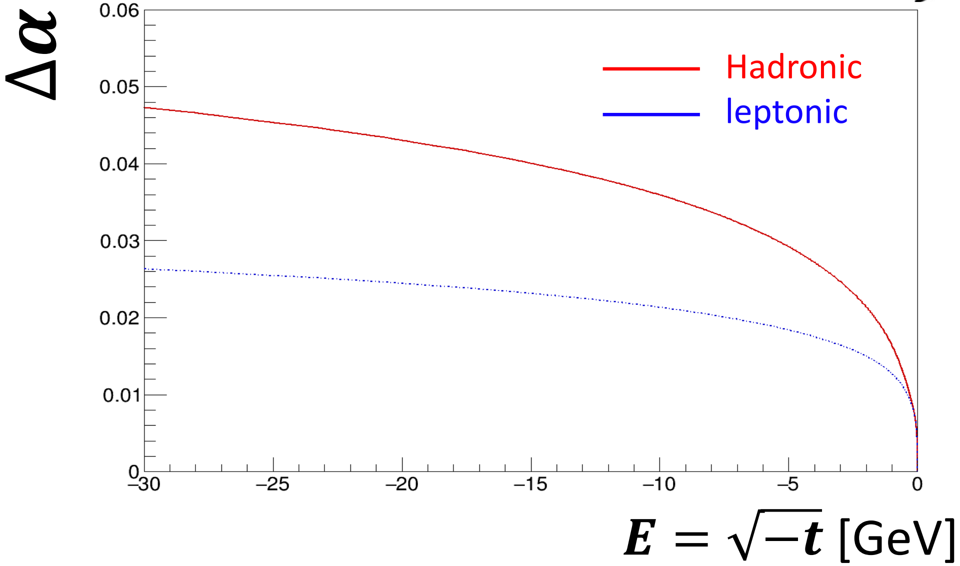
- **Time-like:** characterized by the opening of resonances



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



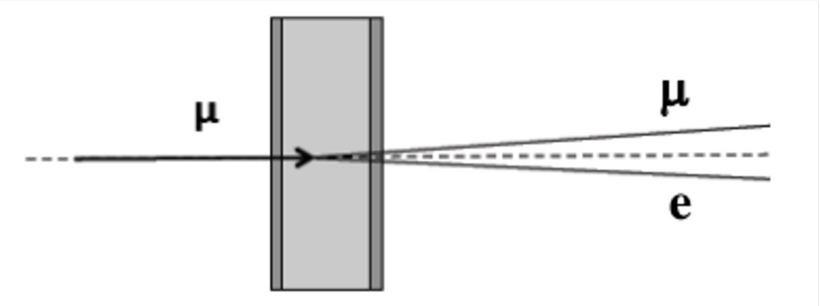




MUonE Experiment

$\Delta\alpha_{\text{had}}$ 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 $\mu^+e^- \to \mu^+e^-$



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

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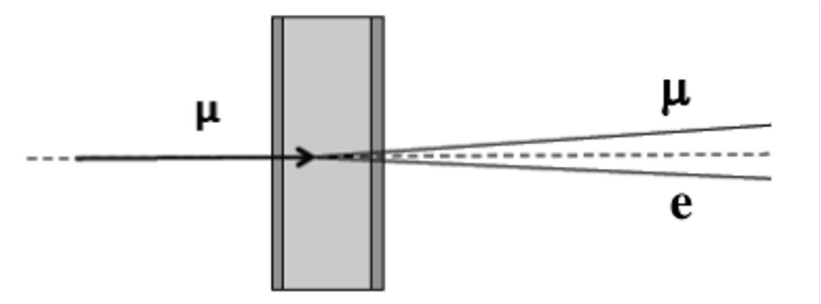

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The NNLO differential cross section from **theoretical calculation**

To be determined in this experiment

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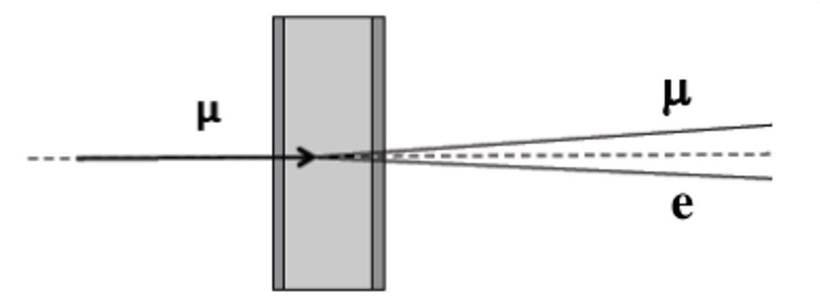

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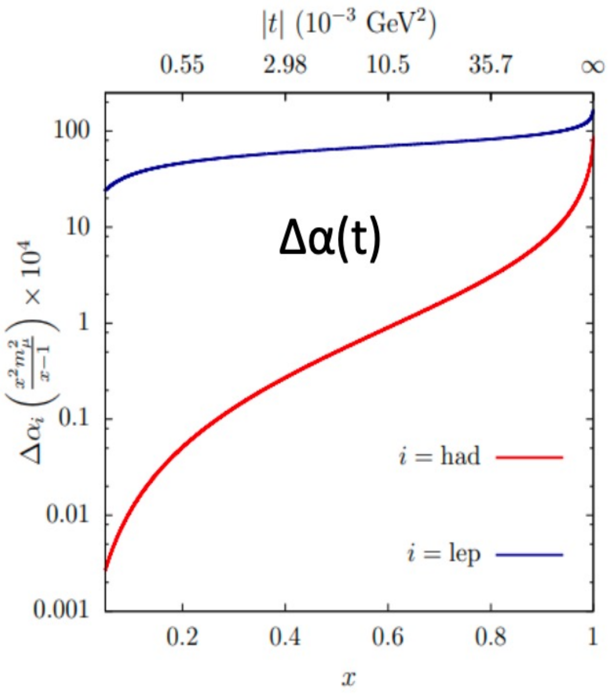

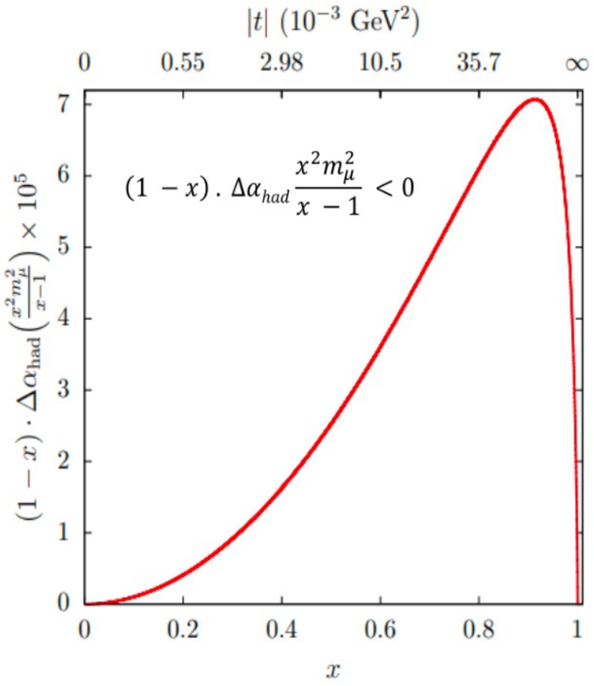

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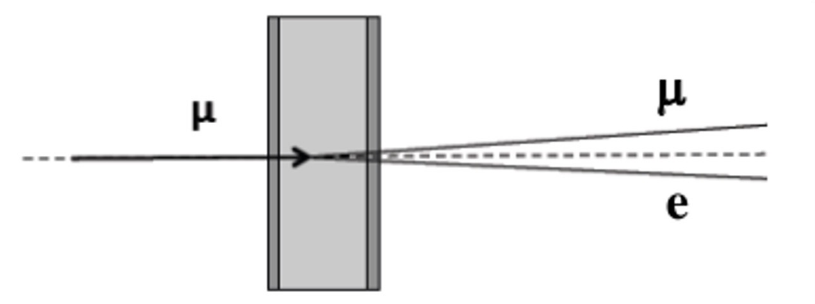

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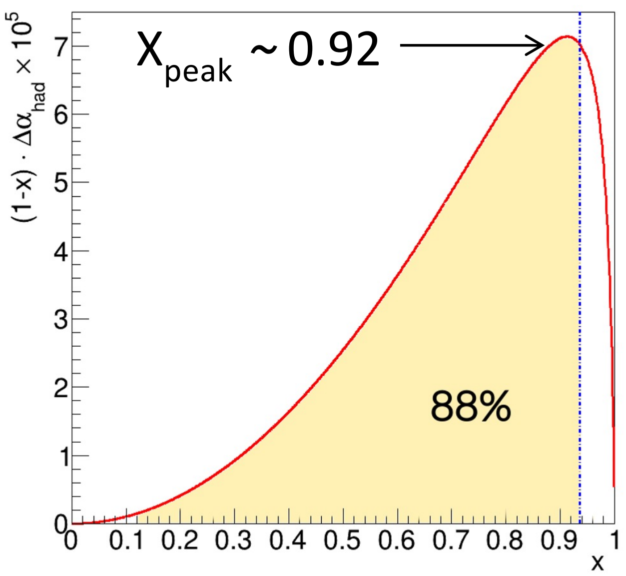
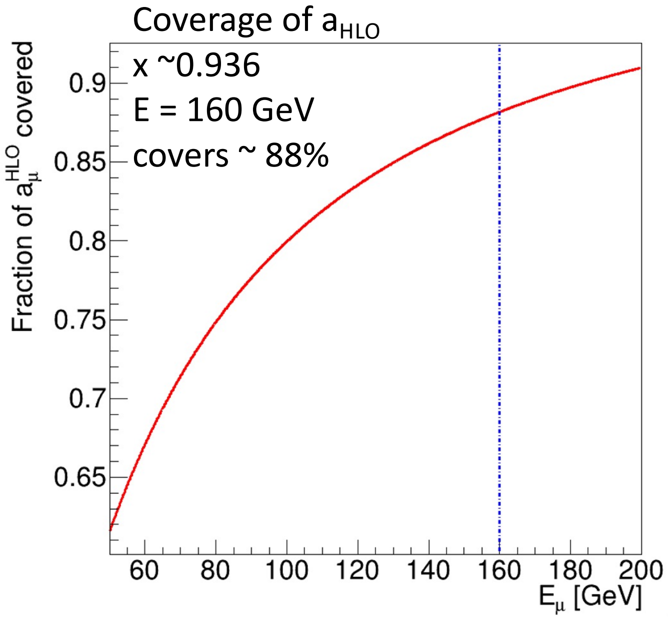
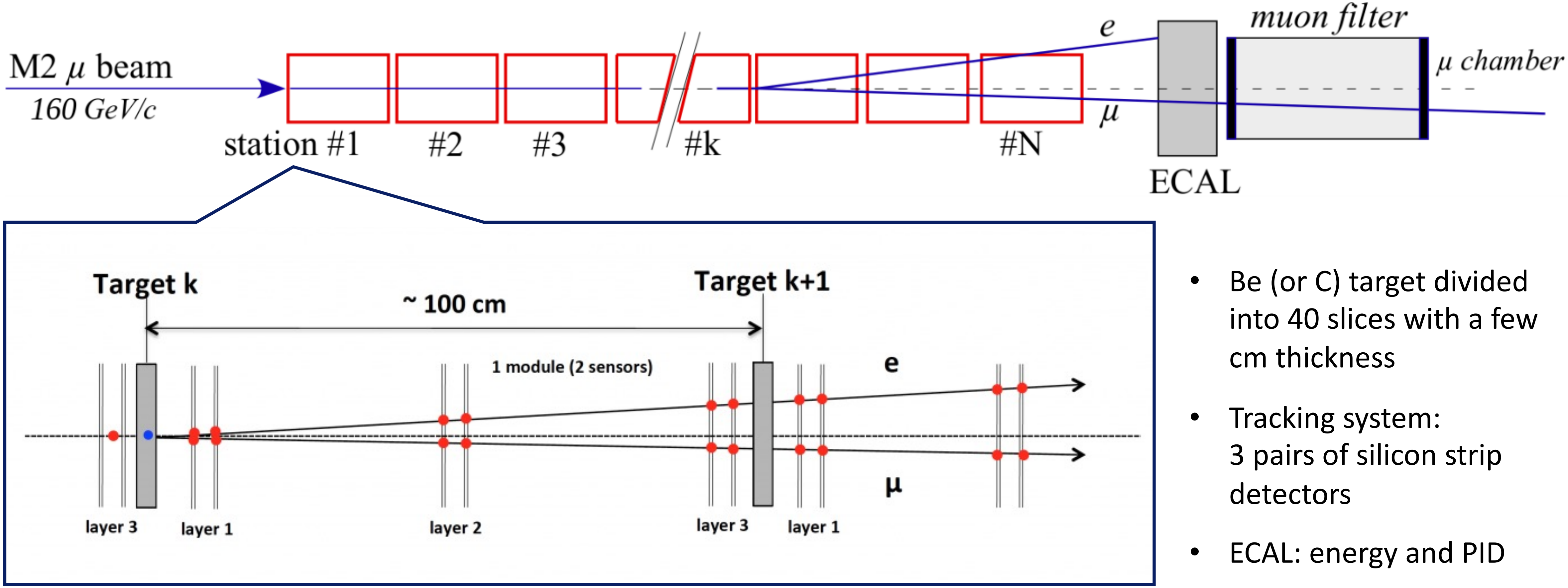




MUonE Experiment

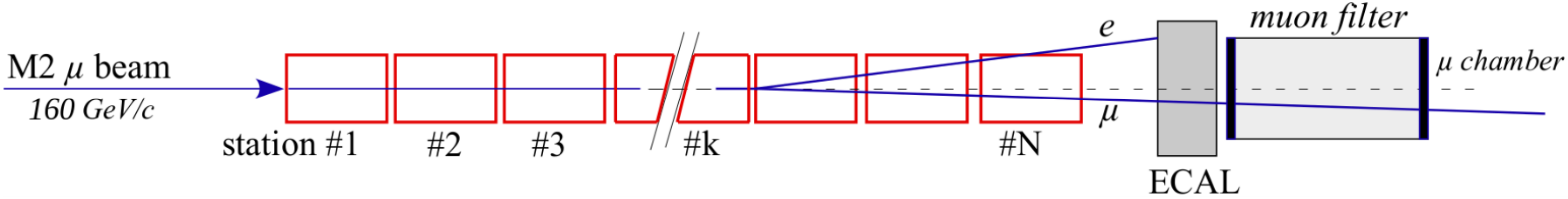
Setup Overview



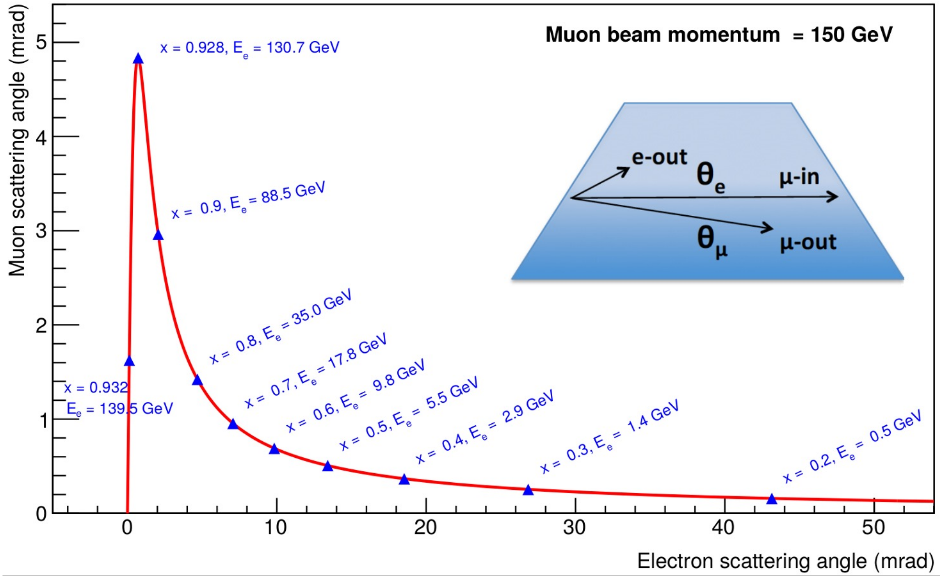
- Be (or C) target divided into 40 slices with a few cm thickness
- Tracking system: 3 pairs of silicon strip detectors
- ECAL: energy and PID

MUonE Experiment

Setup Overview



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



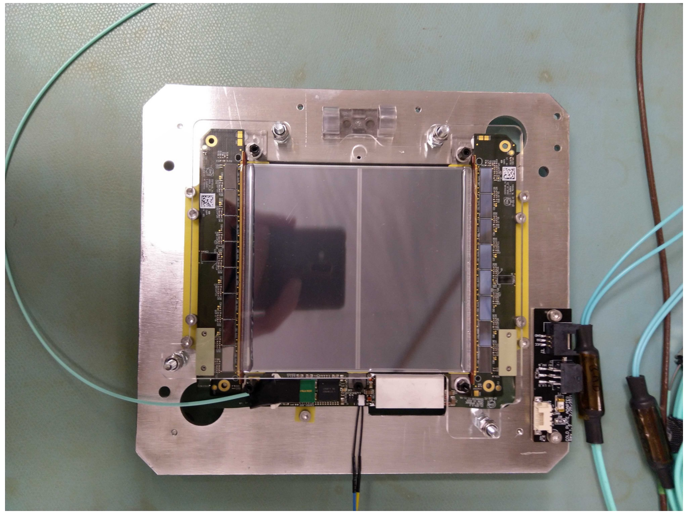
Apparatus

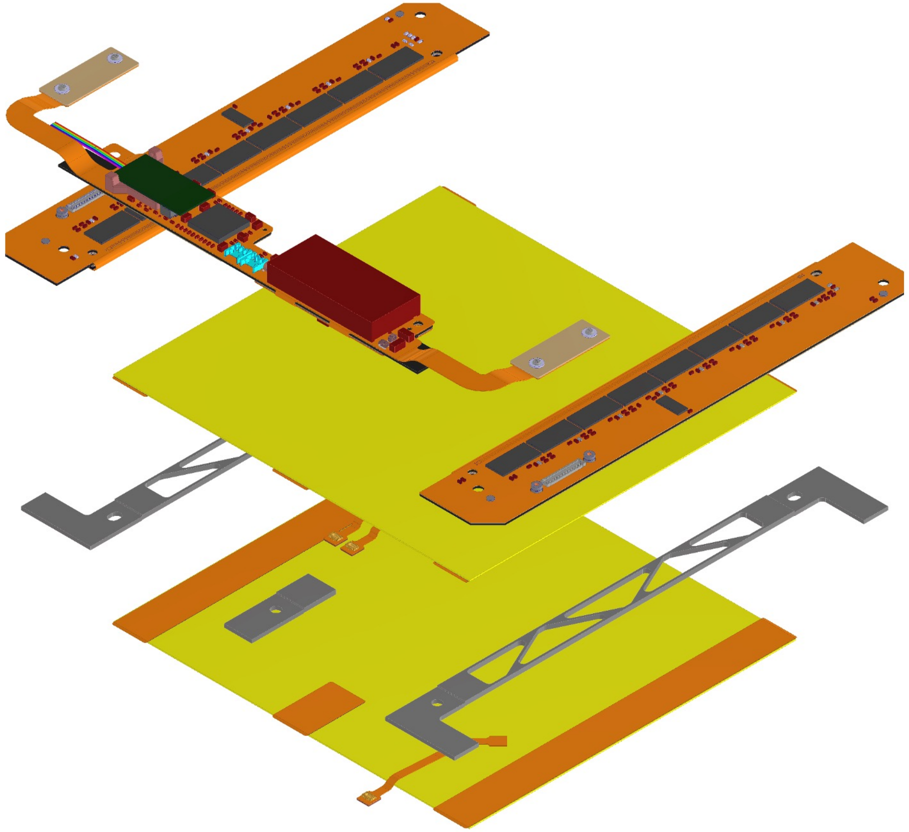
The Tracker (CMS 2S Module)

- 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:

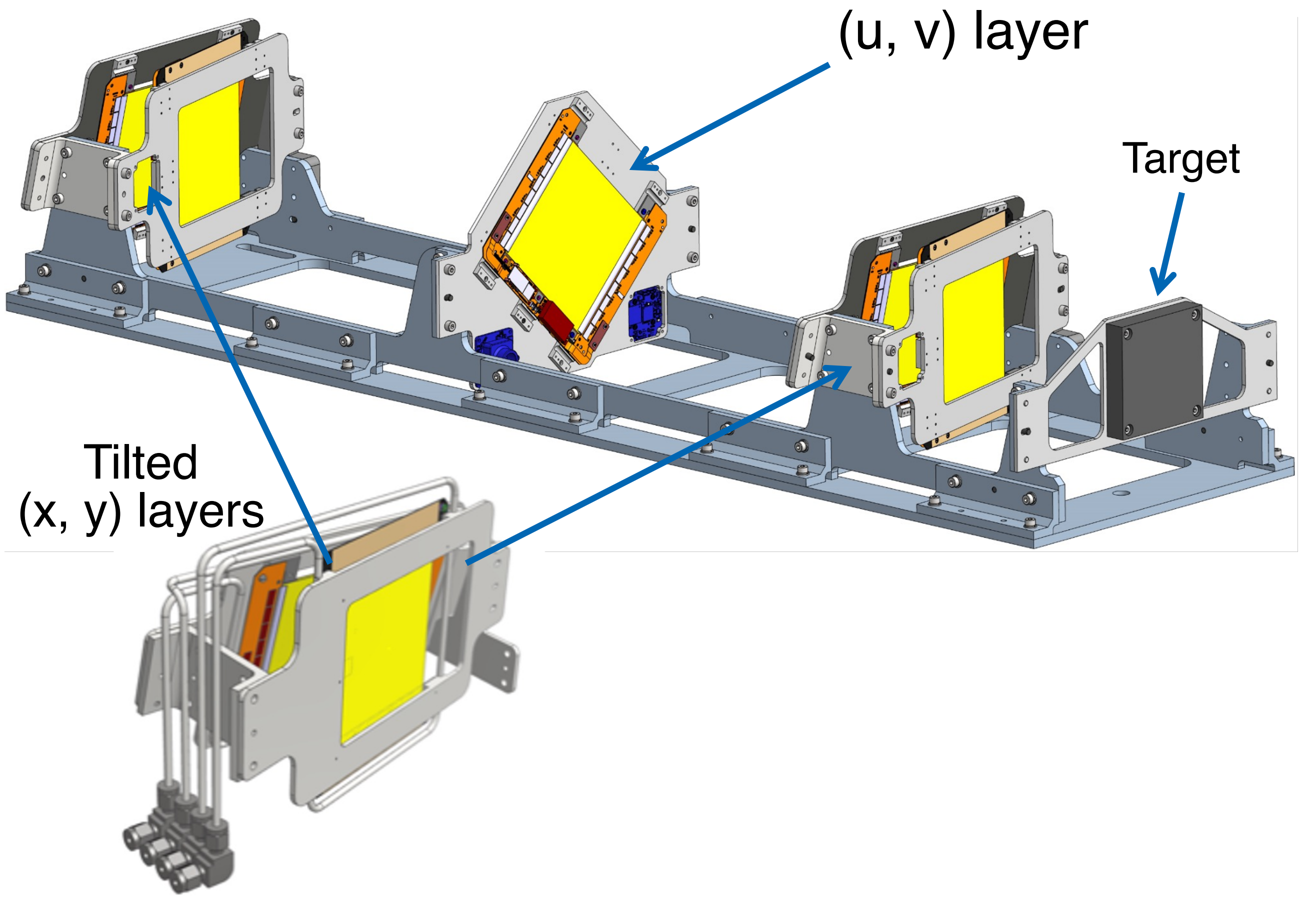
- 1016 strips
- 5 cm long
- Divided in 8 sectors
- Each sector has independent read-out





Apparatus

The Tracking Station



- Two (x, y) layers and (u, v) layer
  - (x, y) layers tilted by 233 mrad
  - (u, v) layer to solve reconstruction ambiguities.
- Relative position within a station must be stable at 10 μm.
  - Low-CTE material (INVAR, carbon)
  - Cooling system + controlled temperature environment
  - Laser holographic system to monitor stability

Apparatus

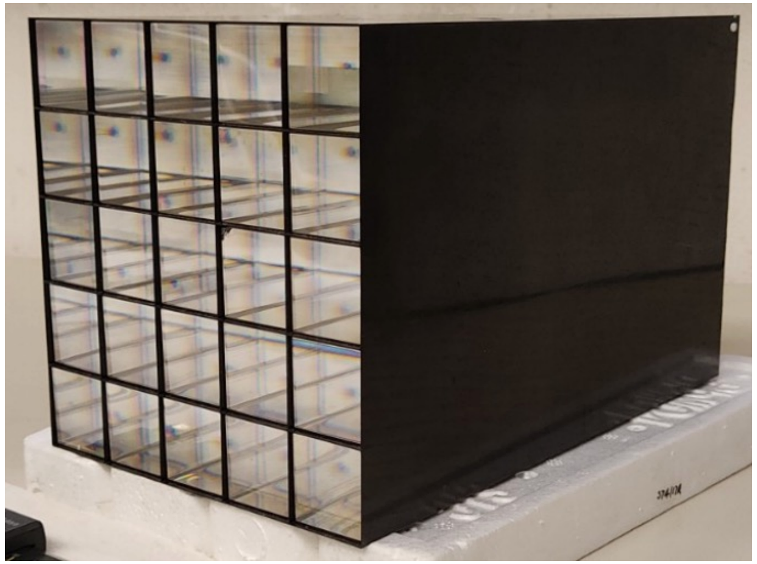
Calorimeter for PID

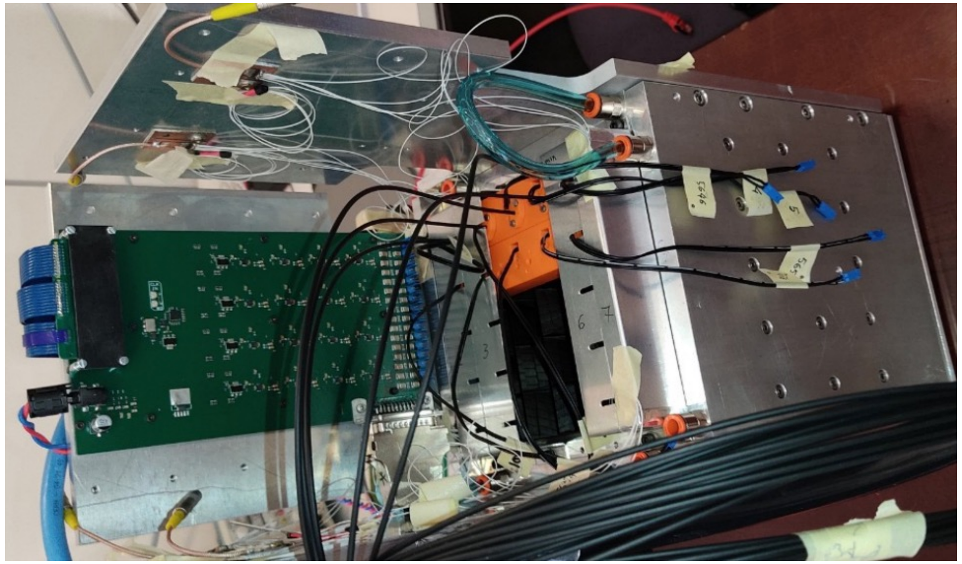
- A forward EM calorimeter (ECAL) covering part of the total acceptance for the elastic scattering.
- Useful for PID & systematic study (an independent kinematic measurement)

Transverse dim: ~ 1x1 m^2

5x5 $PbWO_4$ crystals:

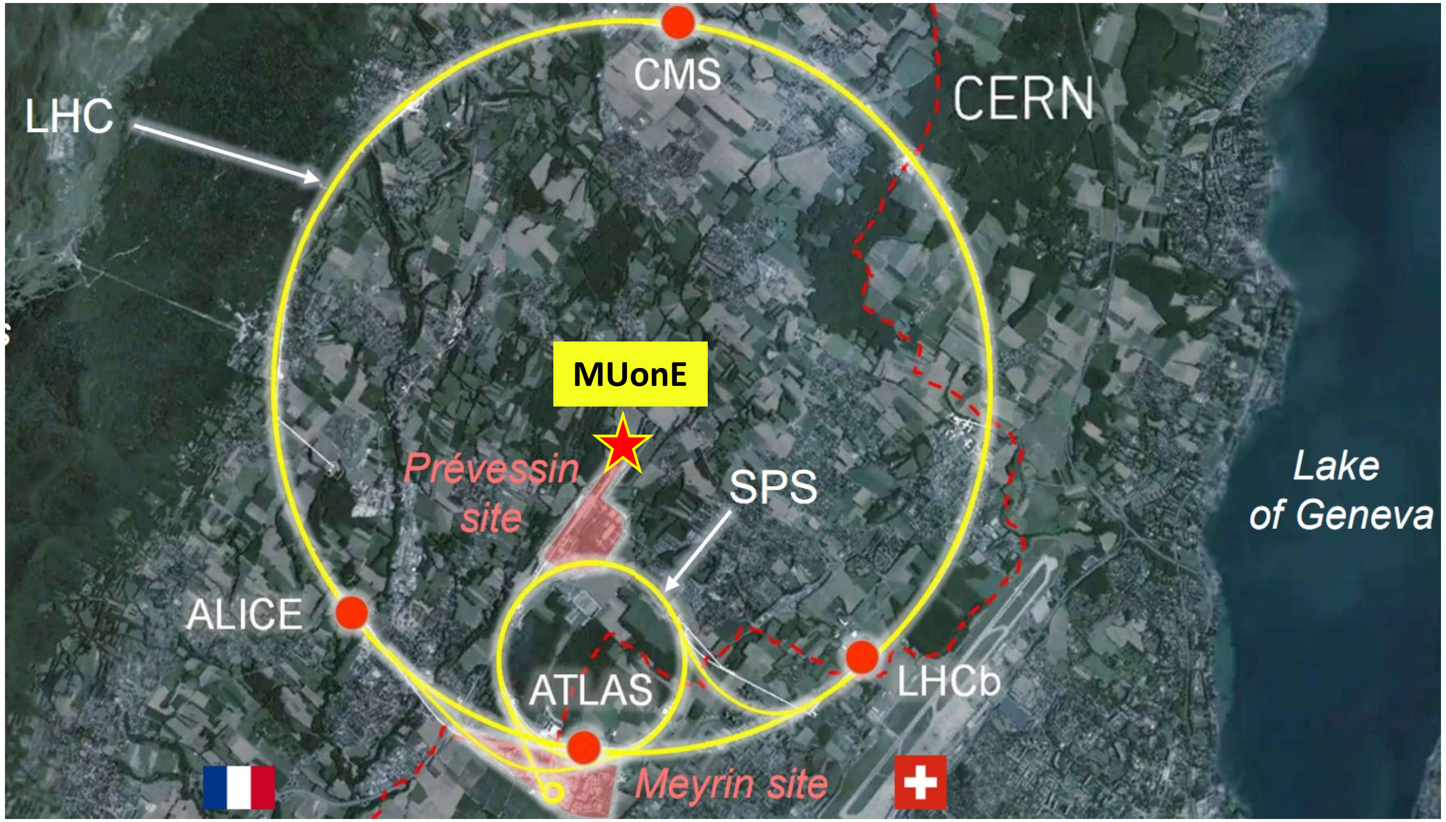
- Area: 2.85x2.85 cm^2
- Length: 22 cm (~25 X0).
- Total area: ~14x14 cm^2.
- Readout: APD sensors.

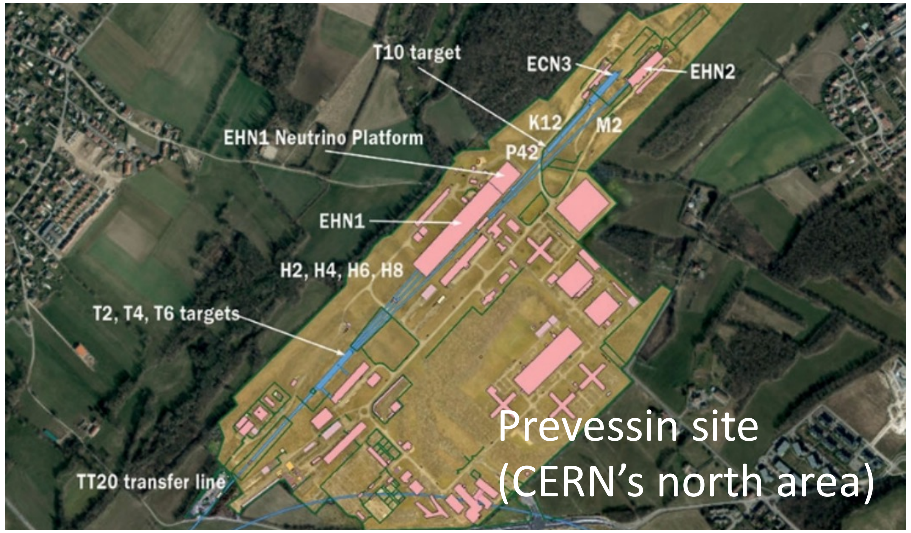


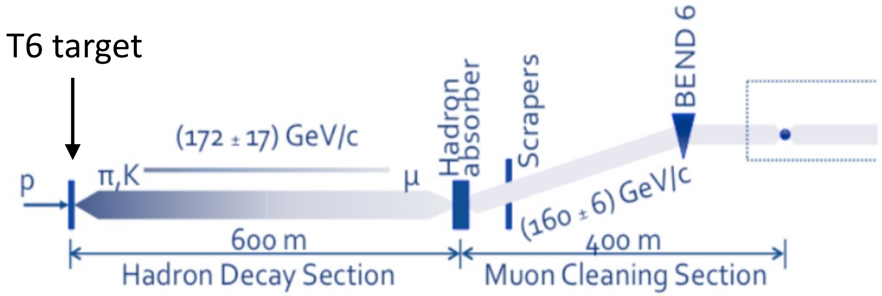


Apparatus

Muon (M2 beam-line) from CERN SPS Ring



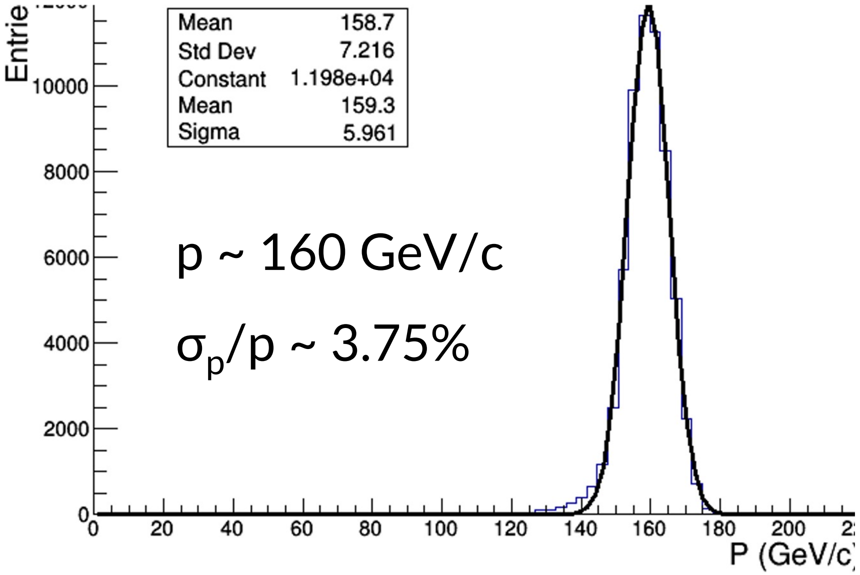


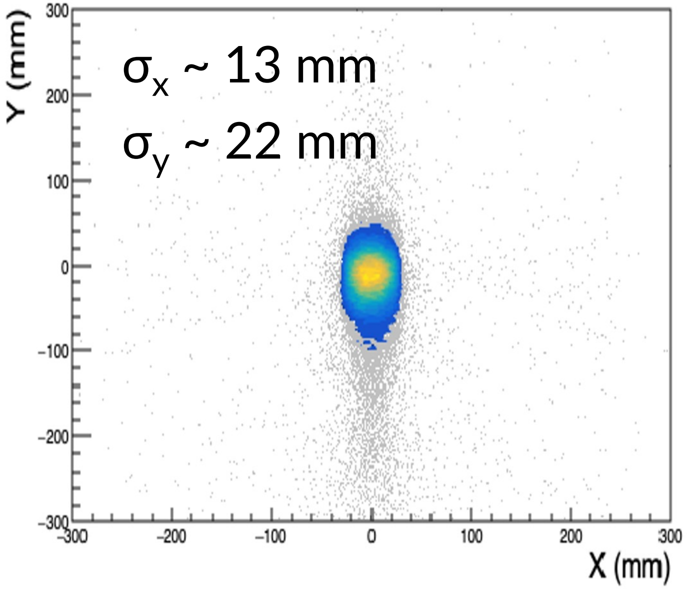


Apparatus

Muon (M2 beam-line) from CERN SPS Ring

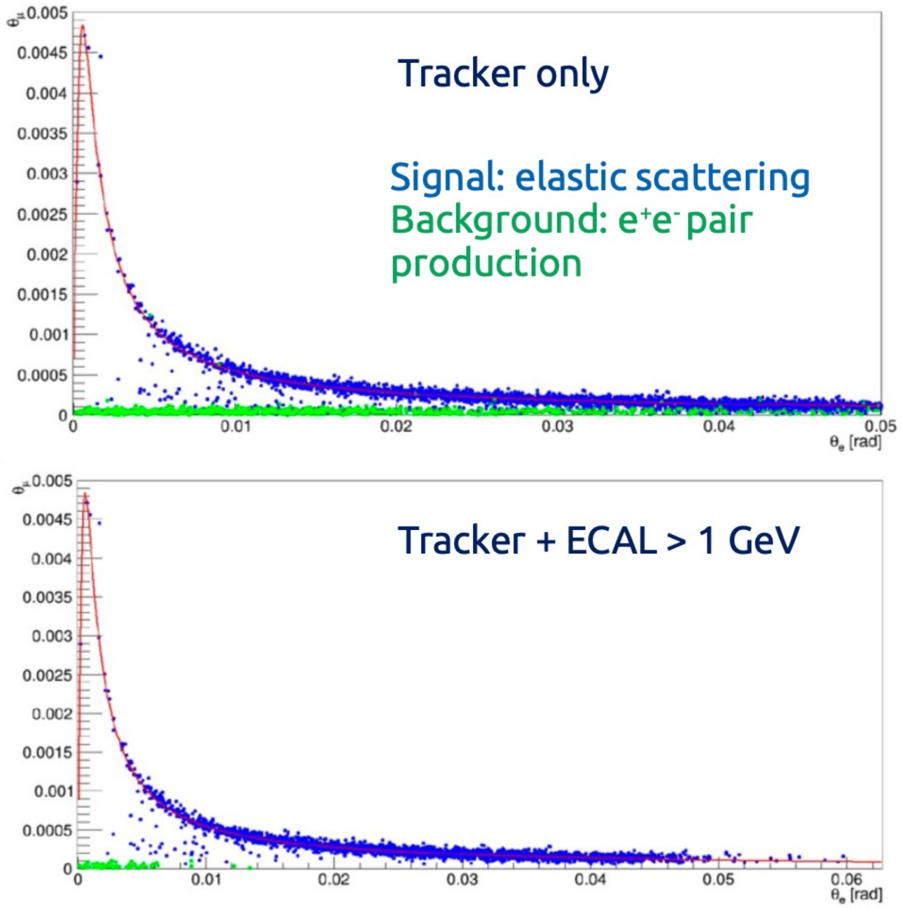
- CERN North Area M2: upstream of the COMPASS detector
  - Maximum 50 MHz (2-3$\times 10^8$ μ^+/spill) for 10^{12} 400 GeV/c incident protons





Simulation Framework

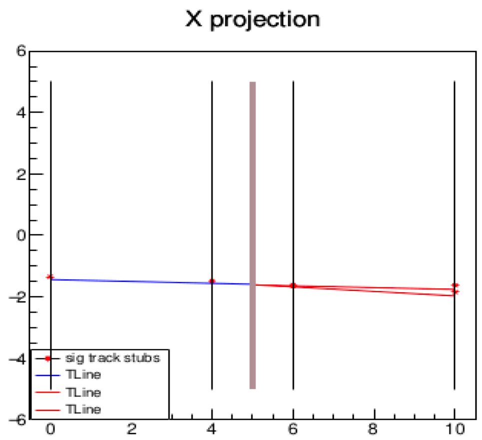
- NLO MonteCarlo generator: MESMER
  - Allows to change the muon beam energy and simulate the energy spread
- 'MuE' fast simulation (Geant4 based)
  - Effects applied to (θ_e, θ_μ) from the NLO generator
  - Part of detector effects (Multiple scattering) included
- 'FairMUonE' dedicated for this project
  - **Full detector effects** and **track reconstruction**
- 'Combine' tool for analyzing systematic effects

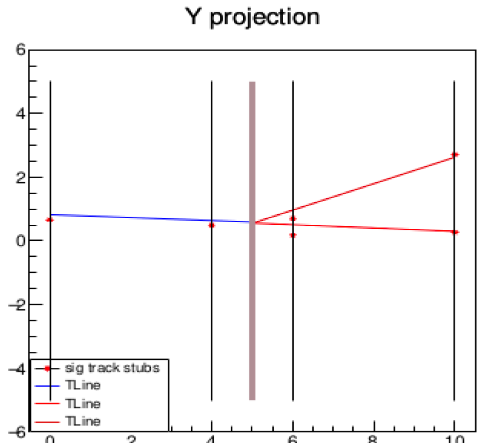


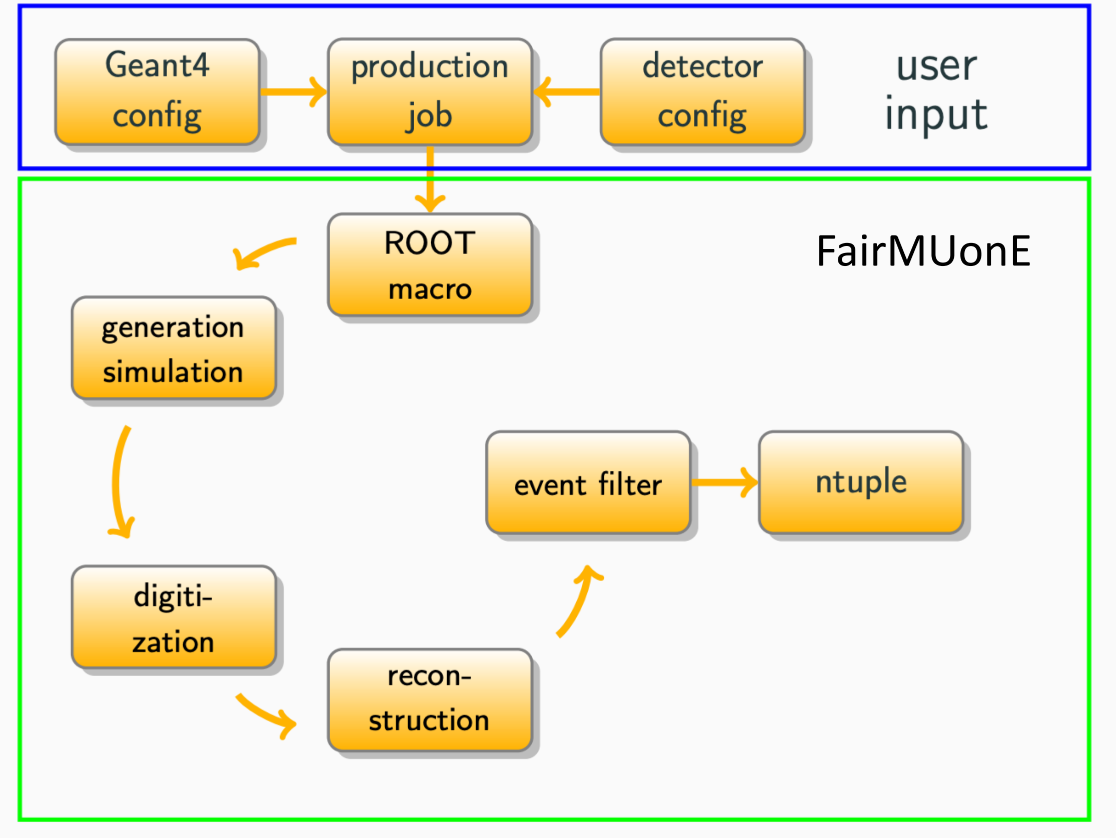
Elastic Scattering Analysis

‘FairMUonE’ Package

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



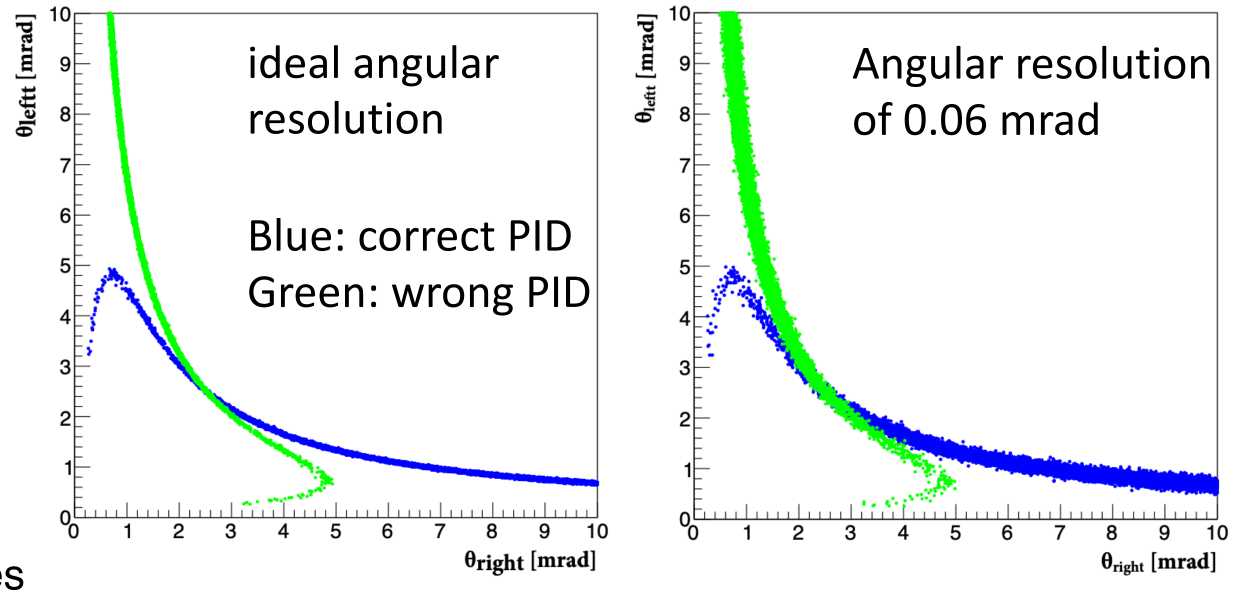




Elastic Scattering Analysis

Event Selection

- 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 (a limited ambiguity region)



Elastic Scattering Analysis

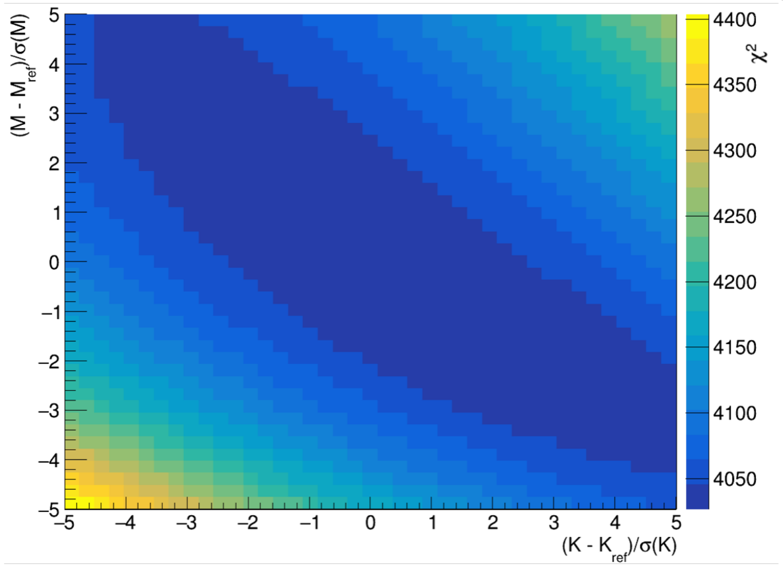
Template Fit

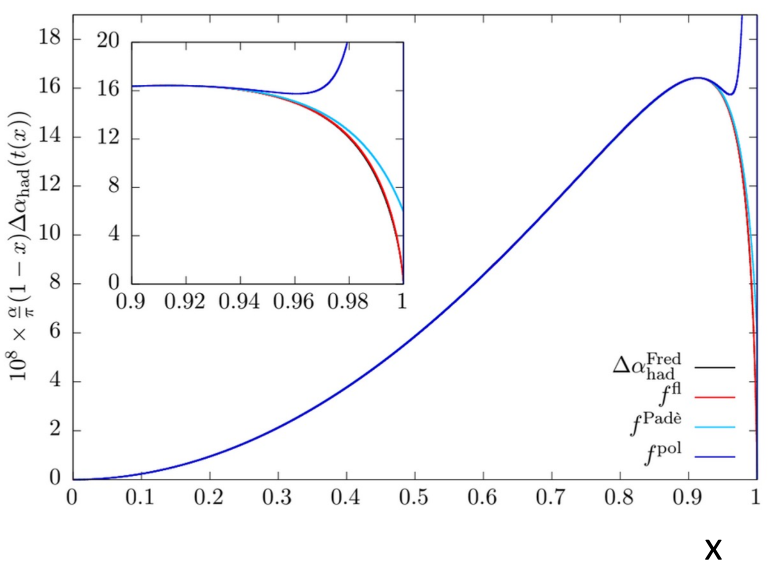
- Extracting $\Delta\alpha_{had}(t)$ through **a template fit** to the (θ_e, θ_μ) distribution
- $\Delta\alpha_{had}$ parameterization **(K, M)**: $$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9} - \frac{4}{3}\frac{M}{t} + \left(\frac{4}{3}\frac{M^2}{t^2} + \frac{M}{3t} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$
    - '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_μ^2, m_τ^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
- $\Delta\alpha_{had}$ parameterization **(K, M)**: $$\Delta\alpha_{had}(t) = KM\left\{-\frac{5}{9}-\frac{4}{3}\frac{M}{t}+\left(\frac{4}{3}\frac{M^2}{t^2}+\frac{M}{3t}-\frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{t}}}\ln\left|\frac{1-\sqrt{1-\frac{4M}{t}}}{1+\sqrt{1-\frac{4M}{t}}}\right|\right\}$$





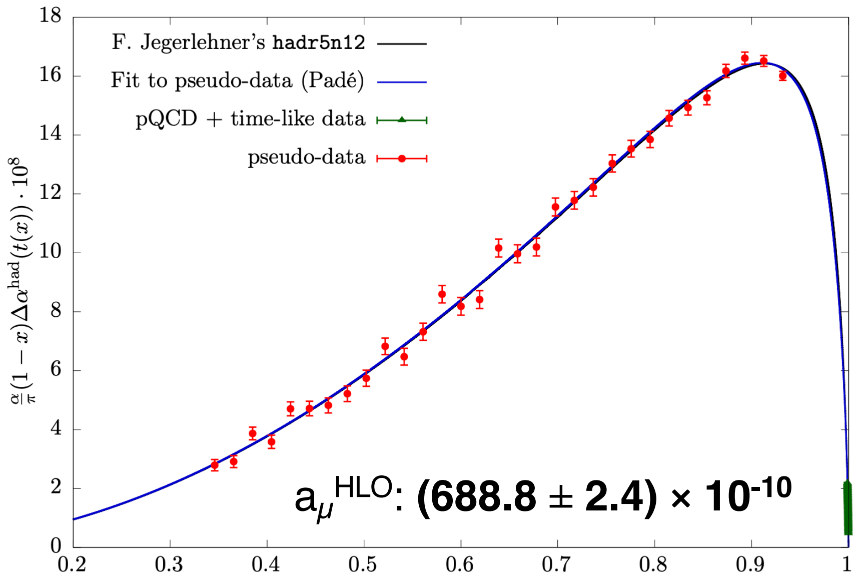
Preliminary template fit:

- 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** ± **2.4)** × **10^{-10}**
- 0.35% statistical error

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 $a_\mu^{\mathrm{HVP,LO}}$
  - Competitive with dispersive data-driven method
  - **3 years data-taking** with full stations → 4E12 events
  - Estimated **10 ppm** systematic uncertainty



Systematic Effects

General Considerations

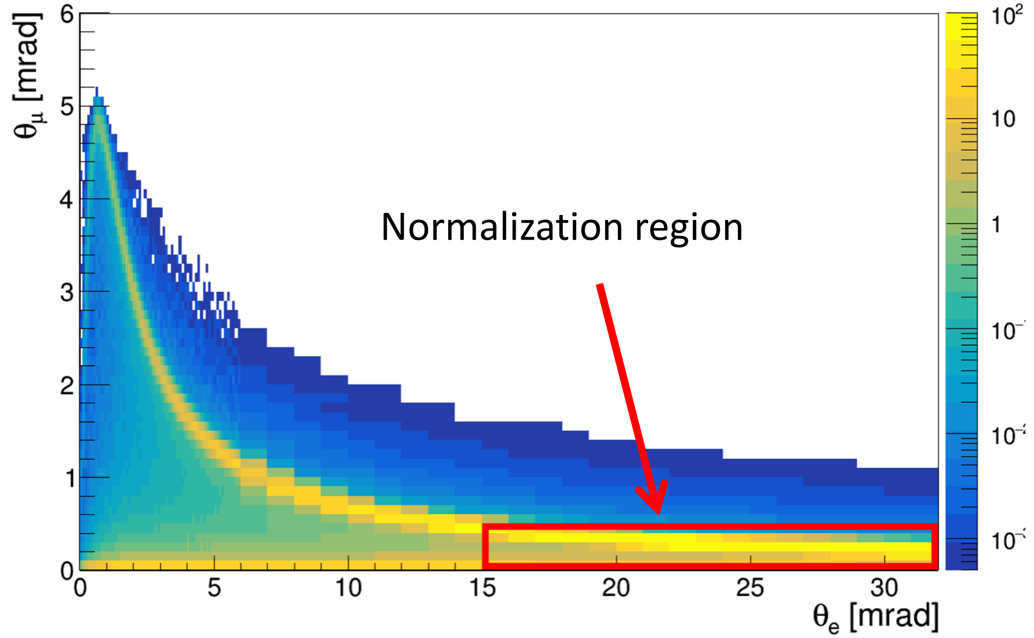
$$R_{\mathrm{had}} = \frac{d\sigma_{\mathrm{data}}(\Delta\alpha_{\mathrm{had}})}{\underline{d\sigma_{\mathrm{MC}}(\Delta\alpha_{\mathrm{had}} = 0)}} \sim 1 + 2\Delta\alpha_{\mathrm{had}}(t)$$

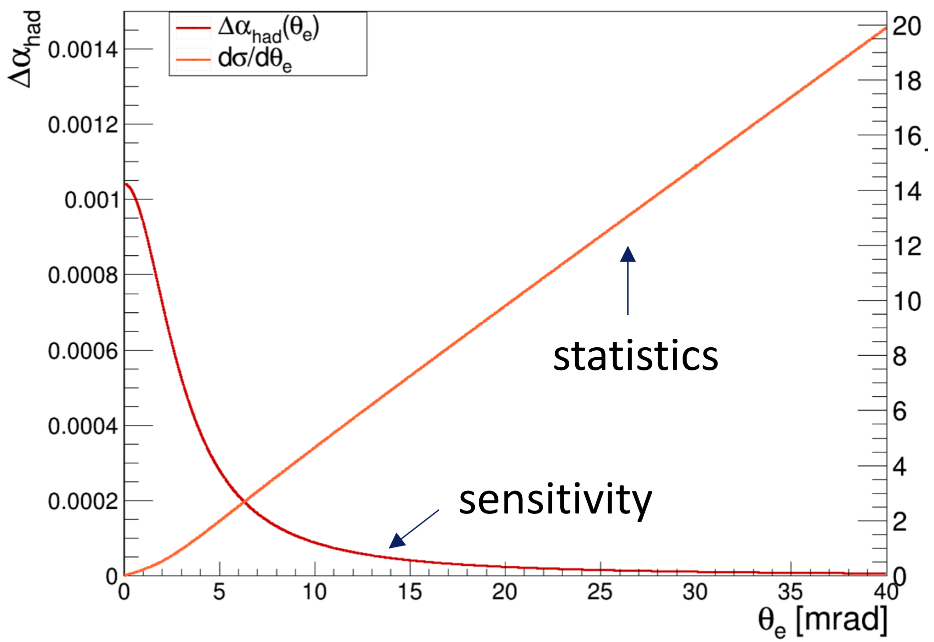
- Theory input: MC generator of radiative contributions at **NNLO** level
- Experimental requirements:
  - Uniform detection efficiency (modules, across all angular range)
  - Precise alignment (10 μm longitudinally)
  - Main sources:
    - **Multiple-scattering** (accuracy of 1%)
    - Angular resolution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

Systematic Effects

Strategy

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

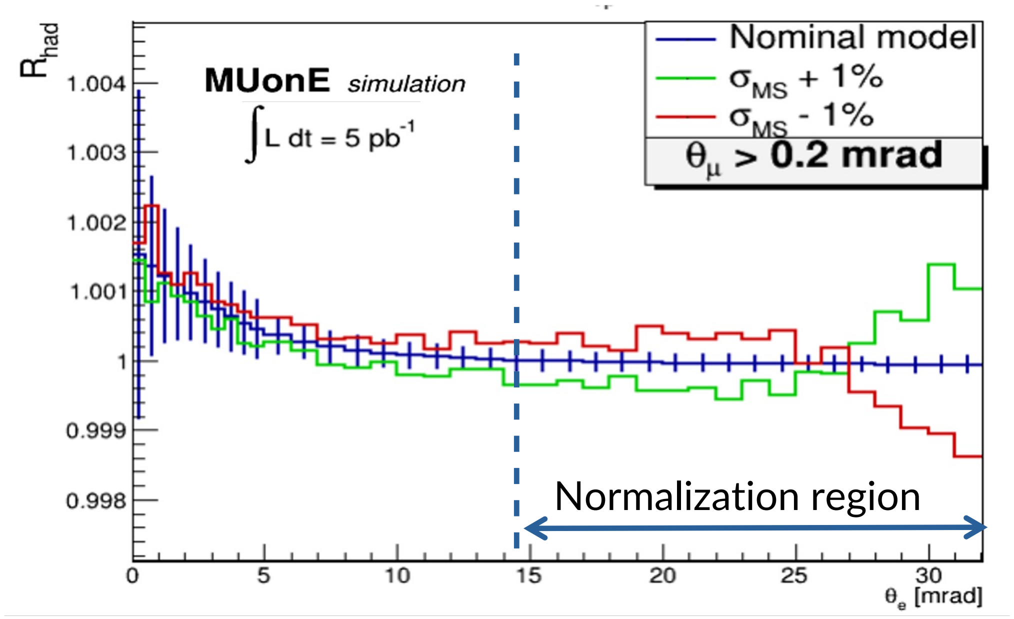


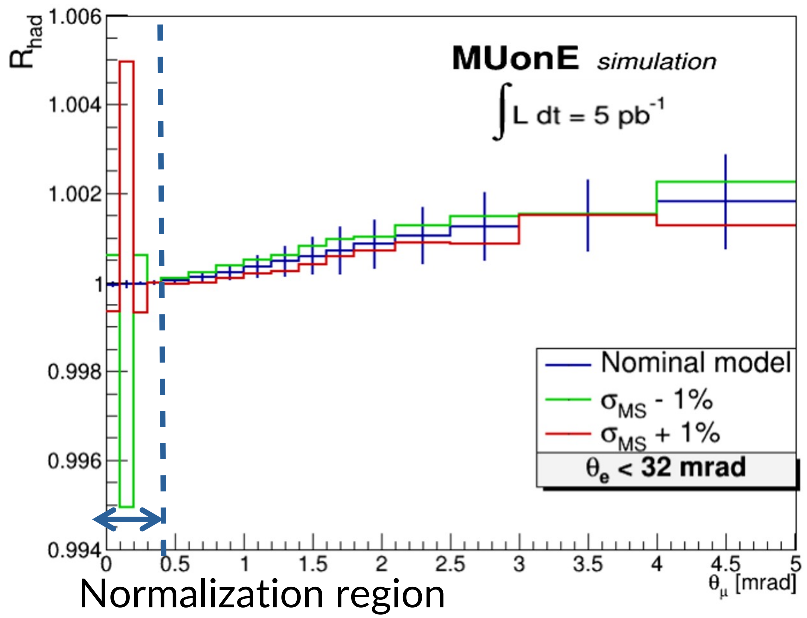


Systematic Effects

① Multiple Scattering

- Effect of α $\pm 1\%$ 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]()

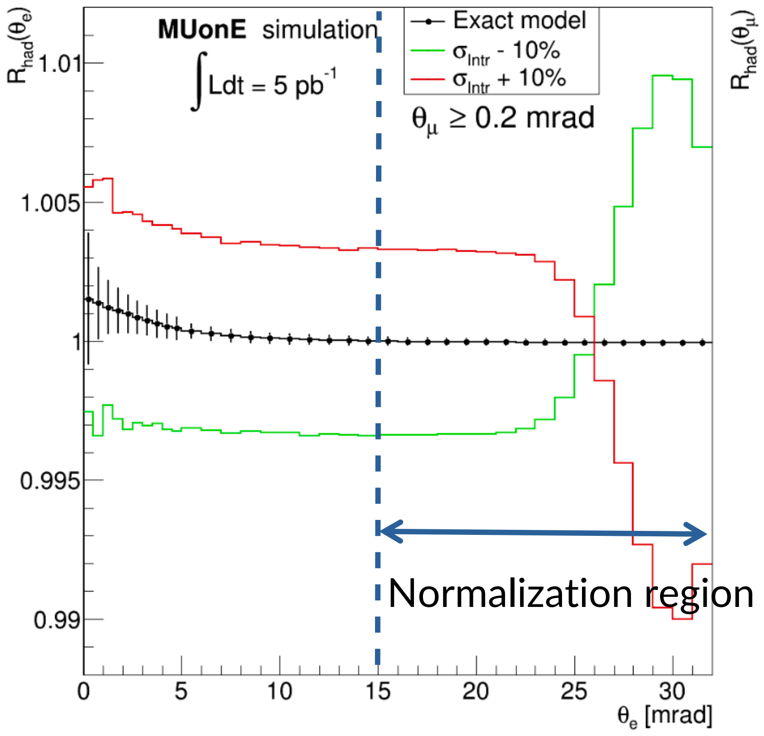


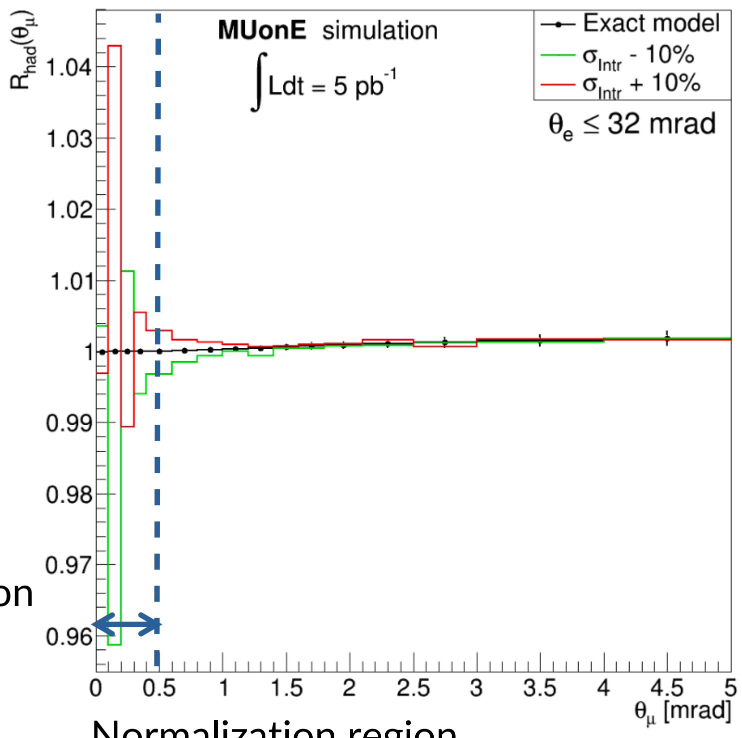


Systematic Effects

② Angular Intrinsic Resolution

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

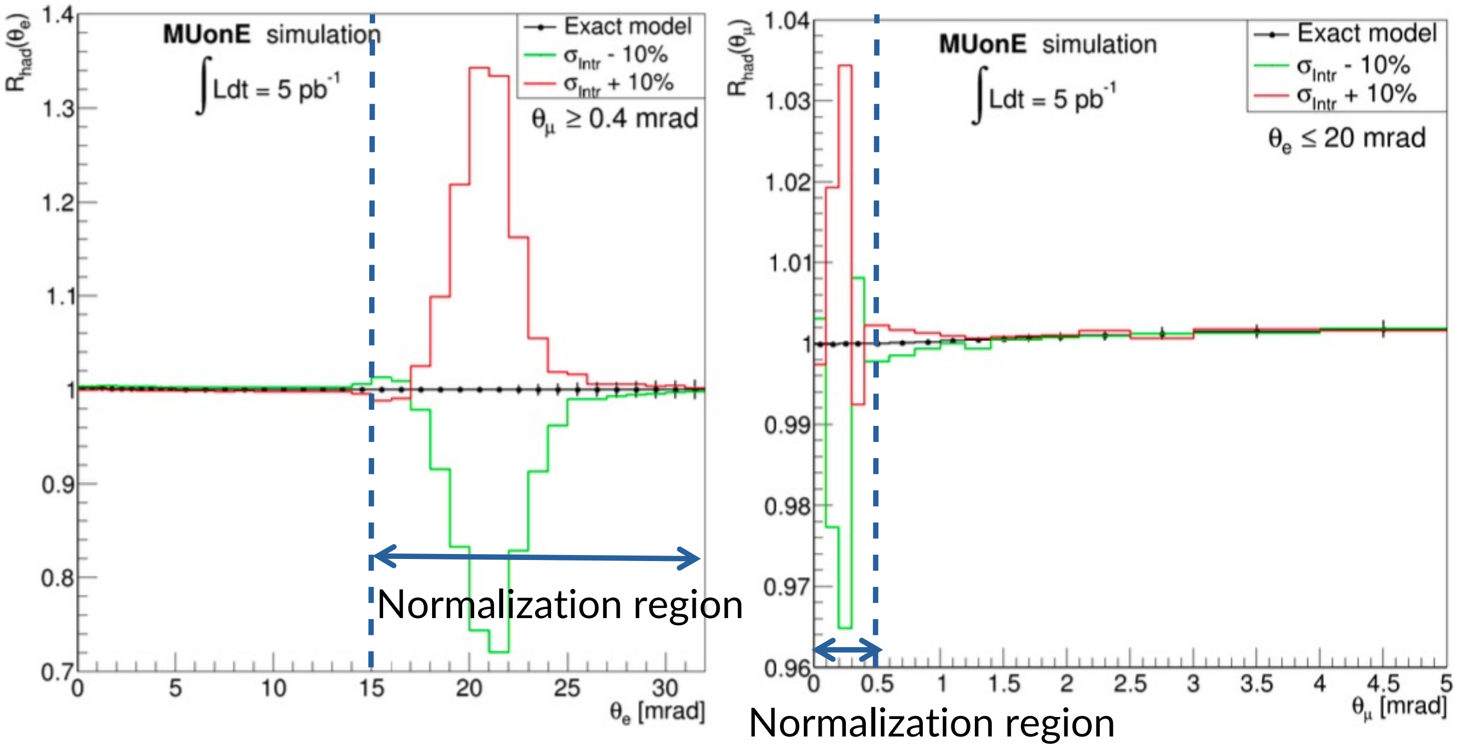




Systematic Effects

② Angular Intrinsic Resolution

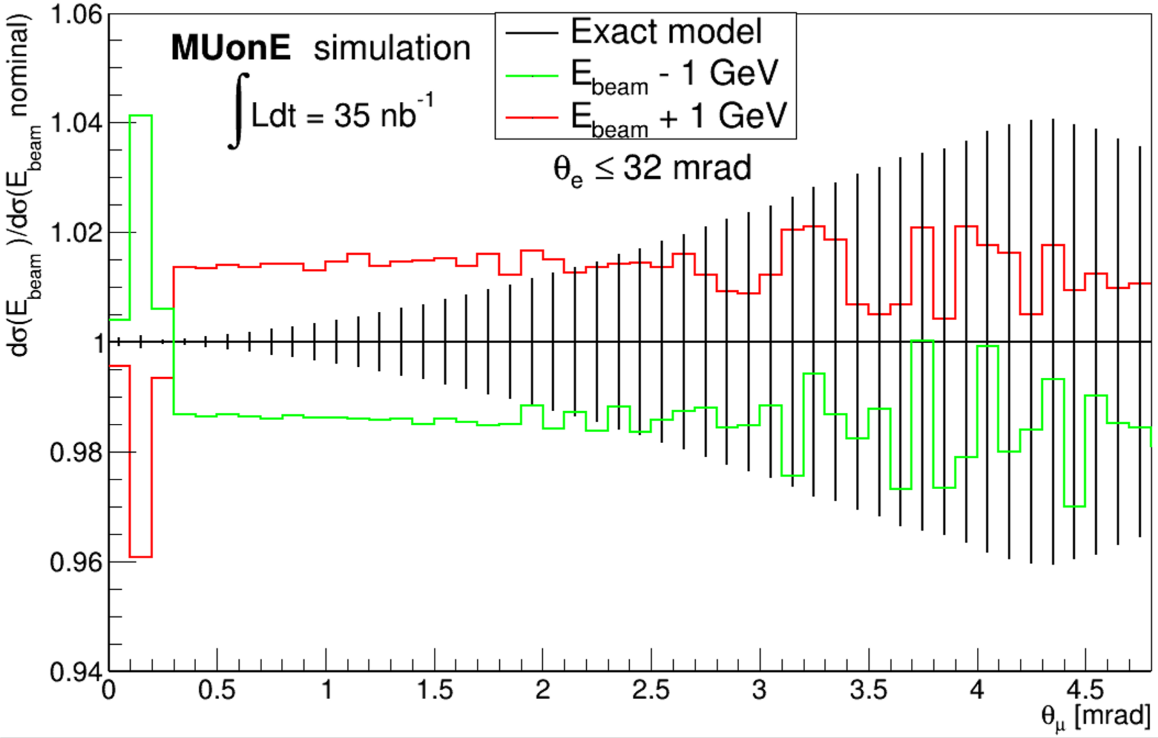
- 2S modules resolution (from beam test): 8-11μm
- An effect of a ±10% error on the angular intrinsic resolution
- $\theta_\mu > 0.4$ mrad ($\theta_e < 20$ mrad) gives better normalization region



Systematic Effects

③ Muon Beam Energy

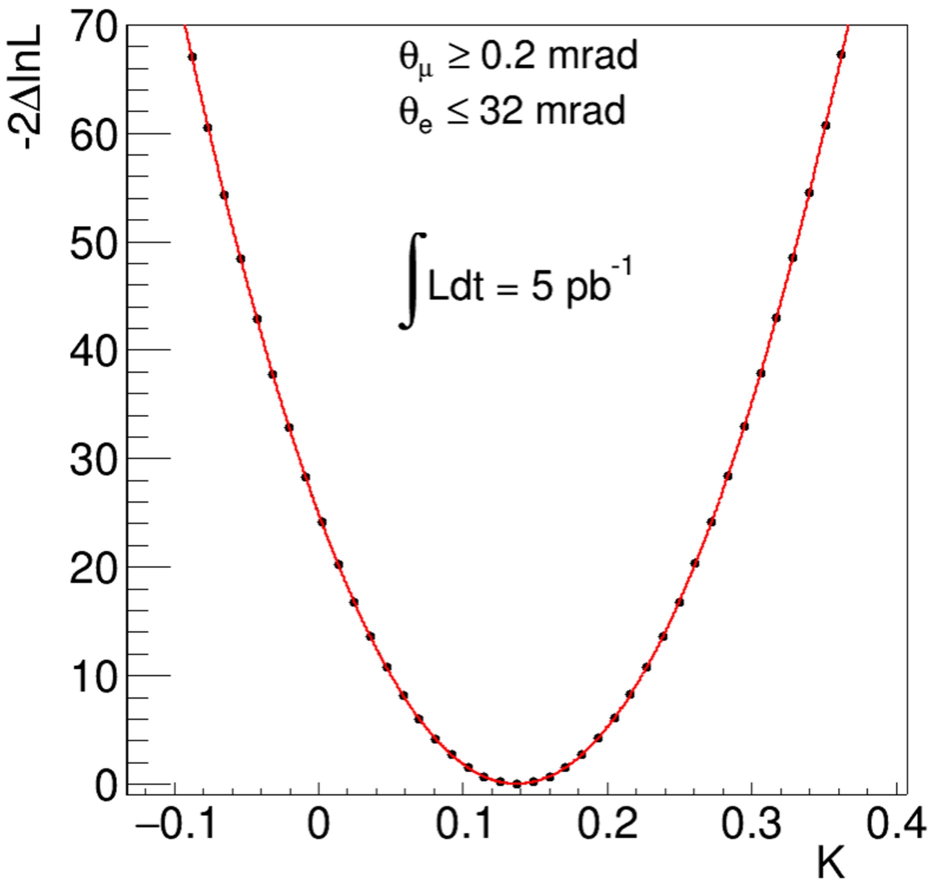
- Accelerator provides E_{beam} with O(1%) precision (~ 1 GeV) → goal of **10 ppm** in the differential cross section
- The effect can also be seen in a quick data taking (~hours) for calibration



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 $K = K_{best\_fit}$



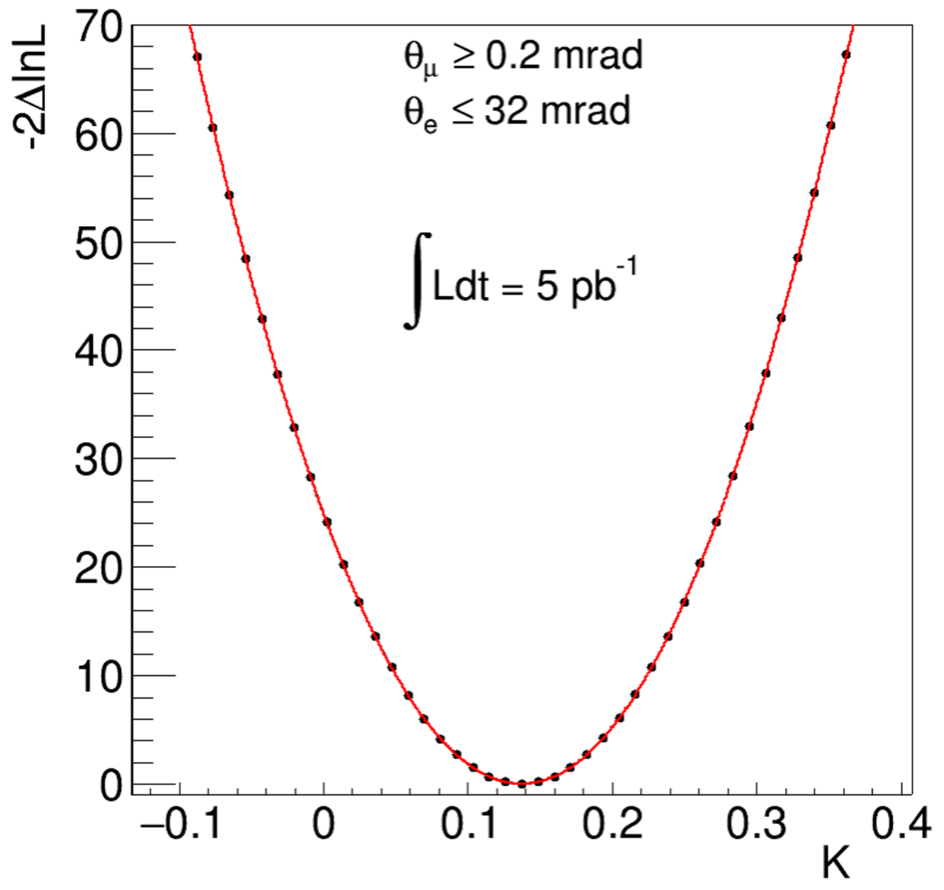
Systematic Effects

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 $\nu = -0.001 \pm 0.003$

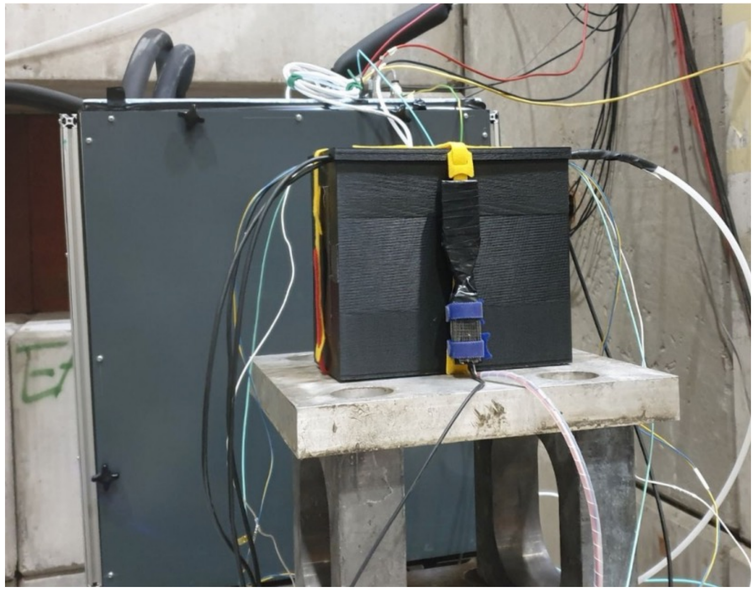
(Input shifts identified correctly)

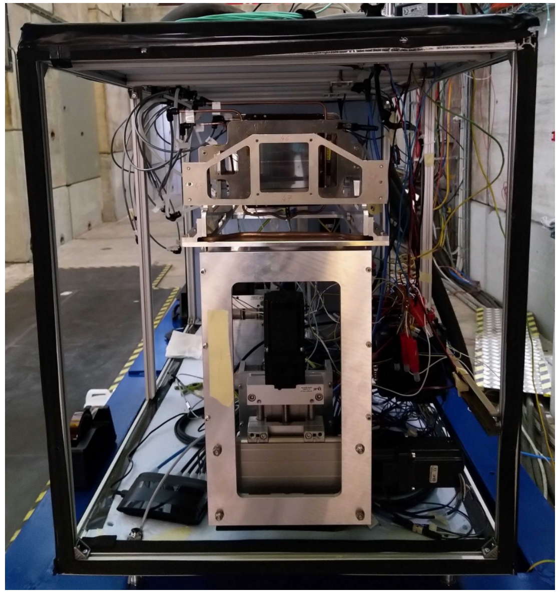


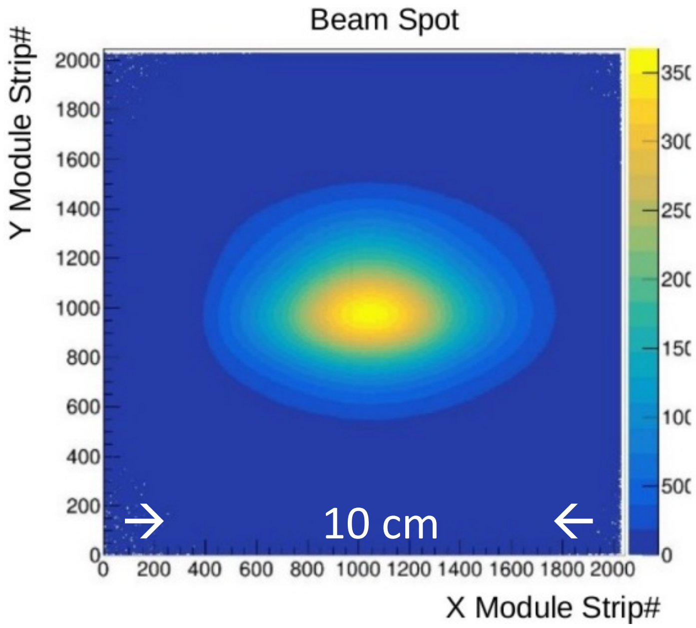
Test Runs

2021 & 2022

- Intense Beam Test activities with detector in real beam conditions





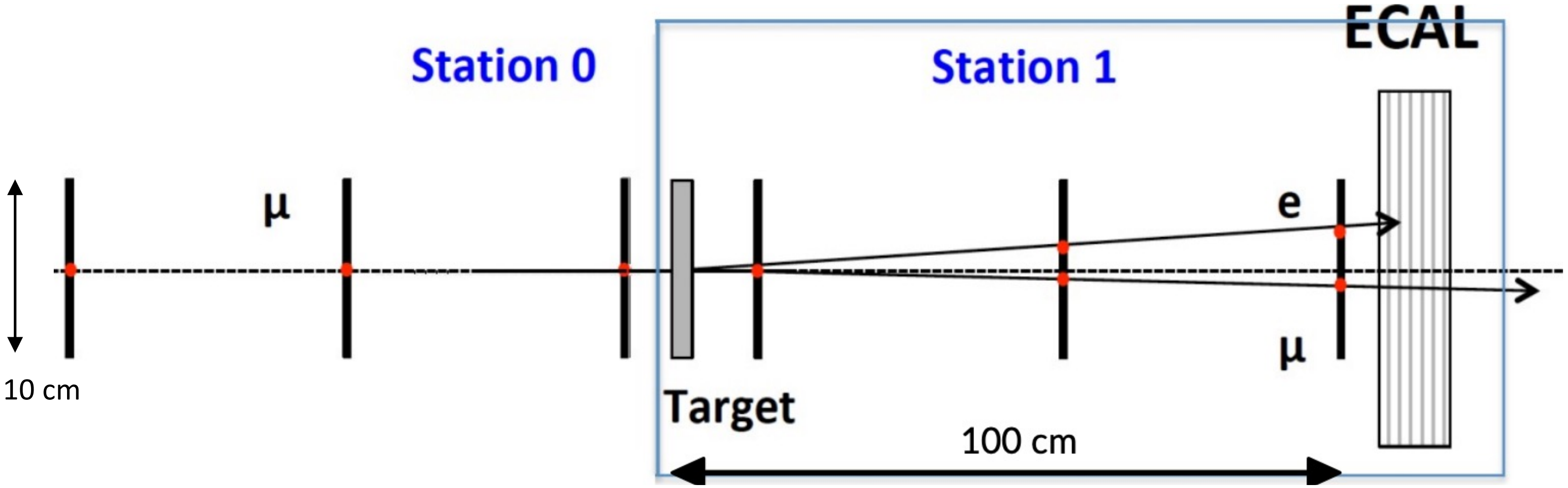


2S module firstly tested on Nov 2021

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

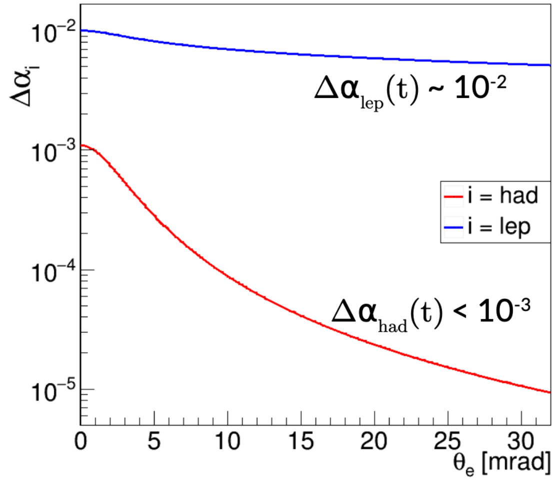
Test Run 2023

- 21 Aug – 17 Sep (ongoing now!)
- 2 stations (pre-tracker + target + tracker) + ECAL
- Expected luminosity: ~ 1pb^{-1}
  - ~10^{12} μ accumulated on target with ~2.5×10^{8} elastic events with $E_e > 1$ GeV

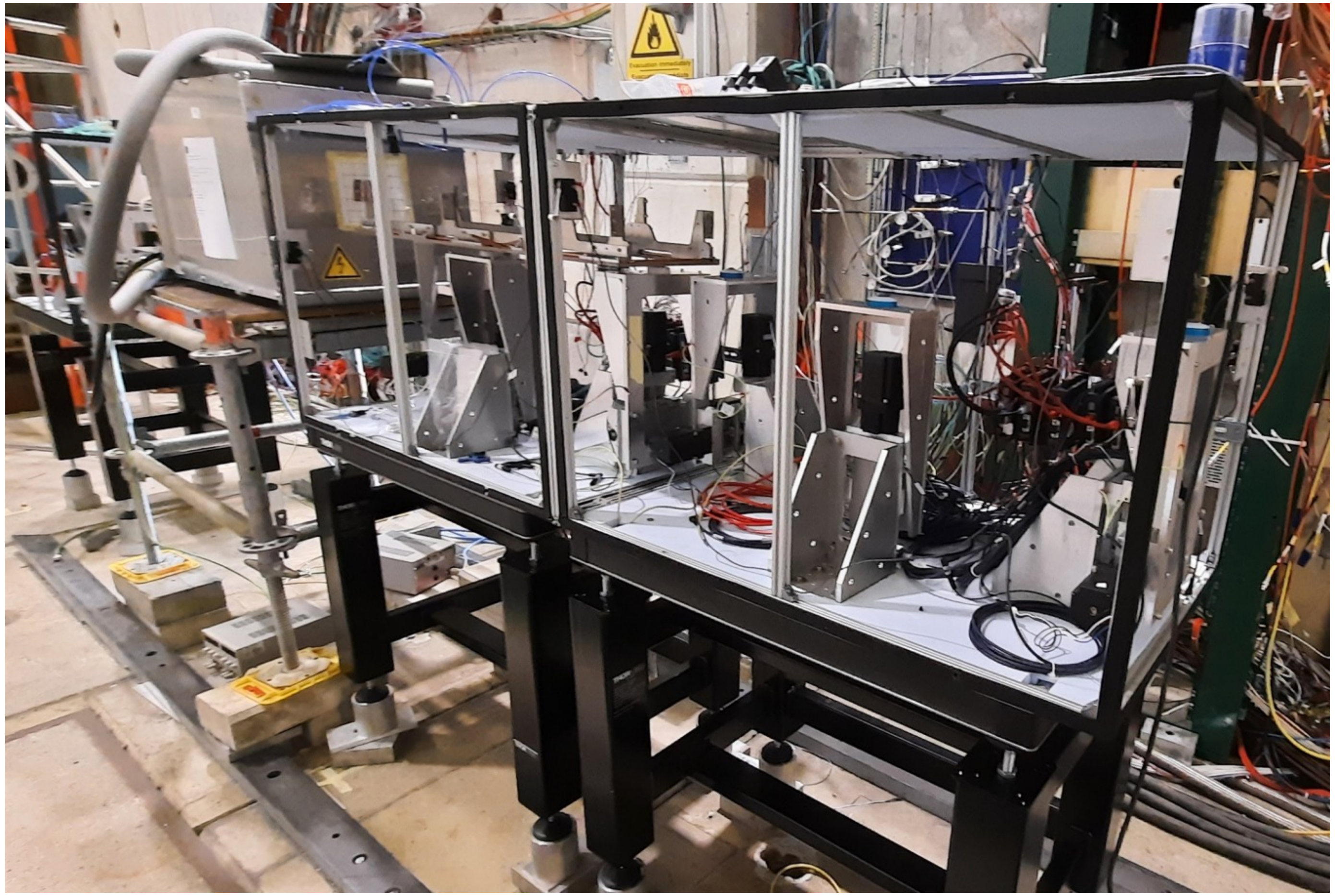


Test Run 2023

- 21 Aug – 17 Sep (ongoing now!)
- 2 stations (pre-tracker + target + tracker) + ECAL
- Expected luminosity: ~ $1 pb^{-1}$
  - ~10^{12} μ accumulated on target with ~2.5×10^{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!

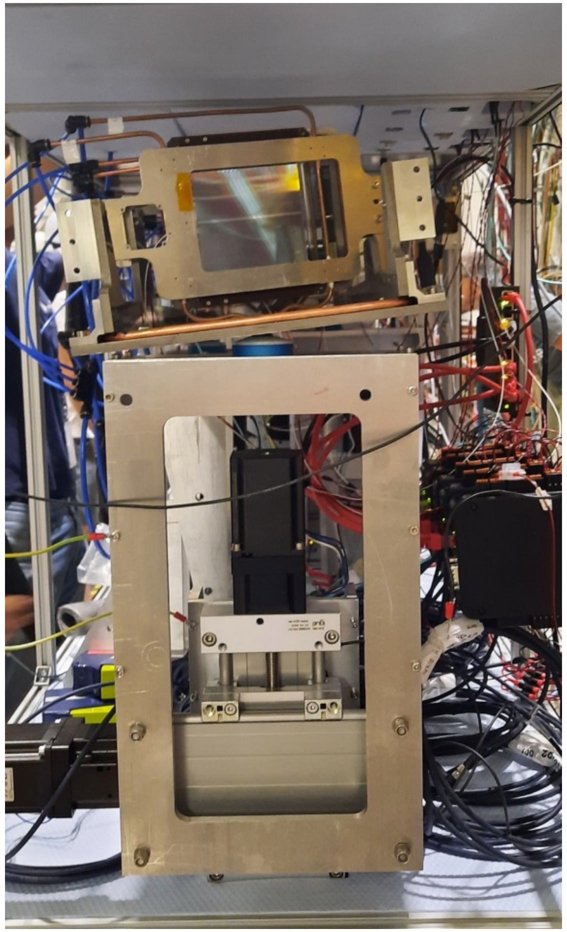


Test Run 2023

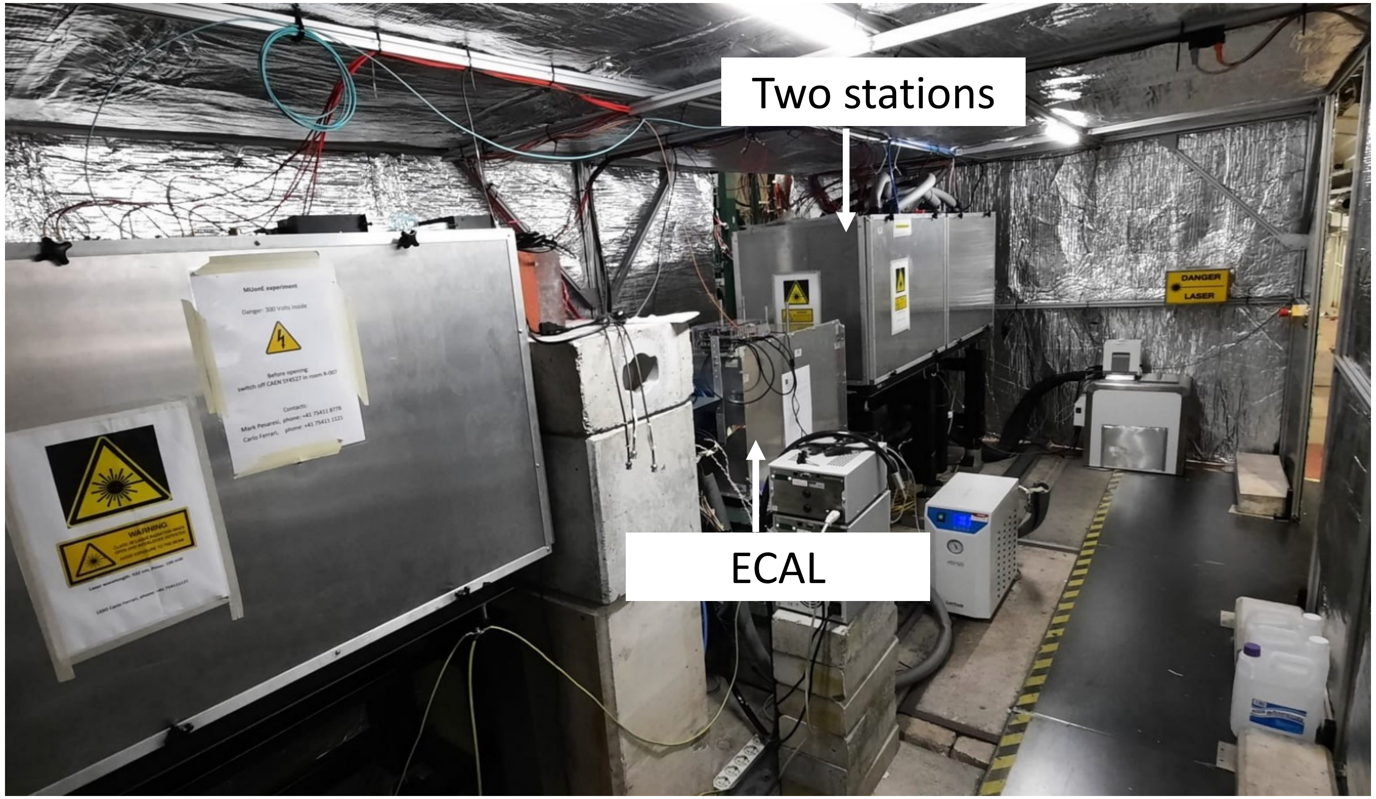


← Two stations

2S module →



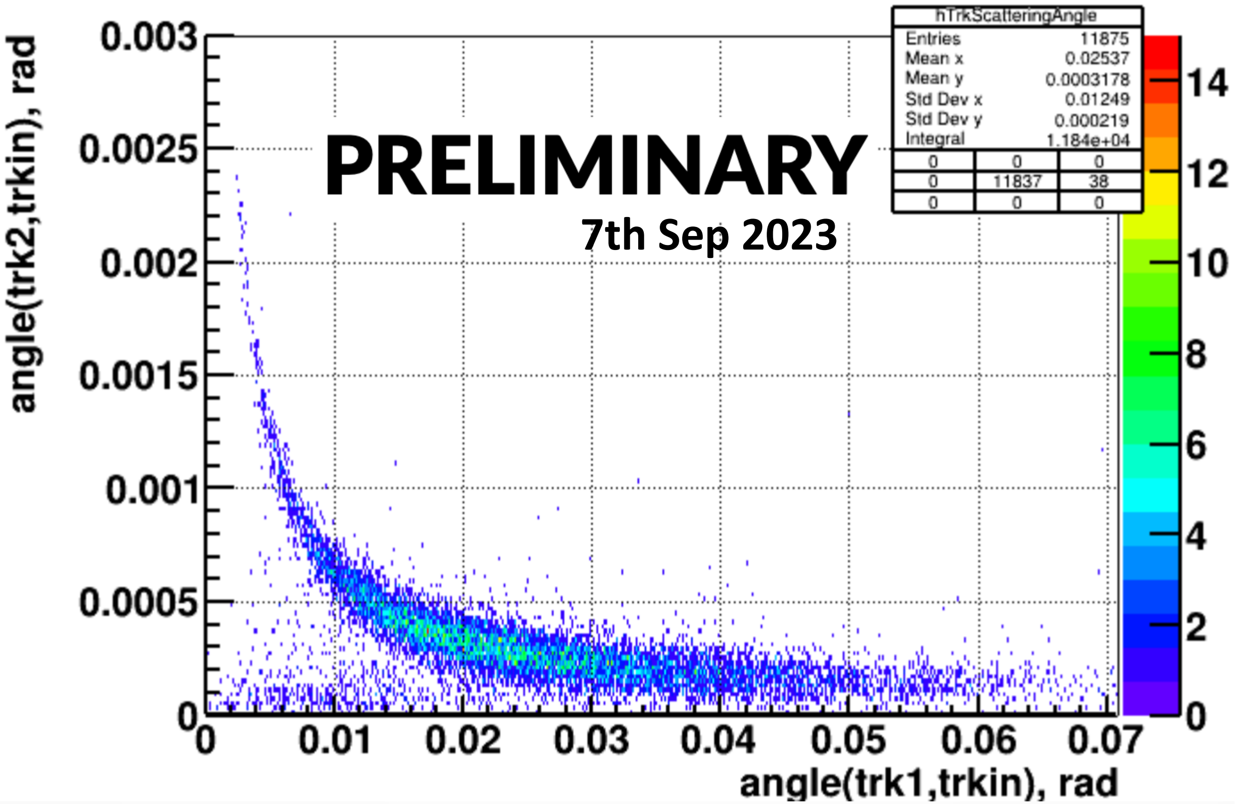
Test Run 2023



Test Run 2023

Preliminary result on scattering events!

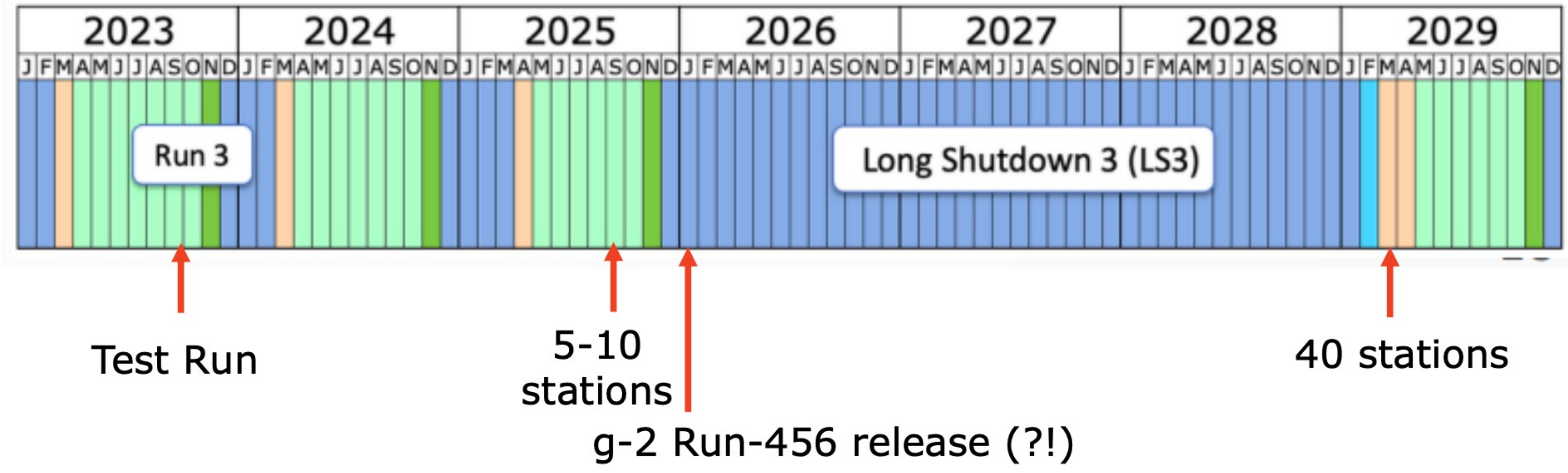
- Runs with a 3-cm target installed
- N single muons 2.9x108 in used sample (assuming no hit loss and overlap)
- One track in the 1st station + 2 tracked in the 2nd station
- Chi2/ndf track cut<5
- Zvtx selection applied after selecting two outgoing tracks within the target position



Current Status

Schedule

- TDR next year (2024)
- **The first physics run** before LHC Long Shutdown (2026 - 2028)
  - 5 – 10 stations; 2- 4 months data-taking; **a few % precision of a_μ^{HLO}**
- **Full run** with 40 stations after LS3 with ~0.3% precision (both sys and stat)



Current Status

The Collaboration

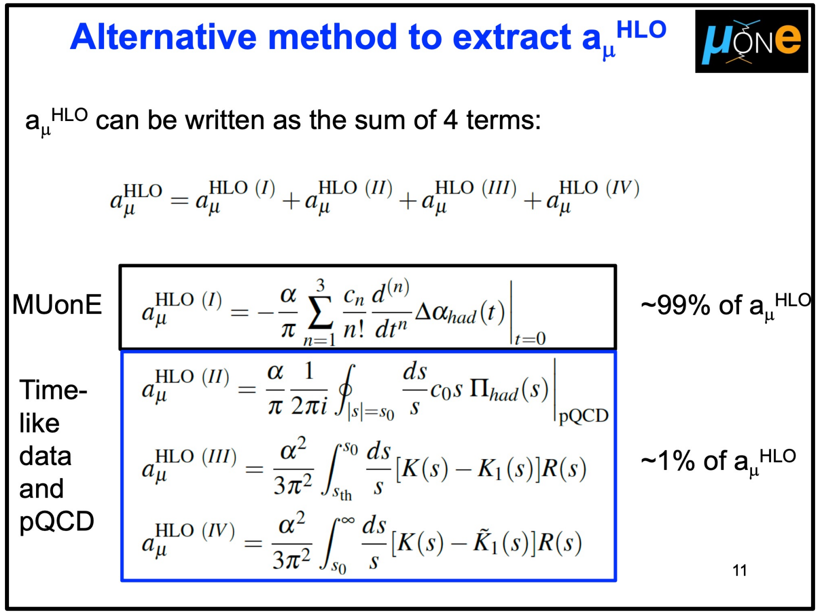
- 50+ people from over 9 countries. Collaboration is growing!

Liverpool (8+ people):

1) Data analysis
2) Simulation
3) Systematics
4) Mechanics
5) Beam Monitoring System (BMS)
6) Sensor dev after LS-3

Current Status

Open to New Ideas!


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}

11

Talk at Bern, 8th Sep by GV

- 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!

Summary

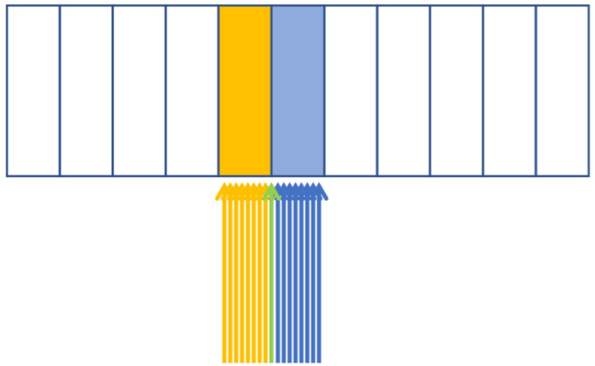
- Muon g-2 puzzles:
  - SM predictions ⇔ Experiments
  - e^+e^- data-driven method ⇔ Lattice method
  - Within data-driven method: ① Babar ⇔ KLOE ② CMD3 ⇔ all the previous data
- MUonE: a new approach to firmer $a_\mu^{\mathrm{HVP,LO}}$ via muon-electron scattering
  - A **independent determination of $\Delta\alpha_{\mathbf{had}}$** directly for the first time
  - Hardware & software developments with muon beam test runs ongoing
  - TDR next year (further info: https://web.infn.it/MUonE/)

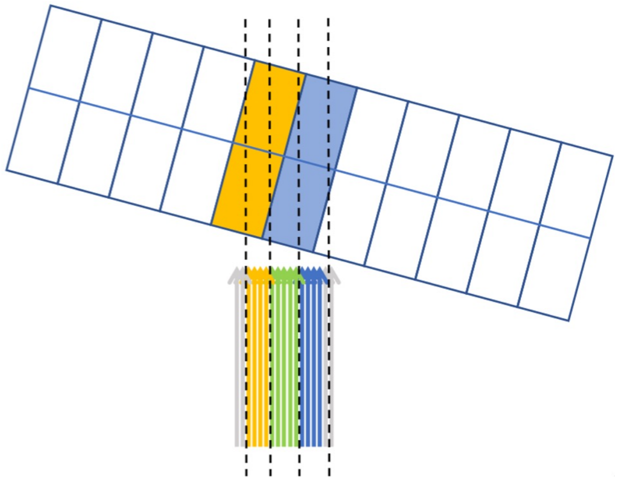
Backup

Improve the intrinsic resolution

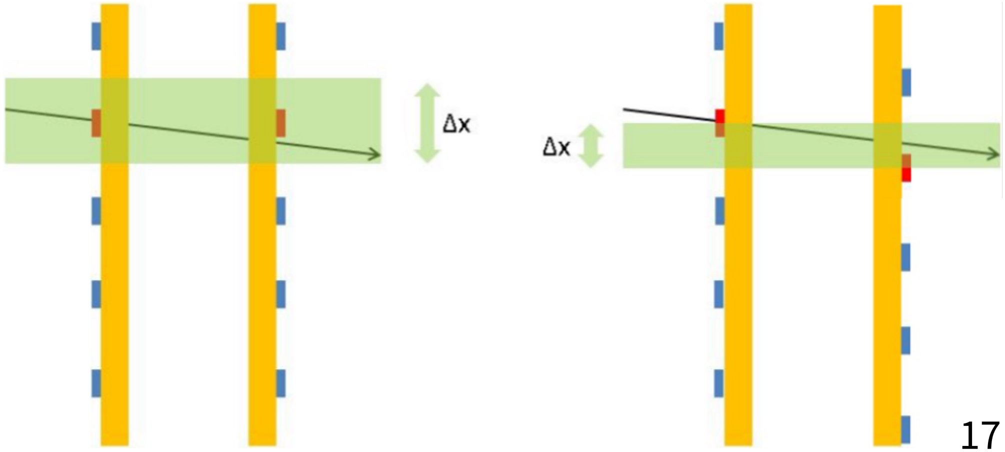
Tilt a 2S module around an axis parallel to the strip direction.

- Charge sharing:
energy deposition
of particles in the Silicon is
shared among adjacent strips.





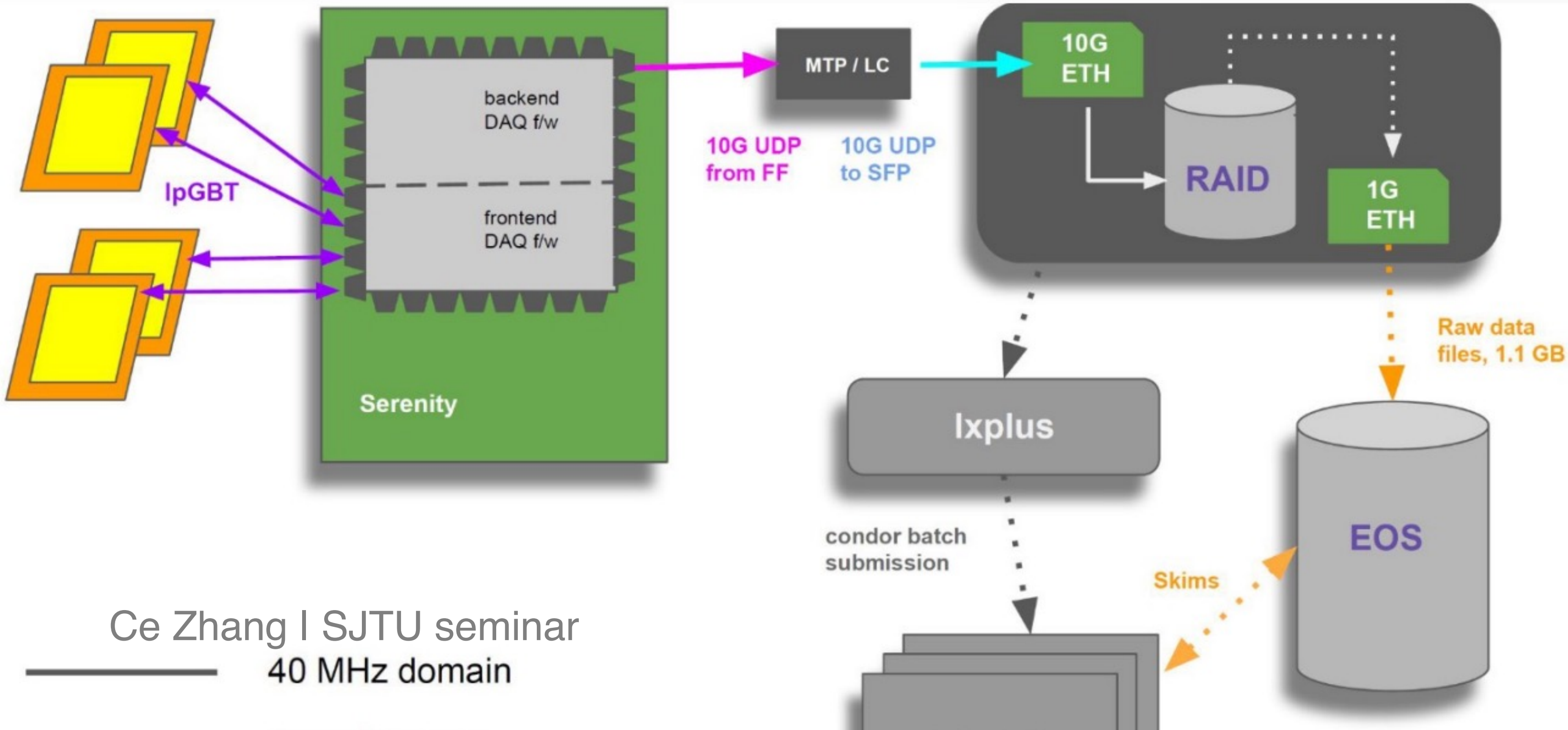
- Effective staggering:
tilting a 2S module by a small angle will provide two measurements
which are not redundant.
(i.e. 25 mrad tilt = ½pitch staggering)



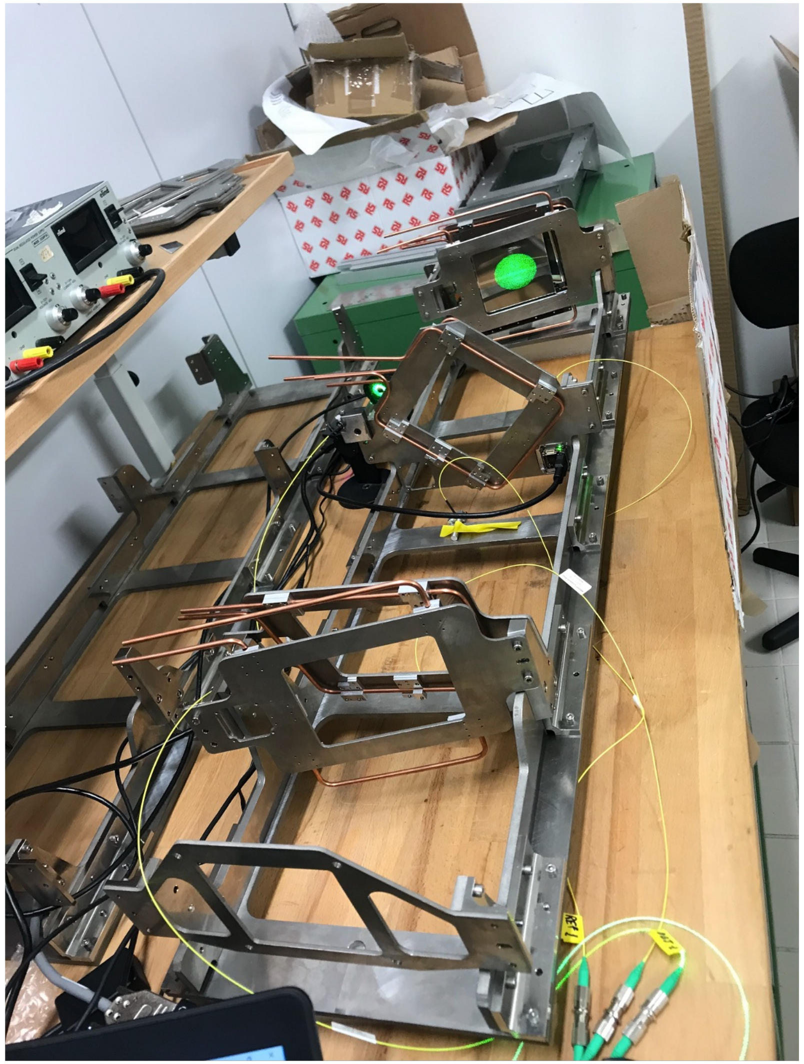
DAQ system

Frontend control and readout via Serenity board
(to be used in the CMS-Phase2 upgrade).

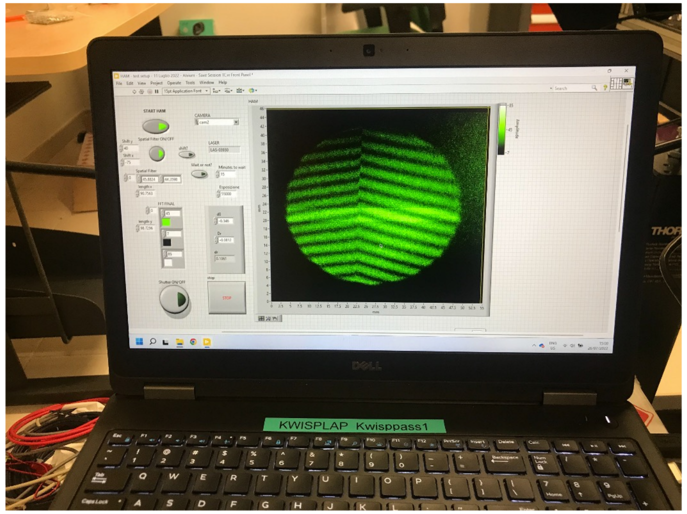
- Asynchronous beam: triggerless readout of the 2S modules @40MHz.
- Event aggregator on FPGA.
- Further data aggregation on the PC.
- Transmission to EOS into ~1GB files.



Laser holographic system

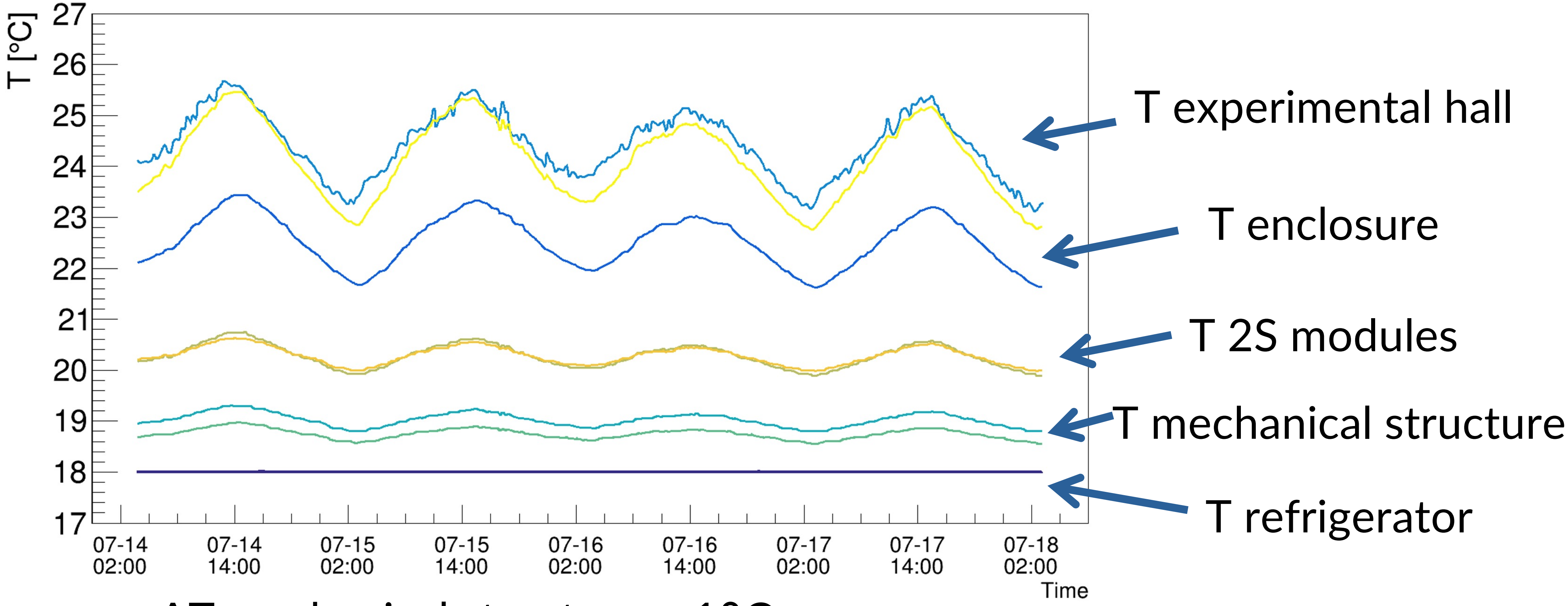


Initial state



- Compare holographic images of the same object at different times.
- Fringe pattern is related to deformations of the mechanical structure.
- Developed at INFN Trieste, tested in 2022 at CERN.

Thermal stability of the tracking station



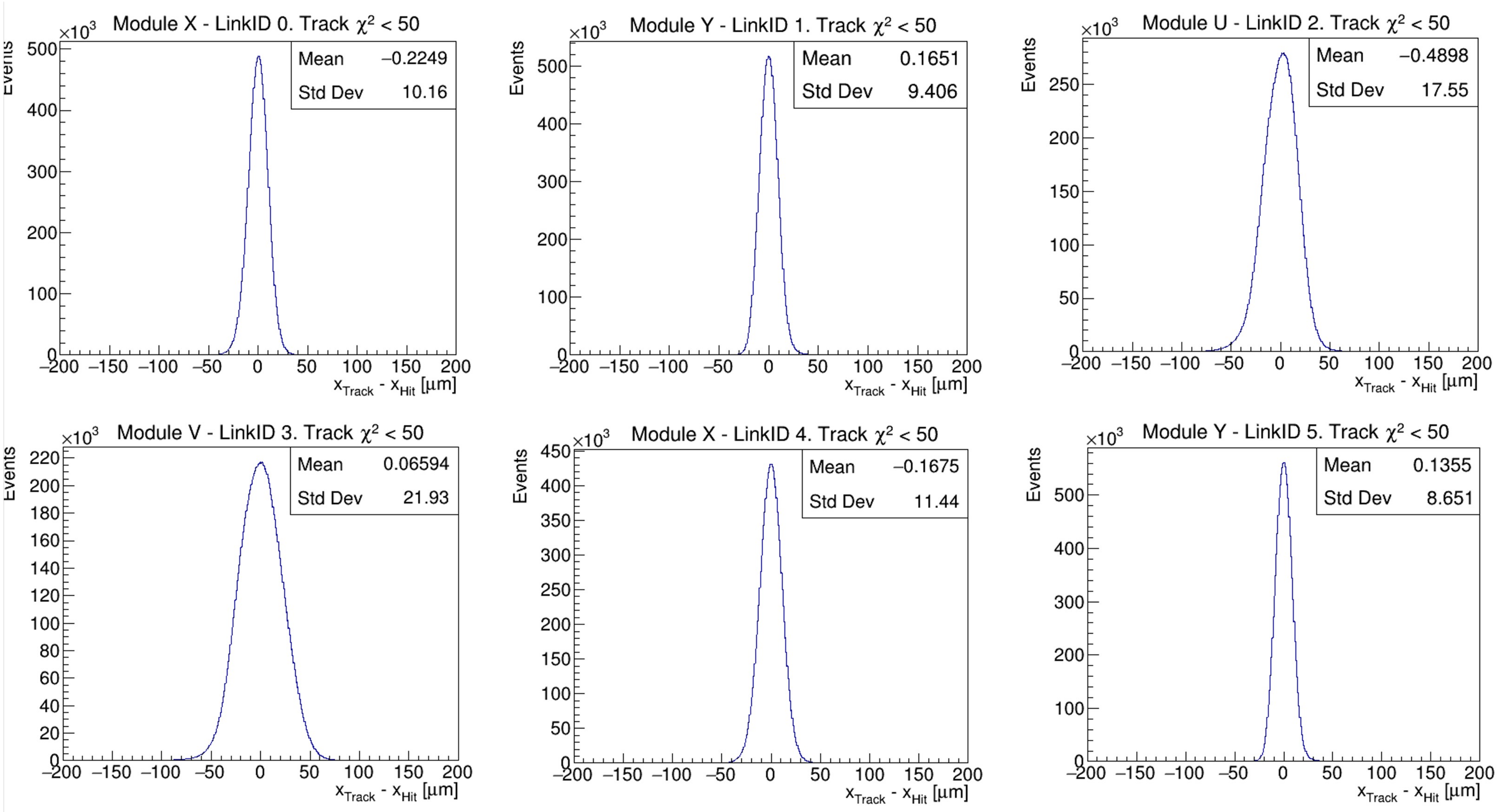
ΔT mechanical structure ~ 1°C

Day/night variations can be reduced by installing the apparatus in a controlled environment.

• TB 2022: Residuals

PRELIMINARY

$\sigma_{UV} \sim 2\sigma_{XY}$

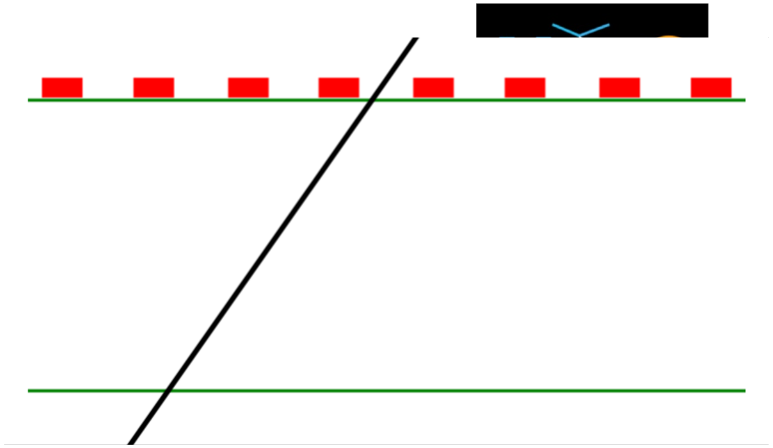


Tracker Reconstruction

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

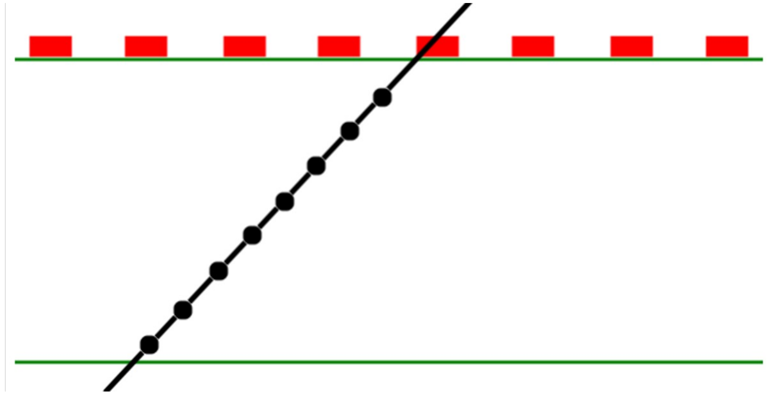
The digitization algorithm



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.

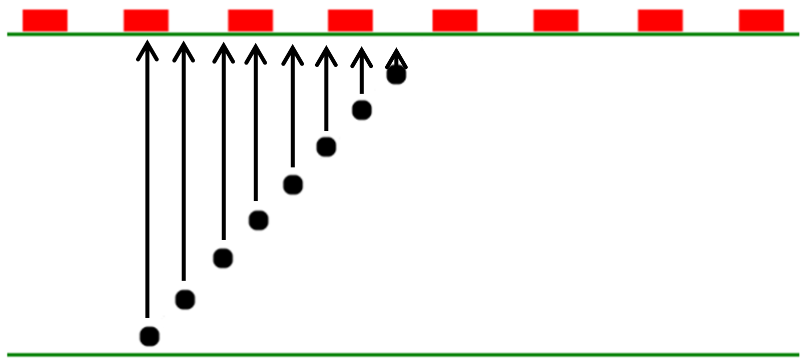


- The fraction of energy deposit is converted into a charge ($Q = E_{dep}/3.6$ eV).

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.



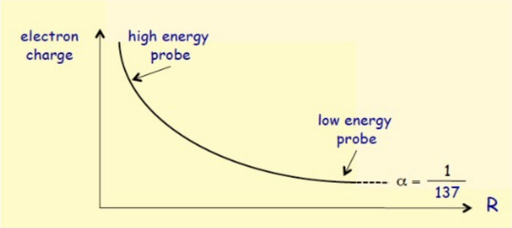
$$\sigma_{drift} \propto \sqrt{\text{drift distance}}$$

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.

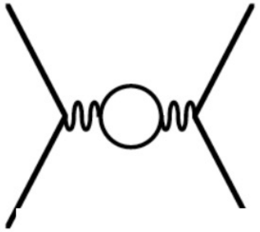
α running and the Vacuum Polarization

- Due to Vacuum Polarization effects $\alpha(q^2)$ is a running parameter depending on the 4-momentum transfer q^2

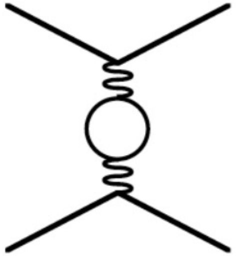


- The "Vacuum Polarization" function $\Pi(q^2)$ can be "absorbed" in a redefinition of an effective charge:

$$e^2 \to e^2(q^2) = \frac{e^2}{1+(\Pi(q^2)-\Pi(0))} \qquad \alpha(q^2) = \frac{\alpha(0)}{1-\Delta\alpha}; \quad \Delta\alpha = -\Re e\left(\Pi(q^2)-\Pi(0)\right)$$



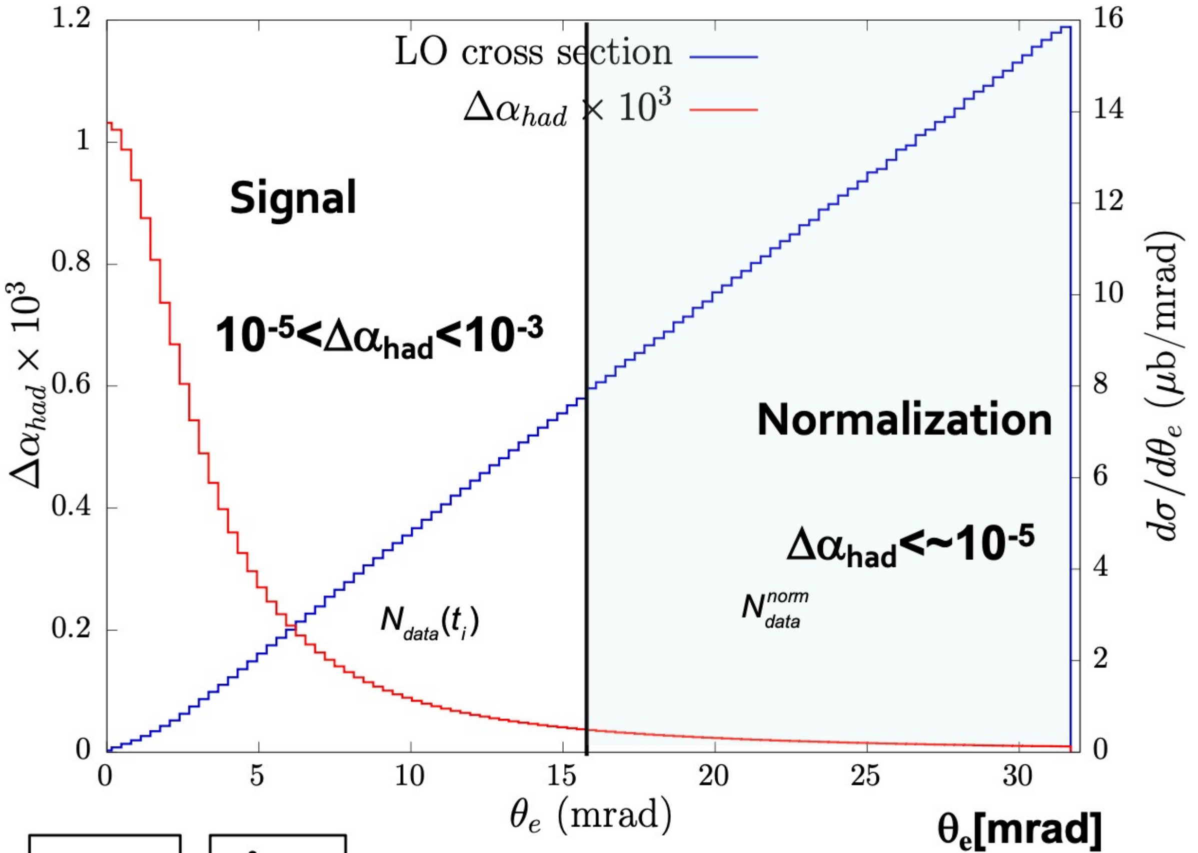
$$\Delta\alpha = \Delta\alpha_l + \Delta\alpha^{(5)}_{had} + \Delta\alpha_{top}$$



- Δa takes a contribution by non perturbative hadronic effects ($\Delta a^{(5)}_{had}$) which exibits a different behaviour in time-like and space-like region

- $\Delta\alpha^{(5)}_{had}$ at limits precision physics (EW fit) at M_Z!

MUonE : signal/normalization region



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

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}