

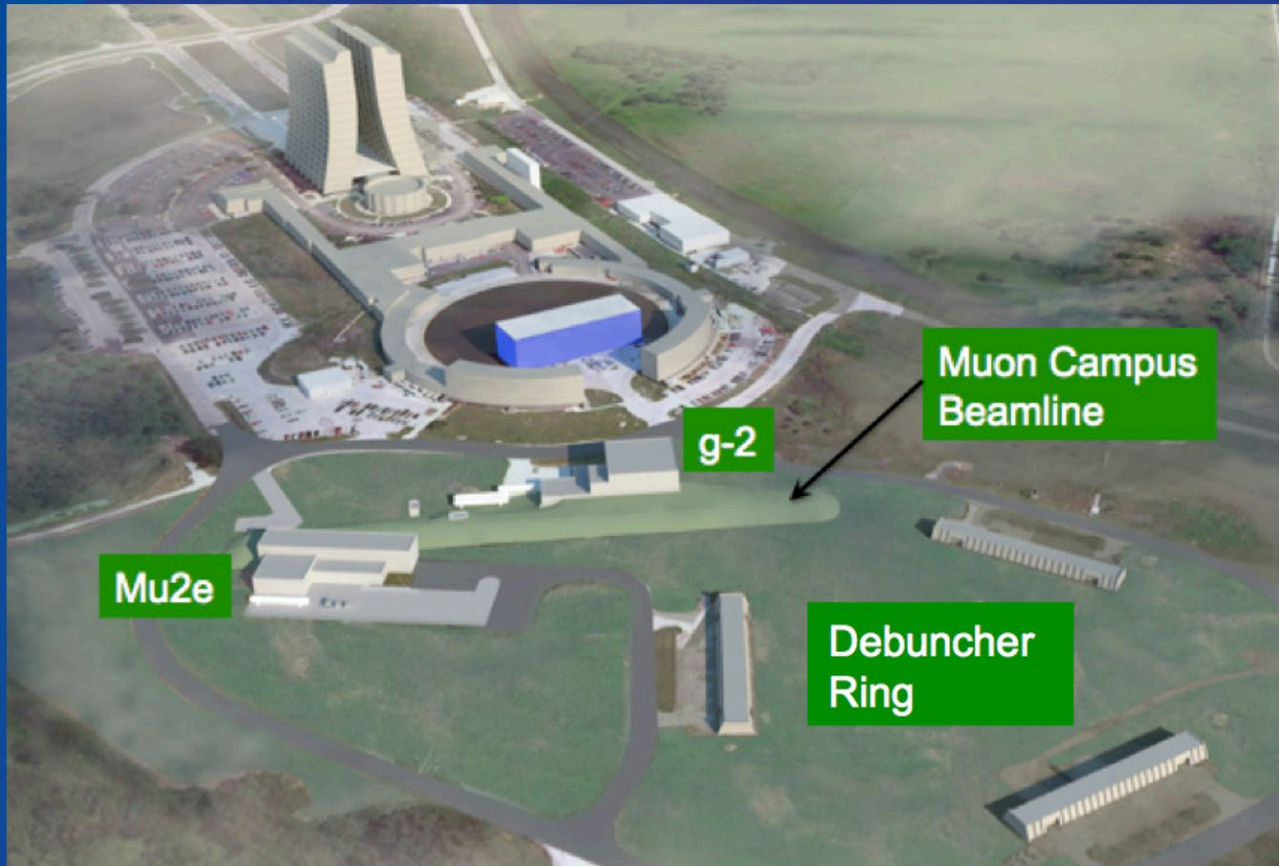


First results from the Muon $g-2$ Experiment at Fermilab

Chris Polly, Fermi National Accelerator Laboratory

Slide from first FNAL seminar on g-2

Exciting time for new Fermilab muon program



6

13 April 2012

Fermilab

Fermilab

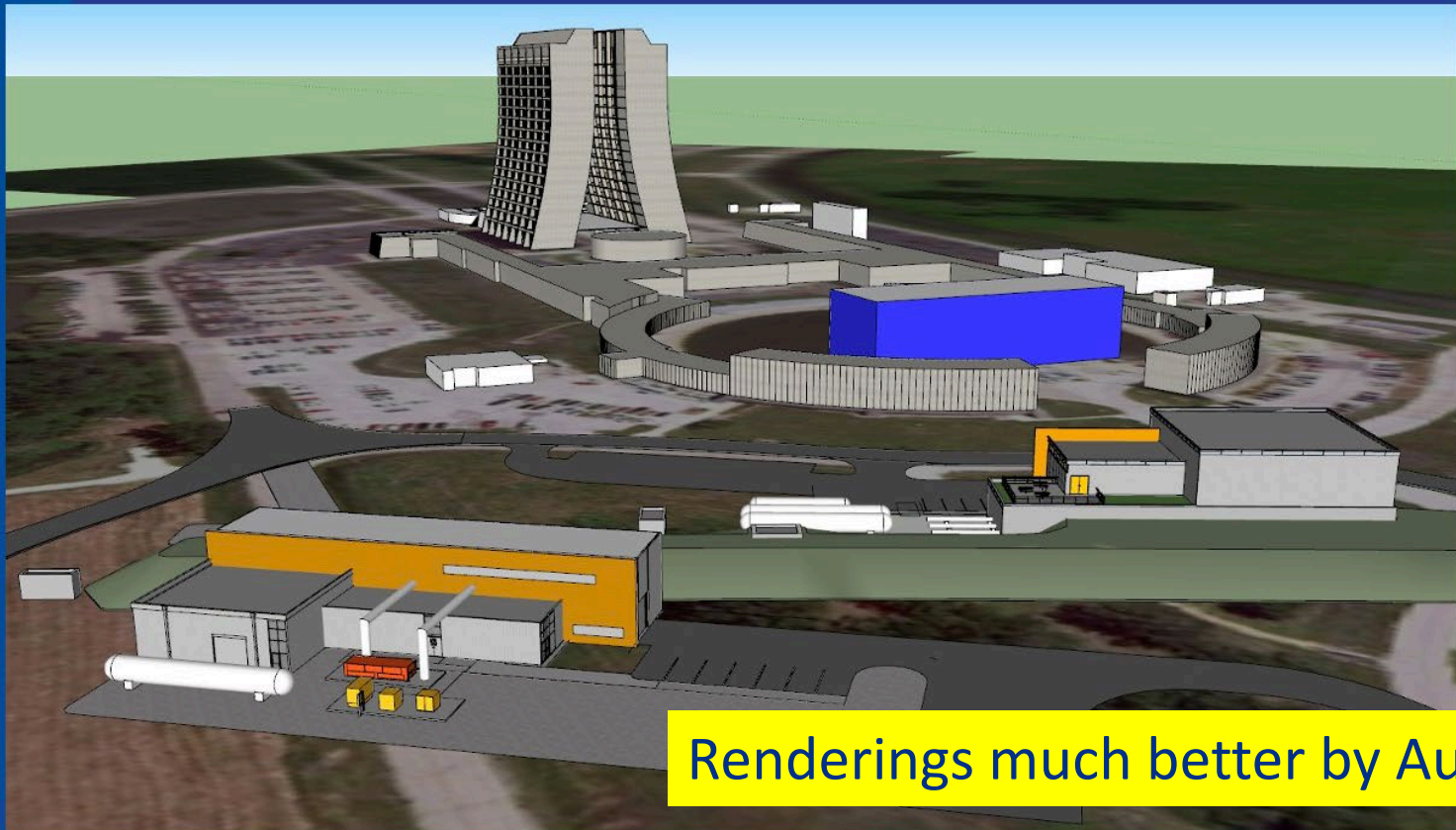
Introduction to Muon $g-2$ (g 'minus' 2)

Chris Polly
Community Advisory Board
August 23, 2012

First presentation to CAB!

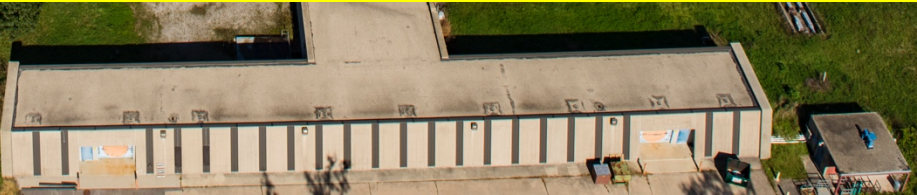
This is an incredible opportunity for the laboratory and the community

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

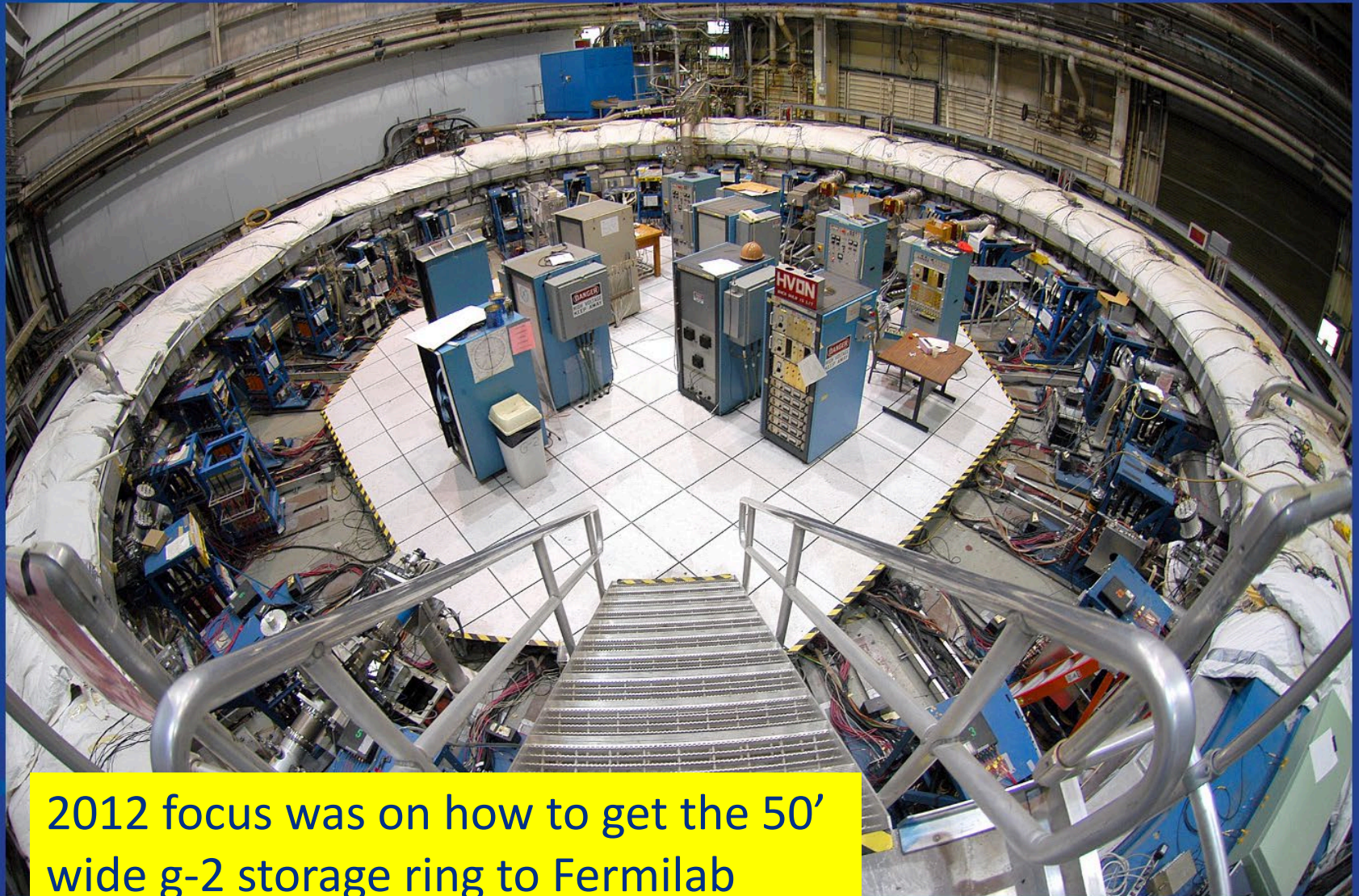


Renderings much better by Aug

Muon Campus today



The exquisite machine circa 2004



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

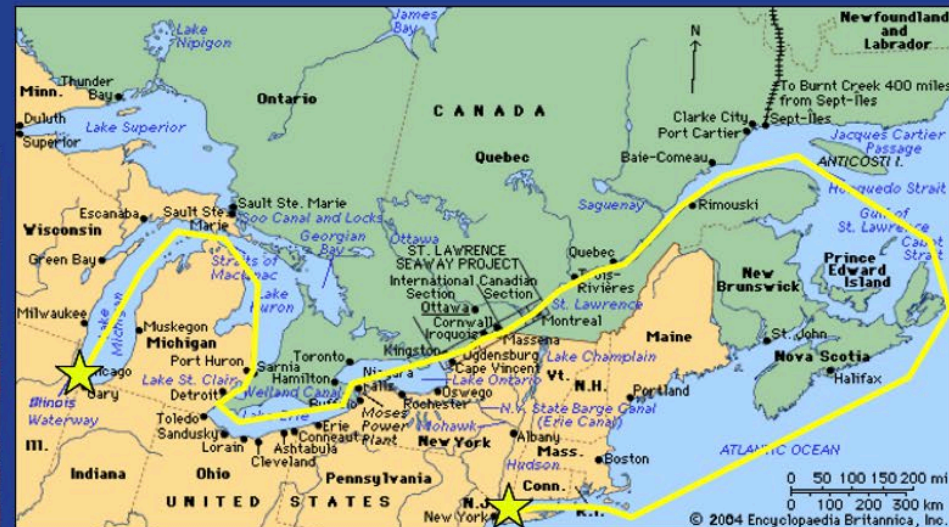
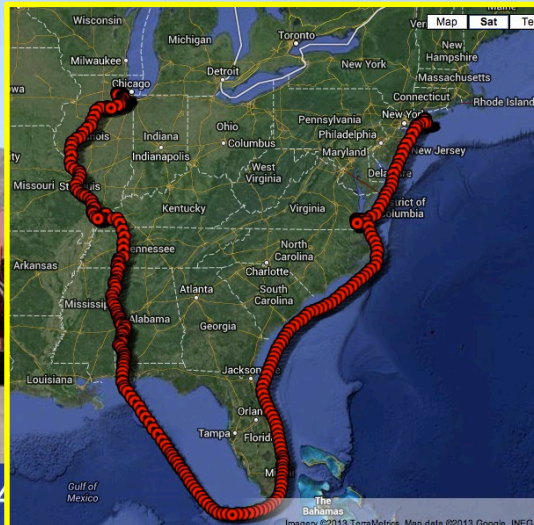
Need to disassemble and transport the machine



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

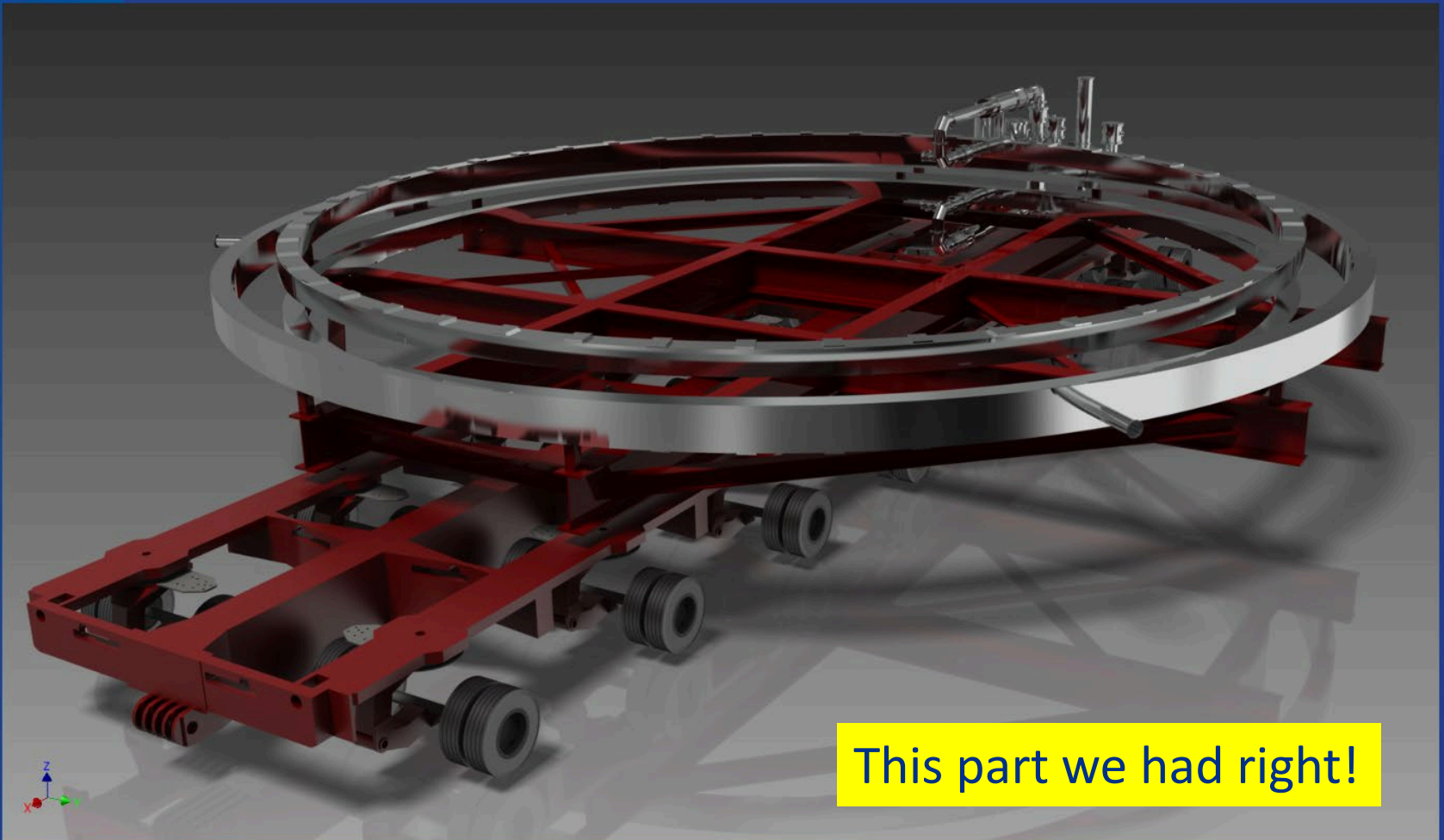
Contracts to develop full transportation plan were awarded to Erickson Air-Crane and Emmert International

We still thought flying might be an option 😊



We took a much longer, but safer route around Florida

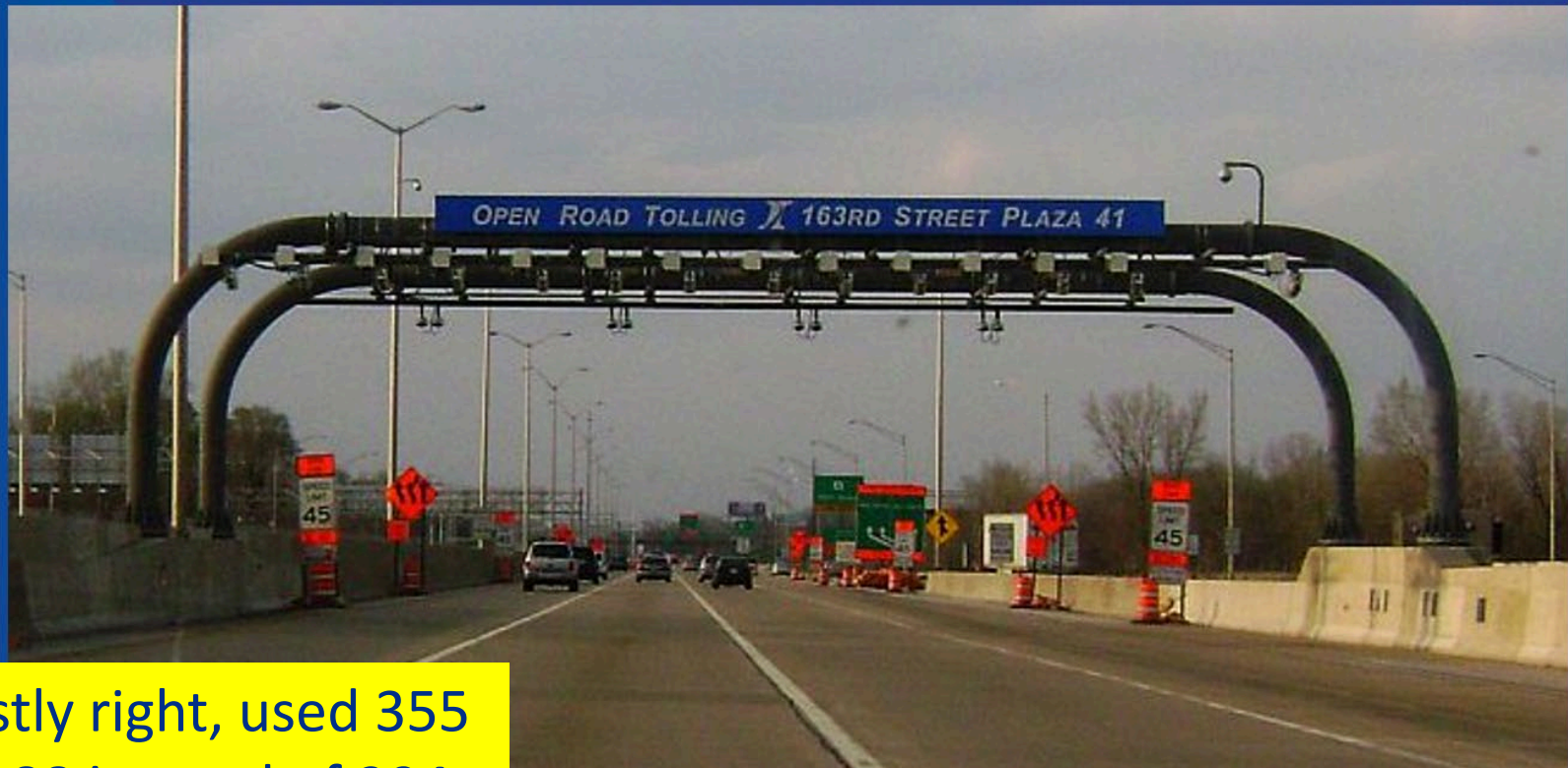
A rendering from Emmert International showing the superconducting coils on 12 axle trailer



This part we had right!

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

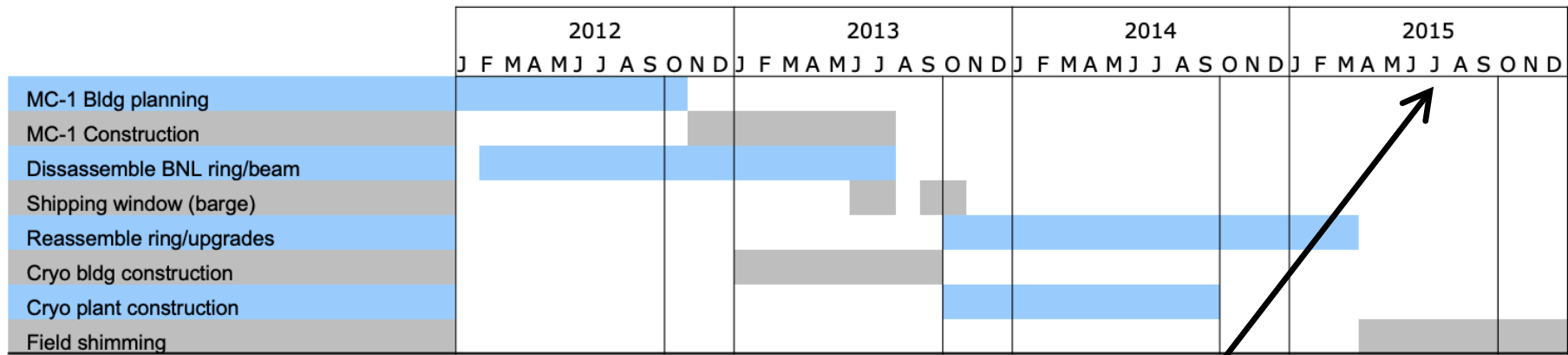


Mostly right, used 355 and 88 instead of 294

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



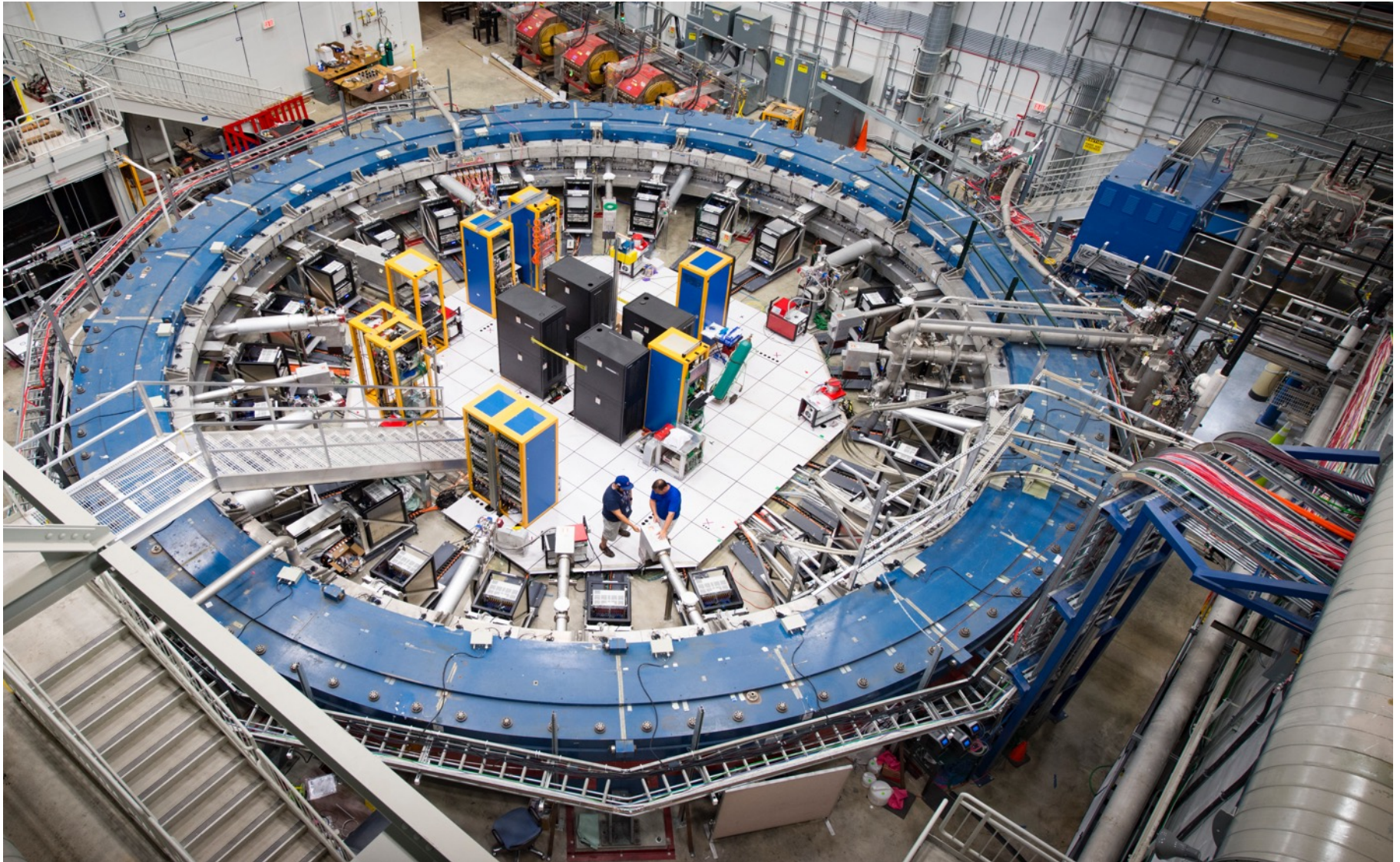
In conclusion...



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

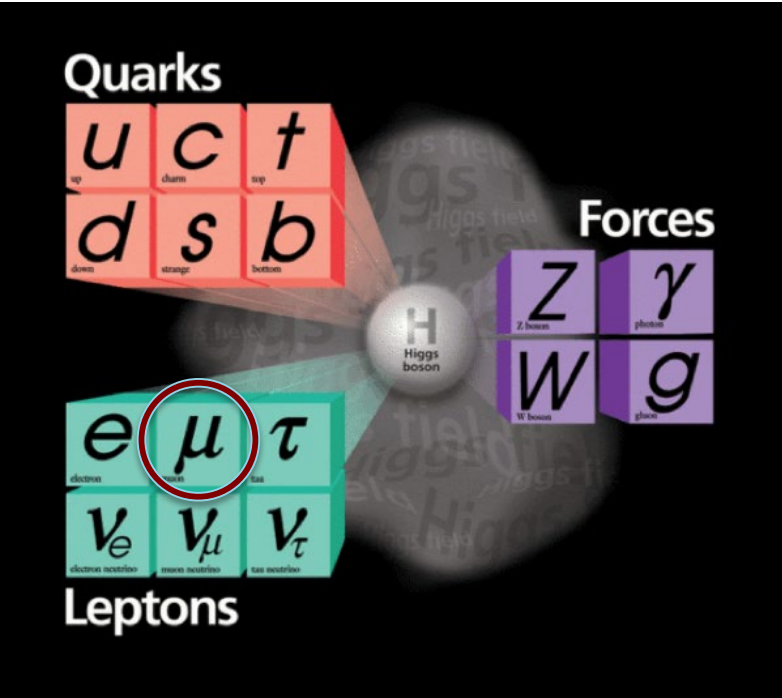
Actually, not too bad here either...1st attempt to power the ring was July 2015
 FY16 – shimming year
 FY17 – first engineering run
 FY18 – first physics data (just published)

All put back together at Fermilab!

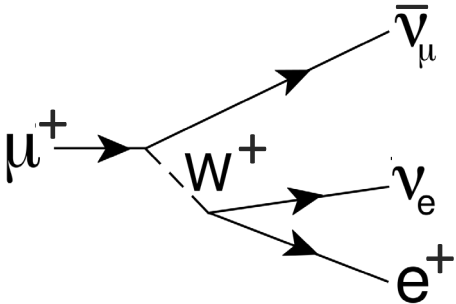


What are muons?

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

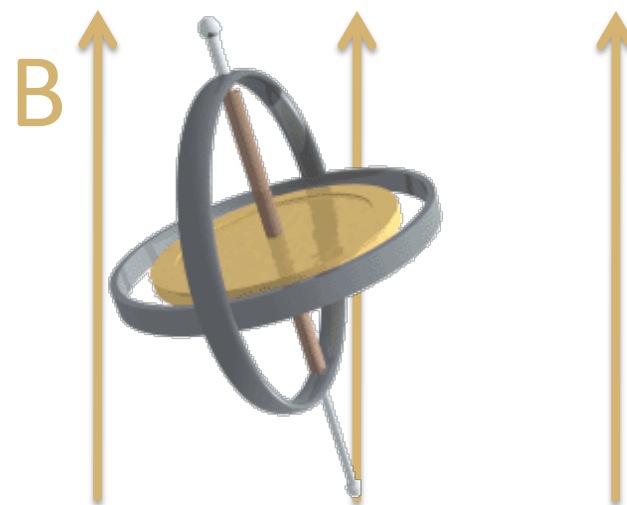
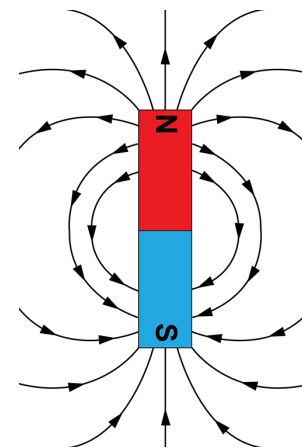


Muon g-2 measures the muon's magnetic moment

- Because of their spin & charge, muon's act like little bar magnets and have a magnetic moment, $\vec{\mu}$
- 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

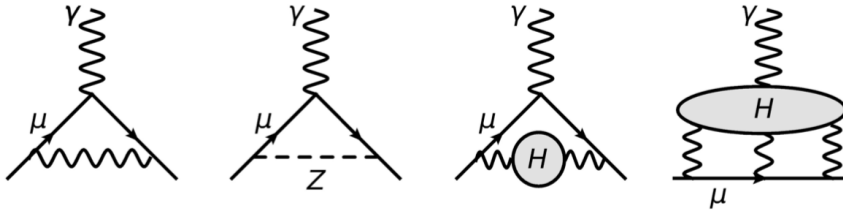
- The strength of the magnetic moment can be written in terms of fundamental constants and an overall coefficient called the g-factor

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

- $g = 1$
 - 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...

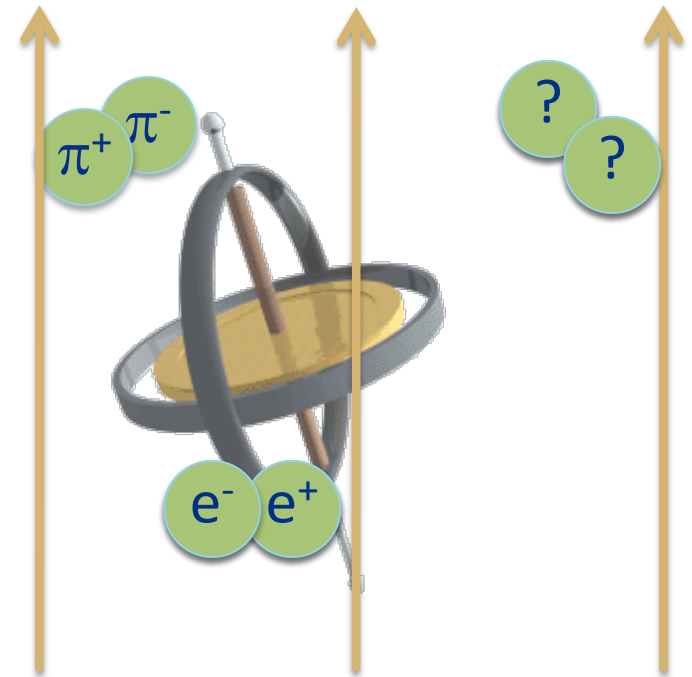
The anomalous magnetic moment, a_μ

- 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

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



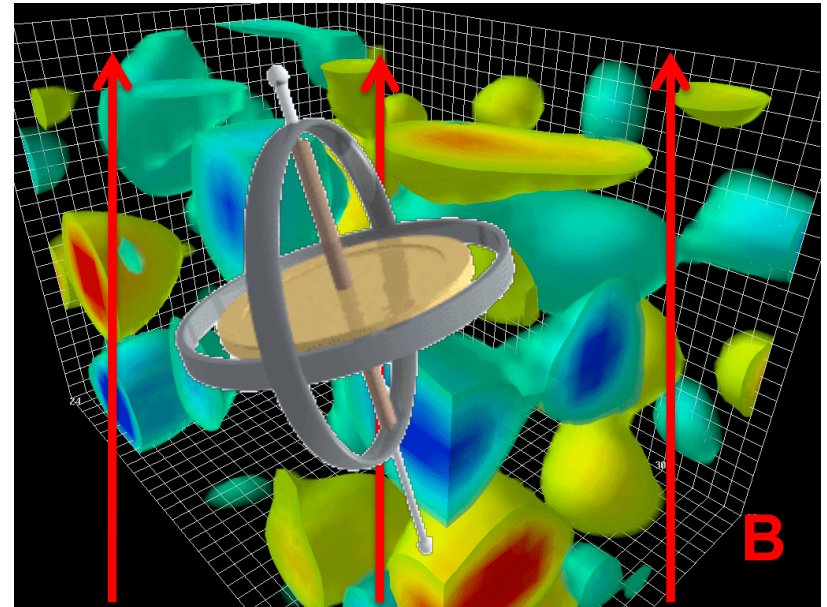
$$\omega_s = g \frac{eB}{2mc}$$

New physics search

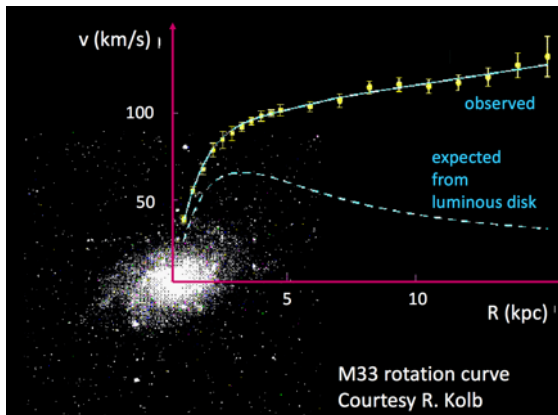
- Measuring the precession tells us the muon magnetic moment
- The high precision allows us to ‘see’ if new particles or forces are contributing to the anomaly!

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

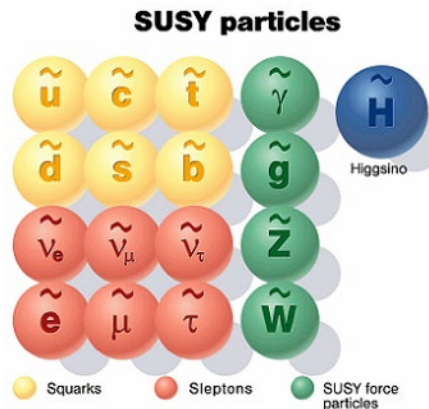
Image Credits: [Derek Leinweber](#)



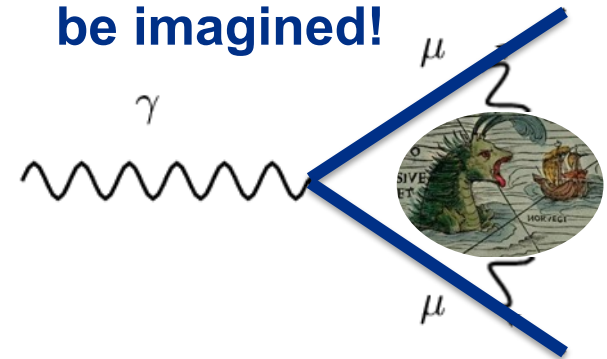
Dark matter!



SUSY!



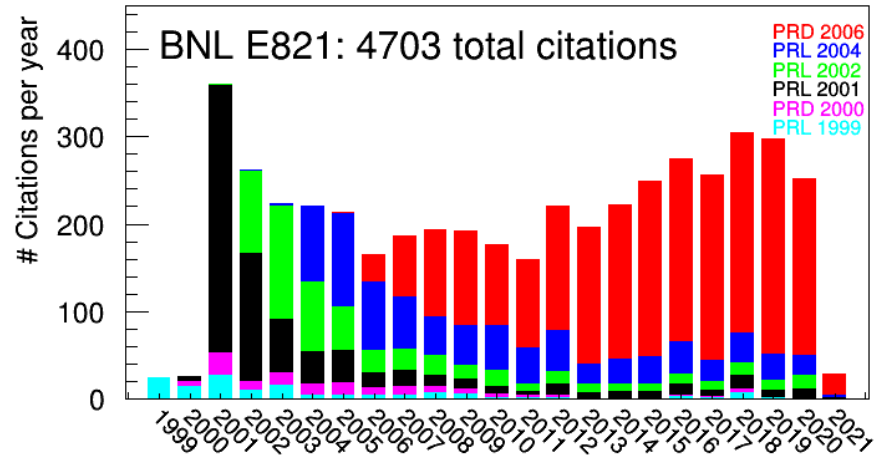
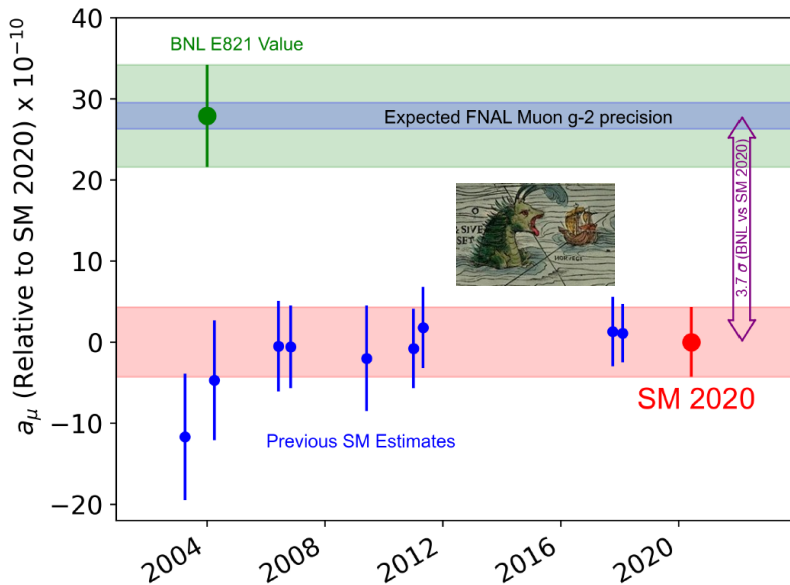
Monsters yet to be imagined!



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 $\sim 27 \times 10^{-10}$ in a_μ

Bringing g-2 to Fermilab

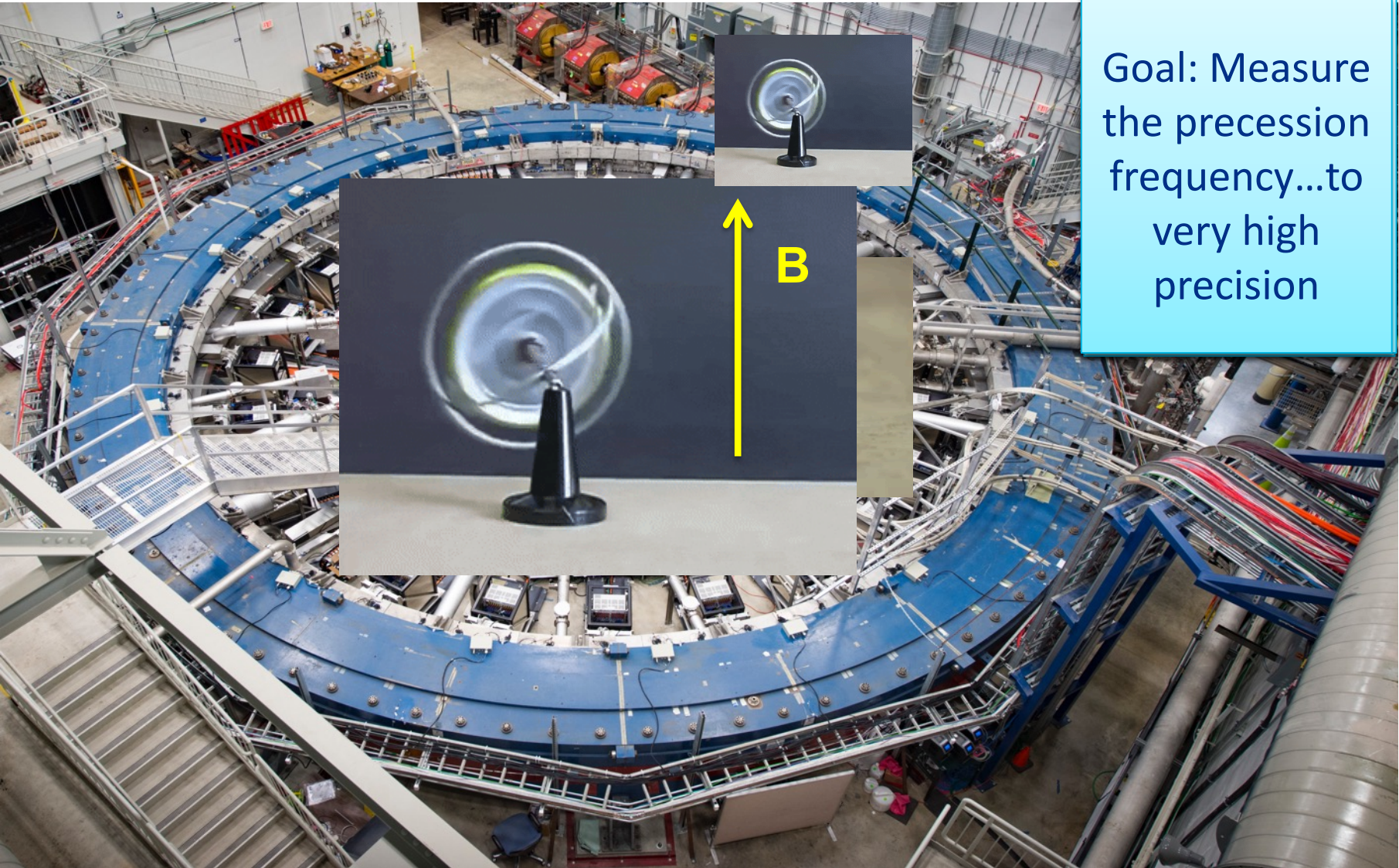
- Goal: Bring the container used to hold the muons from BNL and couple it to Fermilab's powerful accelerator beam
- Reduce the overall error by a factor of 4 to 140 ppb
 - 20x the muons → reduce statistical error from 460 to 100 ppb
 - control systematics at the same 100 ppb level (3x better)

Brookhaven Muon Storage Ring



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

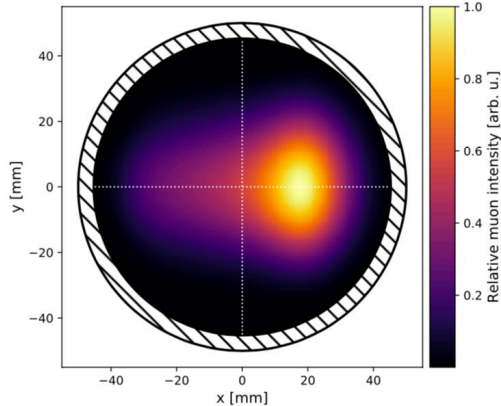
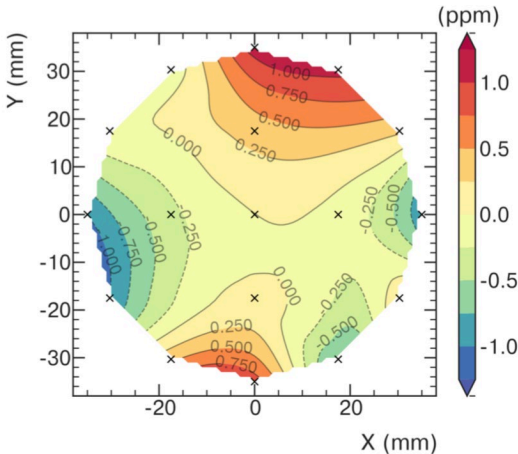
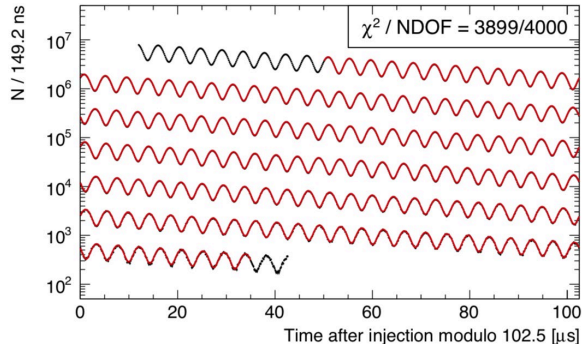
All put back together at Fermilab!



Goal: Measure the precession frequency...to very high precision

The analysis 'big' picture

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



*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/°C
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

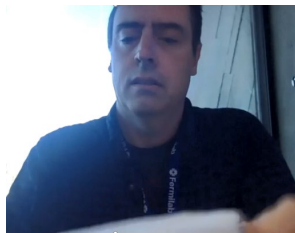
Run-1 Estimate:
 $B_k = -27.4 \pm 37$ ppb

Dataset	correction [ppb]				uncertainty [ppb]			
	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



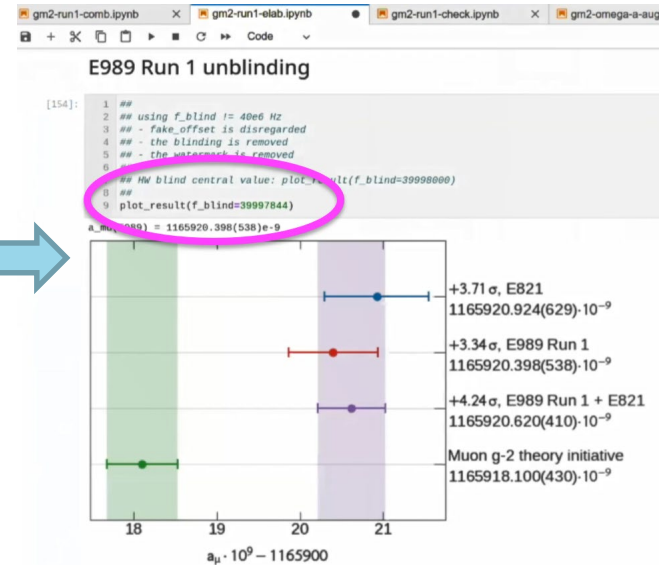
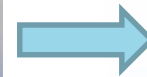
UW envelope



FNAL envelope

g-2 blinding numbers
 2999 8956
 3999 7844

Same numbers!



Four articles on arXiv and published in Phys Rev

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

PRAB

Beam dynamics

T. Albahri,³⁰ A. Anastasi,¹⁰ K. Badgley,⁷ S. Baeßler,^{36, a} I. Bailey,^{17, b} V. A. Baranov,¹⁵ E. Barlas-Yucel,²⁸ T. Barrett,⁶ F. Bedeschi,¹⁰ T. Bowcock,³⁰ G. Cantatore,¹³ A. Chapelain,⁶ S. Charity,⁷ J. D. Crnkovic,³⁴ S. Dabaja,¹⁰ A. Driutti,^{26, 29} V. N. Duginin,¹⁰ A. Fiedler,²⁰ A. T. Fiedler,¹⁰ C. Gabbanini,^{10, h} M. D. Gale,¹⁰ K. L. Giovanetti,¹³ P. G. Heffernan,¹⁰ S. Haciomeroglu,⁵ T. Hertzog,³⁷ G. Heslop,¹⁰ M. Iacovacci,^{9, k} M. Incagli,¹⁰ L. Kelton,²⁹ A. Keshavarzi,¹⁰ B. Kiburz,⁷ O. Kim,¹⁵ K. R. Kim,¹⁵ L. Li,^{22, e} I. Logashenko,^{4, g} B. MacCoy,³⁷ R. Madhavan,¹⁰ W. M. Morse,³ J. Mott,^{2, 7} G. M. Piacentino,^{25, p} B. Quinn,³⁴ N. Raha,¹⁰ S. Raha,¹⁰ L. Santi,^{26, d} D. Sathyanarayanan,¹⁰ M. Sorbara,^{11, q} D. Stöckinger,²⁸ G. Sweetmore,³¹ D. A. Swartz,¹⁰ K. Thomson,³⁰ V. Tishchenko,¹⁰ G. Venanzoni,¹⁰ T. Walton

Magnetic Field Measurement and Analysis for the Muon $g-2$ Experiment at Fermilab

PRA

Proton precession

T. Albahri,³⁹ A. Anastasi,^{11, a} K. Badgley,⁷ S. Baeßler,^{47, b} I. Bailey,^{19, c} V. A. Baranov,¹⁷ E. Barlas-Yucel,³⁷ T. Barrett,⁶ F. Bedeschi,¹¹ M. Berz,²⁰ M. Bhattacharya,⁴³ H. P. Binney,⁴⁸ P. Bloom,²¹ J. Bono,⁷ E. Bottalico,^{11, 32} T. Bowcock,³⁹ G. Cantatore,¹³ A. Chapelain,⁶ S. Charity,⁷ L. Cotrozzi,^{11, 32} J. D. Crnkovic,³⁷ R. Di Stefano,^{10, 30} A. Driutti,¹⁰ C. Ferrari,^{11, 14} M. Fertl,¹⁰ C. Gabbanini,^{11, 14} M. D. Gale,¹⁰ K. L. Giovanetti,¹⁵ P. G. Heffernan,¹⁰ S. Haciomeroglu,⁵ T. Hertzog,³⁷ A. Keshavarzi,¹⁰ D. W. Hertzog,⁴⁸ G. Heslop,¹⁰ M. Iacovacci,^{10, 31} M. Incagli,¹⁰ L. Kelton,³⁸ A. Keshavarzi,¹⁰ B. Kiburz,⁷ M. Kiburz,^{7, 21} O. Kim,¹⁵ K. R. Labe,⁶ J. LaBour,¹⁰ I. Logashenko,^{4, g} A. Lorente,¹⁰ R. Madrak,⁷ K. Makino,²⁰ J. Mott,^{2, 7} A. Nath,^{10, 31} R. N. Pilato,^{11, 32} K. T. Pitts,³⁷ N. Raha,¹¹ S. Ramachandran,¹ C. Schlesier,³⁷ A. Schreyer,¹⁰ M. Sorbara,^{12, 33} D. Stöckinger,²⁸ G. Sweetmore,⁴⁰ D. A. Swartz,¹⁰ K. Thomson,³⁹ V. Tishchenko,¹⁰ G. Venanzoni,¹¹ T. Walton

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

PRD

Muon precession

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Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

PRL

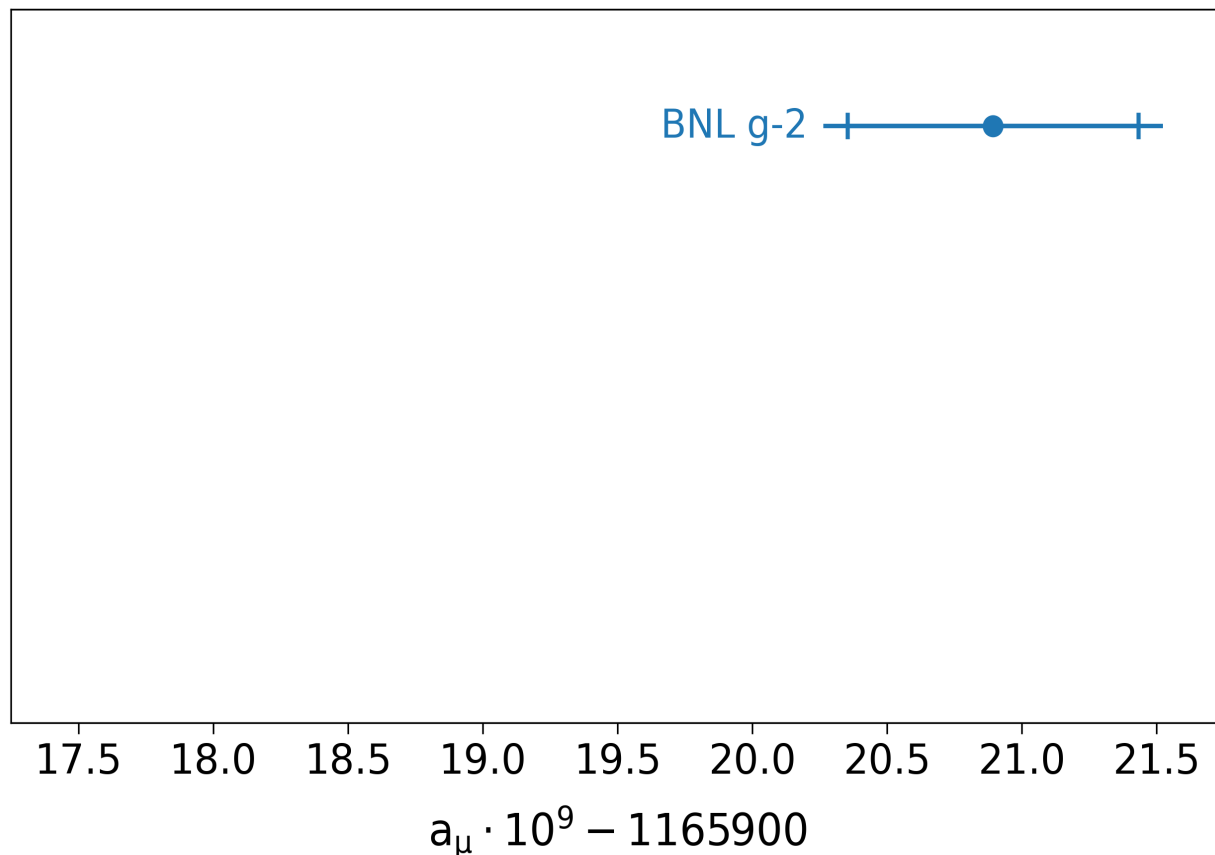
B. Abi,⁴⁴ T. Albahri,³⁹ S. Al-Kilani,³⁶ D. Allspach,⁷ L. P. Alonzi,⁴⁸ A. Anastasi,^{11, a} A. Anisenkov,^{4, b} F. Azfar,⁴⁴ K. Badgley,⁷ S. Baeßler,^{47, c} I. Bailey,^{19, d} V. A. Baranov,¹⁷ E. Barlas-Yucel,³⁷ T. Barrett,⁶ E. Barzi,^{11, 32} F. Bedeschi,¹¹ A. Behnke,²² M. Berz,²⁰ M. Bhattacharya,⁴³ H. P. Binney,⁴⁸ R. Bjorkquist,⁶ P. Bloom,²¹ J. Bono,⁷ E. Bottalico,^{11, 32} T. Bowcock,³⁹ D. Boyden,²² G. Cantatore,^{13, 34} R. M. Carey,² J. Carroll,³⁹ B. C. K. Casey,⁷ D. Cauz,^{35, 8} S. Ceravolo,⁹ R. Chakraborty,³⁸ S. P. Chang,^{18, 5} A. Chapelain,⁶ S. Chappa,⁷ S. Charity,⁷ R. Chislett,⁶ J. Choi,⁵ Z. Chu,^{26, e} T. E. Chupp,⁴² M. E. Convery,⁷ A. Conway,⁴¹ G. Corradi,¹ L. Cotrozzi,^{11, 32} J. D. Crnkovic,^{3, 37, 43} S. Dabagov,^{9, f} P. M. De Lurgio,¹ P. T. Debevec,³⁷ S. Di Falco,¹¹ P. Di Meo,¹⁰ G. Di Sciascio,¹² R. Di Stefano,^{10, 30} B. Drendel,⁷ A. Driutti,^{35, 13, 38} V. N. Duginin,¹⁷ M. Eads,²² N. Eggert,⁶ A. Epps,²² J. Esquivel,⁷ M. Farooq,⁴² R. Fatemi,³⁸ C. Ferrai,¹⁰ M. Fertl,¹⁰ A. Fiedler,²² A. T. Fienberg,⁴⁸ A. Fioretti,^{11, 14} D. Flay,⁴¹ S. B. Foster,² H. Friedsam,⁷ E. Frlež,⁴⁷ N. S. Froemming,^{48, 22} J. Fry,⁴⁷ C. Fu,^{26, e} C. Gabbanini,^{11, 14} M. D. Galati,^{11, 32} S. Ganguly,^{37, 7} A. Garcia,⁴⁸ D. E. Gastler,² J. George,⁴¹ L. K. Gibbons,⁶ A. Gioiosa,^{29, 11} K. L. Giovanetti,¹⁵ P. Girotti,^{11, 32} W. Gohn,³⁸ T. Gorringer,³⁸ J. Grange,^{1, 42} S. Grant,³⁶ F. Gray,²⁴ S. Haciomeroglu,⁵ D. Hahn,⁷ T. Halewood-Leagas,³⁹ D. Hampai,⁹ F. Han,³⁸ E. Hazen,² J. Hempstead,⁴⁸ S. Henry,⁴⁴ A. T. Herrod,^{39, d} D. W. Hertzog,⁴⁸ G. Heslop,¹⁰ A. Hibbert,³⁹ Z. Hodge,⁴⁸ J. L. Holzbauer,⁴³ K. W. Hong,⁴⁷ R. Hong,^{1, 38} M. Iacovacci,^{10, 31} M. Incagli,¹¹ C. Johnstone,⁷ J. A. Johnstone,⁷ P. Kammel,⁴⁸ M. Kargiantoulakis,⁷ M. Karuza,^{13, 45} J. Kaspar,⁴⁸ D. Kawall,⁴¹ L. Kelton,³⁸ A. Keshavarzi,⁴⁰ D. Kessler,⁴¹ K. S. Khaw,^{27, 26, 48, e} Z. Khechadorian,⁶ N. V. Khomutov,¹⁷ B. Kiburz,⁷ M. Kiburz,^{7, 21} O. Kim,^{18, 5} S. C. Kim,⁶ Y. I. Kim,⁵ B. King,^{39, a} N. Kinnaird,² M. Korostelev,^{19, d} I. Kourbanis,⁷ E. Kraegeloh,⁴² V. A. Krylov,¹⁷ A. Kuchibhotla,³⁷ N. A. Kuchinskiy,¹⁷ K. R. Labe,⁶ J. LaBounty,⁴⁸ M. Lancaster,⁴⁰ M. J. Lee,⁵ S. Lee,⁵ S. Leo,³⁷ B. Li,^{26, 1, e} D. Li,^{26, g} L. Li,^{26, e} I. Logashenko,^{4, b} A. Lorente Campos,³⁸ A. Lucà,⁷ G. Lukicov,³⁶ G. Luo,²² A. Lusiani,^{11, 25} A. L. Lyon,⁷ B. MacCoy,⁴⁸ R. Madrak,⁷ K. Makino,²⁰ F. Marignetti,^{10, 30} S. Mastroianni,¹⁰ S. Maxfield,³⁹ M. McEvoy,²² W. Merritt,⁷ A. A. Mikhailichenko,^{6, a} J. P. Miller,² S. Miozzi,¹² J. P. Morgan,⁷ W. M. Morse,³ J. Mott,^{2, 7} E. Motuk,³⁶ A. Nath,^{10, 31} D. Newton,^{39, h} H. Nguyen,⁷ M. Oberling,¹ R. Osofsky,⁴⁸ J.-F. Ostiguy,⁷ S. Park,⁵ G. Pauletta,^{35, 8} G. M. Piacentino,^{29, 12} R. N. Pilato,^{11, 32} K. T. Pitts,³⁷ B. Plaster,³⁸ D. Počanić,⁴⁷ N. Pohlman,²² C. C. Polly,⁷ M. Popovic,⁷ J. Price,³⁹ B. Quinn,⁴³ N. Raha,¹¹ S. Ramachandran,¹ E. Ramberg,⁷ N. T. Rider,⁶ J. L. Ritchie,⁴⁶ B. L. Roberts,² D. L. Rubin,⁶ L. Santi,^{35, 8} D. Sathyanarayanan,² H. Schellman,^{23, i} C. Schlesier,³⁷ A. Schreckenberger,^{46, 2, 37} Y. K. Semertzidis,^{5, 18} Y. M. Shatunov,⁴ D. Shemyakin,^{4, b} M. Shenk,²² D. Sim,³⁹ M. W. Smith,^{48, 11} A. Smith,³⁹ A. K. Soha,⁷ M. Sorbara,^{12, 33} D. Stöckinger,²⁸ J. Stapleton,⁷ D. Still,⁷ C. Stoughton,⁷ D. Stratakis,⁷ C. Strohmman,⁶ T. Stuttard,³⁶ H. E. Swanson,⁴⁸ G. Sweetmore,⁴⁰ D. A. Swartz,⁶ M. J. Syphers,^{22, 7} D. A. Tarazona,²⁰ T. Teubner,³⁹ A. E. Tewsley-Booth,⁴² K. Thomson,³⁹ V. Tishchenko,³ N. H. Tran,² W. Turner,³⁹ E. Valetov,^{20, 19, 27, d} D. Vasilkova,³⁶ G. Venanzoni,¹¹ V. P. Volnykh,¹⁷ T. Walton,⁷ M. Warren,³⁶ A. Weisskopf,²⁰ L. Welty-Rieger,⁷ M. Whitley,³⁹ P. Winter,¹ A. Wolski,^{39, d} M. Wormald,³⁹ W. Wu,⁴³ and C. Yoshikawa⁷

(The Muon $g-2$ Collaboration)

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

Run 1 result

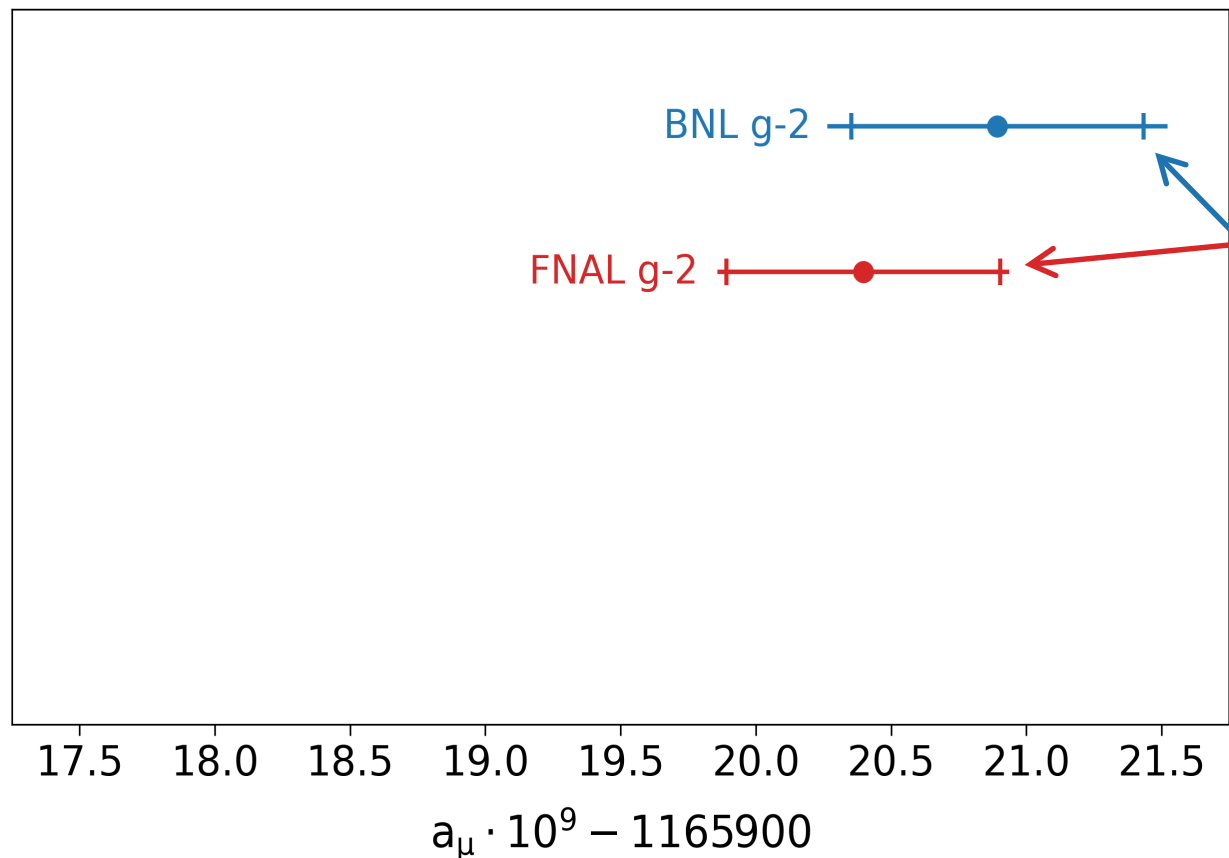
$$a_\mu(\text{BNL}) = 0.00116592089(63) \rightarrow 540 \text{ ppb}$$



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

Run 1 result

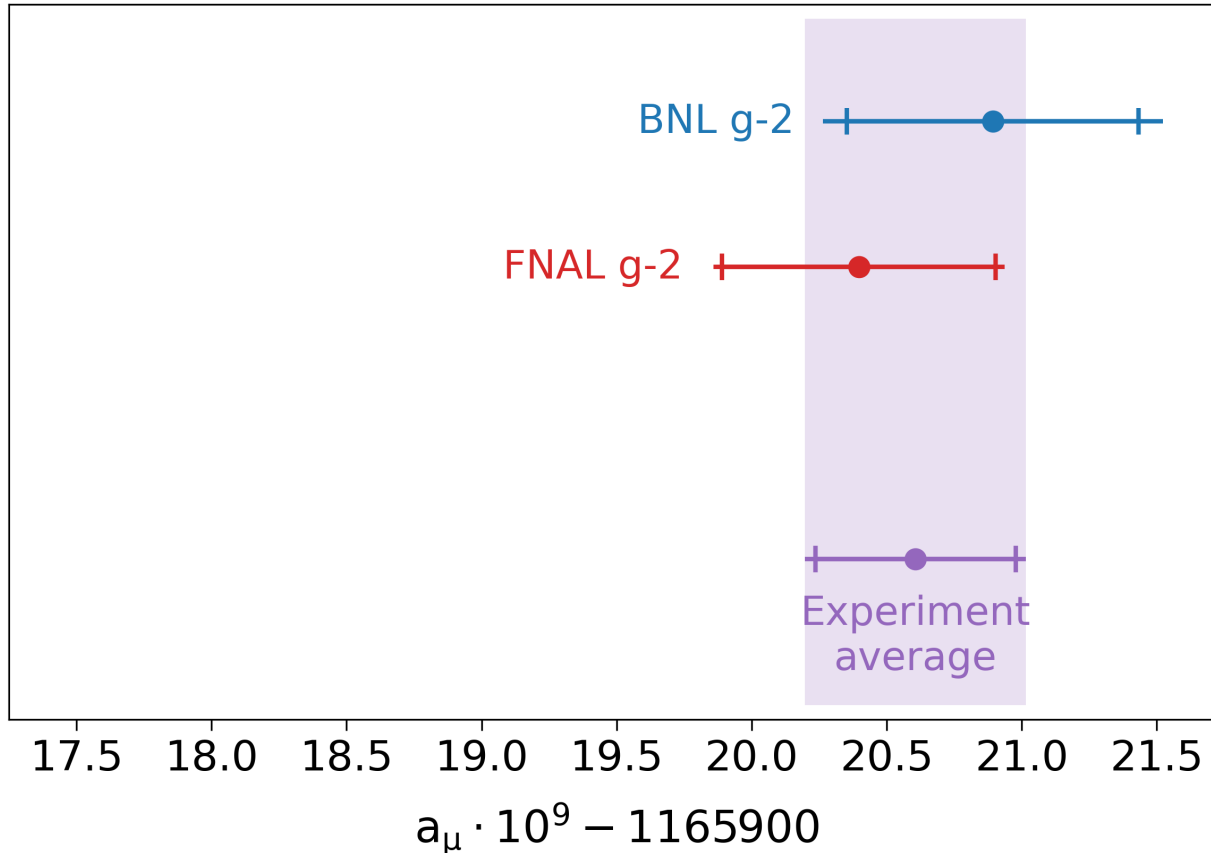
$$a_\mu(\text{FNAL g-2; Run 1}) = 0.00116592040(54) \rightarrow 463 \text{ ppb}$$



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

Experimental combination

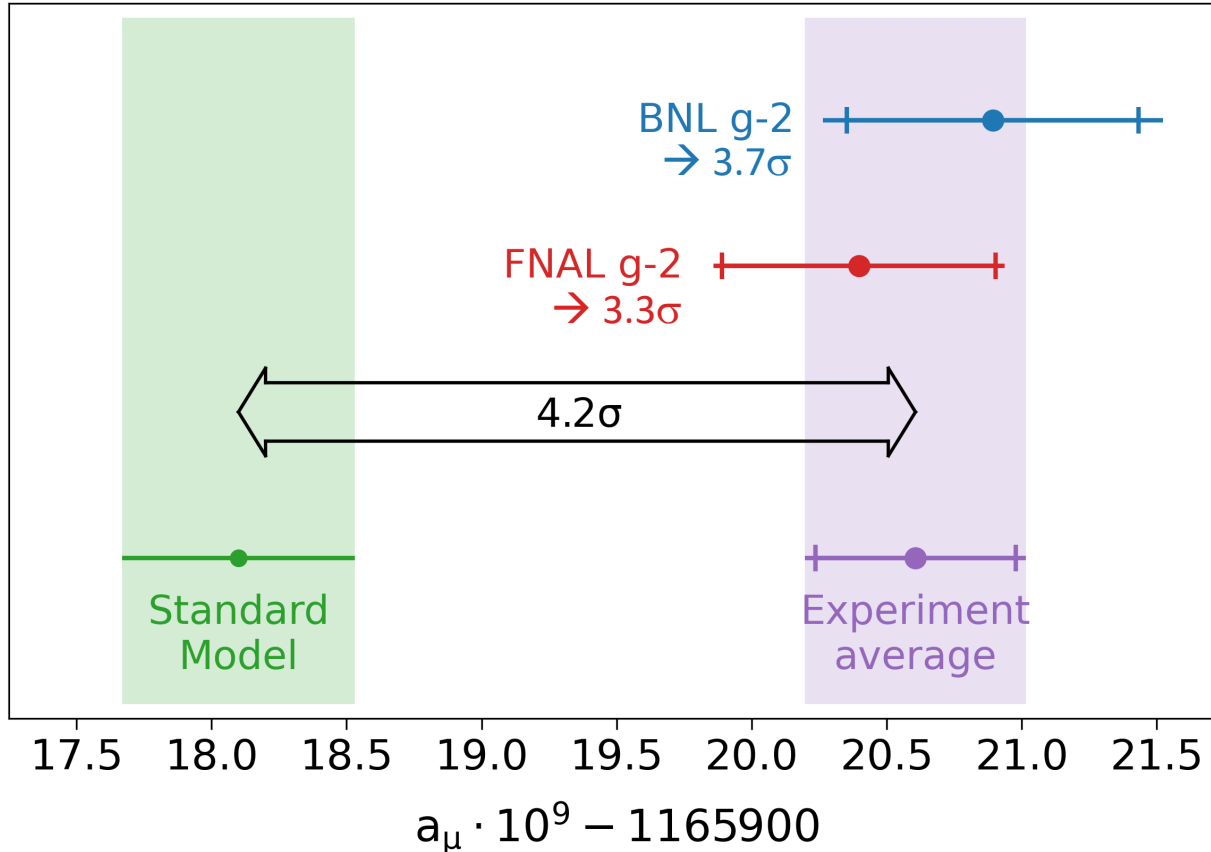
$$a_\mu(\text{Exp}) = 0.00116592061(41) \rightarrow 350 \text{ ppb}$$



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

Comparison to SM prediction

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



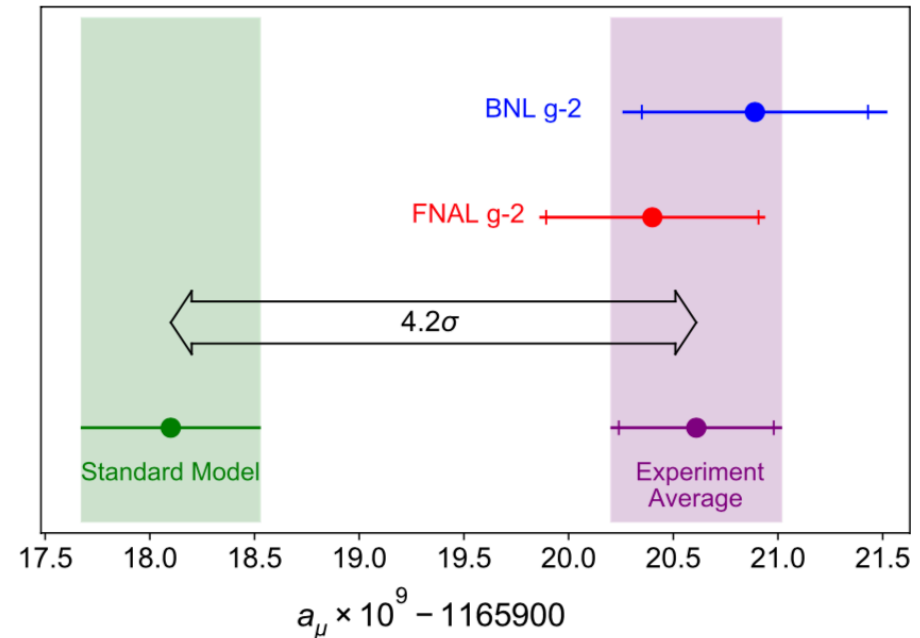
- Individual tension with SM
 - BNL: 3.7σ
 - FNAL: 3.3σ

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

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
 - 3.3 σ tension with SM

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



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



Biden Tax Plan Aims to Curtail

Contagious Variant Is Fueling Surge in Infections Across the U.S.

PAIR OF SETBACKS

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 supporters. *Continued on Page A11*

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 *Continued on Page A16*

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

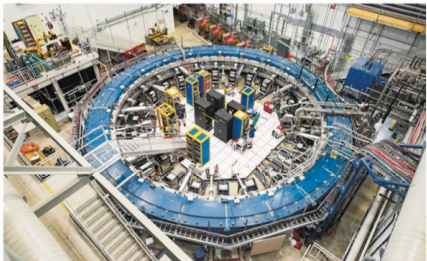
Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday. A finding that would open a vast and tantalizing hole in our understanding of the universe.

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 enunciates the fundamental



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

particles in the universe (7, 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 Fabelo, a physicist at the University of Kentucky.

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 sag 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 ragged 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. Sit at *Continued on Page A17*



A trail in the Wind River Range in western Wyoming.

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.

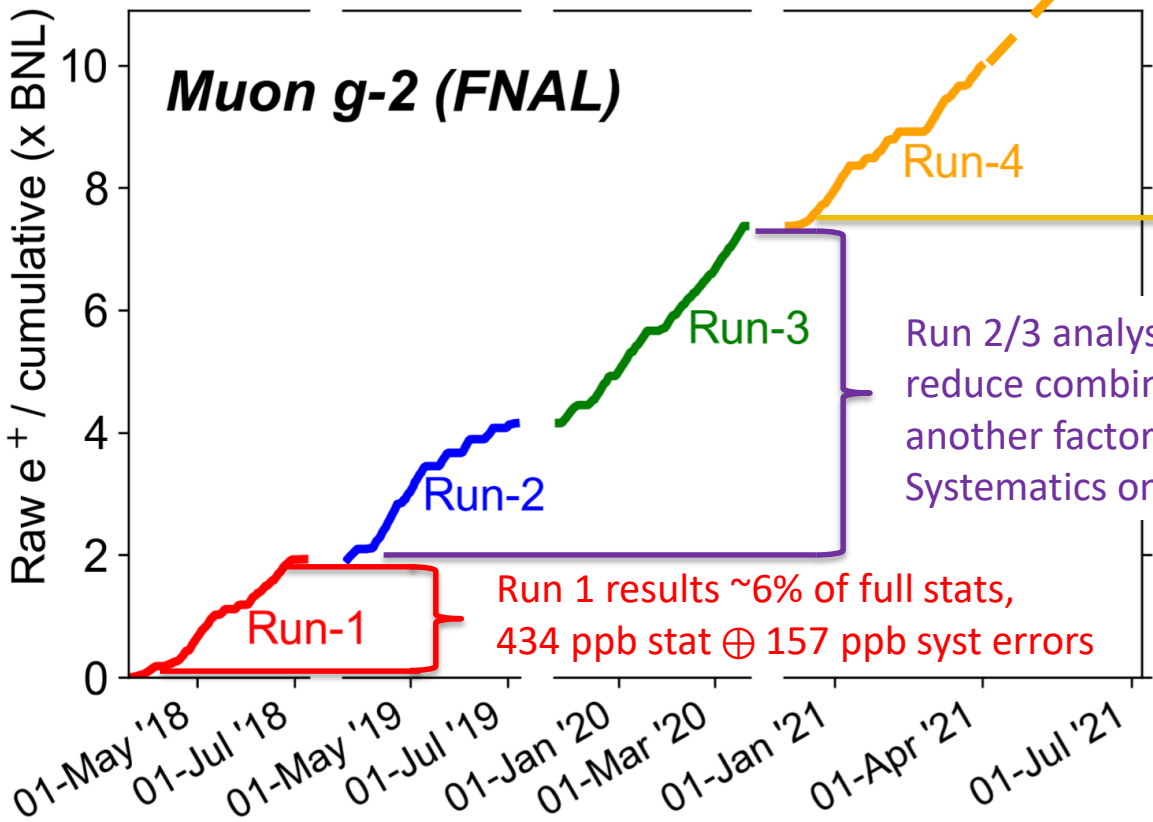


Outlook

Much more data to come!

Last update: 2021-03-31 12:27 ; Total = 9.98 (xBNL)

Muon g-2 (FNAL)

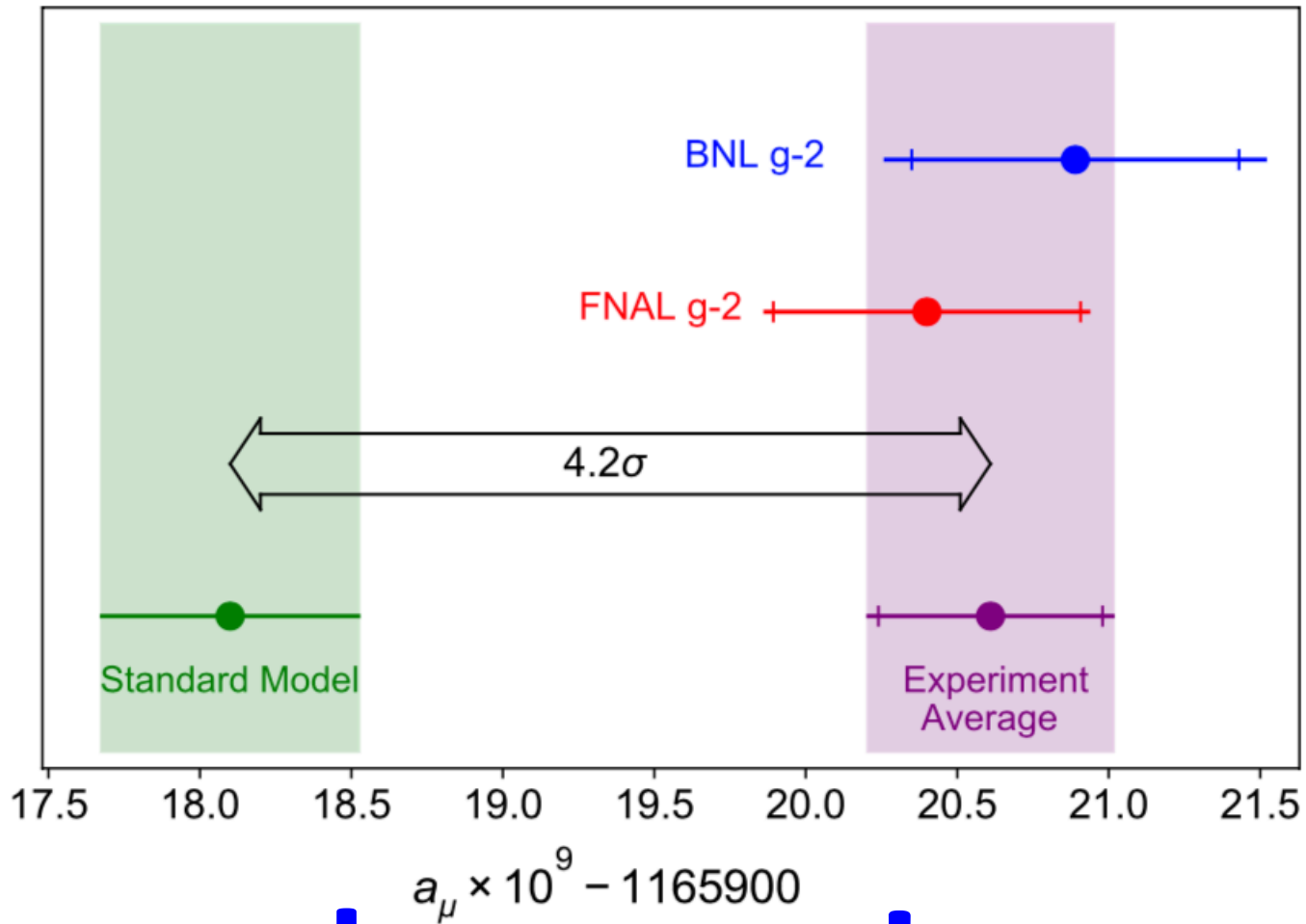


Run 1 results ~6% of full stats,
434 ppb stat \oplus 157 ppb syst errors

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





Thank you!