# The muon magnetic anomaly: an update

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# Outline of the talk

The central topic of this talk is an attempt to answer the question:

> *What can be learned about the* **limits of the standard model** *and* **new physics** *through precise measurements of the magnetic properties of (light) leptons?*

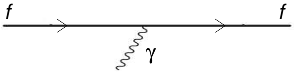
Specifically, we will discuss:

1. fundamental implications of the muon (and electron) magnetic anomaly, $a_\mu$(and $a_e$): hadronic vacuum polarization (HVP);
2. principles of the muon $g-2$ ($a_\mu$) measurement, and Fermilab E989 results to date;
3. the shifting experimental and theoretical landscape of HVP;
4. the path forward.

# Lepton magnetic dipole moments, and the associated anomaly

Our story begins with Dirac's result for a point particle g-factor, defined by $\vec{\mu} = g\frac{e}{2m}\vec{S}$, i.e., $\boxed{g \equiv 2}$, precisely. Quantum fluctuations give rise to the anomalous magnetic moments:

Leading (Dirac) term: g = 2

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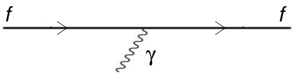



; higher (loop) terms $\Rightarrow$ $\boxed{a = \frac{g-2}{2} \neq 0}$.

For example, the electron magnetic anomaly is **extremely well reproduced by QED**:

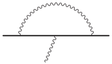
$$a_e = \begin{cases} 0.001\,159\,652\,181\,61\,(23) & [\text{SM}, \ (\alpha/\pi)^5 \text{ order}]^* \\ 0.001\,159\,652\,181\,28\,(18) & [\text{experiment}, \ 0.16\,\text{ppb}]^\dagger \end{cases} \quad ; \ \text{agreement:} \ \sim 1.1\sigma$$

insensitive to massive particle loops ($\Rightarrow$ $a_e$ provides an alternative measurement of $\alpha_{em}$)
We therefore focus on $\boldsymbol{a_\mu}$ as it is much more sensitive than $a_e$ to massive loops.

* Aoyama, Kinoshita & Nio, Atoms **7** (2019) 1.

† Mohr et al., CODATA 2018, posted online 20 May 2019, to be published.

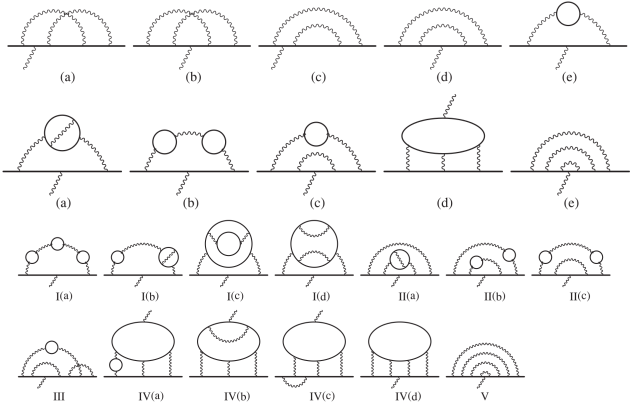
# Lepton magnetic anomaly — representative classes of QED terms in $a_{e,\mu}$:

$\mathcal{O}(\alpha/\pi)$:  $\left[ = \frac{\alpha}{2\pi} \simeq \frac{1}{860} \simeq 0.00116, \text{ Schwinger (1948)} \right]$

$\mathcal{O}(\alpha/\pi)^2$:

$\mathcal{O}(\alpha/\pi)^3$:

$\mathcal{O}(\alpha/\pi)^4$:




Loops, legs:

——— $e, \mu, \tau$

∿∿∿ $\gamma$

T. Aoyama et al., PTEP **2012**, 01A107

$\Rightarrow$ With increasing precision, $a_\ell$ probes ever deeper into the complex structure of vacuum!

# Muon magnetic anomaly, $a_\mu = \frac{1}{2}(g_\mu - 2)$

Analogous to $a_e$, but much more sensitive to loops with massive particles:

$\boxed{\text{sensitivity} \propto (m_\mu/m_e)^2 \approx 43,000}$

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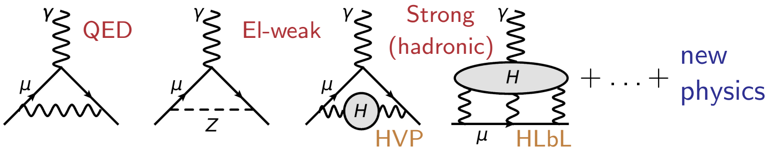
Leading order processes contributing to $a_\mu$:



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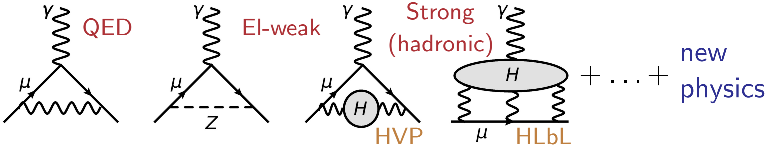


Current status of SM calculations of $a_\mu$:

$$\frac{\Delta a_\mu^{SM}}{a_\mu^{SM}} = 369 \times 10^{-9} \quad (369 \text{ ppb})$$

T. Aoyama, et al., Phys. Rep. **887** (2020) 1, and ref's. therein, [Muon $g-2$ Theory Initiative White Paper]

| $a_\mu$ term | value ($\times 10^{-11}$) | uncert. |
|---|---|---|
| QED | 116,584,718.931 | 0.104 |
| El-weak | 153.6 | 1.0 |
| HVP | 6 845 | 40 |
| HLbL | 92 | 18 |
| Total SM | 116,591,810 | 43 |

$\Rightarrow$ $a_\mu$ is a superb probe of the vacuum, i.e., of new physics if it exists.

HVP . . . hadronic vacuum polarization; HLbL . . . hadronic light by light scattering.

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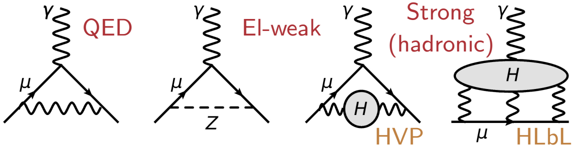


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| | |
|---|---|
| HVP-LO | 6931(40) |
| HVP-NLO | −98.3(7) |
| HVP-NNLO | 12.4(1) |

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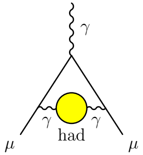
# Calculating HVP-LO in the standard model

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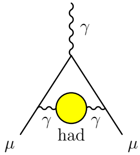


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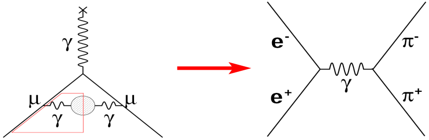
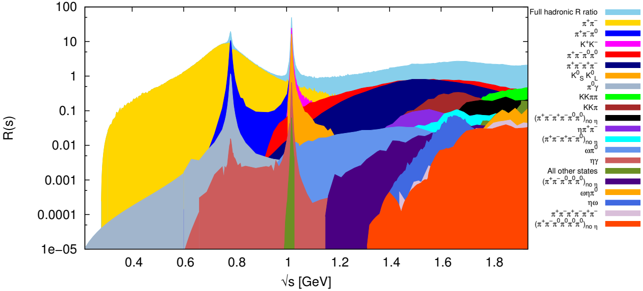



- use dispersion relations: optical theorem and analyticity,
- integral over QCD kernel $K(s)$ heavily weights low $\sqrt{s}$:

$$a_\mu^{\text{HVP-LO}} = \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\text{had}}(s)\,;$$

$$K(s) = \int_0^1 \mathrm{d}x \frac{x^2(1-x)}{x^2 + (1-x)(s/m_\mu^2)}\,.$$

It is mostly $e^+e^- \to \pi^+\pi^-$ / $\pi^+\pi^-\pi^0$ / $\pi^0\gamma$; diverse measurements, in many different labs.



# Muon $g-2$: prior status, and Fermilab E989 goals

Exp. value dominated by results of BNL E821:

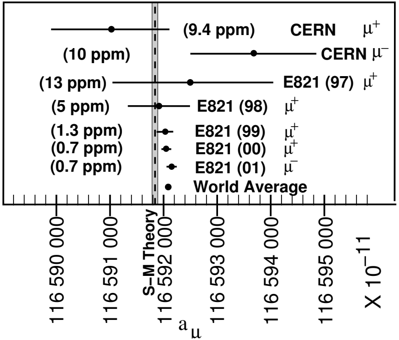
$$a_\mu^{\rm exp} = 116\,592\,089\,(54)_{\rm stat}\,(33)_{\rm syst} \times 10^{-11}\text{, or}$$

$$a_\mu^{\rm exp} = 116\,592\,089\,(63)_{\rm tot} \times 10^{-11},\ \text{i.e., a}$$

0.54 ppm result : statistical uncertainty dominates .

[SM precision is comparable, with a persistent $\sim$ 3.5$\sigma$ discrepancy.]

How to improve this result?



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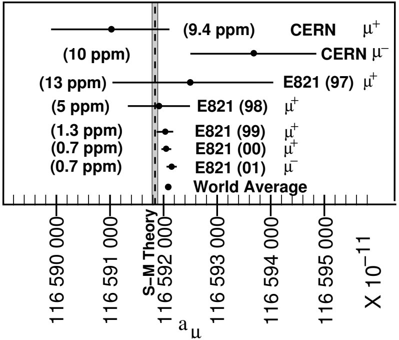


How to improve this result?

- Use the BNL ring in a more intense beam at Fermilab: 21 × statistics of BNL E821, and
- improve key systematics through use of new/improved instruments & techniques.

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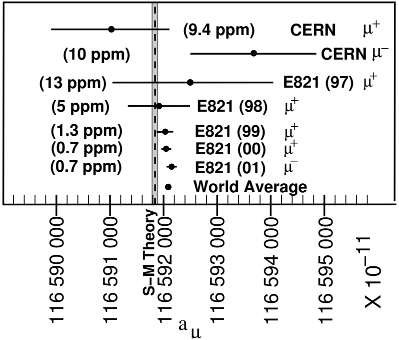


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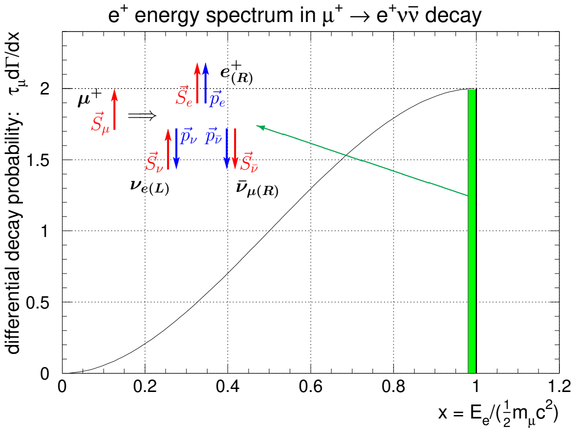
Goal for Fermilab E989:

- obtain overall 4$\times$ reduction in uncertainty, i.e., 0.14 ppm (w. balanced stat/syst unc.).

# Measurement of $a_\mu$ exploits properties of $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay

Maximal parity violation in the weak interaction forces momentum $\vec{p}$ of the highest, near-endpoint energy $e^+$ to align with muon spin $\vec{S}$:



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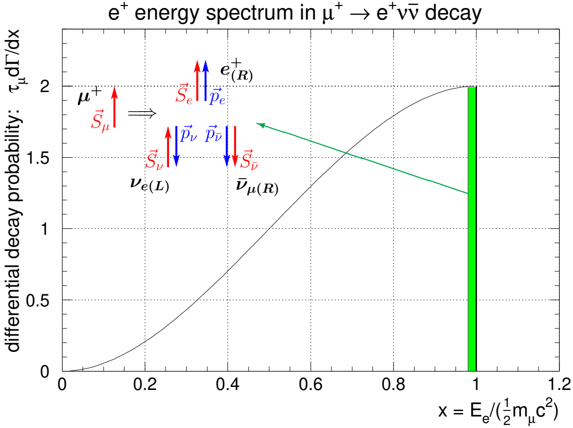
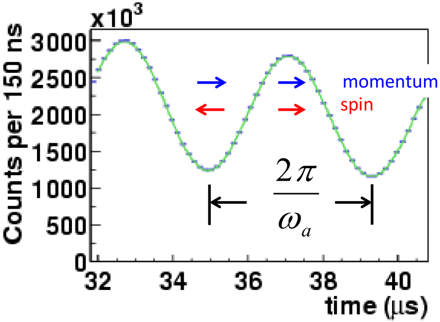



Spins of a polarized beam of muons precess in external magnetic field. An observer will note oscillations between appearance and absence of high energy positrons, as the muons decay.




Rate of detected $e^+$'s above a (high) energy threshold.

# $\omega_a$ from correlation of high-$\vec{p}_e$ with $\vec{S}_\mu$ in a storage ring

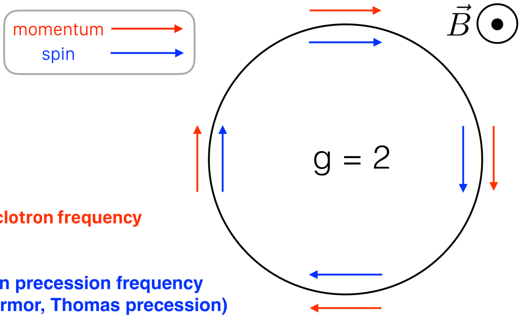
- Inject polarized muon beam (from pion decay) into ring
- Measure **difference** between spin precession and cyclotron frequencies

$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}$$

**cyclotron frequency**

**spin precession frequency (Larmor, Thomas precession)**




- If g = 2, difference of spin precession and cyclotron frequencies is zero

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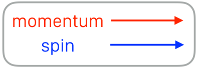
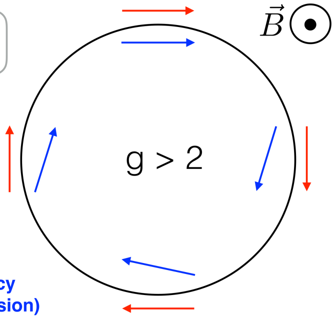



$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

**cyclotron frequency**

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}\left(1+\gamma a_\mu\right)$$

**spin precession frequency (Larmor, Thomas precession)**

0 for γ = 29.3 (p = 3.1 GeV)

$$\vec{\omega}_a \equiv \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{m}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)} \frac{\vec{\beta}\times\vec{E}}{c}\right]$$

E-field vertical focusing allowed at p = 3.1 GeV (higher-order $a_\mu$ contribution cancelled)

# Reasons why the storage ring method works to sub-ppm level in $a_\mu$

A. Muons emitted in pion decay are highly polarized ($\sim$97%). The $a_\mu$ signal would be absent with an unpolarized muon ensemble in a SR.

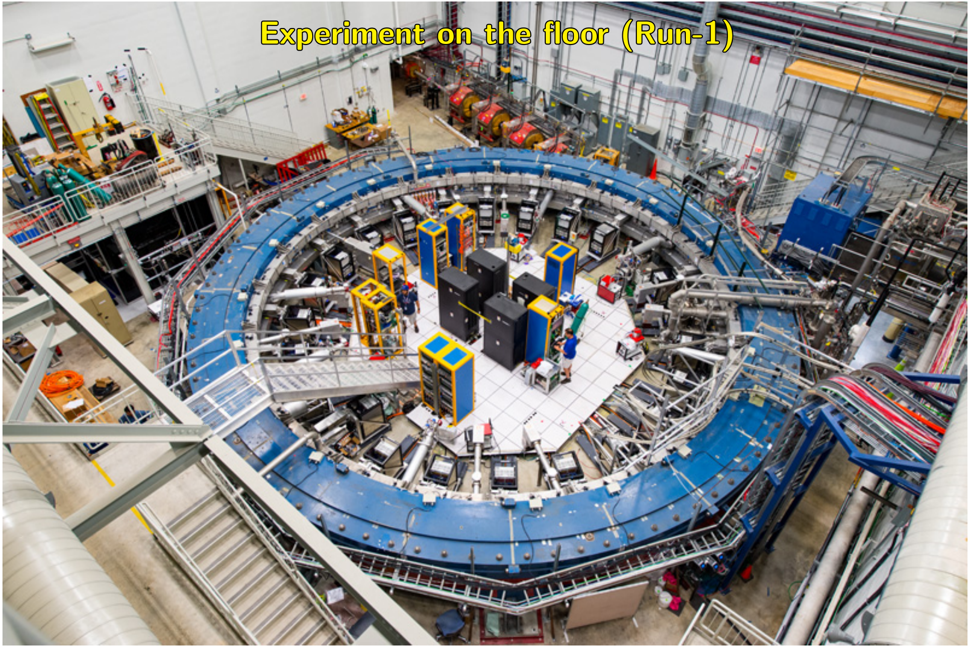
B. The anomalous frequency $\omega_a$ is proportional to $g-2$. This gives a factor of $\sim 860\times$ more sensitivity than decay at rest which measures $\omega_S$, i.e., $g$.

C. At the "magic" momentum, $p_\mu \simeq 3.1\,\text{GeV}$, $\vec{E}$, the electrostatic focusing field needed to keep the beam vertically stable **does not perturb** $\omega_S$, the spin precession frequency, i.e., leaves $\omega_a$ **unaffected**.

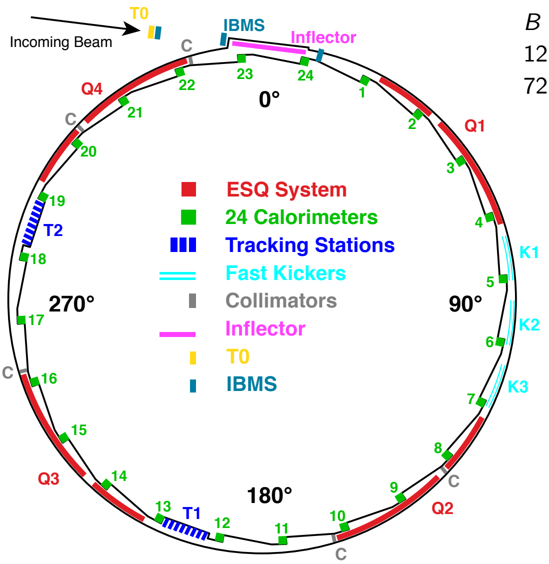
D. For the **most energetic** decay positrons, with $p_e \simeq p_{e,\text{max}}$, the $(V-A)$ nature of the weak interaction strongly aligns $\vec{p}_e$ with $\vec{S}_\mu$, giving a robust signal of the muon $\vec{S}_\mu$ precession w.r.t. the known $\vec{p}_\mu$.

The confluence of these effects is nothing short of miraculous.

# Experiment on the floor (Run-1)

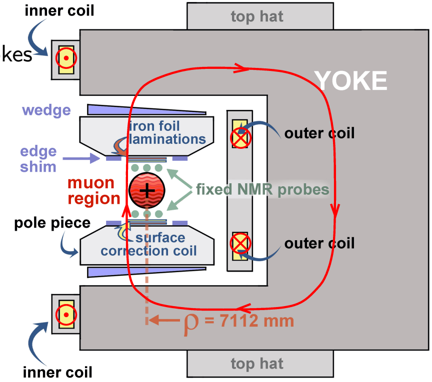


# Muon $g-2$ apparatus overview




## Superconducting storage ring

$B \simeq 1.45\,\mathrm{T}$
12 C-shaped yokes
72 poles




864 wedges: angle−quadrupole (QP)
24 iron top hats: change effective $\mu$
edge shims: QP, sextupole (SP)
8000 surface iron foils: change effective $\mu$ locally
surface coils: add avg. field moments (QP, SP, 360°)

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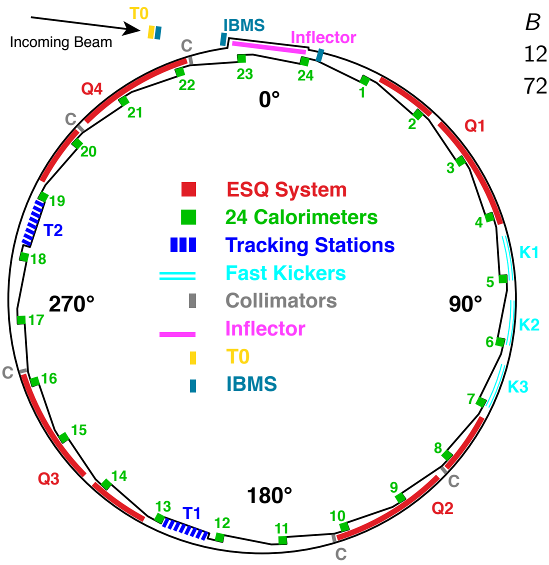


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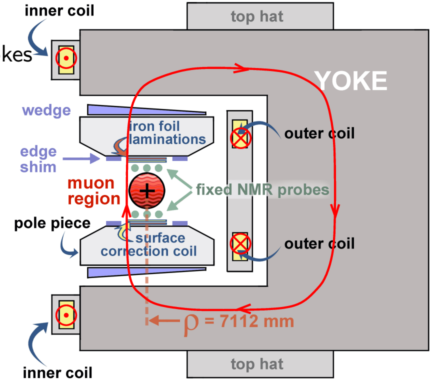
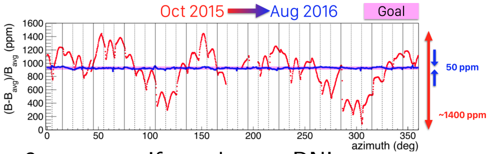
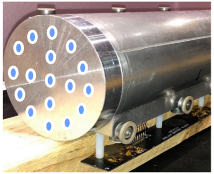


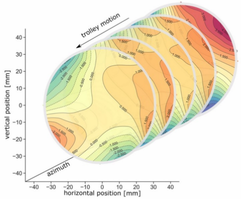




3× more uniform than at BNL

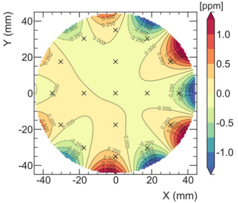
- In-vacuum NMR trolley **maps field every ~3 days**



17 petroleum jelly NMR probes



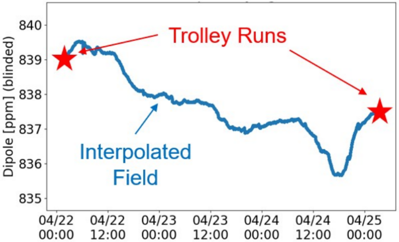

2D field maps (~8000 points)



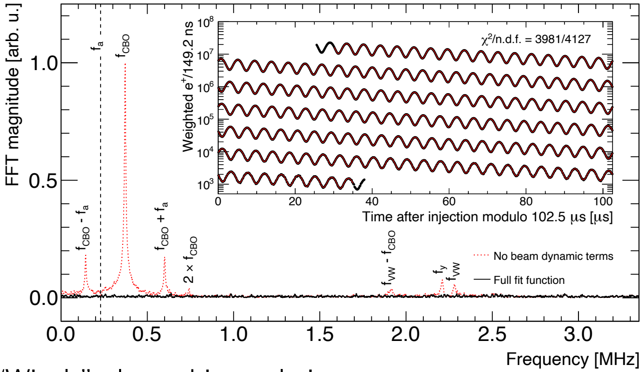

Azimuthally-Averaged **Variation < 1 ppm**

- **378 fixed probes** monitor field during muon storage at 72 locations

Fixed probes above/below muon storage region

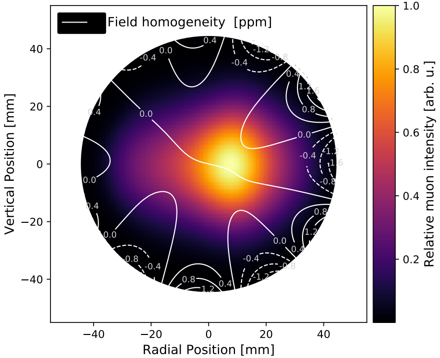


# E989: experimental inputs to muon $g - 2$ determination




"Wiggle" plot and its analysis:

- $f_a$ . . . anomalous precession;
- $f_{\mathrm{CBO}}$ . . . coherent betatron oscillations;
- $f_{\mathrm{VW}}$ . . . vertical waist;
- $f_y$ . . . vertical betatron oscillations.




Magnetic field map (Run-3b) averaged over the ring circumference, and weighted by the stored muon beam intensity.

# Determining $a_\mu$ in FNAL E989

$$a_\mu = \frac{\omega_a}{\langle\tilde{\omega}'_p(T_r)\rangle} \cdot \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

**Measured in the experiment:**

- $\omega_a$: the muon anomalous spin precession frequency,
- $\langle\tilde{\omega}'_p(T_r)\rangle$: precession frequency of protons in water sample mapping the field and weighted by the muon distribution.

Goal (ppb): $140 = 100(\text{stat}) \oplus 100(\text{syst})$

**External inputs (total $< 25$ ppb):**

- $\langle\tilde{\omega}'_p(T_r)\rangle$: proton Larmor prec. freq. in a spherical $H_2O$ sample; $T$ dependence known to $< 1$ ppb/°C; Metrologia **13** (1977) 179, Metrologia **51** (2014) 54, Metrologia **20** (1984) 81
- $\frac{\mu'_p(T_r)}{\mu_e(H)}$: measured to 10.5 ppb at $T = 34.7$°C, Metrologia **13** (1977) 179.
- $\frac{\mu_e(H)}{\mu_e}$: bound-state QED (exact); Rev. Mod. Phys. **88** (2016) 035009.
- $\frac{m_\mu}{m_e}$: known to 22 ppb from muonium hyperfine splitting, PRL **88** (1999) 711.
- $\frac{g_e}{2}$: measured to 0.28 ppt, Phys. Rev. A **83** (2011) 052122.

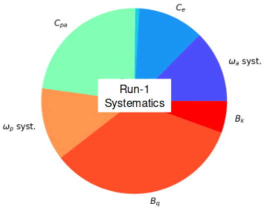
**E-field & Up/Down motion: Spin precesses slower than in basic equation**

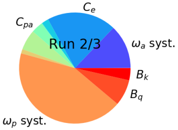
**Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses**

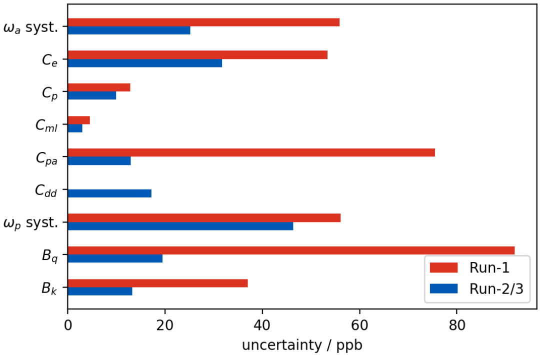
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\,\frac{1 + \overbrace{C_e + C_p}^{} + \overbrace{C_{pa} + C_{dd} + C_{ml}}^{}}{1 + \underbrace{B_k + B_q}_{}}$$

**Measured Values**

**Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,**



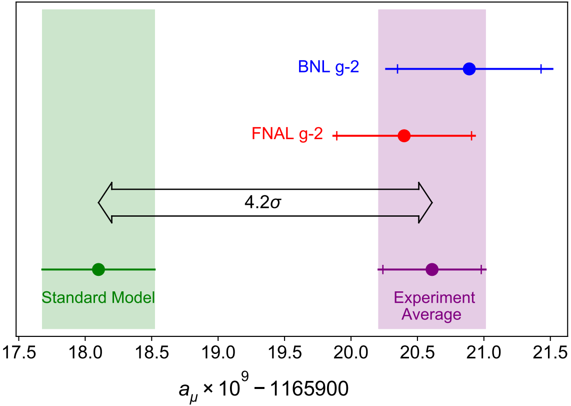




| [ppb] | Run-1 | Run-2/3 | Ratio |
|---|---|---|---|
| stat. | 434 | 201 | 2.2 |
| syst. | 157 | 70 | 2.2 |

$\sim$ equal improvement; still **statistically dominated**

**Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!**

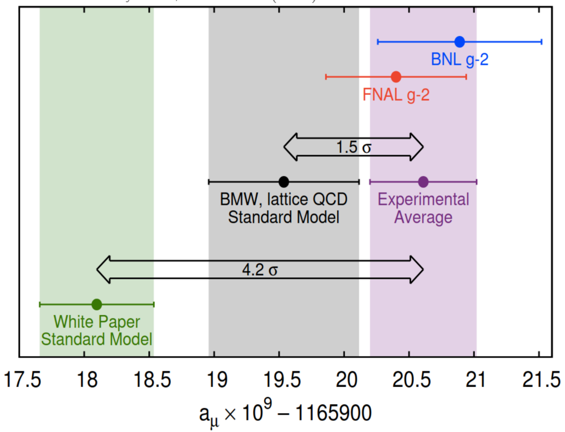
# $a_\mu$ and HVP after E989 Run-1 results (2021)



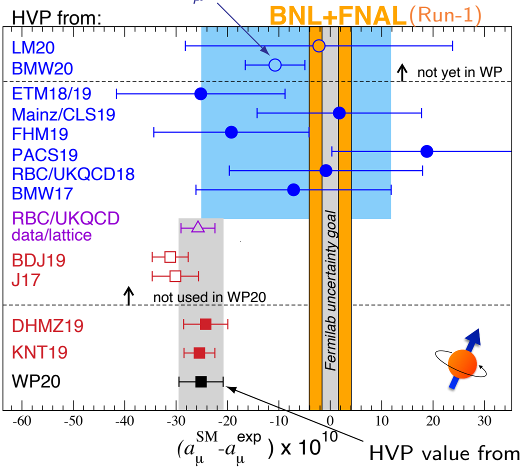
# $a_\mu$ and HVP after E989 Run-1 results (2021)

FNAL E989: Abi et al, PRL **126** (2021) 141801.

BMW: Borsanyi et al, Nature **593** (2021) 51.




First sub-pct. precision LQCD calc. of $a_\mu^{\text{HVP-LO}}$



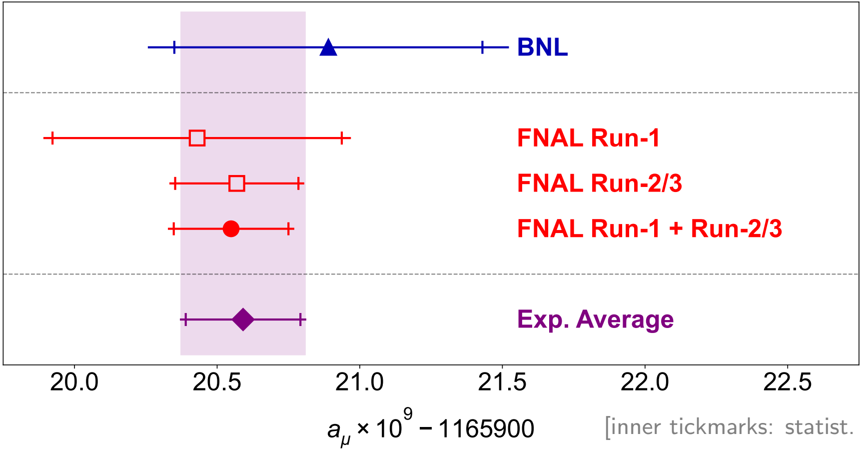

HVP value from $g-2$ Theory Init. 2020 WP

- The BMW result still to be confirmed by other Lattice groups!

# Results after E989 Run 2/3 analysis (August 2023)

New combined world average: [Aguillard et al., arXiv 2308.06230, to appear soon in PRL]

$$a_\mu(\text{Exp}) = 116592059(22) \times 10^{-11} \quad (0.19\,\text{ppm}).$$




[inner tickmarks: statist. unc. only]

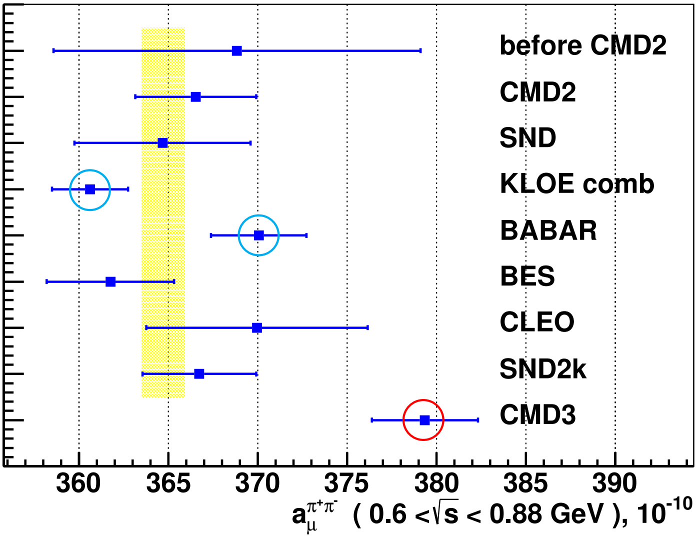
# But, Feb. 2023 brought new tension in the $e^+e^- \to \pi^+\pi^-$ data base

From: F. Ignatov et al., CMD3 Collaboration, arXiv:2302.08834.

The **CMD3 result** would bring $a_\mu^{\rm SM}$ even closer to the experimental world average.

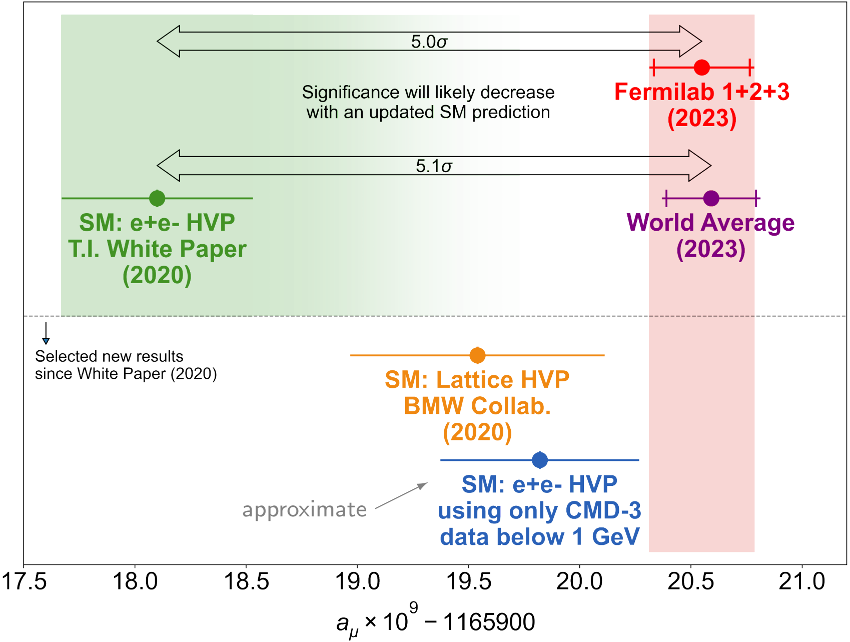
This tension needs to be further explored and resolved.

New approaches are needed: **MUonE** at CERN.



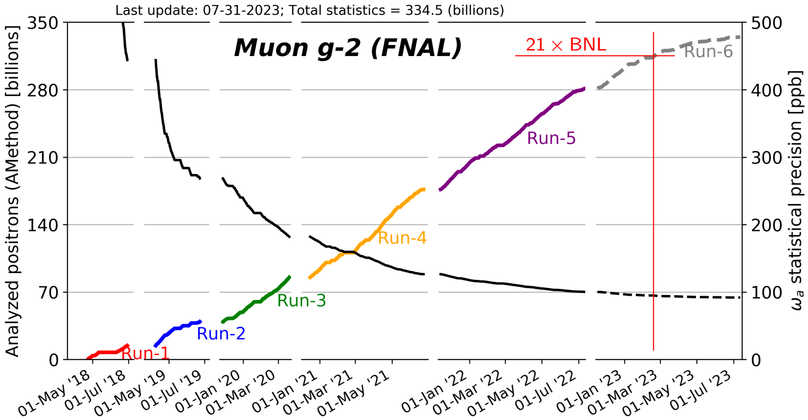
# The current landscape of HPV:

Significant effort will be required to resolve this situation definitively.



# Outlook for Muon $g-2$ at Fermilab

Lots of data left to analyze:




- Already **beat the systematics goal**; expect also to **surpass the statistical unc. goal**.
- Theory improvements expected on a similar timescale.
- Forthcoming analyses on EDM, CPT/LV and dark matter searches.

# Status of $a_\mu$/HVP, and future plans

**Muon $g$–2/E989 at Fermilab:**

- All $a_\mu$ DAQ concluded in July '23 (Run 6).
- Full data statistics goal, $21\times$ BNL E821, reached in Feb. 2023.
- Results for Runs 2 and 3, unblinded in Aug '23: confirm BNL and FNAL Run-1: **$2.8\times$ precision improvement in $a_\mu$**!
- Analysis of Run 4–6 is advancing steadily; results in $\sim$2025.
- Systematic uncertainties under control; statistical unc. expected to surpass goal.

**Other experiments on HVP and $a_\mu$:**

- MUonE at CERN, a space-like measurement of $a_\mu^{\mathrm{HVP}}$ through evolution of electromagnetic coupling $\Delta\alpha_{\mathrm{hadr}}$ in muon scattering on $e^-$.
- J-PARC Muon $g-2$ (and muon EDM): a novel approach to prepare and store a muon beam, without electrostatic focusing.
- Efforts to improve $\sigma_{\mathrm{had}}^{\mathrm{exp}}(s)$ continue at $e^+e^-$ facilities worldwide.

Significant developments are expected throughout the next 3–5 years!

# E989: Muon $g-2$ Collaboration

**USA**
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

**USA National Labs**
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

**China**
- Shanghai Jiao Tong

**Germany**
- Dresden
- Mainz

**Italy**
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

**Korea**
- CAPP/IBS
- KAIST

**Russia**
- Budker/Novosibirsk

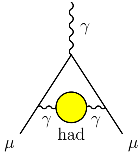
**United Kingdom**
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London


Muon g-2 Collaboration Meeting @ Elba, May 2019

# Extra slides:

## Other planned and ongoing experiments on HPV and $a_\mu$

# MUonE experiment: **spacelike** determination of $a_\mu^{\mathrm{HVP}}$

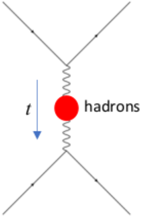



Instead of the dispersion approach:

$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\mathrm{had}}(s)\,;$$

$$K(s) = \int_0^1 \mathrm{d}x \frac{x^2(1-x)}{x^2+(1-x)(s/m_\mu^2)}\,,$$

$\Rightarrow$




we swap the $s$ and $x$ integrations:

$$a_\mu^{\mathrm{HLO}} = \frac{\alpha(0)}{\pi}\int_0^1 \mathrm{d}x\,(1-x)\Delta\alpha_{\mathrm{had}}(t)\,;$$

$$t \equiv t(x) = \frac{x^2 m_\mu^2}{x-1} < 0\,.$$

The task is reduced to a measurement of the change (running) of the effective fine structure constant $\alpha(0) \simeq 1/137 \to \alpha(t)$ in a single scattering process $\boldsymbol{\mu} + \boldsymbol{e} \to \boldsymbol{\mu} + \boldsymbol{e}$:

$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}, \quad \text{with} \quad \Delta\alpha = \Delta\alpha_{\mathrm{lepton}} + \Delta\alpha_{\mathrm{hadron}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{weak}}\,,$$

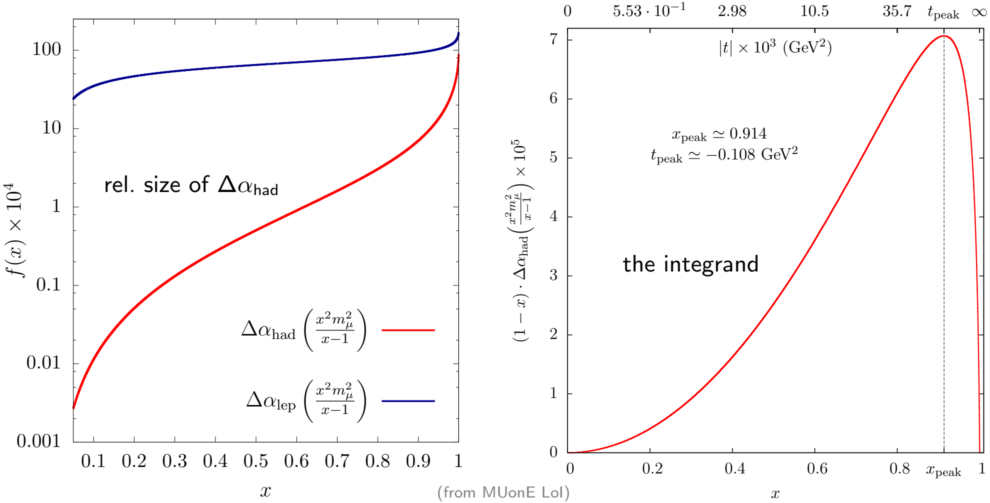
where all terms except $\Delta\alpha_{\mathrm{hadron}}$ are known extremely well.

The sole integral is over a well-behaved, smooth function.

MUonE will measure hadron-related changes in the running of $\alpha$ in scattering of $\mu^+$ on $e^-$.

# Practical aspects of the measurement

Recall: $\quad a_\mu^{\text{HVP-LO}} = \dfrac{\alpha}{\pi} \displaystyle\int_0^1 dx\,(1-x)\Delta\alpha_{\text{had}}(t)\,;$




(from MUonE LoI)

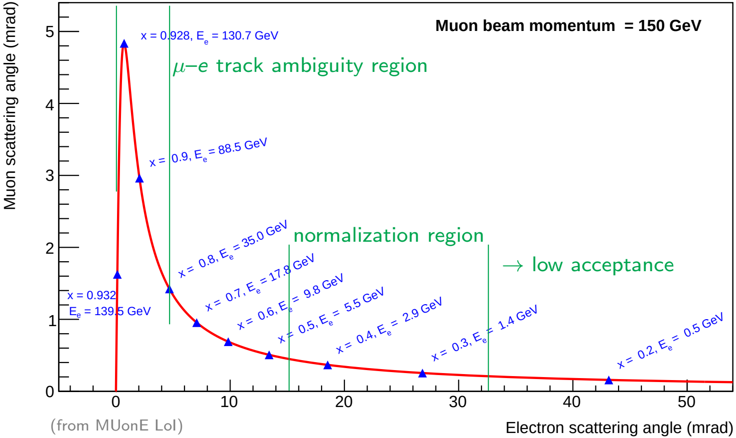
# Further practical aspects of the measurement

- High-energy muon beam on atomic electrons in target
- $d\sigma \propto \alpha^2$ at leading order $\rightarrow$ a sensitive observable
- $\Delta\alpha_{\text{had}}$ extracted from **shape** $R_{\text{had}}(t)$ of $d\sigma(t)$
- Elastic events selected using correlated track angles:

from measurement

$$R_{\text{had}}(t) = \frac{d\sigma(\Delta\alpha_{\text{had}})}{d\sigma(\Delta\alpha_{\text{had}} = 0)} \simeq 1 + 2\Delta\alpha_{\text{had}}$$

from Monte Carlo sim.




(from MUonE LoI)

Elastic kinematics:

- $t$ is entirely determined by $E_e$:
  $t = (p_e^{\text{i}} - p_e^{\text{f}})^2 = 2m_e(m_e - E_e)$
- $E_e$ from track angle and $E_\mu^{\text{inc}}$:

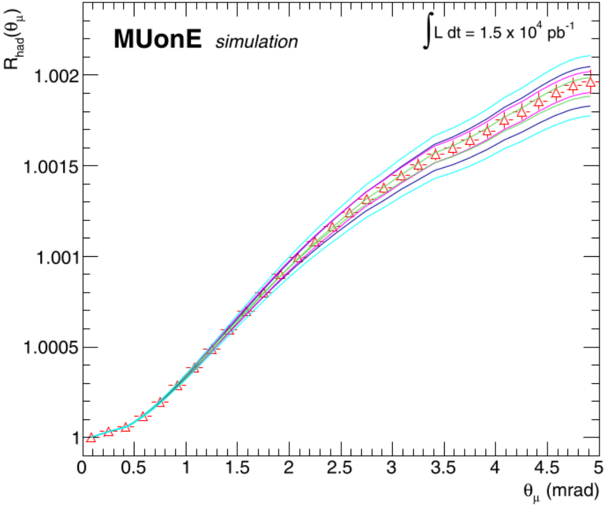
$$E_e = m_e \frac{1 + r^2 \cos\theta_e}{1 - r^2 \cos\theta_e}$$

$$r = \frac{\sqrt{(E_\mu^{\text{inc.}})^2 - m_e^2}}{E_\mu^{\text{inc}} + m_e}$$

- $E_\mu^{\text{inc}} \simeq 160$ GeV muon beam
- $x < 0.936 \sim 88\%$ of integral; rest extrapolated.

# Analysis approach and challenges

Expected signal size:




Recall that: $R^{\mathrm{LO}}_{\mathrm{had}} \simeq 1 + 2\Delta\alpha_{\mathrm{had}}$ .

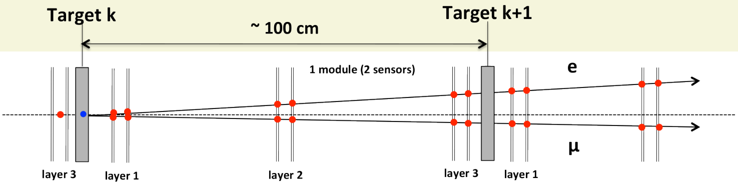
Critical considerations:

- $\theta_\mu$ is robust – primary observable
- detector alignment & its stability
- tracking reconstruction efficiency and accuracy
- detailed understanding of detector response
- optimized cuts to eliminate bgds
- particle ID useful, not indispensable
- accurate simulation of all processes at goal measurement precision
- reliable event generators for higher order and radiative terms; theory support essential!: Mesmer (Pavia), McMule (PSI).

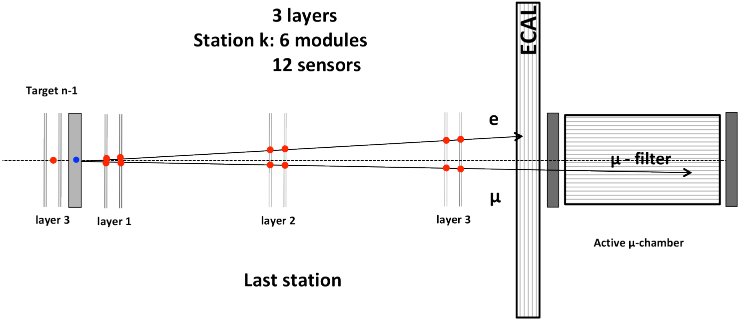
# MUonE apparatus

A single tracking station:

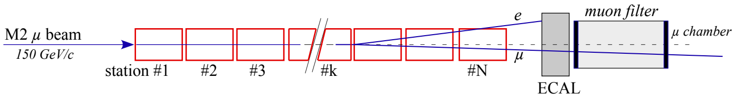
Target: 15 mm/Be or C




The last tracking station:

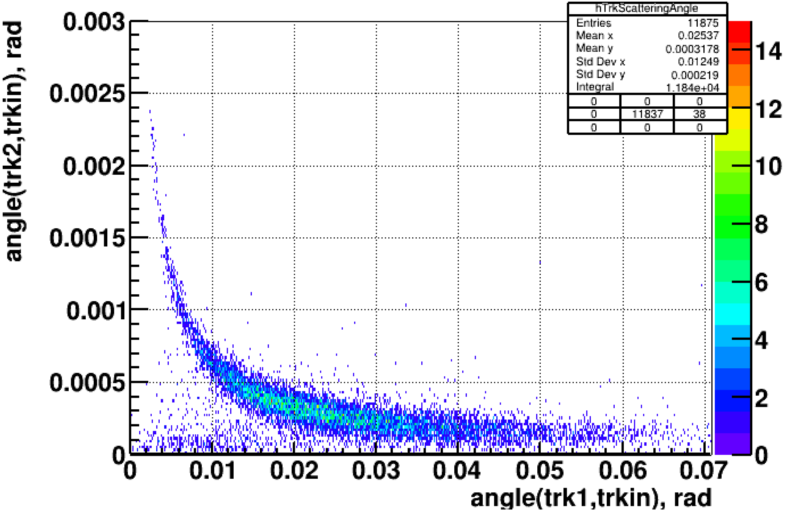



Full layout (extensible):



# First results: test beam time in M2 beamline, SPS/CERN, Sept. 2023

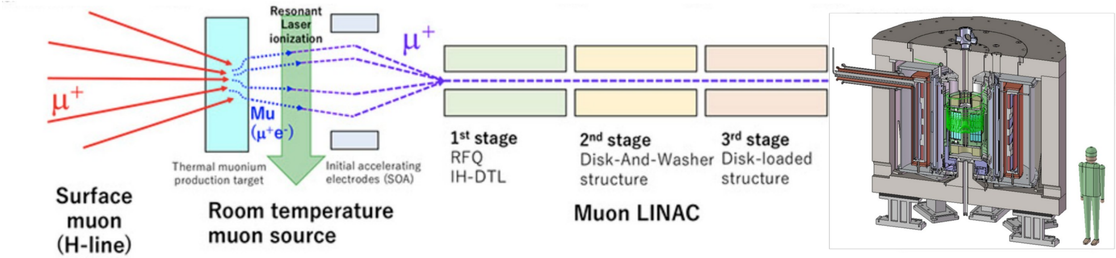
Two tracking stations and ECAL



# Goals and future plans

- **Long-term goal:** 40 stations $\times$ 3 years of data collection, which yields
  - $1.5 \times 10^7\ \mathrm{nb}^{-1}$,
  - 10 ppm statistical uncertainty on $\sigma(t)$ measurement at peak of integrand function,
  - $\sim 0.3\%$ on $a_\mu^{\text{HVP-LO}}$ ... competitive with other methods.
- **Interim goal:** 10 stations $\times$ 4 months of data collection $\rightarrow$ $\sim 2\%$ on $a_\mu^{\text{HVP-LO}}$, a first physics result before 2026 (start of 3-year CERN accelerator shutdown).
- Systematics to be controlled at the 10 ppm level, including on the shape:
  - detector alignment, especially longitudinal,
  - multiple scattering,
  - intrinsic tracker angular resolution,
  - muon beam energy.
- Ongoing test runs are demonstrating feasibility of this novel approach to resolving $\Delta a_\mu$,
- A full technical proposal is under preparation; completion planned for 2024.

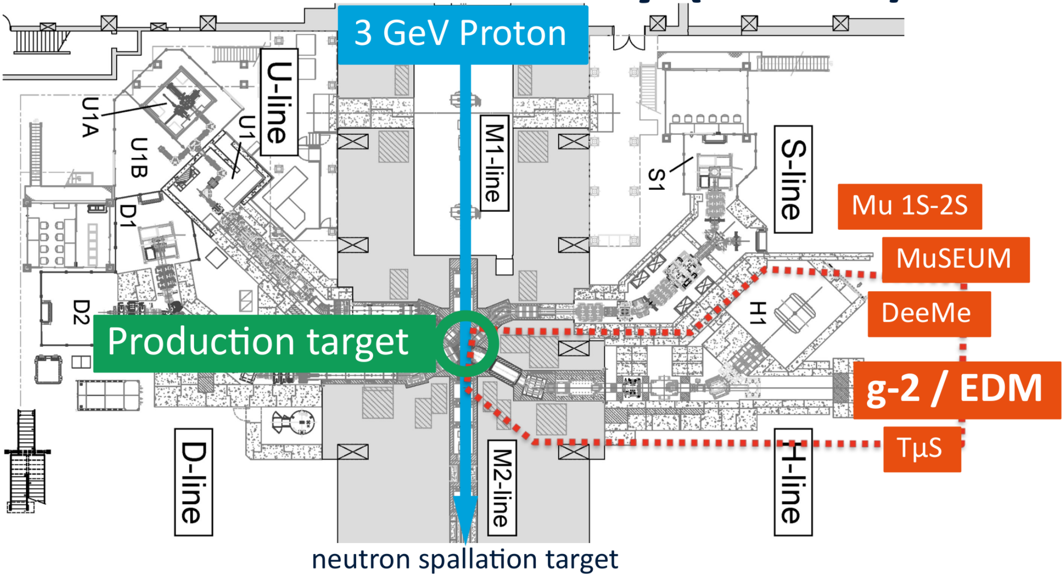
## Part of a wide-range muon physics programme



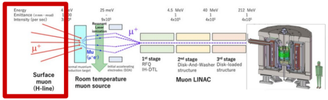

**Aim: competitive measurement of muon g-2 and EDM**

https://g-2.kek.jp/portal/index.html

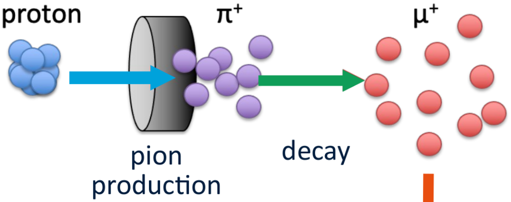
# Muon Science Facility (MUSE)

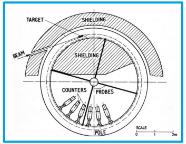


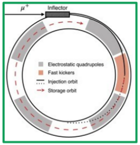
# Production

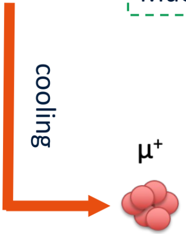



## ↦ CERN




## ↦ BNL FNAL

**Emittance ~ 1000π mm·mrad**
Proton and pion contamination
Need strong (electric) focussing
Need 'magic' $\gamma = \sqrt{(1/a_\mu+1)} = 29$
Muon loss

## ↦ JPARC

**Emittance ~ 1π mm·mrad**
(after reacceleration)
little/no need for focussing
Can run at any $\gamma$
**Allows a compact setup**

# J-PARC Muon $g-2$/EDM vs. BNL, FNAL experiments

| | BNL-E821 | Fermilab-E989 | Our experiment |
|---|---|---|---|
| Muon momentum | 3.09 GeV/$c$ | | 300 MeV/$c$ |
| Lorentz $\gamma$ | 29.3 | | 3 |
| Polarization | 100% | | 50% |
| Storage field | $B = 1.45$ T | | $B = 3.0$ T |
| Focusing field | Electric quadrupole | | Very weak magnetic |
| Cyclotron period | 149 ns | | 7.4 ns |
| Spin precession period | 4.37 $\mu$s | | 2.11 $\mu$s |
| Number of detected $e^+$ | $5.0\times10^9$ | $1.6\times10^{11}$ | $5.7 \times 10^{11}$ |
| Number of detected $e^-$ | $3.6\times10^9$ | – | – |
| $a_\mu$ precision (stat.) | 460 ppb | 100 ppb | 450 ppb |
| (syst.) | 280 ppb | 100 ppb | <70 ppb |
| EDM precision (stat.) | $0.2 \times 10^{-19}\ e\cdot$cm | – | $1.5 \times 10^{-21}\ e\cdot$cm |
| (syst.) | $0.9 \times 10^{-19}\ e\cdot$cm | – | $0.36 \times 10^{-21}\ e\cdot$cm |

Abe *et al.*, DOI: 10.1093/ptep/ptz030 (2019)

**Commissioning and data taking to begin at the earliest in 2028.**