Muon magnetic anomaly & hadronic vacuum polarization: experimental status and prospects

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Vietnam

Outline of the talk

1. Brief recap of the muon magnetic anomaly $a_\mu = \frac{1}{2}(g_\mu - 2)$, and hadronic vacuum polarization (HVP). [Thanks, Hartmut!]
2. Principles of the muon $g-2$ measurement.
3. Fermilab E989 results on a_μ to date, and how we got there.
4. The shifting landscape of HVP.
5. Experimental path forward: MUonE at CERN, and E34 at J-PARC.

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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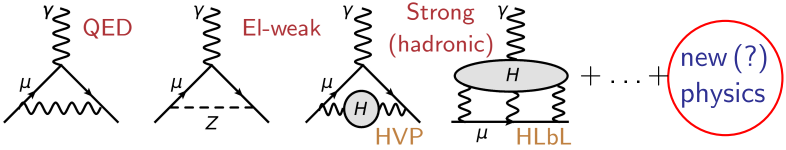
Leading order processes contributing to a_μ:



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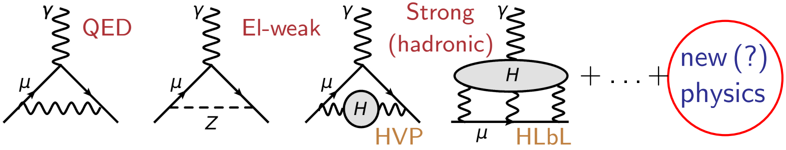

Current status of SM calculations of a_μ:

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

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

a_μ 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

⇒ a_μ 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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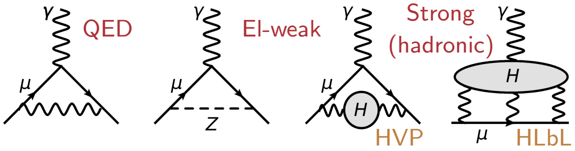

$+ \dots +$ new (?) physics

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Total SM	116,591,810	43

0.6%

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

$\Rightarrow$ a_μ 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.

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

Exp. value dominated by results of BNL E821:

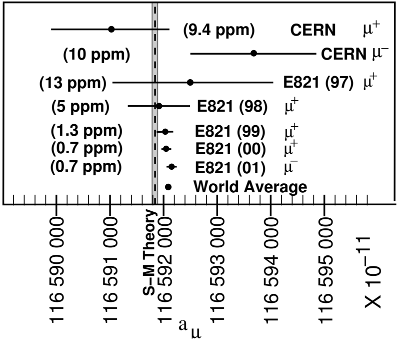
$$a_\mu^{\rm exp} = 116\,592\,089\,(54)_{\rm stat}\,(33)_{\rm syst} \times 10^{-11}\text{, or}$$

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

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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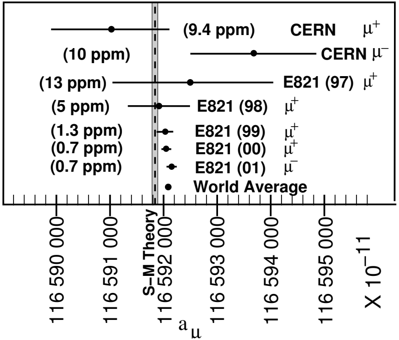

How to improve this result?

- 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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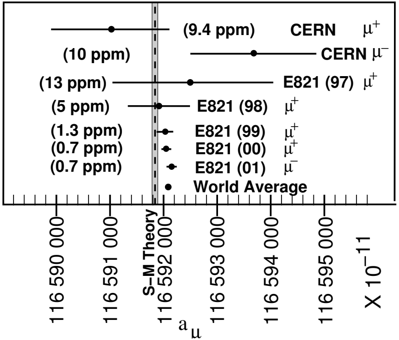

How to improve this result?

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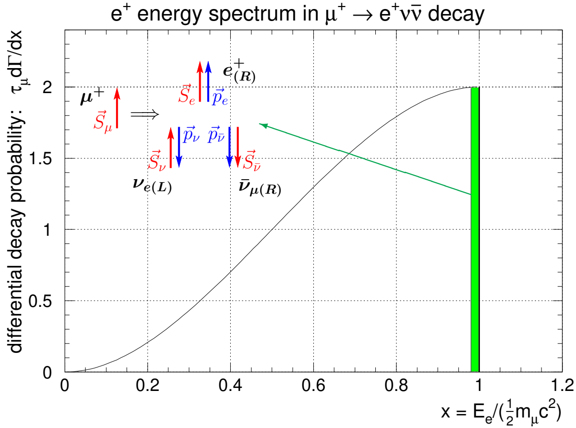
Goal for Fermilab E989:

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

Measurement of a_μ 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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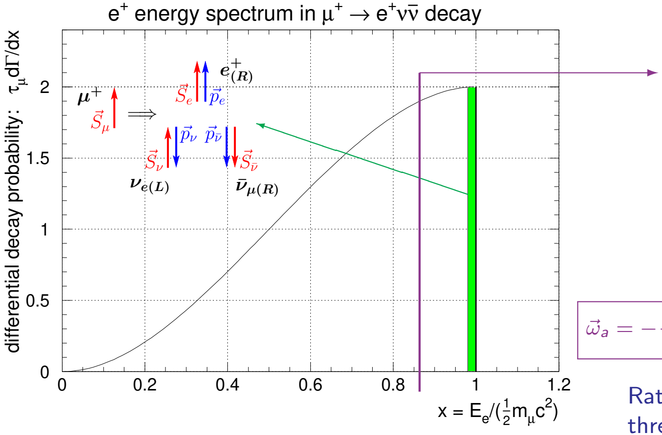
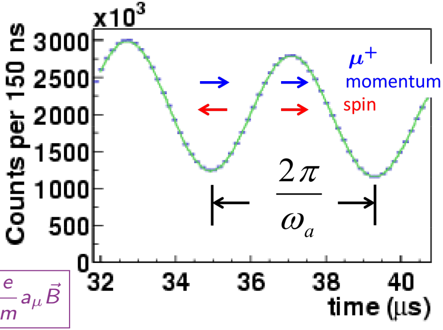


$\vec{S}$ of a stored muon precesses in the ring $\vec{B}$ field. An observer notes Lorentz boost induced oscillations between presence and absence of high energy positrons, from muon decay.



$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

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

Reasons why storage ring (SR) method works to sub-ppm level in a_μ

A. Muons emitted in pion decay are highly polarized ($\geq$97%).
The a_μ signal would be absent with unpolarized muons in SR.

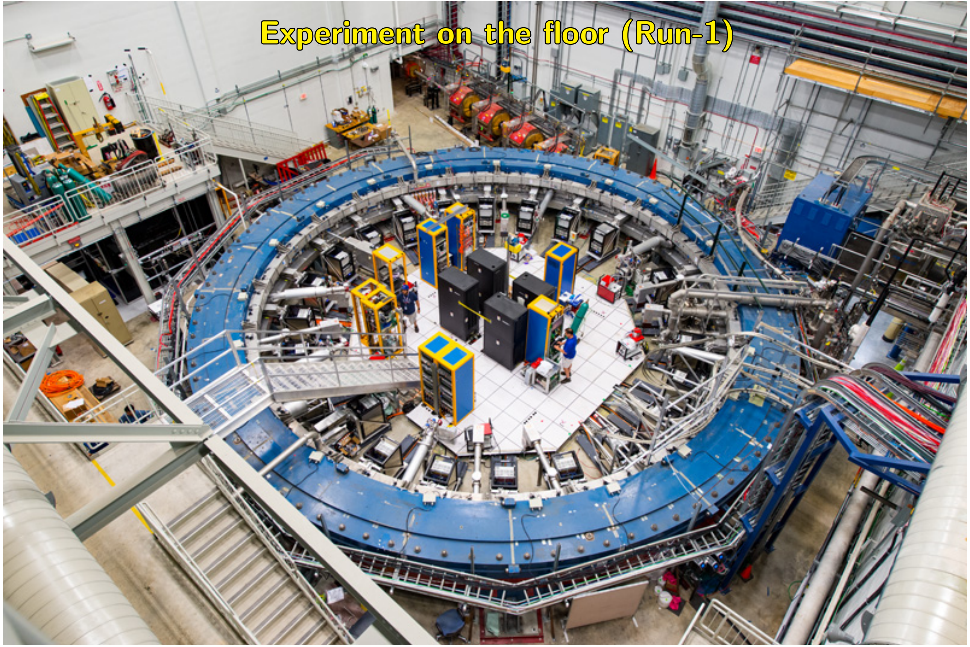
B. Anomalous frequency $\omega_a \propto (g-2)$, giving $\sim 860\times$ more sensitivity than decay at rest which measures $\omega_S \propto g$.

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

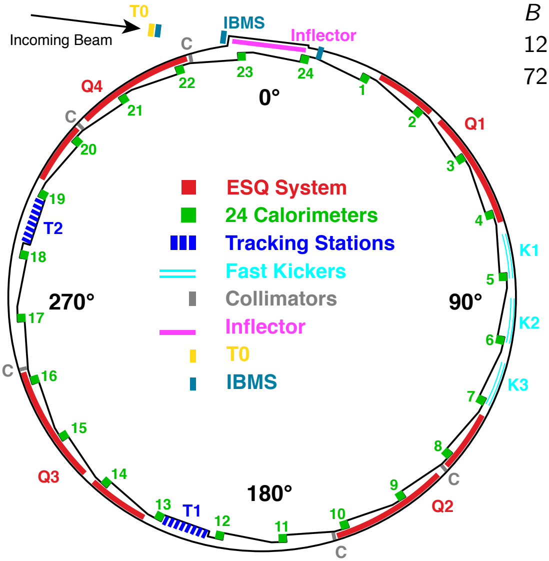
D. For **most energetic** decay e^+s, with $p_e \simeq p_{e,\mathrm{max}}$, the $(V-A)$ weak int. strongly aligns $\vec{p}_e$ with $\vec{S}_\mu$, $\Rightarrow$ robust signal for $\vec{S}_\mu$ precession w.r.t. $\vec{p}_\mu$.

The confluence of these effects is truly exceptional!

Experiment on the floor (Run-1)



Muon $g-2$ apparatus overview

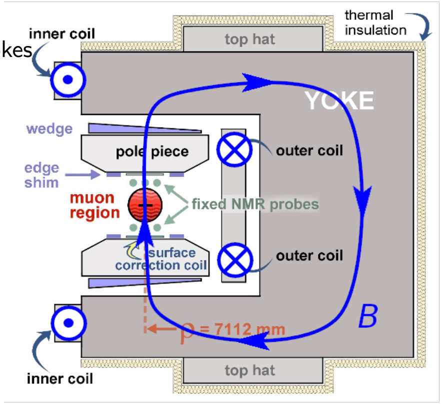


Superconducting storage ring

$B \simeq 1.45\,\mathrm{T}$

12 C-shaped yokes

72 poles



864 wedges: angle – quadrupole (QP)

24 iron top hats: change effective μ

edge shims: QP, sextupole (SP)

8000 surface iron foils: change effective μ locally

surface coils: add avg. field moments (QP, SP, 360°)

Muon $g{-}2$ apparatus overview

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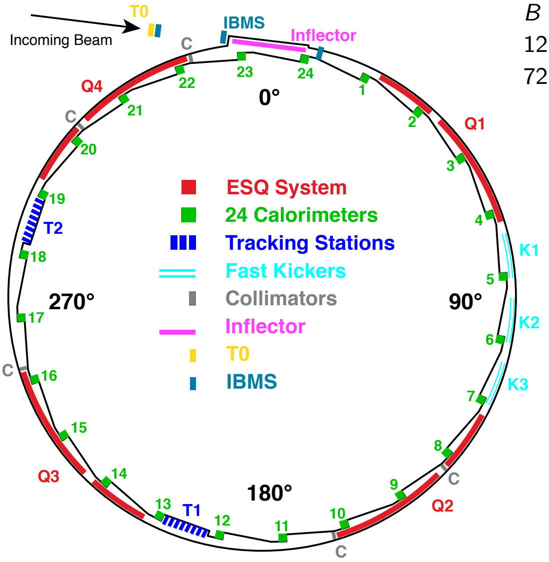

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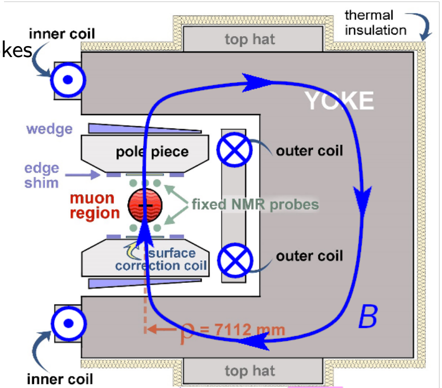
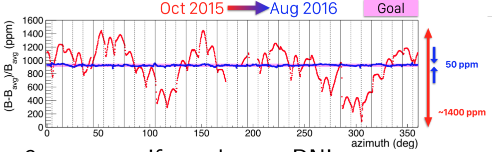
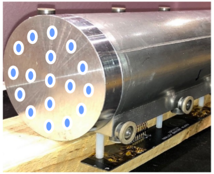




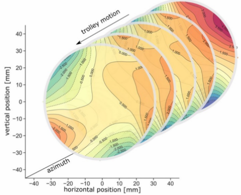
3× more uniform than at BNL

Measuring the field: NMR probes

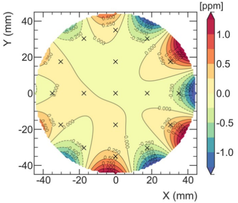
- In-vacuum NMR trolley **maps field every ~3 days**



17 petroleum jelly NMR probes



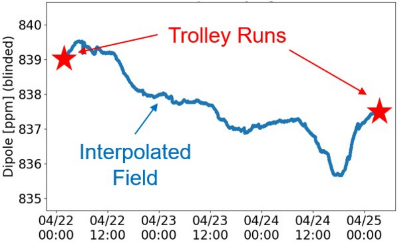
2D field maps (~8000 points)



Azimuthally-Averaged
Variation < 1 ppm

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

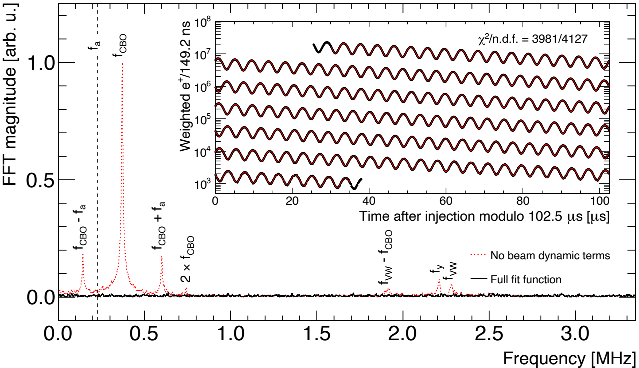
Fixed probes above/below muon storage region



Trolley Runs

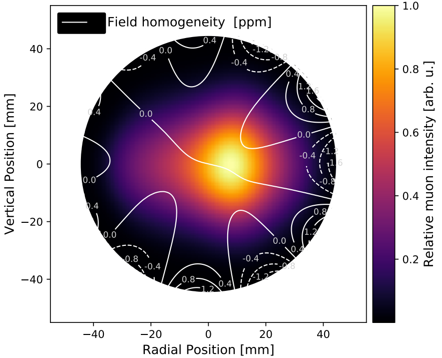
Interpolated Field

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



“Wiggle” plot and its analysis:

- f_a . . . anomalous precession;
- f_{CBO} . . . coherent betatron oscillations;
- f_{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_μ 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:

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

independently blinded!

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 $T = 34.7^\circ$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.

Real world corrections for small effects

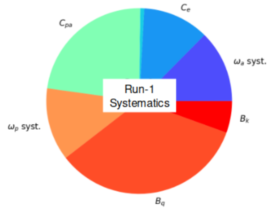
E-field & Up/Down motion: Spin precesses slower than in basic equation

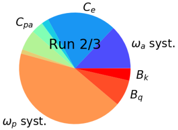
Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

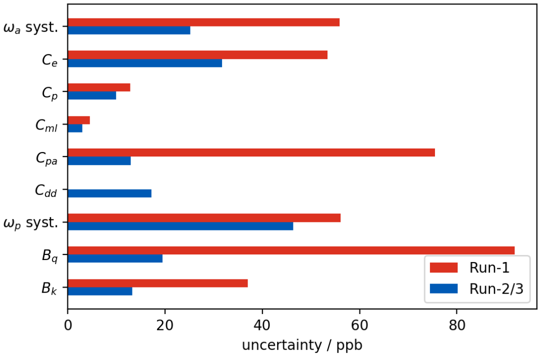
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\,\frac{1+\overbrace{C_e+C_p}+\overbrace{C_{pa}+C_{dd}+C_{ml}}}{1+\underbrace{B_k+B_q}}$$

Measured Values

Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,





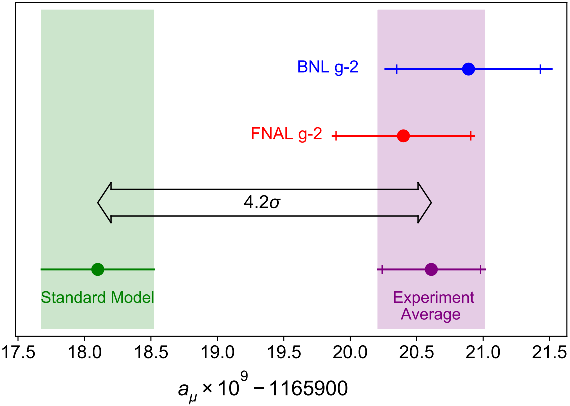


[ppb]	Run-1	Run-2/3	Ratio
stat.	434	201	2.2
syst.	157	70	2.2

∼ equal improvement; still **statistically dominated**

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

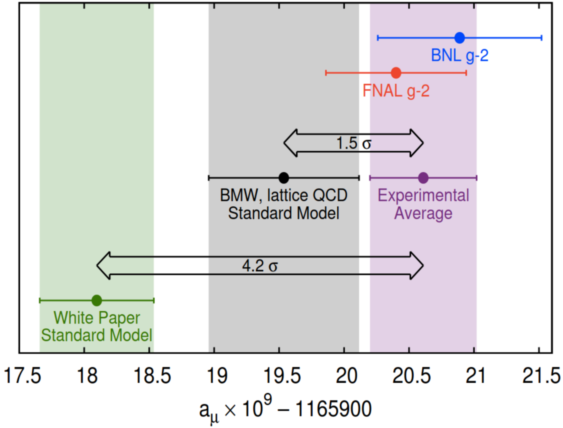
a_μ and HVP after E989 Run-1 results (2021)



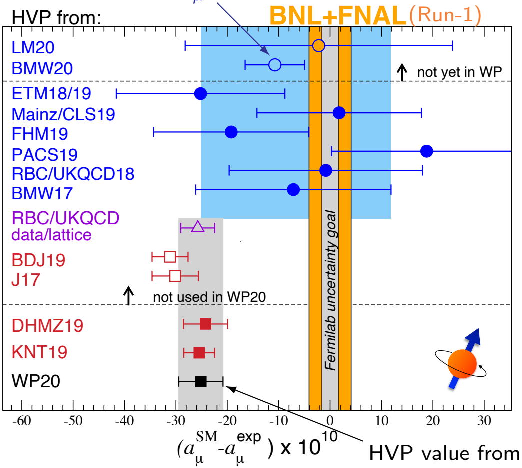
a_μ and HVP after E989 Run-1 results (2021)

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 Initiative 2020 WP

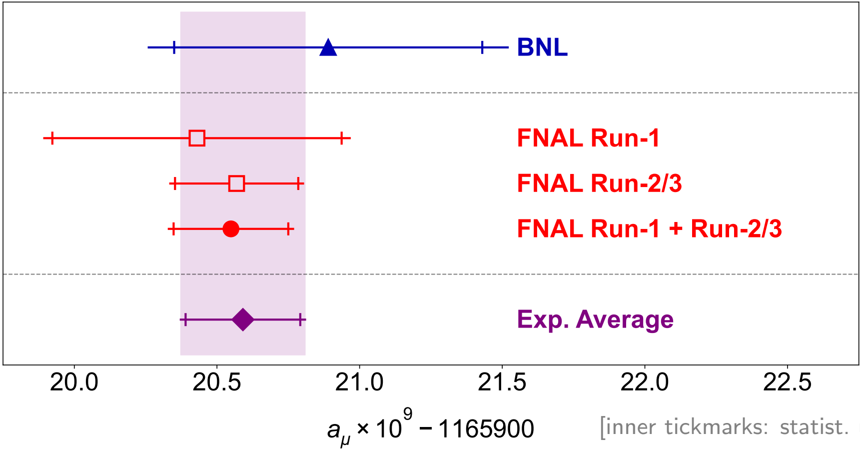
- The BMW result still to be confirmed by other Lattice groups!

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

New combined world average:

Aguillard et al., arXiv 2308.06230 / PRL **131** (2023) 16;
full analysis details: arXiv 2402.15410 (submitted to PRD)

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



[inner tickmarks: statist. unc. only]

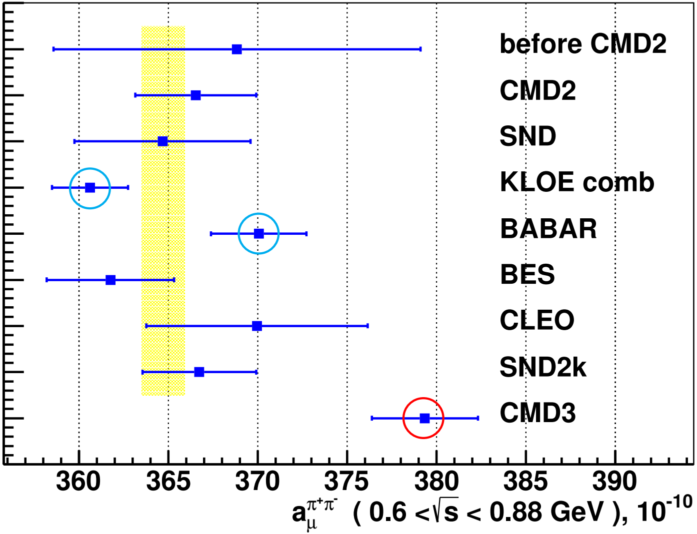
But, Feb. 2023 brought new tension in the $e^+e^- \to \pi^+\pi^-$ data base

From: F. Ignatov et al., CMD-3 Collaboration, arXiv:2302.08834.

The **CMD-3 result** would bring $a_\mu^{\rm SM}$ even closer to the experimental world average.

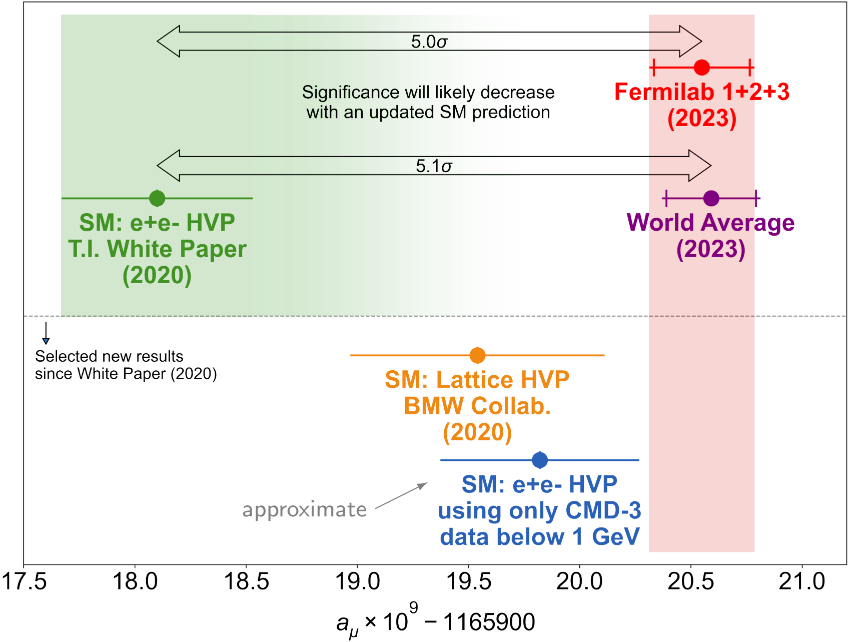
This tension needs to be further explored and resolved.

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



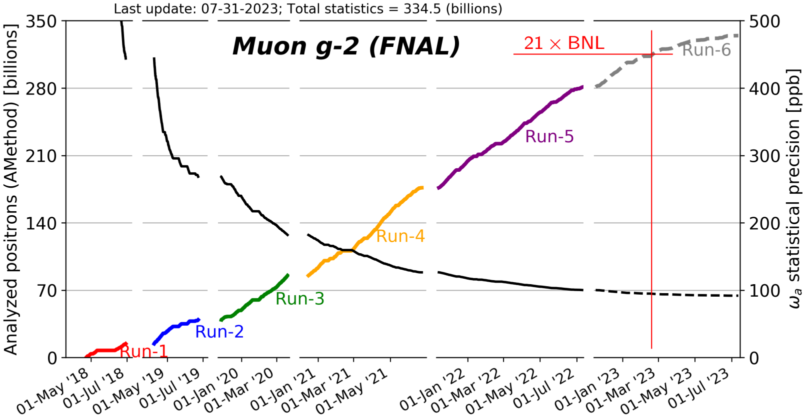
The current landscape of HVP:

Significant effort will be required to resolve this situation definitively.



Outlook for further results from Fermilab Muon $g-2$

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_μ/HVP, and future plans

Muon g–2/E989 at Fermilab:

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

Other experiments on HVP and a_μ:

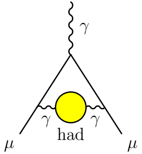
- **MUonE at CERN**, a space-like measurement of a_μ^{HVP} through evolution of electromagnetic coupling $\Delta\alpha_{\mathrm{hadr}}$ in muon scattering on e^-.
- **J-PARC Muon $g-2$** (and muon EDM): a novel approach to prepare and store a muon beam, without electrostatic focusing.
- Efforts to **improve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

Other experiments on HVP and a_μ:

- MUonE at CERN (muonic Bhabha scattering),
- E34 at J-PARC (a new $g_\mu\!-\!2$ measurement).

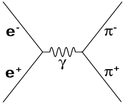
MUonE experiment: **spacelike** determination of a_μ^{HVP}

Instead of the dispersion approach:



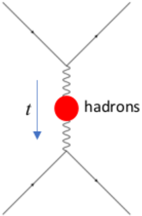
$$a_\mu^{\mathrm{HLO}} = \frac{1}{4\pi^3}\int_{m_\pi^2}^{\infty} \mathrm{d}s\, K(s)\sigma_{\mathrm{had}}(s)\,;$$

$\Rrightarrow$



(timelike channels [noisy])

$\Rightarrow$



we swap the s and x integrations:

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

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

Task: measure the change (running) of the eff. FS const. $\alpha(0) \simeq 1/137 \to \alpha(t)$ in a single scattering process $\mu^+ + e^- \to \mu^+ + e^-$:

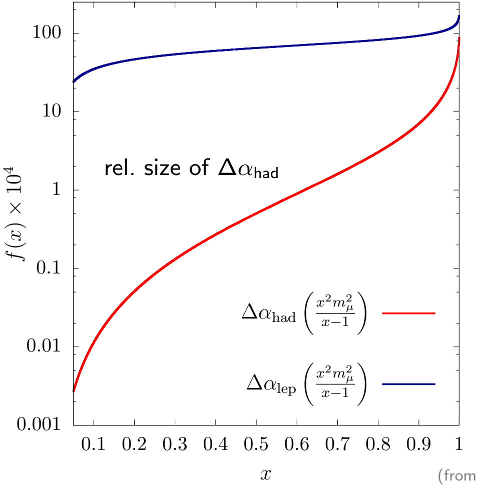
known extremely well

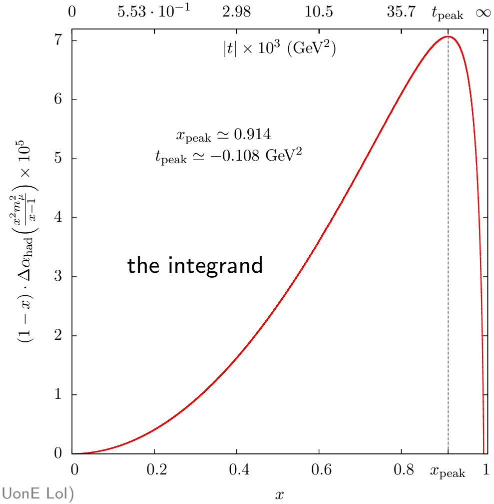
$$\alpha(t) = \frac{\alpha(0)}{1-\Delta\alpha(t)}, \quad \text{with} \quad \Delta\alpha = \Delta\alpha_{\mathrm{lepton}} + \Delta\alpha_{\mathrm{hadron}} + \Delta\alpha_{\mathrm{top}} + \Delta\alpha_{\mathrm{weak}}\,.$$

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

Practical aspects of the measurement

Recall: $a_\mu^{\text{HVP-LO}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\Delta\alpha_{\text{had}}(t)\,; \qquad t \equiv t(x) = \frac{x^2 m_\mu^2}{x-1}$





(from MUonE LoI)

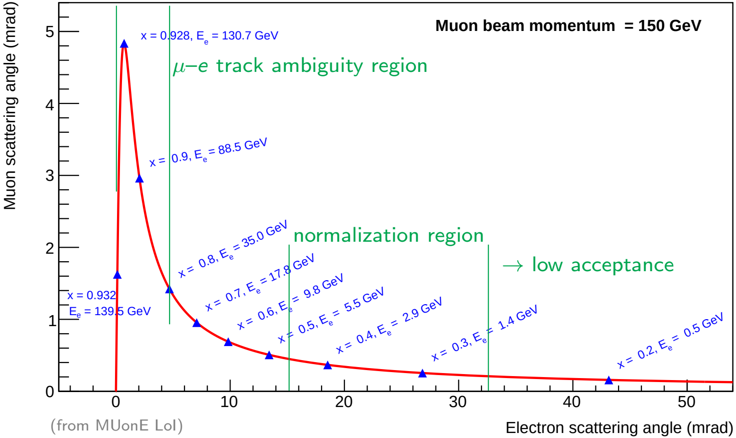
Further practical aspects of the MUonE measurement

- High-energy muon beam on atomic electrons in target
- $d\sigma \propto \alpha^2$ at leading order → a sensitive observable
- $\Delta\alpha_{\text{had}}$ extracted from **shape** $R_{\text{had}}(t)$ from $d\sigma(t)$
- 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_μ^{inc}:

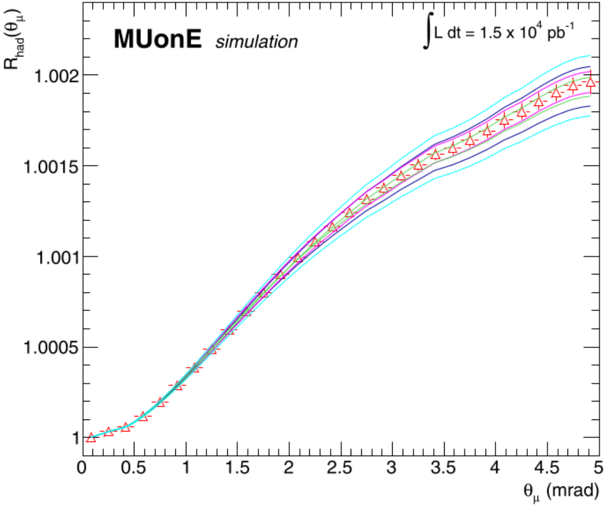
$$E_e = m_e \frac{1 + r^2 \cos^2\theta_e}{1 - r^2\cos^2\theta_e}$$

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

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

MUonE analysis approach and challenges

Expected signal size:



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

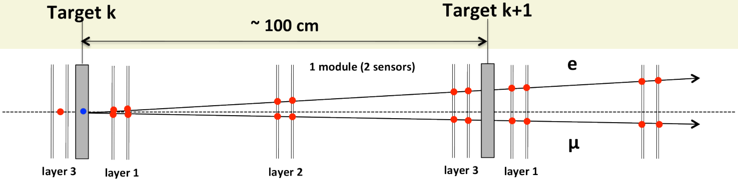
Critical considerations and requirements:

- θ_μ 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).

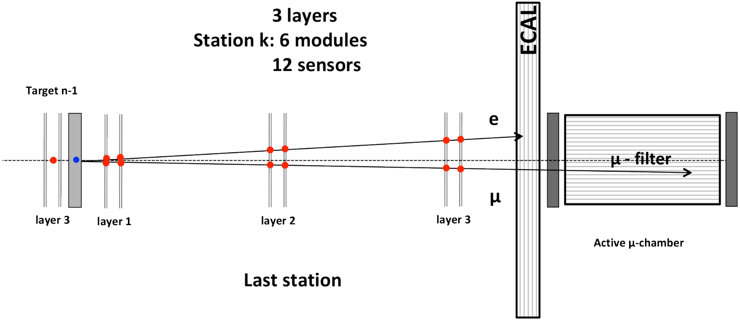
MUonE apparatus

A single tracking station:

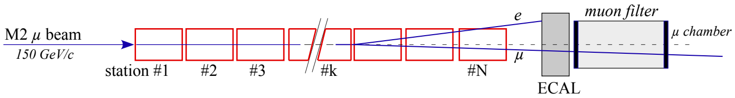
Target: 15 mm / Be or C



The last tracking station:



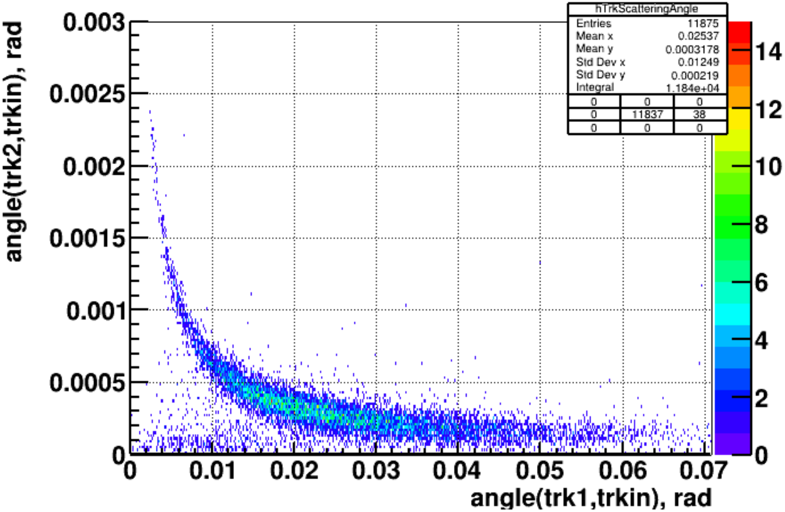
Full layout (extensible):



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

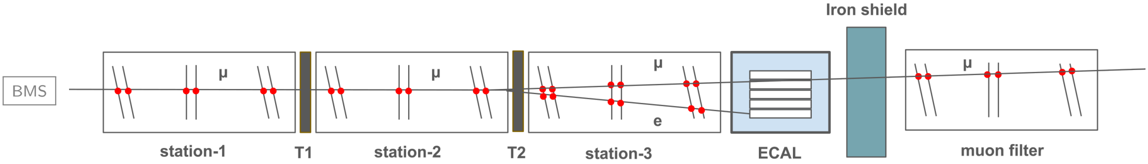
Two tracking stations
and ECAL

Proof of principle!



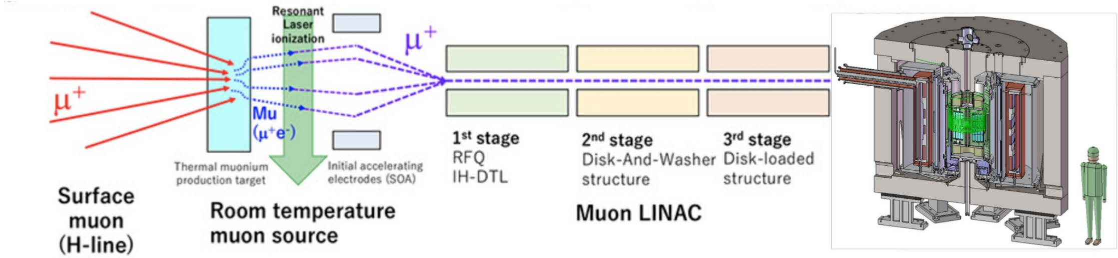
MUonE goals, status and plans

- **Long-term goal** (post LS3): 40 stations × 3 yrs. of data collection, yielding
  - $1.5 \times 10^{7}\ \mathrm{nb}^{-1}$, 10 ppm stat. unc. on $\sigma(t)$ measurement at peak of integrand function,
  - $\sim 0.3\%$ on $a_\mu^{\text{HVP-LO}}$ . . . competitive with other methods.
- Proof of MUonE measurement principle has been established.
- **Full technical proposal** submitted to SPSC in April 2024 for a **2025 interim run**.
- **2025 run:** 3 tracking st., ECAL, BMS, MF × 4 wks of beam → $\sim 20\%$ on $a_\mu^{\text{HVP-LO}}$, a first physics result **before 2026** (start of LS3, 3-yr CERN accelerator shutdown):



Experiment E34 at J-PARC: Muon $g\!-\!2$ and EDM

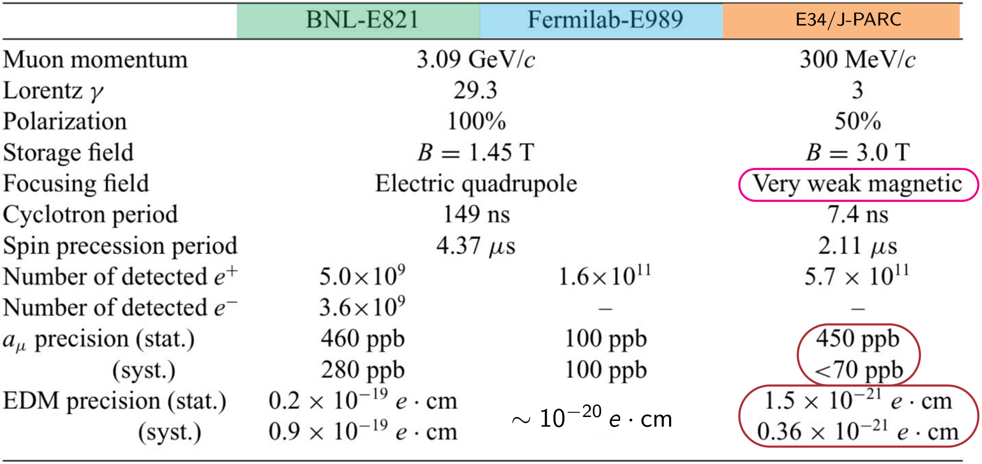
Part of a wide-range muon physics programme



Aim: competitive measurement of muon g-2 and EDM

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

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



	BNL-E821	Fermilab-E989	E34/J-PARC
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	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 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e\cdot$cm	$\sim 10^{-20}$ $e\cdot$cm	1.5×10^{-21} $e\cdot$cm
(syst.)	0.9×10^{-19} $e\cdot$cm		0.36×10^{-21} $e\cdot$cm

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

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

Current status, prospects, experimental path forward

- Fermilab E989 Muon $g-2$ is on course to improve a_μ precision significantly by $\sim$2025.
- Significant questions surround the SM determination of $a_\mu^{\text{HVP-LO}}$, and the underlying data set on $e^+e^- \to$ hadrons.
- MUonE at CERN offers a completely independent way to determine $a_\mu^{\text{HVP-LO}}$.
- E34 at J-PARC will measure a_μ with different systematics from E989, but with far lower event statistics.

As the experimental precision of a_μ improves, the focus shifts on getting a better understanding of the HVP!