The Muon g-2 Experiment

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UIUC FNAL g-2 collaborators
Departmental colloquium April 15, 2021

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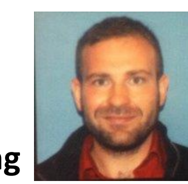


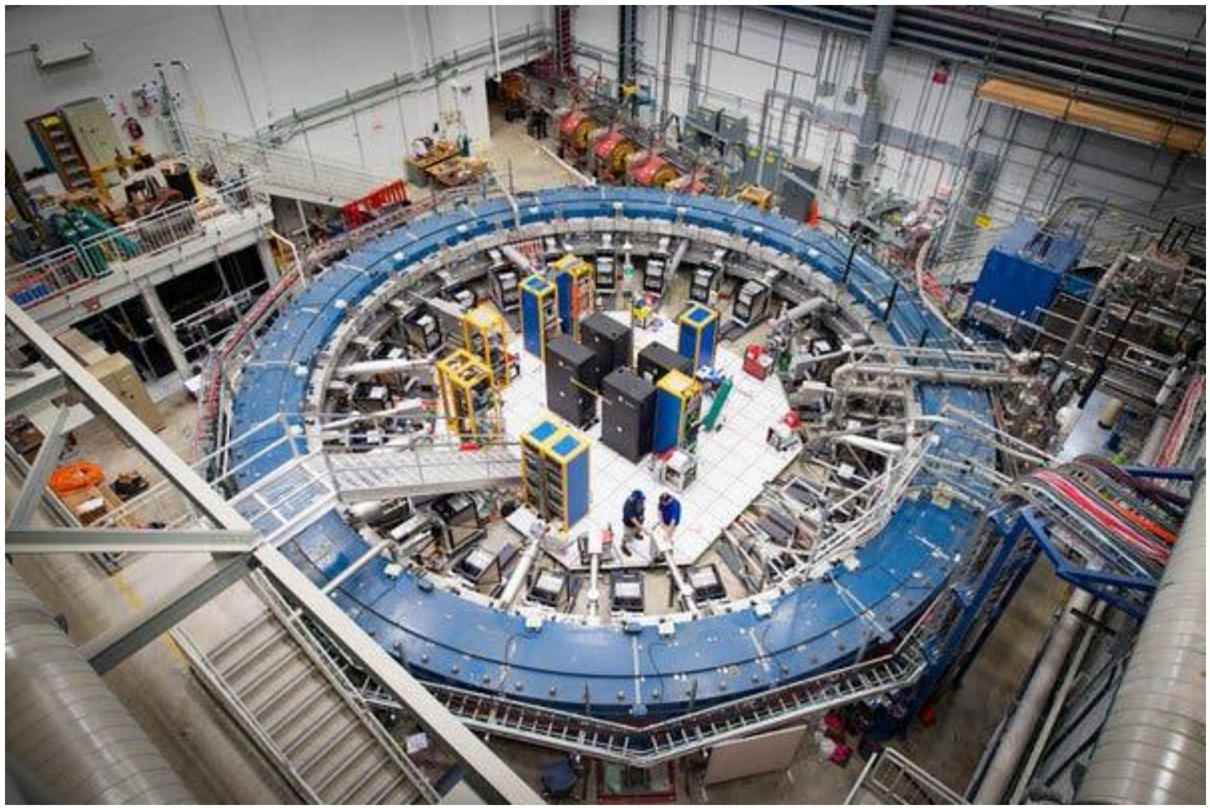
April 7, 2021
Press Conference: First results from the muon g-2 experiment at Fermilab

https://www.youtube.com/watch?v=nrus0aIa94I

The New York Times

April 7, 2021

“Finding From Particle Research Could Break Known Laws of Physics”

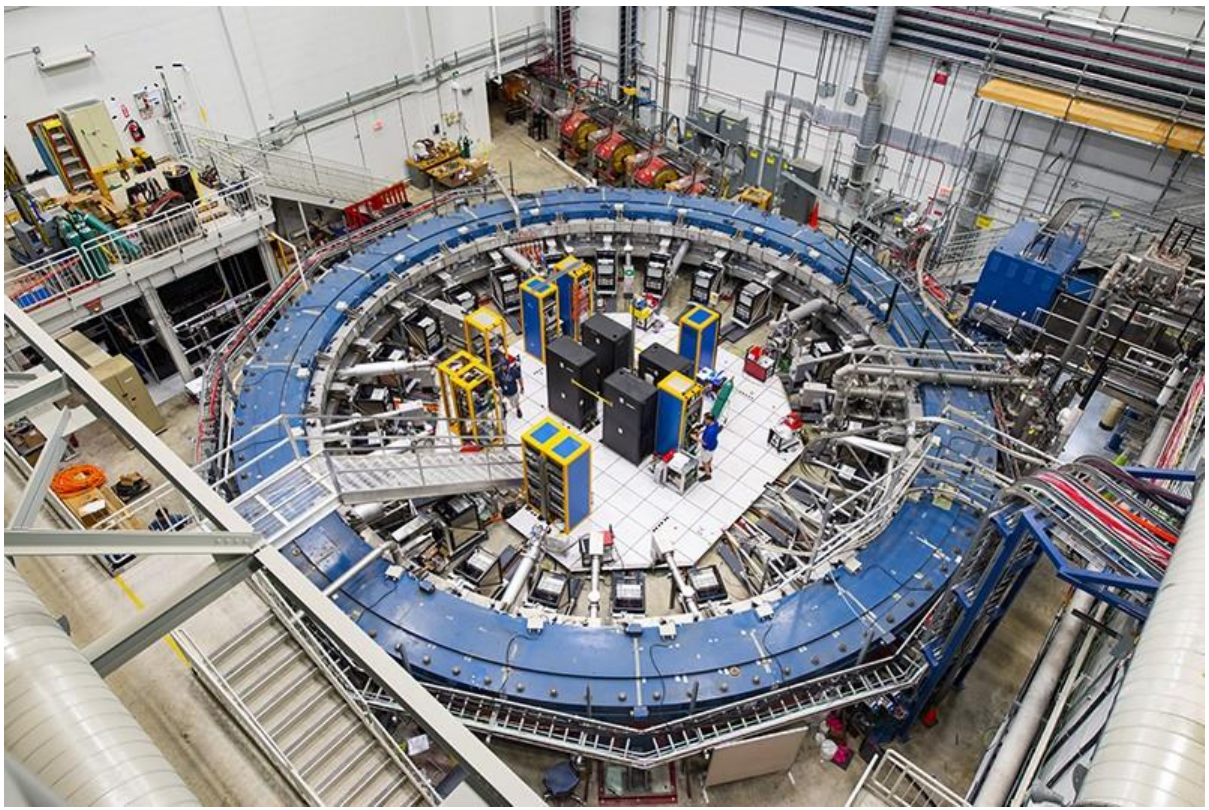


The Muon g-2 ring, at the Fermi National Accelerator Laboratory in Batavia, IL

nature

April 7, 2021

“Is the standard model broken? Physicists cheer major muon result.”



The storage-ring magnet used for the g – 2 experiment at Fermilab.

Science

April 7, 2021

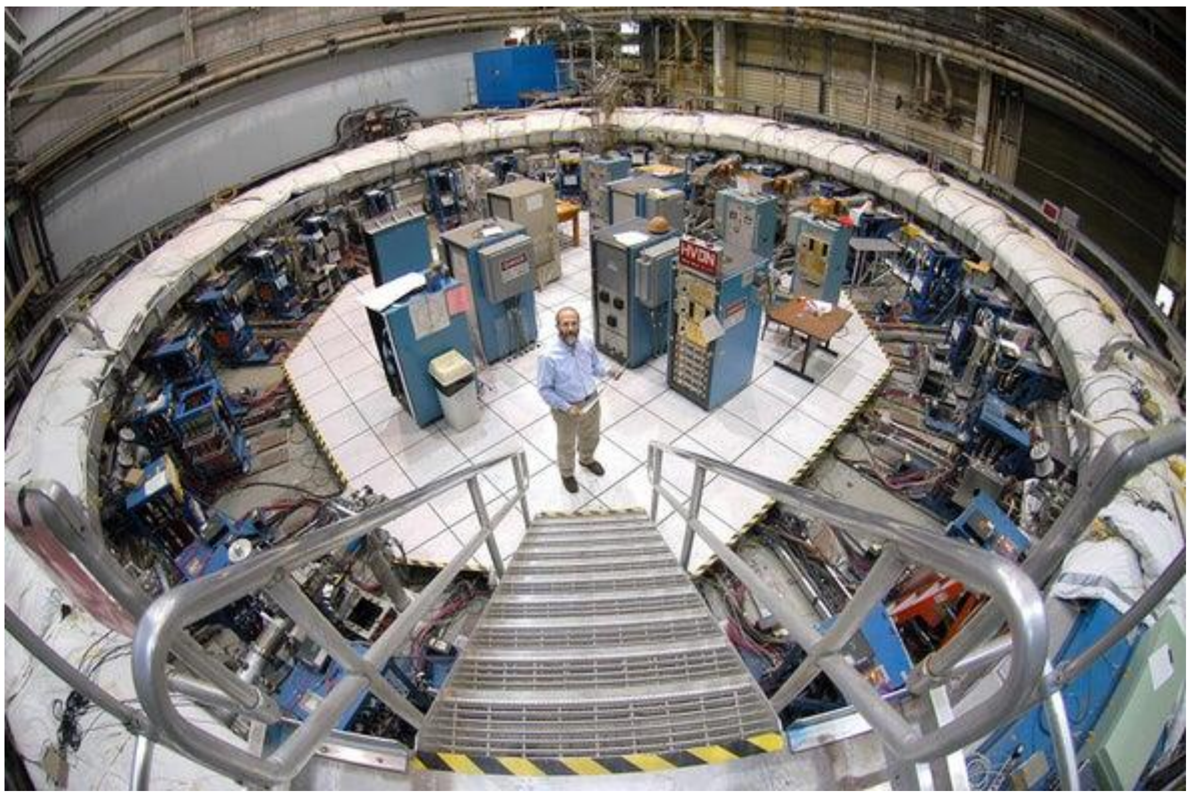
“Particle mystery deepens, as physicists confirm that the muon is more magnetic than predicted.”

Muons twirl as they circulate in this ring-shaped accelerator at Fermilab, like race cars perpetually spinning out.

SCIENTIFIC AMERICAN™

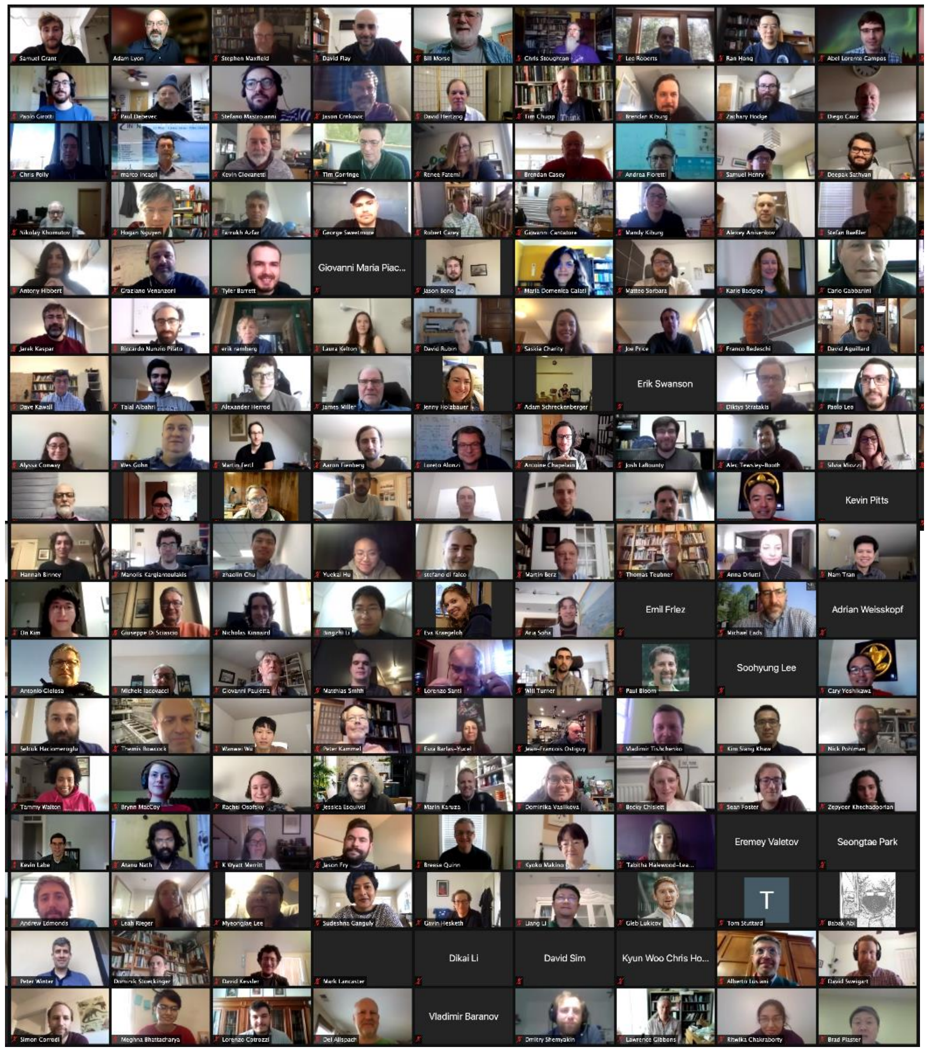
April 7, 2021

"Long-Awaited Muon Measurement Boosts Evidence for New Physics"



The muon g-2 magnetic storage ring, seen here at Brookhaven National Laboratory in New York before its 2013 relocation to Fermi National Accelerator Laboratory in Illinois.

February 27, 2021
FNAL E989 unblinding decision Zoom



FNAL E989 2019 collaboration meeting photo

Muon g-2 Collaboration

7 countries, 35 institutions, 190 collaborators

What did we do between February 27 and April 7?

PHYSICAL REVIEW LETTERS **126**, 141801 (2021)

Editors' Suggestion | Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

PHYSICAL REVIEW A **103**, 042208 (2021)

Featured in Physics

Magnetic-field measurement and analysis for the Muon $g-2$ Experiment at Fermilab

PHYSICAL REVIEW D **103**, 072002 (2021)

Editors' Suggestion | Featured in Physics

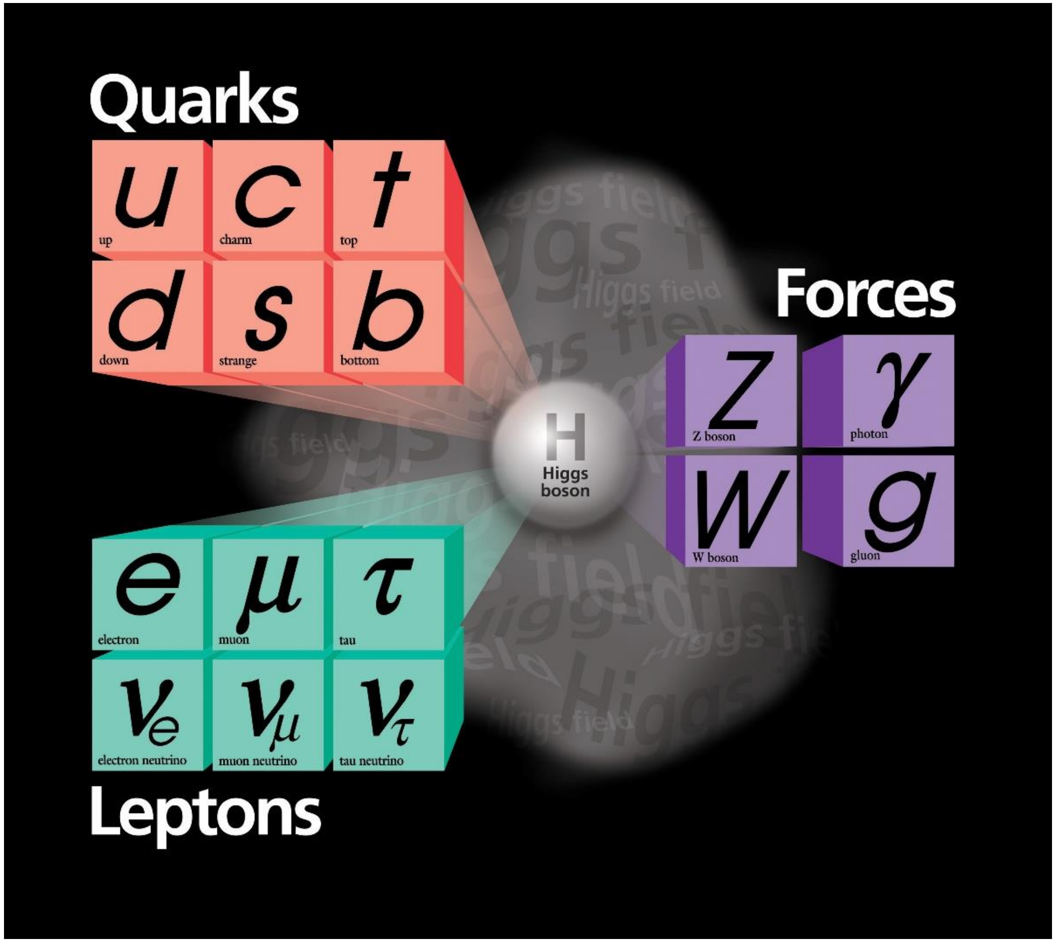
Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g-2$ Experiment

PHYSICAL REVIEW ACCELERATORS AND BEAMS **24**, 044002 (2021)

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

Brief overview of particle physics

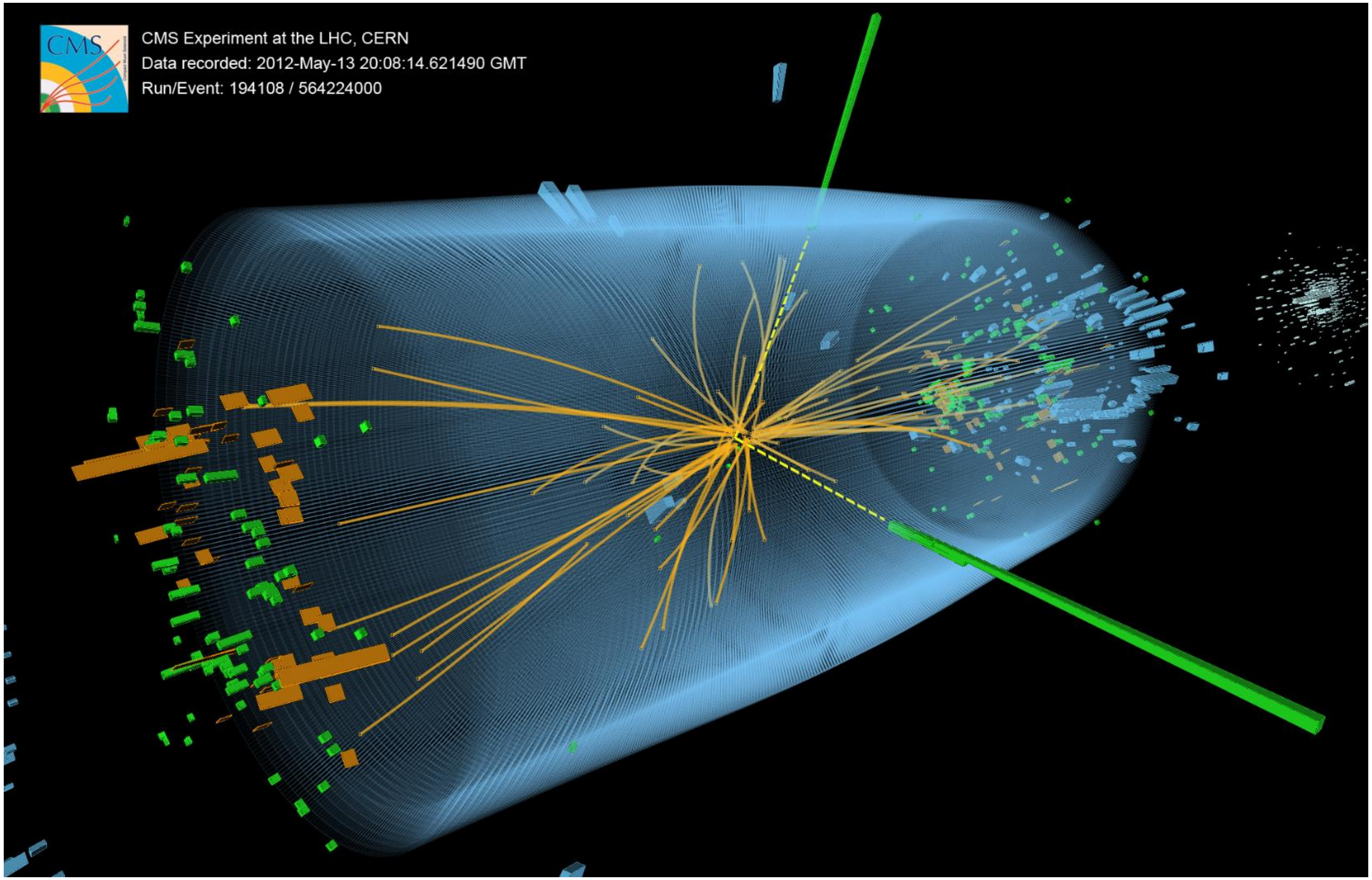
The standard model
6 quarks, 6 leptons, 3 forces, 1 Higgs



The standard model is incomplete.

- origin of neutrino masses
  - neutrino oscillations change flavor
- what is dark matter?
  - ordinary matter is only 5% of observed universe
- matter/anti-matter asymmetry
  - why did anti-matter disappear? other CP violation?
- universe expansion is accelerating
  - dark energy?
- gravity not in standard model
  - grand unification of all forces?

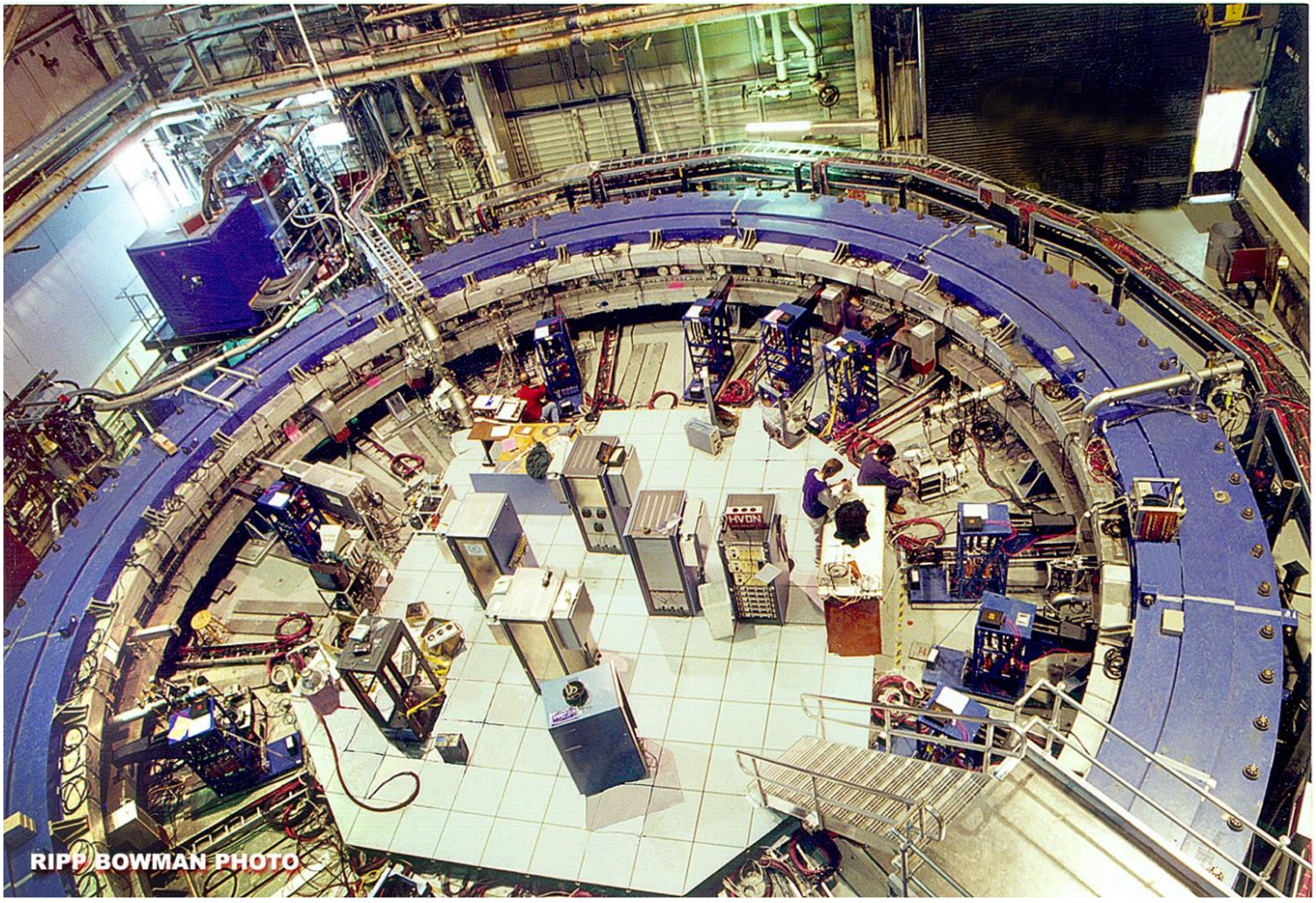
Search by direct production in high-energy collisions



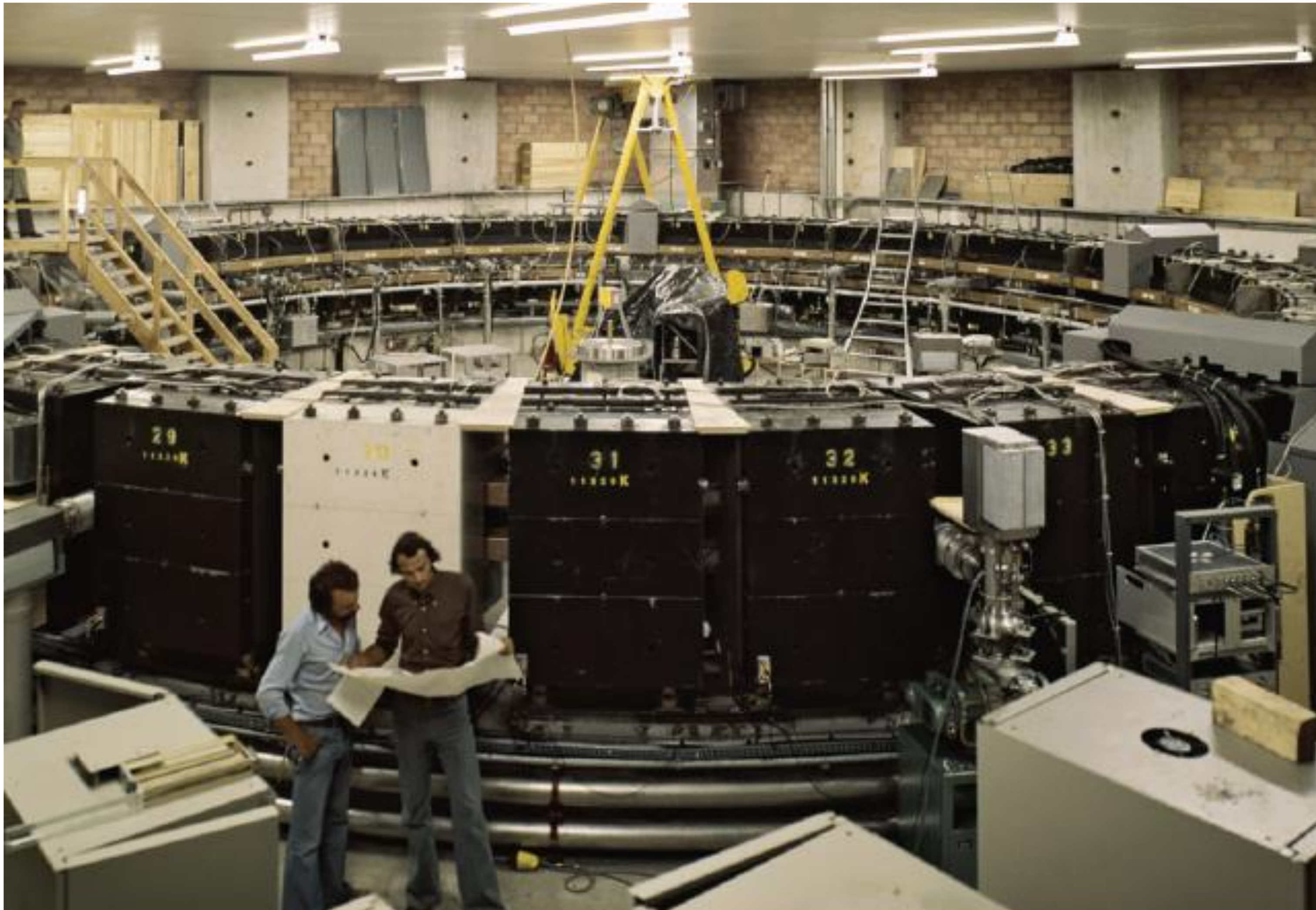
Higgs boson discovery event

Search by precision measurements of fundamental properties

g-2 storage ring at Brookhaven National Laboratory circa 2005

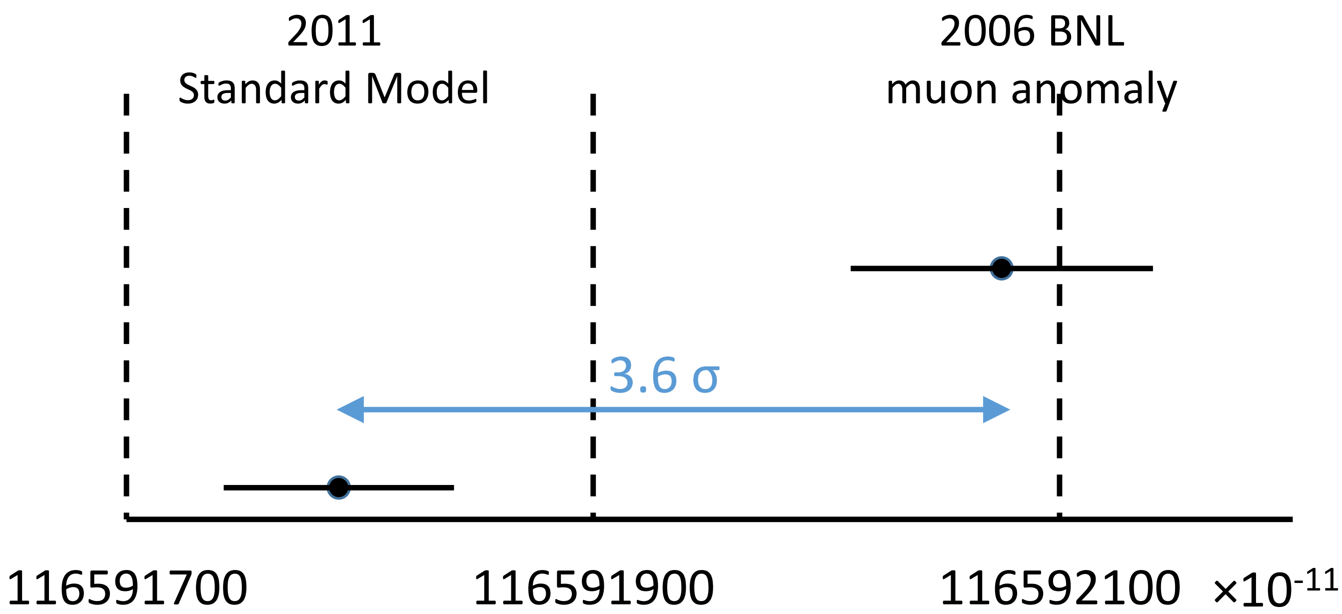


CERN g-2 storage ring circa 1976



CERN final result 7 ppm precision from runs in 1974-1976 (positive muons), and 1975-1976 (negative muons)

Precision Experimental Result – 2006 BNL g-2 Compared to Precision Standard Model Calculation of 2011



discovery gold standard is 5 σ

BNL final result 0.54 ppm precision from runs in 1999 and 2000 (positive muons), and 2001 (negative muons)

CERN and BNL results history

TABLE I. Summary of a_μ results from CERN and BNL, showing the evolution of experimental precision over time. The average is obtained from the 1999, 2000 and 2001 data sets only.

Experiment	Years	Polarity	$a_\mu \times 10^{10}$	Precision [ppm]	Reference
CERN I	1961	μ^+	11450000(220000)	4300	[2]
CERN II	1962–1968	μ^+	11661600(3100)	270	[3]
CERN III	1974–1976	μ^+	11659100(110)	10	[5]
CERN III	1975–1976	μ^-	11659360(120)	10	[5]
BNL	1997	μ^+	11659251(150)	13	[6]
BNL	1998	μ^+	11659191(59)	5	[7]
BNL	1999	μ^+	11659202(15)	1.3	[8]
BNL	2000	μ^+	11659204(9)	0.73	[9]
BNL	2001	μ^-	11659214(9)	0.72	[10]
Average			11659208.0(6.3)	0.54	[10]

g-2 moves to FNAL

The Big Move June - July 2013

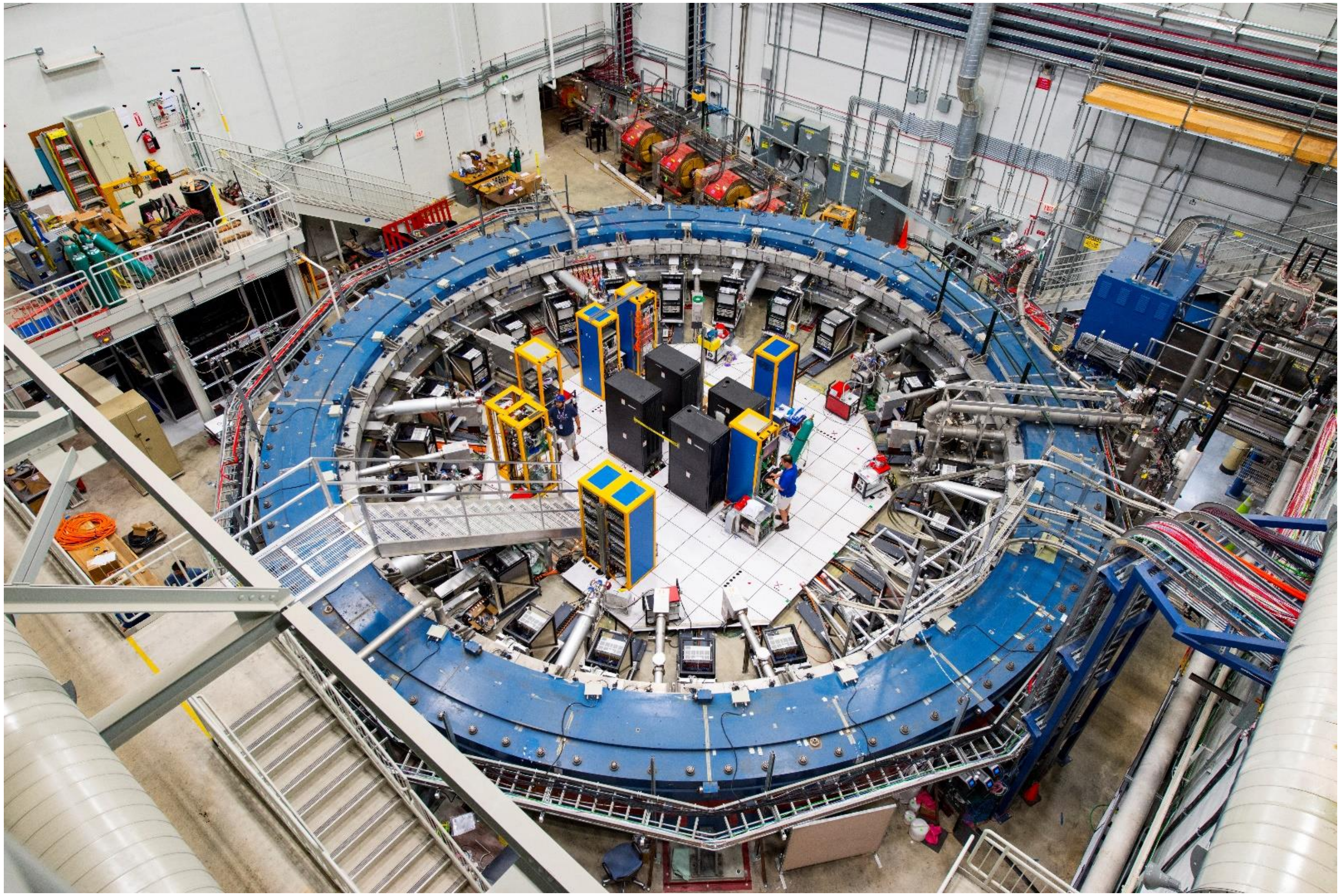
Leaving Brookhaven National Laboratory

On Illinois tollway towards Fermilab

GPS record of barge carrying magnet coils

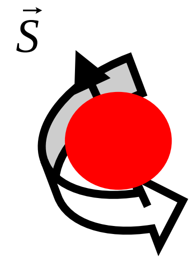
g-2 storage ring coils arrive at FNAL July, 2013

g-2 storage ring at FNAL operational April, 2018



Back to the Beginning. What's g?

A particle with spin (angular momentum) has a (spin) magnetic moment.



$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

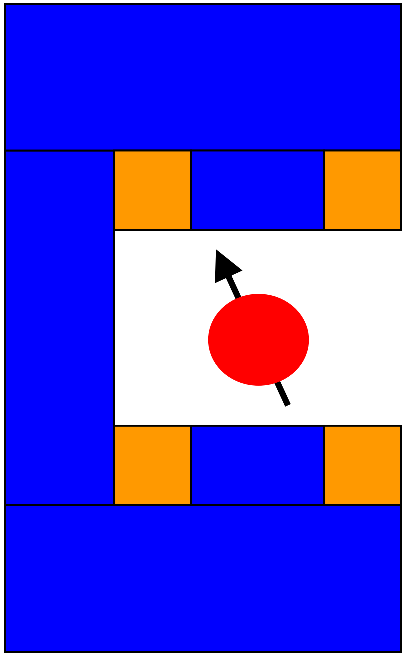
Spin is quantized.
For spin ½ particles

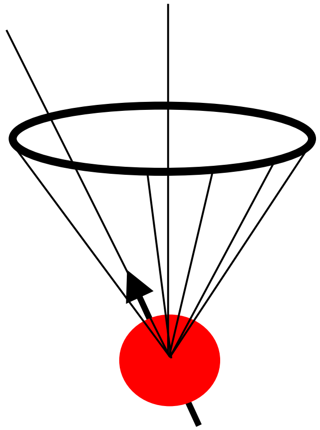
$$\mu = g\frac{e}{2m}\frac{\hbar}{2}$$

According to quantum mechanics and special relativity as combined in the Dirac equation, for structureless spin one-half particles, e.g. electron and muon, the g-factor is exactly 2.

So, for the electron and muon $\mu = 2\frac{e}{2m}\frac{\hbar}{2}$

magnetic moments precess in a magnetic field





$$\vec{\tau} = \vec{\mu} \times \vec{B} = \frac{d}{dt}\vec{S}$$ torque equation

$$\omega_s = g\frac{e}{2m}B$$ precession frequency equation

The precession (angular) frequency is proportional to g and B.

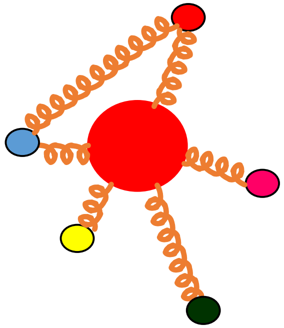
Measure B and ω_s to determine g.

g-factor anomaly – g is not exactly 2

anomaly defined $a \equiv \frac{g-2}{2}$

anomaly illustrated

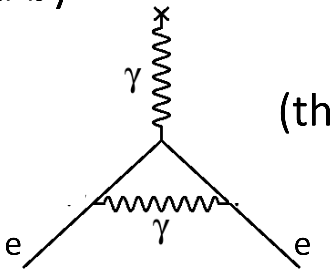
all particles are surrounded by virtual particles and fields



(this figure is a cartoon)

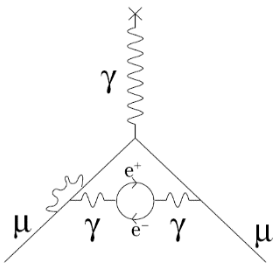
lowest order QED contribution first calculated by Schwinger (1947)

$$a_e = \frac{\alpha}{2\pi} = 0.00116141$$

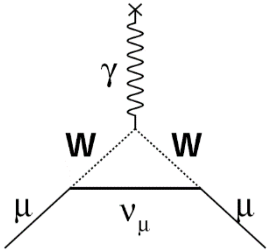


(this figure is a Feynman diagram)

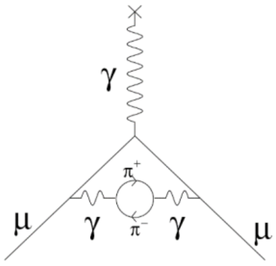
complete standard model contributions to g-2



QED



Electroweak



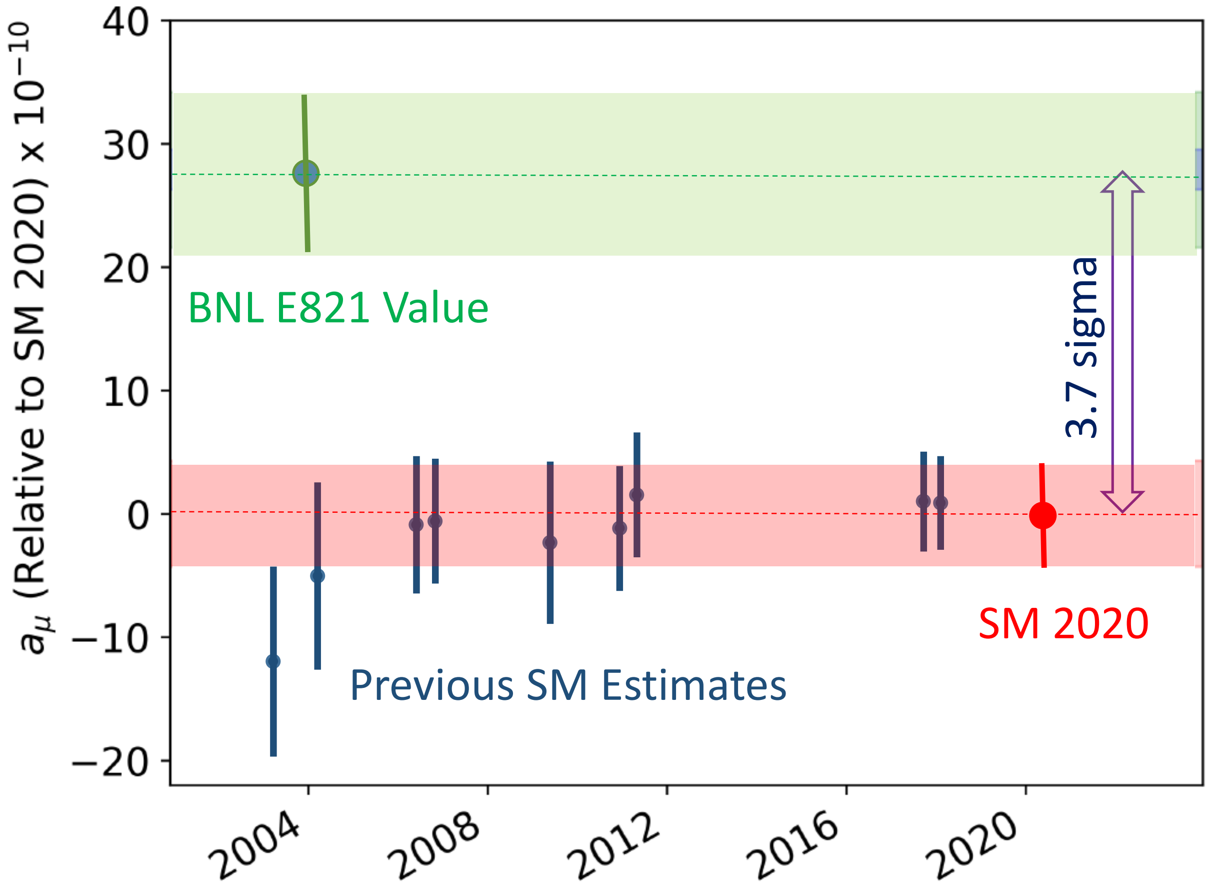
Hadronic

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

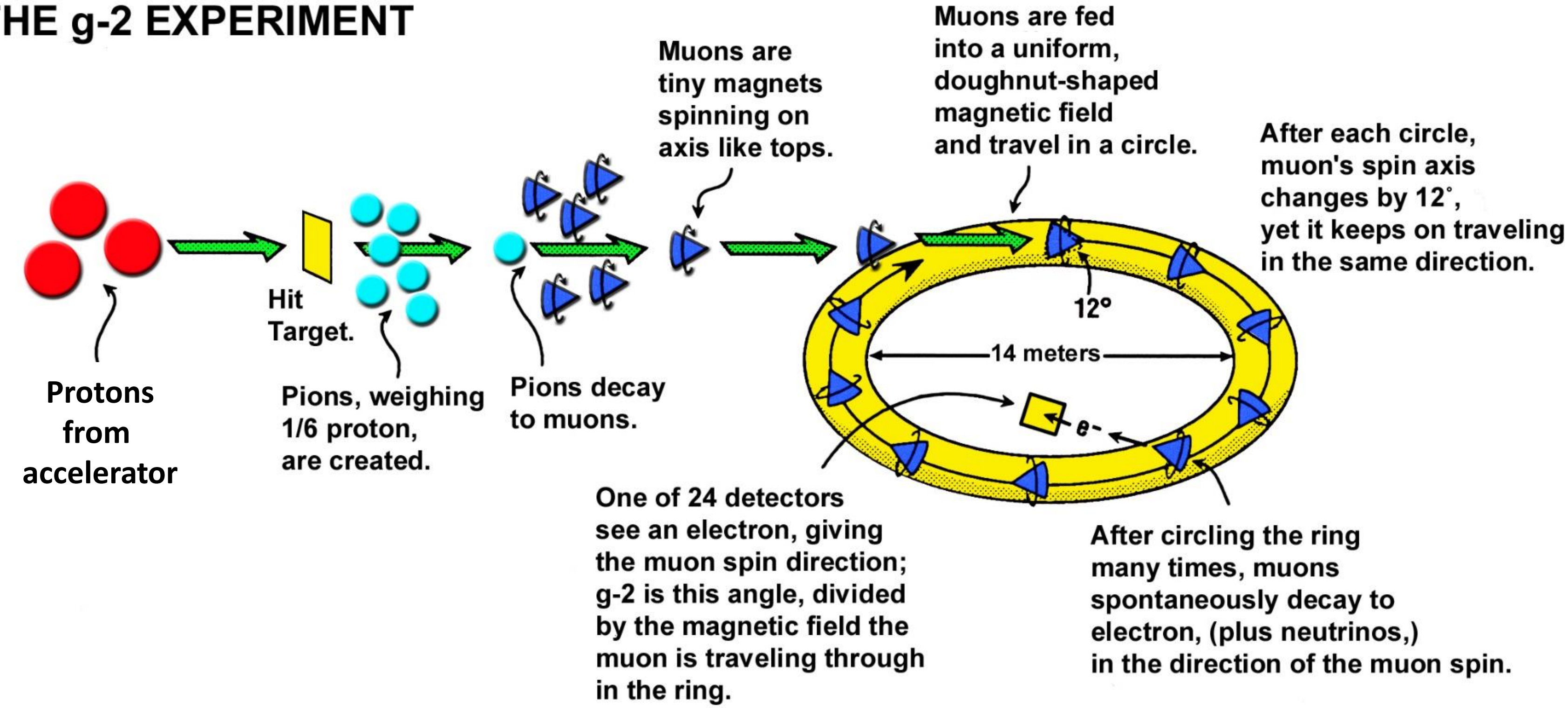
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP}$$

QED	116 584 718.853 ± 0.036	
EW	153.6 ± 1.0	
HLBL	105 ± 24	
HVP	6 923 ± 42	all in units of $\times 10^{-11}$
HOHVP	-98.4 ± 0.7	
Total	116 591 802 ± 49	(0.43 ppm)

BNL muon g-2 experiment compared to standard model theory calculations



LIFE OF A MUON: THE g-2 EXPERIMENT



Elements of the g-2 experiment

1. Polarized muons

pion decay produces polarized muons

2. Precession gives (g-2)

in a storage ring the spin precesses relative to the momentum at a rate proportional (g-2)

3. Parity violation

positron energy indicates the direction of the muon spin

4. P_m The magic momentum

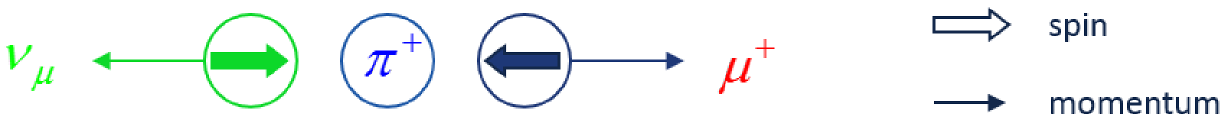
at one special momentum, the precession is independent of the electric focusing fields

1. Polarized Muons

Pions are produced in proton nucleus collisions

Pion decay is the source of polarized muons

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

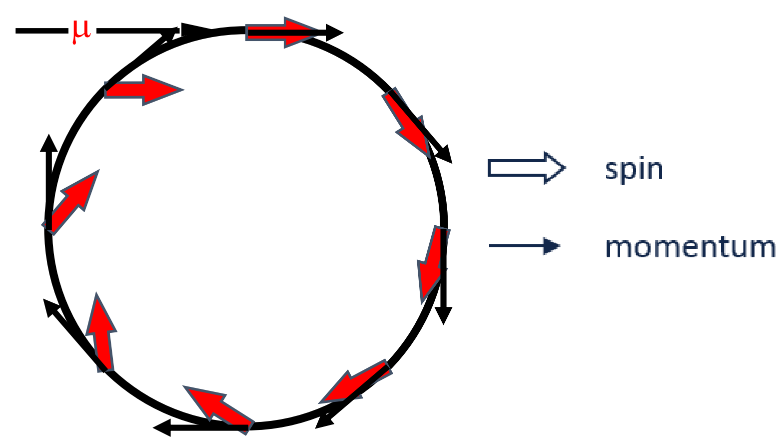


2. Spin and Cyclotron Motion in a Storage Ring

spin $$\omega_s = \left[1 + \gamma \frac{g-2}{2}\right] \frac{e}{m} \frac{1}{\gamma} B$$

momentum $$\omega_c = \frac{e}{m} \frac{1}{\gamma} B$$

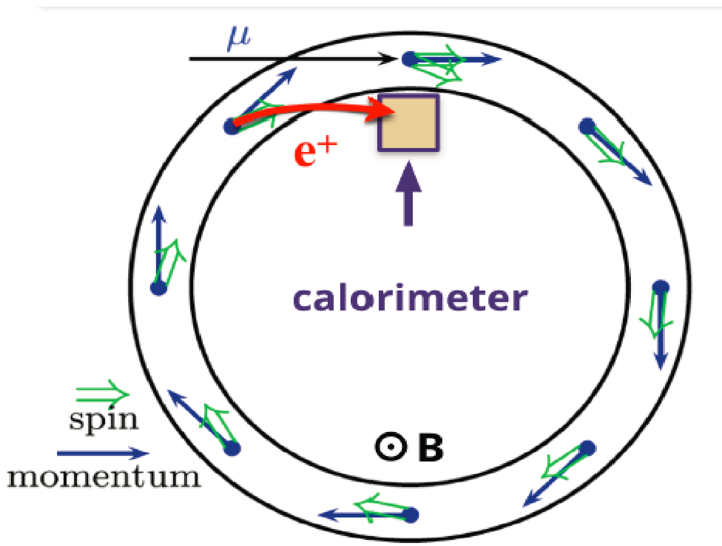
difference $$\omega_a = \omega_s - \omega_c = \frac{g-2}{2} \frac{e}{m} B$$



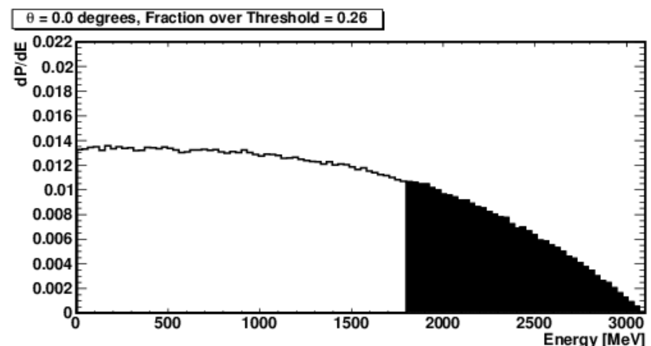
difference proportional to g-2, not g, independent of momentum

3. Measuring the Spin Direction

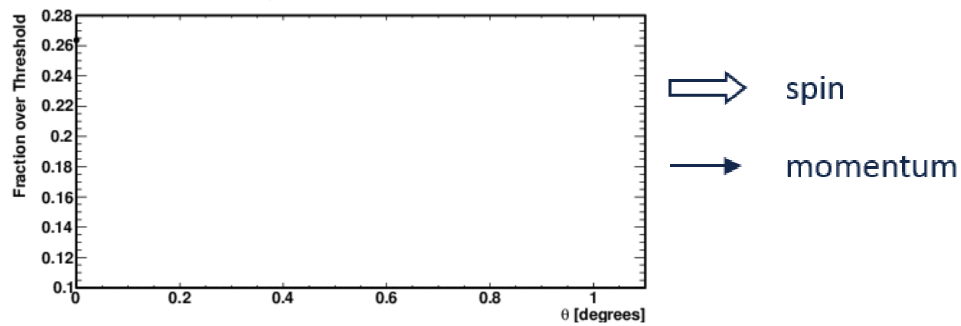
The g-2 experiment measures no angles. The energy of the positron depends on the direction of the muon spin.



$$\omega_a = \omega_s - \omega_c = \frac{g-2}{2}\frac{e}{m}B$$

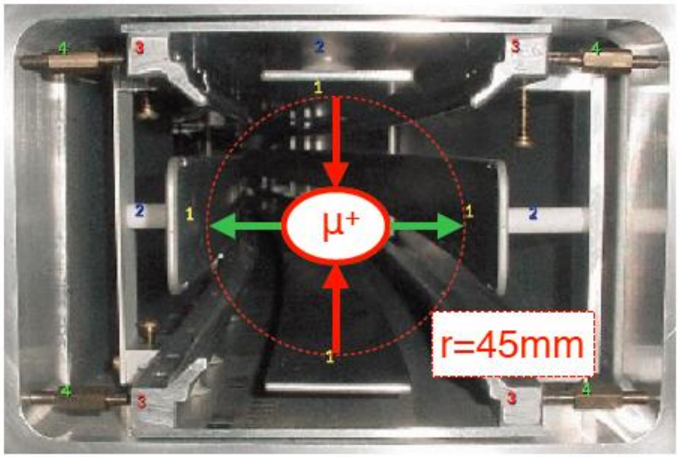


Energy in Calorimeters



Phase of Muon Spin

4. The Magic Momentum



Muons in the storage ring must be confined by focusing elements. Following the third CERN g-2 experiment, electrostatic focusing is used. Motional magnetic field is seen by circulating muons which would precess the spin, except at the "magic momentum" of 3.094 GeV/c

The difference frequency expression including *E*-field focusing and possible out of plane oscillations

obtain a_μ

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

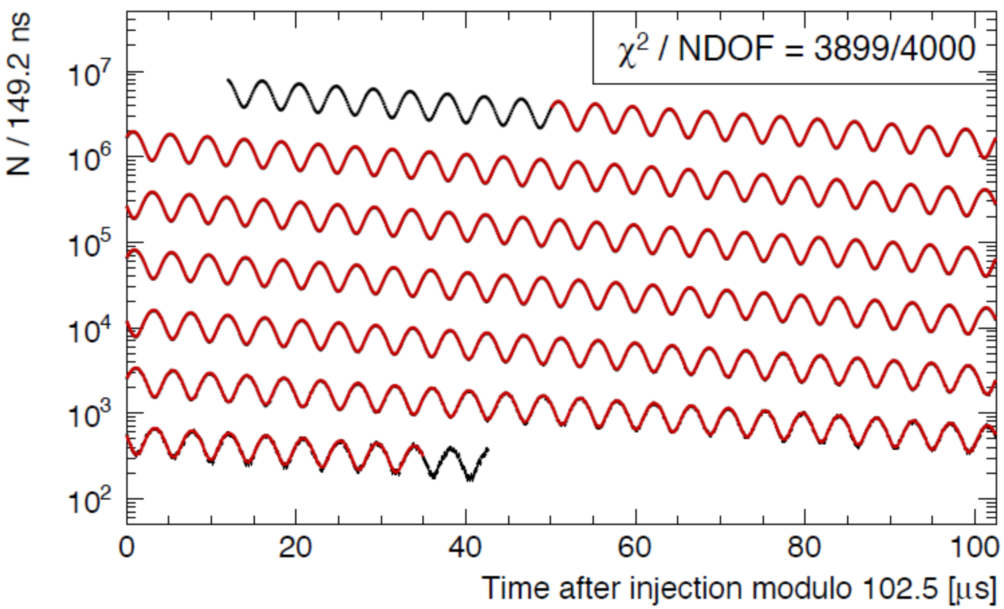
measure these

0 if "in plane"

term cancels at 3.094 GeV/c, the "magic momentum"

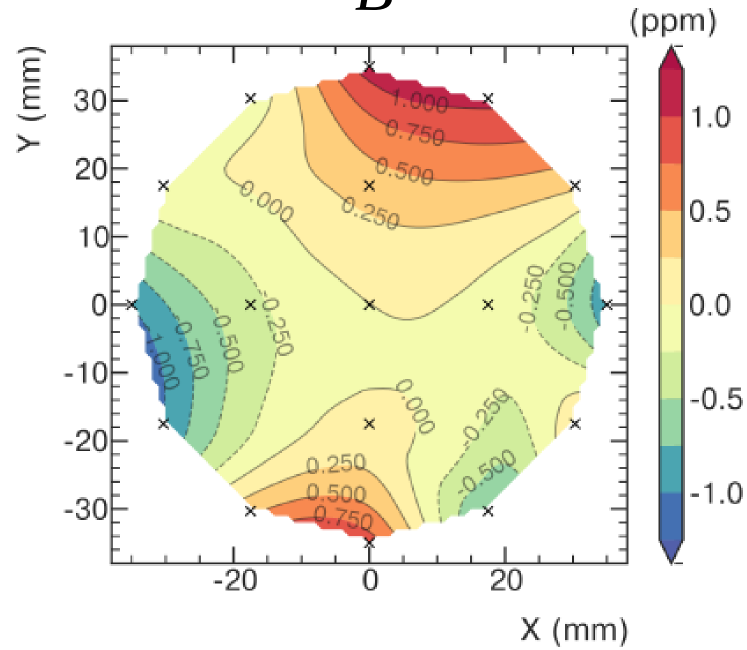
Precession Frequency

ω_a



Azimuthal Average Magnetic Field

B

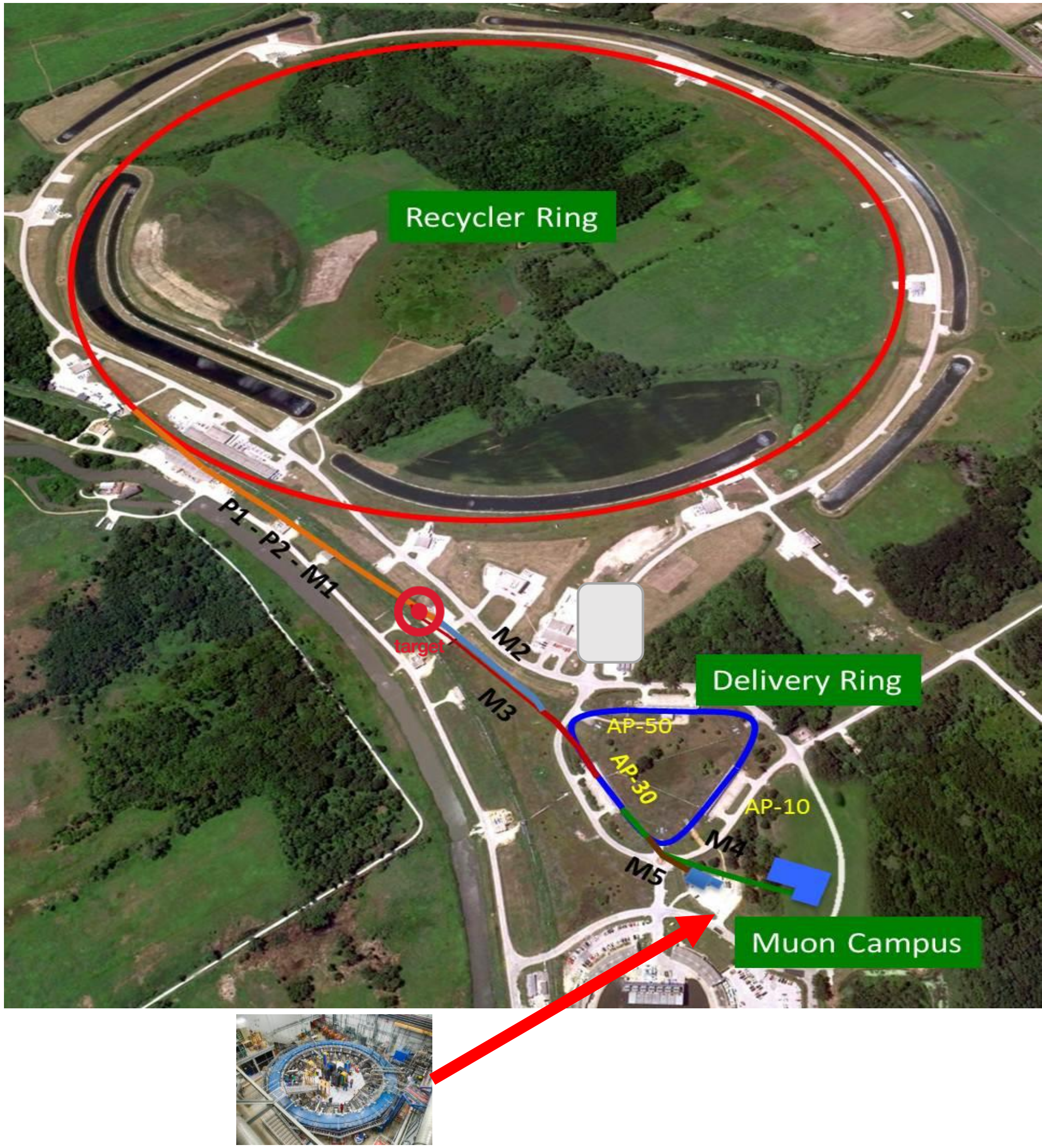


a_μ is determined from these two data sets.

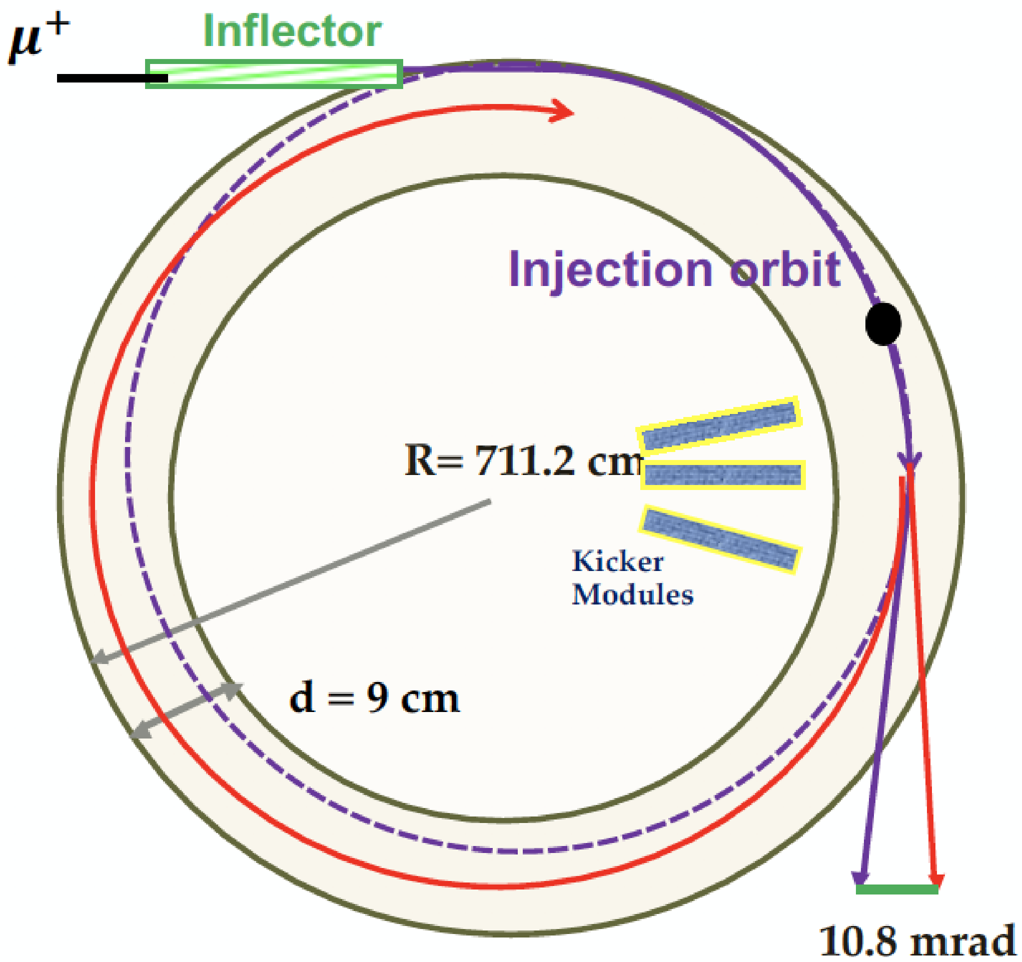
some of many experimental details

making the muon beam

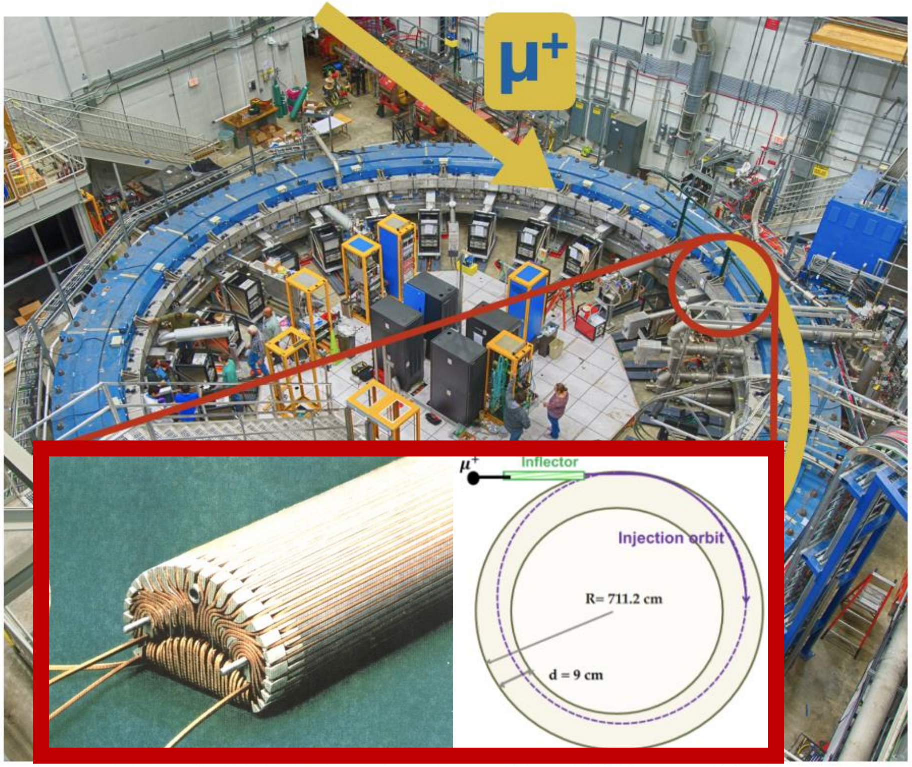
- Fermilab accelerator chain gets protons into Recycler ring
- Extracted bunches hit nickel-based target
  - Left mainly with protons, pions, and muons
  - Particles enter Delivery Ring
    - Protons get removed from the beam
    - Pions decay into muons
  - Muons enter Muon g-2 ring through M5 line



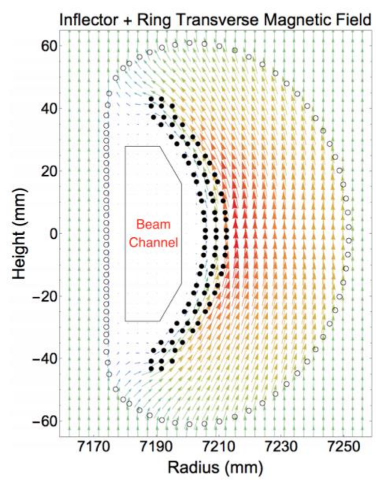
two crucial elements: inflector and kicker



muon injection into storage ring

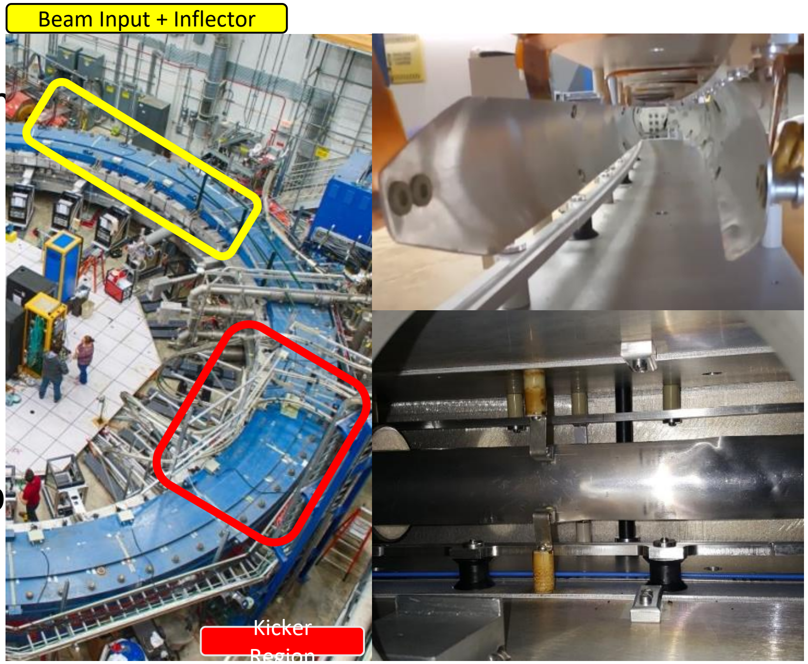


- Weak decay of pions produces highly polarized muon beam
  - Muon spins aligned to momenta
- Inflector is the entryway
  - Superconducting magn
  - Cryogenically cooled
  - Cancels ring's 1.45T fiel in $18 \times 56\ mm^2$ windo
- Muons displaced 77 mm from closed orbit radius



muons need a kick

- 77-mm displacement presents challenge!
  - Without action, not much physics is happenin
- Three non-ferric kickers nudge beam onto closed orbit trajectory
  - Pulsed current drives perturbation
  - No magnetic material as ferric items would interfere with main measurement
  - System requirements drove R&D for Fermilab
  - Big difference between systems at BNL and Fermilab

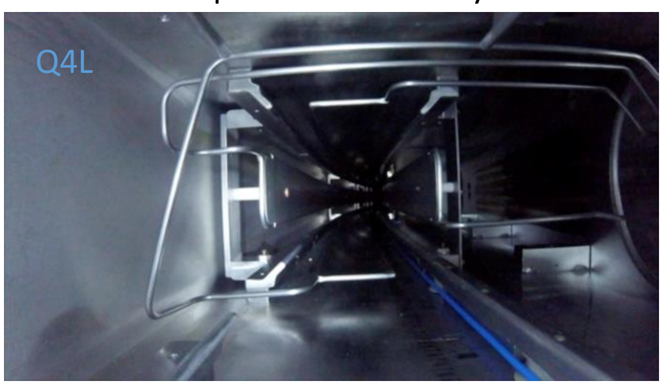


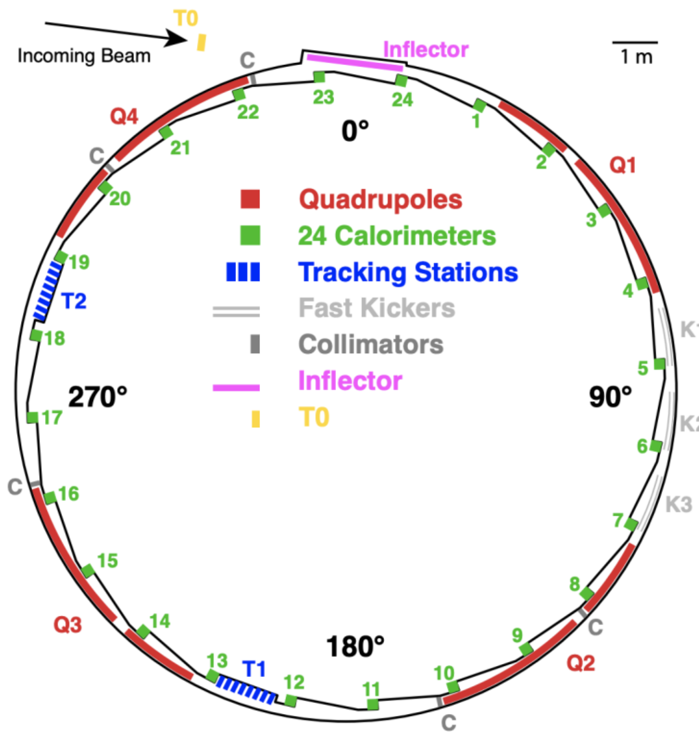
storing the muons

Electrostatic Quadrupoles

- **Covers 43% of the storage ring**
- Provides vertical beam focusing while magnet contains radial focusing
- Minimizes electric field contribution running at magic momentum p=3.094 GeV/c

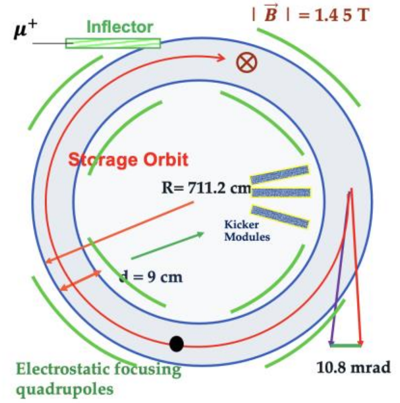
Captured with trolley





storing the muons
electrostatic quadrupole system

- Electrostatic Quadrupoles
  - Covers 43% of the storage ring
  - Provides vertical beam focusing while magnet contains radial focusing
  - **Minimizes electric field contribution running at magic momentum p=3.094 GeV/c**



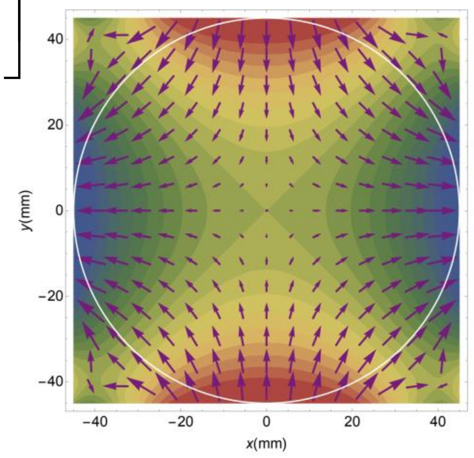
obtain a_μ

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

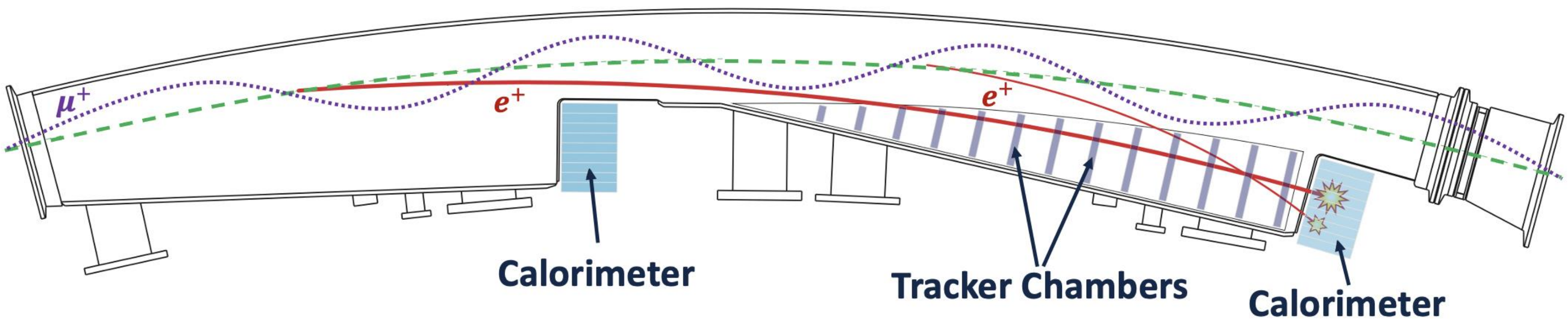
measure these

0 if “in plane”

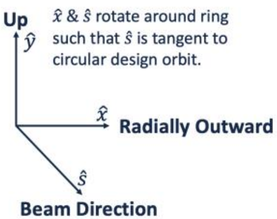
term cancels at the magic momentum



beam motion



- **Magnetic field provides radial confinement: $\vec{B} \sim B_0 \hat{y}$.**
- **Electric fields provide vertical focusing: $\vec{E} \sim E_1 (x\hat{x} - y\hat{y})$.**



$$x(s) \sim x_e + A_x \cos\left(\frac{\nu_x}{R_0} s + \phi_{x0}\right)$$

$$y(s) \sim A_y \cos\left(\frac{\nu_y}{R_0} s + \phi_{y0}\right)$$

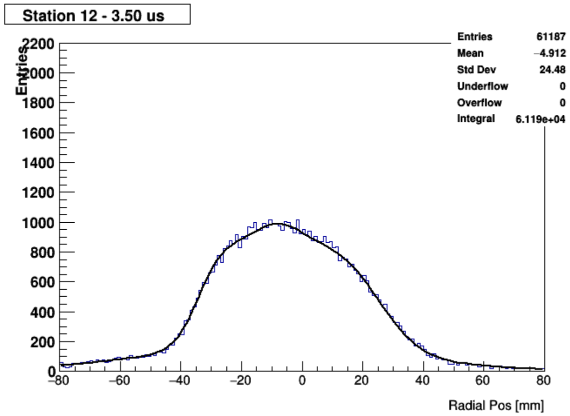
Betatron Motion

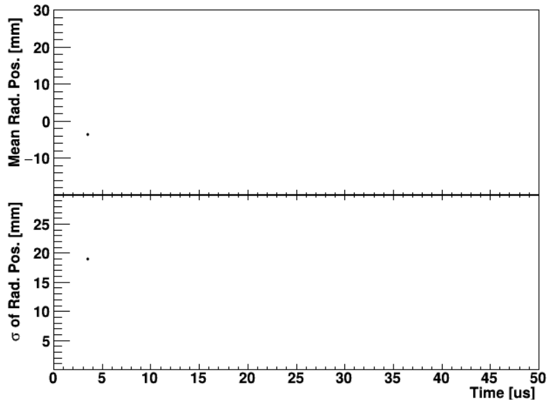
$$\nu_x^2 + \nu_y^2 \sim 1$$

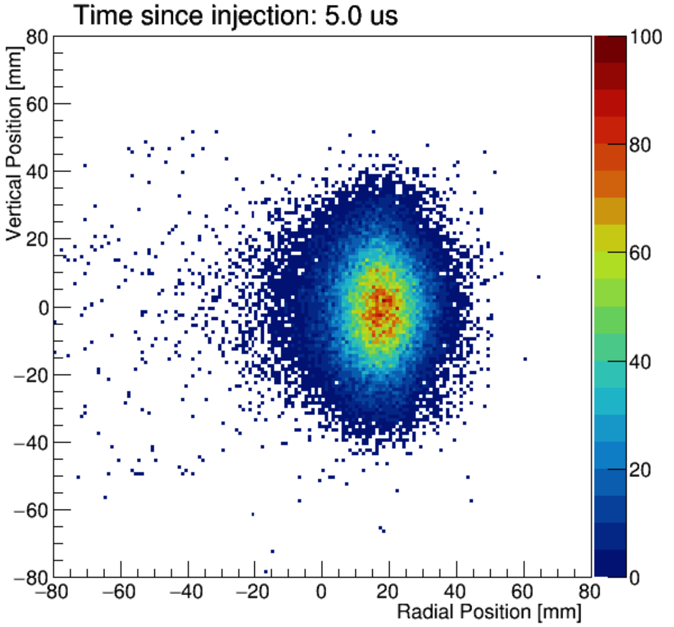
To extract ω_a, need to know:
1. where decay occurs
2. energy + position of positron
3. how the beam motion couples with detector acceptance

Use Calorimeters and Trackers

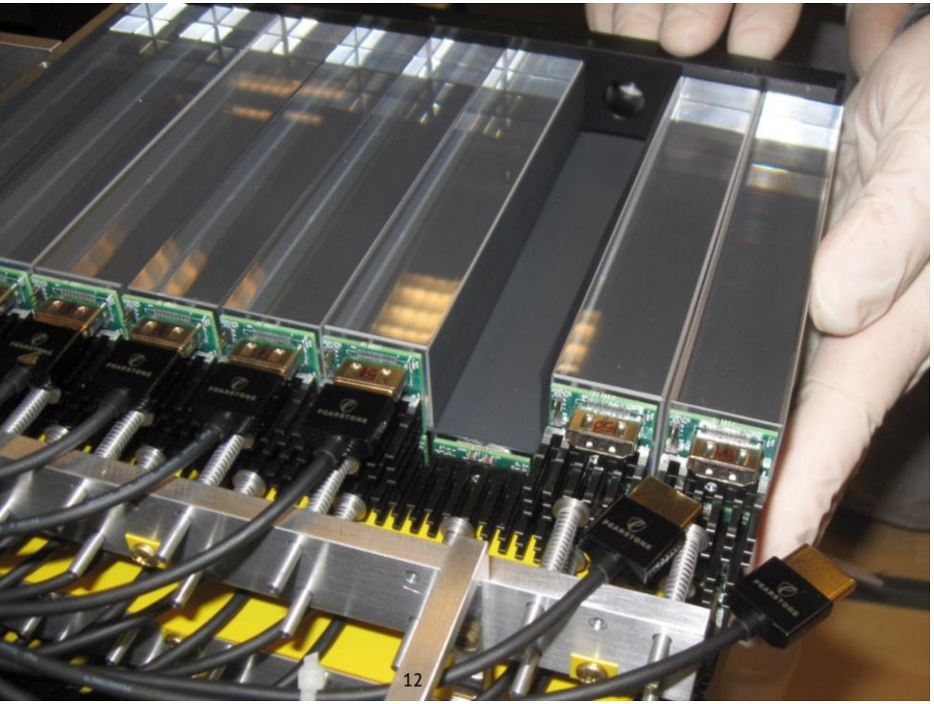
trackers are used to measure the transverse beam motion

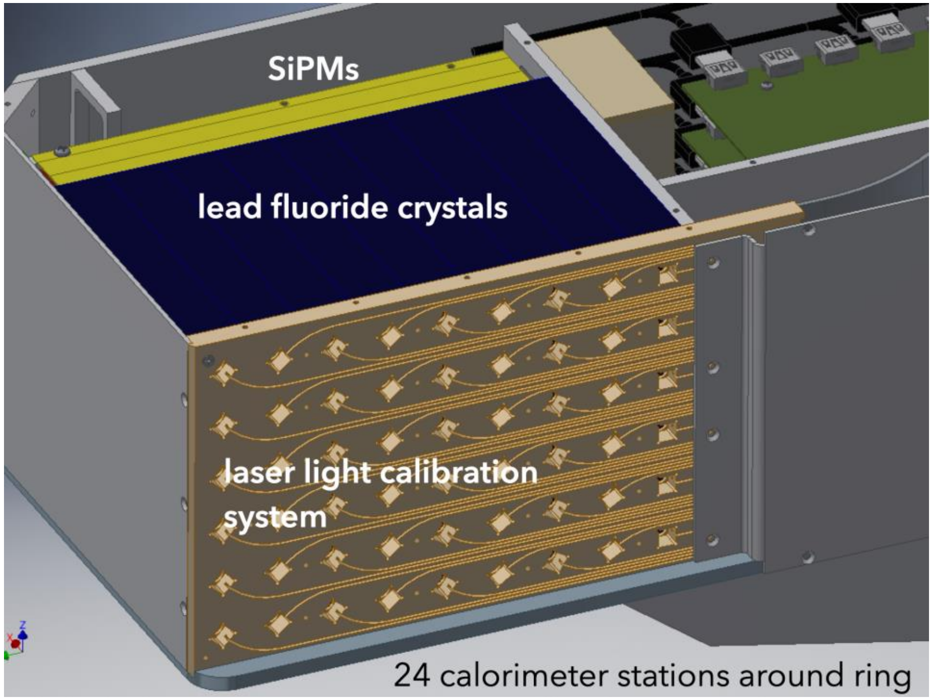




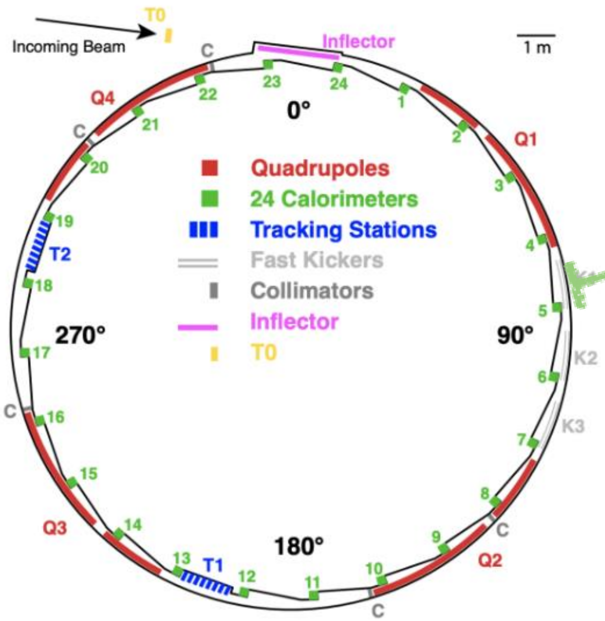


calorimeters
primary instrument of ω_a measurement



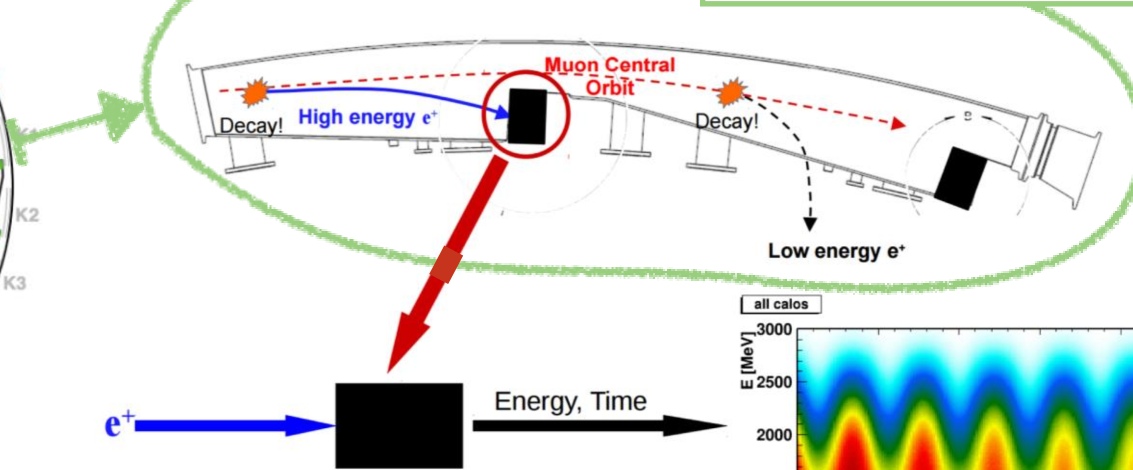


What does the calorimeter do?

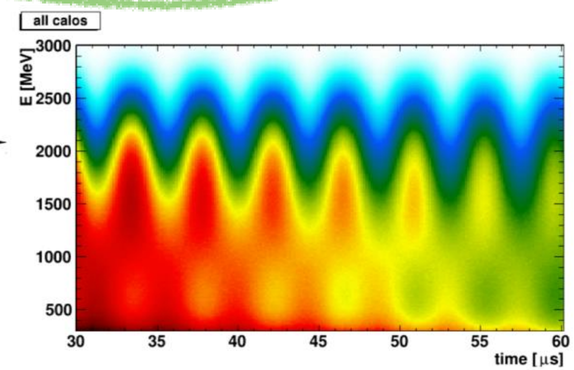


24 calorimeters evenly spaced around the inner perimeter of the ring

Storage Ring segment:
Calorimeters positioned to catch high energy decay positrons

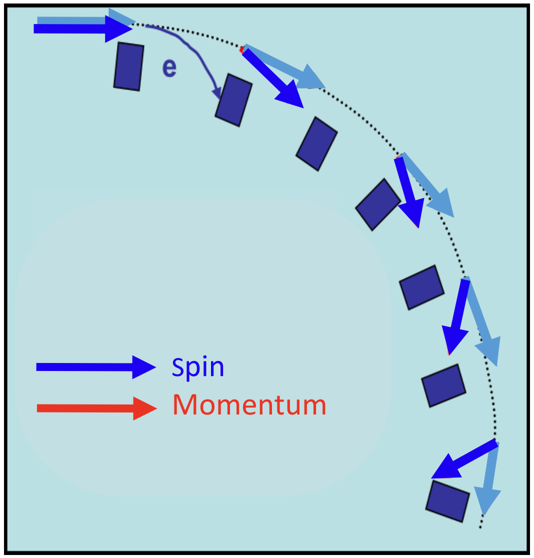


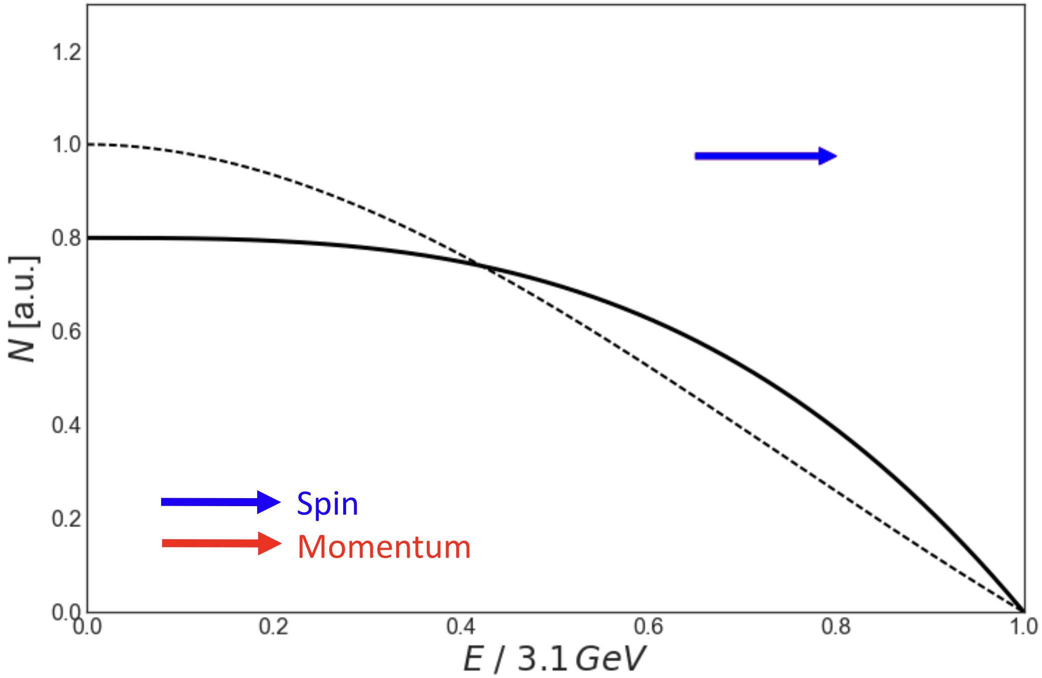
reconstruction



(E,t) distribution from 60h dataset

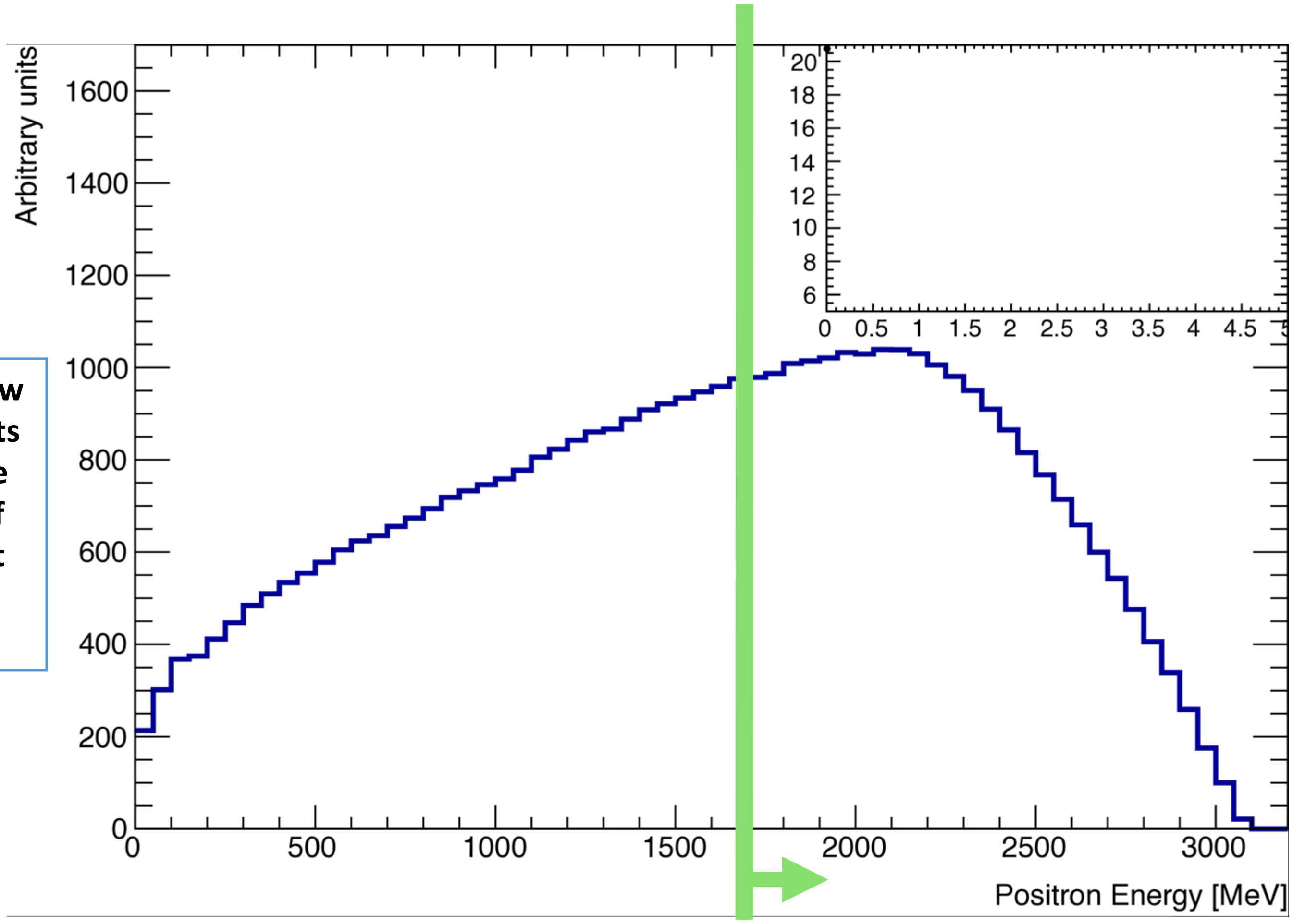
Calorimeter detects positron energy oscillating at ω_a



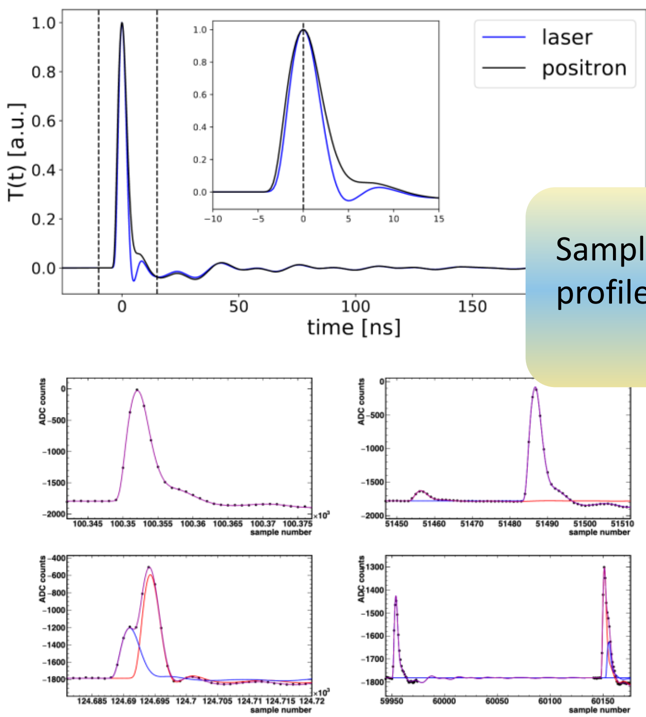


$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g_\mu - 2}{2}\right)\frac{q\vec{B}}{m} = -a_\mu \frac{q\vec{B}}{m}$$

Removing low energy events increases the amplitude of the wiggle at the cost of statistics

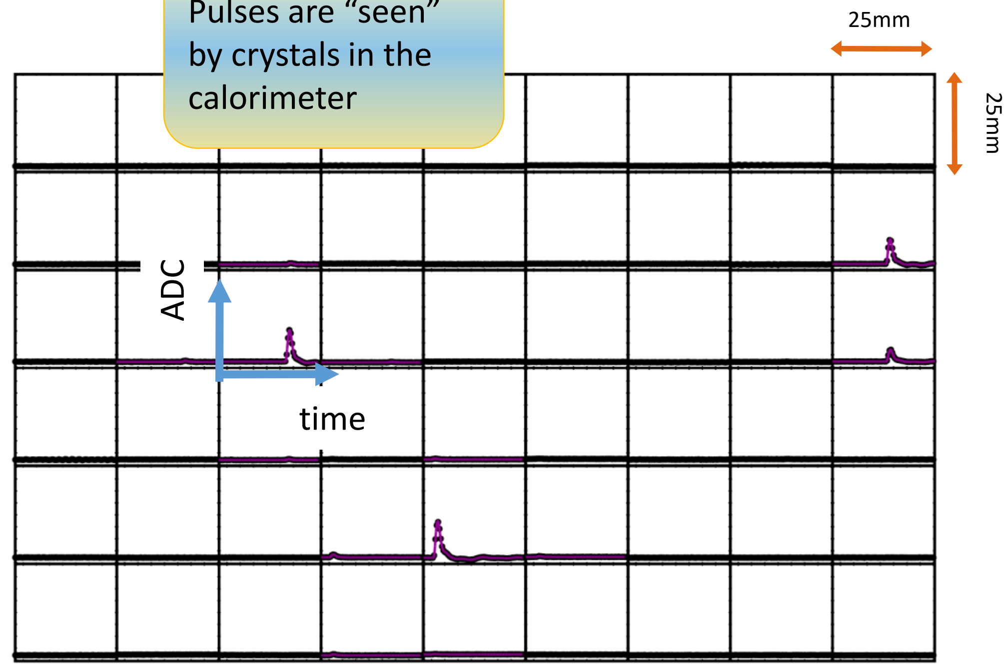


positrons deposit energy in the calorimeter



Sample pulse profiles

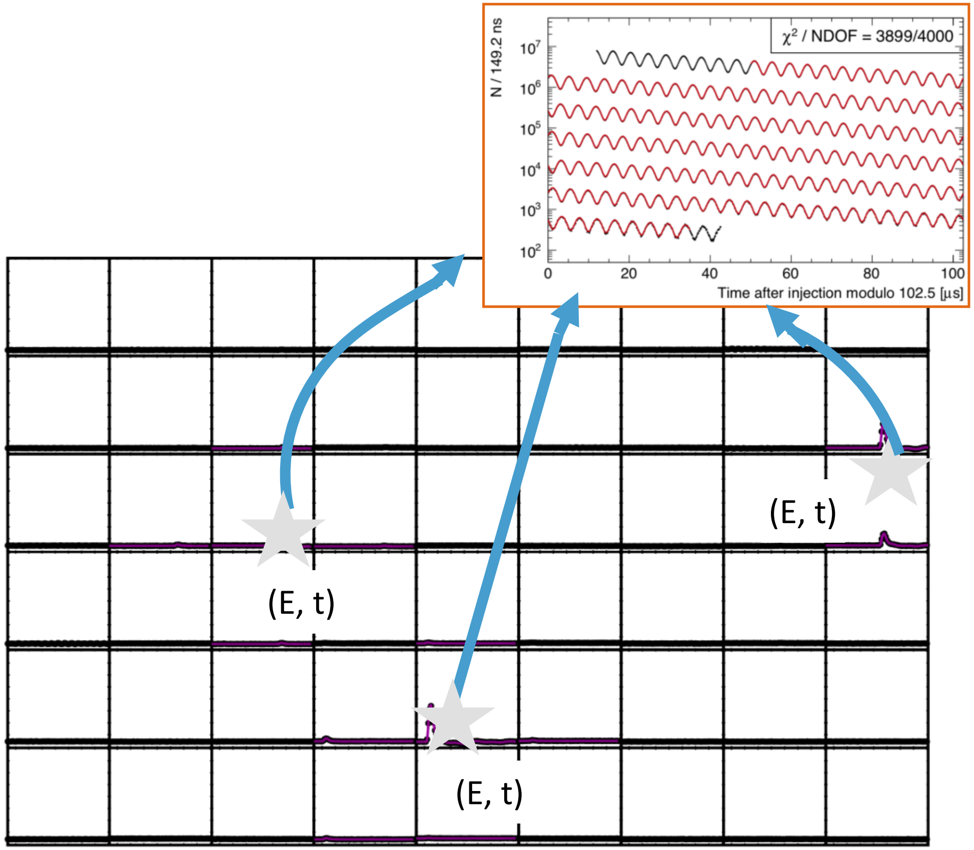
Pulses are “seen” by crystals in the calorimeter



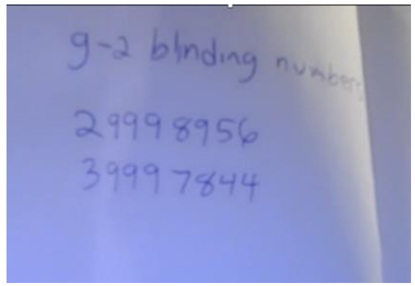
Pulses become (E,t) data & enter histogram (with some steps in between)

Data Reconstruction process assigns the correct energy and time to each positron event

Hardware blinding shifts the clock time — prevents analyzer from seeing true ω_a before analysis is complete



unblinding meeting February 27, 2021



Envelope with secret blinding code

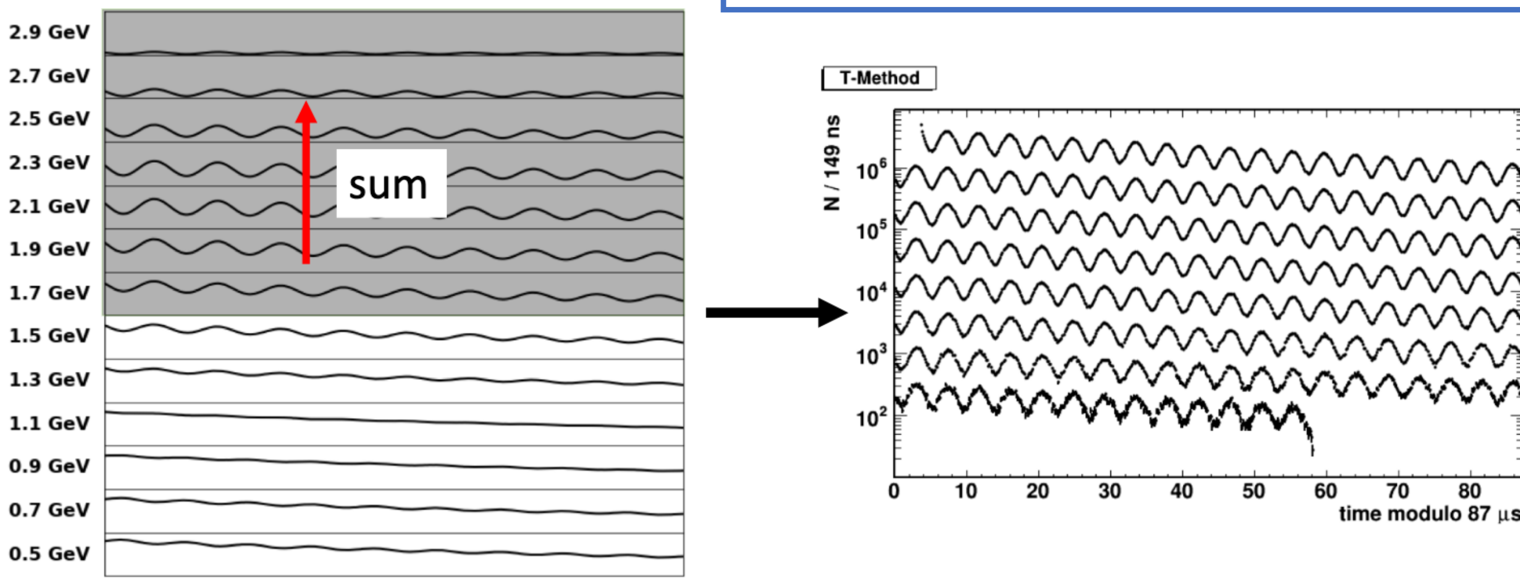
Collaborators eager to learn the result

fit wiggle plot for ω_a

$$\omega_a(R) = 2\pi\, 0.2291\,\mathrm{MHz} \cdot \left[1 + (R - \Delta R) \times 10^{-6}\right]$$

Software blinding

$$N(t) = \boldsymbol{N_0} e^{-t/\boldsymbol{\tau}} \left[1 + \boldsymbol{A} \cos\left(\omega_a(R)\boldsymbol{t} - \boldsymbol{\phi}\right)\right].$$



interpretation of g-2 result

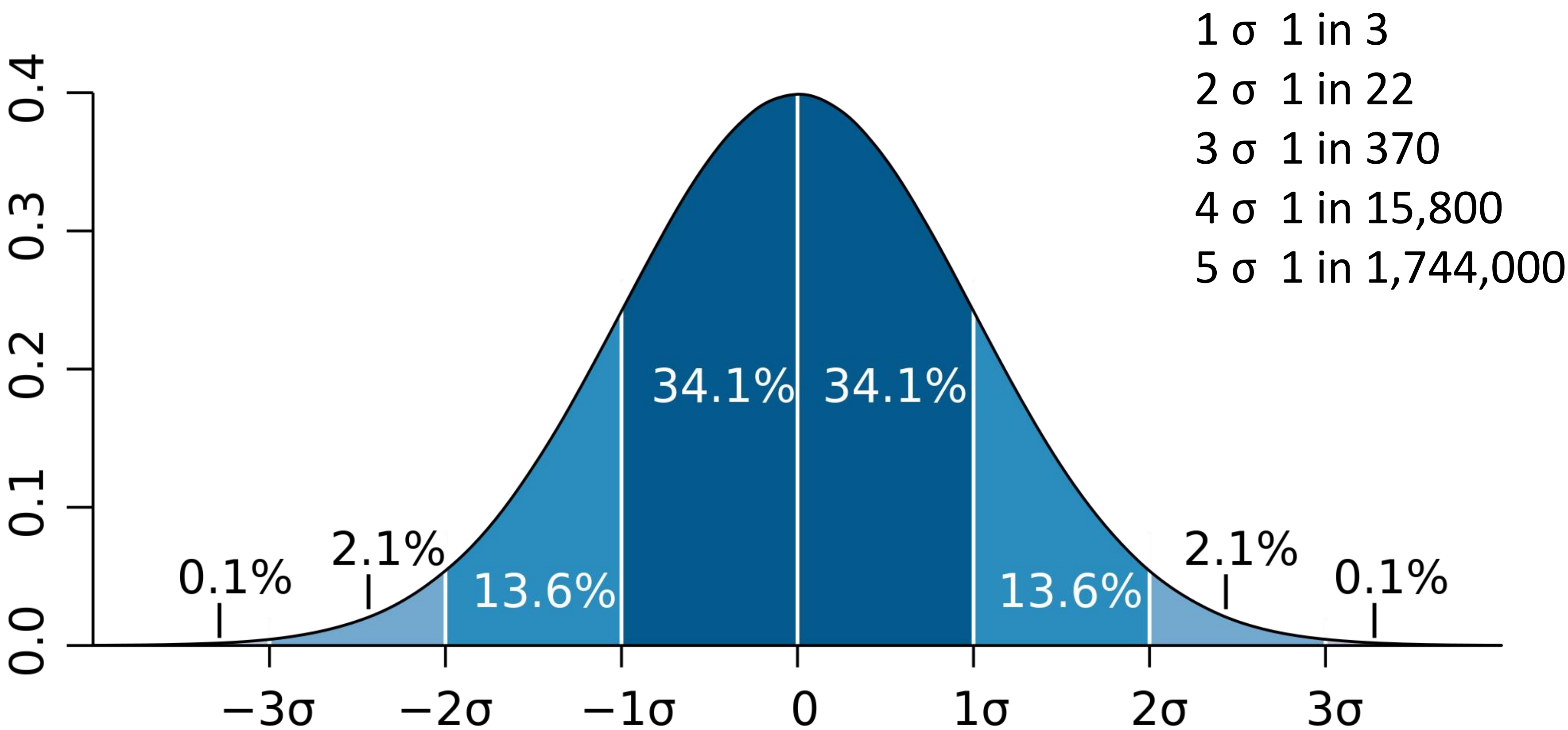
SCIENTIFIC AMERICAN®

Observations

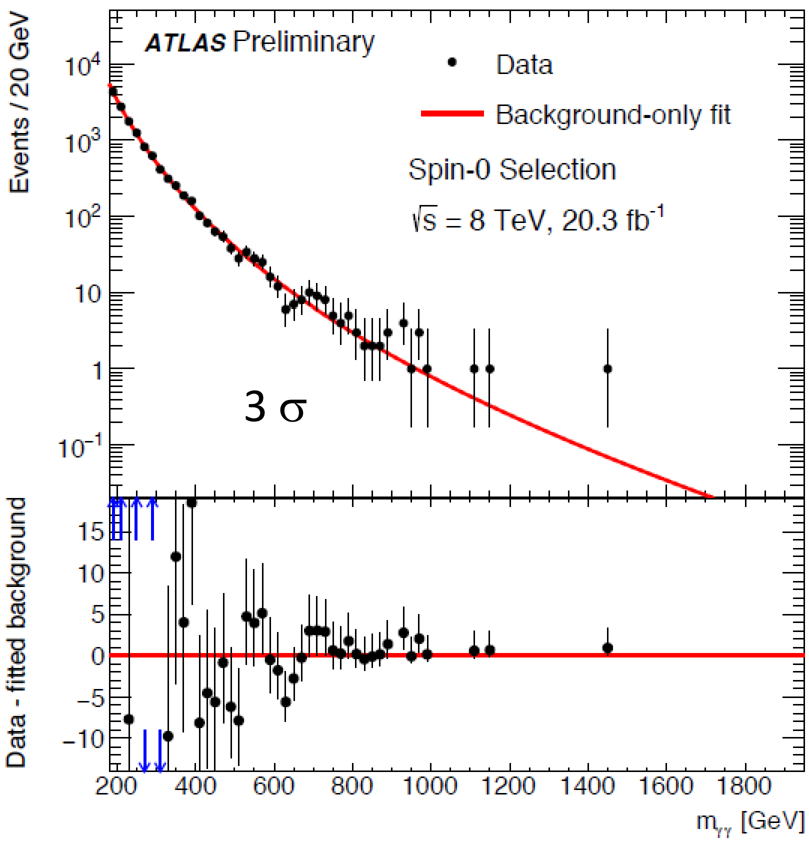
5 Sigma What's That?

By [Evelyn Lamb] on July 17, 2012

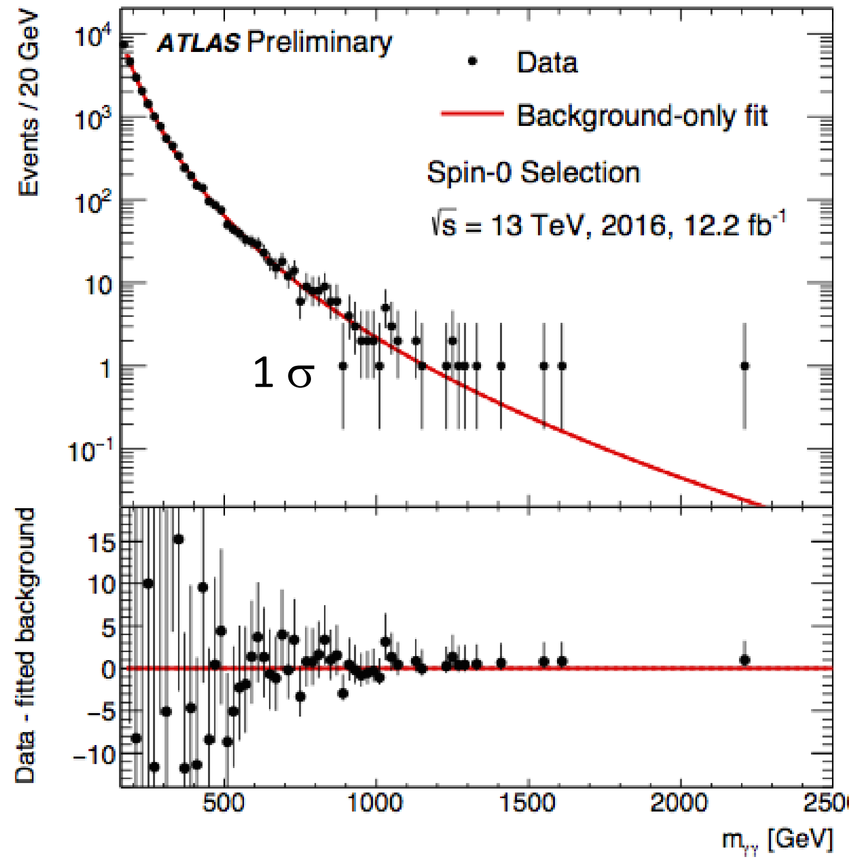
Normal Distribution to Three Sigma



disappearance of the 750 GeV bump



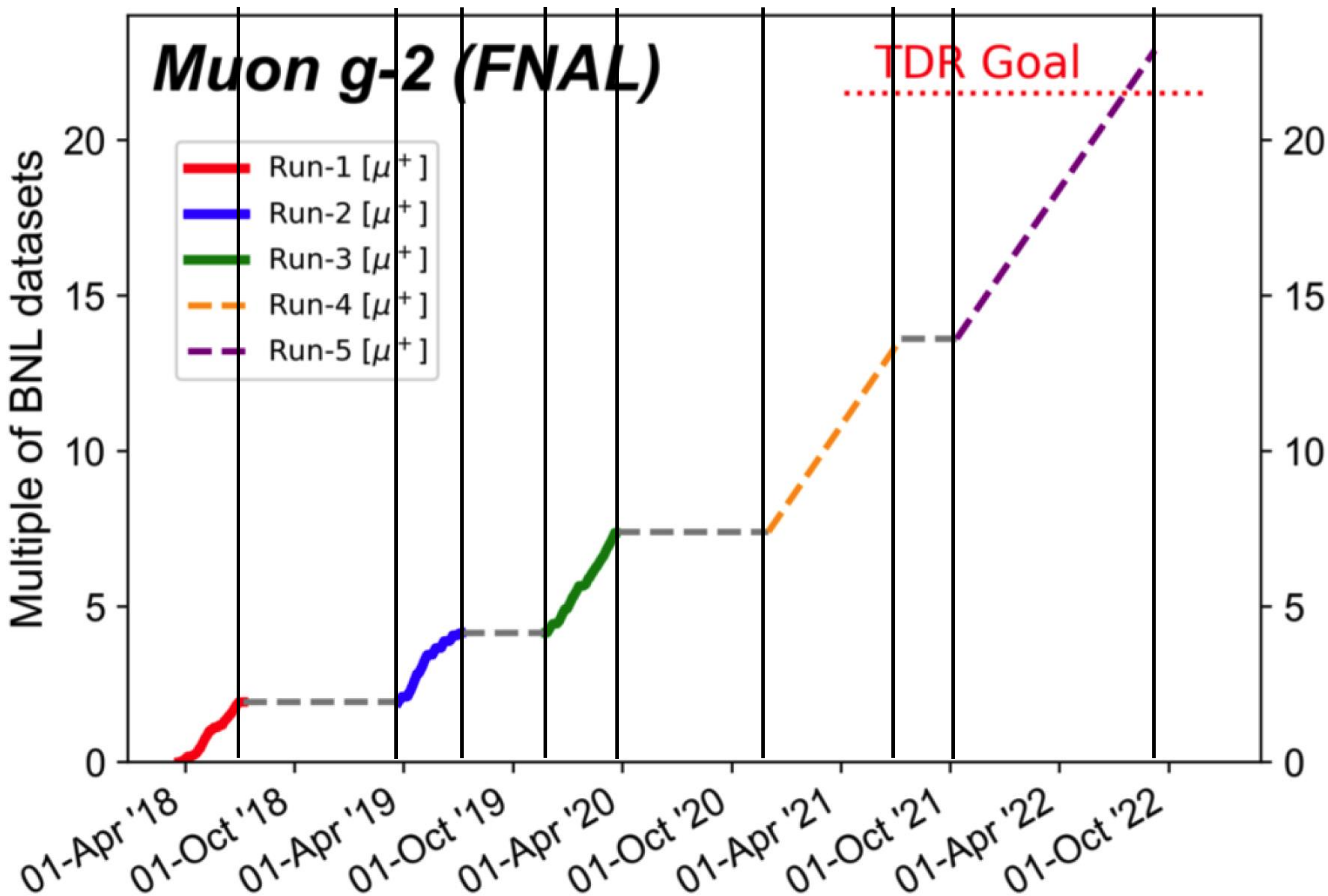
ATLAS December 2015



ATLAS August 2016

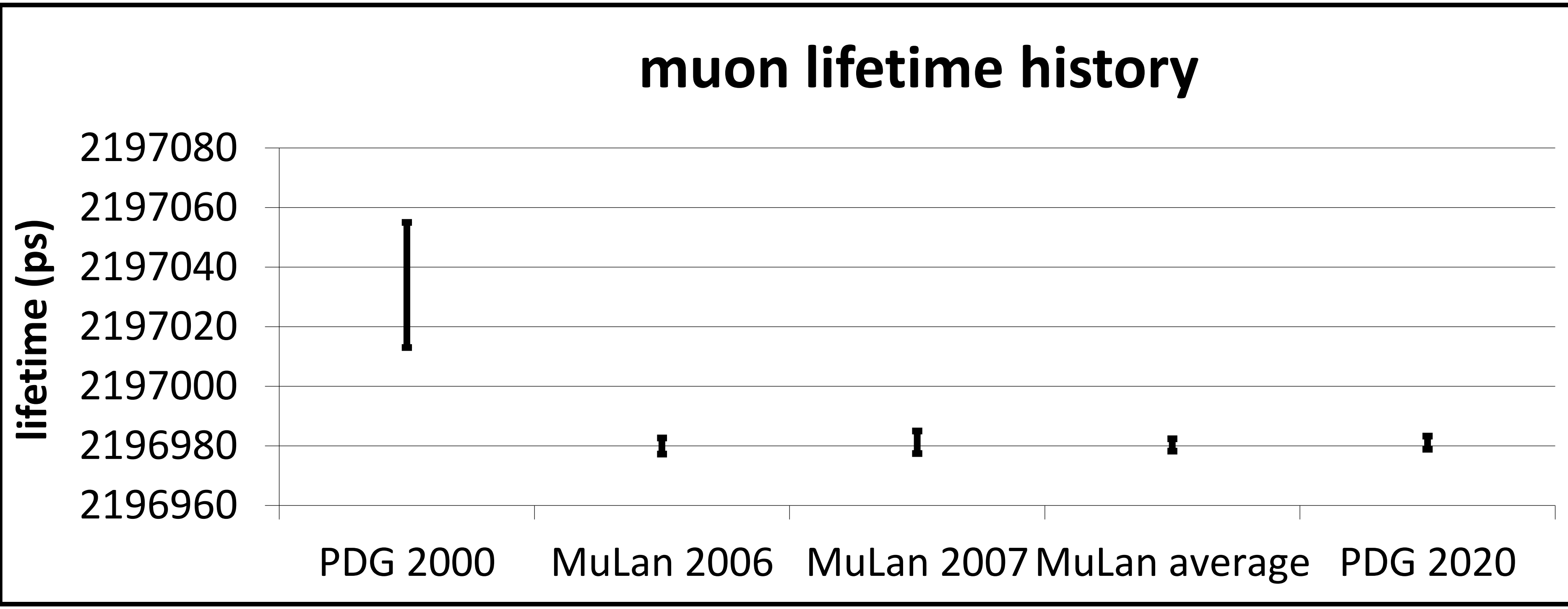
What BSM Physics Could the New Muon g-2 Result Address?

- supersymmetry
- extra dimensions
- technicolor
- baryon asymmetry
- extra gauge bosons
- neutrino mass generation
- charged lepton flavor violation
- strong CP problem
- hierarchy problem
- dark matter
- dark energy
- flavor changing neutral currents
- neutrino oscillations
- family problem
- SM parameters problem
- grand unified theories



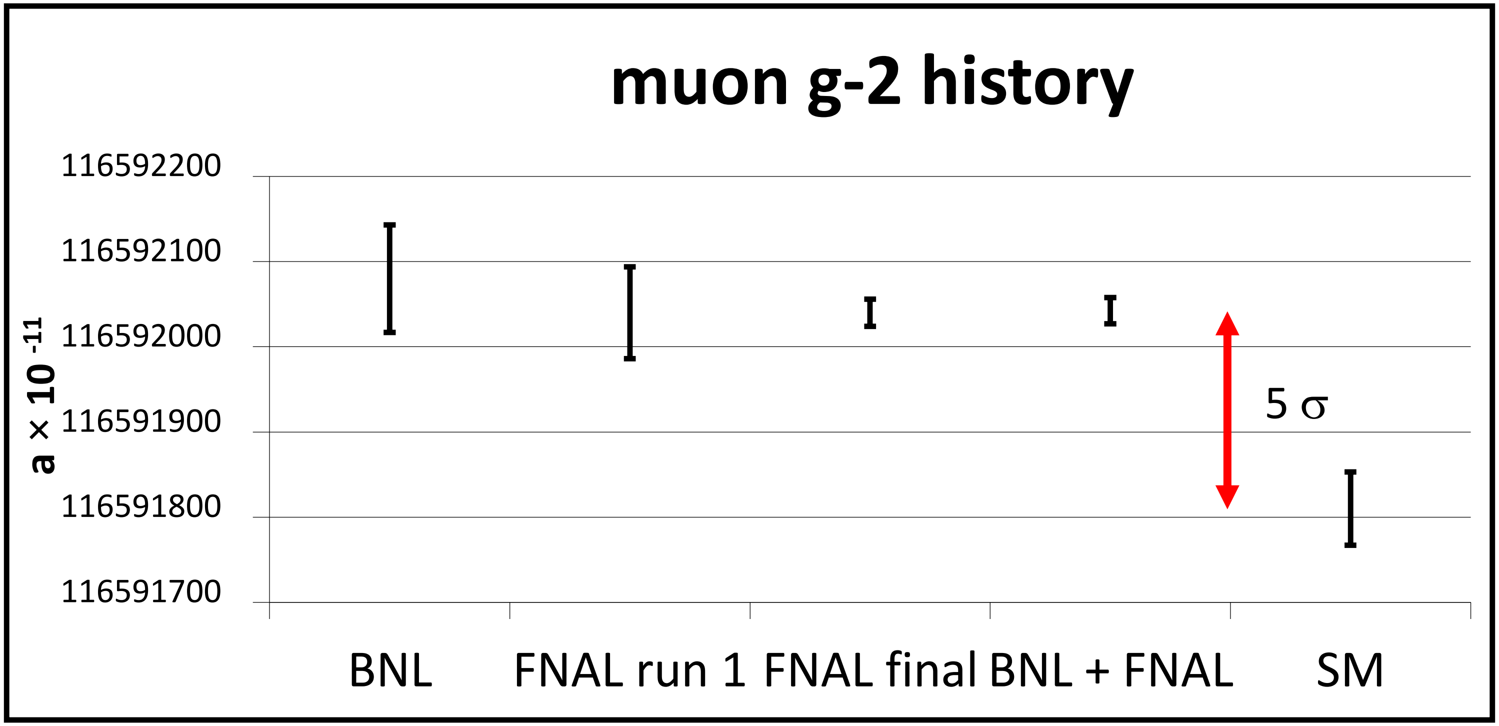
Muon g-2 (FNAL)
TDR Goal
Multiple of BNL datasets
Run-1 [μ^+]
Run-2 [μ^+]
Run-3 [μ^+]
Run-4 [μ^+]
Run-5 [μ^+]
0
5
10
15
20
01-Apr '18
01-Oct '18
01-Apr '19
01-Oct '19
01-Apr '20
01-Oct '20
01-Apr '21
01-Oct '21
01-Apr '22
01-Oct '22

most precise measurement dominates average



PDG 2000 average of 5 experiments 1972 – 1985
PDG 2020 dominated by MuLan

FNAL measurement will dominate BNL measurement



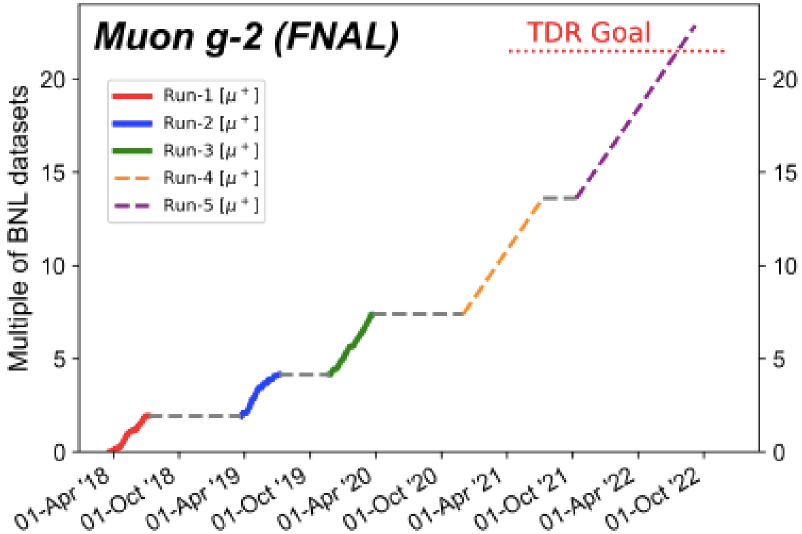
2006	2021	2024	2024	2021
0.54 ppm	0.46 ppm	0.14 ppm	0.13 ppm	0.37 ppm

FNAL final same value as FNAL run1, error smaller.
SM value and error as of 2021.

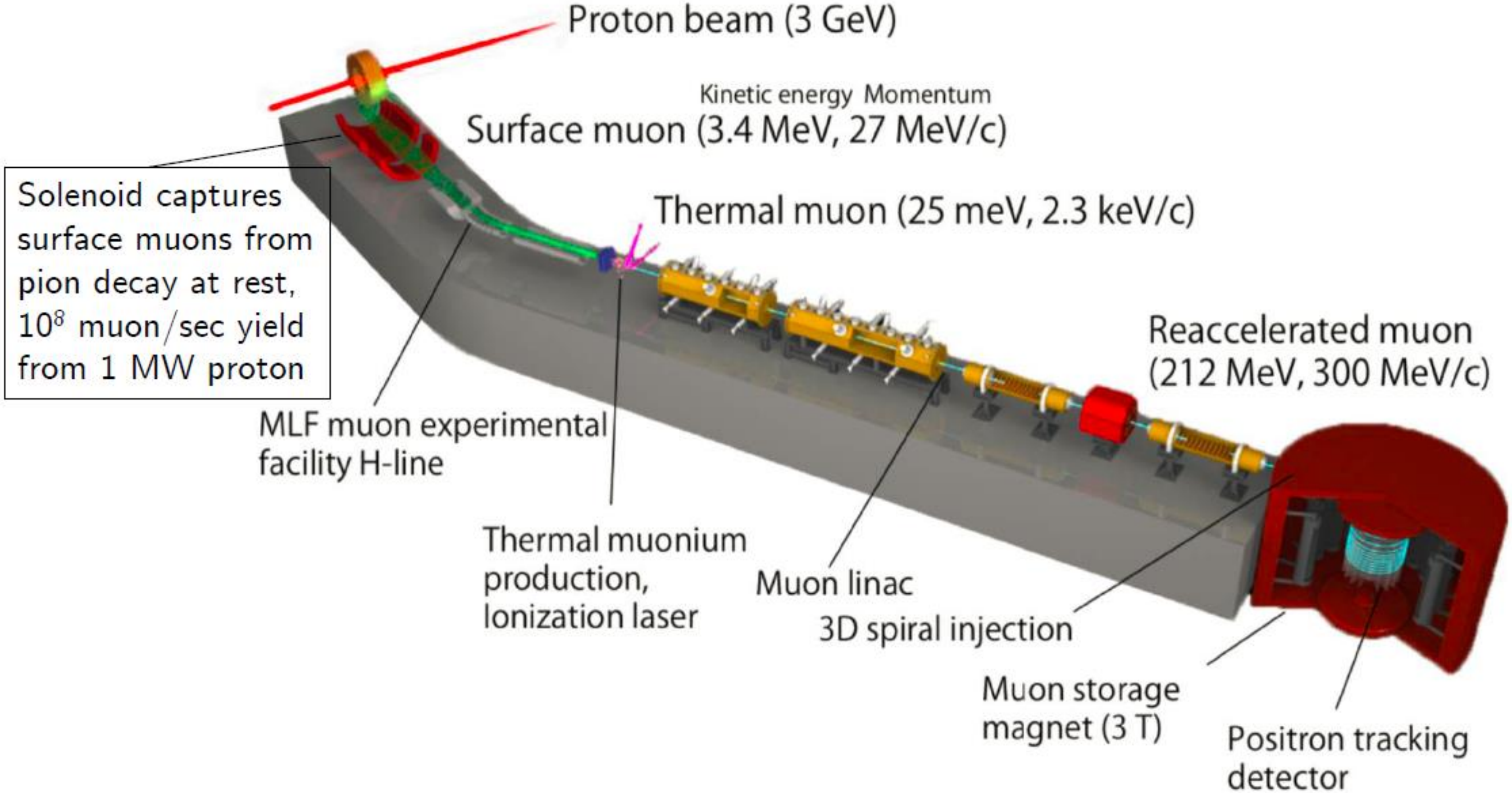
g-2 experiment continues

- **Collecting even more data**
  - **Run-1 ~ 6% of the final dataset**
  - **Run-2 + Run-3 + Run-4 ~ 10 times the Run-1 dataset**
  - **Run-5 ~ achieve project goal !**

100 ppb statistical goal!

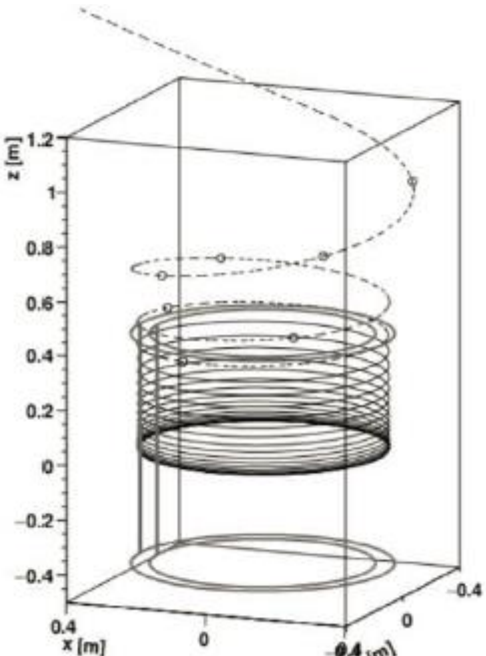


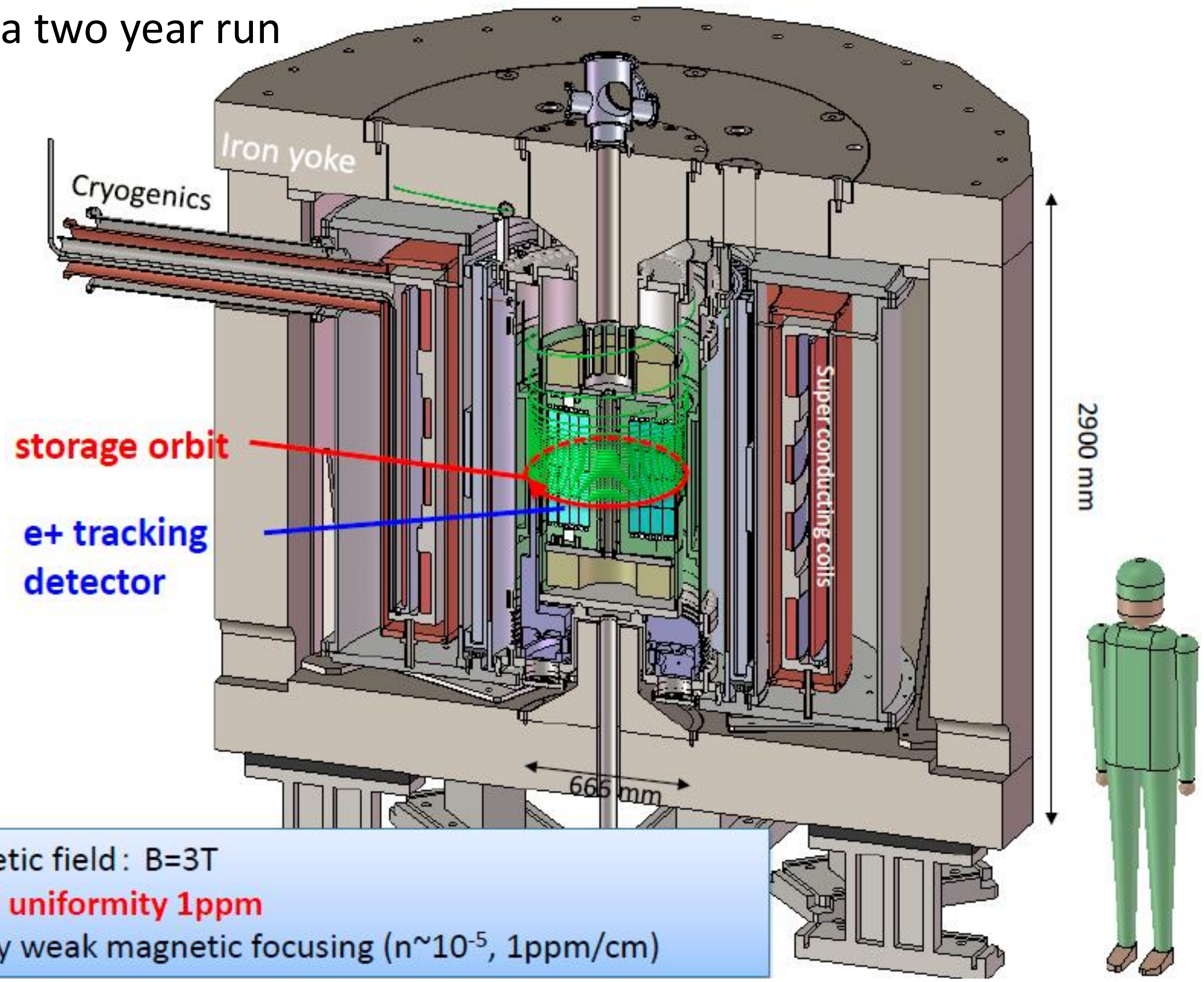
Muon g-2 Experiment at JPARC
completely different from CERN/BNL/FNAL method



Muon storage magnet and detector

450 ppb measurement with a two year run





Magnetic field: B=3T

local uniformity 1ppm

+very weak magnetic focusing ($n\sim10^{-5}$, 1ppm/cm)

Is Muon g-2 Alone in a Standard Model Deviation? No – Some Examples

- B meson to D meson decay branching ratios $>3\ \sigma$ at LHC
- B meson to K meson decay branching ratios 2-3 σ at LHC
- Lepton flavor universality violation 3 σ at LHC
- K meson to neutral pi decay branching ratio $>4\ \sigma$ at JPARC
- CKM matrix unitarity violation 2-3 σ
- neutrino oscillation MiniBooNE at FNAL

The Standard Model is incomplete.
Theory and experiment continue to search beyond.

Thank you!

g-2 experiment is just one piece of the puzzle.