Muon g-2 at Fermilab

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On behalf of the Muon g-2 Collaboration

Fermilab Summer Lecture Series

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The E989 Muon g-2 Experiment

- Goal: Measure muon magnetic moment.
- Purpose: Search for physics beyond the Standard Model.
  - SM predicts one value.
  - Potential new models (supersymmetry) predict different values.
  - Precision measurement will give evidence for or against new models.

Muon g-2 Collaboration group photo, November 2014.

Presentation Overview

- Introduction: the Muon g-2 Experiment
- Background: Muons, Magnetic Moments, and “g”
- Goals: Significance of Muon g-2
- Methodology: Measuring Muons
- Design: Muon Storage Ring
- Design: Magnetic Field Probes
- Results (so far)
- Conclusion and Discussion

Background

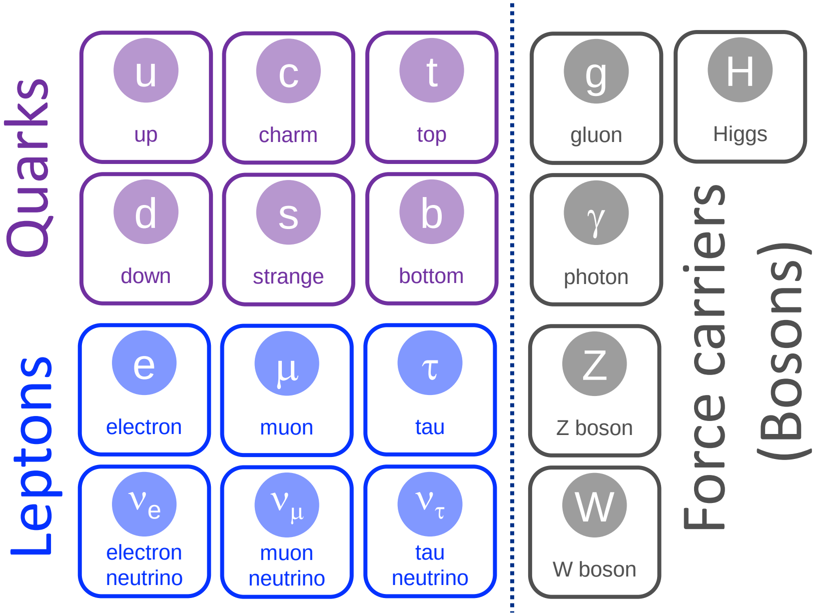
Muon?

g-2?

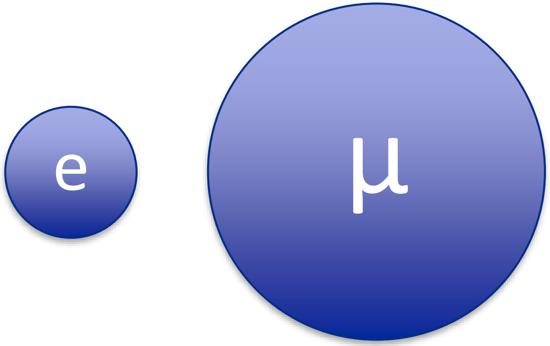
Experiment?

The?

Meet the Muon!



Standard Model Particles



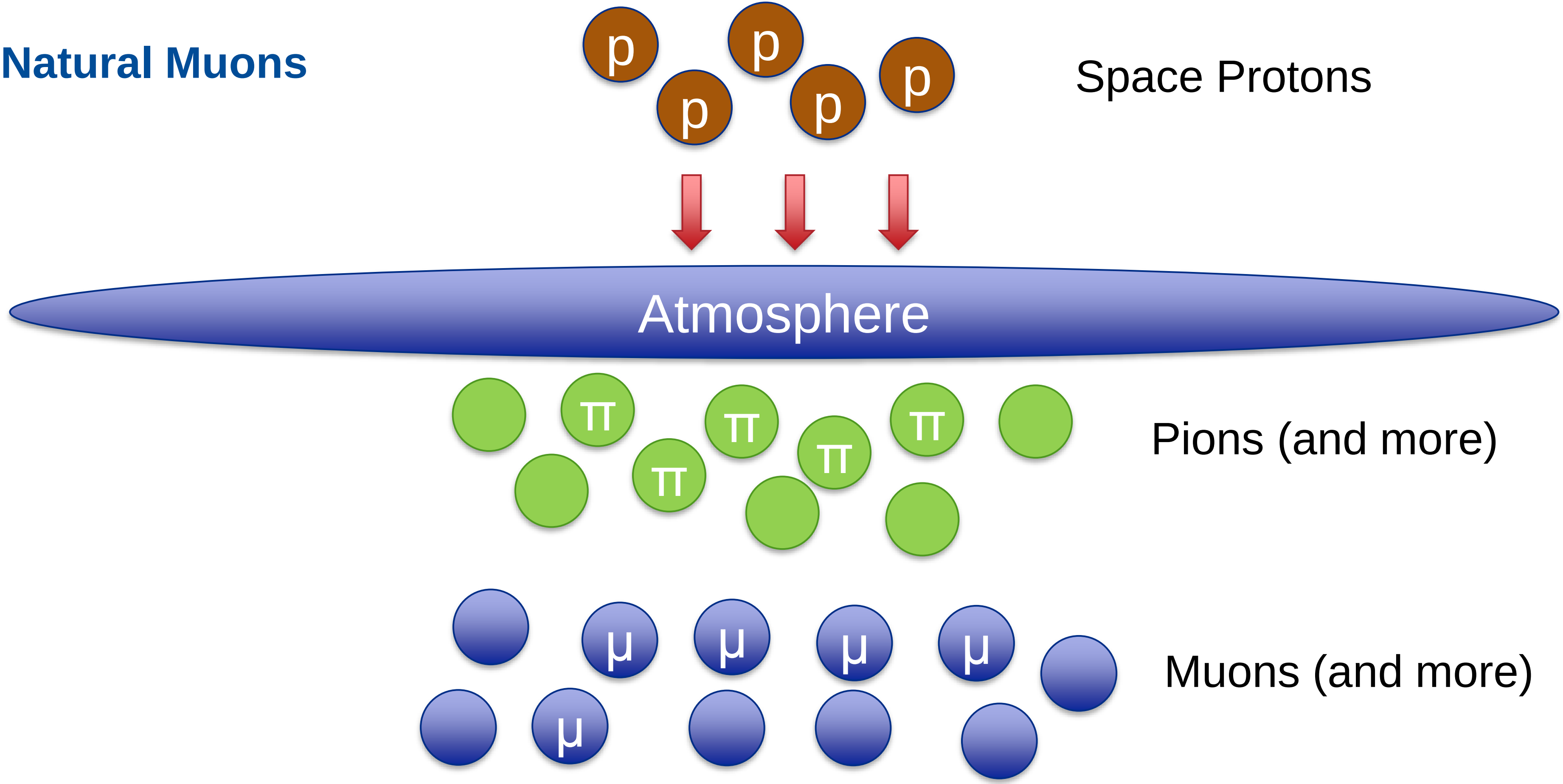
Same charge,
same spin,
207x larger mass.

Muon Decay

$$\mu^- \to e^- + \nu_\mu + \bar{\nu}_e$$

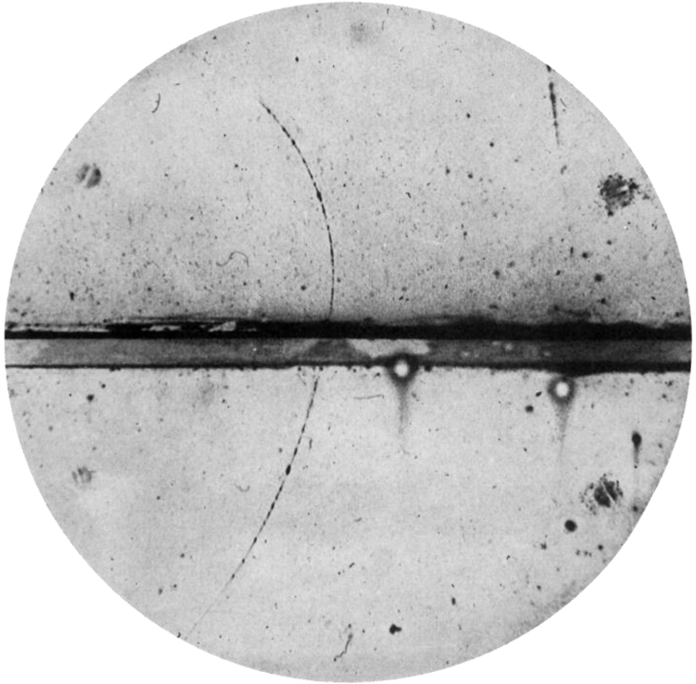
Muon lifetime: 2.2 microseconds.

Natural Muons



Discovering Muons

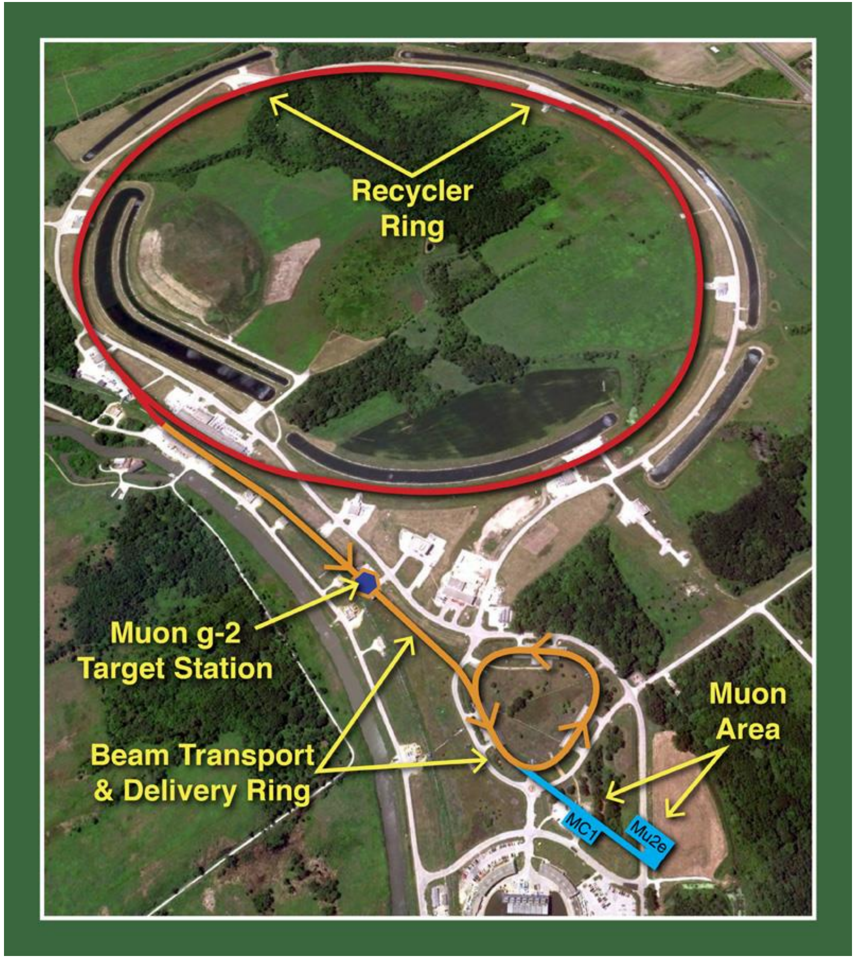
- Discovered in 1936 by Carl Anderson and Seth Neddermeyer.
  - Observed in cosmic ray showers.



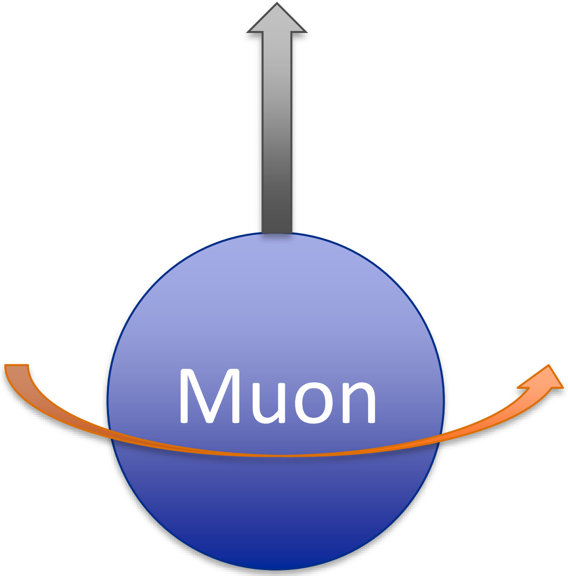
Cosmic ray tracks visible in a magnetic cloud chamber.

Making Muons at Fermilab

- Particle accelerator provides protons.
- Protons hitting target create pions.
- Pions decay into muons.
- Filters select positive muons, with “magic momentum” 3.094 GeV/c.



Magnetic Moments



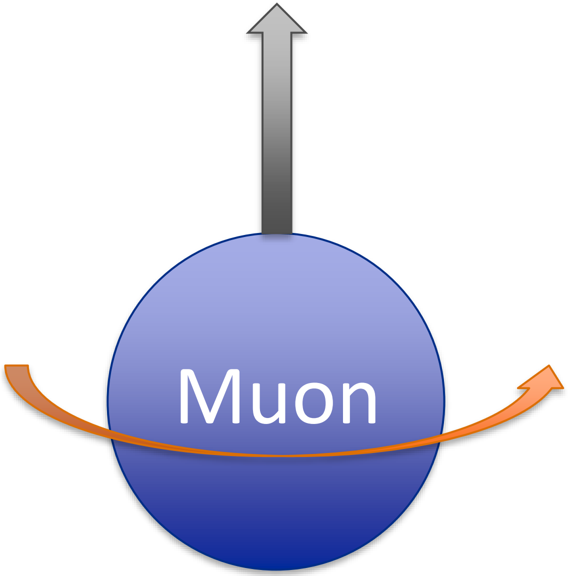
Muon Magnetic Moment $\vec{\mu}$:

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

Charge q and Spin $\vec{S}$ make muons magnetic.

Magnetic moment $\vec{\mu}$ describes how strongly muons respond to magnetic fields.

The g-factor



Muon Magnetic Moment $\vec{\mu}$:

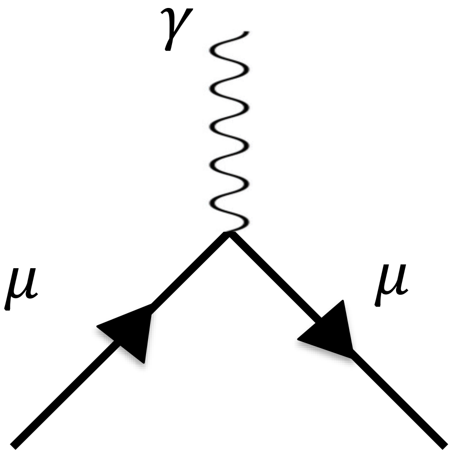
$$\vec{\mu} = g * \left(\frac{q}{2m}\right) * \vec{S}$$

The quantum correction factor "g".
(It's the "g" in "Muon g-2".)
Measuring it is our goal!

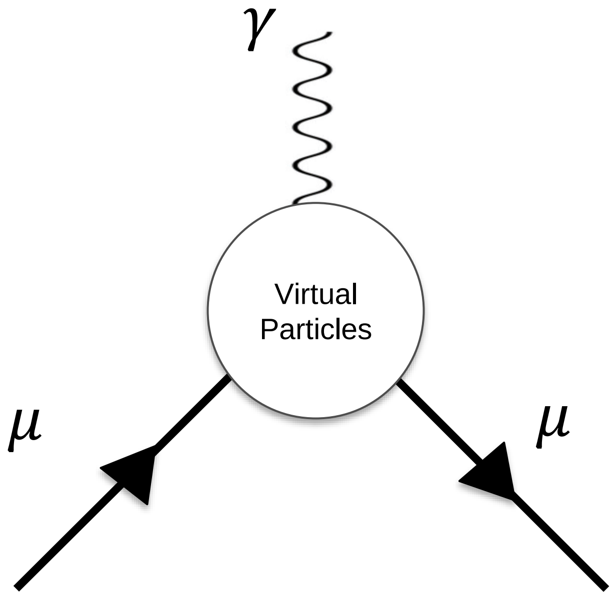
But a_μ makes equations nicer, so we usually end up writing a_μ instead.

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

Quantum Corrections



In quantum physics, all possible paths impact the outcome.



Basic Feynman Diagram: Muon interacts with magnetic field.

(With just this, g would be 2.)

Additional diagrams cover the superposition of many possibilities!

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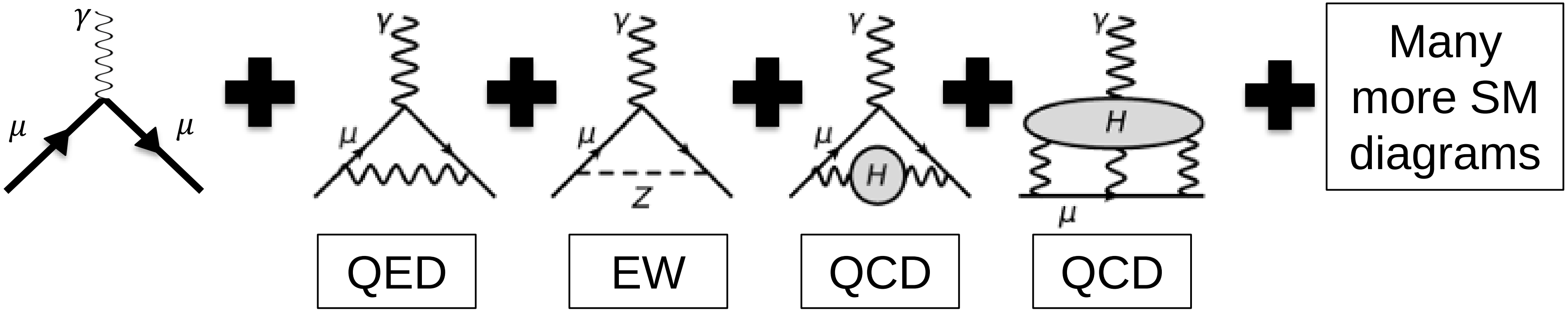
Predicting "g"

- The Standard Model lets us calculate diagrams using all known particles, forces, and interactions.

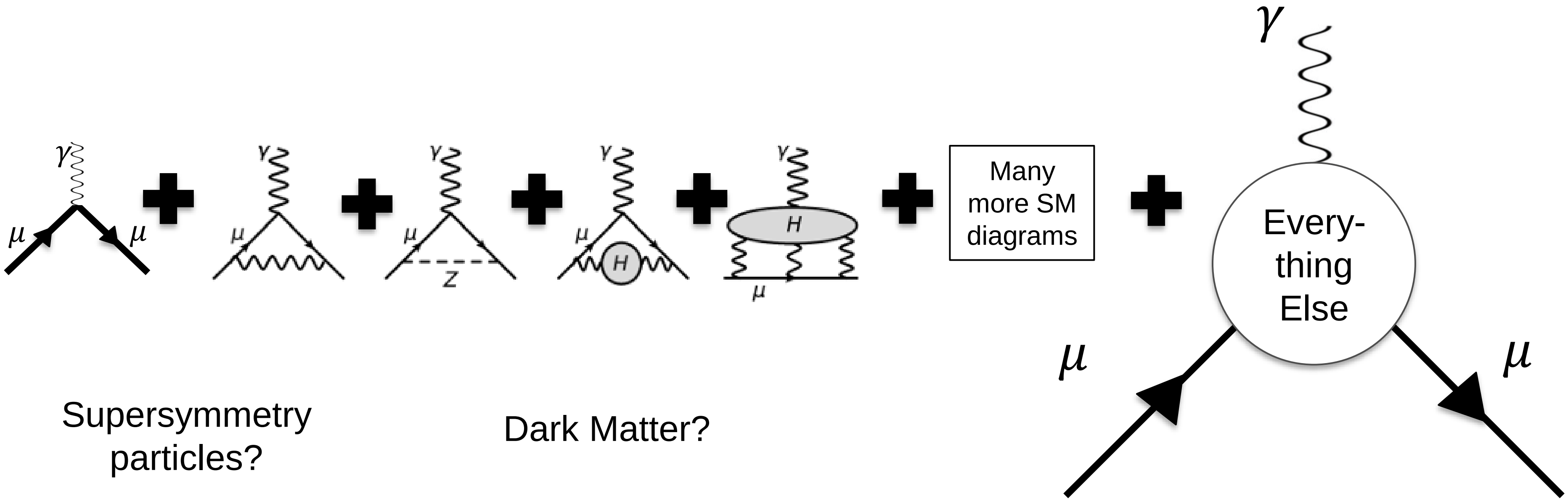


- Standard Model Prediction (as of 2020)*:
  - $g = 2.0023318362$
  - (*Technically undetermined since 2021, due to two conflicting HVP calculations.)

Why this is important

The true value of "g"

- All of physics goes into determining "g". Including undiscovered physics!



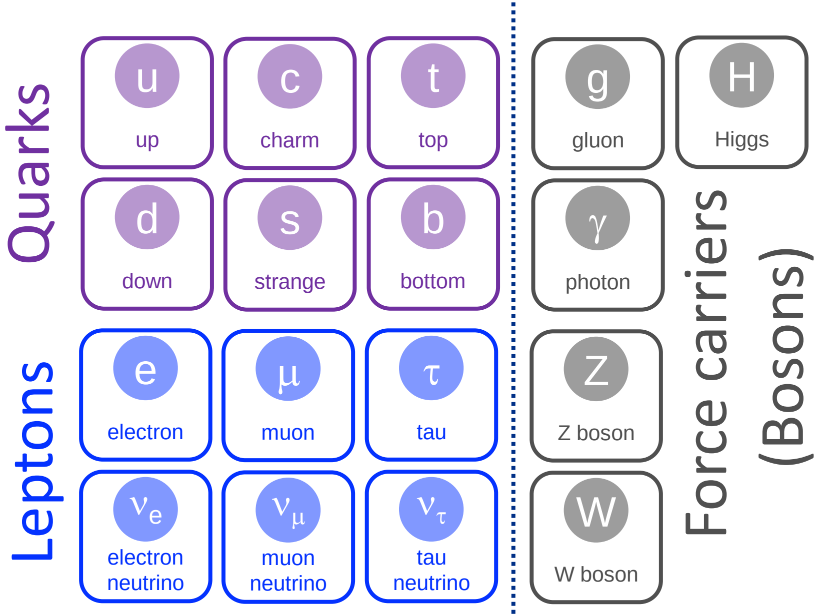
Supersymmetry particles?

Dark Matter?

Humans might not know about them yet, but muons do!

Testing the Standard Model

- The Standard Model is incomplete.
  - There are ideas for Beyond the Standard Model (BSM), but none have supporting evidence yet.
- This experiment will help clarify what's missing.
  - Agreement with theory -> Constrain BSM models
  - Disagreement with theory -> Confirm BSM models



Clarification

Supersymmetry particles?

Dark Matter?

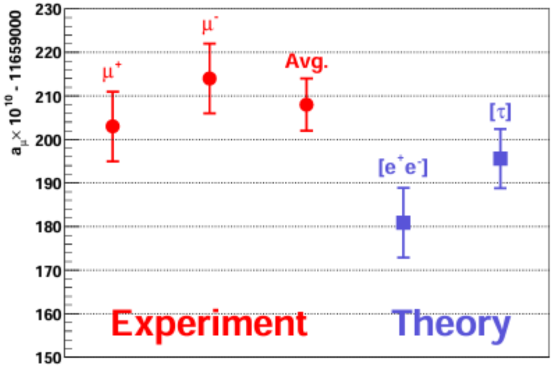
"Humans might not know about them yet, but muons do!" *

- *Technically true for all particles.
- Muon magnetic moment is special for two reasons:
  - High mass makes it more sensitive to possible supersymmetry particles.
  - We might have seen new physics in it already!

Brookhaven E821

- A muon magnetic moment experiment at Brookhaven National Lab, running 1997 – 2001.
- Found discrepancy with Standard Model!
- But, only by ~3.5σ.

Standard for a new discovery: 5σ



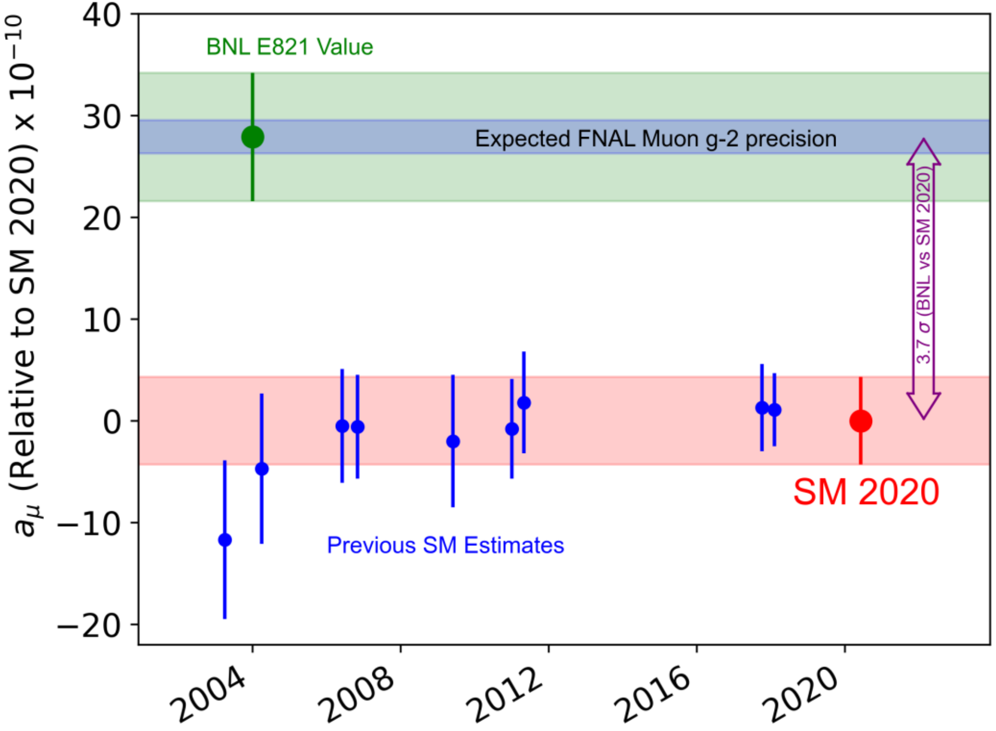
Brookhaven E821 g-2 Experiment.
Collaboration photo (left),
Results comparison (above).

Muon g-2 Beyond Standard Model

- Several BSM models match Brookhaven's findings.
  - Supersymmetries mostly.
- Experimental uncertainty must be reduced before conclusions can be made.
- This motivated Muon g-2 at Fermilab:
  - Improve and redo Brookhaven's measurement with 4x lower uncertainty.
  - Uncertainty goal: 140 parts per billion (ppb).
  - One of the most precise measurements in human history!

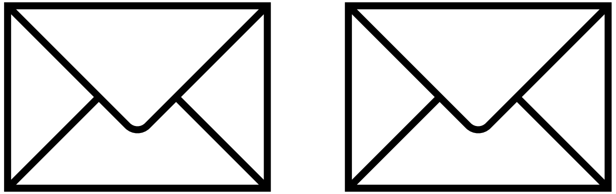
Difference > 5σ ? → Physics beyond the Standard Model!

Uncertainty Goal



Blinding system

- Major experiments reduce risk of bias by scrambling (“blinding”) incoming data.
  - All analysis is performed using blinded data.
- Muon g-2 had separate blinding for each year of data collection.
- Unblinding meetings are very exciting!



Unblinding codes are kept in sealed envelopes, held by trusted peers outside the collaboration.

Run-1 Unblinding Meeting (2021)

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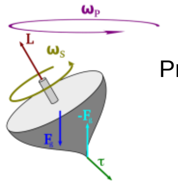
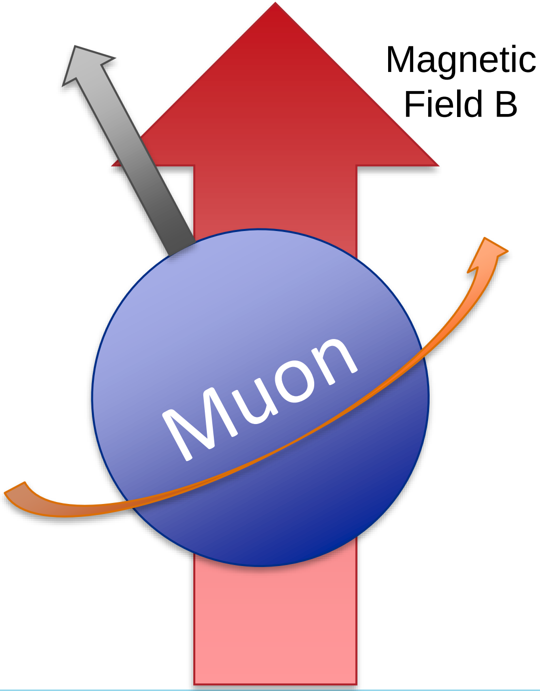
Measuring Muons and a_μ

Precession



Precession for a spinning top, from gravity.

- In external B fields, muons precess.
- Precession frequency is proportional to muon magnetic moment, and to external B.



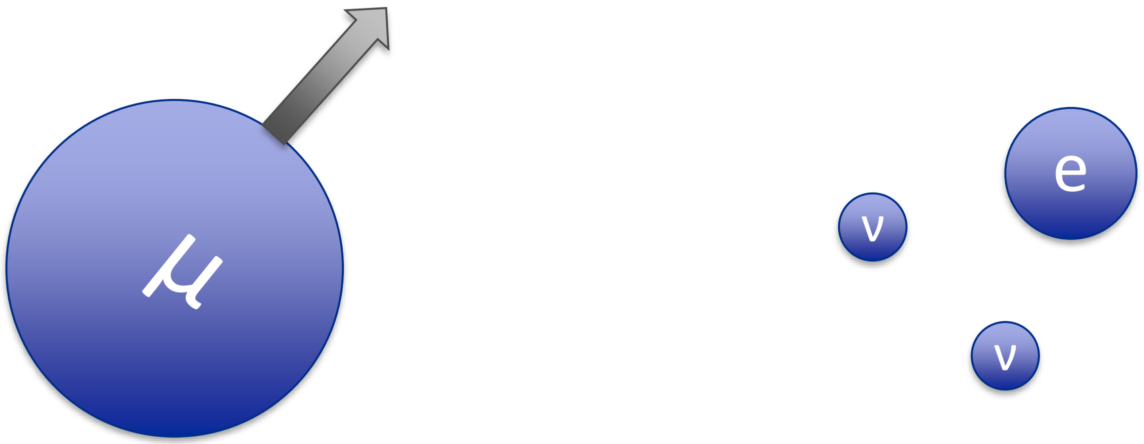
$$w_s = g * \left(\frac{-q}{2m}\right) * B$$ (Non-relativistic)

$$w_s = \left(g - 2 + \frac{2}{\gamma}\right) * \left(\frac{-q}{2m}\right) * B$$ (Relativistic)

- With muons in a big magnetic storage ring, we need to measure precession.

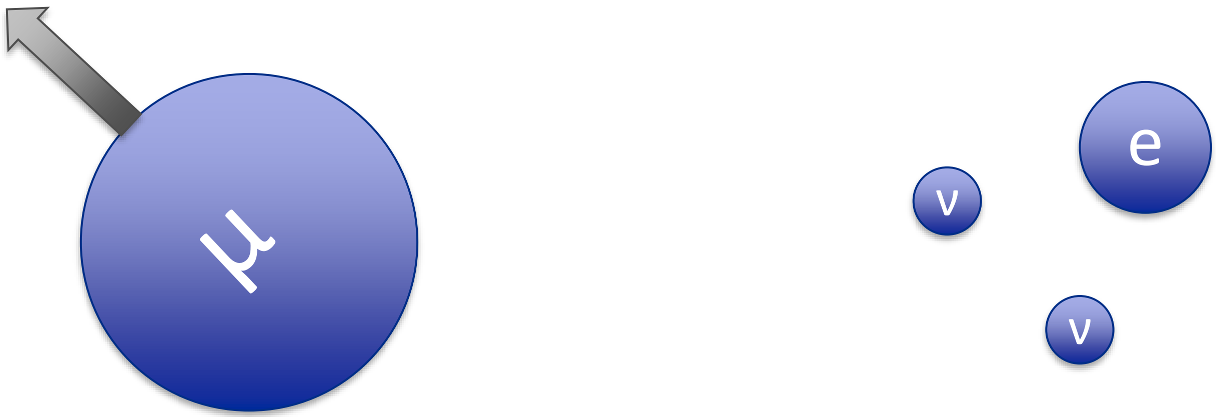
Precession Frequency and Muon Decay

- Special property of muon decays:
  - Energy of emitted positrons is higher when spin is aligned with linear momentum!



Precession Frequency and Muon Decay

- Special property of muon decays:
  - And it’s lower (on average) when spin is counter-aligned with linear momentum.

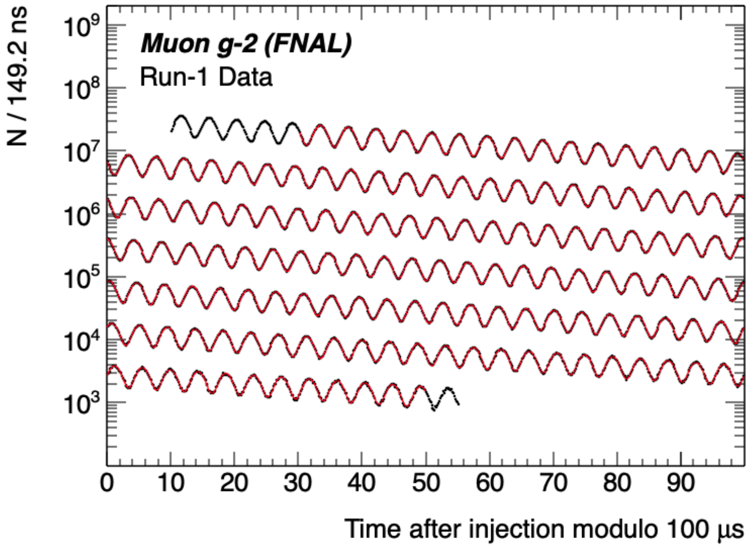


High-Energy Positron Plot

- With many aligned muons decaying, the # of high-energy positrons is $N(t)$.

$$N(t) = N_0 * e^{-\frac{t}{\tau}} * (1 + \cos(\omega_a * t + \varphi_0))$$

  - Oscillates at ω_a, based on the **angle between muon spin and momentum vectors.**



Run-1 "wiggle plot" of $N(t)$.

Fitting this provides ω_a.

ω_a, ω_s, and ω_c

$$\omega_a = \omega_s - \omega_c$$

Wiggle-plot Frequency

Spin Precession Frequency

Momentum Cyclotron Frequency

Cyclotron Frequency ω_c

- For muons moving on a circular path.
- Derived using centripetal force and Lorentz force.

$$\frac{\gamma * mv^2}{r} = qBv$$

$$\frac{v}{r} = \left(\frac{q}{\gamma m}\right) * B$$

$$\overrightarrow{\omega_c} = (-)\left(\frac{q}{\gamma m}\right) * \vec{B}$$

Getting a_μ

$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = \left(g - 2 + \frac{2}{\gamma}\right) * \left(\frac{-q}{2m}\right) * B - \left(\frac{-q}{\gamma m}\right) * B$$

$$\omega_a = -\left(\frac{g-2}{2}\right) * \left(\frac{q}{m}\right) * B$$

a_μ

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(Sneak Peek: Less-simplified Version)

$$\vec{\omega}_a = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Off-plane motion term

Electric field influence term

"Magic Momentum" 3.094 GeV/c shrinks these extra terms.

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Measurement Teams

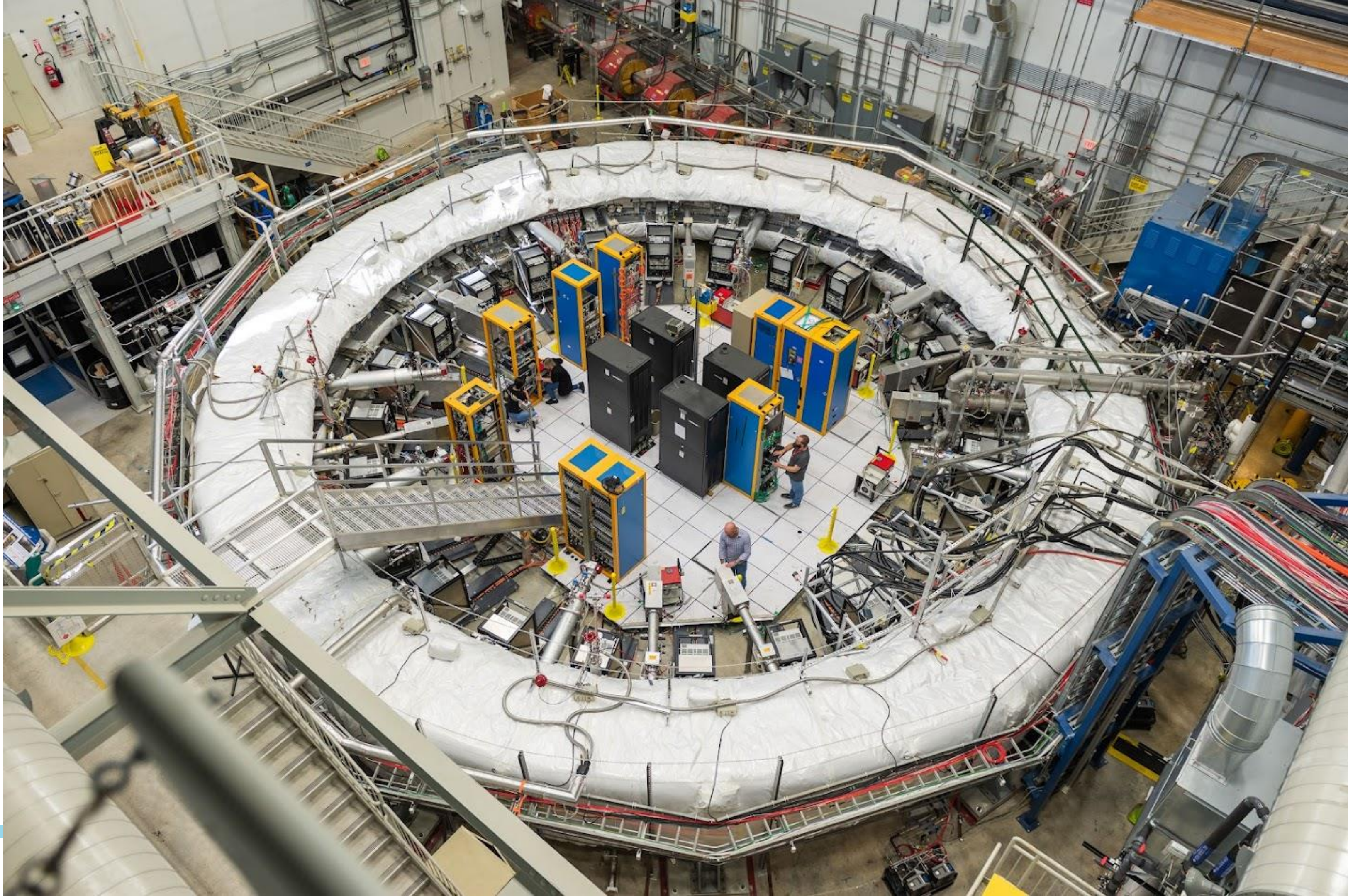
$$\omega_a = -a_\mu * \left(\frac{q}{m}\right) * B$$

- We send a bunch of muons into a big magnetic storage ring.
  - One team measures ω_a.
  - One team measures B.

  } Combine to get a_μ!
- Additional teams:
  - Muon tracking team.
  - Data processing team.
  - Simulations team.
  - Theory team.
  - Engineering team.
  - And more!

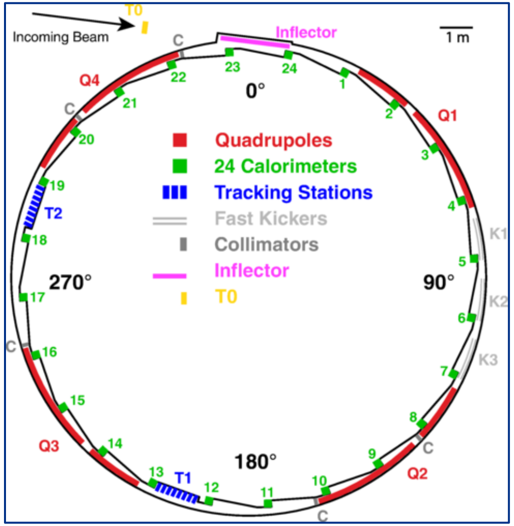
The Muon Storage Ring

The Muon g-2 Storage Ring Magnet

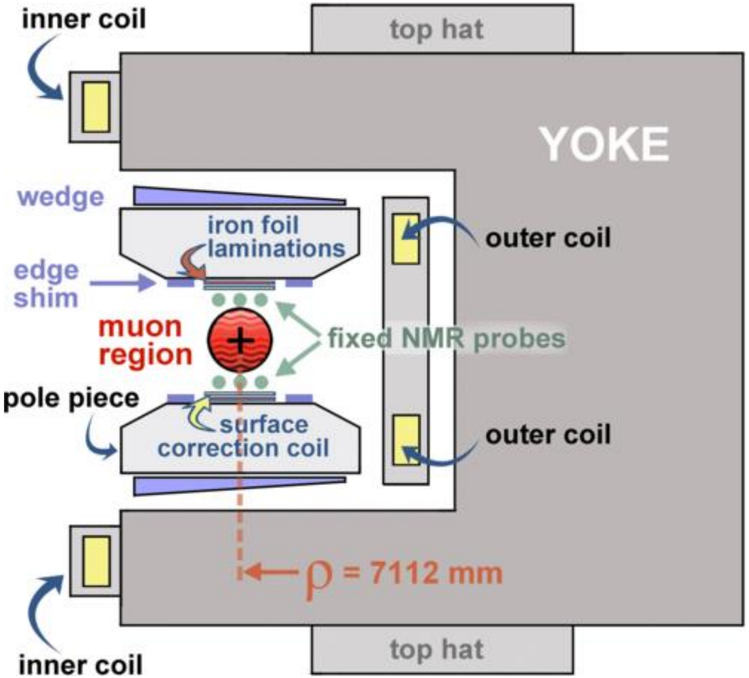


Ring Overview

- Creates a strong and stable magnetic field.
- Analyzes muons, decay positrons, and magnetic field strength.



Ring Stations Diagram



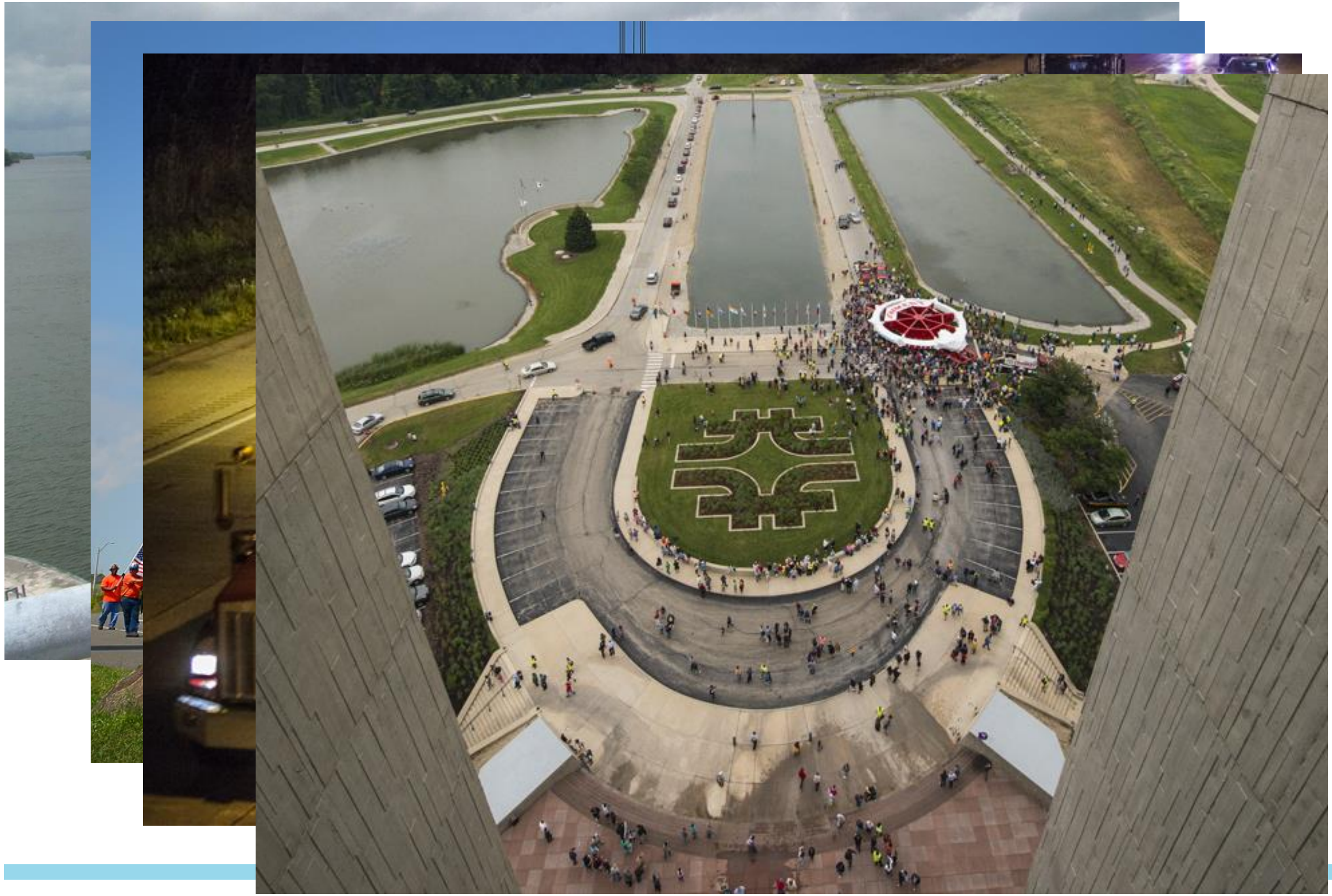
Cross-section Diagram

The Big Move

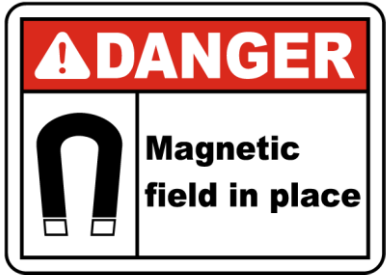
Map illustration from Symmetry Magazine, August 2013.

Storage ring moved from BNL to FNAL in Summer 2013.

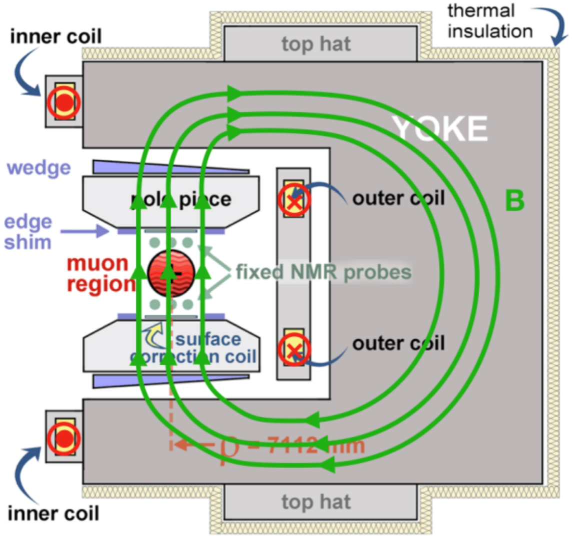
The Big Move: Photos



Superconducting Magnets



- Superconductors create a 1.45-Tesla magnetic field.
  - As strong as an MRI machine!
- Shimming tools stabilize the field (in time and space).
  - Iron shims.
  - Surface Correction Coils.
  - Power Supply Feedback.

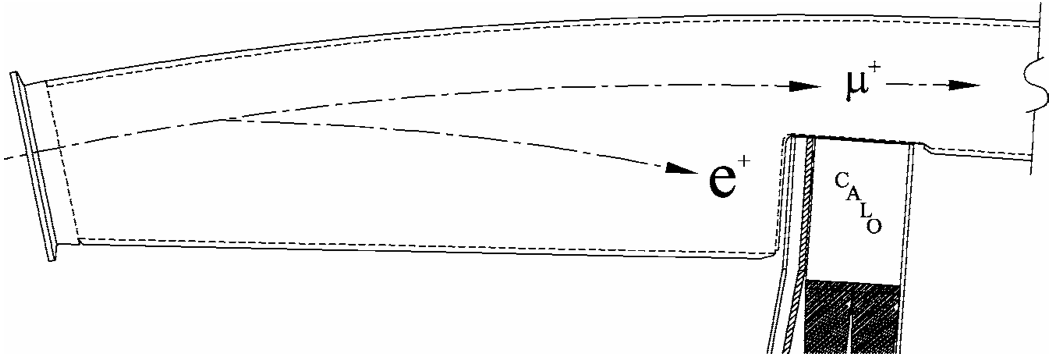


Current Direction given by red markers

LN2 storage, for cooling.

Calorimeters

- Calorimeters measure positrons from muon decay.
  - 24 stations around the ring.
  - 9x6 arrays of PbF2 crystals with silicon photomultiplier tubes.
  - Signals contain location, timing, and energy of positrons.
  - Processed data creates “wiggle plot” for ω_a.

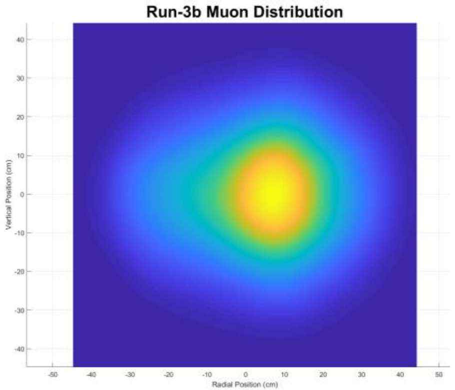


Two calo stations.

Trackers

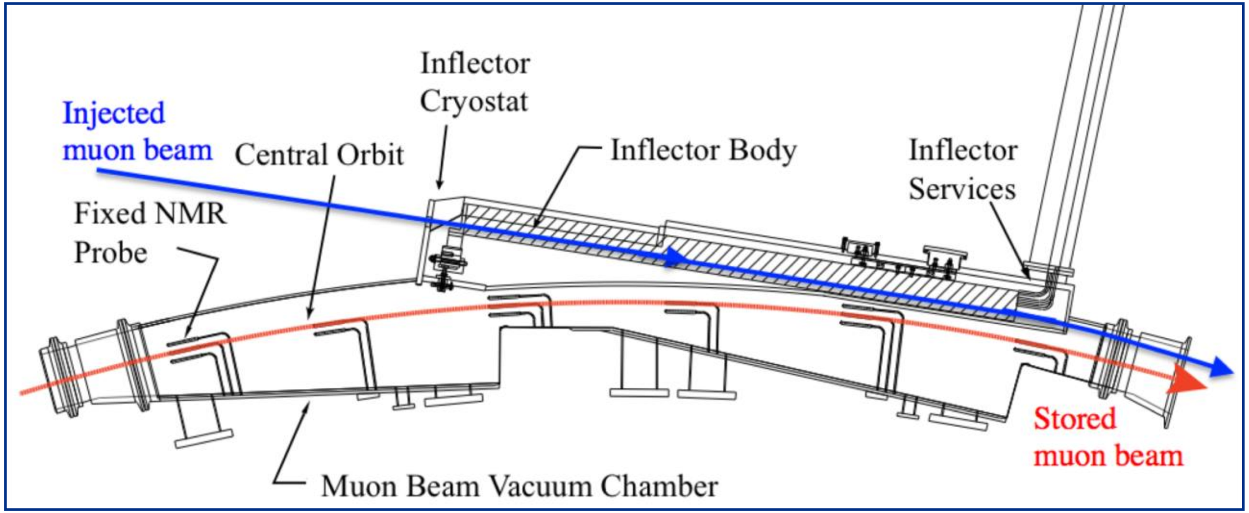
- Trackers measure positrons too, but in 3D.
  - 2 tracker stations, inside the ring.
  - 3D cell arrays of straw tubes with argon-ethane gas.
  - Positron trajectories are analyzed to learn muon beam distribution.
    - Important for both ω_a and B.

One tracker station.



Inflector, Kickers, Quads

- These adjust muon trajectories to make them orbit through the ring.
- Inflector: cancels out magnetic field where muons enter the ring.
  - Prevents deflection by gradient.

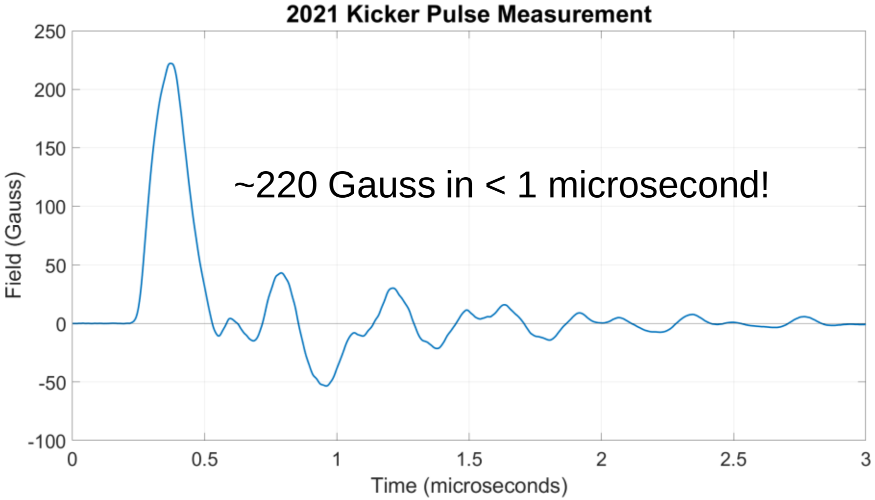


Inflector diagram.

Inflector, Kickers, Quads

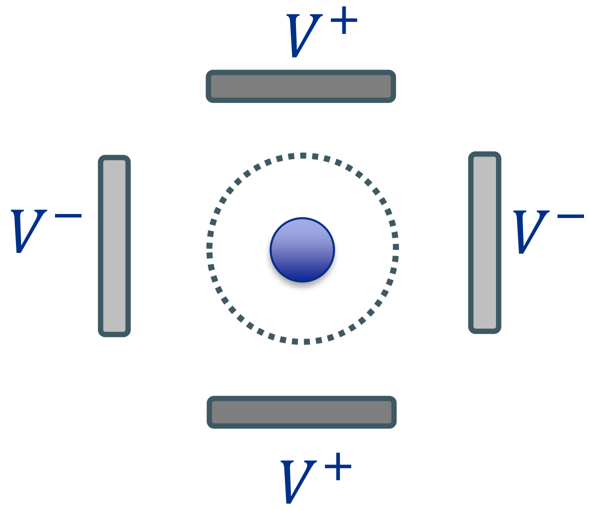
- Kickers: Fast magnetic pulse from 3 stations.
  - “Kicks” initial muon trajectories
  - Allows closed orbit.

Kicker plates.



Inflector, Kickers, Quads

- Quads: Electric quadrupole field focuses muon beam.
  - Improves beam centering, reduces lost muons.



Video

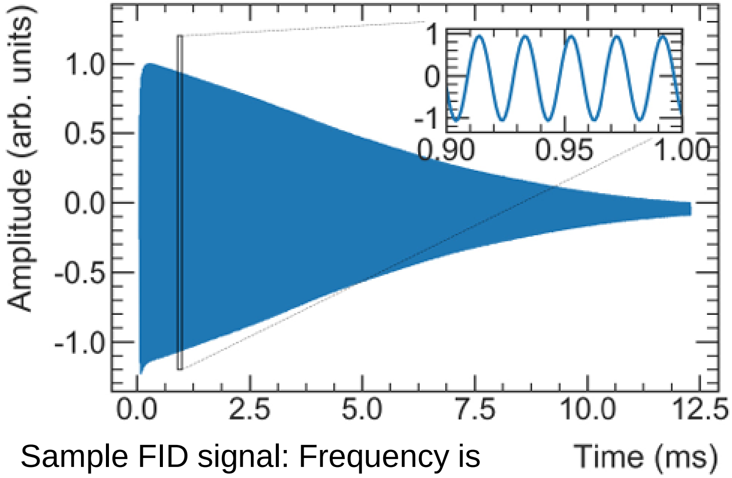
- https://gm2-docdb.fnal.gov/cgi-bin/sso/ShowDocument?docid=9251
  - Made by Adam Lyon.

Magnetic Field Measurements

Nuclear Magnetic Resonance (NMR)

- NMR probes measure magnetic fields via proton precession.
  - Like what we do with muons.
  - But much easier. Protons are plentiful and stable, with precisely-known g_p.
- NMR probes have many aligned protons precessing at w_p.
  - Electrically induces "Free Induction Decay" (FID) signal in a coil.

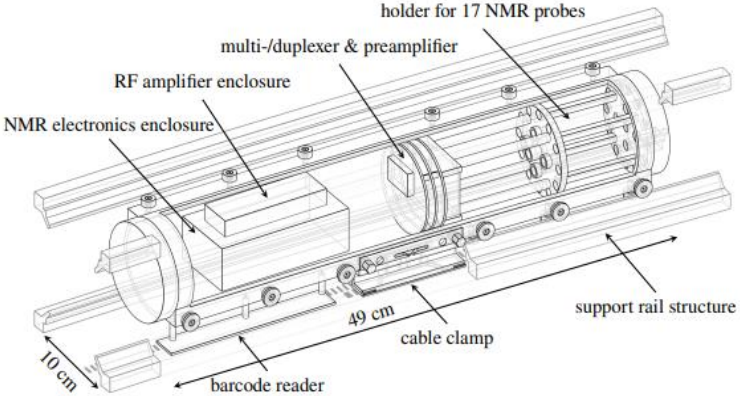
$$w_p = -\frac{g_p q}{2m_p} B$$



Sample FID signal: Frequency is proportional to field strength.

Trolley

- The trolley maps the magnetic field inside the storage ring.
  - Carries 17 NMR probes through the entire ring, stopping periodically to measure.
  - Rides on rails, pulled by motorized fishing line.
  - Can't run while muons are present.

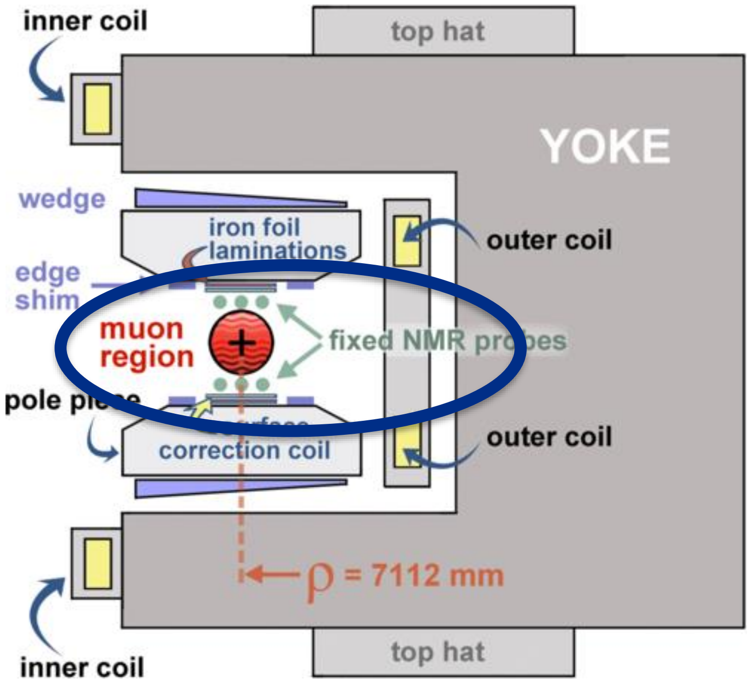


Trolley photographs and diagram.

Fixed Probes

- Fixed NMR probes track changes in field while muons are present.
  - 378 fixed probes above and below beam region.

- Interpolation Analysis:
  - Combining fixed probes data with trolley data, to learn field inside beam region while muons are present.



Storage Ring Cross-section Diagram

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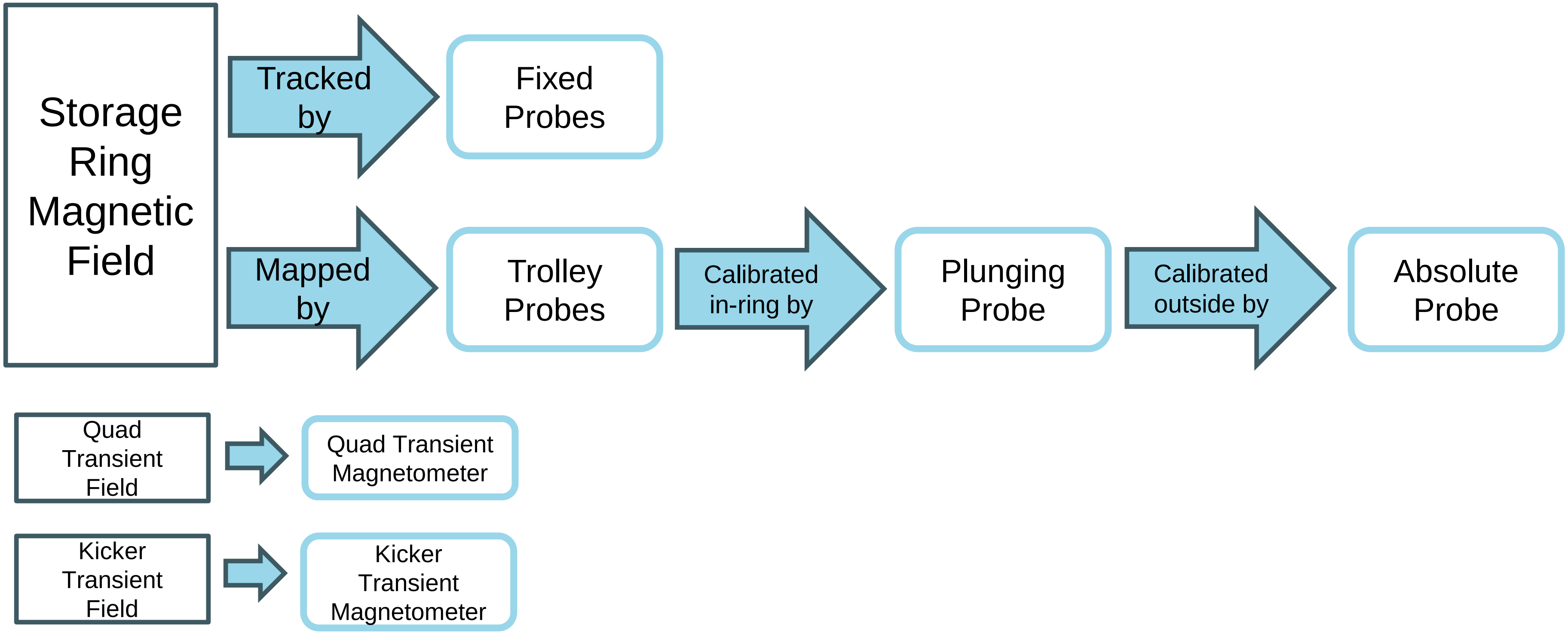
Calibration

- The trolley changes the field while measuring it.
  - *(Not a quantum thing, it's just big and metal.)*
  - Minor effect, but major when the goal is 70 ppb!



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Results (so far)

Published Results

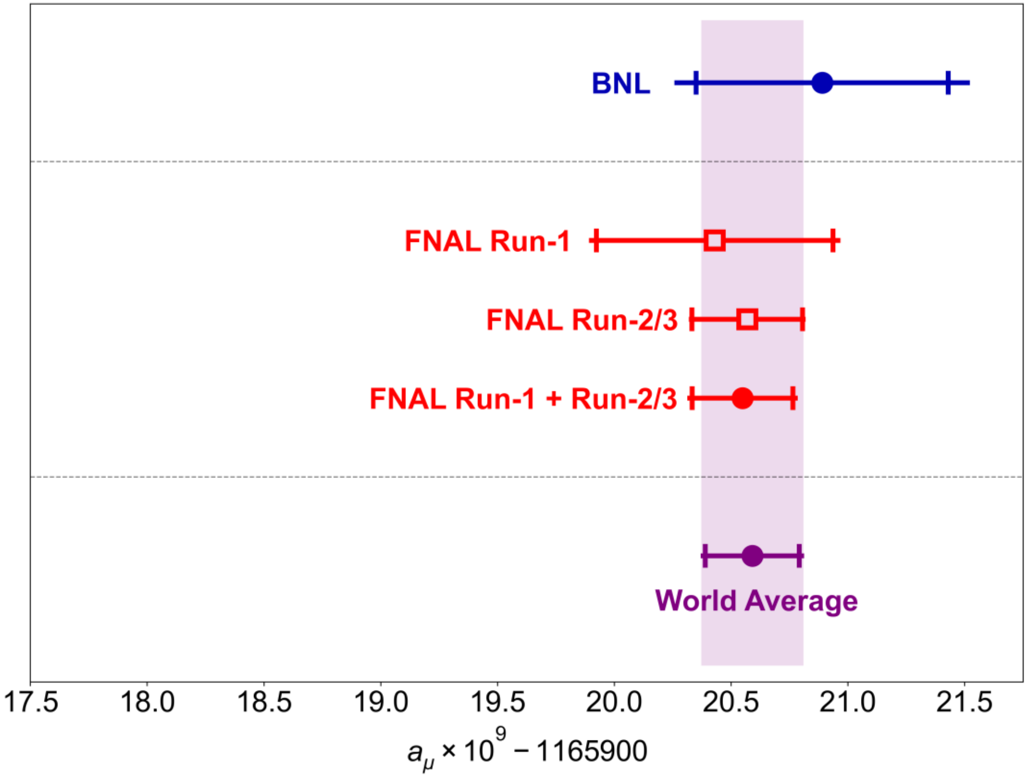
- Run-1 result, published in 2021:

$$a_\mu = 116592040(54) * 10^{-11}.$$

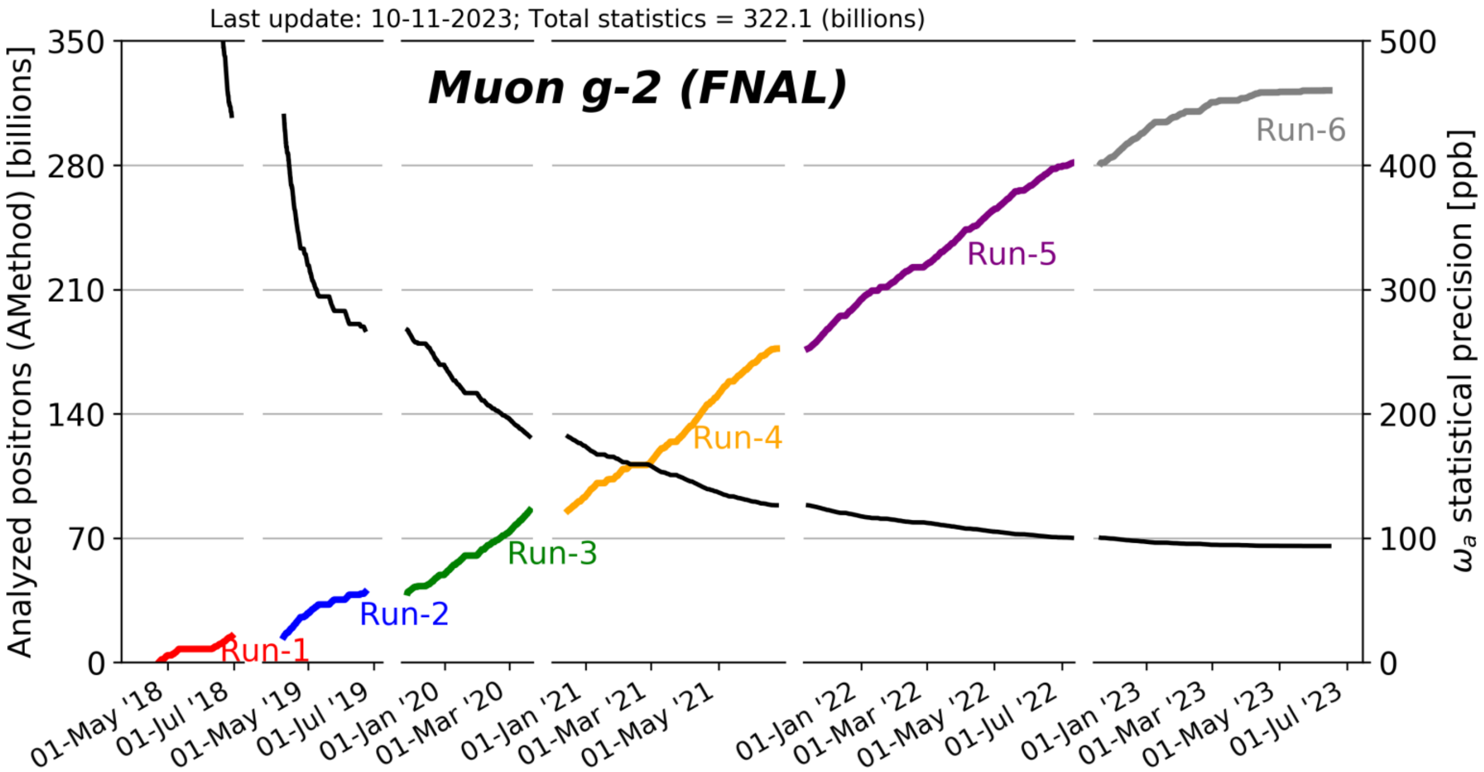
- Run-2/3 result, published in 2023:

$$a_\mu = 116592057(25) * 10^{-11}.$$

- Consistent with BNL, with reduced uncertainty!



Total Data Collected



Uncertainties

Run-1 Uncertainties Table

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	434
ω_a^m (systematic)	$\cdots$	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	$\cdots$	56
B_k	−27	37
B_q	−17	92
$\mu'_p(34.7°)/\mu_e$	$\cdots$	10
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic	$\cdots$	157
Total fundamental factors	$\cdots$	25
Totals	544	462

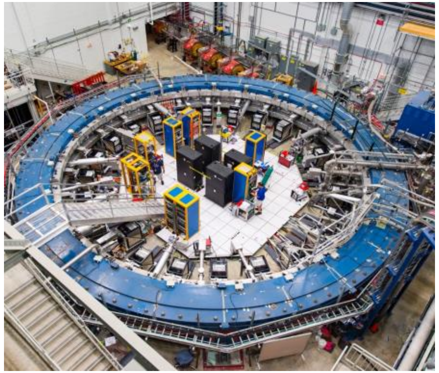
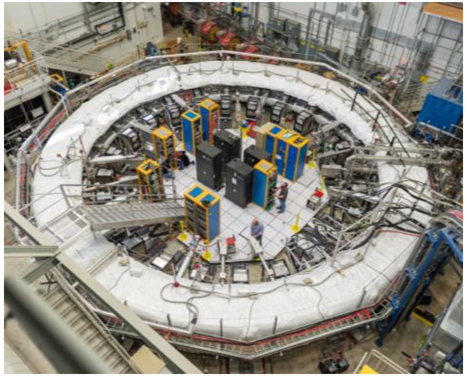
Run-2/3 Uncertainties Table

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	201
ω_a^m (systematic)	$\cdots$	25
C_e	451	32
C_p	170	10
C_{pa}	−27	13
C_{dd}	−15	17
C_{ml}	0	3
$f_{\text{calib}}\cdot\langle\omega'_p(\vec{r})\times M(\vec{r})\rangle$	$\cdots$	46
B_k	−21	13
B_q	−21	20
$\mu'_p(34.7°)/\mu_e$	$\cdots$	11
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic for $\mathcal{R}'_\mu$	$\cdots$	70
Total external parameters	$\cdots$	25
Total for a_μ	622	215

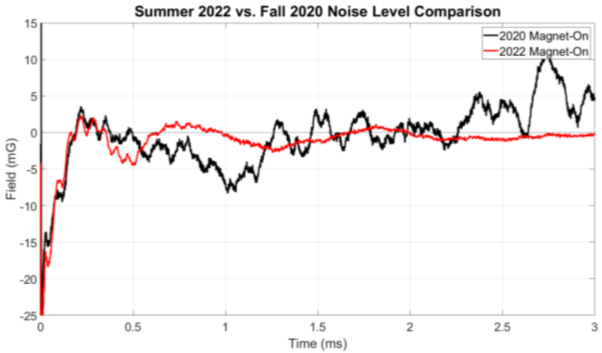
Statistical: 434 -> 201 ppb
Systematic: 157 -> 70 ppb

Improvements between Runs

- Statistics:
  - More muons.
- Ring upgrades:
  - Thermal insulation.
  - Kicker electronics.
  - Muon beam centering.
- Systematic studies:
  - Trolley calibration campaigns.
  - Kicker and quad transient measurements.
- And many more!

Storage ring before (left) and after (right) new thermal insulation.



Kicker transient field measurement comparison.

Next Steps

- Data collection is complete!
- Runs 4, 5, and 6 are being processed and analyzed.
- Overall uncertainty goal,140 ppb, is within reach!

Conclusion

Collaboration

- Muon g-2 is a worldwide effort!
- Everyone working together makes it possible.
- We're all excited to learn more about the universe!

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

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

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

Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

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

182 collaborators
33 Institutions
7 countries

Fermilab

Questions or Comments?