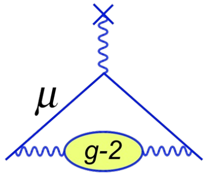
# Muon $g - 2$ in 10 minutes


**Samuel Grant**

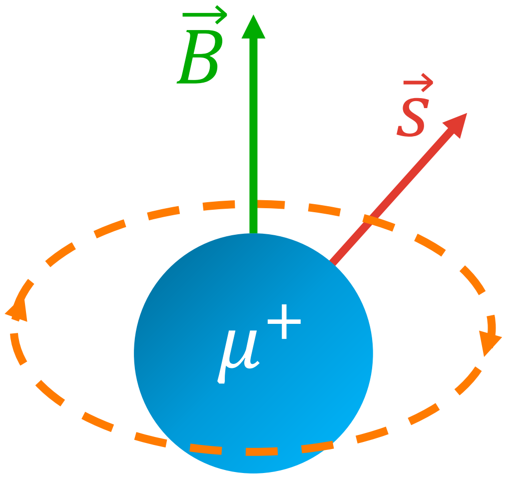
(on behalf of the $g - 2$ collaboration)


New Perspectives 2024



# What is $g - 2$?

- A charged fermion will react to an external magnetic field: its spin will precess about the field lines.




- The rate of precession depends on the size of the magnetic dipole moment, $\mu$

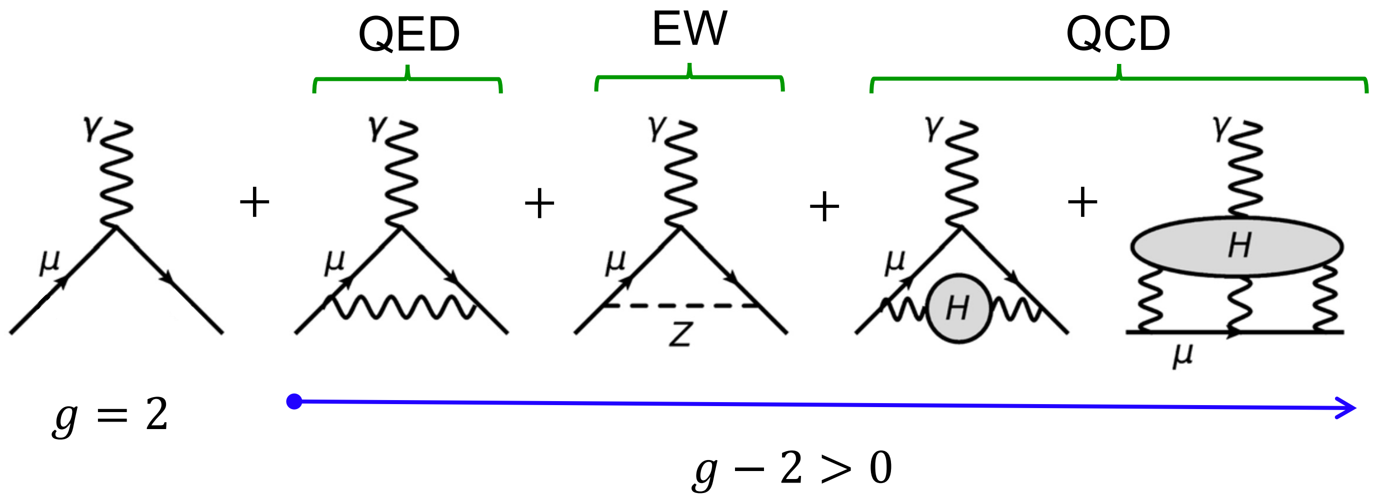
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

- Which in turns depends on a dimensionless "g-factor"

$$\vec{\mu} = g\left(\frac{q}{2m}\right)\vec{s}.$$

# What is $g - 2$?

- Dirac found the g-factor to be equal to 2 at leading order, but higher order diagrams also contribute, making $g = 2.002331\ldots$




- $g - 2$ encodes all possible interactions between the fermion and the magnetic field!

**Why muons?**

- Sensitivity to the "new physics" mass scale goes with the fermion mass squared, so muon $g - 2$ is 40,000 times more sensitive to new heavy particles than electron $g - 2$; and

- It presents a persistent anomaly when compared with the Standard Model, more on this later...

# Measuring $g-2$

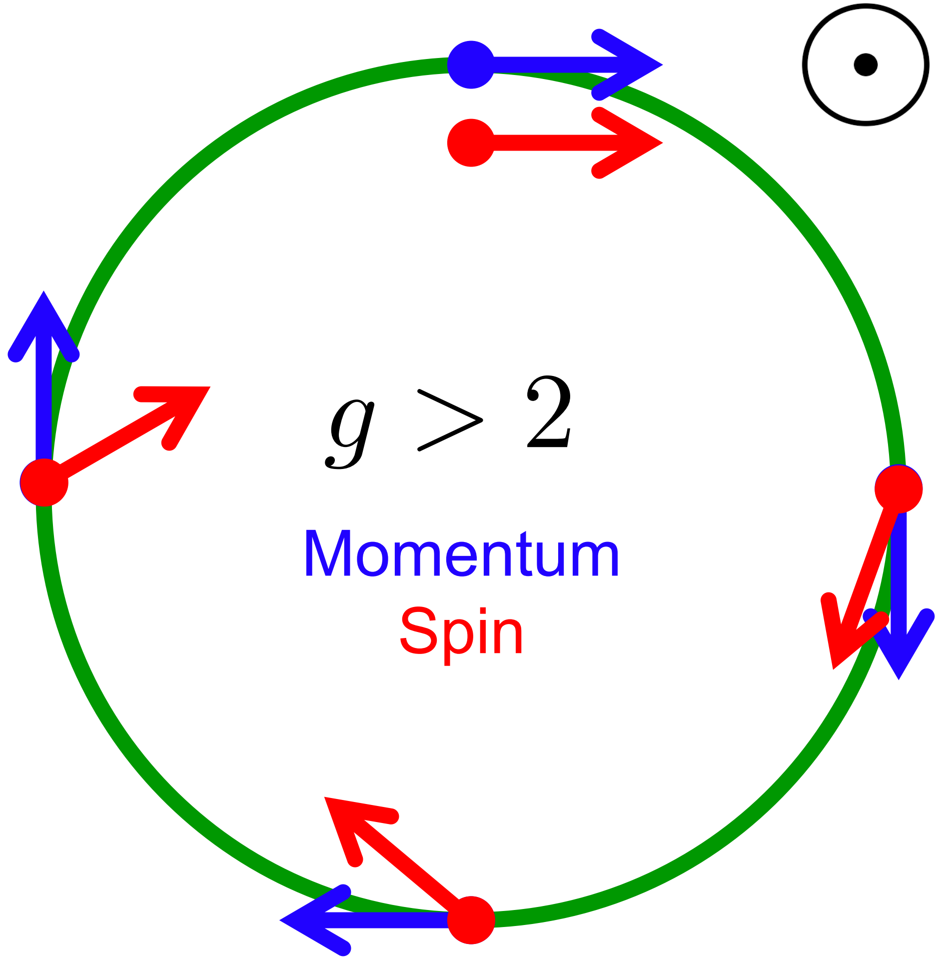
- Store polarized muons in a storage ring with a vertical B-field.
- The cyclotron and spin frequencies are proportional to B.

$$\vec{\omega}_c = -\frac{e\vec{B}}{m\gamma} \qquad \vec{\omega}_s = -g\frac{e\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma}$$

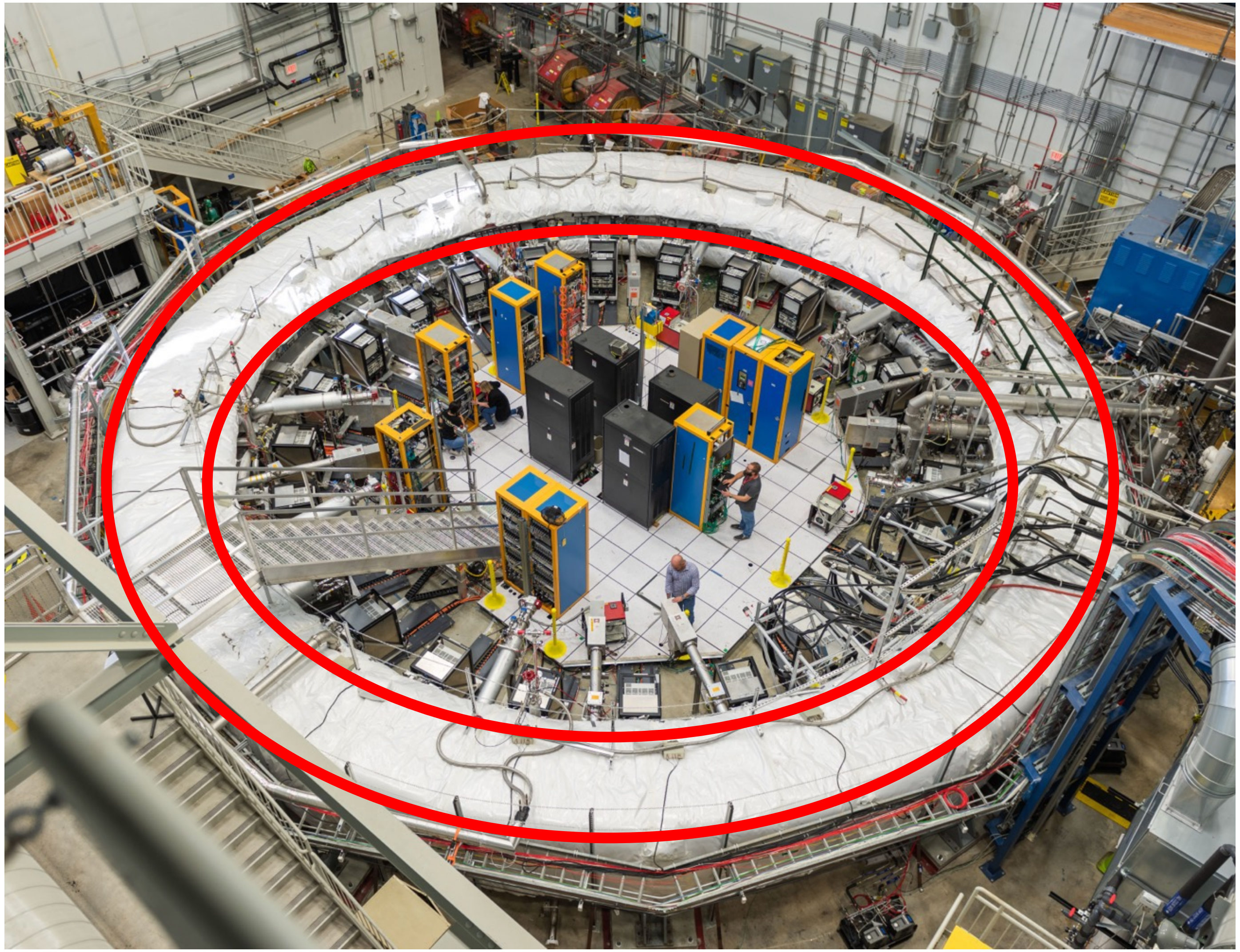
- The difference in frequency depends directly on $g-2$ and B.

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \qquad a_\mu = \frac{g-2}{2}$$

- The spin rotates relative to the momentum vector at the difference frequency, $\omega_a$.
- **Measure $\omega_a$, measure B, measure $g-2$!**

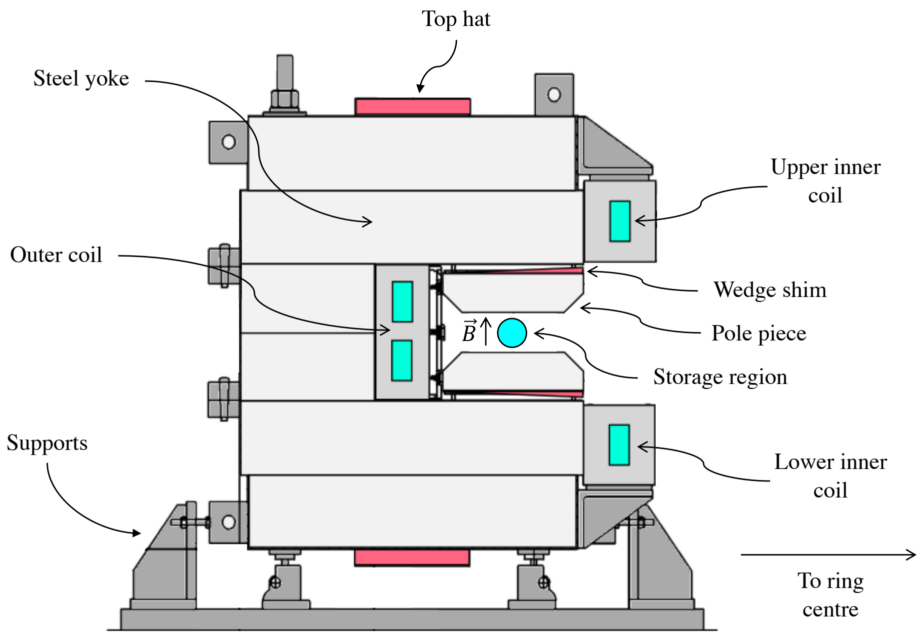


# The magnetic field

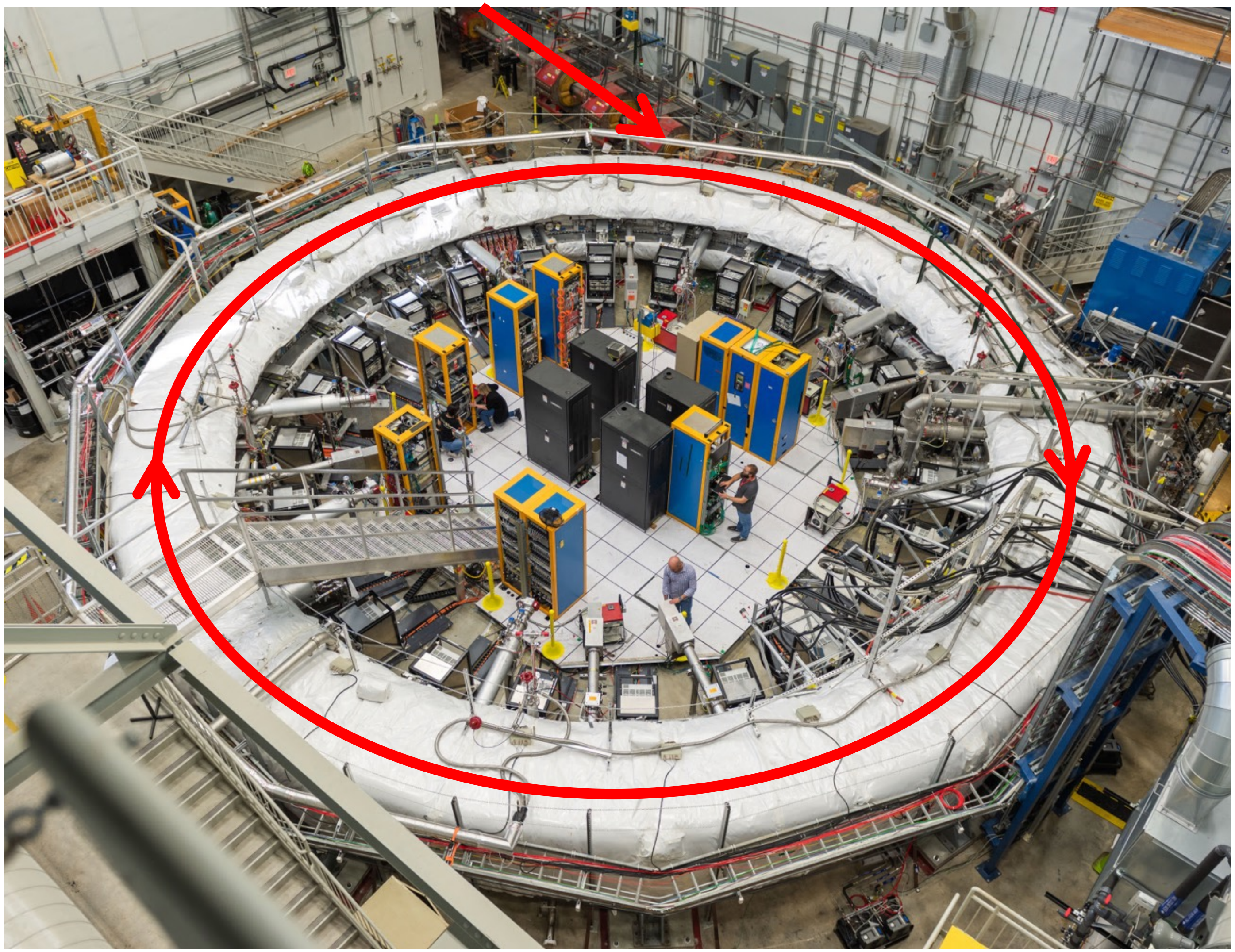


- 14 m diameter, 1.45 T superconducting magnet.
- ~700 metric tons! Moved from BNL in New York.
- Muons are stored inside a C-shaped cross-section.

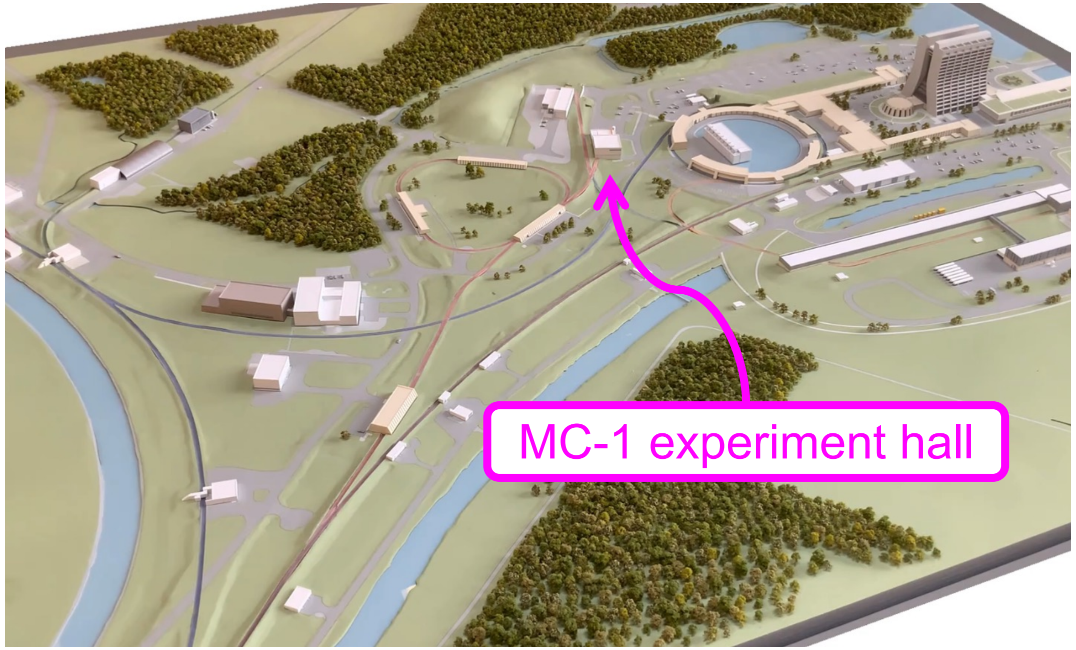
[ppm]

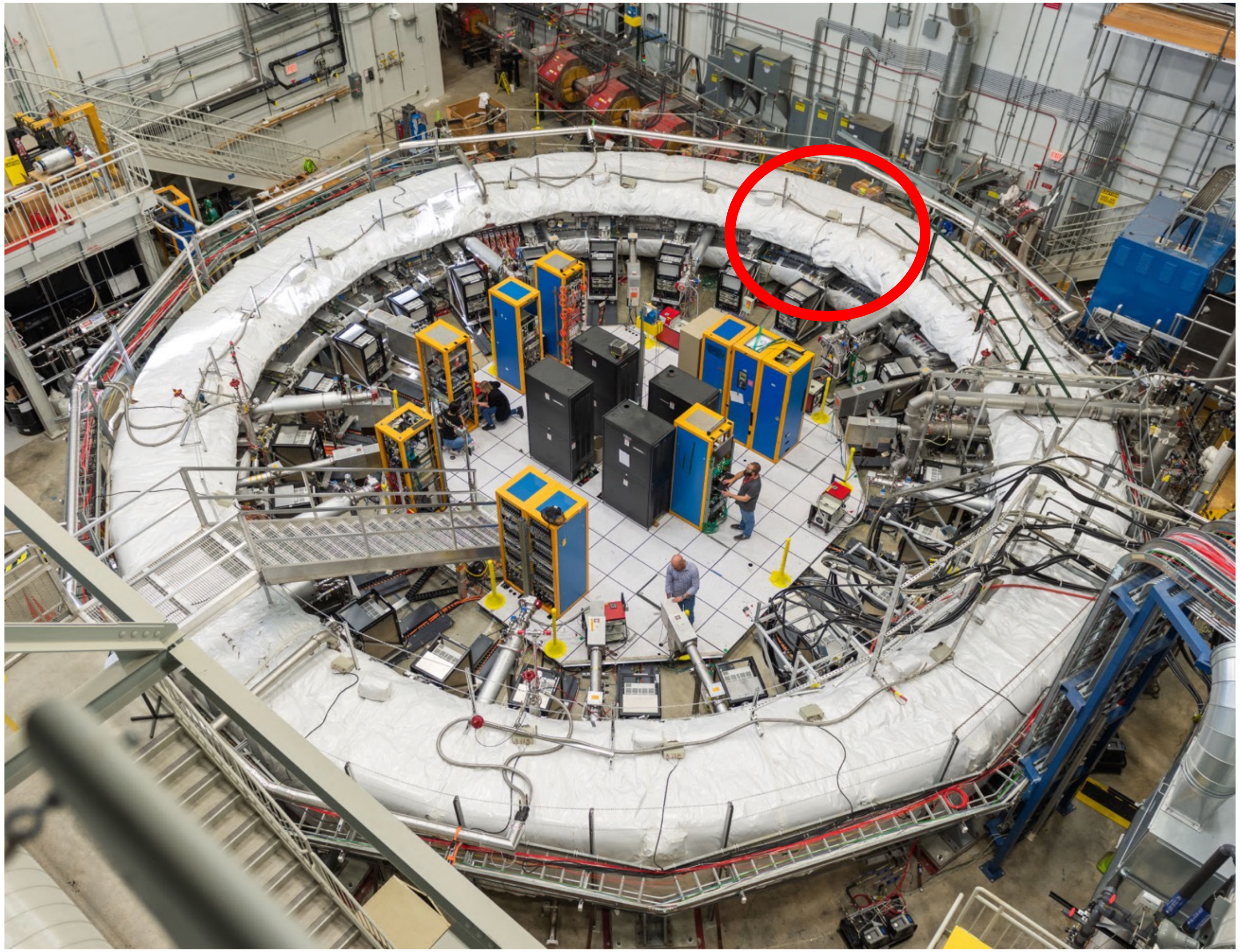


# The beam

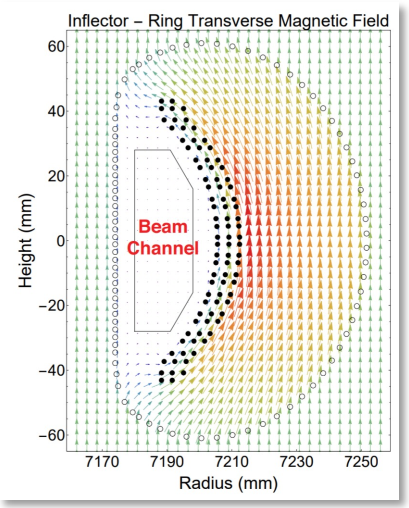


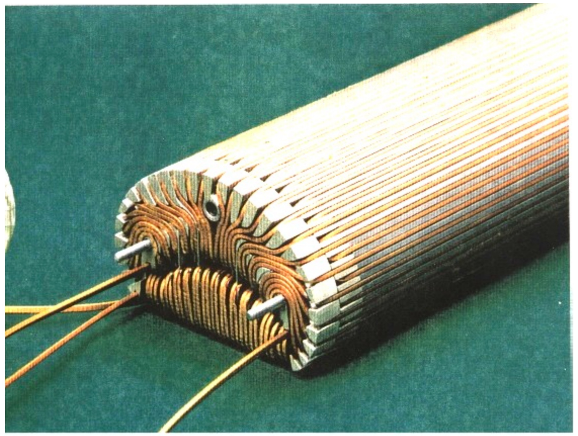
- We receive 3.094 GeV/c polarized muons from the Fermilab accelerator complex.
- $\mu^+$ are produced via upstream $\pi^+$ decay.



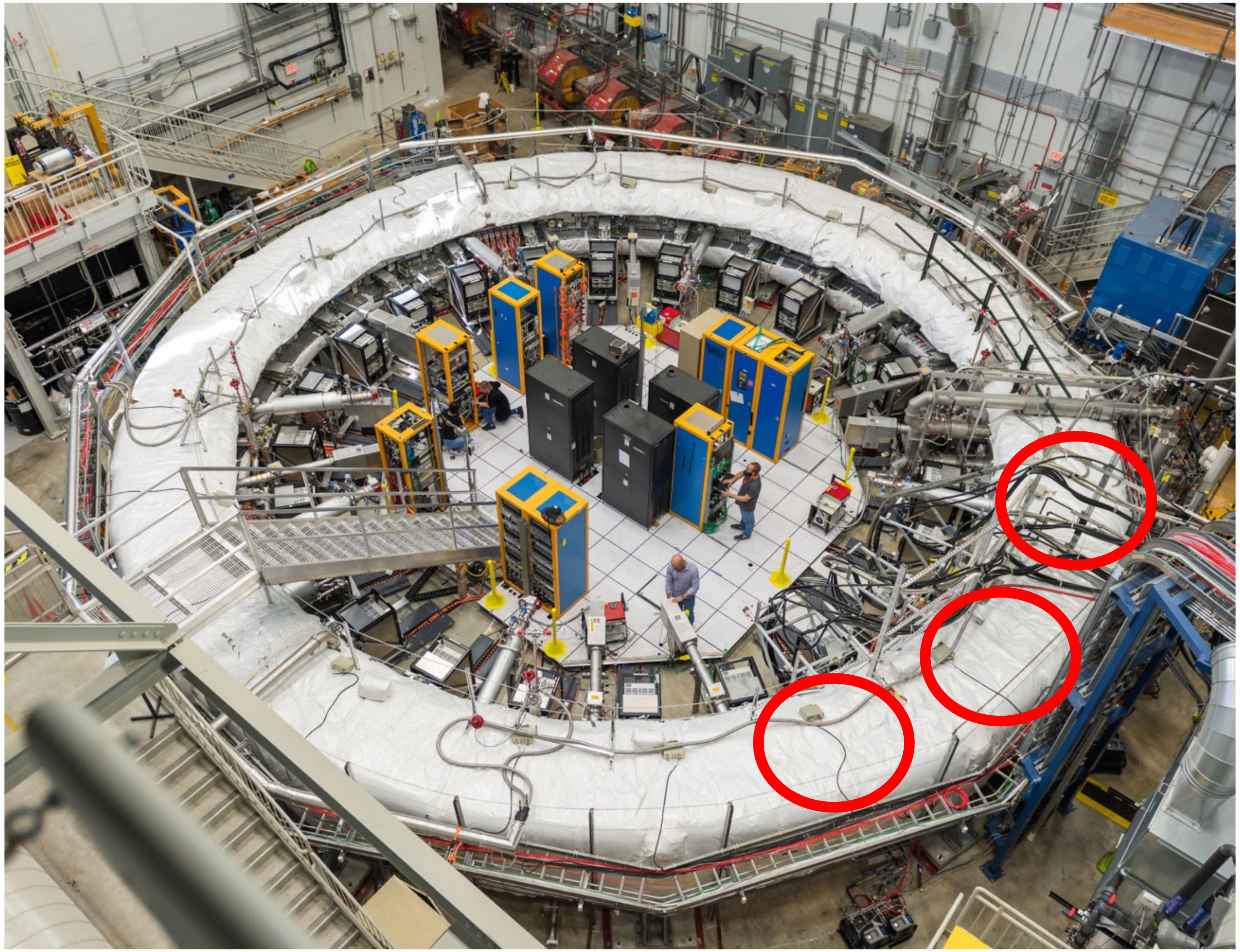


- Muons are injected through a field cancelling superconducting inflector magnet.

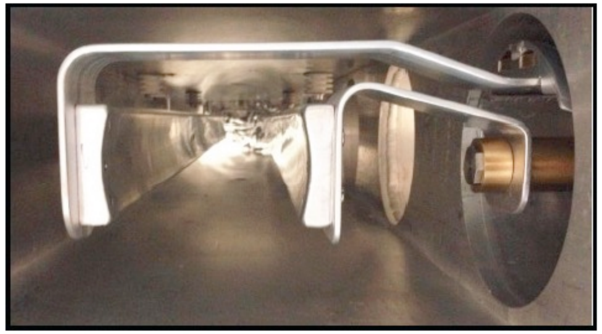


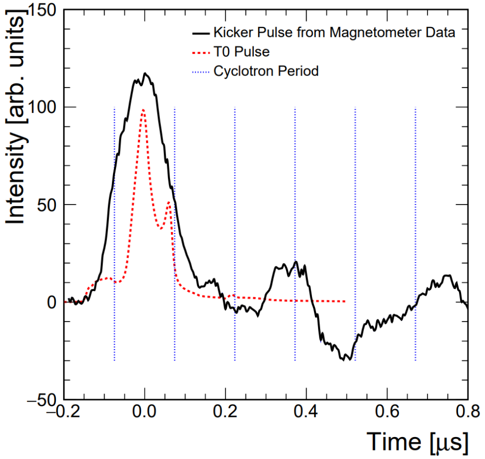



# The kick

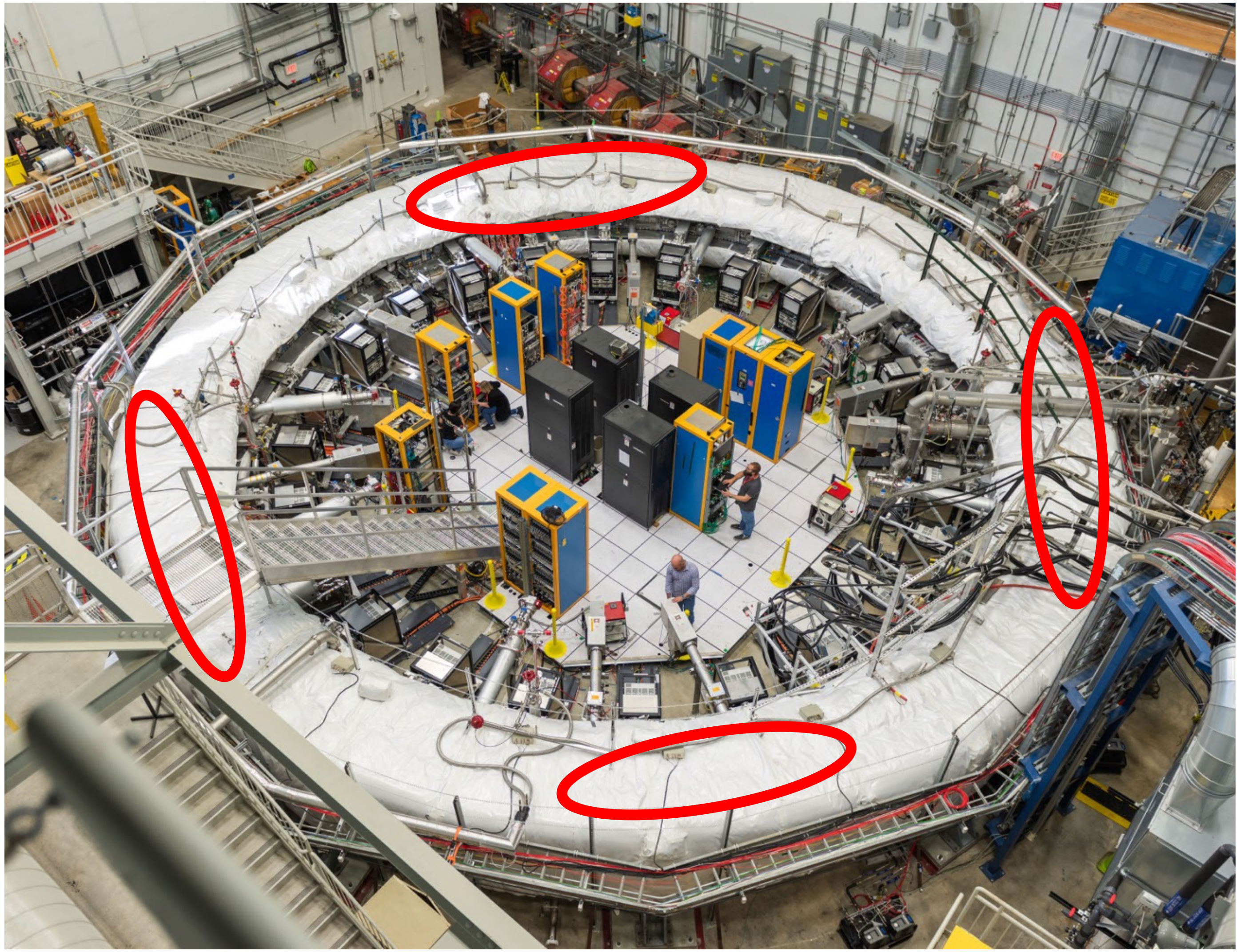


- Three fast electromagnetic kickers set the beam on a stable orbit.

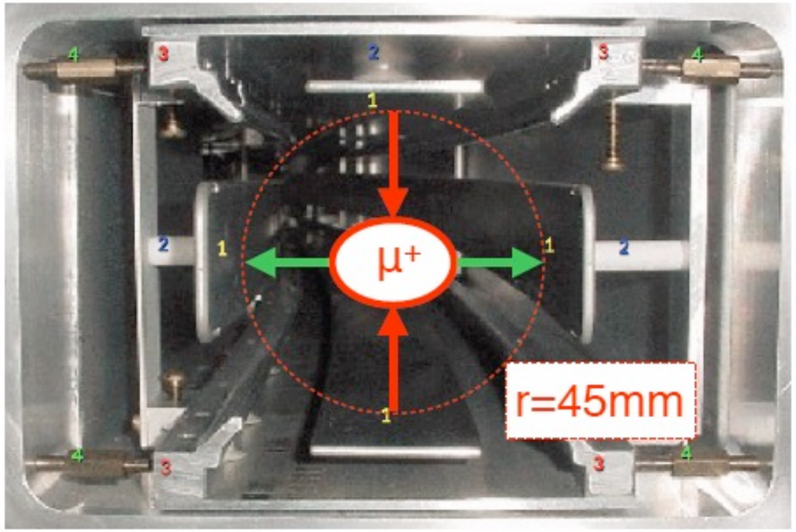




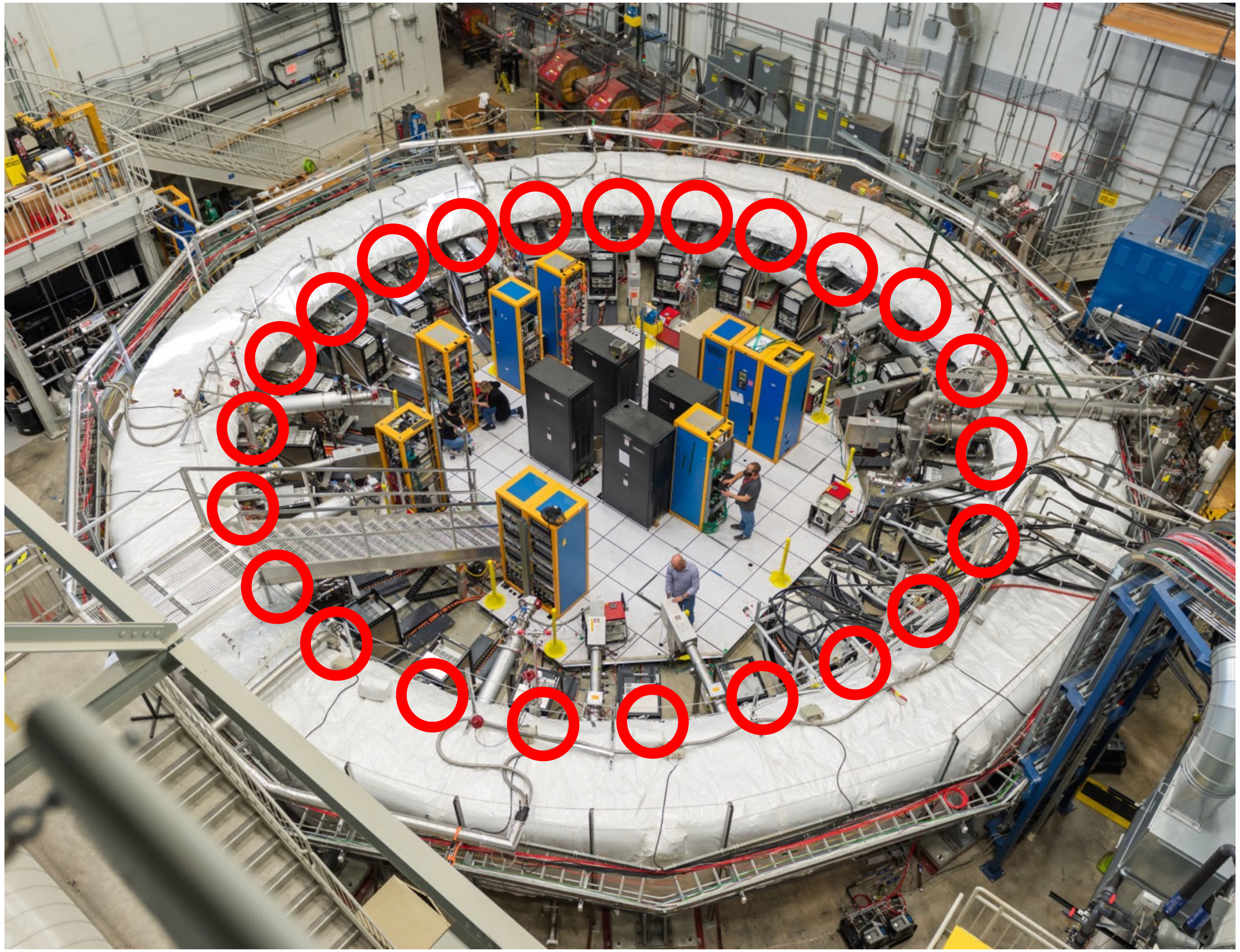
# Focusing



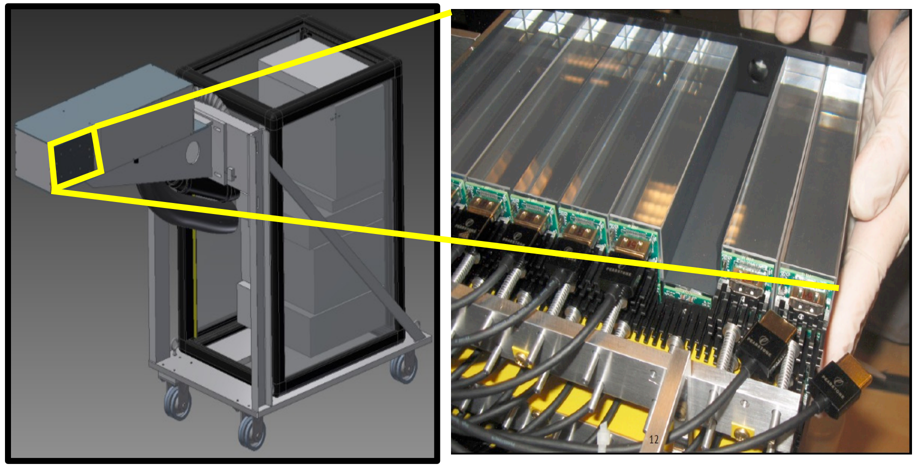
- Four set of electrostatic quadrupole plates provide vertical focusing.
- The magnetic field provides net radial focusing.

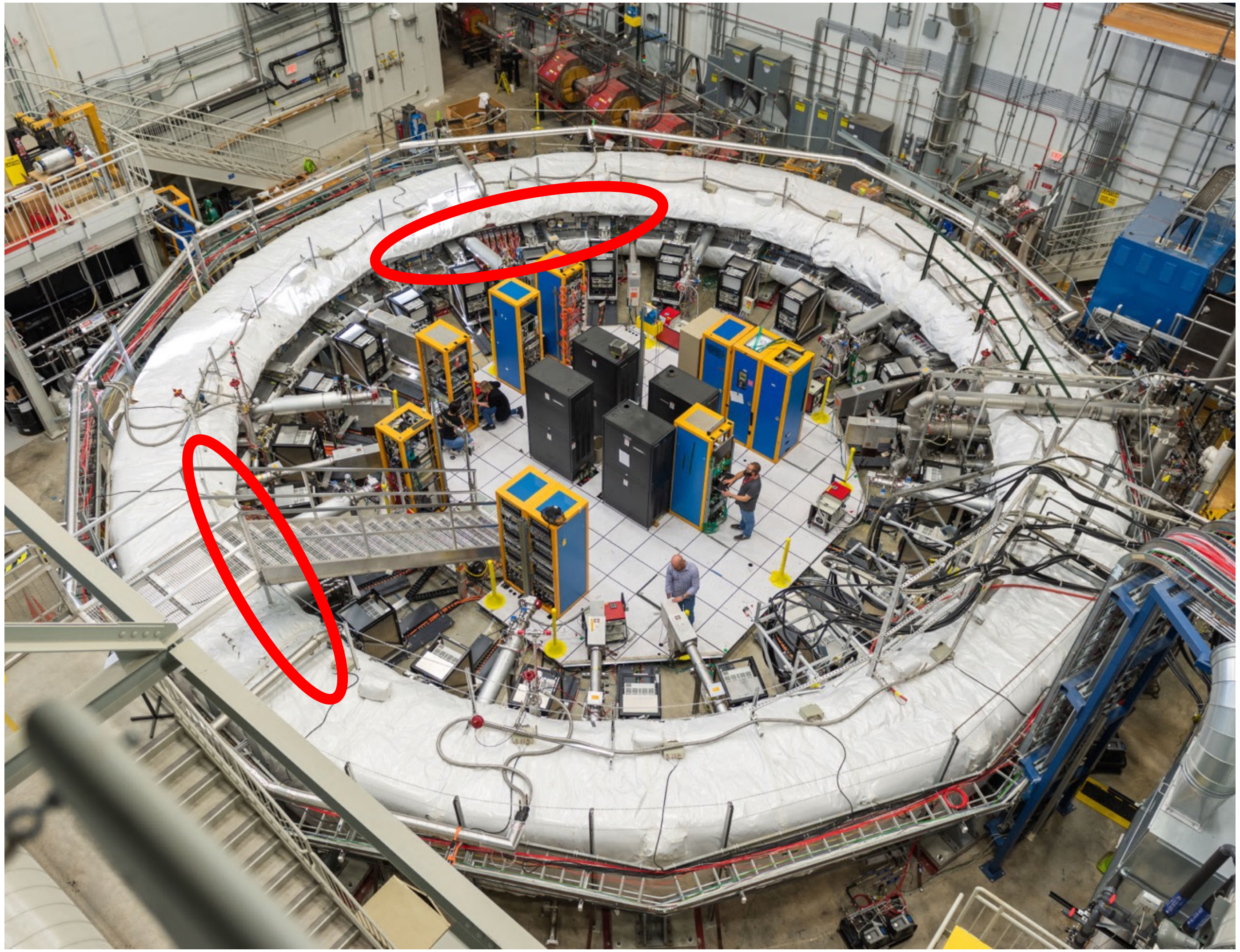


# Calorimeters

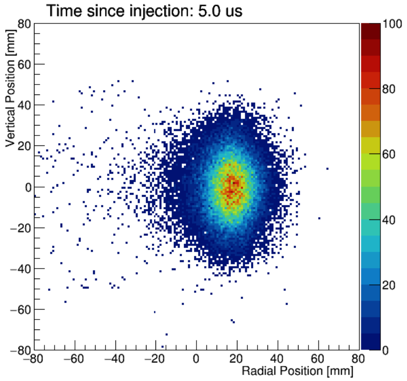


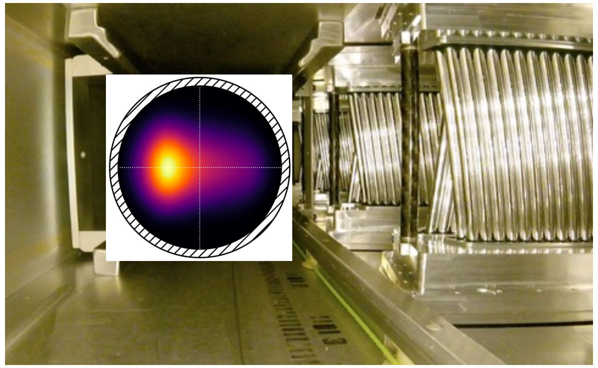
- Twenty-four calorimeters measure the time and energy spectrum of decay positrons falling out of the magnetic field.
- Charged particles produce Cherenkov light in a 9-wide x 6-high array of lead-fluoride crystals, sensed by silicon photomultipliers.





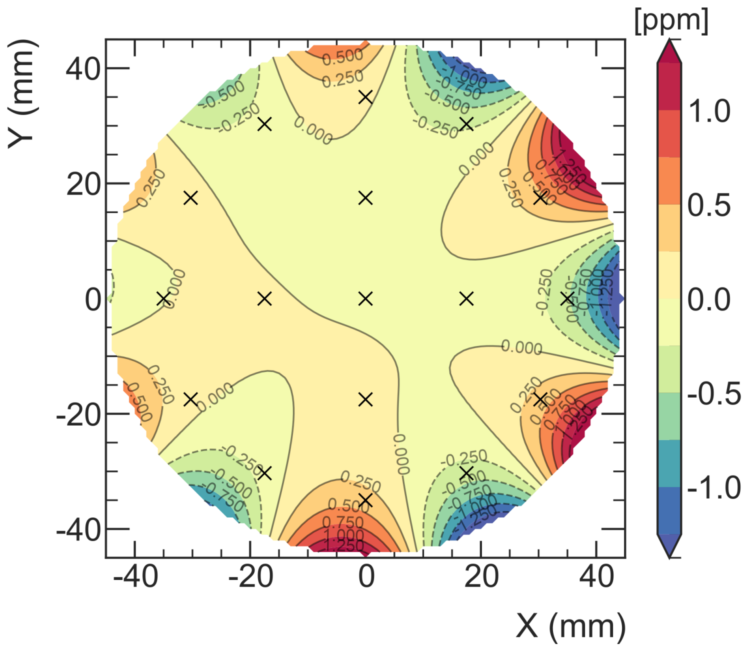
- Two in-vacuum straw tracker detectors measure decay positron position and momentum.
- 2048 Mylar straws enclosing argon-ethane atmosphere. A sense wire, surrounded by a radial electric field, records hits which are reconstructed into tracks.
- Essential for understanding our beam!



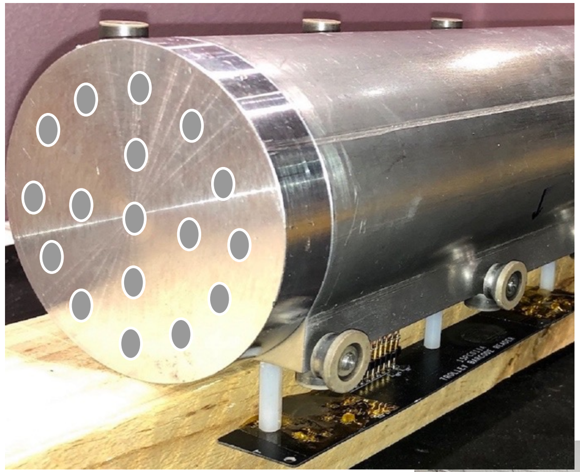



# Measuring the magnetic field

- The field is measured with a suite of fixed and mobile NMR probes.




Field variation around the ring is <1 part-per-million!

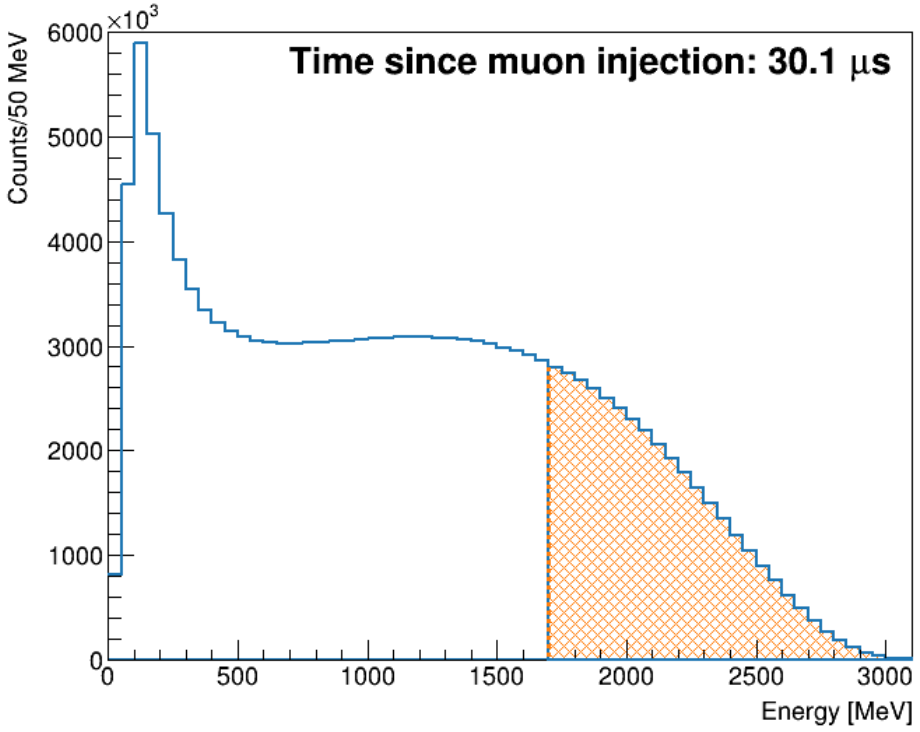


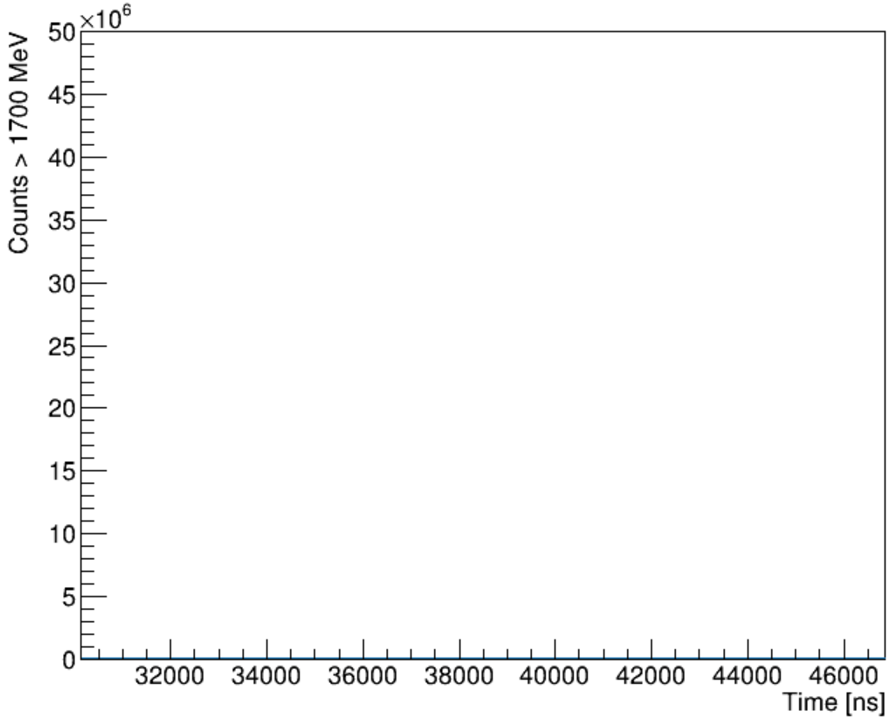
In-vacuum NMR trolley

378 fixed probes

# Measuring spin precession

- High energy decay positrons are preferentially emitted in the direction of the muon spin vector.
- Count hits landing in the calos above some energy threshold: the resulting oscillation is at $\omega_a$!



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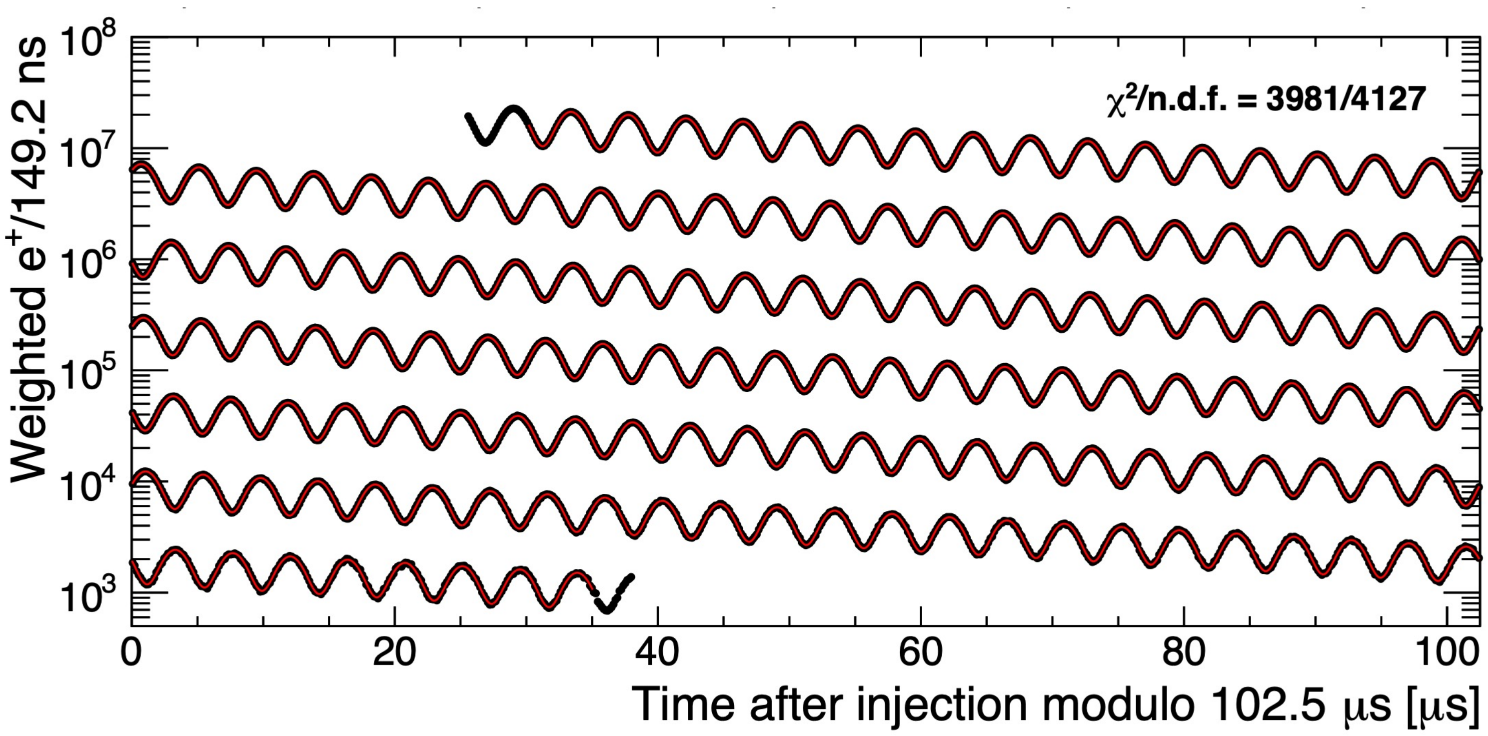
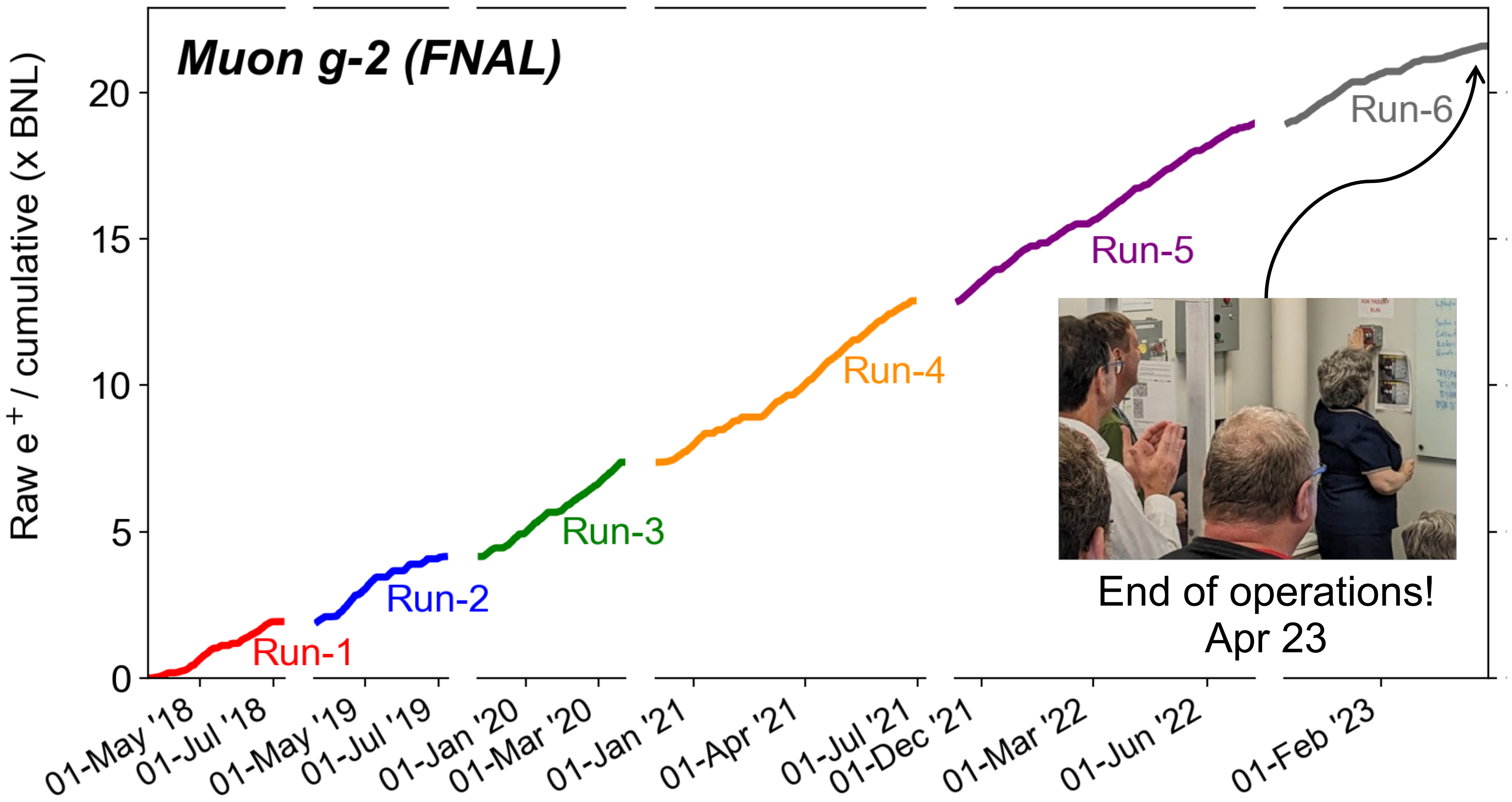


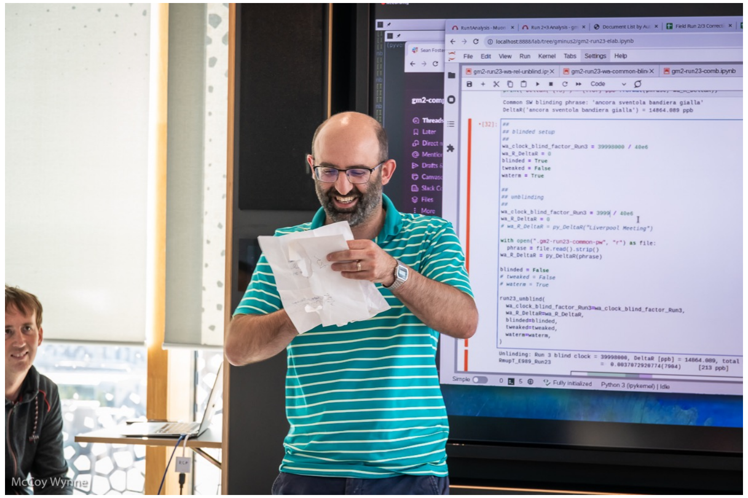

Fit to a Run-3 “wiggle plot”.

# Data taking (2018-2023)

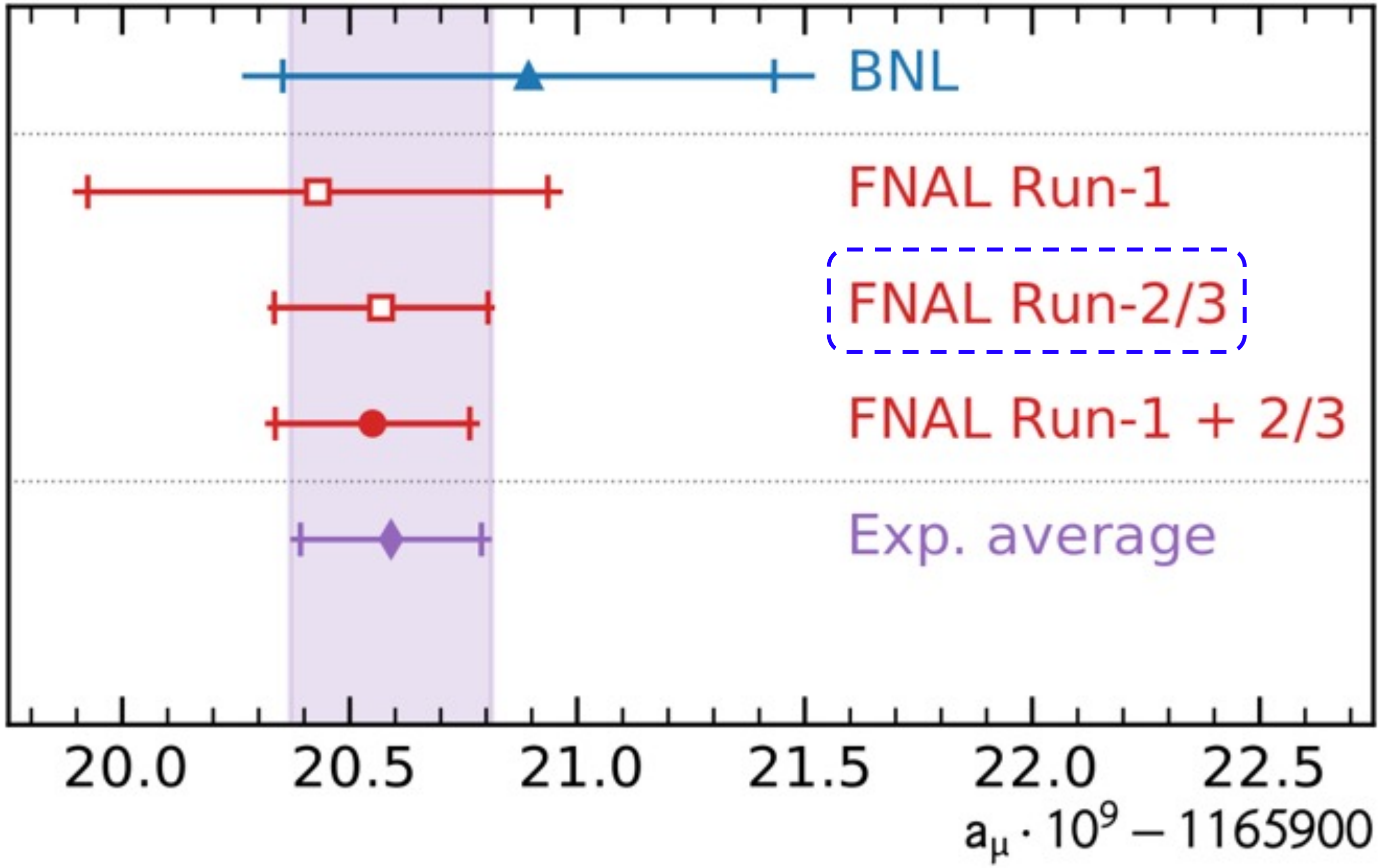



- Exceeded proposal goal for collected positrons and completed operations last year.
- Latest results encompass Run-2/3, Run-4/5/6 still to come…

# Latest results (Run-2/3)

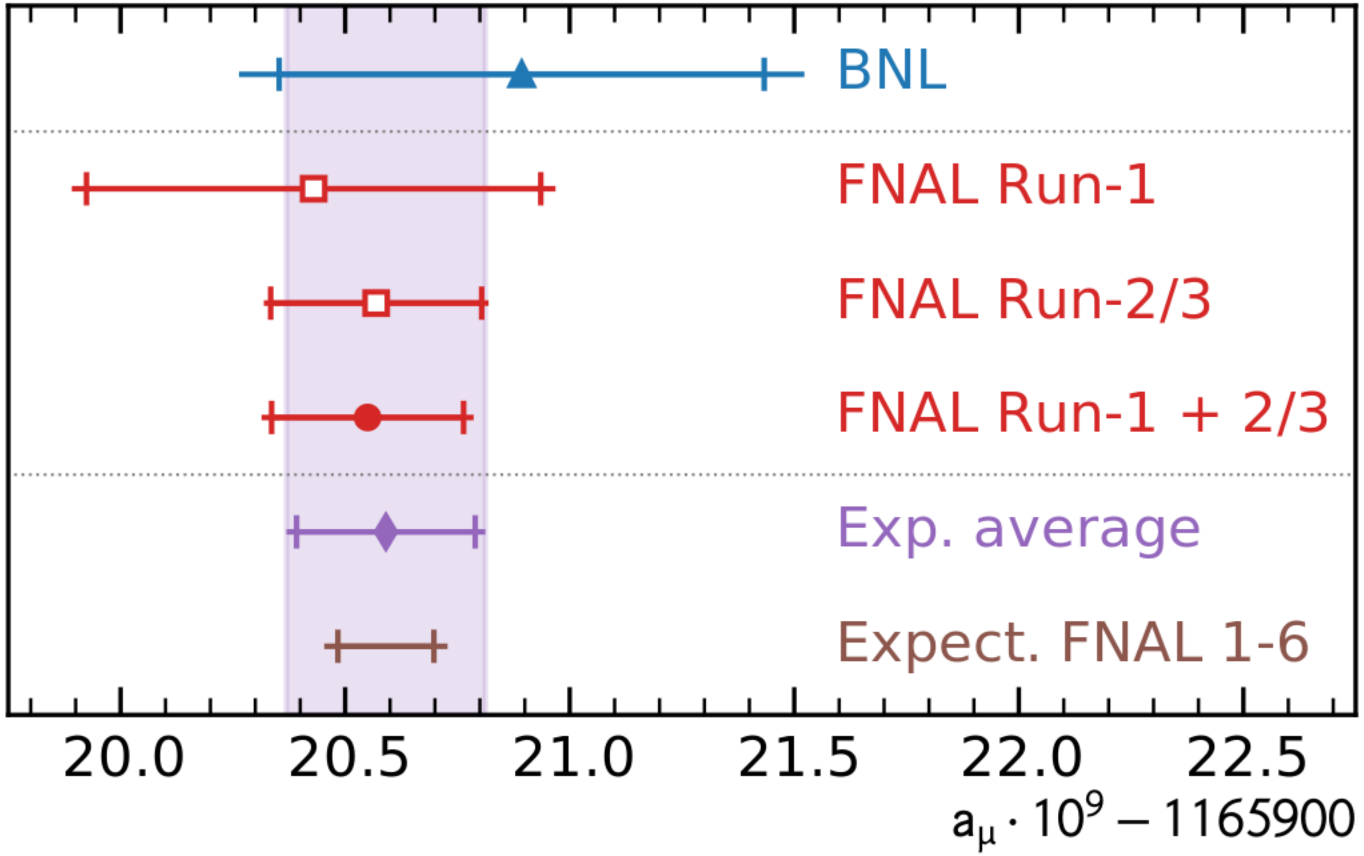



Unblinding Run-2/3 in July 23!




- Excellent agreement with previous results and an uncertainty of 215 ppb, which is mostly statistical!
- FNAL dominates the world average, which has a combined uncertainty on Muon $g-2$ of 190 ppb!
- For context, if $1.00 comprised 190 ppb of your bank balance, you would have $5,263,157.89 …

# Future results



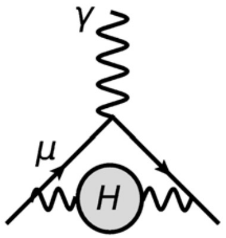

- Full dataset expected to be published in 2025 (2x precision).

**More physics results to come:**

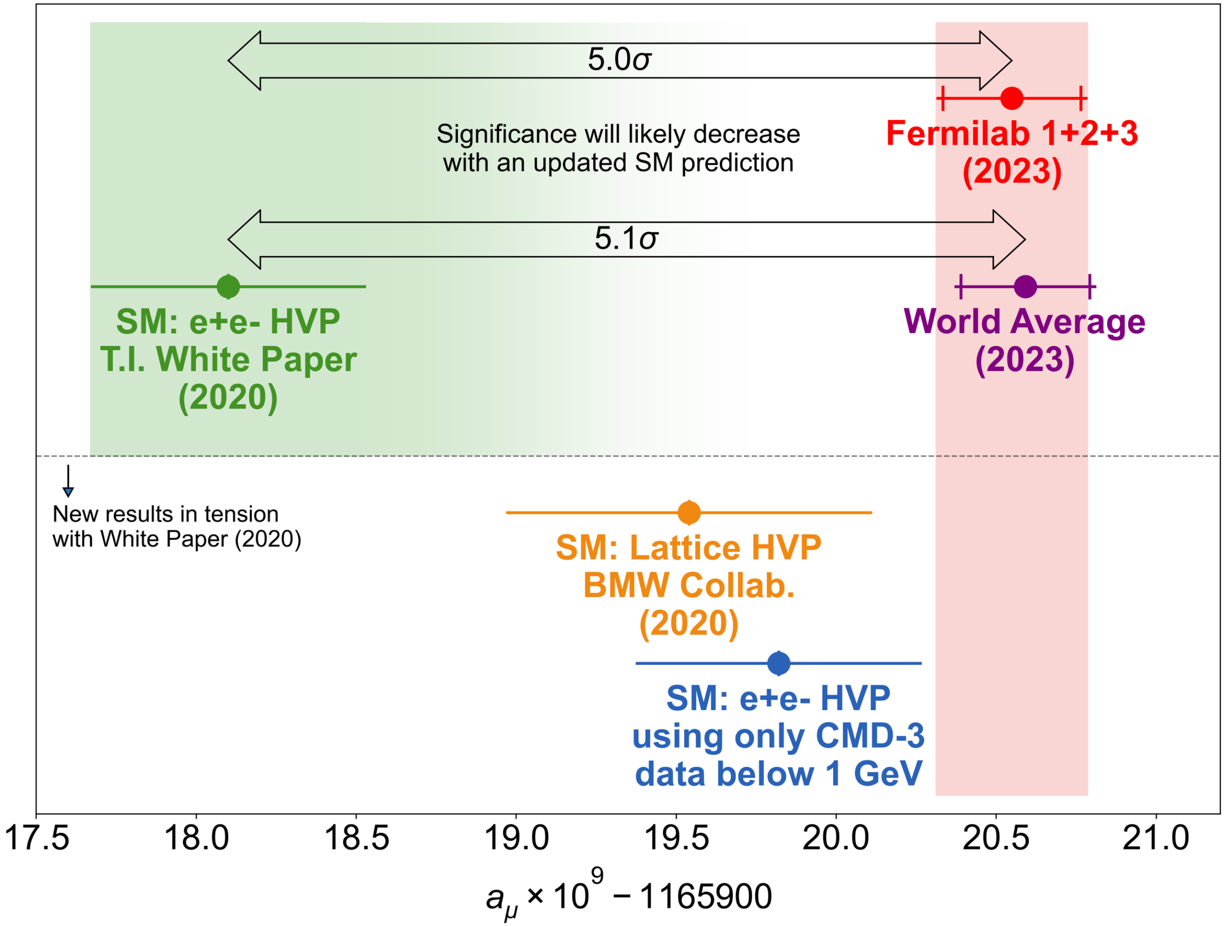
- Muon EDM search!
- BSM CPT/LV & Dark Matter searches!

# A puzzle for theorists

- The non-perturbative "hadronic vacuum polarization" (HVP) contribution to Muon $g-2$ is tricky to handle.




- Official data driven result using $e^+e^- \to \text{hadrons}$ scattering cross sections indicate a $>5\sigma$ anomaly.
- Lattice QCD simulations indicate consistency with the SM.
- New $e^+e^-$ measurements disagree with numerous previous measurements and confuse things further.
- Something has to give, stay tuned!




A. Keshavarzi

IMPORTANT: THIS PLOT IS VERY ROUGH!
- 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!

# Thanks for listening!

# Extra slides

# Full treatment of $\omega_a$

The full treatment of $\omega_a$ goes as follows:

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

Second term to zero if the momentum is set to the **magic momentum** (3.094 GeV/c, ɣ=29.3). → 0

Third term goes to zero if the momentum vector is perpendicular to the field (**the pitch is zero).** → 0

# Systematics

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

| Quantity | Correction [ppb] | Uncertainty [ppb] |
|---|---|---|
| $\omega_a^m$ (statistical) | – | 201 |
| $\omega_a^m$ (systematic) | – | 25 |
| $C_e$ | 451 | 32 |
| $C_p$ | 170 | 10 |
| $C_{pa}$ | -27 | 13 |
| $C_{dd}$ | -15 | 17 |
| $C_{ml}$ | 0 | 3 |
| $f_{\mathrm{calib}} \langle \omega_p'(\vec{r}) \times M(\vec{r}) \rangle$ | – | 46 |
| $B_k$ | -21 | 13 |
| $B_q$ | -21 | 20 |
| $\mu_p'(34.7°)/\mu_e$ | – | 11 |
| $m_\mu/m_e$ | – | 22 |
| $g_e/2$ | – | 0 |
| Total systematic | – | 70 |
| Total external parameters | – | 25 |
| Totals | 622 | 215 |