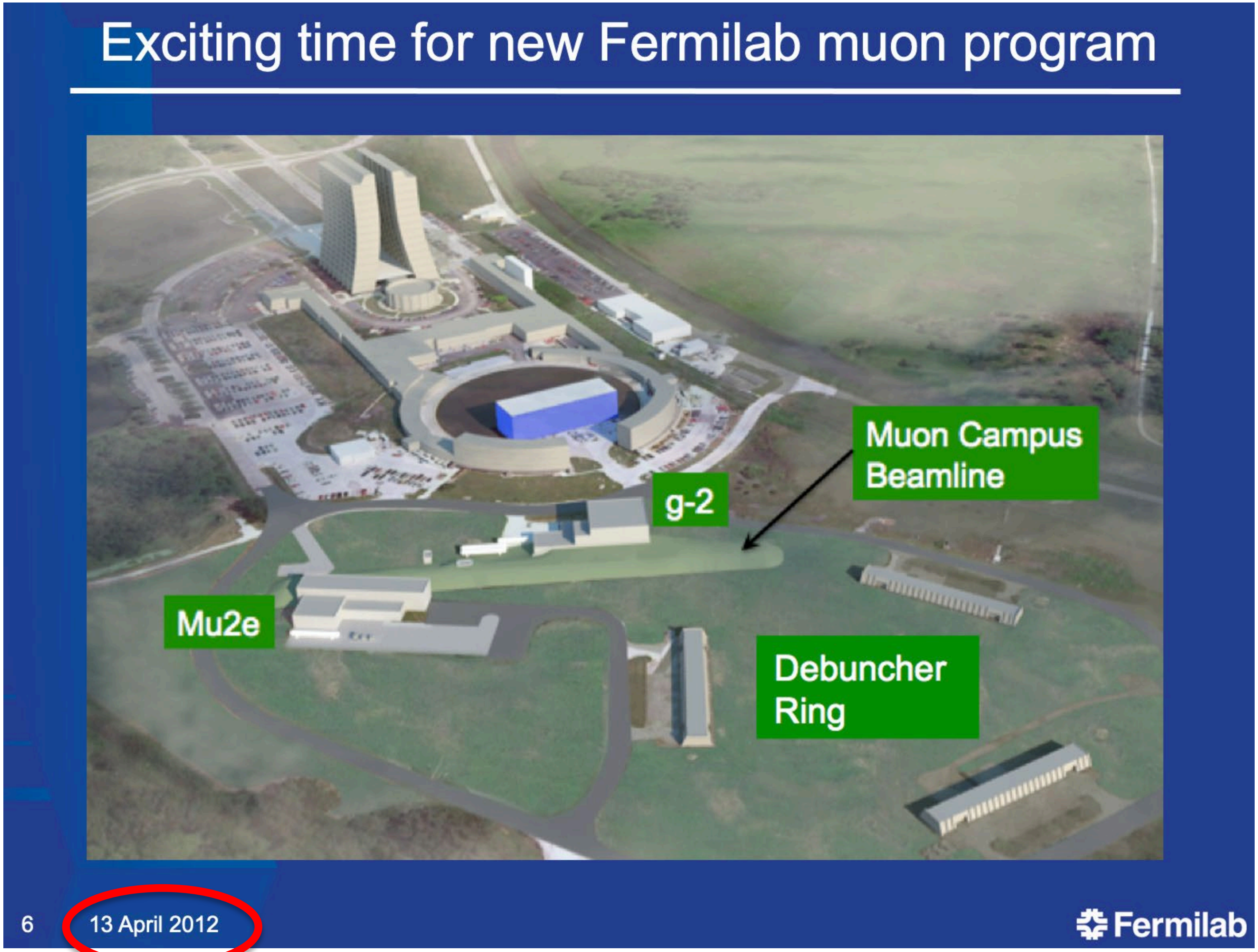
First results from the Muon g-2 Experiment at Fermilab

Chris Polly, Fermi National Accelerator Laboratory

Slide from first FNAL seminar on g-2



Introduction to Muon g-2
(g ‘minus’ 2)

Chris Polly
Community Advisory Board
August 23, 2012

First presentation to CAB!

This is an incredible opportunity for the laboratory and the community

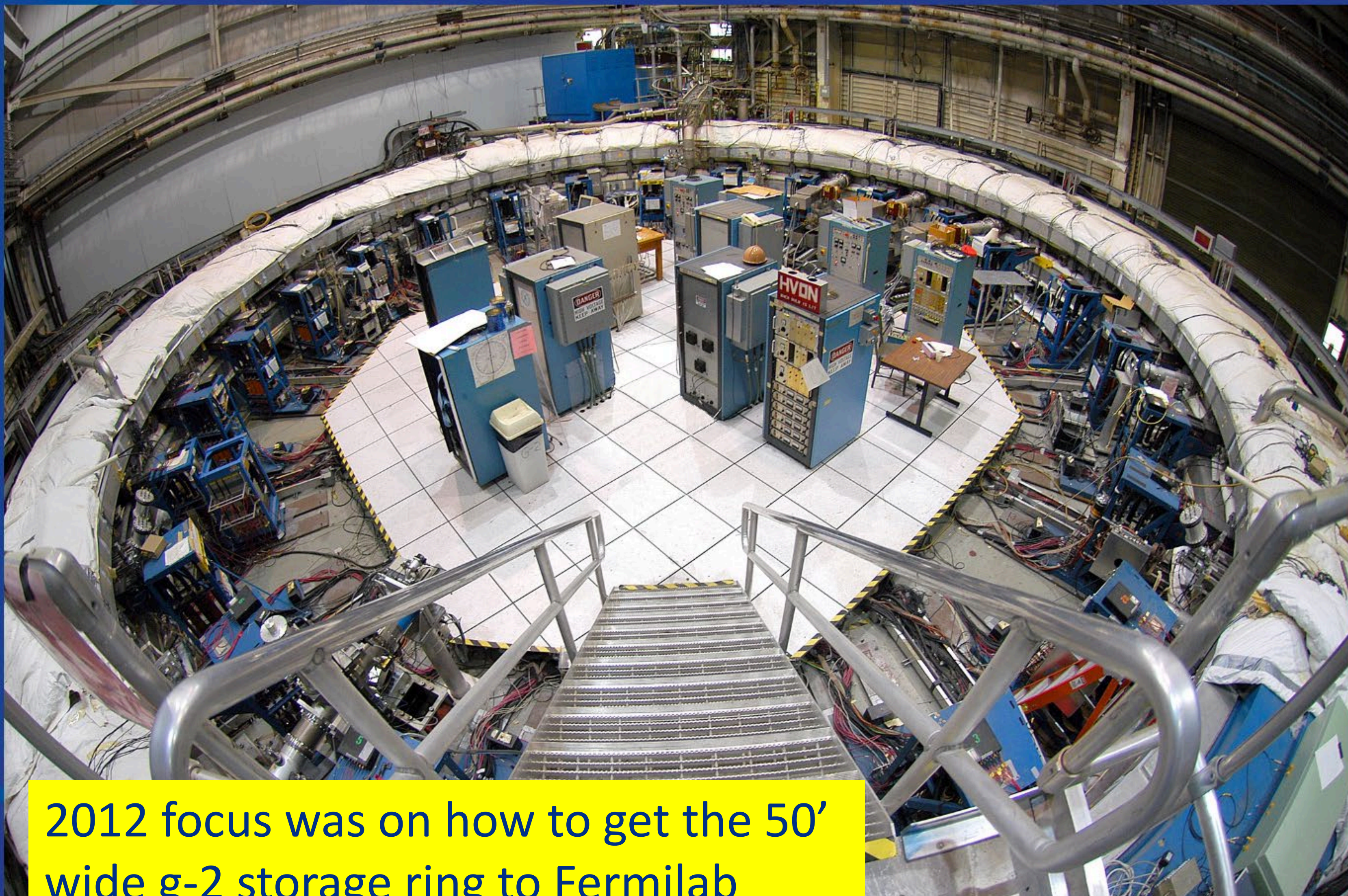
Part of a broader $300M initiative to build a whole Muon Campus that starts with two very compelling experiments, Muon g-2 and Mu2e, but leads to a 20 or more year program

Renderings much better by Aug

Fermilab

Muon Campus today

The exquisite machine circa 2004



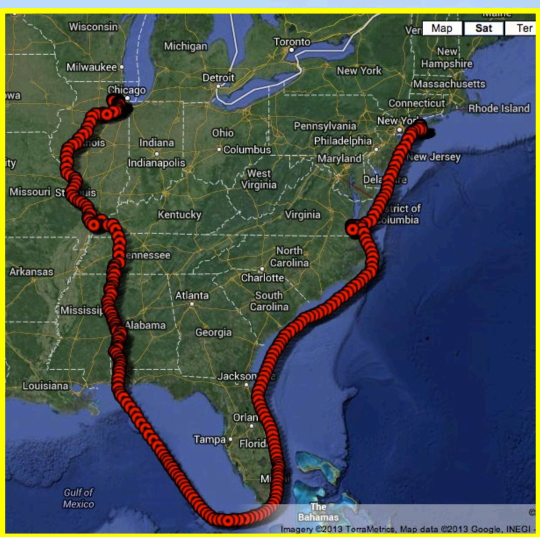
2012 focus was on how to get the 50' wide g-2 storage ring to Fermilab

Need to disassemble and transport the machine

Barge transport for most of trip, but specialty ground transport company or aircrane required to go from labs to barge

Contracts to develop full transportation plan were awarded to Erickson Air-Crane and Emmert International

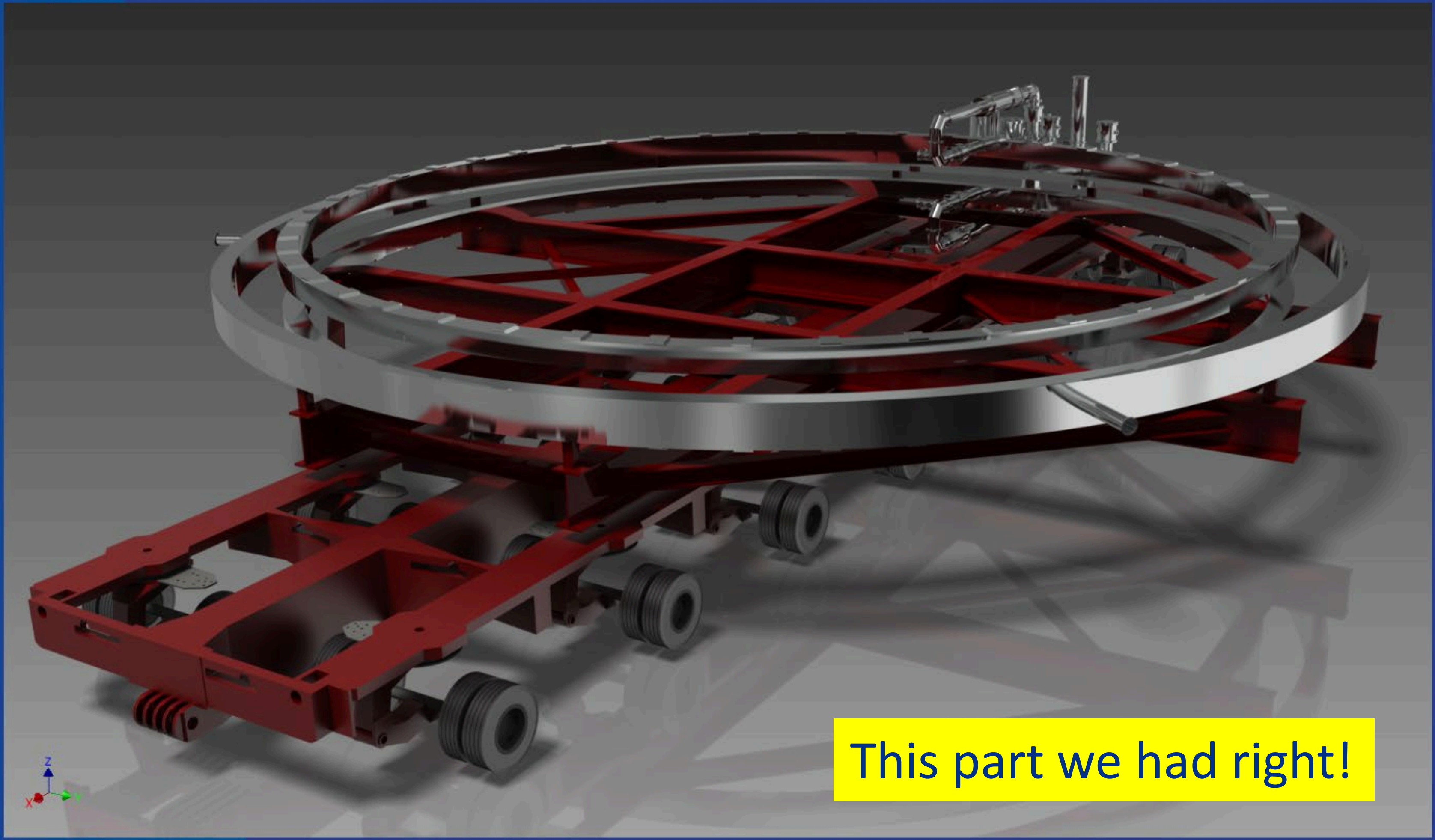
We still thought flying might be an option 😂



We took a much longer, but safer route around Florida

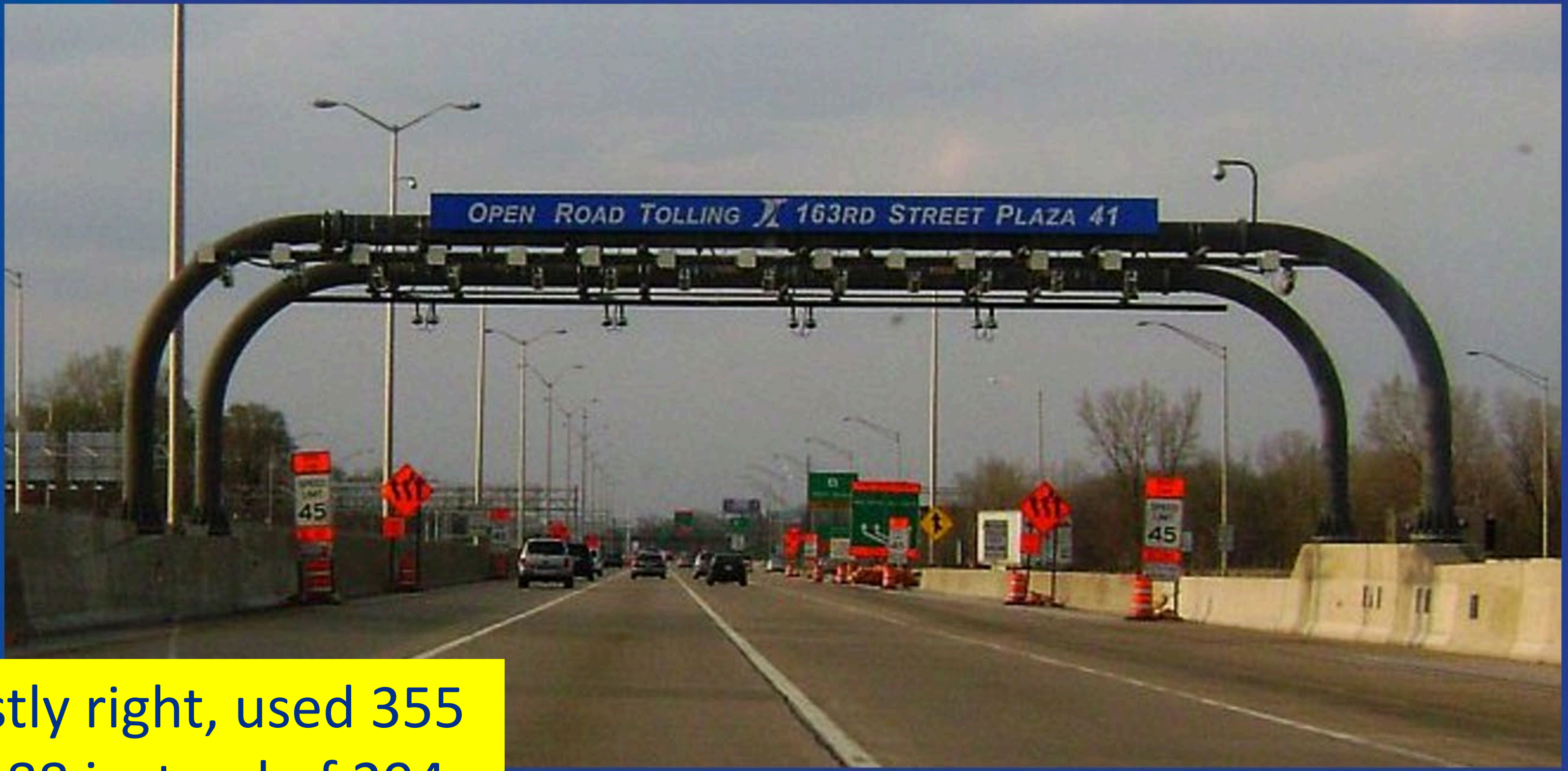
Fermilab

A rendering from Emmert International showing the superconducting coils on 12 axle trailer



With transportation plans in hand, it looks like the transport from the Lemont area to Fermilab will be primarily by truck. Might use a ground or air-crane to assist if needed.

Nothing for perspective on that last picture, but here is something you are probably familiar with



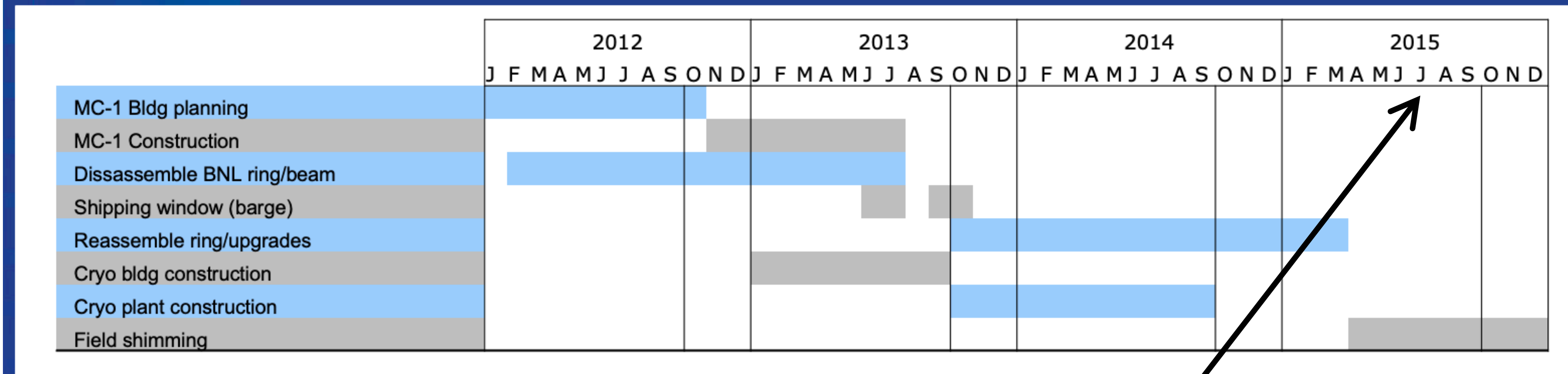
Mostly right, used 355 and 88 instead of 294

The trailer loaded with the coils passes through the open road tolling arches with about 12 inches to spare

Fermilab


OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

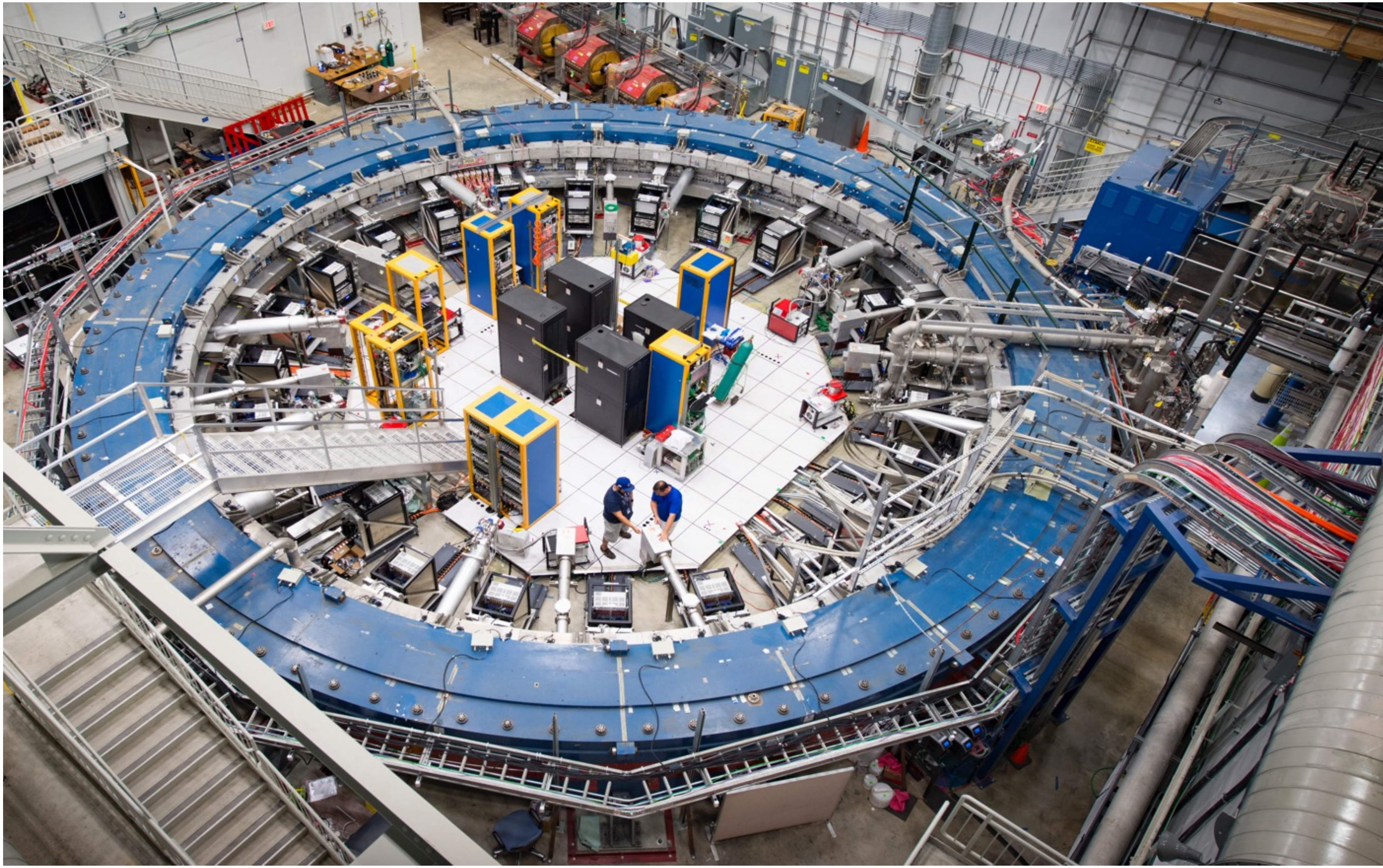
In conclusion…



If all goes as planned, look for the superconducting coils to go rolling by next October!

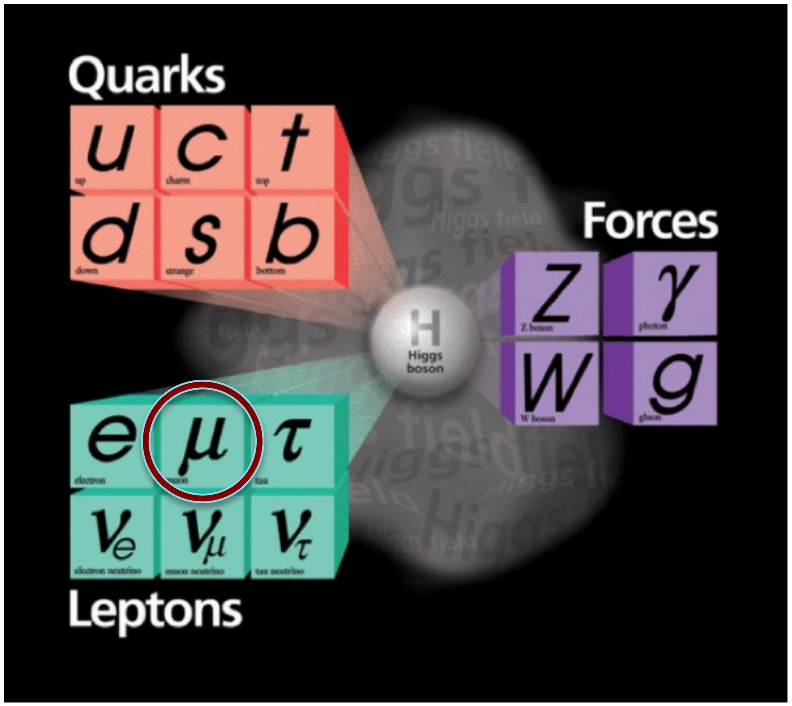
Actually, not too bad here either…1st attempt to power the ring was July 2015
FY16 – shimming year
FY17 – first engineering run
FY18 – first physics data (just published)

All put back together at Fermilab!

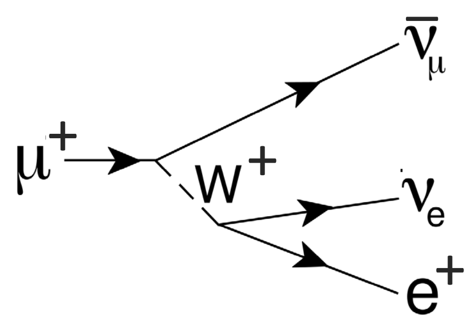


What are muons?

Fundamental building blocks of the Standard Model



- Similar to electrons
  - Same charge
  - Same spin properties
- Important differences
  - 200x more massive
  - Unstable, live ~2 millionths of a second before they decay

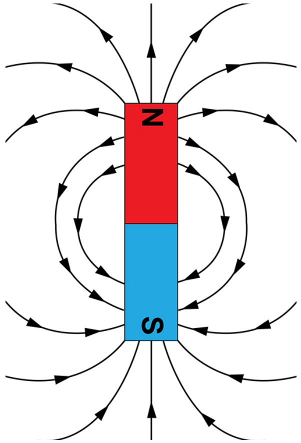


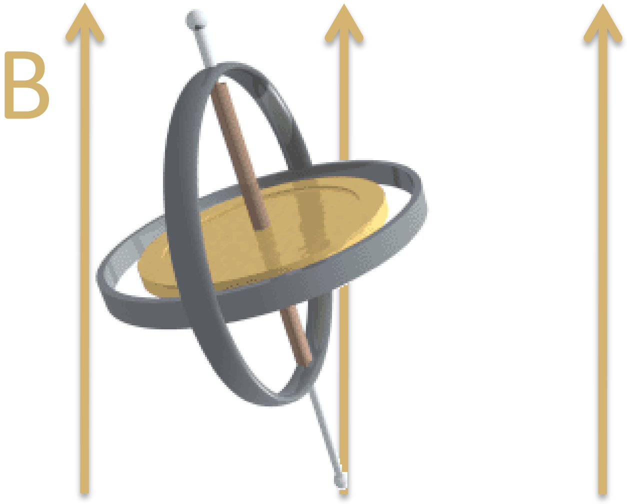
Muon g-2 measures the muon's magnetic moment

- Because of their spin & charge, muon's act like little bar magnets and have a magnetic moment, μ
- Like a bar magnet, they feel a torque when placed in a magnetic field

$$\vec{\tau} = \vec{\mu} \times \vec{B}, \quad U = -\vec{\mu} \cdot \vec{B}$$

- That torque causes the muon spin to precess around the magnetic field at a rate that increases or decreases depending on the strength of μ & B





The g-factor

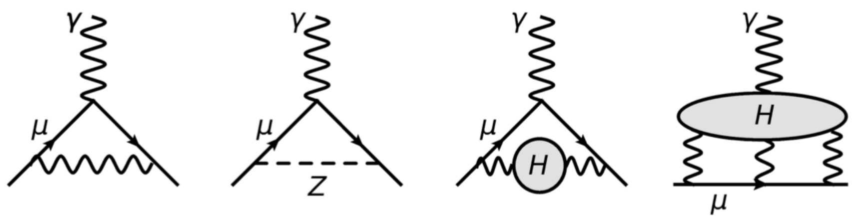
- The strength of the magnetic moment can be written in terms of fundamental constants and an overall coefficient called the g-factor

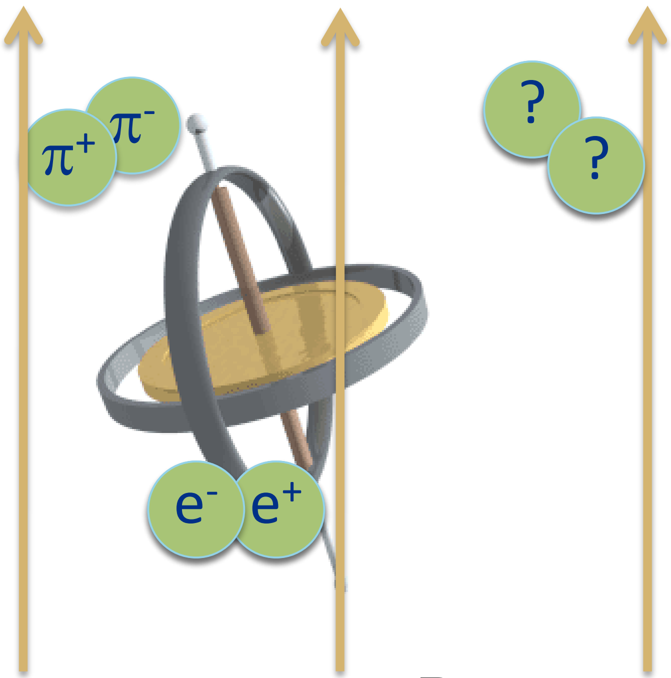
$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

- g = 1
  - This was the classical expectation around 1900
- g = 2
  - Folding in relativistic quantum mechanics, the expectation was shown to be 2 by Thomas and predicted by Dirac's wave equation
- As you can guess from the experiment name, Muon g-2, there is more to the story...

The anomalous magnetic moment, a_μ

- Particles are never truly alone, constantly surrounded by an entourage of other particles blinking in and out of existence
- What particles? All of them!





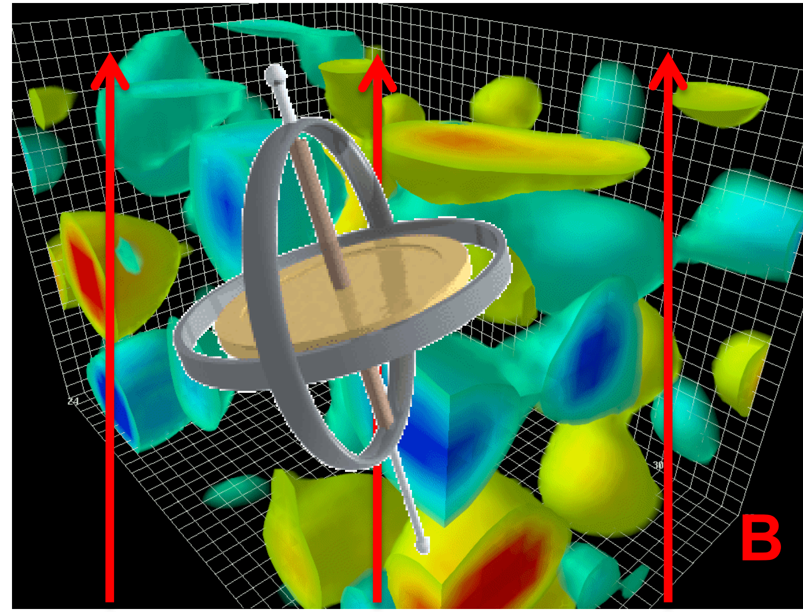
- The anomalous magnetic moment, a_μ, is the interesting part

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

$$\omega_s = g\frac{eB}{2mc}$$

New physics search

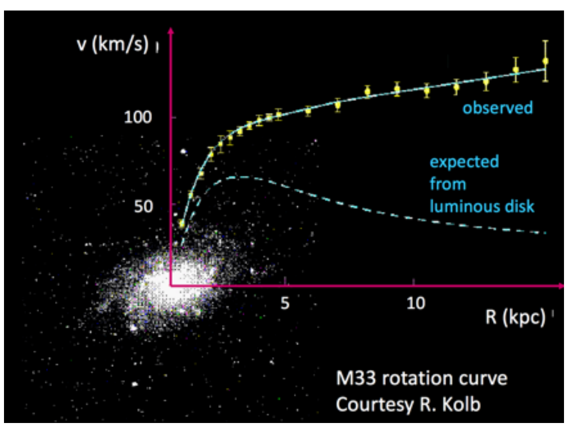
Image Credits: Derek Leinweber



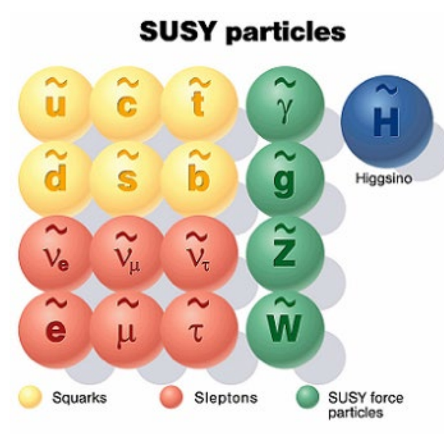
- Measuring the precession tells us the muon magnetic moment
- The high precision allows us to ‘see’ if new particles or forces are contributing to the anomaly!

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

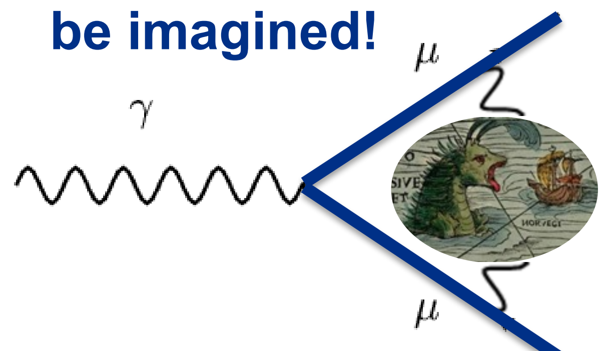
Dark matter!



SUSY!



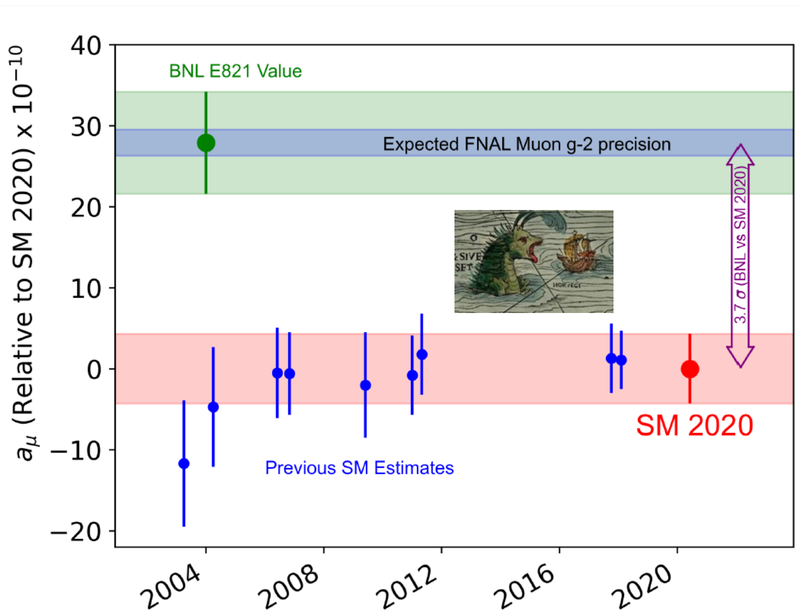
Monsters yet to be imagined!

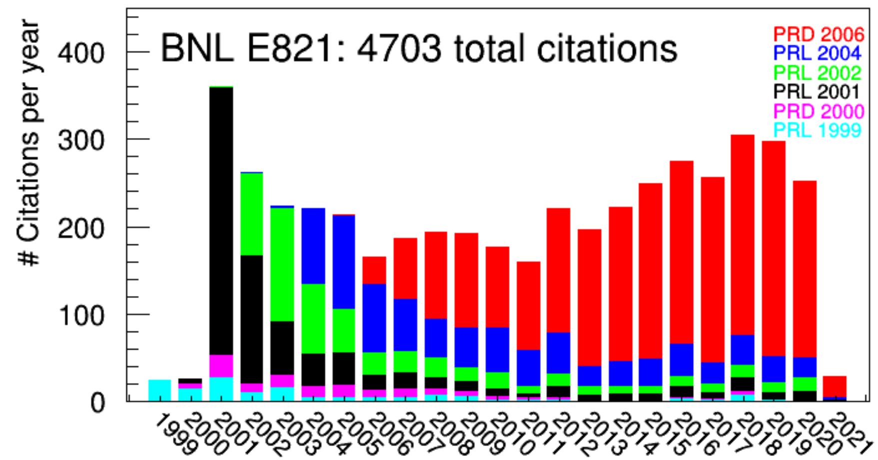


A hint of new physics

- a_μ last measured 20 years ago at Brookhaven National Lab (BNL) where an interesting 2.7σ hint of new physics was discovered
  - Has grown to 3.7σ with improvements in theory

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





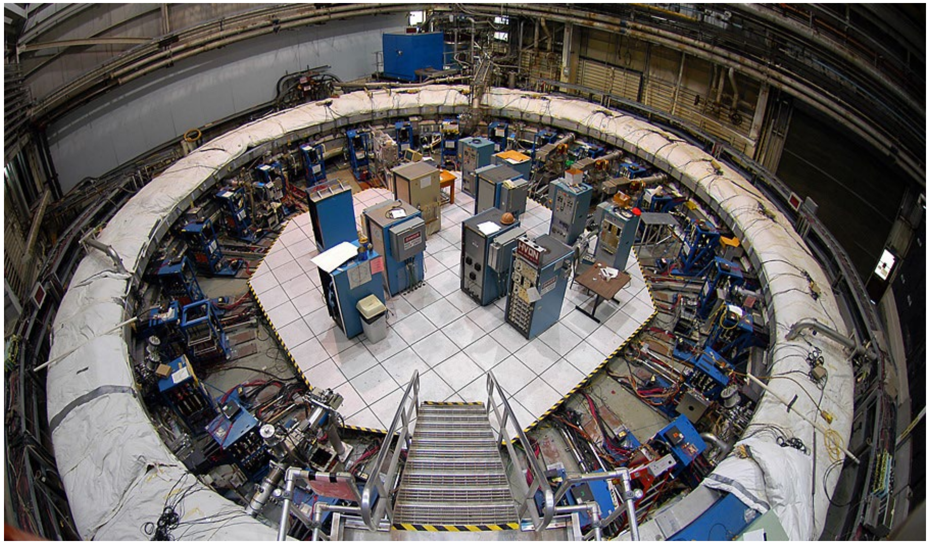
- The difference has intrigued physicists for years
  - Difference is ~27 x 10^{-10} in a_μ

Bringing g-2 to Fermilab

- Goal: Bring the container used to hold the muons from BNL and couple it to Fermilab's powerful accelerator beam

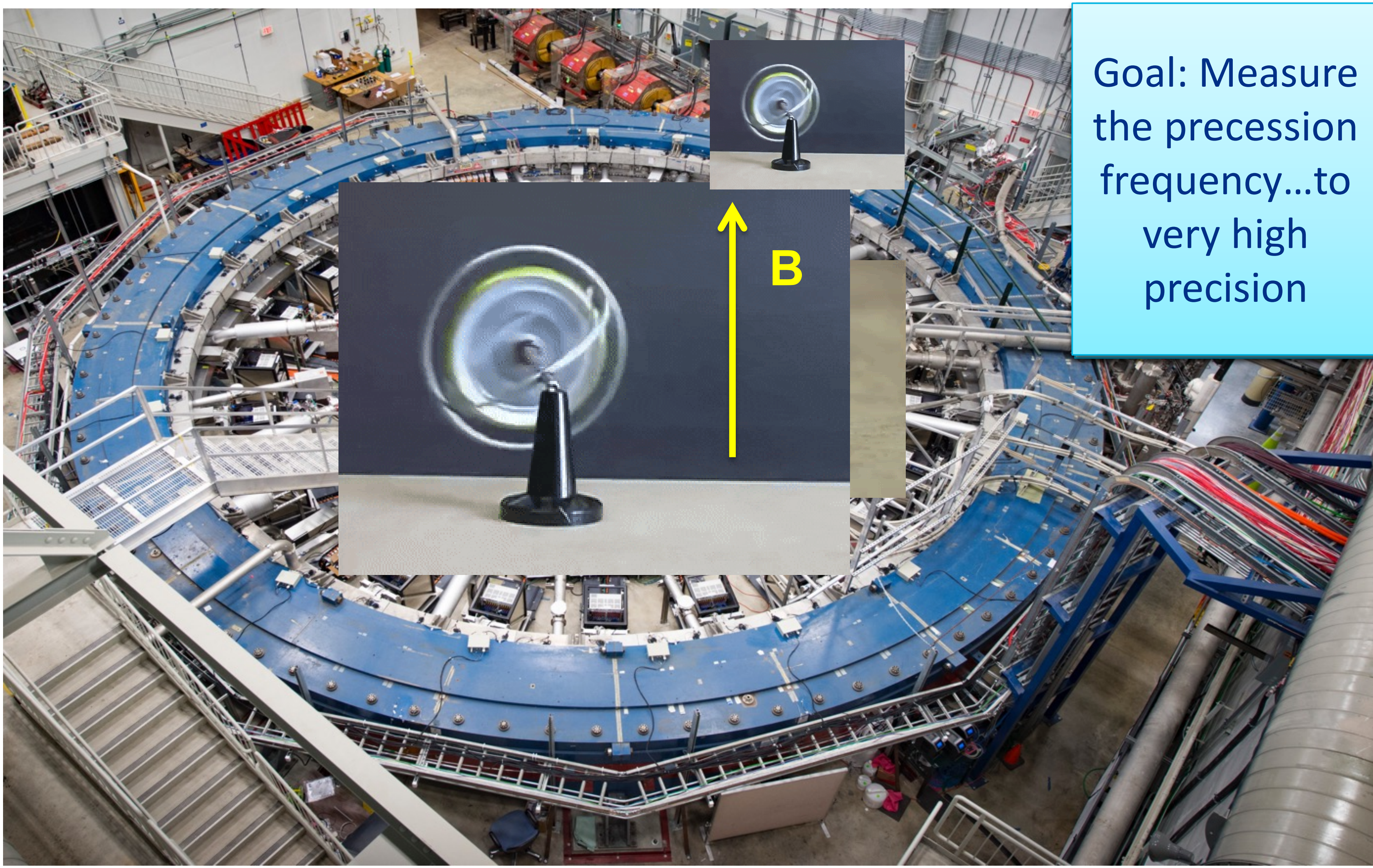
- Reduce the overall error by a factor of 4 to 140 ppb
  - 20x the muons → reduce statistical error from 460 to 100 ppb
  - control systematics at the same 100 ppb level (3x better)

Brookhaven Muon Storage Ring



Parts of the 50' diameter storage ring could not come apart!!

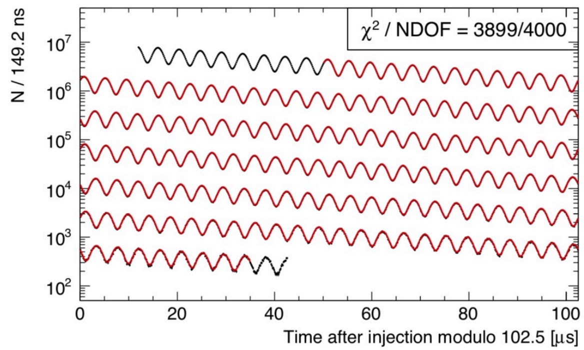
All put back together at Fermilab!

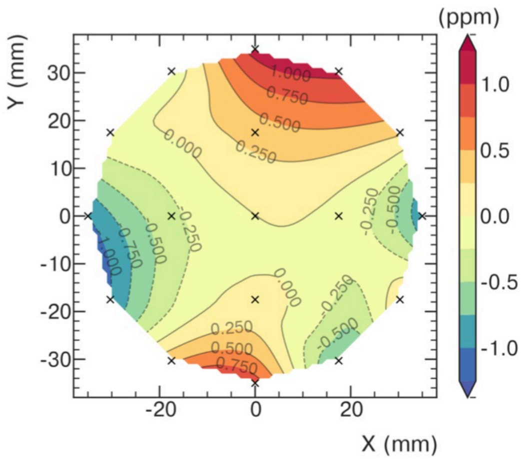


Goal: Measure the precession frequency…to very high precision

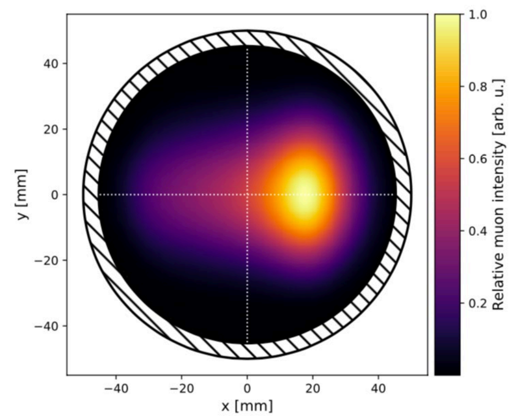
The analysis ‘big’ picture

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





$\otimes$



*All plots actual Run 1 data

Systematics (numerator)

Source	Uncertainty
Frequency Standard	1 ppt
Frequency Synthesizers	0.1 ppb
Digitization Frequency	2 ppb
Total Systematic	2 ppb

Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{pa}	-184	-165	-117	-164
Stat. uncertainty	23	20	15	14
Tracker & CBO	73	43	41	44
Phase maps	52	49	35	46
Beam dynamics	27	30	22	45
Total uncertainty	96	74	60	80

$R(\omega_a)$ with detailed systematics categories [ppb]				
Total systematic uncertainty	65.2	70.5	54.0	48.8
Time randomization	14.8	11.7	9.2	6.9
Time correction	3.9	1.2	1.1	1.0
Gain	12.4	9.4	8.9	4.8
Pileup	39.1	41.7	35.2	30.9
Pileup artificial dead time	3.0	3.0	3.0	3.0
Muon loss	2.2	1.9	5.2	2.4
CBO	42.0	49.5	31.5	35.2
Ad-hoc correction	21.1	21.1	22.1	10.3

*Run 1 ω_a data analyzed in four subsets

	1a	1b	1c	1d
C_p (ppb)	**176**	**199**	**191**	**166**
Statistical uncertainty	<0.1	<0.1	<0.1	<0.1
Tracker alignment/reco.	11.0	12.3	12.0	10.7
Tracker res. & acc. removal	3.3	3.9	3.7	3.0
Azimuthal avg. & calo. acc.	1.0	1.3	2.2	1.1
Amplitude fit	1.2	0.4	1.0	2.9
Quad alignment/voltage	4.4	4.4	4.4	4.4
Systematic uncertainty	**12.4**	**13.7**	**13.6**	**12.3**

Data Set	Run-1a	Run-1b	Run-1c	Run-1d
C_{ml}	-14	-3	-7	-17
Phase-momentum	2	0	1	3
Form of $l(t)$	2	0	1	1
f_{loss} function	2	1	2	2
Linear sum ($\sigma_{C_{ml}}$)	6	2	4	6

	1a	1b	1c	1d
C_e (ppb)	**471**	**464**	**534**	**475**
Statistical uncertainty	0.4	0.5	0.4	0.2
Fourier method	8.4	13.4	14.4	3.9
Momentum-time correlation	52	52	52	52
Quad alignment/voltage	6.4	6.4	6.4	6.4
Field index	1.7	1.5	1.7	4.0
Systematic uncertainty	**53**	**54**	**54**	**53**

Systematics (denominator)

run-1 (substructure)	77.4 ppb
azimuthal shape*	7.6 ppb
skin depth	12.6 ppb
frequency extraction (0.4/1ms)	4.6 ppb
Q3L: fit, position	1.5 ppb
repeatability	13.3 ppb
drift	10.2 ppb
radial dependency	4.4 ppb
2^{nd} 8-pulses	14.0 ppb
total −15.0 ppb	81.7 ppb

Source	Uncertainty (ppb)
Temperature	**15 – 28**
Configuration	**22**
Trolley	**25**
Fixed Probe Production	**<1**
Fixed Probe Baseline	**8**
Tracking Drift	**22 – 43**
Total	**43 – 62**

PROBE	Calibration Coefficients		
	Value (Hz)	Stat (Hz)	Syst (Hz)
1	90.81	0.38	2.02
2	84.21	0.65	1.18
3	95.02	0.53	2.19
4	86.03	0.25	1.28
5	92.96	0.51	1.10
6	106.24	0.46	1.35
7	116.64	0.96	1.61
8	76.39	0.60	1.21
9	83.52	0.23	1.64
10	24.06	1.39	1.26
11	177.55	0.22	1.99
12	110.85	0.44	1.73
13	122.89	2.08	1.93
14	77.11	0.53	1.88
15	74.82	1.06	1.59
16	20.35	0.44	2.94
17	172.12	1.23	1.96
AVG		**0.70**	**1.70**

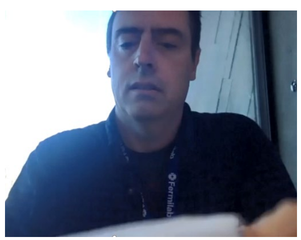
Quantity	Symbol	Value	Unit
Diamagnetic Shielding T dep	$(1/\sigma)d\sigma/dT$	-10.36(30)	ppb/℃
Bulk Susceptibility	δ_b	-1504.6 ± 4.9	ppb
Material Perturbation	δ_s	15.2 ± 13.3	ppb
Paramagnetic Impurities	δ_p	0 ± 2	ppb
Radiation Damping	δ_{RD}	0 ± 3	ppb
Proton Dipolar Fields	δ_d	0 ± 2.3	ppb

Run-1 Estimate:
B_k = -27.4 ± 37 ppb

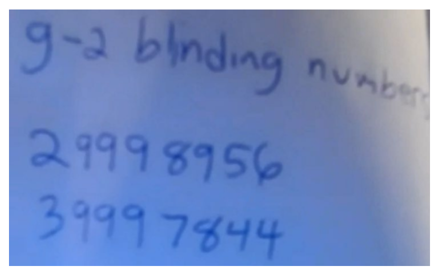
	correction [ppb]				uncertainty [ppb]			
Dataset	**1a**	**1b**	**1c**	**1d**	**1a**	**1b**	**1c**	**1d**
1. Tracker and calo effects	-	-	-	-	9.2	13.3	15.6	19.7
2. COD effects	1.6	1.5	1.7	1.4	5.2	4.7	5.2	4.9
3. In-fill time effects	-1.9	-2.3	-1.2	-4.1	-	-	-	-
Total	**-0.3**	**-0.8**	**0.5**	**-2.7**	**10.6**	**14.1**	**16.5**	**20.3**

Gathered on Feb 25 to unblind

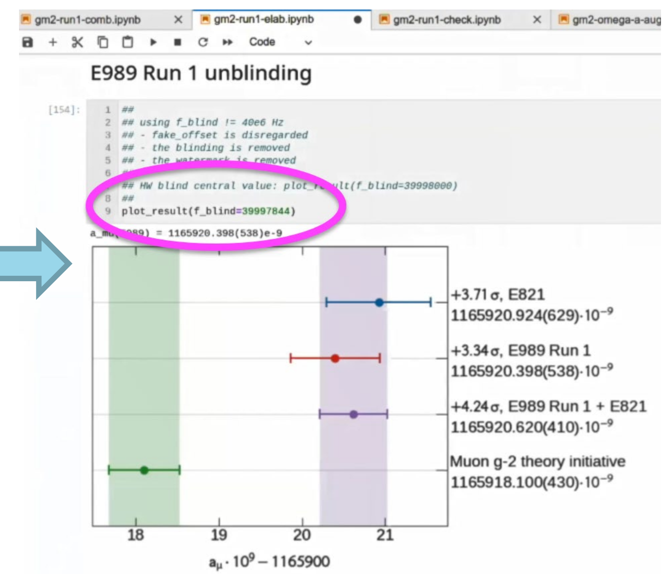
UW envelope



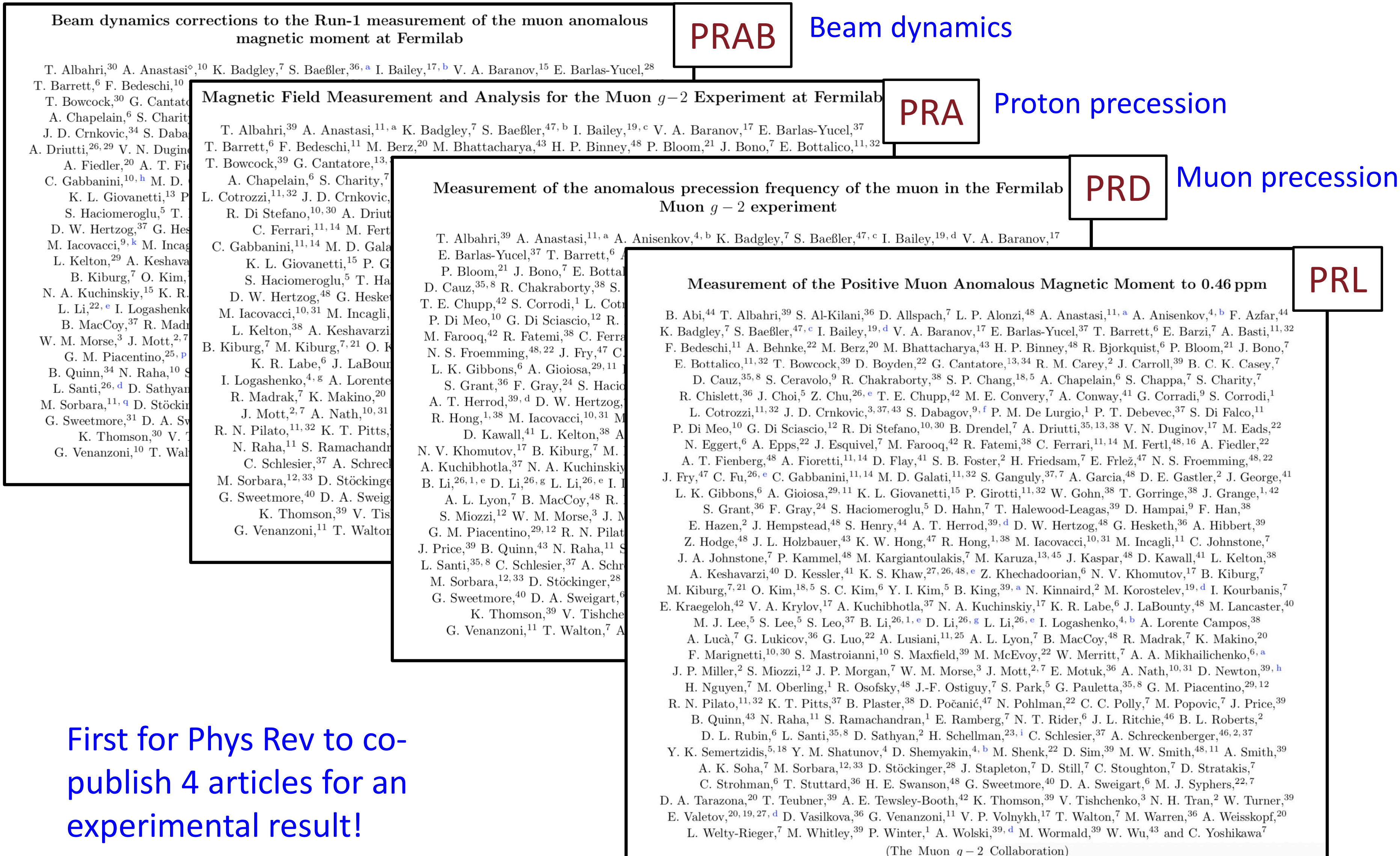
FNAL envelope



Same numbers!



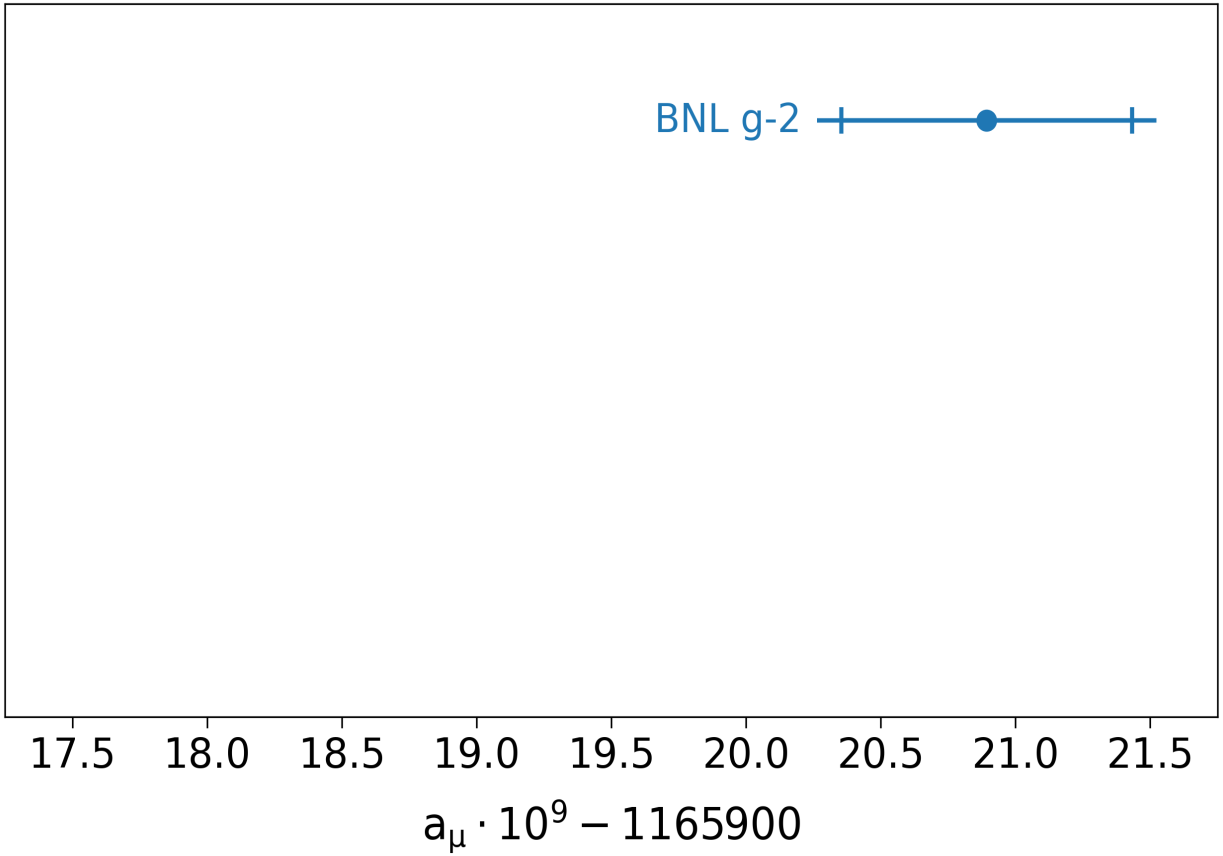
Four articles on arXiv and published in Phys Rev



First for Phys Rev to co-publish 4 articles for an experimental result!

Run 1 result

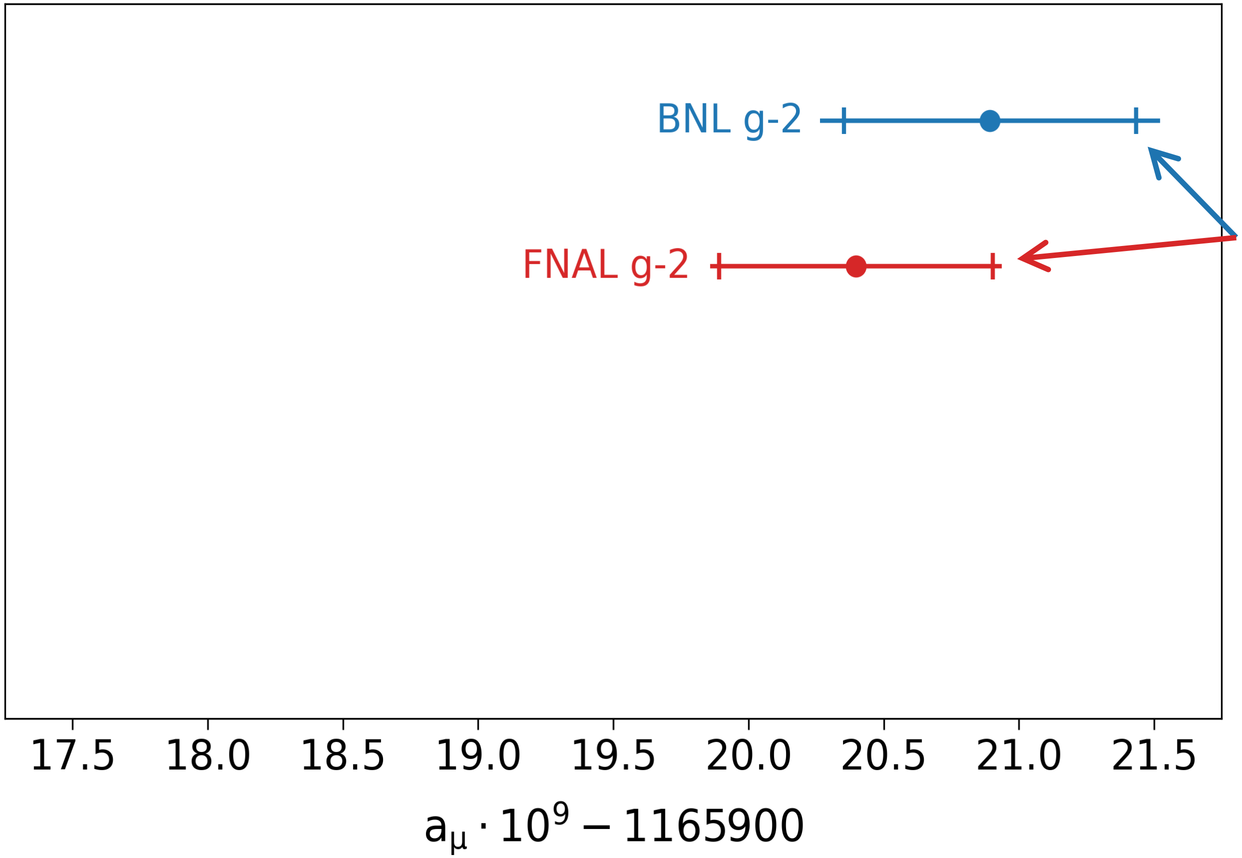
$a_\mu(BNL) = 0.00116592089(63) \rightarrow 540$ ppb



- We found nothing that would change BNL result
  - Larger collaboration
  - Higher purity beam
  - More advanced instrumentation
  - More powerful simulations

Run 1 result

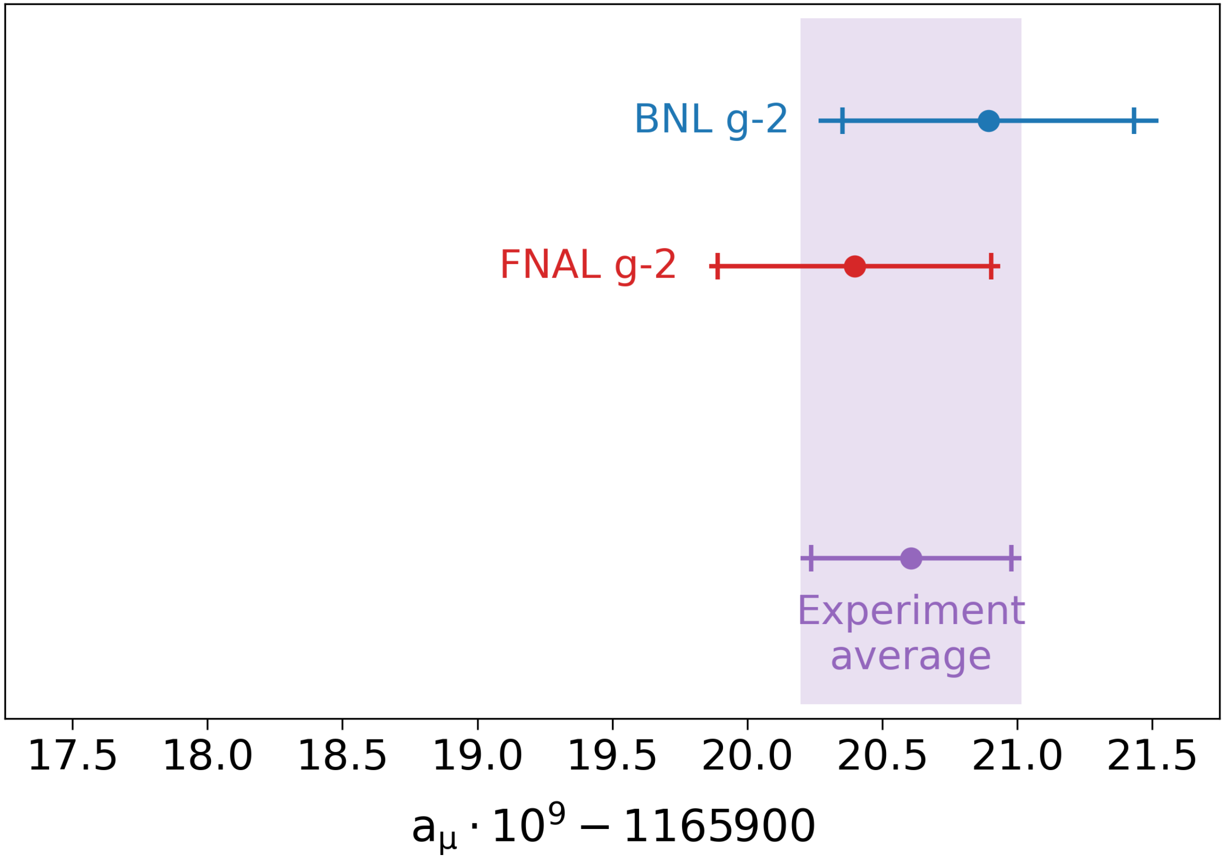
a_μ(FNAL g-2; Run 1) = 0.00116592040(54) → 463 ppb



- 15% smaller error than BNL
- Both experiments dominated by statistical error
- Good agreement → safe to combine

Experimental combination

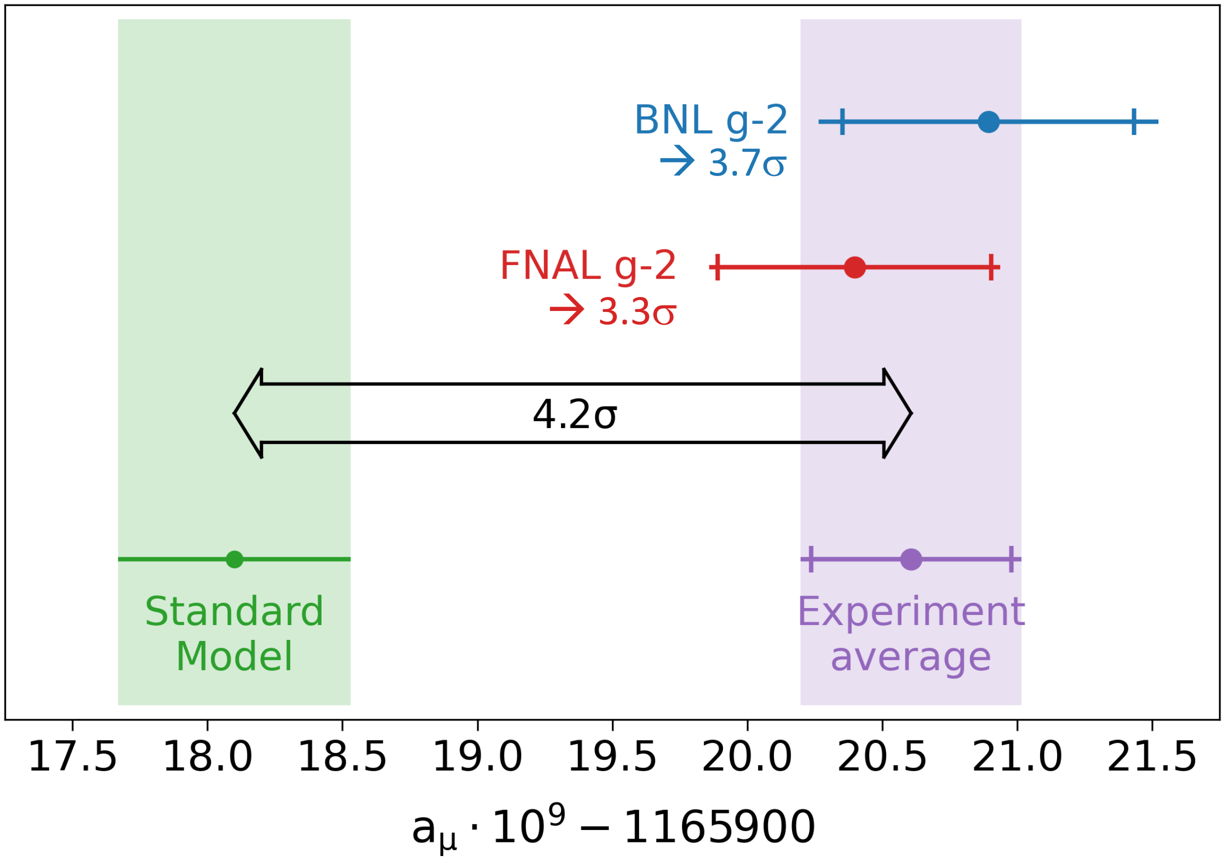
$a_\mu(\text{Exp}) = 0.00116592061(41) \rightarrow 350$ ppb



- 15% smaller error than BNL
- Both experiments dominated by statistical error
- Good agreement → safe to combine

Comparison to SM prediction

$a_\mu(SM) = 0.00116591810(43) \rightarrow 368$ ppb



- Individual tension with SM
  - BNL: 3.7σ
  - FNAL: 3.3σ

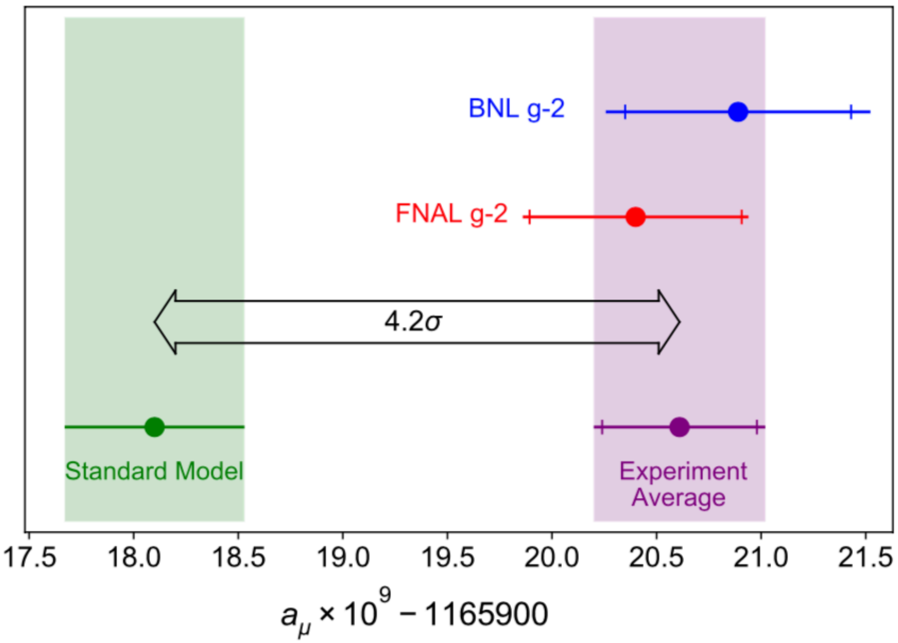
$a_\mu(Exp) - a_\mu(SM) = 0.00000000251(59) \rightarrow 4.2\sigma$

Conclusions

- We have determined a_μ to an unprecedented 460 ppb precision!

- The Run 1 result
  - 6% of ultimate data sample
  - 15% smaller error than BNL
  - 3.3σ tension with SM

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11}$$



- After 20 years, we confirm the BNL experimental results!
- Combining BNL/FNAL and comparing to theory → 4.2σ tension

The results heard round the world!

- The worldwide press coverage was astounding
  - Over 3000 media outlets covered the story
  - Total estimated media reach of those outlets **3.5 billion people!** (Pop. Earth 7.7 billion)
- Nobel prize committee invited us to present the results at the Manne Siegbahn Memorial Lecture in Stockholm
  - Frist time this honor has gone to particle physics since the Higgs discovery in 2013

Mark Hamill
@HamillHimself

Evidence is mounting that The Force has been with us...
ALWAYS.

The New York Times @nytimes · 3h
Breaking News: Evidence is mounting that a tiny subatomic particle is being influenced by forms of matter and energy that are not yet known to science but which may nevertheless affect the nature and evolution of the univer...

"All the News That's Fit to Print"

The New York Times

Late Edition
Today, mostly sunny, remaining quite mild for early April, high 67. **Tonight,** partly cloudy, low 48. **Tomorrow,** variably cloudy, a bit cooler, high 62. Weather map, Page B10.

VOL. CLXX .... No. 59,022 © 2021 The New York Times Company NEW YORK, THURSDAY, APRIL 8, 2021 $3.00

Biden Tax Plan Aims to Curtail

Contagious Variant Is Fueling Surge in Infections Across the U.S.
Some states where new cases of the coronavirus are rising have been hit hard by the B.1.1.7 variant. Page A6.

PAIR OF SETBACKS FOR ASTRAZENECA

would have applied to companies with $100 million or more in profits per year.
Continued on Page A18

reached a record high, the Islamic State has trumpeted these battlefield wins to project an image of strength and inspire its support-

researchers.
"As an organization more broadly, ISIS is hurting," said Col-
Continued on Page A11

the pandemic. The effort — a $2.1 billion fund in the state budget — is by far the biggest of its kind in the country and a sign of the

budget deal that was reached on Tuesday, was one of the most contentious points of debate during
Continued on Page A16

in Europe, the safety concerns have delayed inoculations, sunk confidence in the shot and created
Continued on Page A9

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

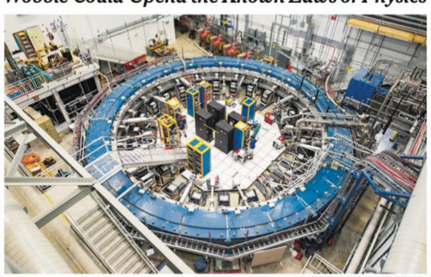
Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental



REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A19

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

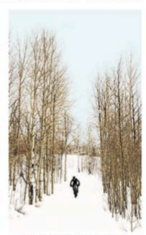
By ALI WATKINS

PINEDALE, Wyo. — Kenna Tanner and her team can list the cases from memory: There was the woman who got tired and did not feel like finishing her hike; the campers, in shorts during a blizzard; the base jumper, misjudging his leap from a treacherous granite cliff face; the ill-equipped snowmobiler, buried up to his neck in an avalanche.

All of them were pulled by Ms. Tanner and the Tip Top Search and Rescue crew from the rugged Wind River mountain range in the last year, in this sprawling, remote pocket of western Wyoming. And all of them, their rescuers said, were wildly unprepared for the brutal backcountry in which they were traveling.

"It is super frustrating," said Ms. Tanner, Tip Top's director. "We just wish that people respected the risk."

In the throes of a pandemic that has made the indoors inherently dangerous, tens of thousands more Americans than usual have flocked outdoors, fleeing crowded cities for national parks and the public lands around them. But as



MAX WHITTAKER FOR THE NEW YORK TIMES

A trail in the Wind River Range in western Wyoming.

these hordes of inexperienced adventurers explore the treacherous terrain of the backcountry, many inevitably call for help. It has strained the patchwork, volunteer-based search-and-rescue

Continued on Page A17

The New York Times

Quotation of the Day: A Particle's Tiny Wobble Could Upend the Known Laws of Physics

April 7, 2021

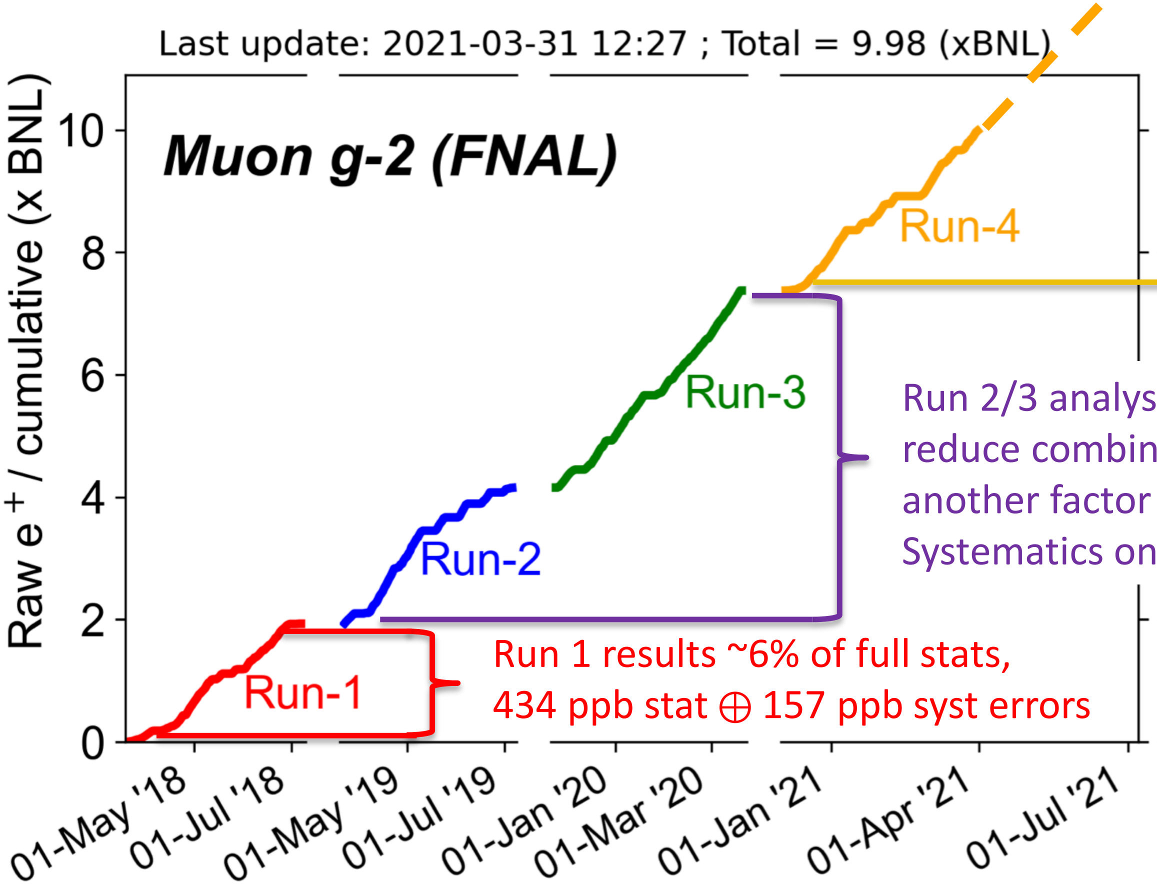
"What monsters might be lurking there?"

CHRIS POLLY, a physicist at the Fermi National Accelerator Laboratory in Illinois, referring to mounting evidence that tiny subatomic particles called muons seem to disobey the known laws of physics.

Fermilab

Outlook

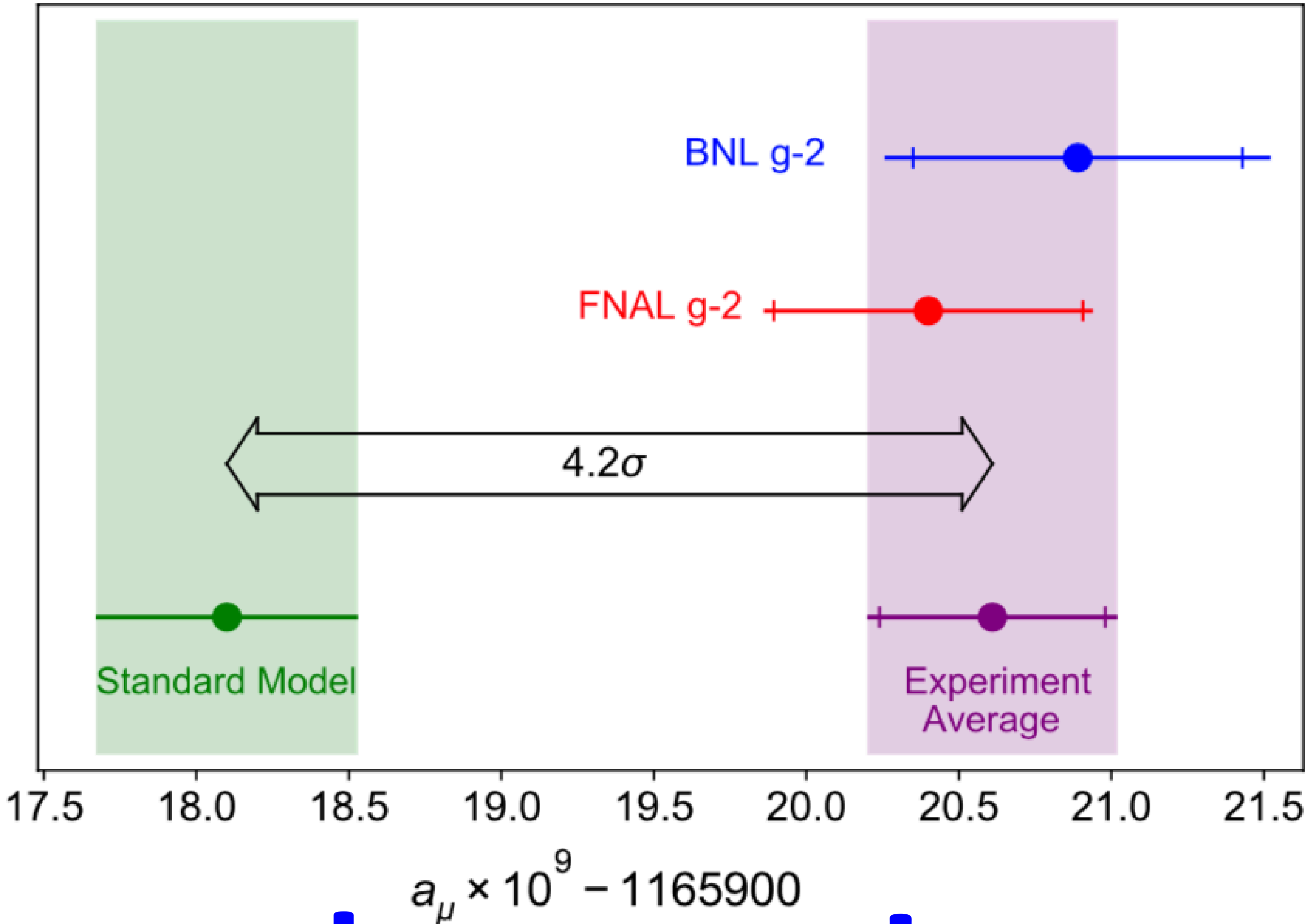
Much more data to come!



Run 4 (now) and beyond, aiming for 20xBNL and another factor of ~2 reduction in error

Run 2/3 analysis in progress, expecting to reduce combined experimental error by another factor of 2 by next summer. Systematics on track for < 100 ppb

Run 1 results ~6% of full stats, 434 ppb stat ⊕ 157 ppb syst errors


BNL g-2
FNAL g-2
4.2σ
Standard Model
Experiment
Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

Thank you!