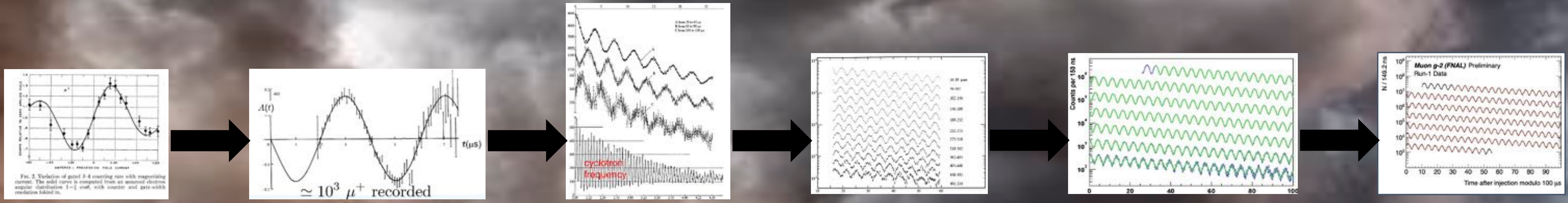


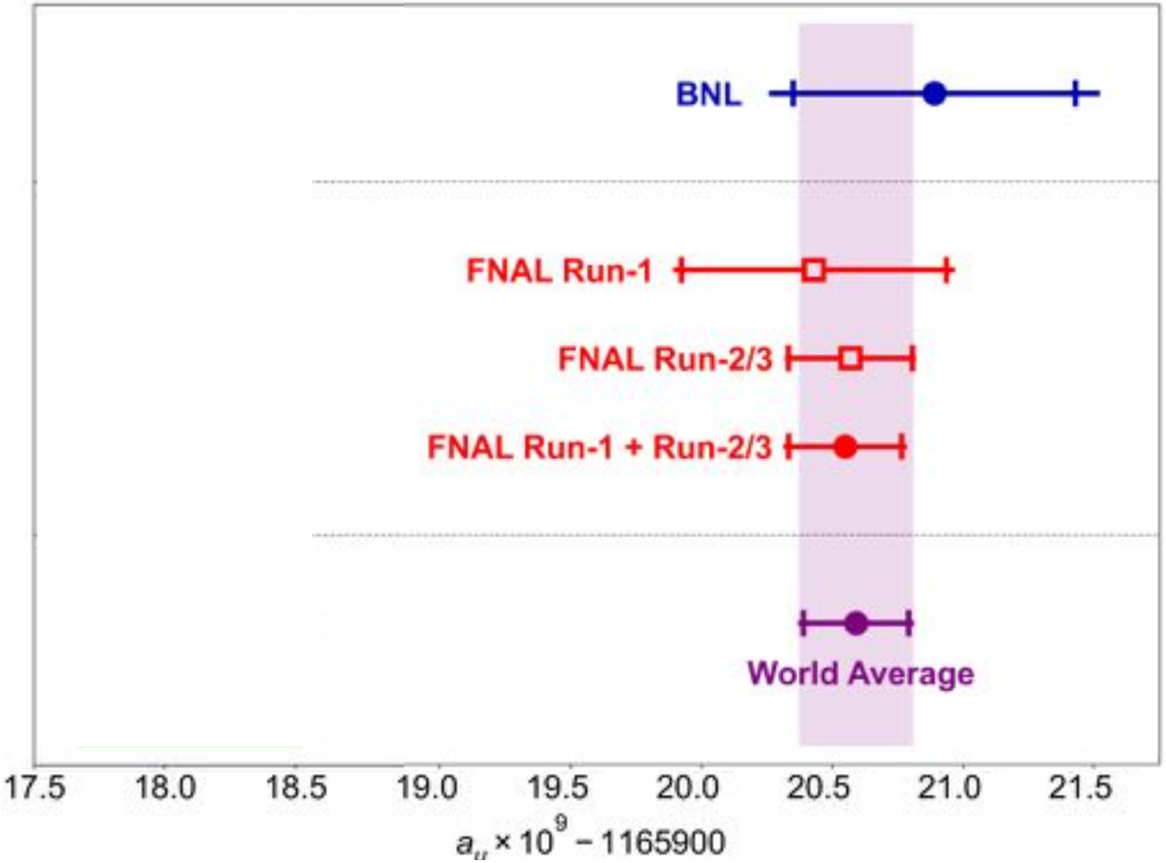
50+ Years of Muon “g-2” experiments

CENPA
Center for Experimental Nuclear Physics and Astrophysics

David Hertzog
University of Washington
Wojcicki Symposium, Nov. 10, 2023

The Buzz around the Muon g-2 Measurement …

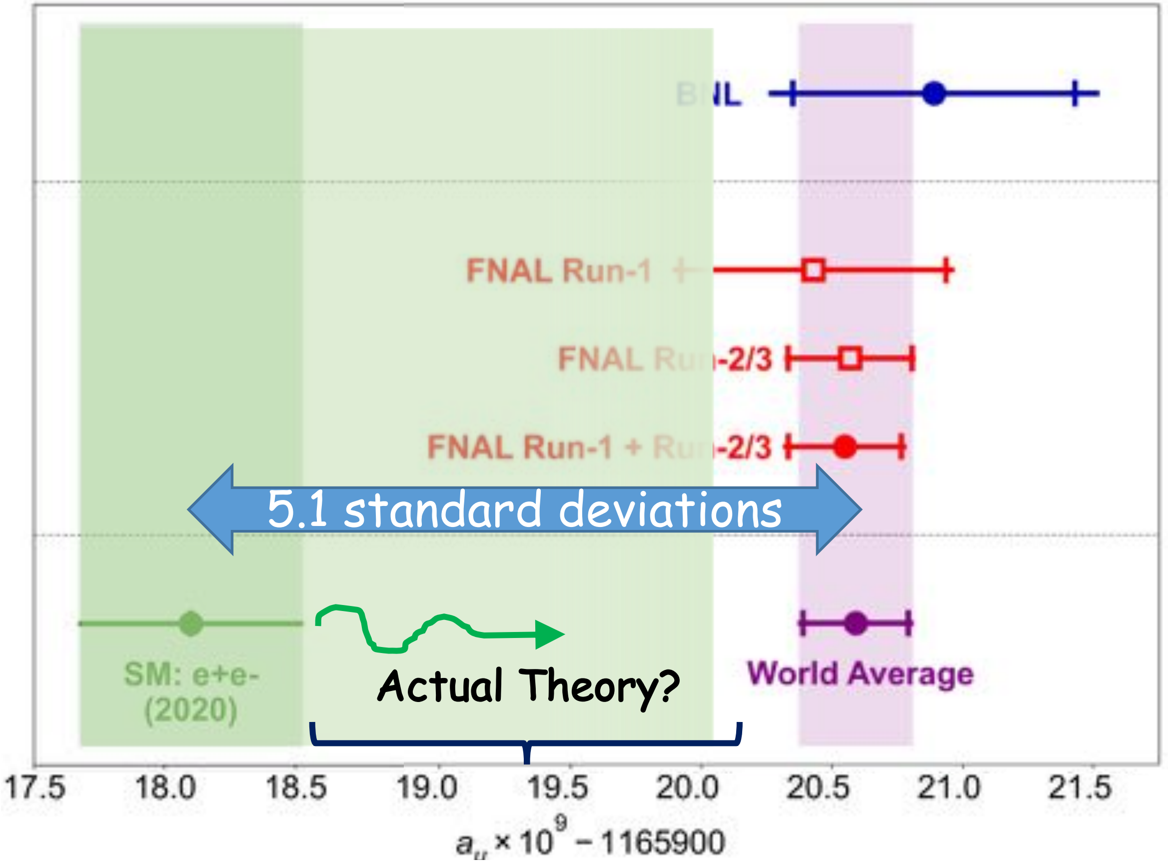
$$a_\mu \equiv \frac{(g-2)}{2}$$



FNAL (2023)
precision ± 200 ppb

The Buzz around the Muon g-2 Measurement …

$$a_\mu \equiv \frac{(g-2)}{2}$$



World-wide g-2 Theory
Initiative Recommendation
(340 ppb)

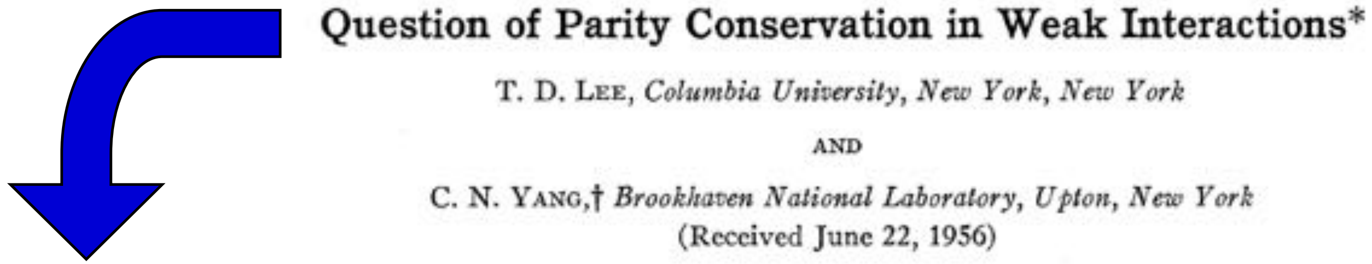
Looks like a Discovery !!

FNAL (2023)
precision ± 200 ppb

Various Wrenches in the Works
(to be explained)

A truly radical thought …

1956



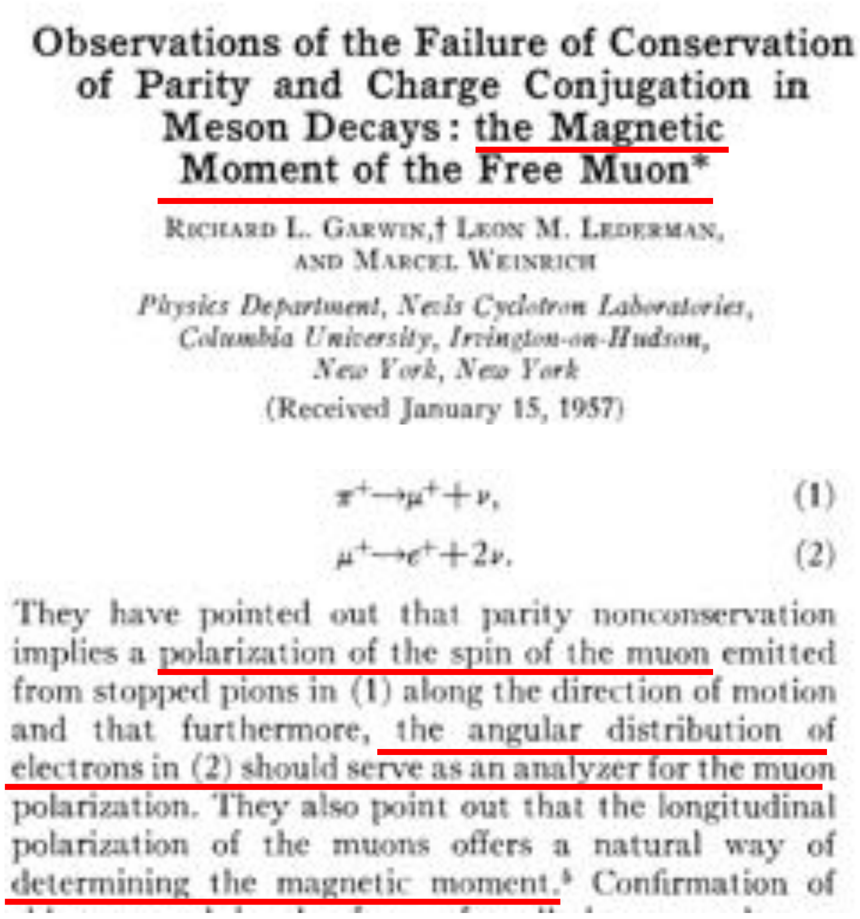
Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)



Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

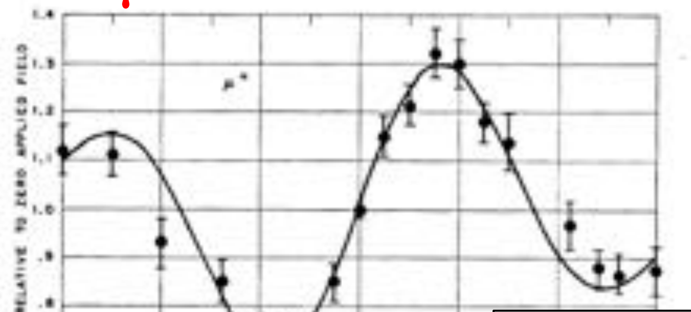
(Received January 15, 1957)

$$\pi^+\to\mu^++\nu, \qquad (1)$$

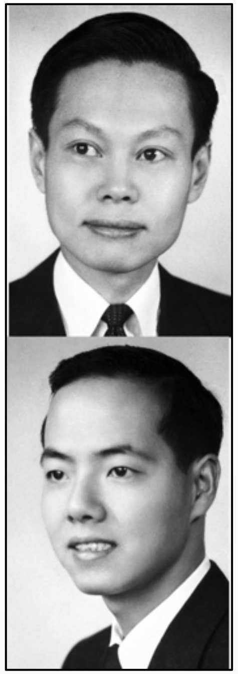
$$\mu^+\to e^++2\nu. \qquad (2)$$

They have pointed out that parity nonconservation implies a polarization of the spin of the muon emitted from stopped pions in (1) along the direction of motion and that furthermore, the angular distribution of electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal polarization of the muons offers a natural way of determining the magnetic moment.[4] Confirmation of

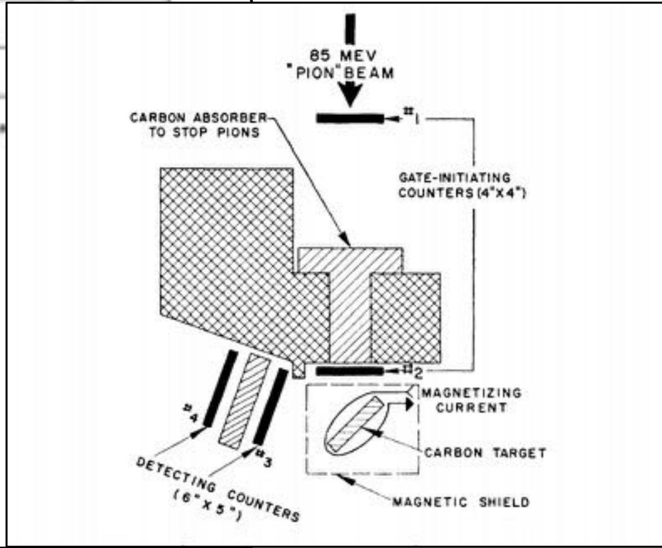
… g_μ = 2.0 ±0.1 …



Particles with spin can be Left Handed or Right Handed



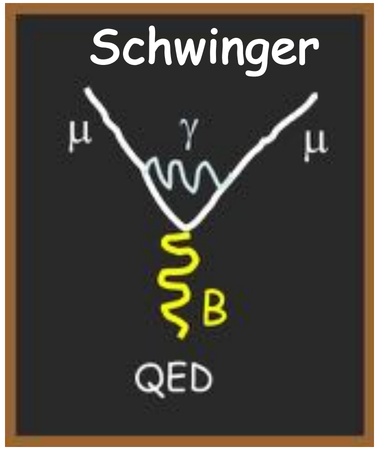
1957 Nobel prize



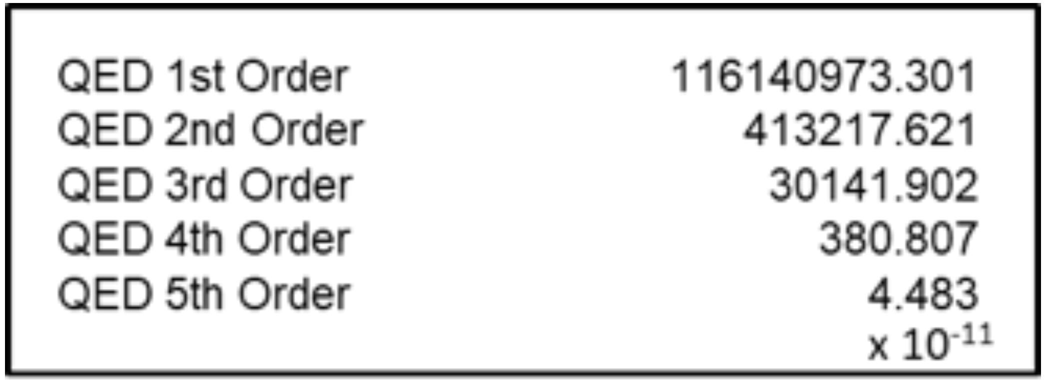
In 1947, deviations from g = 2 at ~ 0.1% level observed for the "point-like" electron → development of quantum electrodynamics

$$a_e = \frac{(g-2)}{2} \approx \frac{1}{2}\frac{\alpha}{\pi} \approx \frac{1}{800}$$

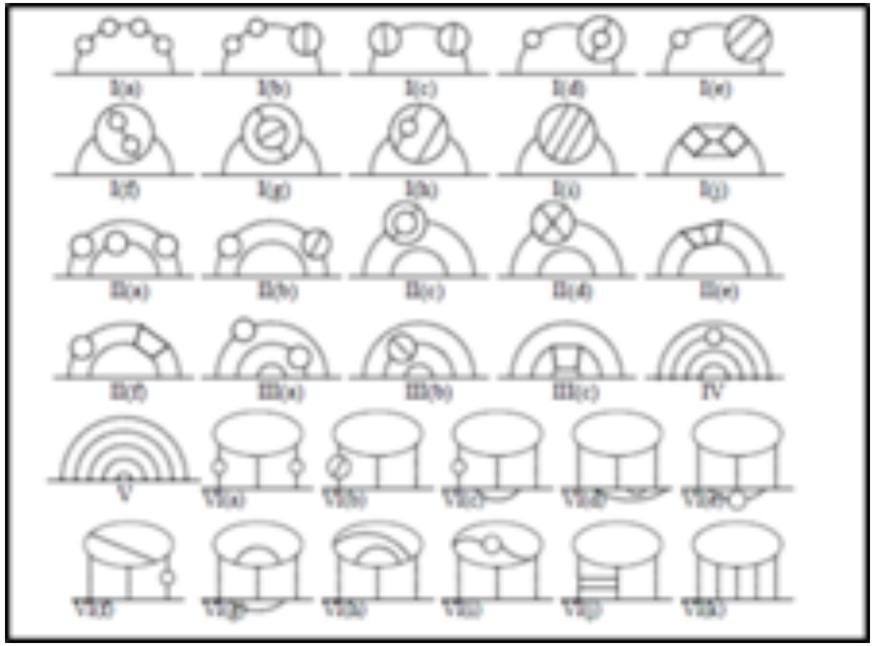
→ 116 140 973.301 x 10^{-11}



Improved over decades, reaching extraordinary levels of precision

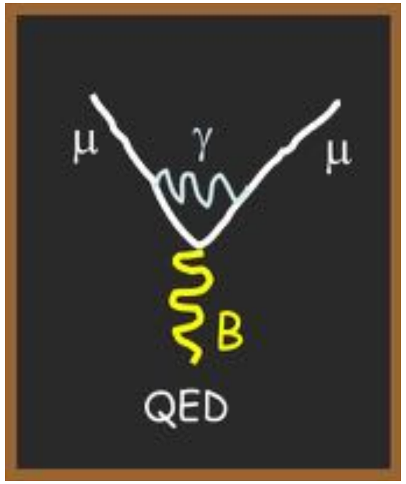


QED 1st Order	116140973.301
QED 2nd Order	413217.621
QED 3rd Order	30141.902
QED 4th Order	380.807
QED 5th Order	4.483
	x 10^{-11}

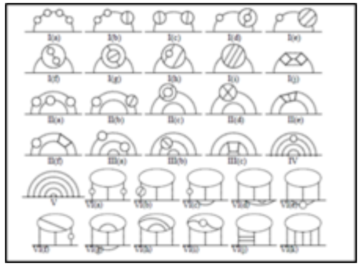


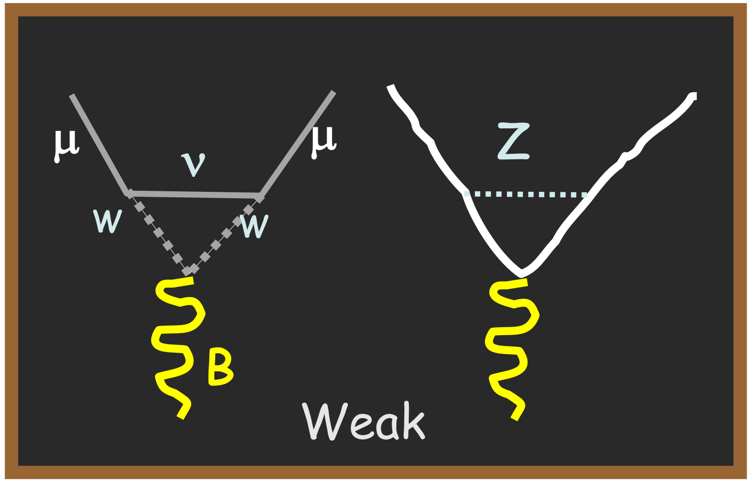
Takeaway: Uncertainty totally negligible

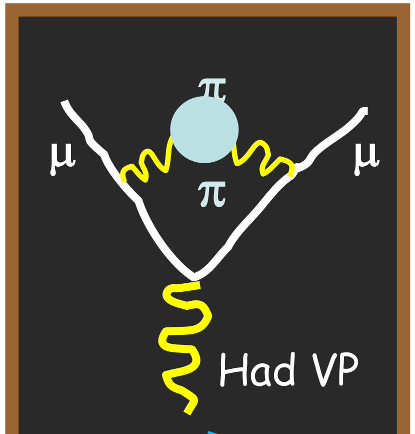
The Muon anomaly is sensitive to all particles that interact with it …

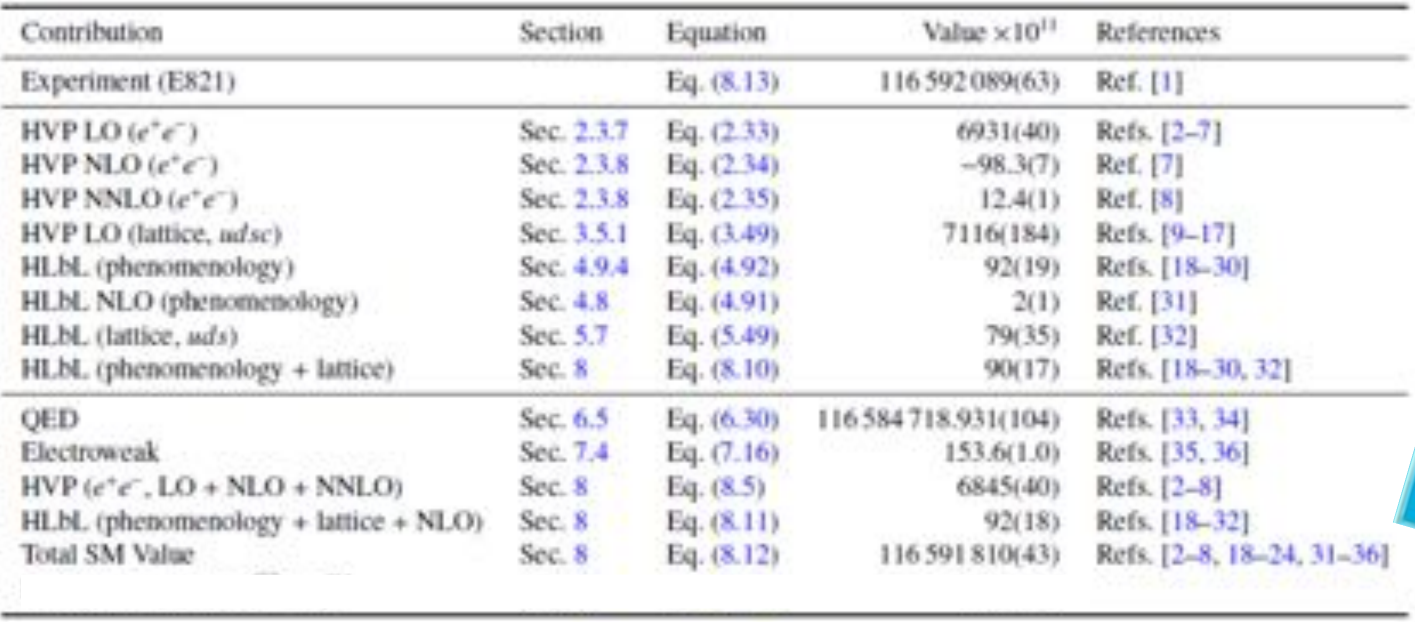


…



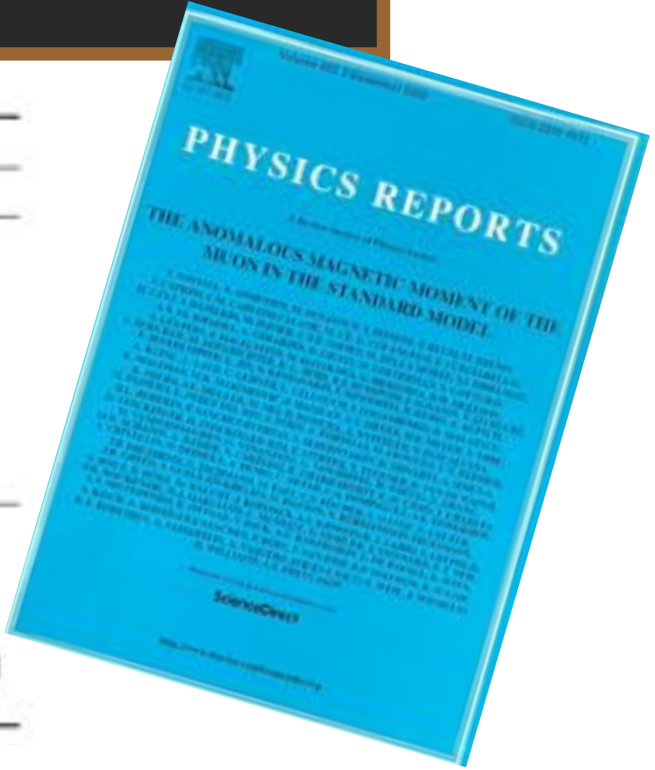






Contribution	Section	Equation	Value ×10^{11}	References
Experiment (E821)		Eq. (8.13)	116 592 089(63)	Ref. [1]
HVP LO (e^+e^-)	Sec. 2.3.7	Eq. (2.33)	6931(40)	Refs. [2–7]
HVP NLO (e^+e^-)	Sec. 2.3.8	Eq. (2.34)	−98.3(7)	Ref. [7]
HVP NNLO (e^+e^-)	Sec. 2.3.8	Eq. (2.35)	12.4(1)	Ref. [8]
HVP LO (lattice, *udsc*)	Sec. 3.5.1	Eq. (3.49)	7116(184)	Refs. [9–17]
HLbL (phenomenology)	Sec. 4.9.4	Eq. (4.92)	92(19)	Refs. [18–30]
HLbL NLO (phenomenology)	Sec. 4.8	Eq. (4.91)	2(1)	Ref. [31]
HLbL (lattice, *uds*)	Sec. 5.7	Eq. (5.49)	79(35)	Ref. [32]
HLbL (phenomenology + lattice)	Sec. 8	Eq. (8.10)	90(17)	Refs. [18–30, 32]
QED	Sec. 6.5	Eq. (6.30)	116 584 718.931(104)	Refs. [33, 34]
Electroweak	Sec. 7.4	Eq. (7.16)	153.6(1.0)	Refs. [35, 36]
HVP (e^+e^-, LO + NLO + NNLO)	Sec. 8	Eq. (8.5)	6845(40)	Refs. [2–8]
HLbL (phenomenology + lattice + NLO)	Sec. 8	Eq. (8.11)	92(18)	Refs. [18–32]
Total SM Value	Sec. 8	Eq. (8.12)	116 591 810(43)	Refs. [2–8, 18–24, 31–36]

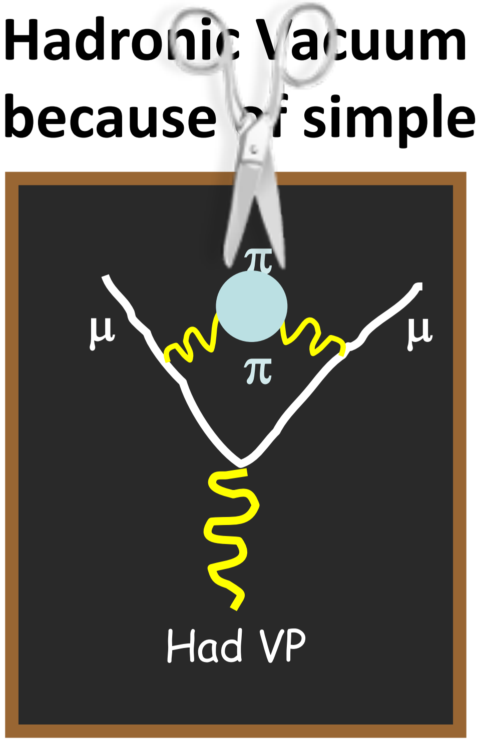
370 ppb

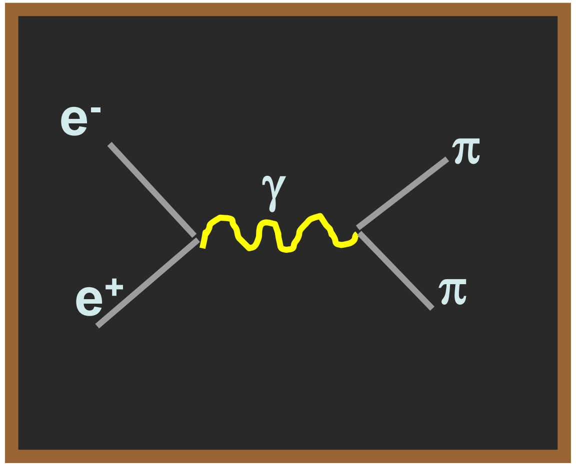


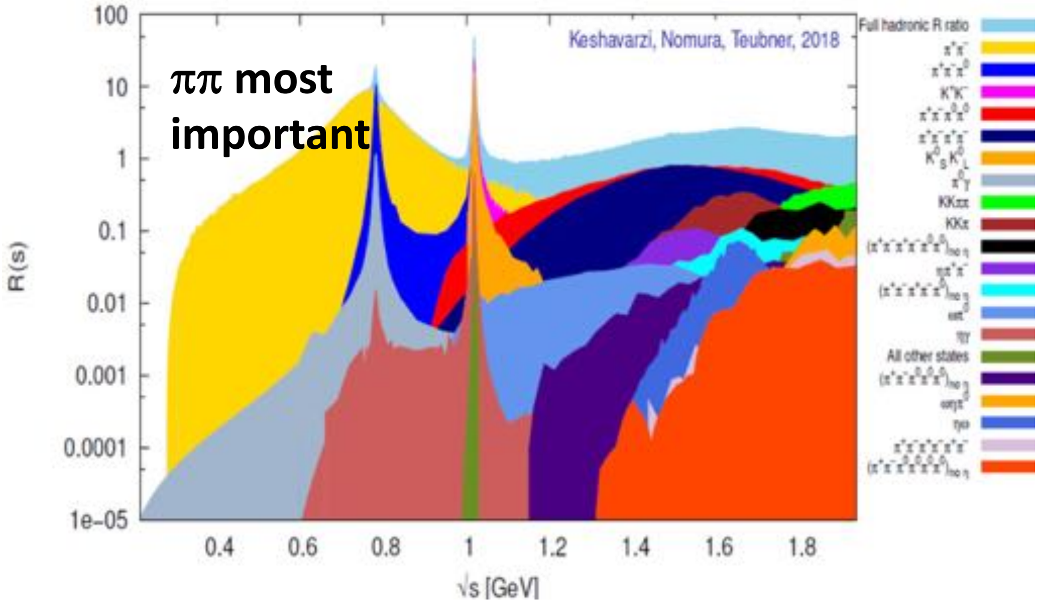
PHYSICS REPORTS

THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL

Hadronic Vacuum Polarization is obtained from decades of precise e^+e^- experiments because of simple dispersion relation that connects a_μ to data:







The uncertainty is entirely from experimental errors (statistics dominates)

1. **Cut diagram down middle**
2. **It now looks like $\gamma \rightarrow \pi\pi$**

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mathrm{muons})}$$

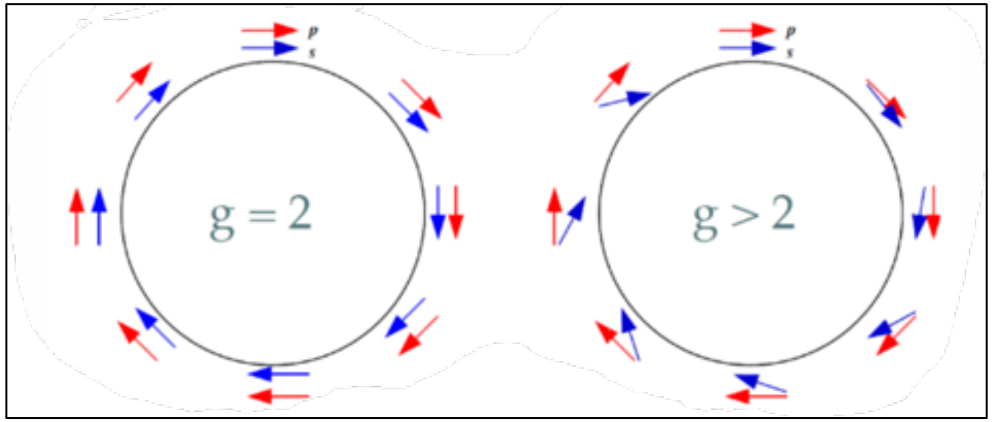
Takeaway: This uncertainty **dominates** SM prediction …
and will become the important end of today’s story

The physics of interest is the small difference of g from 2 to test the completeness of the SM

$$g_\mu = 2.00\underbrace{2\,331\,840\,80}(11)$$

Design the experiment to measure this part to high precision.

The Fundamental Experimental Principle: *In-flight* measurement



$$\omega_C = \frac{eB}{mc\gamma}$$

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

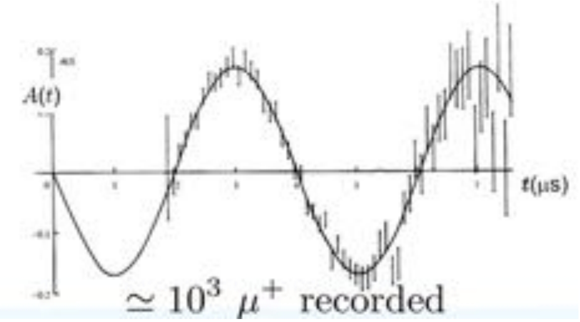
The difference between spin precession frequency and cyclotron frequencies, $\vec{\omega}_a$, does not depend on γ ! Therefore,

Get a_μ

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

Measure these

begin to precisely test leading QED predictions



$\simeq 10^3\ \mu^+$ recorded

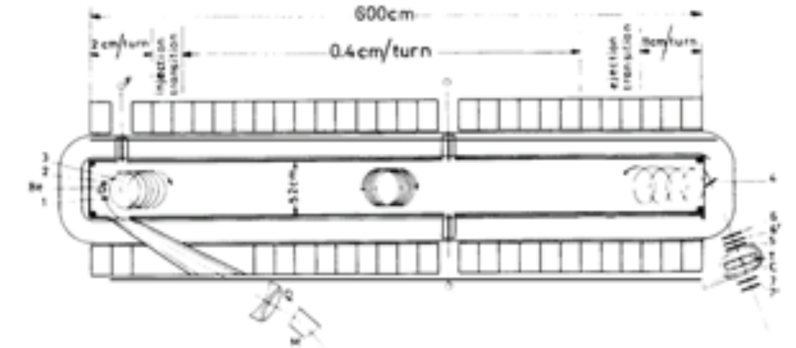
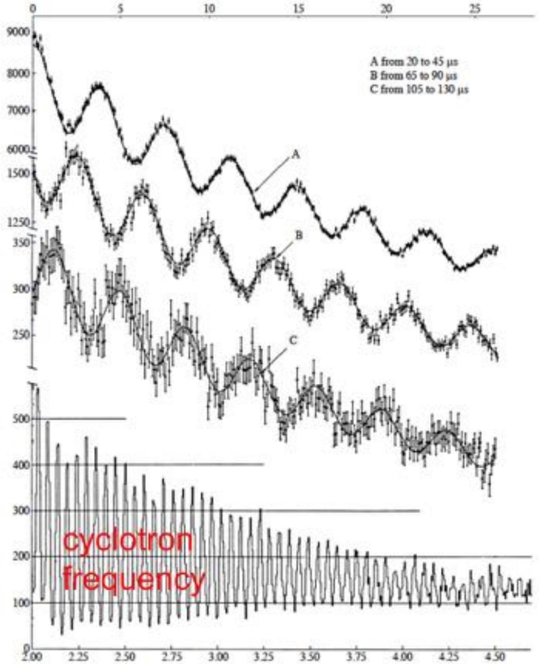


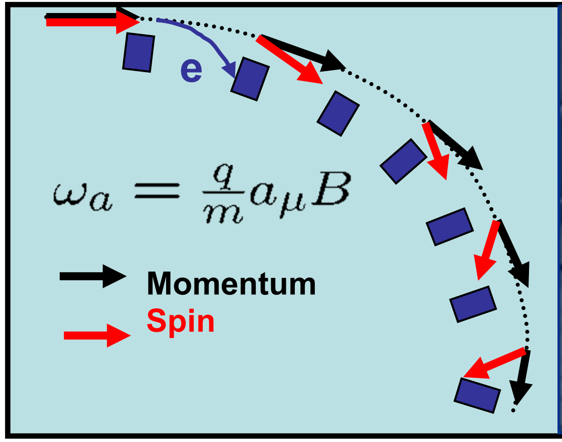
Fig. 2. The storage of muons in the 6 m bending magnet used in the first CERN (g-2) experiment. The field gradient makes the orbits walk to the right and at the end a large gradient is used to eject the particles so that they are stopped in the polarization analyser. Injected and ejected muons which stopped in the analyser were signalled by a coincidence between detectors 123 and $466'\bar{5}\bar{7}$, respectively. The decay electrons were separated into forward $[77'4(\overline{66'})]$ and backward $[66'4(\overline{77'})]$ events and collected in 0.1 μs time bins as a function of storage time.

CERN I (1965): precision ± 4 300 000 ppb

CERN II (1968): 1st use of a magnetic ring
Precision: 265 000 ppb



The expression is more complicated when you add in *E*-field (vertical) focusing and out of plane oscillations



THE CERN III EXPERIMENT

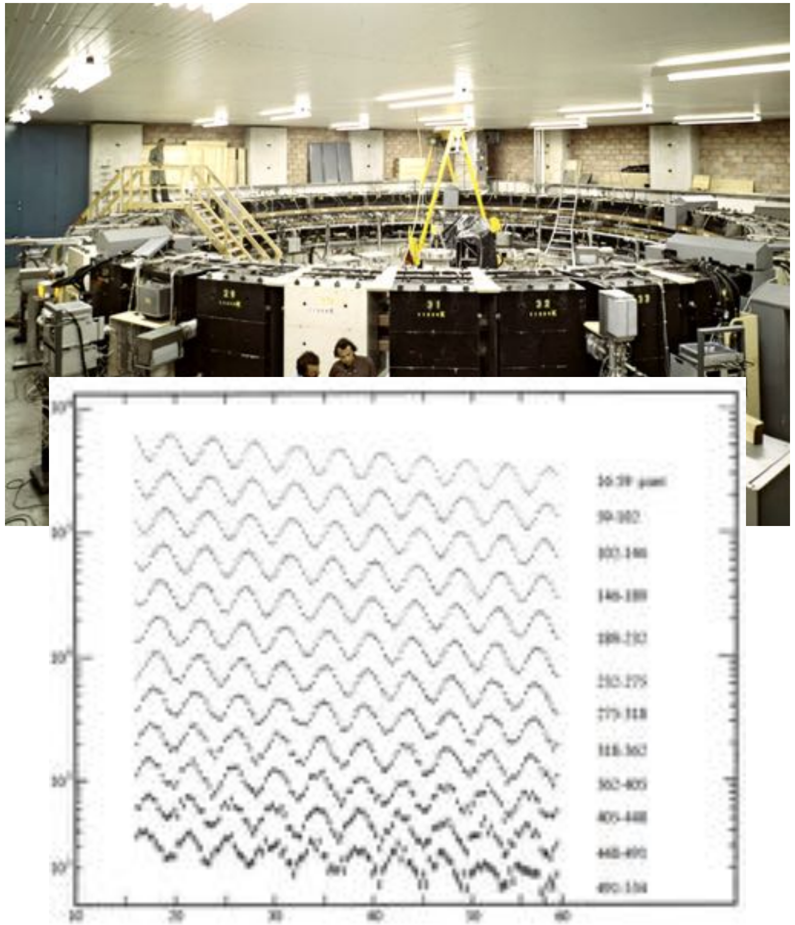
The motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections

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

0 if “in plane”

Term cancels at 3.094 GeV/c, the “Magic γ”

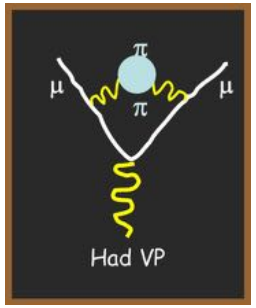
Summary of the CERN III Experiment



Precision: 7000 ppb

The main conclusions:

1. The QED calculation of the anomaly is verified up to the sixth order, the experimental uncertainty being equivalent to 5% of this term.
2. The hadronic contribution to the anomaly is observed and measured to an accuracy of 20%
3. There is no evidence for a special coupling of the muon.



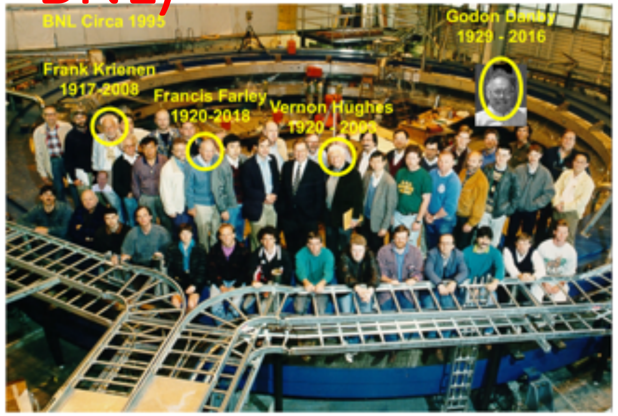
Key Limitation:
Stored Muons came from injected Pions that "accidentally" decayed in the first turn with kinematics to leave a Muon on orbit

Only 25 ppm chance !!!

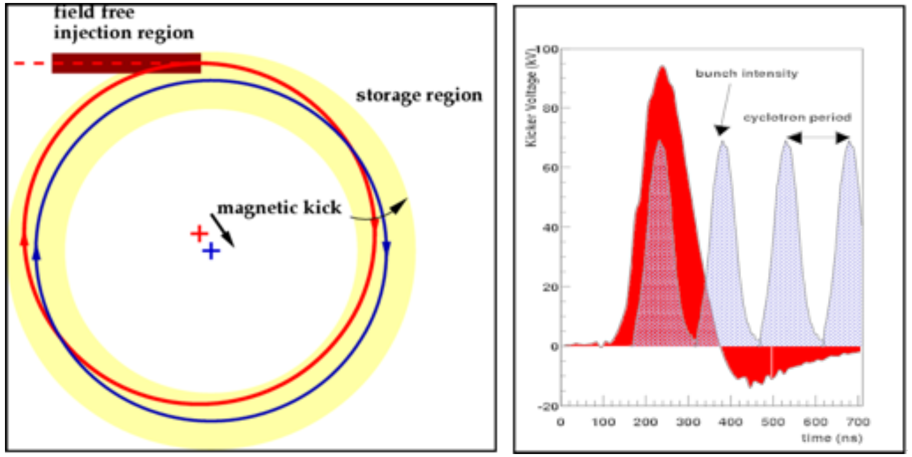
Final Report on the CERN Muon Storage Ring Including the Anomalous Magnetic Moment and the Electric Dipole Moment of the Muon, and a Direct Test of Relativistic Time Dilation; Nucl.Phys.B 150 (1979) 1-75

J. Bailey, K. Borer, F. Combley, H. Drumm, C. Eck, F.J.M. Farley, J.H. Field, W. Flegel, P.M. Hattersley, F. Krienen, F. Lange, G. Lebee, E. McMillan, G. Petrucci, E. Picasso, O. Runolfsson, W. von Ruden, R.W. Williams, S. Wojcicki

With the technique “perfected” (more or less), the next big idea involved getting a higher intensity muon storage: Direct Muon Injection (now at BNL)

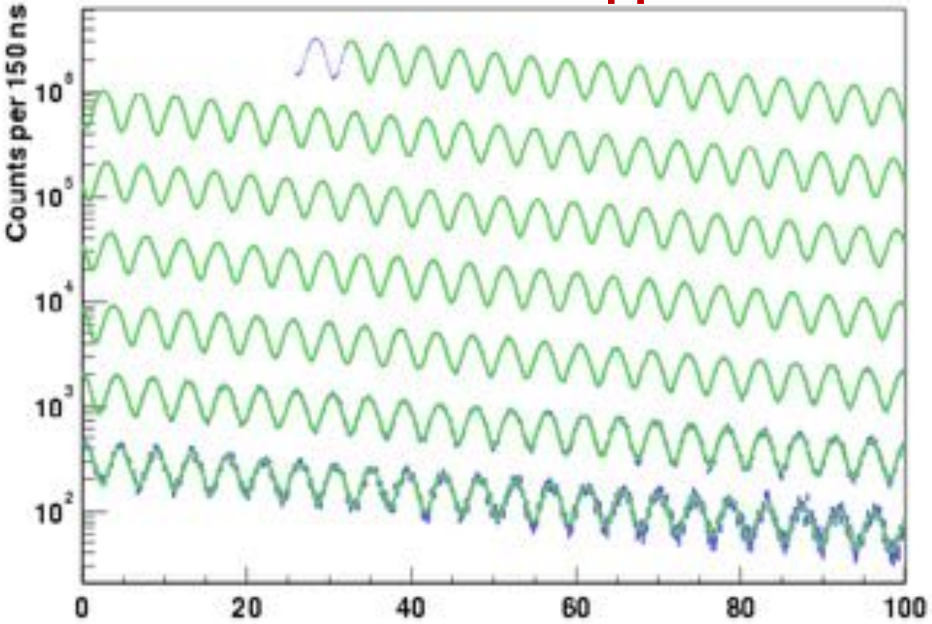



Superconducting Storage Ring

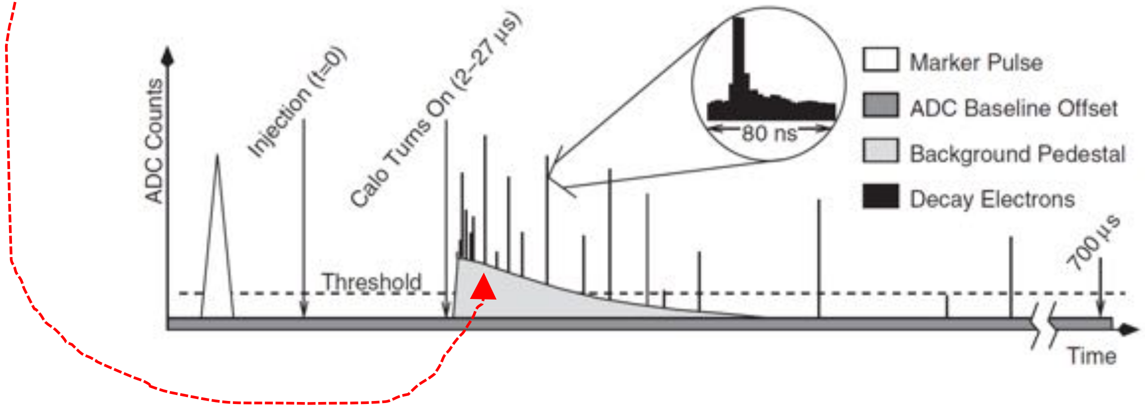


Kick them sideways onto a stored orbit

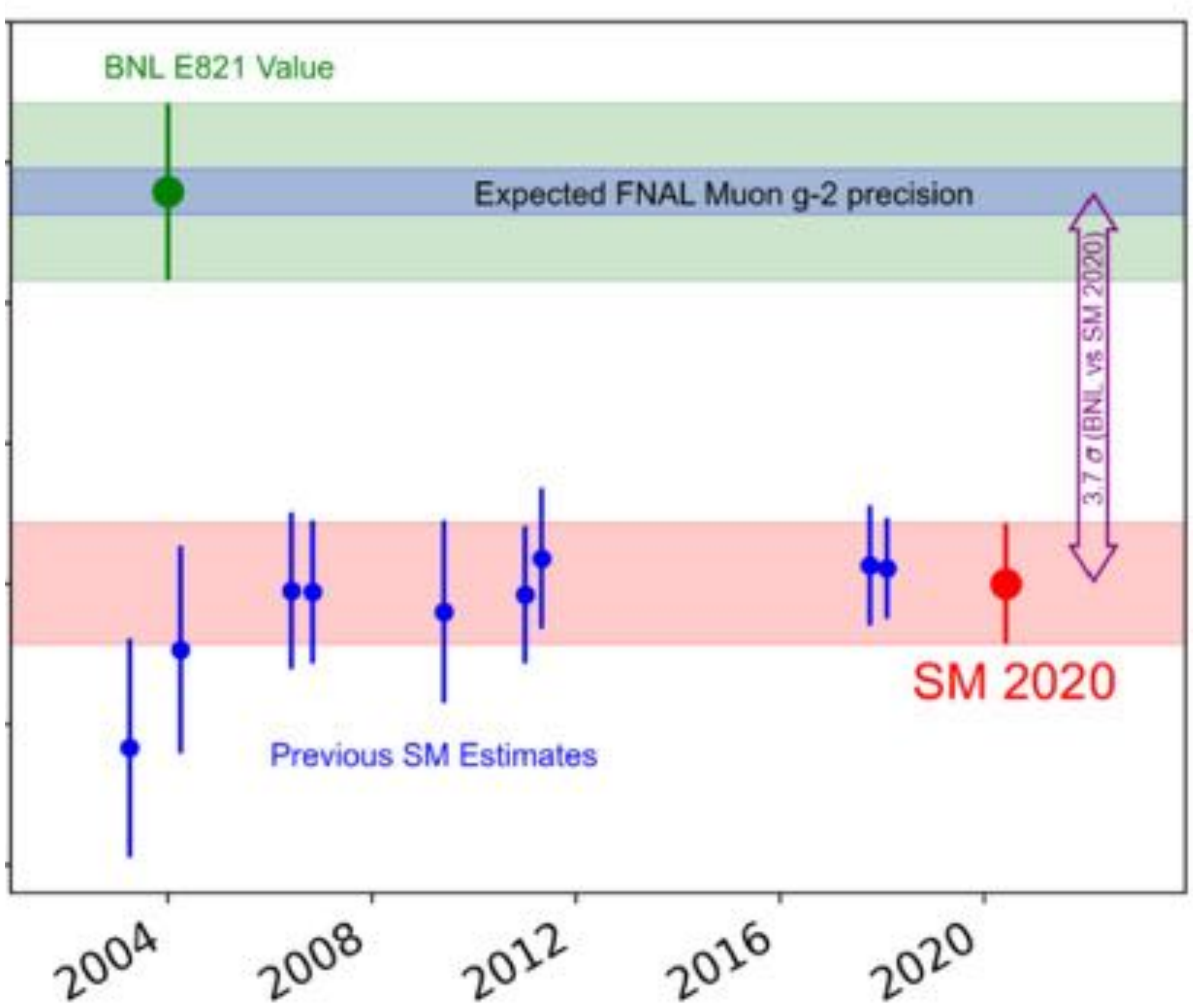
Precision: 540 ppb



Big problem remained: Short beamline meant pions dominated and caused a huge hadronic flash in the detectors



@540 ppb precision, the BNL measurement remained in tension with Theory, and slightly increasing over 2 decades! Why?



g-2 measured

g-2 predictions

Is the measurement wrong?

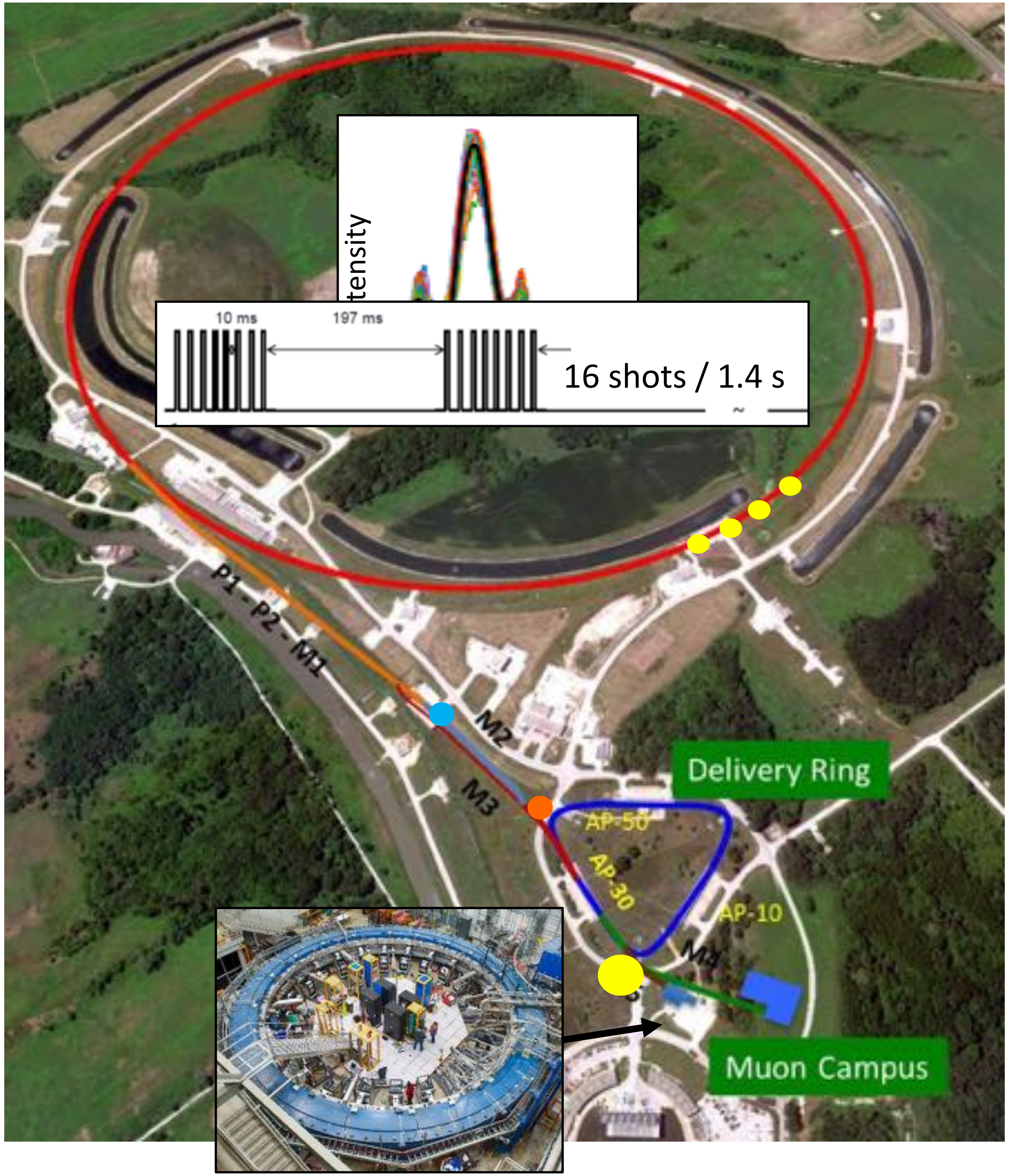
Is Theory wrong ???

Time for a New and Improved Measurement

(to settle the situation)

The Fundamental Experimental Principle is Unchanged, but the FNAL Muon g-2 represents significant improvements in all aspects

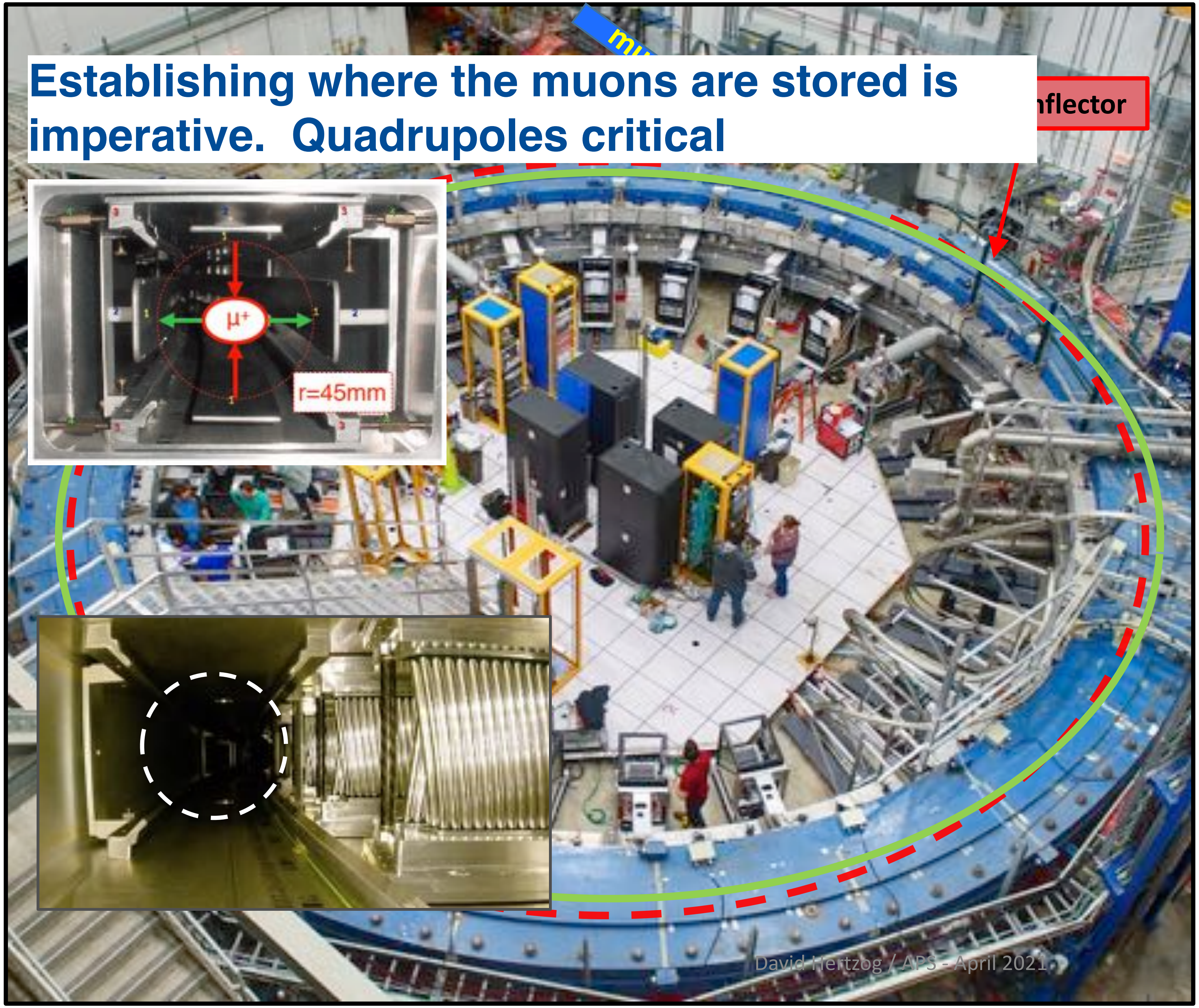
We include: **Particle-, Nuclear-, Atomic-, Optical-, Accelerator-, and Theory Physicists**



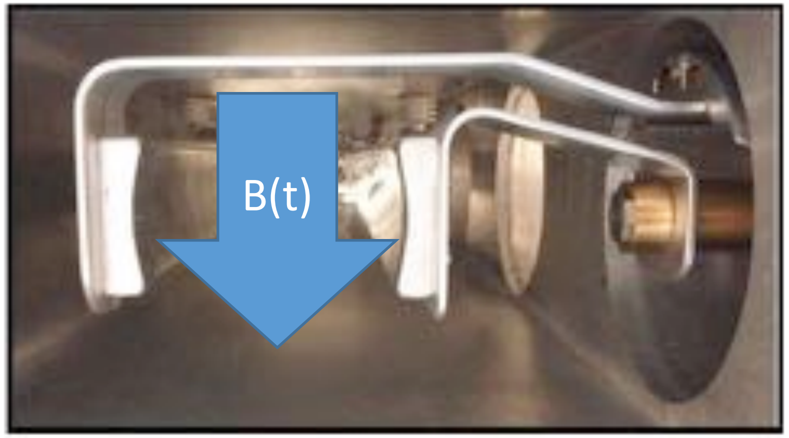
Creating the Polarized Muon Beam for g-2

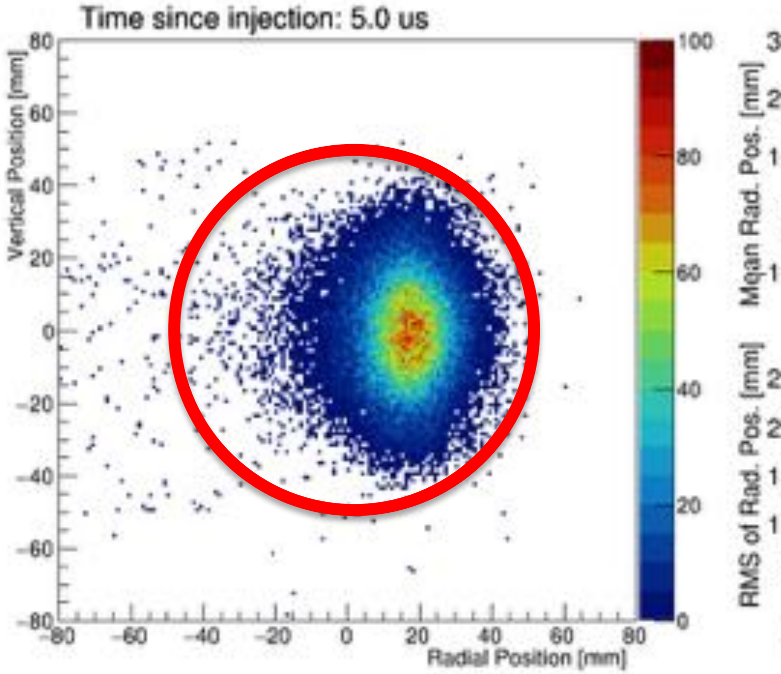
- 8 GeV protons
- Divide in 4 bunches
- Extract each to strike target
- Magnetic lenses collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters Delivery Ring – protons get kicked out; pions decay away
- **And only muons enter storage ring**

Establishing where the muons are stored is imperative. Quadrupoles critical

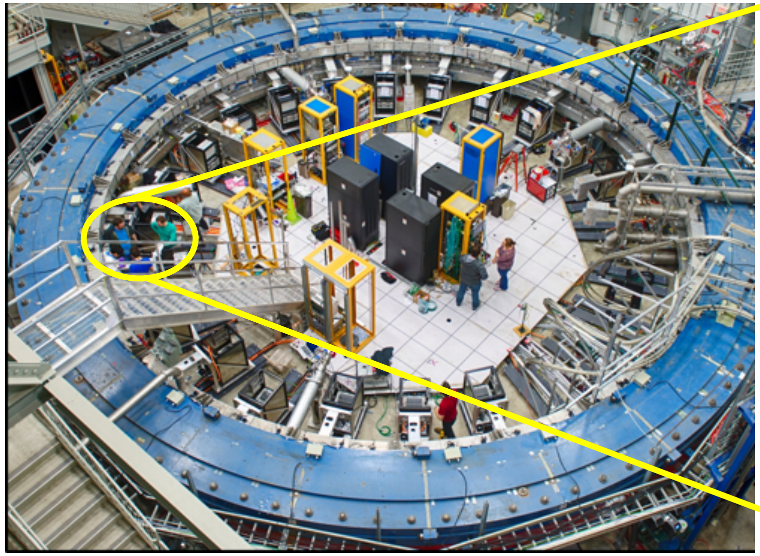


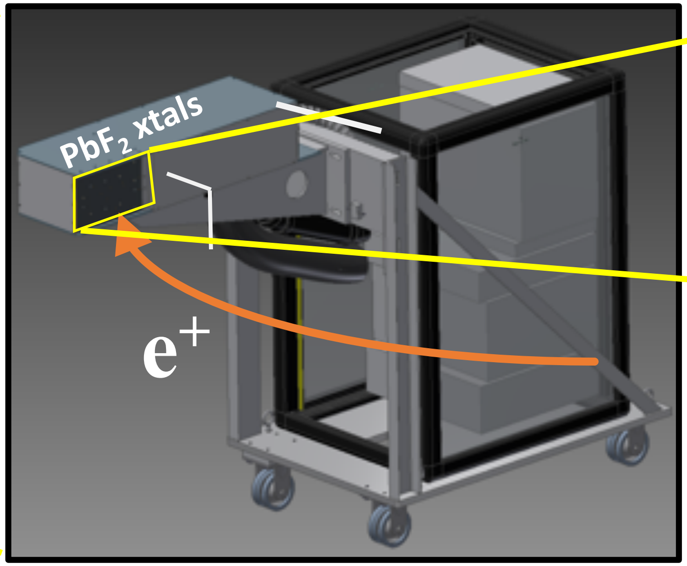
Muons enter and get "Kicked" onto stable orbits

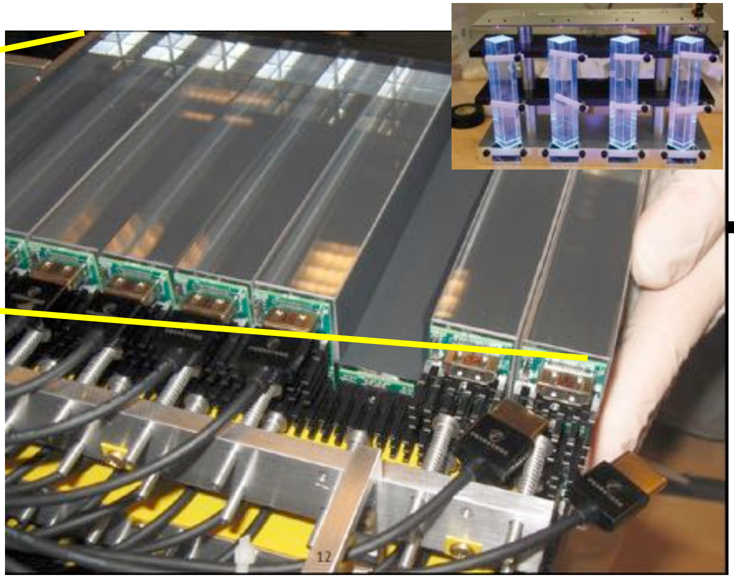


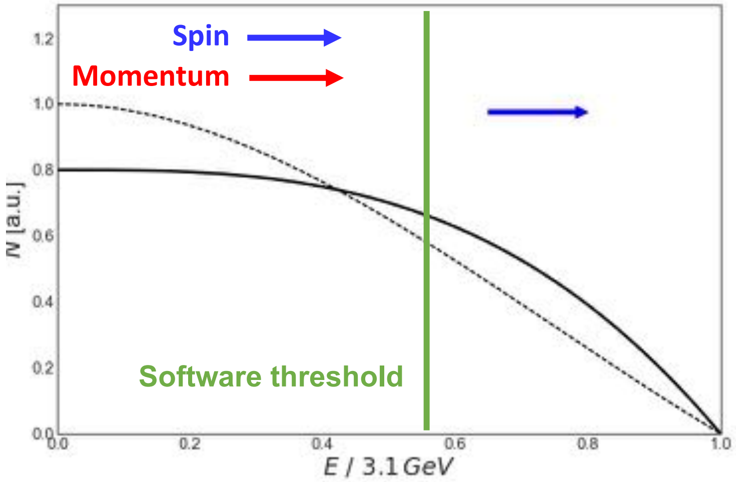


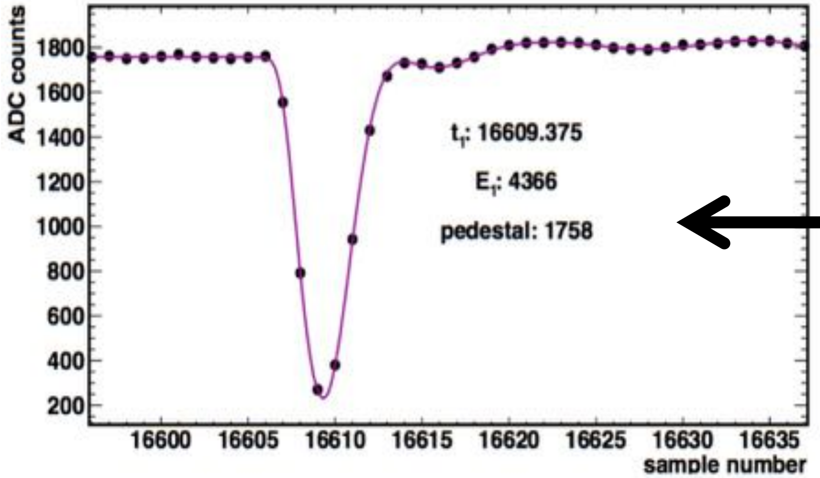
The precession frequency, ω_a is derived from a time histogram of high-energy e^+ decay events



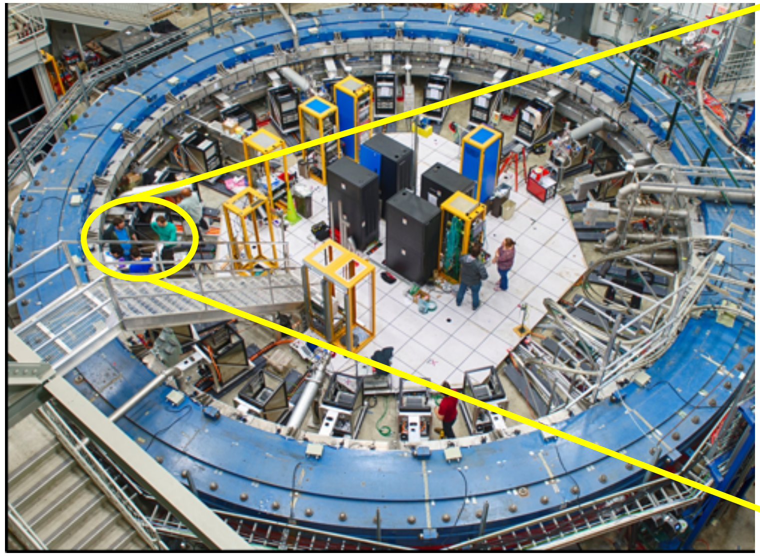


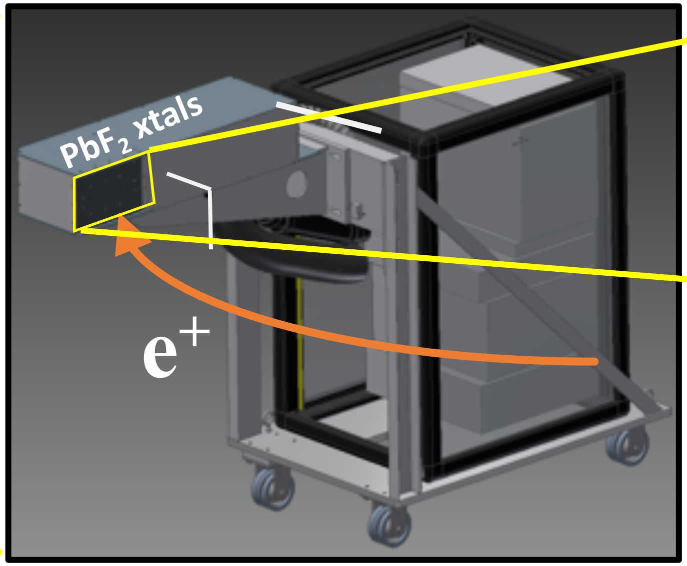


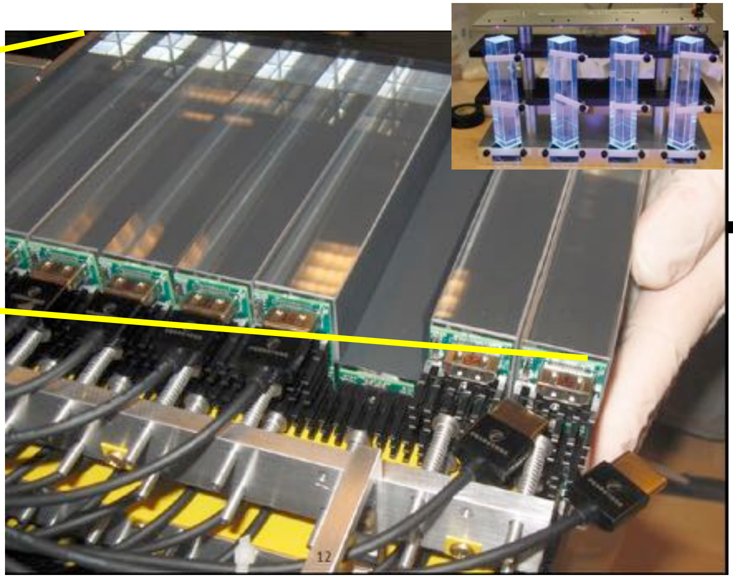




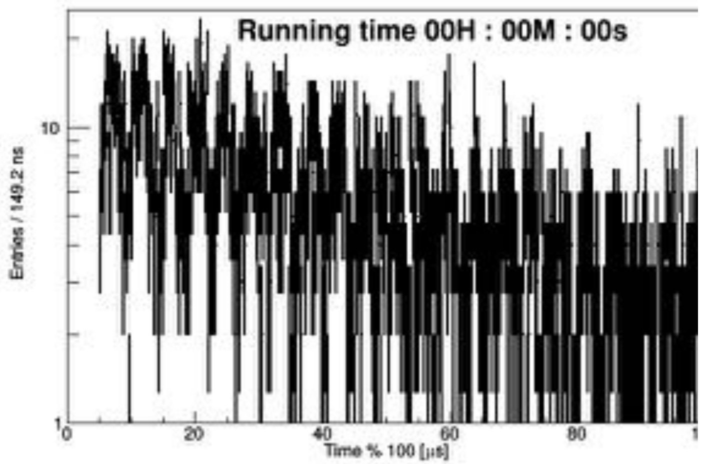
The precession frequency, ω_a is derived from a time histogram of high-energy e^+ decay events

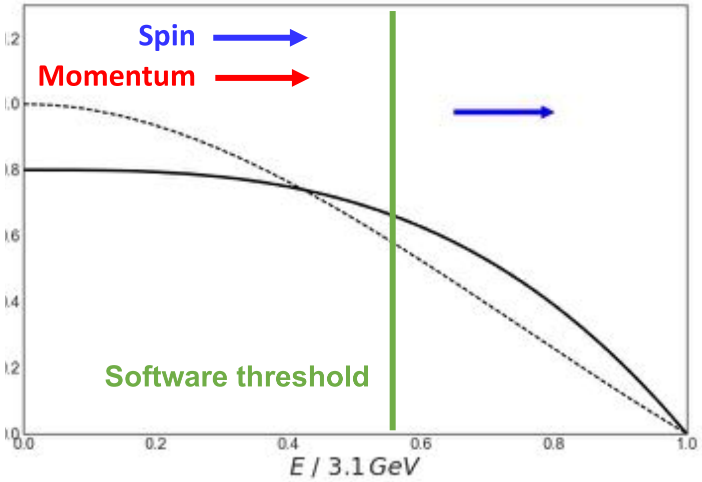


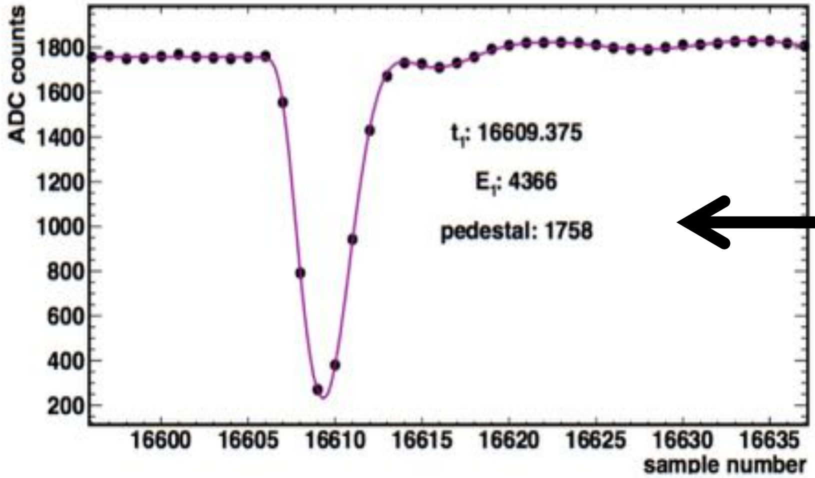




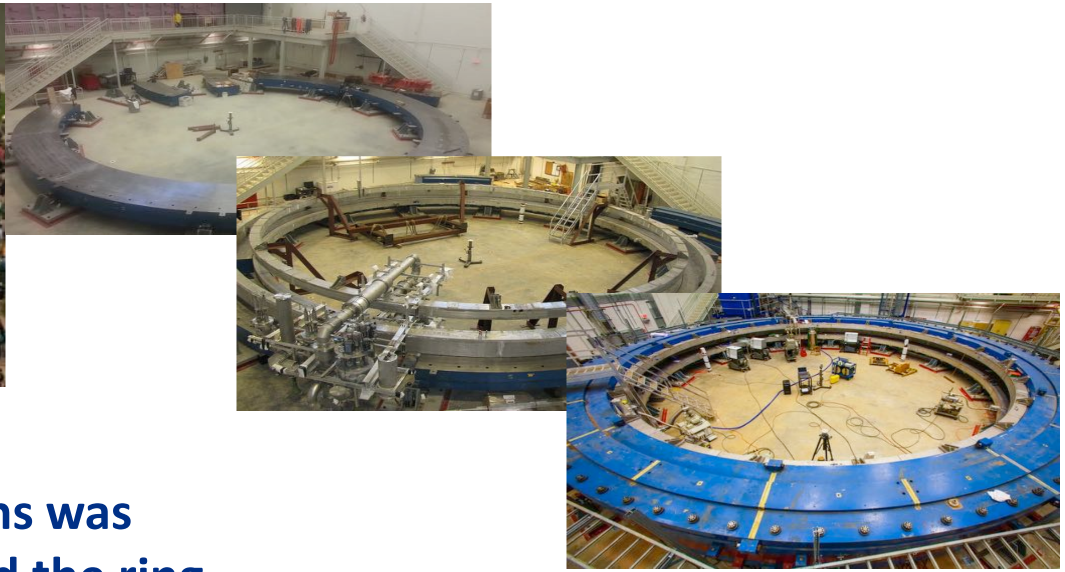
Events above threshold



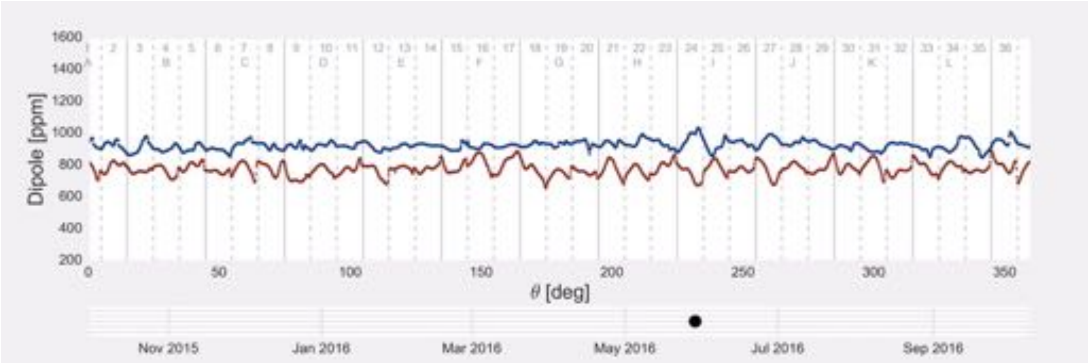


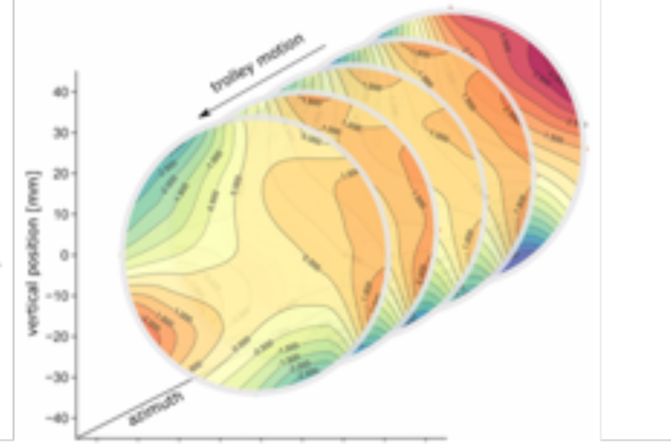


The Field, ω_p begins with the BNL magnet moved to Fermilab and shimmed and monitored to unprecedented levels



An innovative installation of ~8000 tiny iron laminations was used to minimize field inhomogeneity locally all around the ring



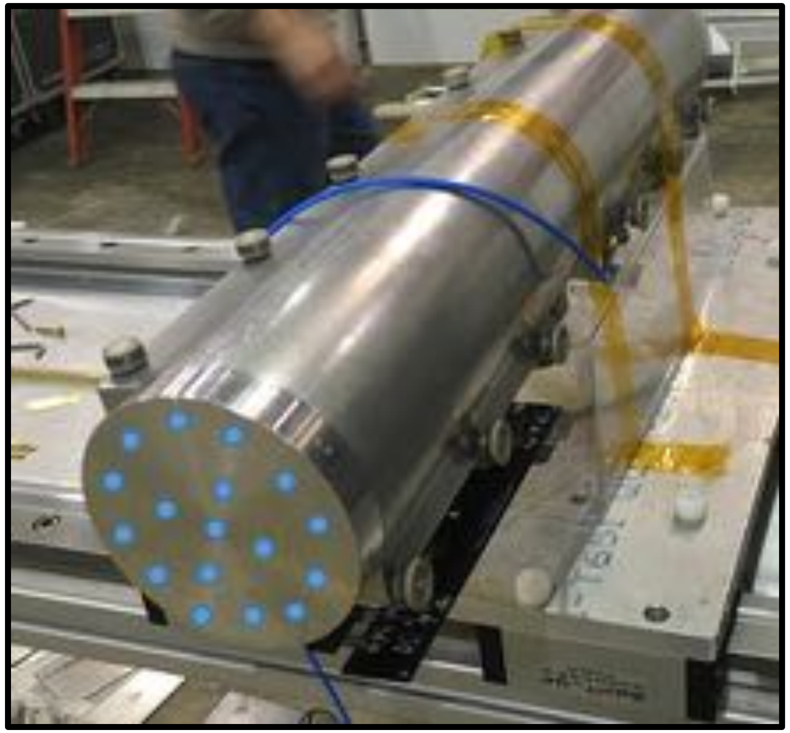


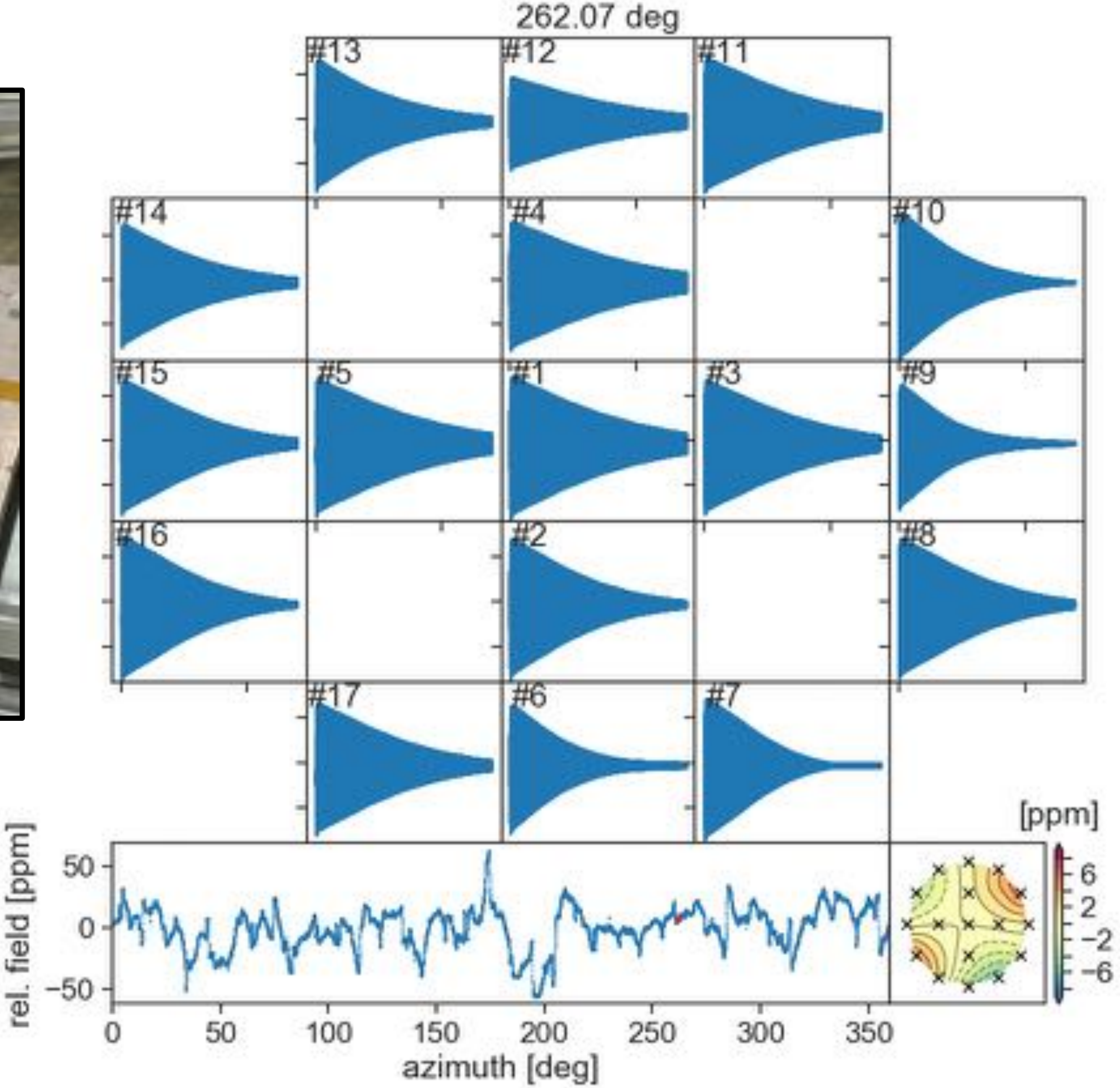
Sequence of field 2D field slices as trolley moves

Final field uniformity is ~3 x finer than BNL !

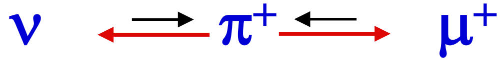
Taking you on a Trolley Run

…

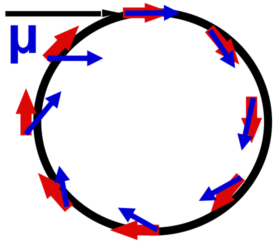




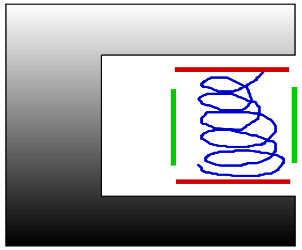
5 “miracles permit measurements of g-2 to sub-ppm Precision



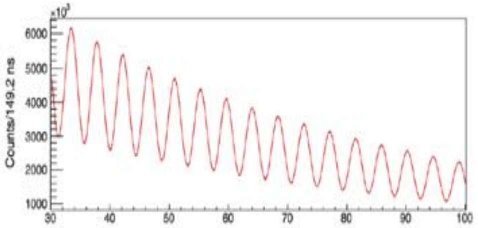
- **Polarized muons produced naturally in pion decay**
  ~97% for forward decays



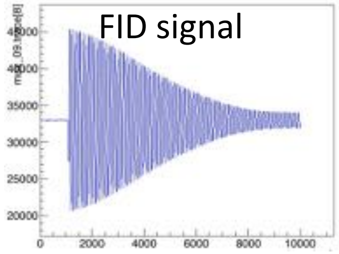
- **Precession frequency is proportional to (g-2)**
  Independent of speed (γ) of the muon



- **P$_\mu$ The magic momentum**
  The E field does not perturb the spin frequency at 3.094 GeV/c



- **Parity violation in the decay** $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$
  - encodes the anomalous precession frequency in e^+ vs time



- **Proton NMR magnetometers**
  - Continuous determination of the magnetic field throughout the volume in which the muons are stored

a_μ is obtained from the **2 frequency measurements** we make … and well-known fundamental factors from others

We measure these 2 frequencies

$$a_\mu = \left[\frac{\omega_a}{\tilde{\omega}'_p(T_r)}\right] \underbrace{\frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}$$

$\dfrac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb at T = 34.7℃

Metrologia **13**, 179 (1977)

$\dfrac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)

Rev. Mod. Phys. **88** 035009 (2016)

$\dfrac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting

Phys. Rev. Lett. **82**, 711 (1999)

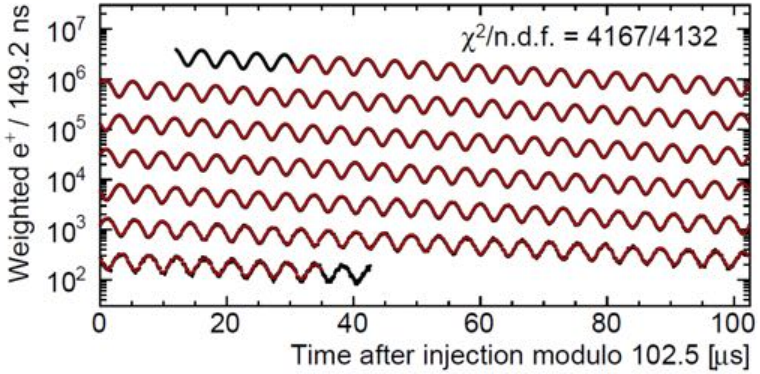
$\dfrac{g_e}{2}$ Measured to 0.28 ppt

Phys. Rev. A **83**, 052122 (2011)

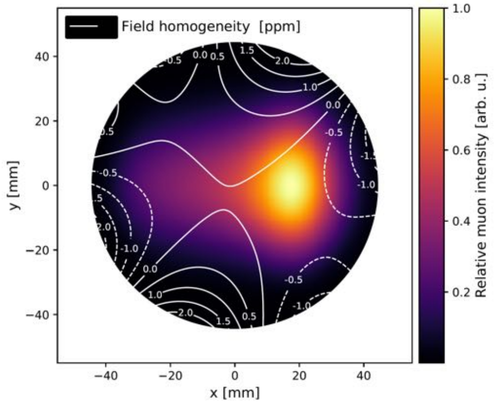
Many measurements determine a_μ. This is our working analysis recipe (but I'll spare you the details behind each term)

$$a_\mu \propto \frac{f_{\text{clock}}\ \ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\ (1 + B_k + B_q)}$$

f_{clock}	• Blinded clock
ω_a^m	• Measured precession frequency
C_e	• Electric field correction
C_p	• Pitch correction
C_{ml}	• Muon loss correction
C_{pa}	• Phase-acceptance correction



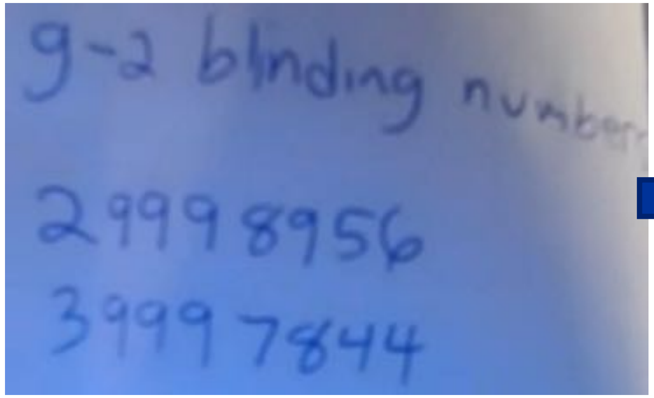
f_{calib}	• Absolute magnetic field calibration
$\omega_p'(x,y,\phi)$	• Field tracking multipole distribution
$M(x,y,\phi)$	• Muon weighted multipole distributed
B_k	• Transient field from the eddy current in kicker
Bq	• Transient field from the quad charging



The First “Unblinding” in 2021 (6% of the full data set)

UW envelope

FNAL envelope



g-2 blinding number

29998956

39997844

Same numbers!

E989 Run 1 unblinding

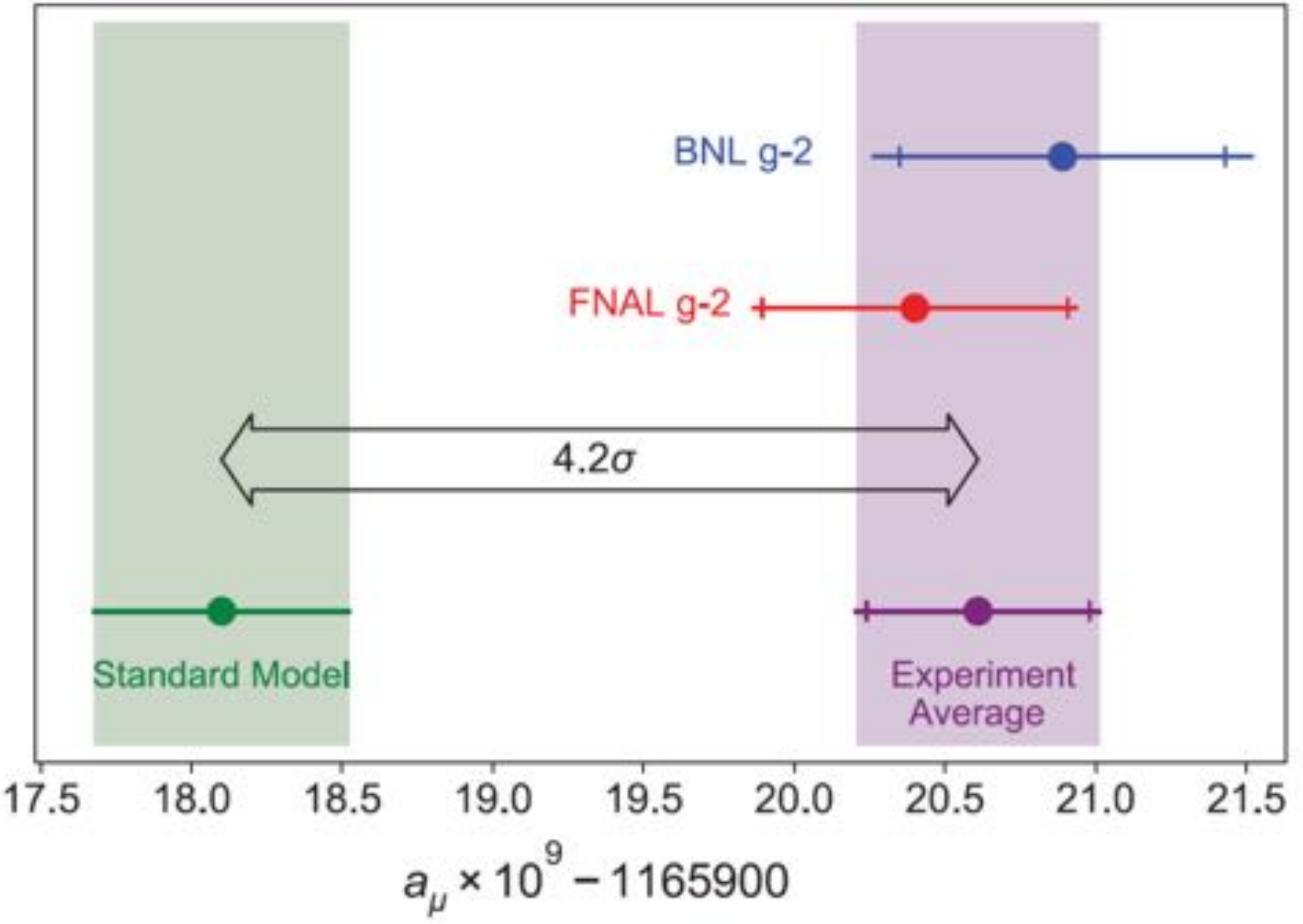
```
[154]:
##
## using f_blind != 40e6 Hz
## - fake_offset is disregarded
## - the blinding is removed
## - the watermark is removed
##
## HW blind central value: plot_result(f_blind=39998000)
##
plot_result(f_blind=39997844)
```

```
a_mu(E989) = 1165920.398(538)e-9
```

It means:

1) The 20-year-old BNL result is confirmed

2) The combined discrepancy with the Standard Model increases to 4.2 σ



The Aftermath, the Near, and Far Future

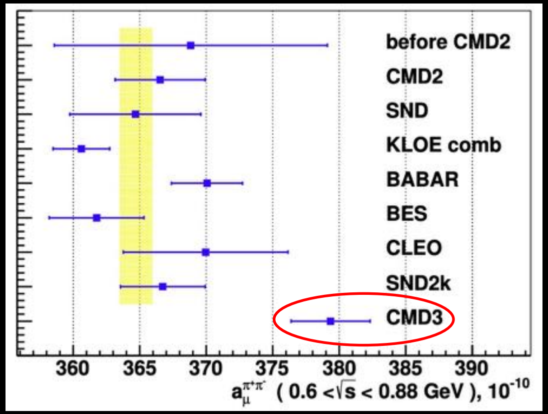
BSM?

Supersymmetry

Axion-like particles

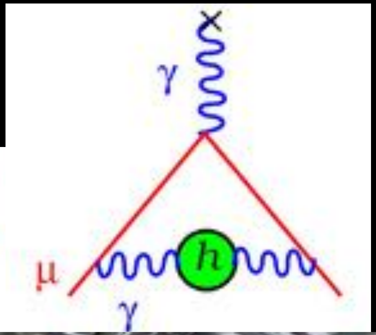
Two-Higgs Doublet Model

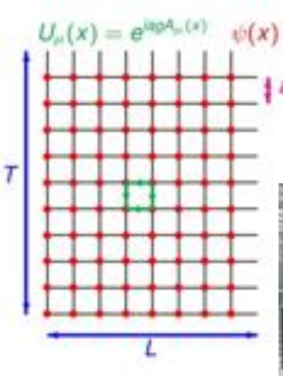
Lepto-quarks

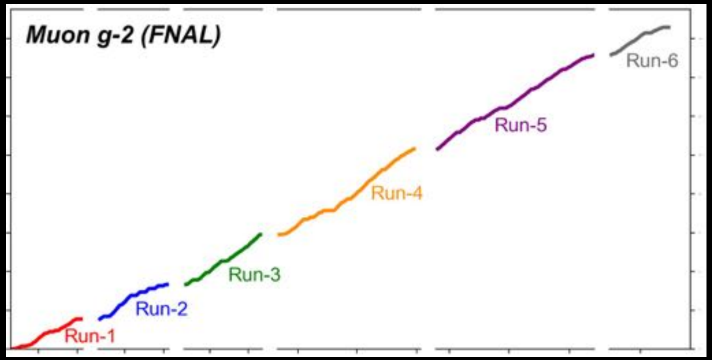


New $\pi\pi$ data

Lattice HVP







Next g-2 Results

The 2021 Result generated many creative BSM explanations

Supersymmetry

Axion-like particles

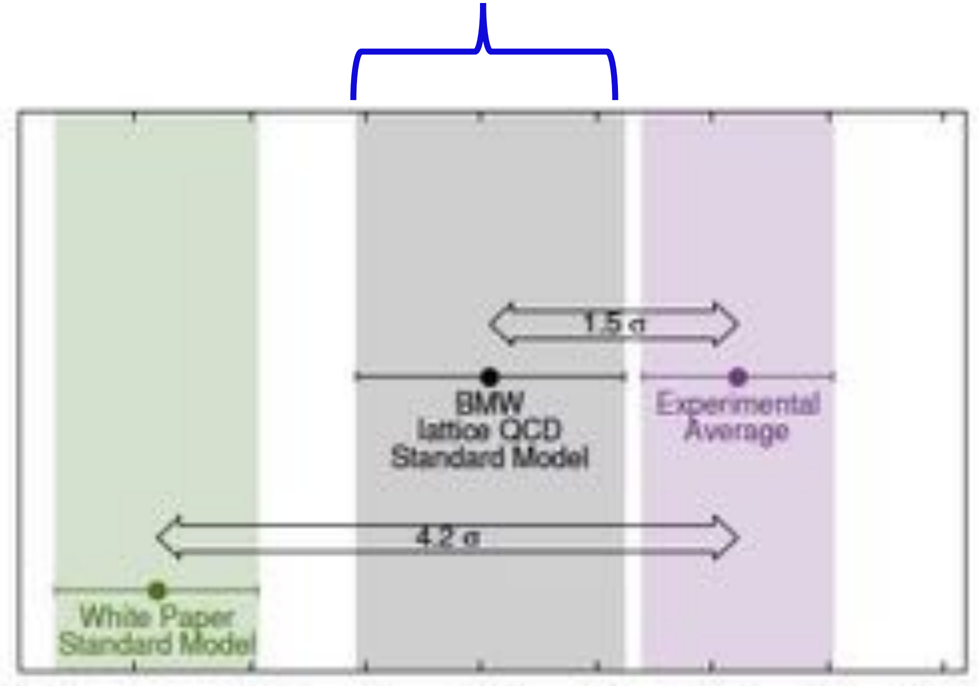
Two-Higgs Doublet Model

Lepto-quarks

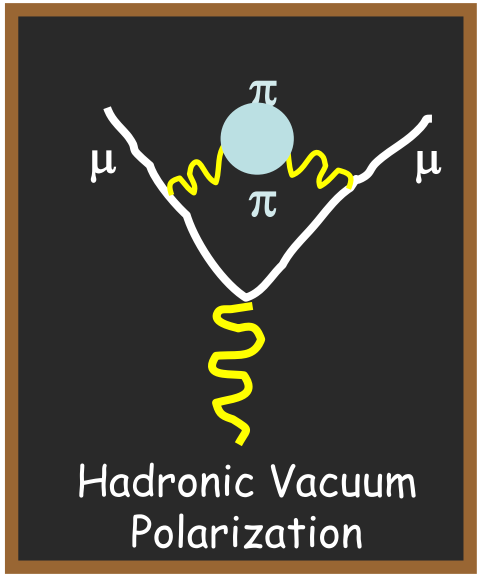
Most agree that it’s not easy to explain the results without “tuning” their models more than one might wish

But, others believe the Standard Model might be *wrong* ☹

A Lattice QCD team calculated HVP and got a different result, shown in gray here

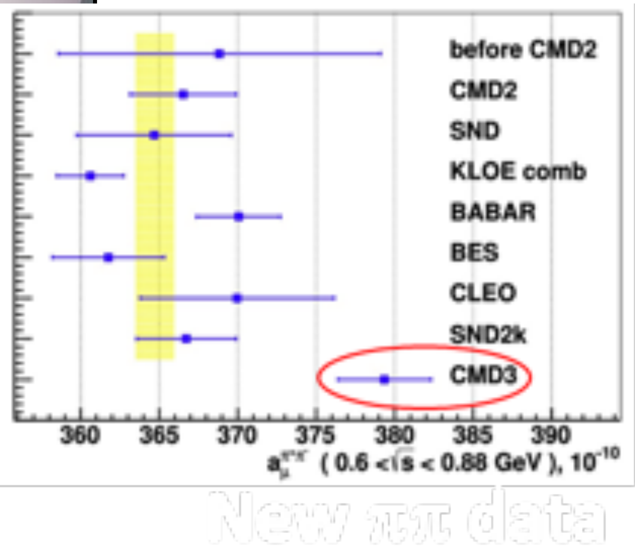


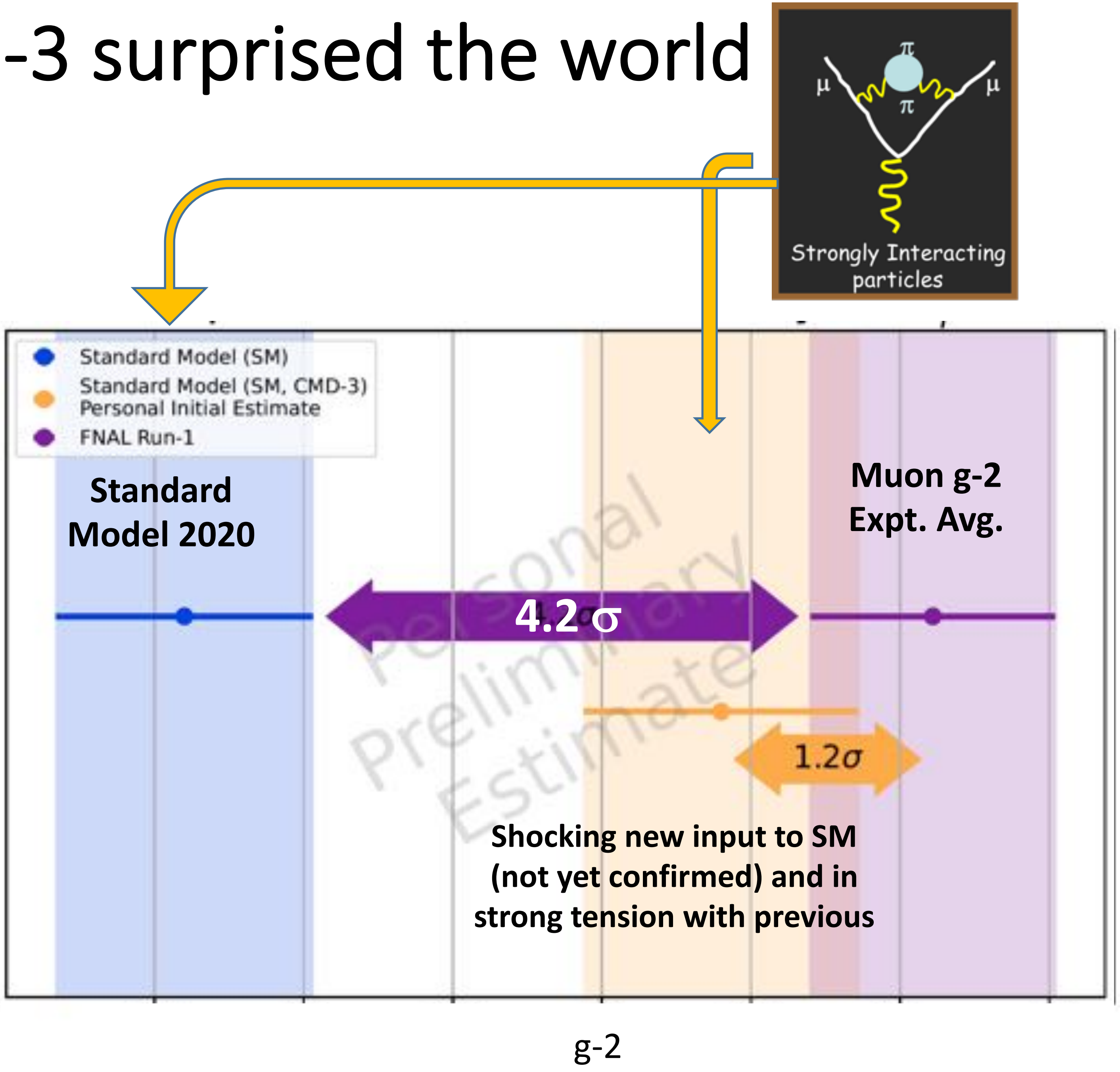
g-2



At present, many other LQCD groups are working on the same calculation, with intermediate step comparisons and blinded techniques. Stay tuned

On the data side, CMD-3 surprised the world





Standard Model 2020

Muon g-2 Expt. Avg.

4.2 σ

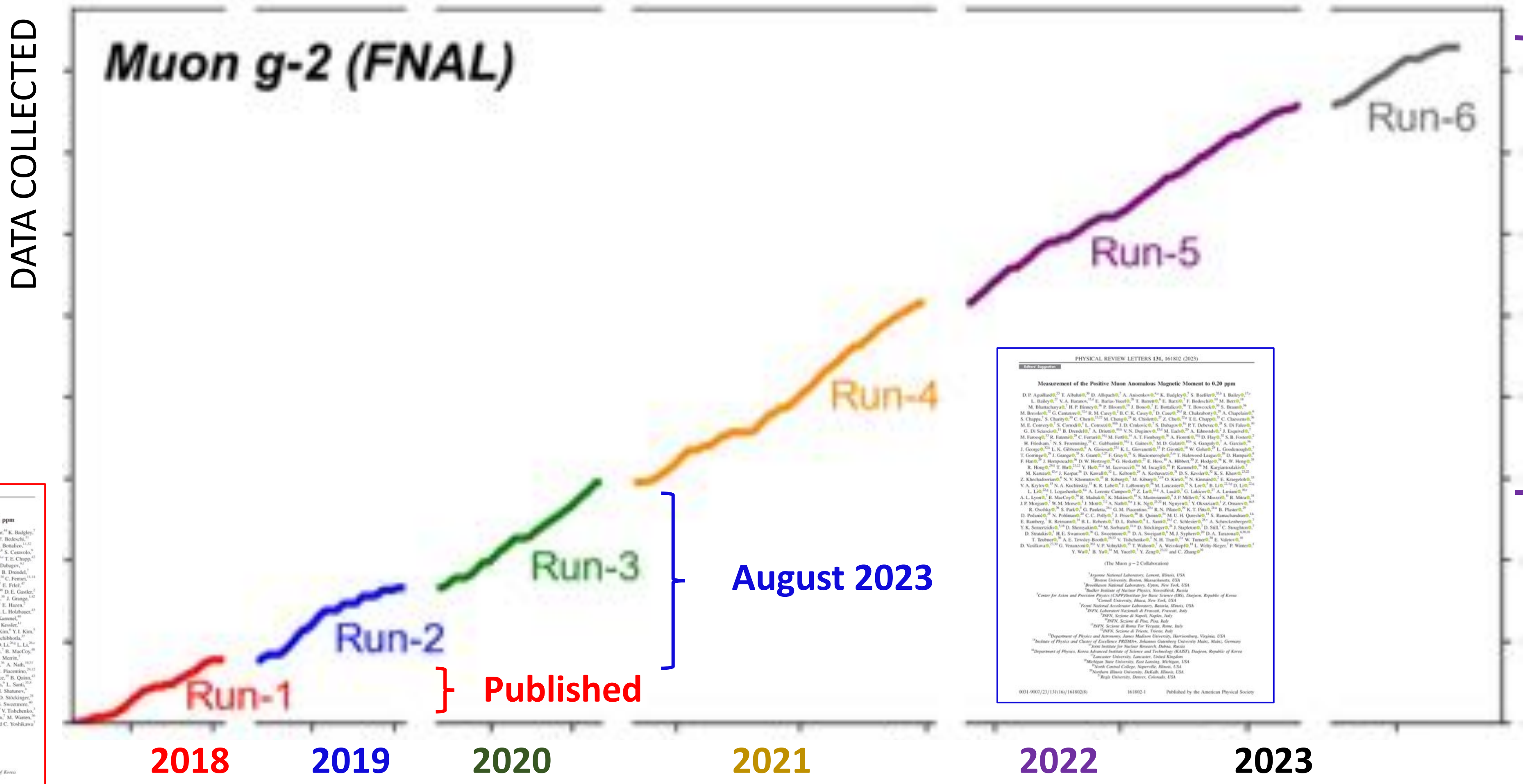
1.2σ

Shocking new input to SM (not yet confirmed) and in strong tension with previous

Remember: This Diagram is evaluated using **DATA** other experiments

The community is bewildered !
Their new data **disagrees with all previous experiments**, including their own!

2023: Data taking is complete, >21x more data compared to BNL. Published first 25% so far



Published

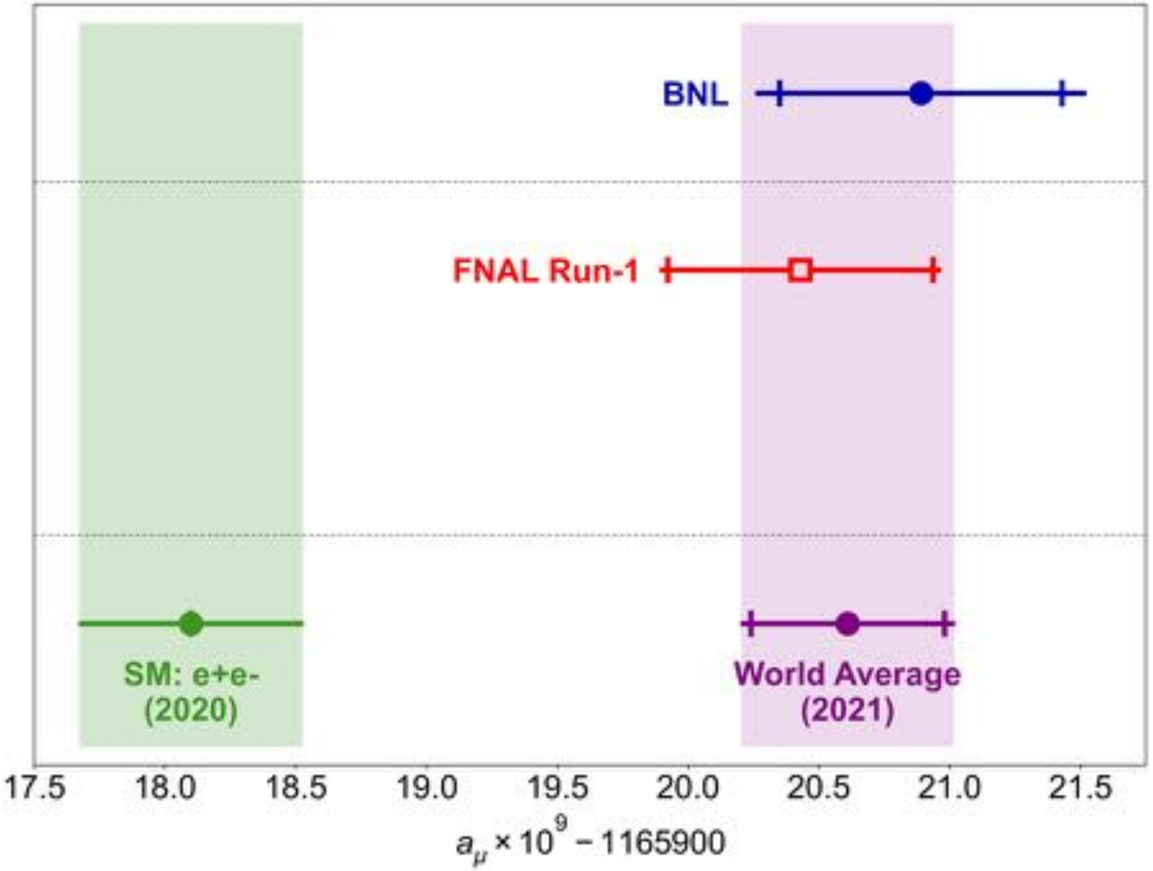
August 2023

?? 2025?

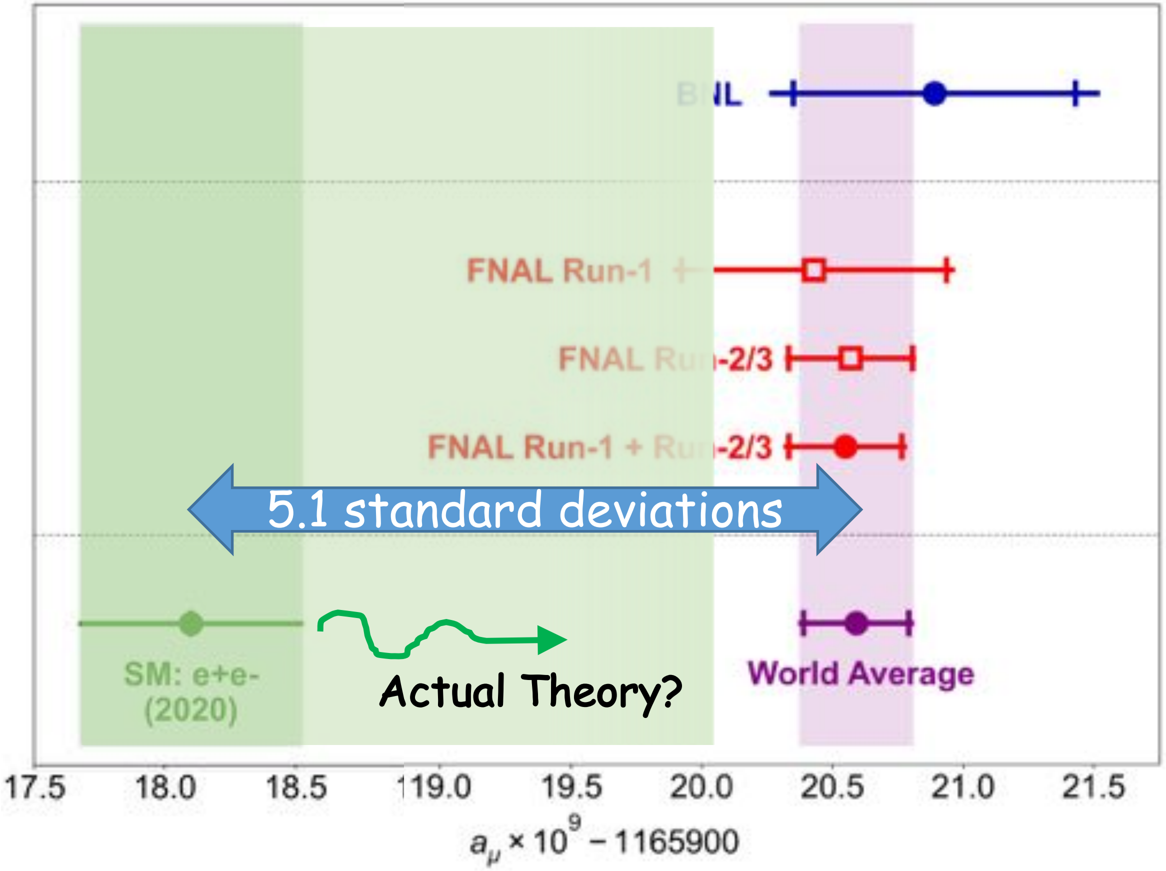
PHYSICAL REVIEW LETTERS 126, 141801 (2021)

PHYSICAL REVIEW LETTERS 131, 161802 (2023)

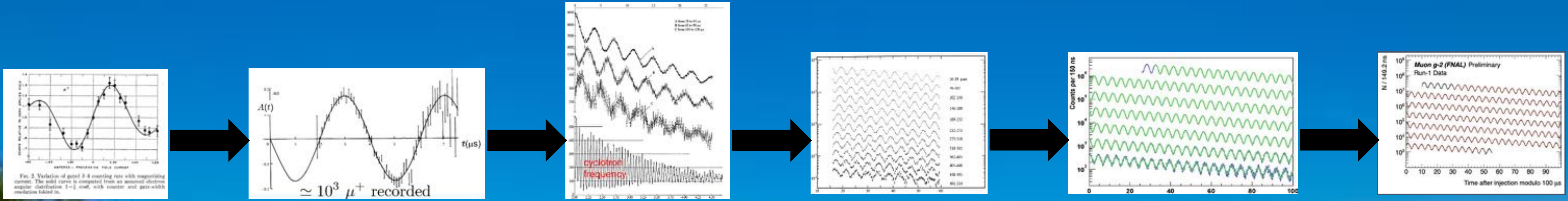
Our 2023 result: with half the uncertainty and bettering our systematic proposal budget already



Our 2023 result: with half the uncertainty and bettering our systematic proposal budget already



The Chess Game continues !!

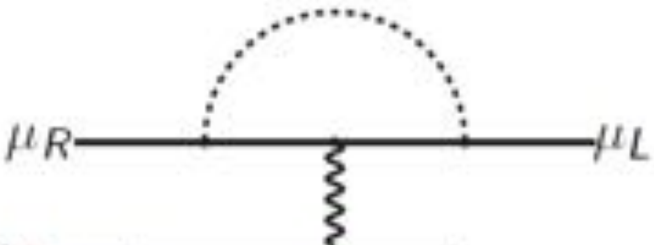


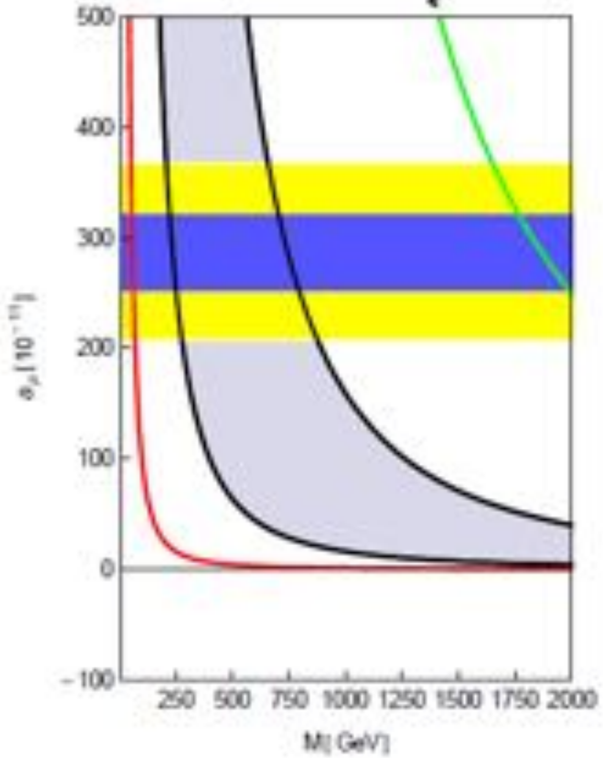
50+ Years of Muon “g-2” experiments

- I believe Stanley would enjoy this ebb and flow of precision experimental work and high-level theory
- The road is long, can be hard and bumpy, but ultimately we are seeking Nature’s truth
- On our side, we have one more big data set to release … 2025 is the target
- Until then, there is a vigorous SM Theory campaign ongoing to determine the hadronic contributions

In a generic sense, these are “loop effects” that couple to the muon mass and moment in similar fashion, characterized ▯ *C,* a coupling:

$$\mathcal{O}(C)\left(\frac{m_\mu}{M}\right)^2 \qquad\qquad C = \frac{\delta m_\mu(\mathrm{N.P.})}{m_\mu}$$

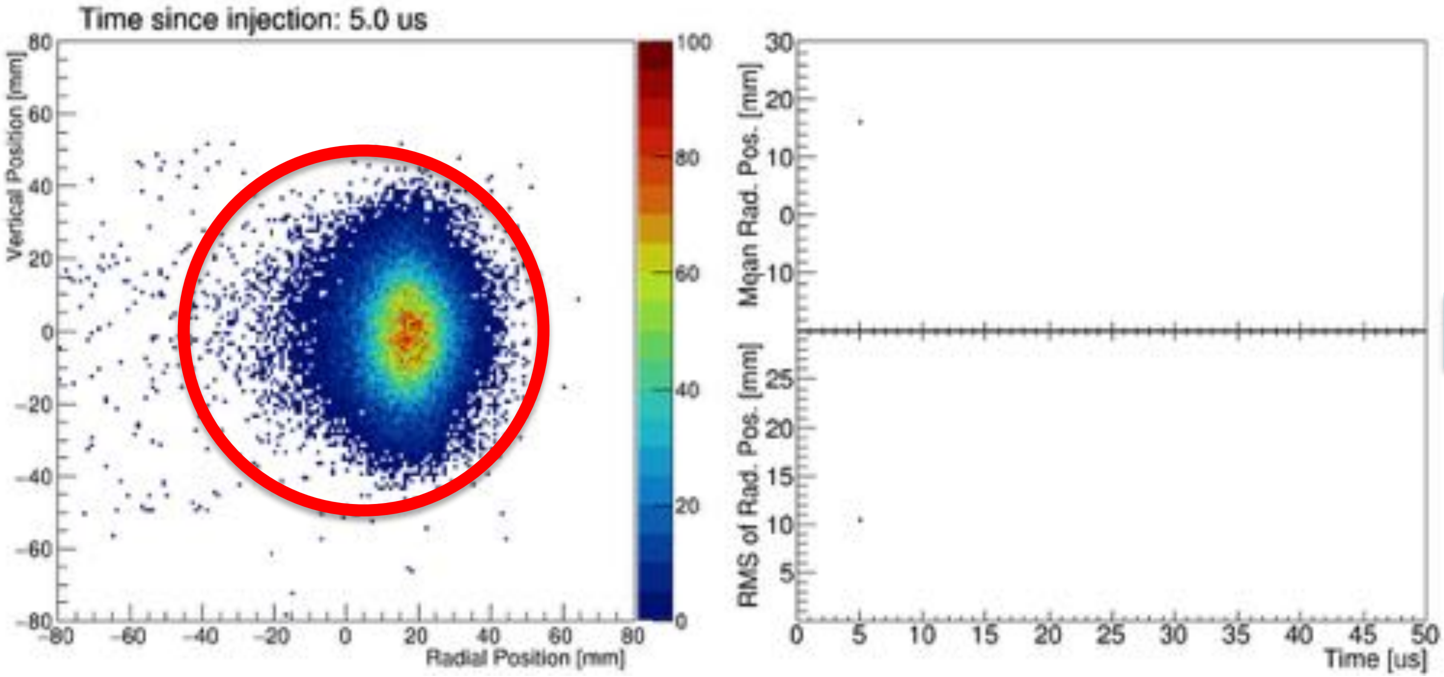


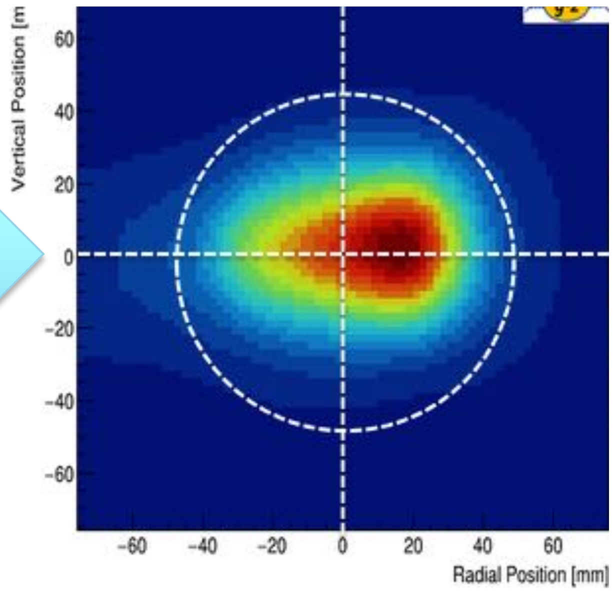


$\mathcal{O}(1)$	radiative muon mass generation . . . [Czarnecki,Marciano '01] [Crivellin, Girrbach, Nierste '11][Dobrescu, Fox '10]
$\mathcal{O}(\frac{\alpha}{4\pi}\ldots)$	supersymmetry (tan β) vectorlike fermions . . .
$\mathcal{O}(\frac{\alpha}{4\pi})$	SM: Z, W. New physics: Z', W'. . .
$< \frac{\alpha}{4\pi}$	2-Higgs doublet model, dark photon .

Following Czarnecki, Marciano, and Stockinger

An example looking “inside” the storage ring at the dynamic motion of the muons as they go around… which adds to the complexity





Average x-y profile around the ring

2 sets of these trackers