FERMILAB MUON $g-2$:

FROM a_μ TO g

A.P. Schreckenberger [on behalf of the Muon g-2 Collaboration]

Planck 2021

Acknowledgments
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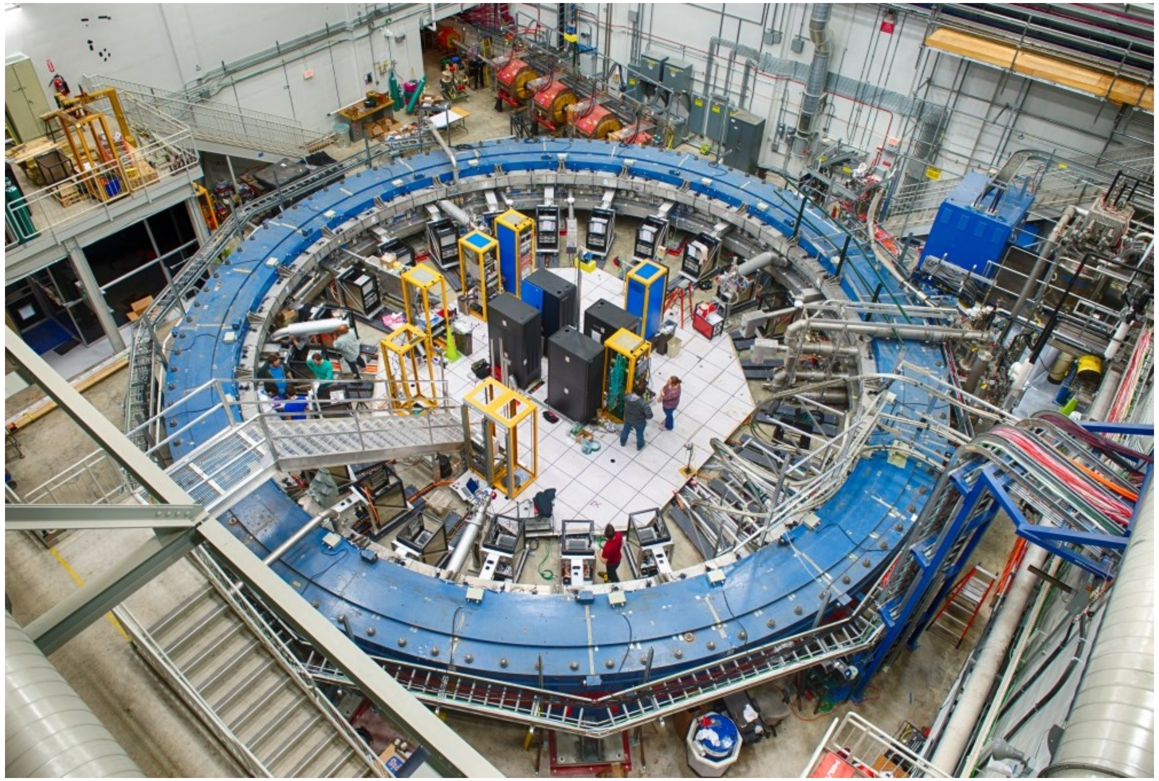
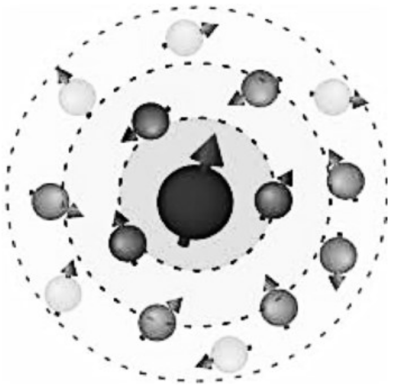
German Research Foundation (DFG)

TO PEEK BEYOND

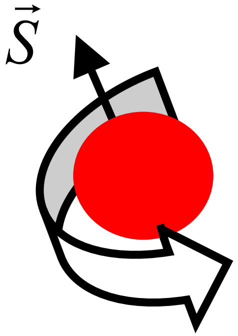
- **Standard Model does a lot…**
  - Predictions of interactions, masses, experiment observables
- **Still some unanswered questions**
  - Matter-antimatter asymmetry
  - Presence of dark matter
  - Mass and strength hierarchy
  - *A bunch of anomalies*
- **Muon g-2 indirect new physics search**
  - Virtual particles + behavior of muons



THROUGH WHICH EYES?



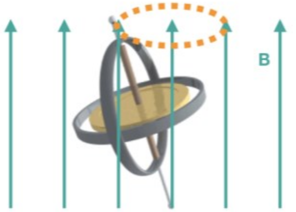
- Muon's magnetic moment is used as the handle to search for potential new physics
  - Relation between moment and spin through g-factor



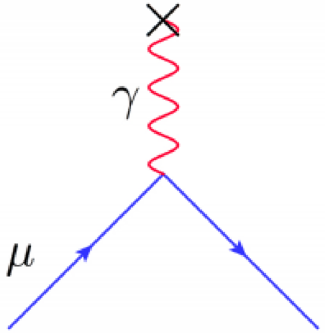
$$\vec{\mu} = g\,\frac{q}{2m}\vec{S}$$

  - g also tells us the precession rate of the spin vector in a magnetic field

$$\omega_{spin} = g\,\frac{eB}{2m}$$



  - For Dirac point-like particle, $g = 2$
    - **And if nature only cared about one Feynman diagram…**



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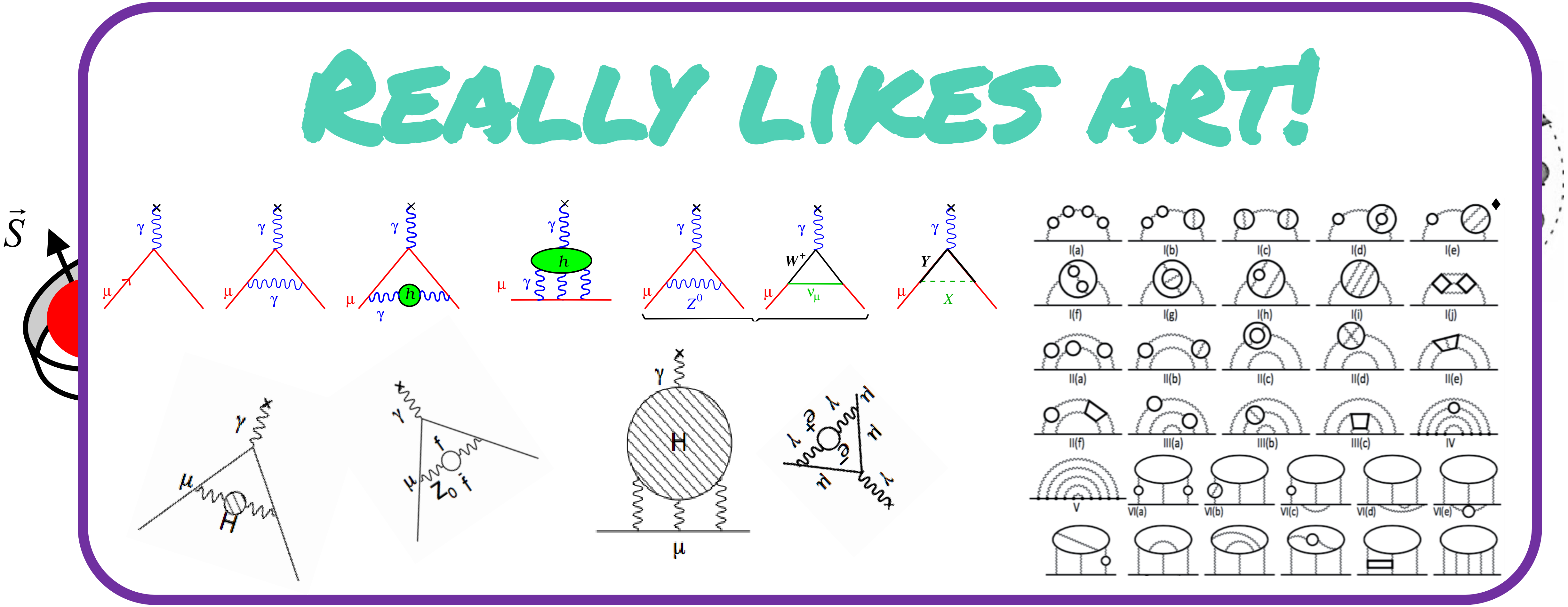
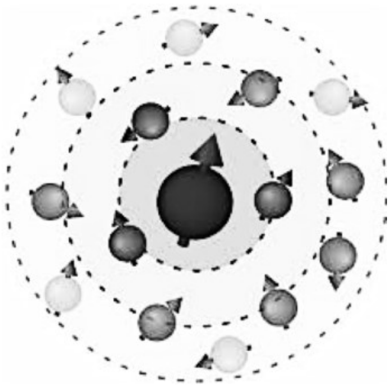
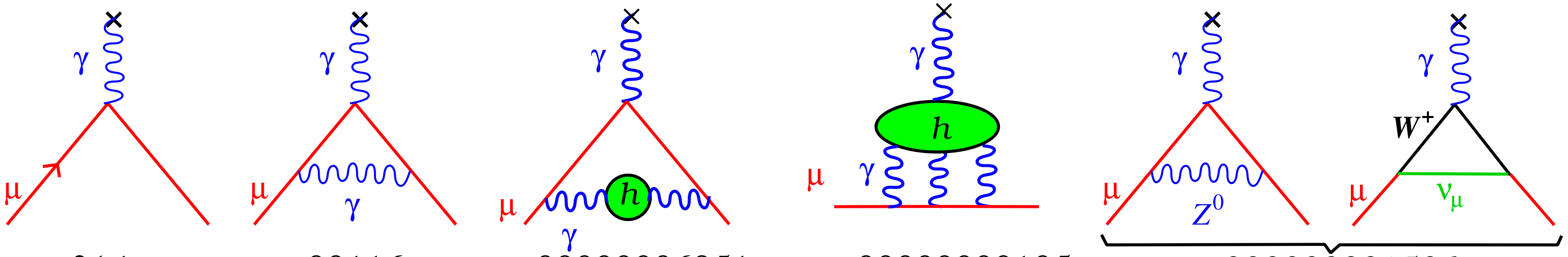


♦T. Aoyama et al., Phys. Rev. Lett. **109**, 111807 (2012)

THROUGH WHICH EYES?

- **For Dirac point-like particle, $g = 2$**
  - *Radiative corrections* from fundamental forces increase value of g





$$g = 2(\,1 \quad + .00116\ldots \quad + .00000006951\ldots + .00000000105\ldots \quad + .000000001536$$

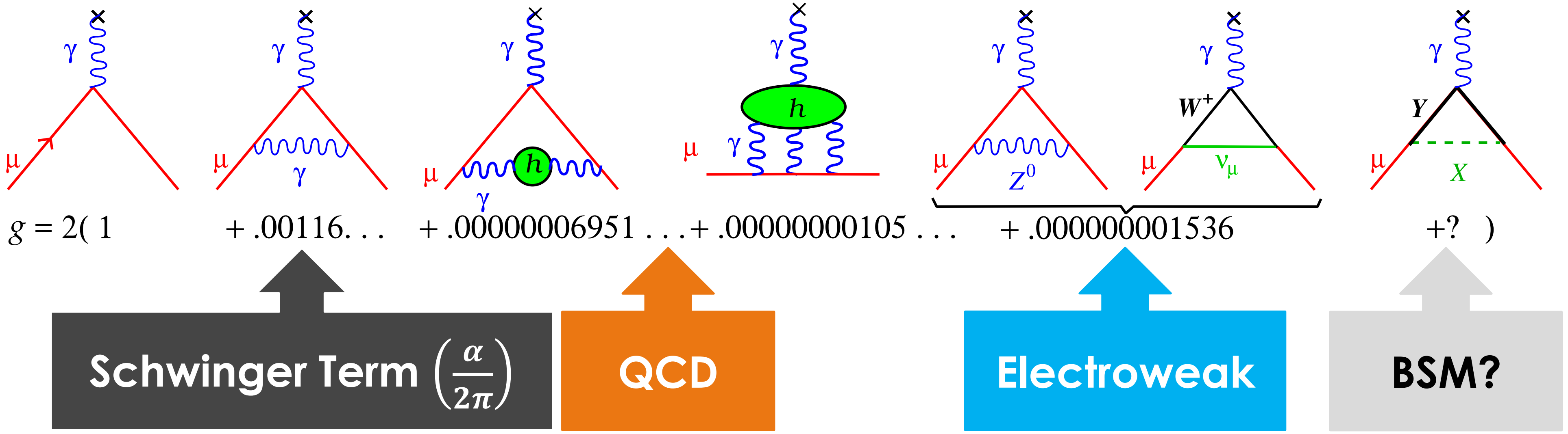
Schwinger Term $\left(\frac{\alpha}{2\pi}\right)$

QCD

Electroweak

- Standard Model predicts g > 2, so what gives?

DEFINING AN ANOMALY



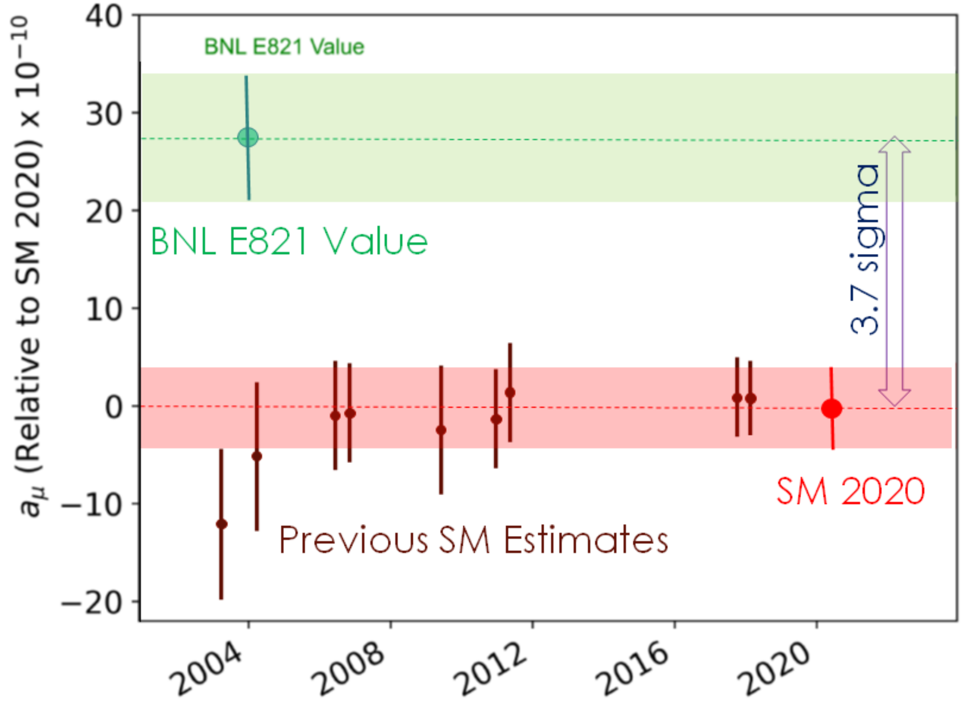
- **Indicator for potential unknown processes**
  - **Define the anomaly (a_μ), which tells us the fractional difference between exciting things and a Boring Universe**
  - **Anomaly is the parameter of interest for the Muon g-2 Experiment**

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

REWIND TO MARCH 2021

- **QED contributes most to anomaly, least to uncertainty**
- **Hadronic terms bring most uncertainty – QCD is non-perturbative**
- **Hints from tension between Brookhaven (BNL) result and theory**

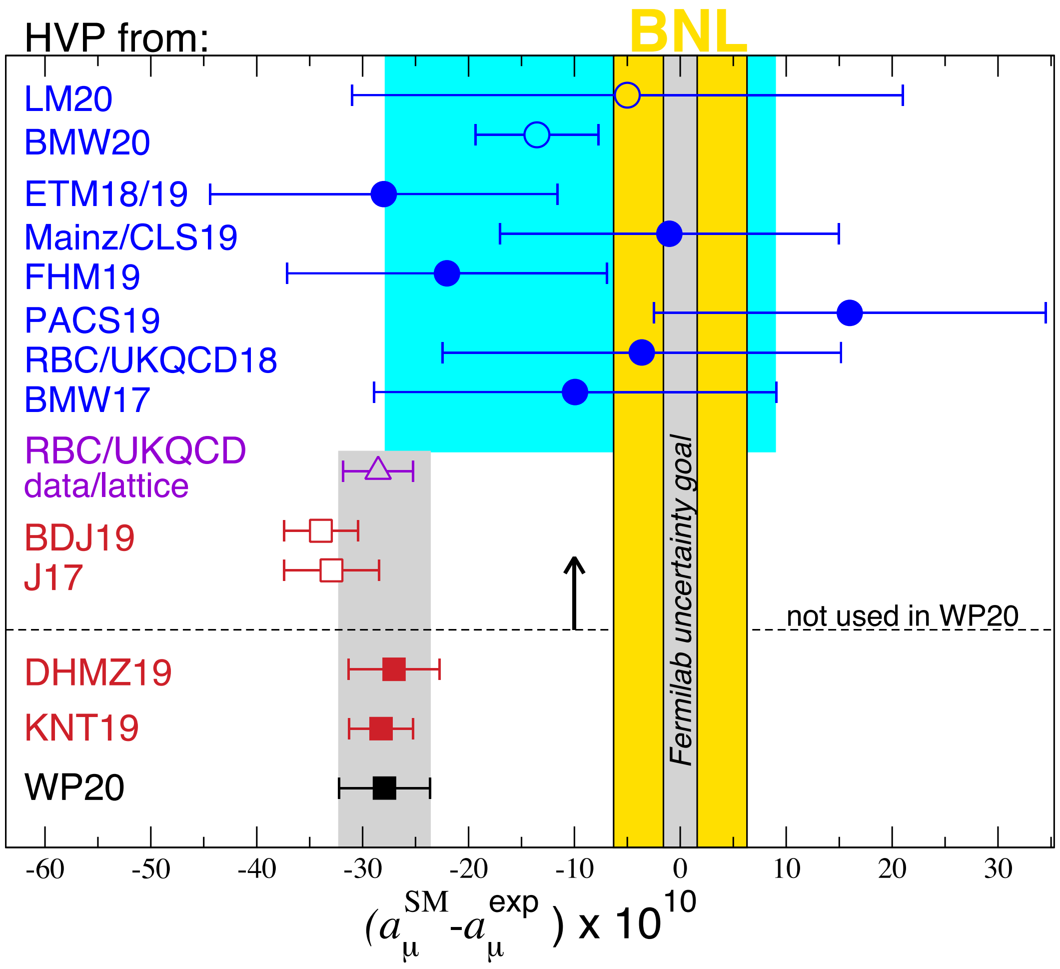
$$\boldsymbol{a_\mu = \frac{g_\mu - 2}{2}}$$

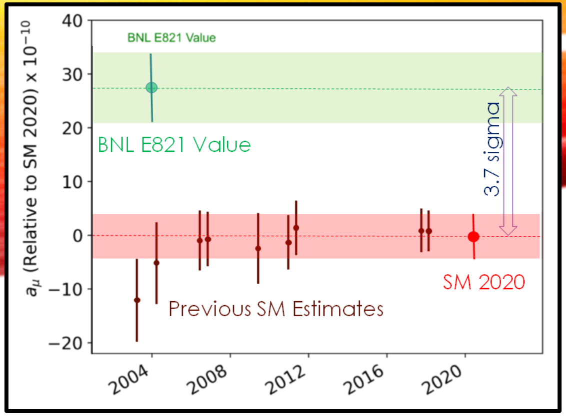


CONTRIBUTION	VALUE $\times 10^{11}$
Experiment (Final BNL)	116 592 089. (63)
QED	116 584 718.931(104)
Electroweak	153.6 (1)
HVP (e^+e^-, LO + NLO + NNLO)	6845. (40)
HLbL (pheno. + lattice + NLO)	92. (18)
Total Standard Model (SM) Value	116 591 810. (43)
Difference: a_μ(Final BNL) − a_μ(SM)	279. (76)

BRIEF THEORETICAL ASIDE

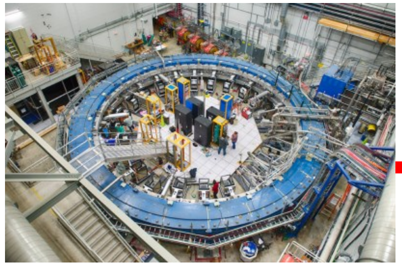
- **Collaboration compares result to WP20 prediction value**
  - From Muon g-2 Theory Initiative
    - Group continues to update its result
  - BMW20 Lattice QCD calculation is first lattice result with sub-percent precision
    - Potential decrease in tension with experiment
    - Still being discussed in theory community
- **Focus on explaining the experiment**

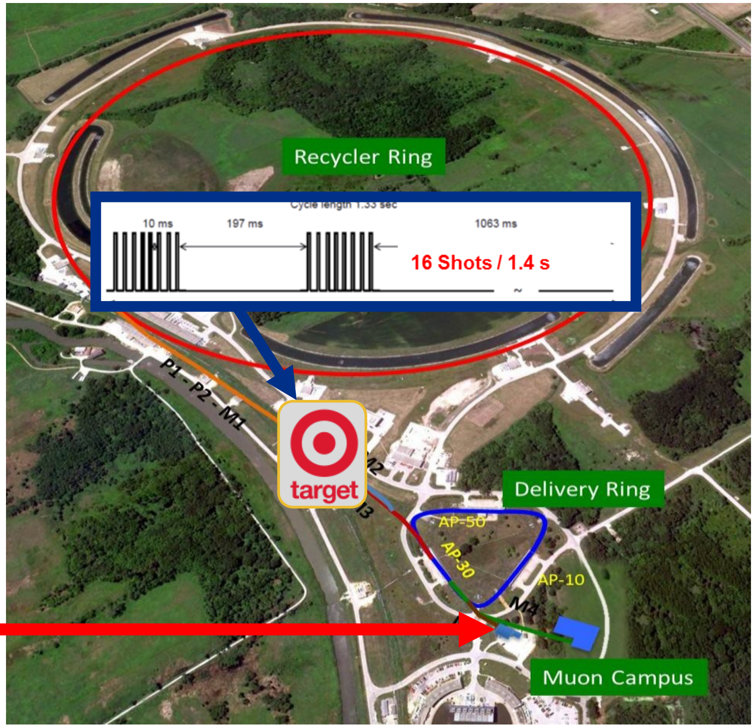




BUILDING AT FERMILAB

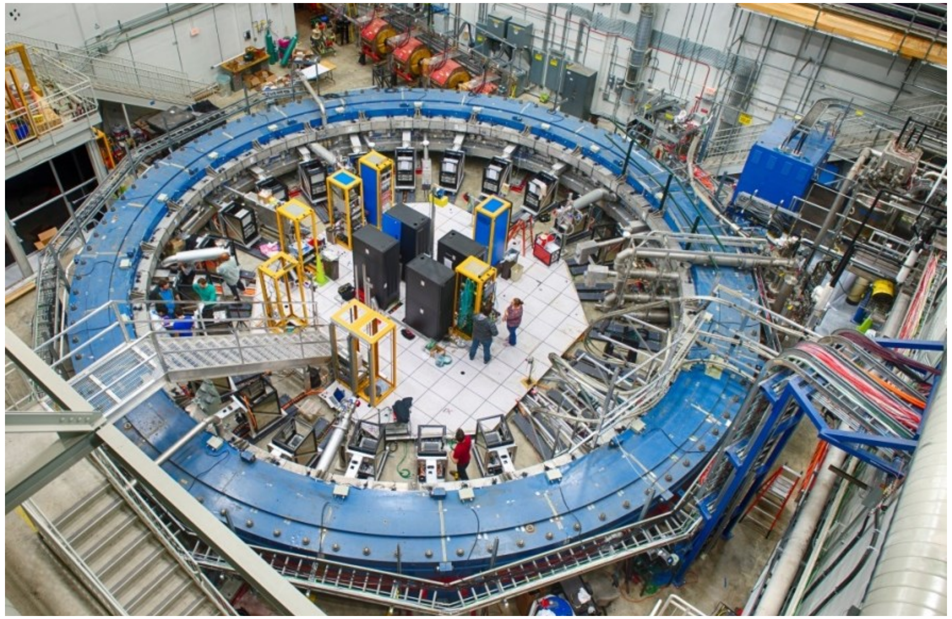
- **Physicists love tension… finding it… resolving it…**
  - The Universe is the most imaginative thing in the room. How imaginative is it?
- **After ~20 years, Fermilab Muon g-2 formed to try to answer the underlying questions from BNL**
  - Fermilab experiment aims to make 140 ppb measurement
- **Why the move? Lots of muons!**
  - 8 GeV protons extracted from Recycler Ring
  - Sent incident on nickel-based target
  - Left with a highly polarized muon beam at the end of this beamline

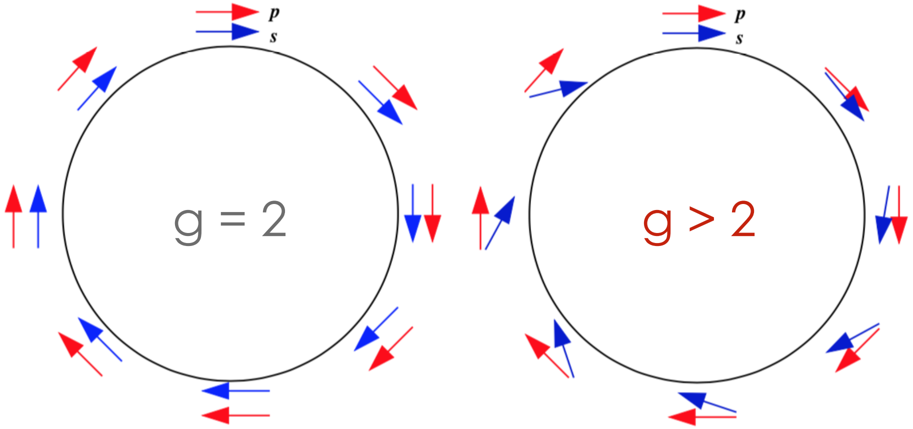




THE EXPERIMENTAL PRINCIPLE

- Storage ring provides 1.45T field
- Physics ensnared in mismatch between cyclotron and spin precession frequencies
  - $\vec{\omega}_C = -\frac{q}{\gamma m}\vec{B}$
  - $\vec{\omega}_S = -\frac{q}{\gamma m}\vec{B}\left(1 + \gamma a_\mu\right)$
  - $\vec{\omega}_a \cong \vec{\omega}_S - \vec{\omega}_C = -\frac{q}{m} a_\mu \vec{B}$





A MAGIC MOMENTUM

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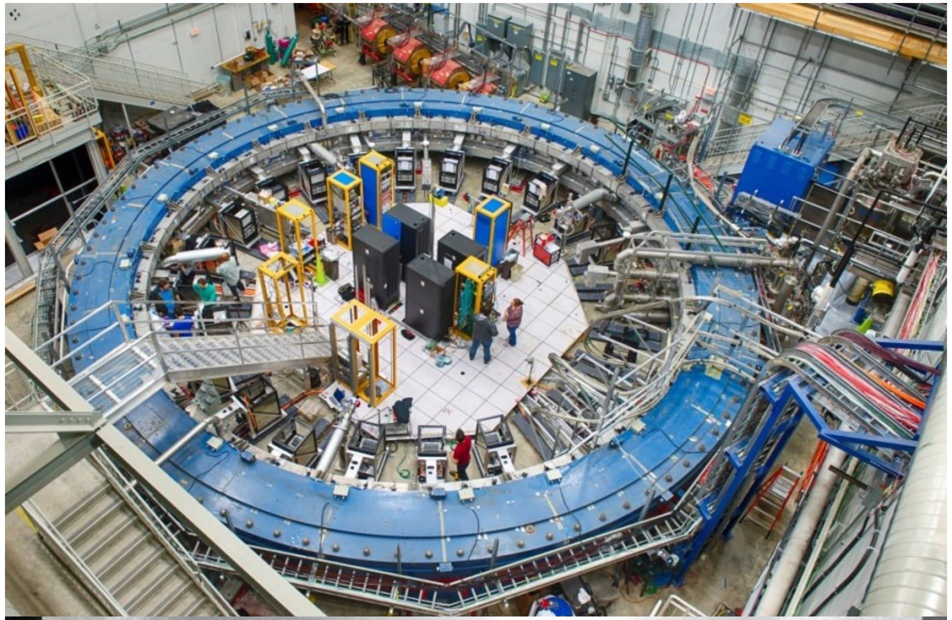
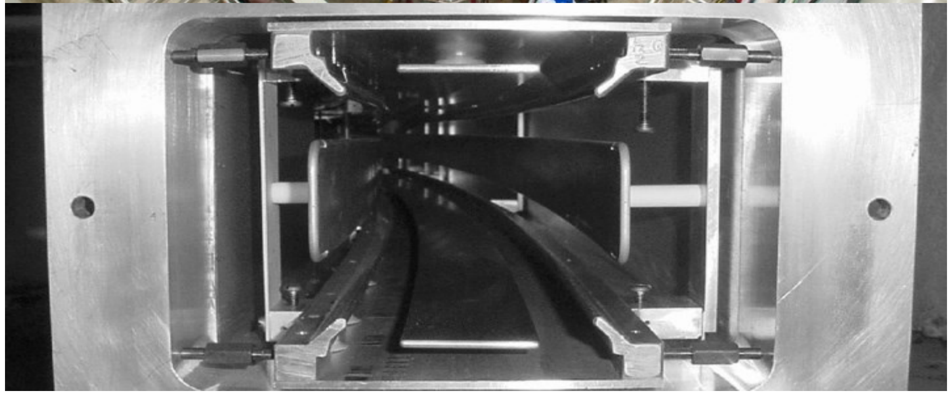
  - $\vec{\omega}_C = -\frac{q}{\gamma m}\vec{B}$
  - $\vec{\omega}_S = -\frac{q}{\gamma m}\vec{B}(1 + \gamma a_\mu)$
  - $\vec{\omega}_a \cong \vec{\omega}_S - \vec{\omega}_C = -\frac{q}{m} a_\mu \vec{B}$
- Ring field = horizontal focusing
- Electrostatic quadrupoles used for vertical
  - Muons observe magnetic field

$$\vec{\omega}_a \cong -\frac{q}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right)$$





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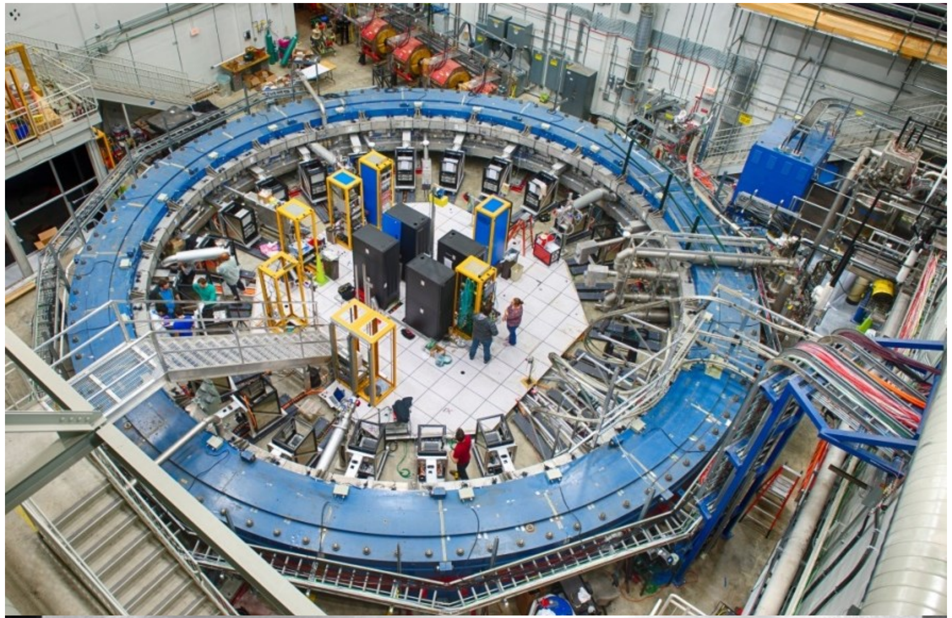
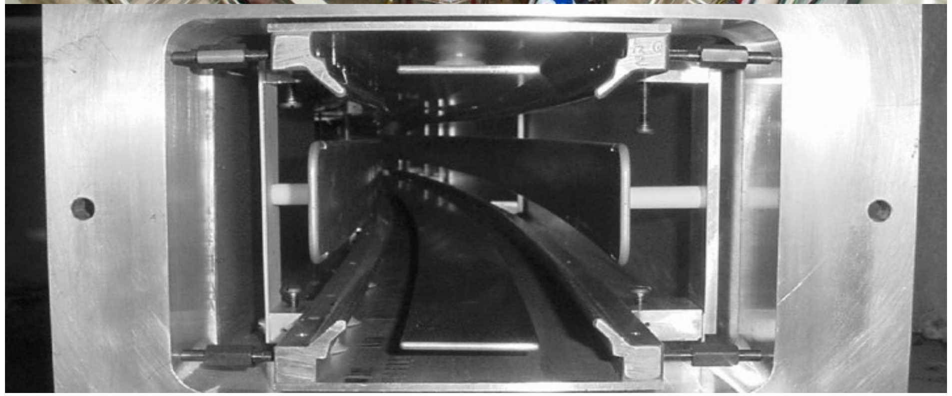
$\gamma \sim 29.3$





ADDED COMPLEXITY

- **"Magic Momentum" minimizes electric field correction**

$$\vec{\omega}_a \cong -\frac{q}{m}\left(a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right)$$

$\boldsymbol{\gamma \sim 29.3}$

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

- **Muon beam swims and breathes in both horizontal and vertical directions**
  - Pitch correction needed to address motion outside the ring plane
  - Beam dynamics effects become more pertinent to analysis

- **Lots of effects to consider, but eventually we reach a form for the anomaly…**

HOW WE TACKLE a_μ

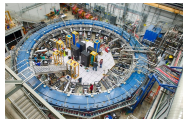
$$a_\mu(expt) = \frac{g_e}{2}\frac{m_\mu \mu_p}{m_e \mu_e}\frac{\omega_a}{\langle \omega_p \rangle} = \boxed{\frac{g_e}{2}\frac{m_\mu}{m_e}\frac{\mu_e(H)}{\mu_e}\frac{\mu'_p(T_r)}{\mu_e(H)}}\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$$

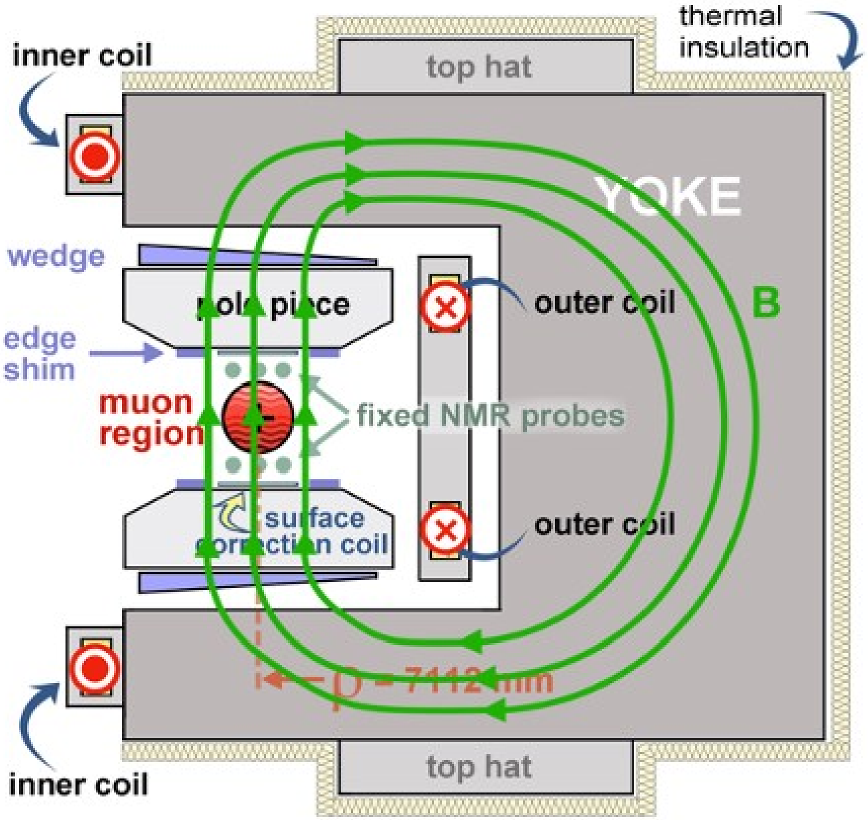
$\tilde{\omega}'_p(T)$	Proton Larmor precession frequency in a spherical water sample. Temperature dependence known to < 1ppb/°C. Metrologia **13**, 179 (1977), Metrologia **51**, 54 (2014), Metrologia **20**, 81 (1984)
$\frac{\mu_e(H)}{\mu'_p(T)}$	Measured to 10.5 ppb accuracy at T = 34.7°C Metrologia **13**, 179 (1977)
$\frac{\mu_e}{\mu_e(H)}$	Bound-state QED (exact) Rev. Mod. Phys. **88** 035009 (2016)
$\frac{m_\mu}{m_e}$	Known to 22 ppb from muonium hyperfine splitting Phys. Rev. Lett. **82**, 711 (1999)
$\frac{g_e}{2}$	Measured to 0.28 ppt Phys. Rev. A **83**, 052122 (2011)

- ω_a is the anomalous precession frequency
- $\tilde{\omega}'_p(T_r)$ is the Larmor precession frequency of protons in a water sample mapping the B field and weighted by the muon distribution
  - **Evaluates the magnetic field observed by the muons as they propagate around the ring**
- **Goal: 140 ppb [100 ppb (stat) + 100 ppb (sys)]**

TOOLS OF THE TRADE

- **Storage ring:** 1.45T field, horizontal focusing
  - High uniformity through shimming process





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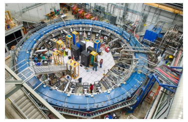
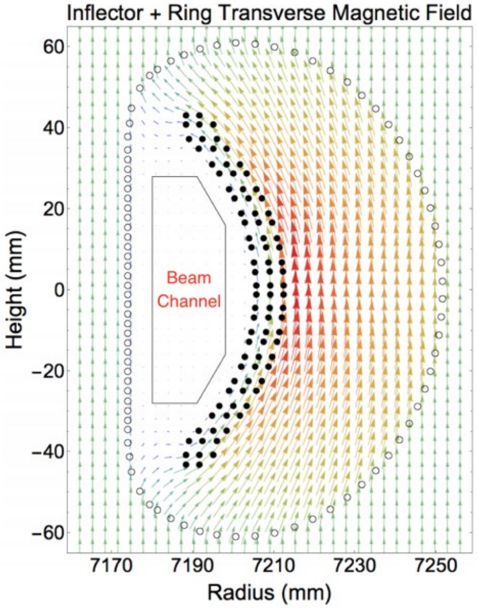
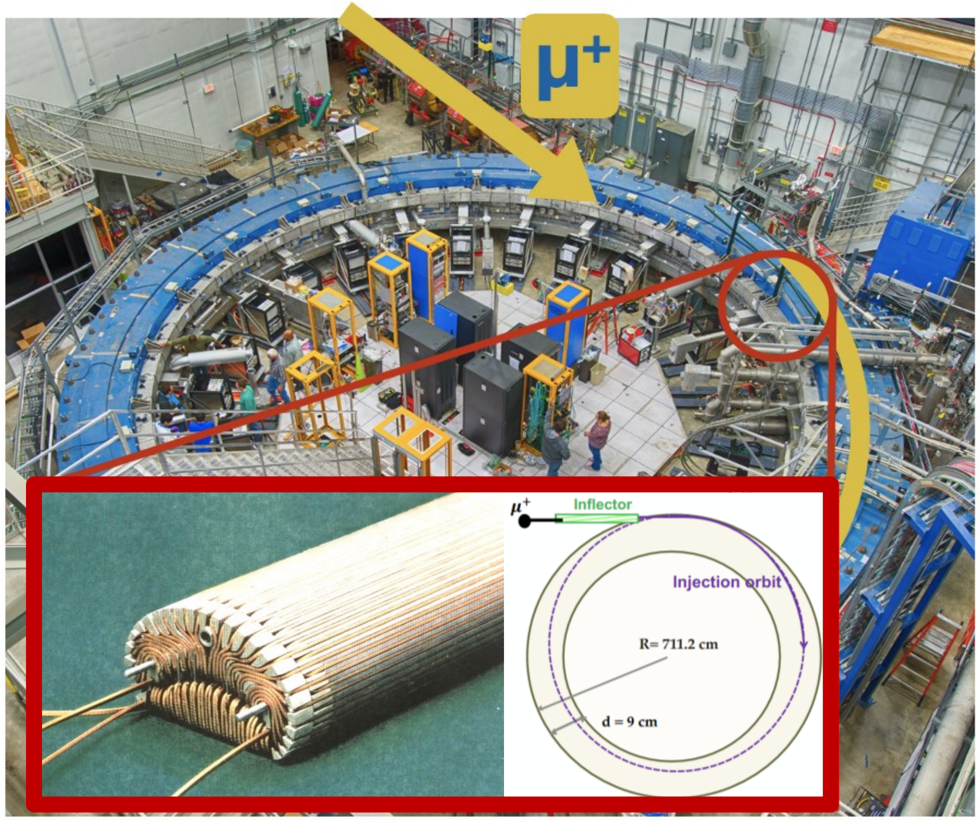
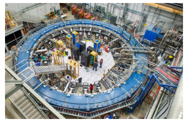
- **Storage ring:** 1.45T field, horizontal focusing 
  - High uniformity through shimming process
- **Inflector:** Superconducting magnet
  - Entryway for muon beam

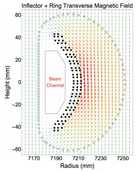


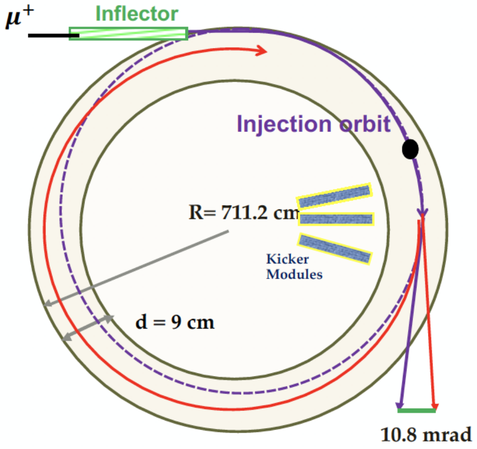


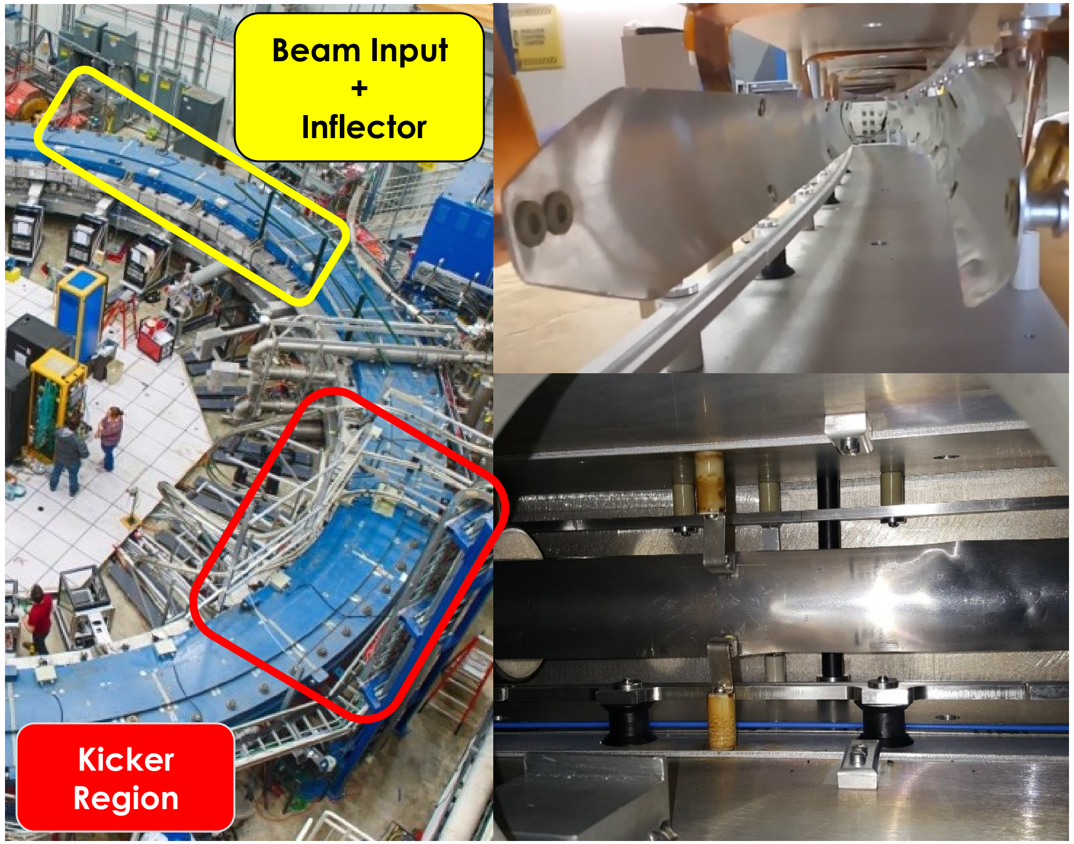
TOOLS OF THE TRADE

- **Storage ring:** 1.45T field, horizontal focusing
  - High uniformity through shimming process
- **Inflector:** Superconducting magnet
  - Entryway for muon beam
- **Kickers:** Nudge injected beam onto storable trajectories



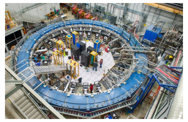


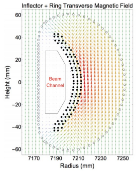


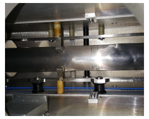


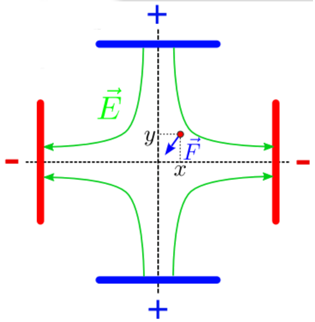
TOOLS OF THE TRADE

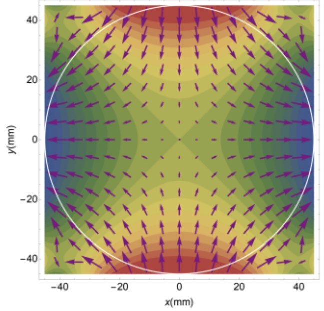
- **Storage ring:** 1.45T field, horizontal focusing
  - High uniformity through shimming process
- **Inflector:** Superconducting magnet
  - Entryway for muon beam
- **Kickers:** Nudge injected beam onto storable trajectories
- **Electrostatic Quadrupoles:** vertical focusing
  - Four quads cover 43% of the storage ring

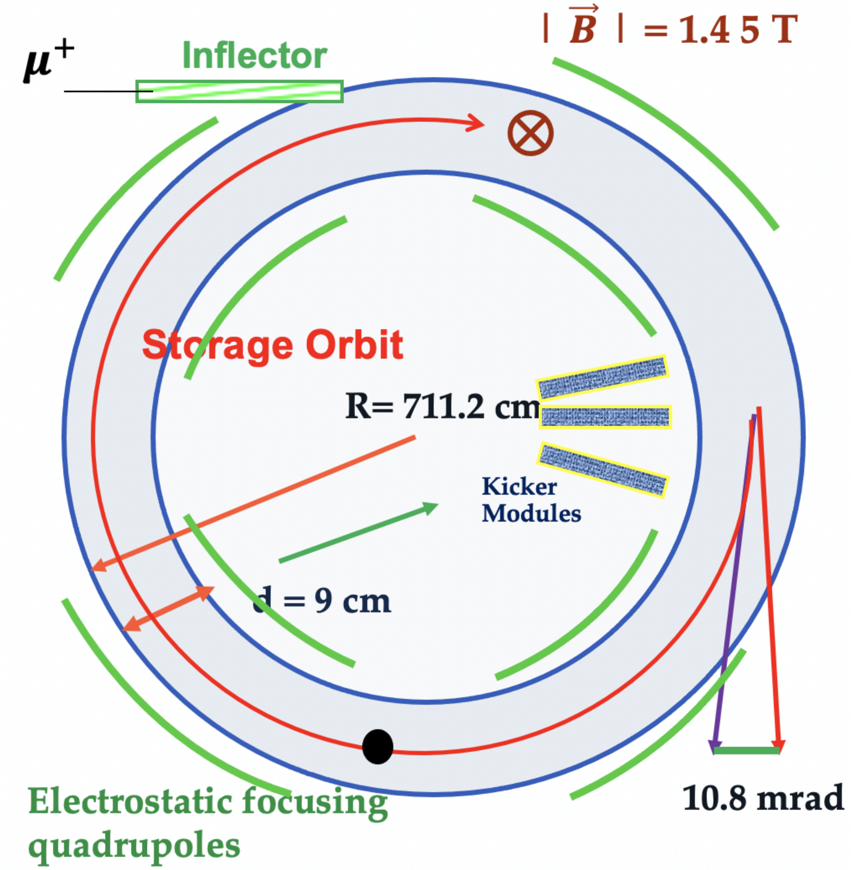








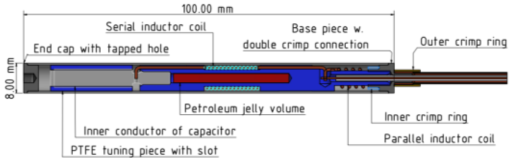




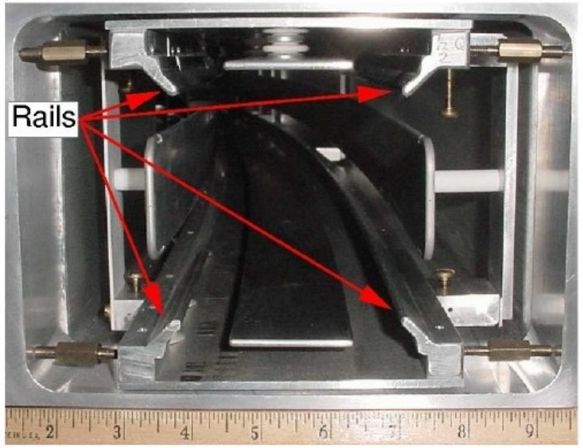
TOOLS FOR $\omega_a/\tilde{\omega}'_p(T_r)$

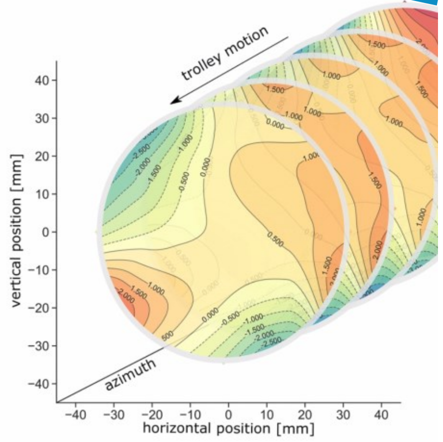
- **Need to determine B at < 100 ppb to determine a_μ**
  - Use NMR to assess B-field in terms of proton precession frequency ω_p

378 fixed probes continuous monitoring

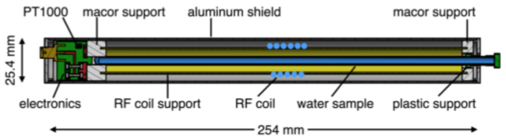


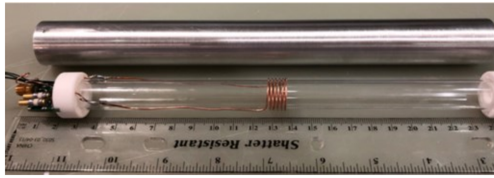
NMR Trolley maps field every three days





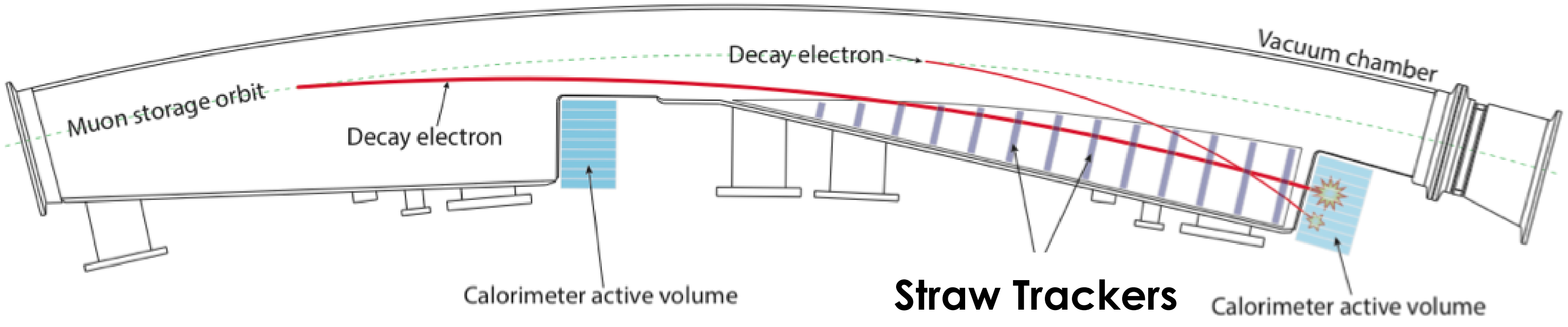
Trolley cross-calibrated to absolute probes

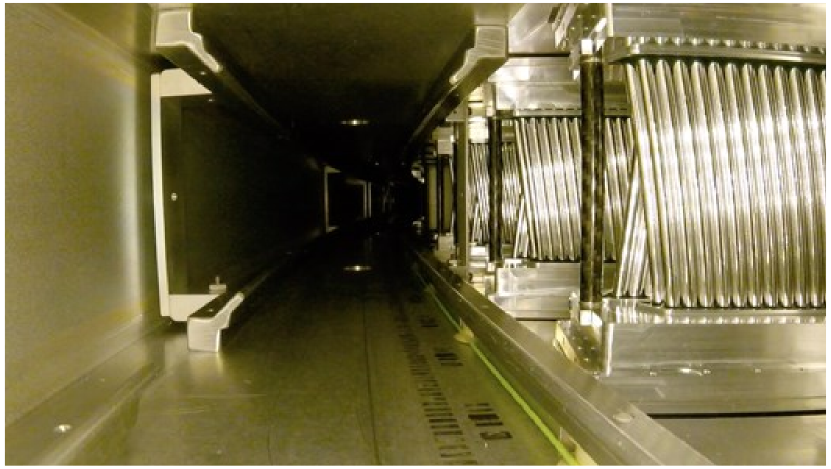


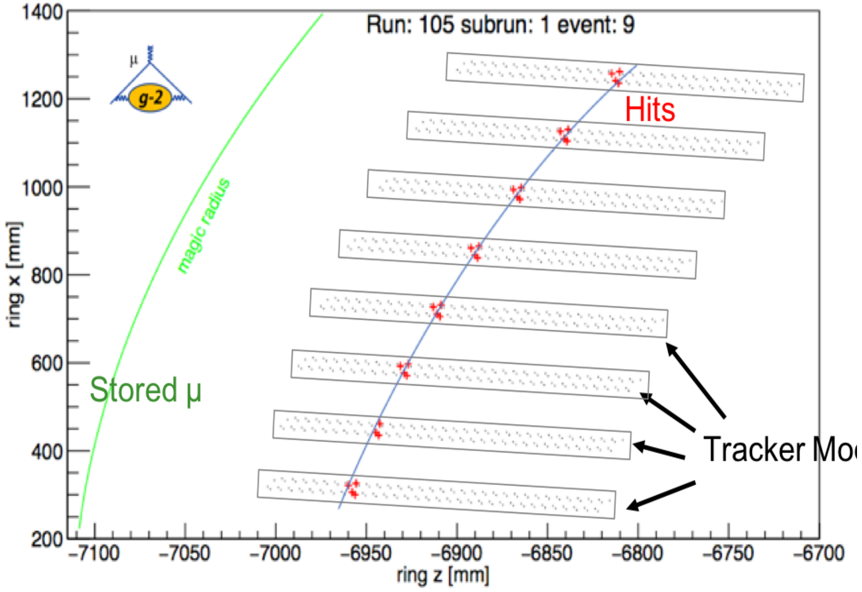


Absolute probes all cross-calibrated at ANL test magnet

MORE THAN JUST THE B-FIELD



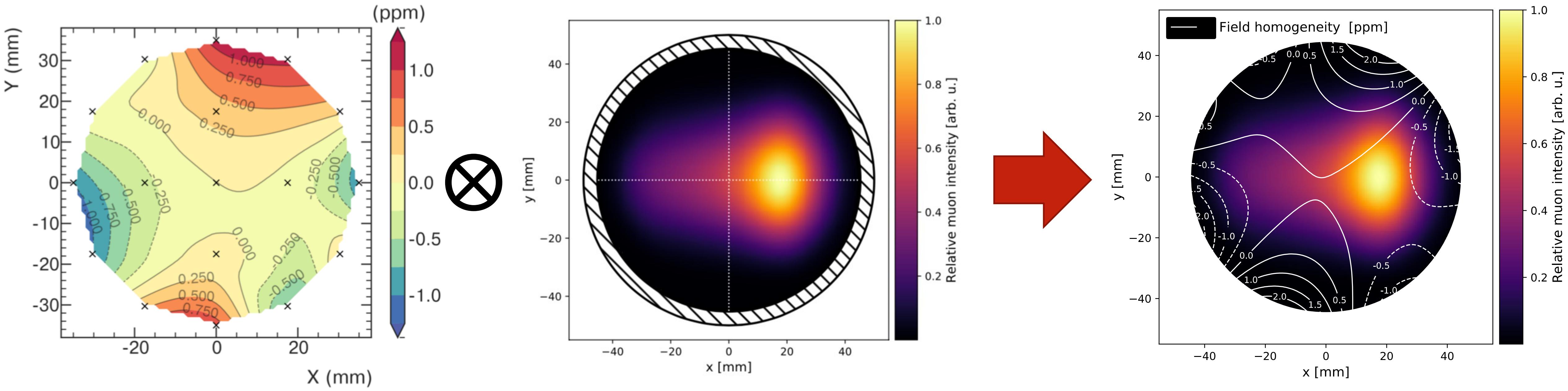




- **Muons in beam weakly decay** $[\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+]$
  - Decay positrons pass through straw trackers
- **Construct muon beam profile from tracker data**
- **Combine with field map**

THE DENOMINATOR

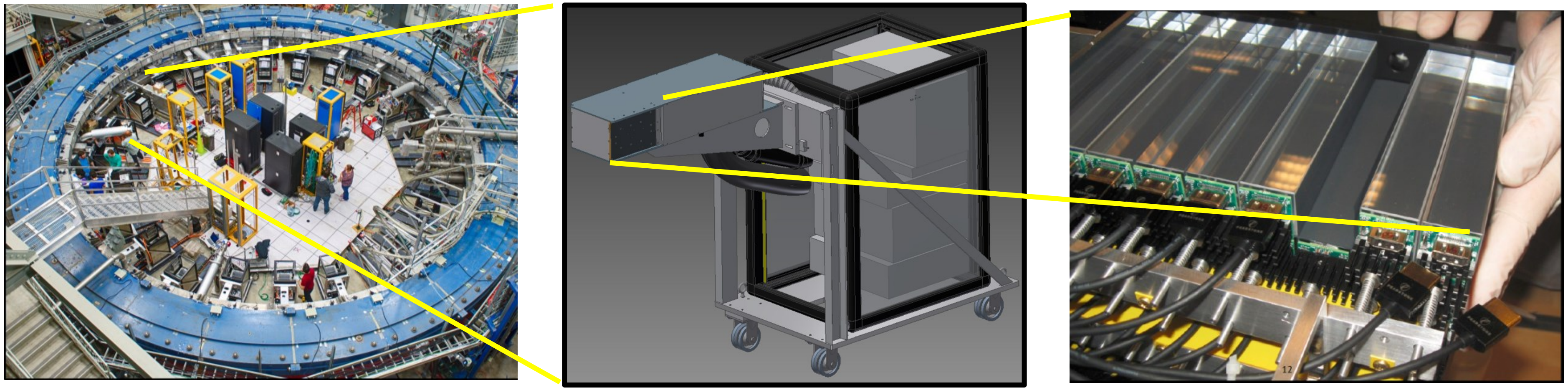
- **Magnetic field map + Beam profile = AVERAGE FIELD THE MUONS OBSERVE**



related to $\widetilde{\omega}'_p(T_r)$

THE NUMERATOR

- **24 calorimeters placed around the ring measure positron energy spectrum**



- The power of an energy cut…
- **Parity-violating weak decay $[\mu^{+} \rightarrow \bar{\nu}_{\mu}\nu_{e}e^{+}]$ → high-energy positrons preferentially emitted in direction of muon spin**

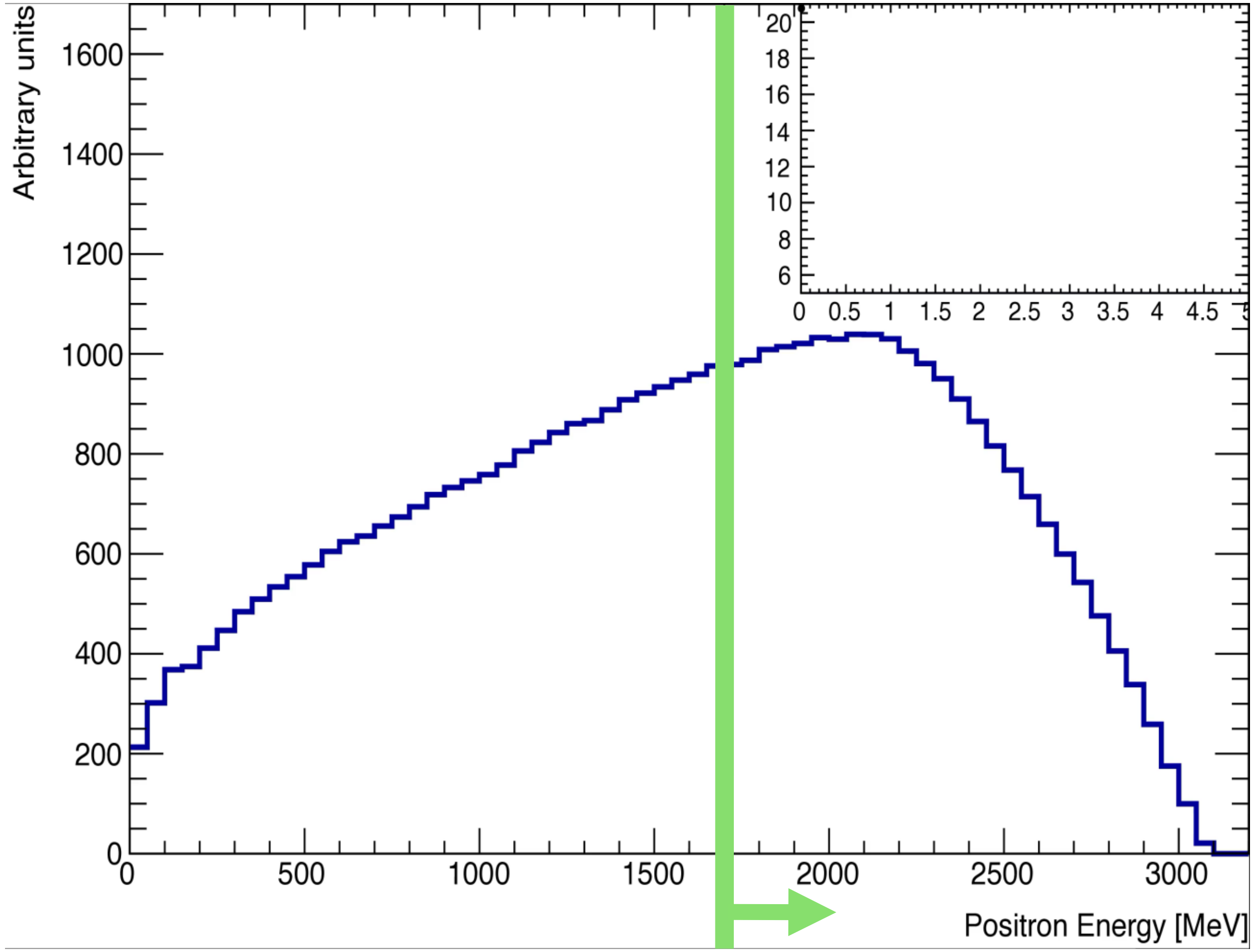
THE NUMERATOR

- **Cut at events above 1.7 GeV**

  $f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$

- **Number of events in that range depends on the anomalous precession frequency**
  - Fit to determine ω_a

- **All of the pieces are in place…**



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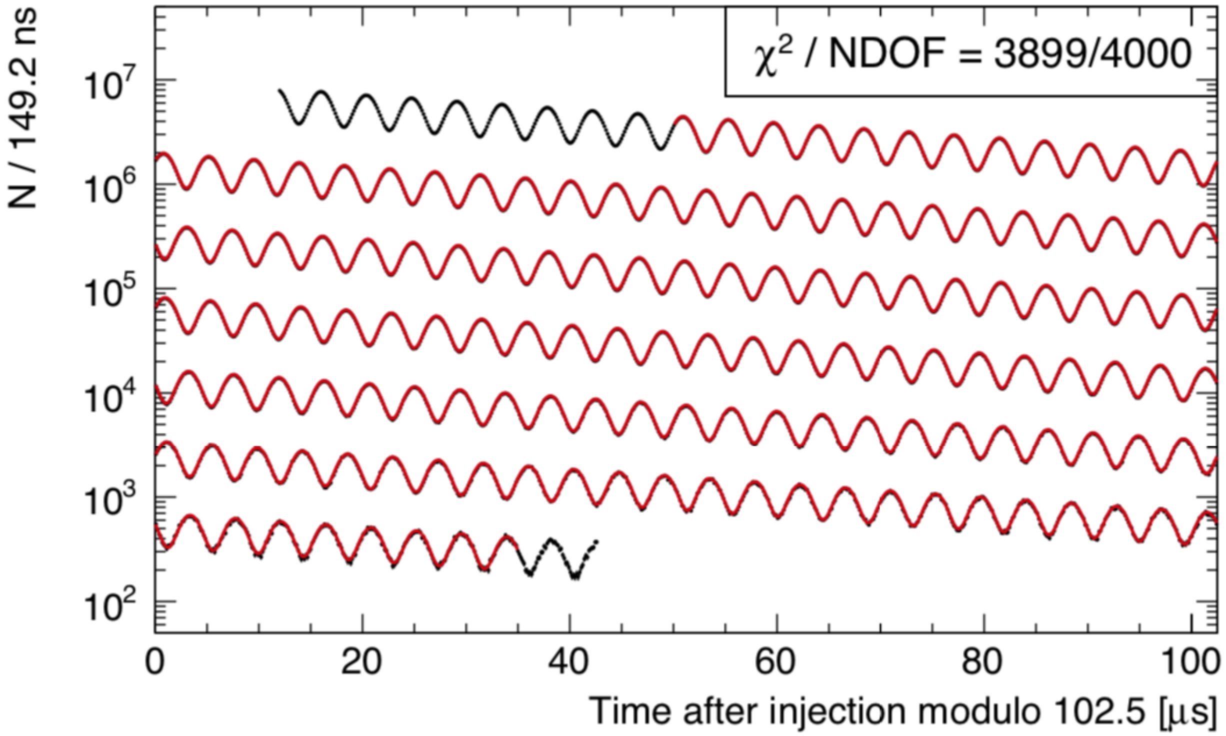


THE WIGGLE PLOT

THE REALITIES OF ANALYSIS

- **Complexities discovered and considerations made**
  - Kickers and quads operations required four subruns
  - Pulse-power systems also involved with the field transients

- **Corrections and systematics studied in excruciating detail**
  - "Expect results in a year!" ~Talk circa 2018

$$\frac{\omega_a}{\tilde{\omega}_p} = \left(\frac{f_{\mathrm{clock}}\,\omega_a\,(1 + \overbrace{C_e + C_p}^{\text{E-field \& pitch corrections}} + \overbrace{C_{ml} + C_{pa}}^{\text{Muon loss \& phase acceptance corrections}})}{\underbrace{(1 + B_q + B_k)}_{\text{Field transients}}\;\underbrace{f_{\mathrm{field}}}_{\text{Field calibration}}\,\omega_p \otimes \rho(\mathbf{r})} \right)$$

$$f_{clock}\,\omega_a\,(1 + C_e + C_p + C_{ml} + C_{pa})$$

EXCRUCIATING DETAIL

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

f_{clock}

$R(\omega_a)$ 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

ω_a

	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**

C_e

	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**

C_p

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

C_{ml}

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

C_{pa}

$$(1 + B_q + B_k)\, f_{\text{field}}\, \omega_p \otimes \rho(\mathbf{r})$$

EXCRUCIATING DETAIL

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

Run-1 Estimate:
B_k = -27.4 ± 37 ppb

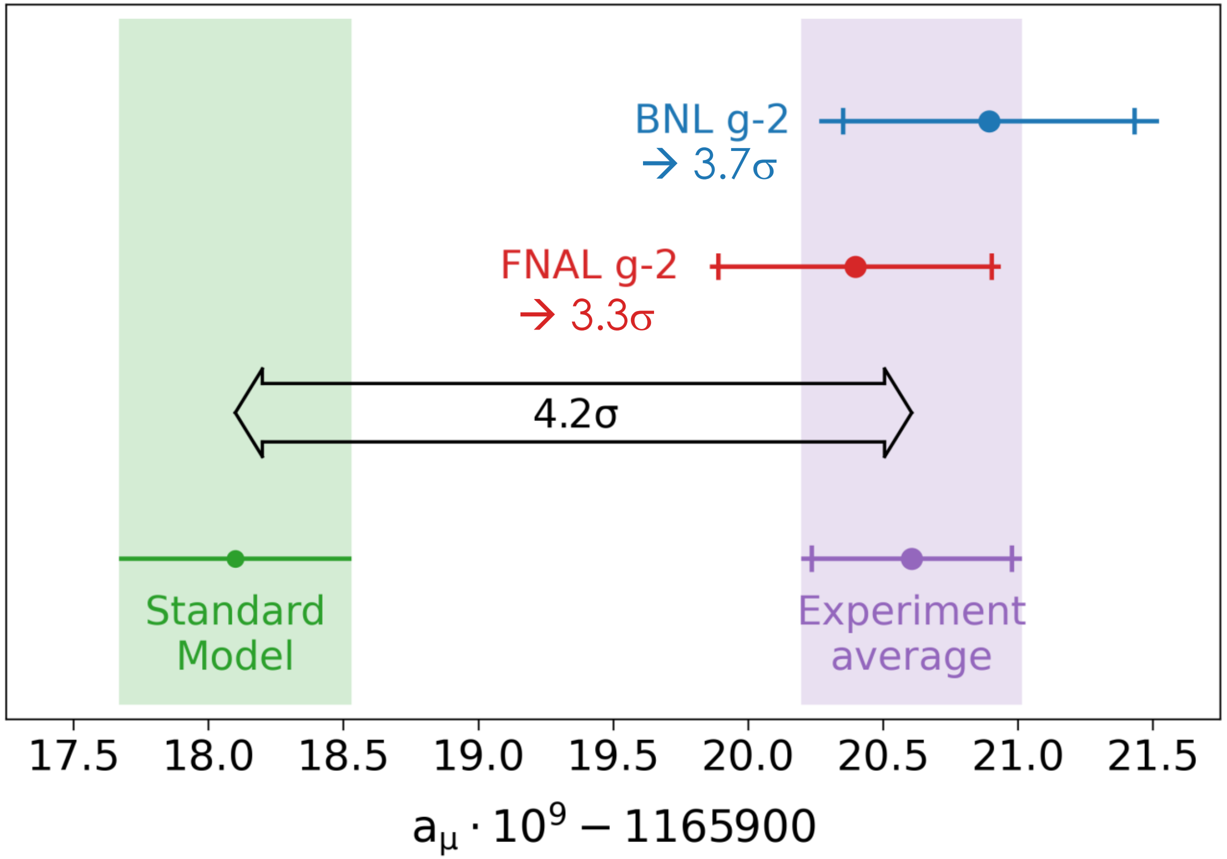
PROBE	Calibration Coefficients		
	Value (Hz)	Stat (Hz)	Syst (Hz)
1	90.81	0.38	2.02
2	84.21	0.65	1.18
3	95.02	0.53	2.19
4	86.03	0.25	1.28
5	92.96	0.51	1.10
6	106.24	0.46	1.35
7	116.64	0.96	1.61
8	76.39	0.60	1.21
9	83.52	0.23	1.64
10	24.06	1.39	1.26
11	177.55	0.22	1.99
12	110.85	0.44	1.73
13	122.89	2.08	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**

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**

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

	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**

REACHING A RESULT



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

- **a_μ(SM) = 0.00116591810(43) → 368 ppb [Muon g-2 Theory Initiative]**
- **a_μ(Exp) - a_μ(SM) = 0.00000000251(59) → 4.2σ**

DIGGING A LITTLE DEEPER

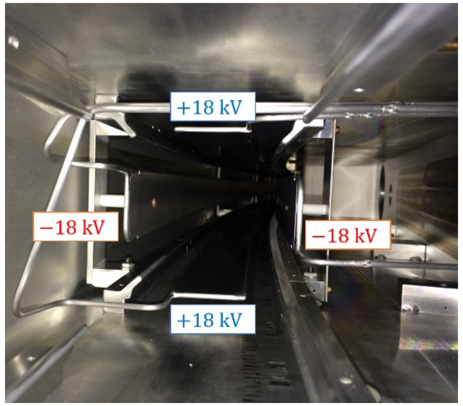
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–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

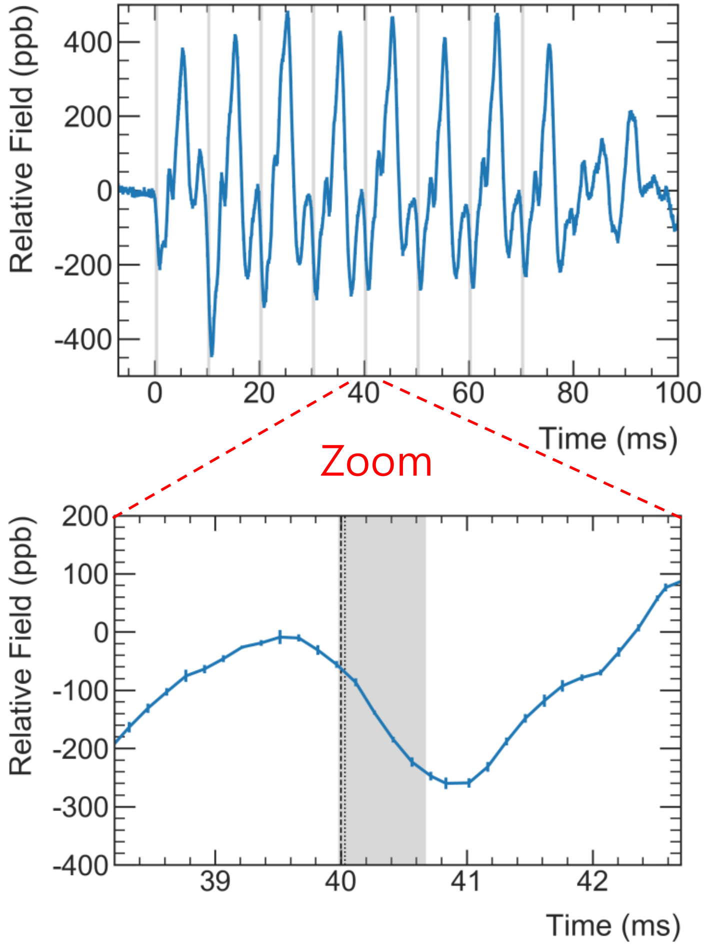
- **FNAL experiment determined a_μ to unprecedented precision**
- **Run-1 uncertainties dominated by statistics**
  - **6% of ultimate data sample**
  - **15% smaller error than BNL**
  - **157 ppb systematic error is half BNL level**
- **Phase acceptance and field transient systematics became major topics of study for Muon g-2**

QUAD TRANSIENT (B_q)

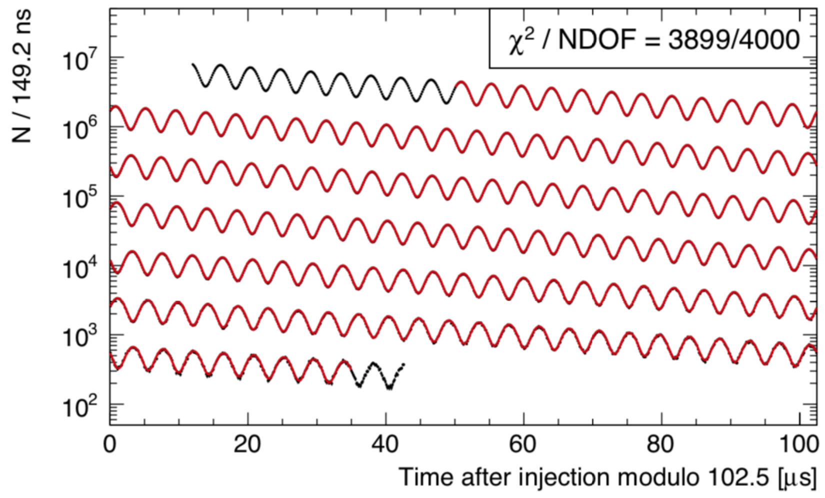
- **At FNAL repetition rate, quad pulsing induces mechanical vibrations** — this is a new problem
  - *Vibrations perturb the B-field!*
- **Special NMR probes built to map this effect**
  - Long & Winding Road

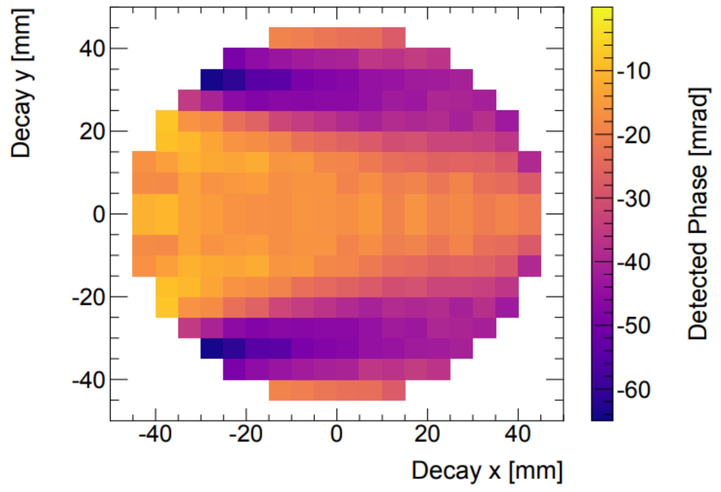
- **17 ppb correction**
  - Only matters in window when muons are present (grey band in plot), averaged over 8 bunches and 43% of the ring
- **92 ppb uncertainty dominated by lack of information**
  - Run-1 did not have complete map
  - Run-2 and beyond will = 2x-3x reduction





PHASE ACCEPTANCE (C_{pa})





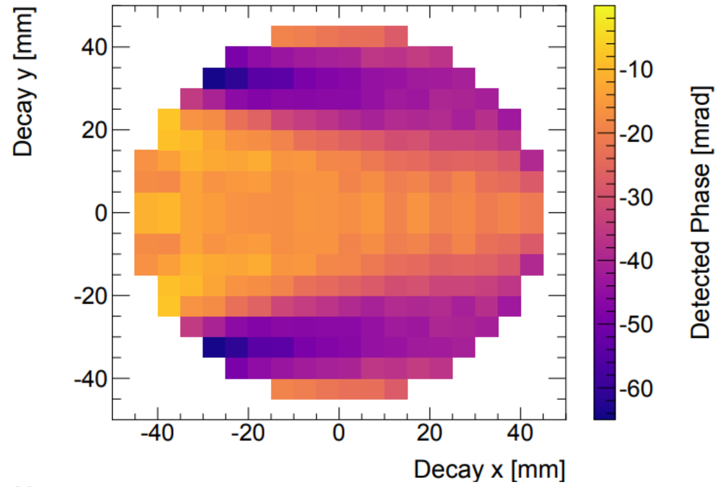
- Basic fit function follows: $f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$
  - Consider case where $\phi \rightarrow \phi(t)$:

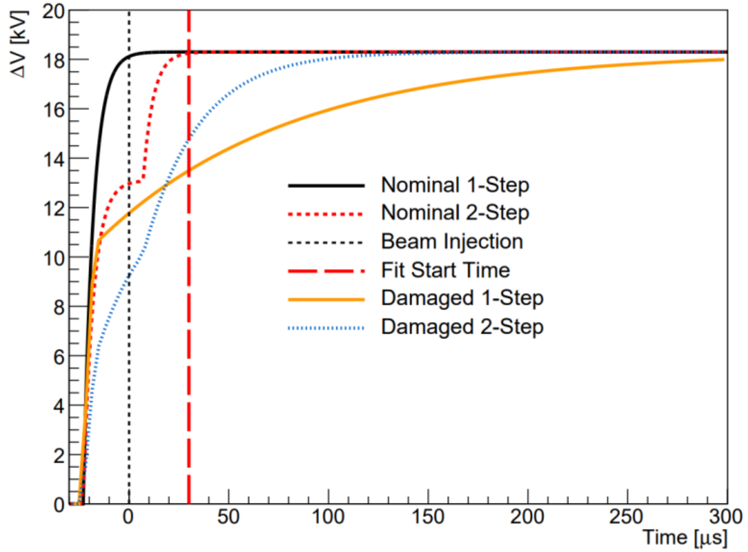
$$cos(\omega_a t + \phi(t)) = cos(\omega_a t + \phi_0 + \phi' t + ...)$$
$$= cos((\omega_a + \phi')t + \phi_0 + ...)$$

  - **Extracted ω_a is shifted by ϕ'**

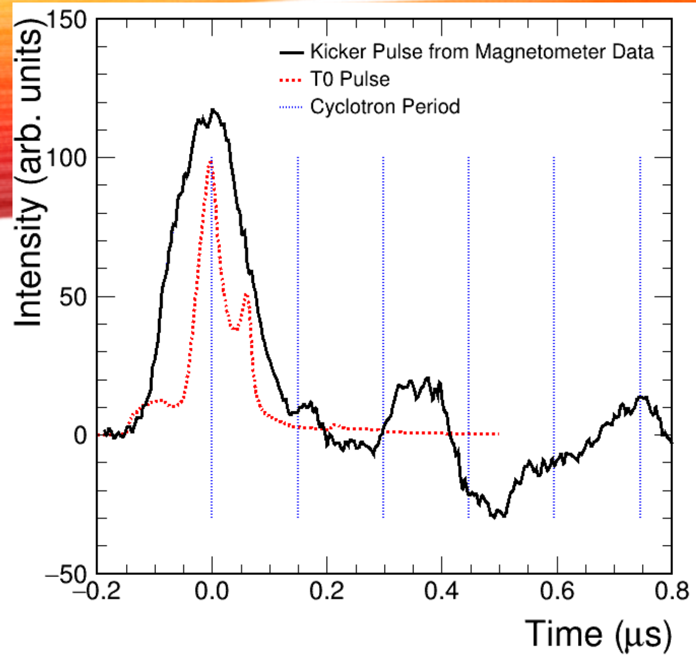
- Detected decay positrons carry particular phase
  - Phase depends on decay position (x,y) and energy (E)
  - Not a big issue if muon distribution remains stable

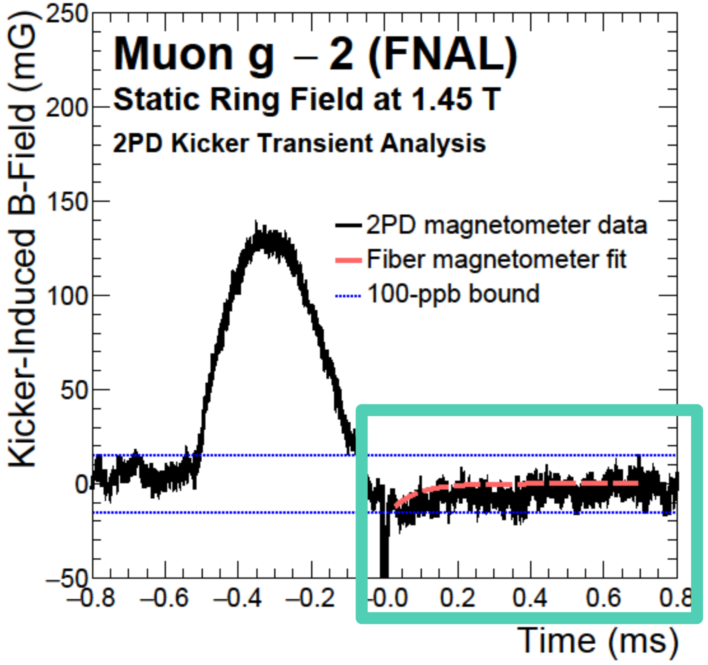
PHASE ACCEPTANCE (C_{pa})





- Detected decay positrons carry particular phase
  - Phase depends on decay position (x,y) and energy (E)
  - Not a big issue if muon distribution remains stable
- **Equipment failure in quad circuit led to instability**
  - Damaged resistors changed E-field
  - Vertical distribution → changing acceptance → changing measurement
- **158 ppb correction with 75 ppb uncertainty**
  - Resistors fixed by Run-2, remove significant impact





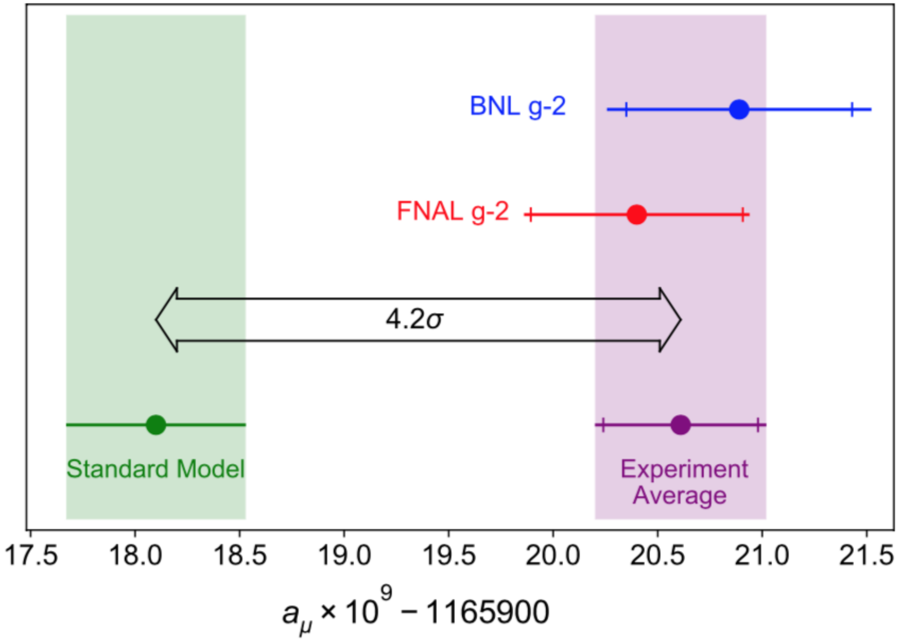
"Getting a charged particle to go in a circle is easy.
Getting it to go in the one you want is a miracle of science" ~Adam

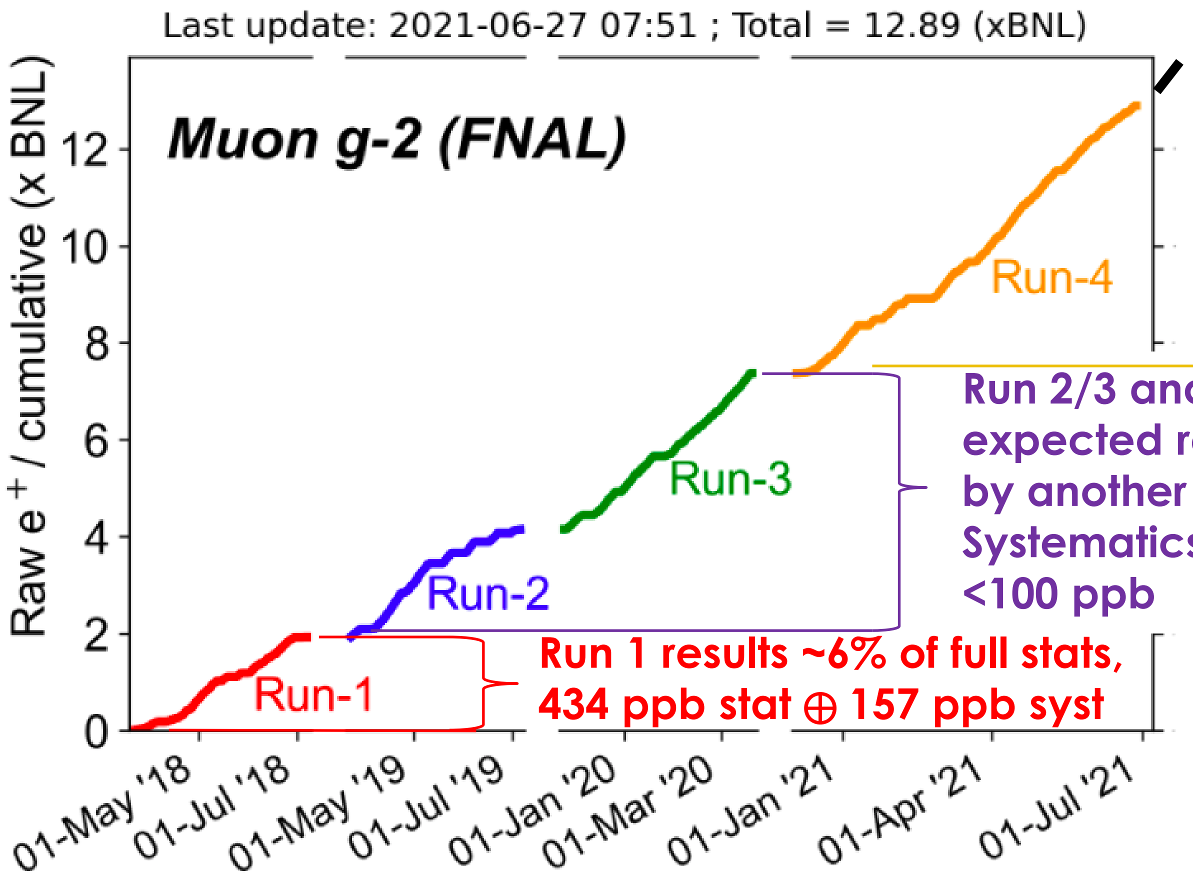
KICKER EFFECTS (C_e) (B_k)

- Kicker plates receive 4kA in 200-ns timescale
  - Presents a technical challenge to the experiment
  - Current vs. muon beam distribution – factors into momentum-time correlation
    - Part of the (C_e) correction
  - Concerned about eddy currents produced by main kick
    - Multiple magnetometers and groups assessed the induced-field relaxation
    - Complementary methods agree on -27 ppb correction
      - Ongoing work to see if we can reduce 37 ppb uncertainty
- Kicker paper in peer review

THANK YOU!

- **FNAL result confirms BNL**
  - Unprecedented precision
  - 4.2σ tension with theory
    - More likely to come
- Run-1 is small piece of data



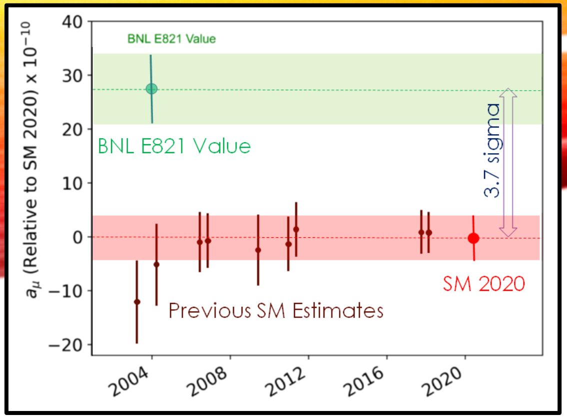


Run 4 and beyond, aiming for 20xBNL

Run 2/3 analysis in progress, expected reduction in error by another factor of 2. Systematics on track for <100 ppb

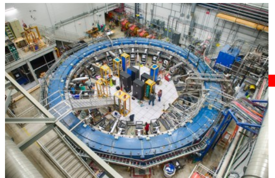
Run 1 results ~6% of full stats, 434 ppb stat ⊕ 157 ppb syst

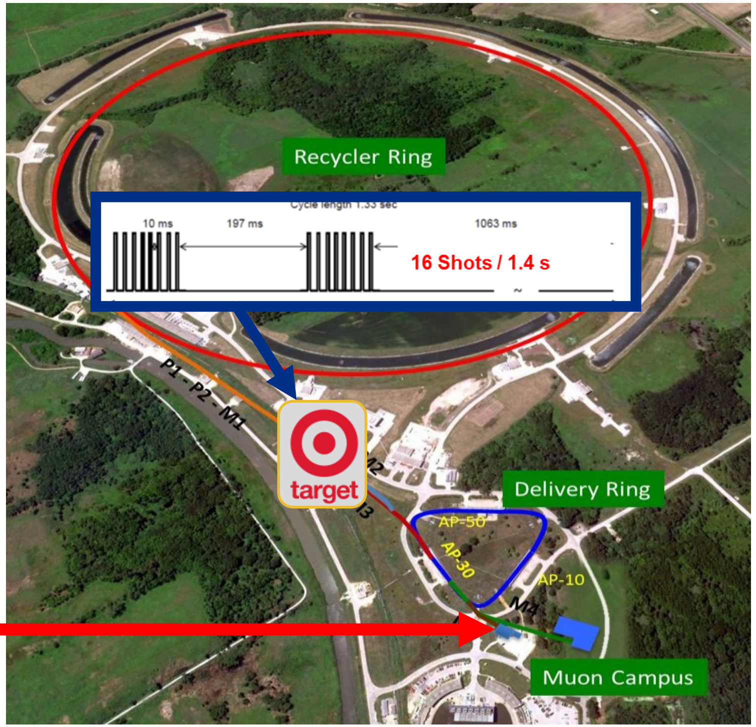
BACKUP THINGS

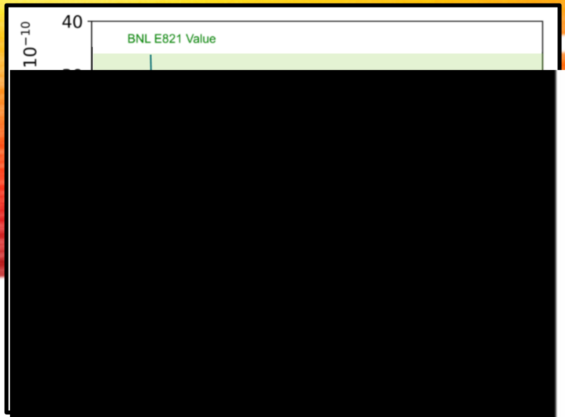


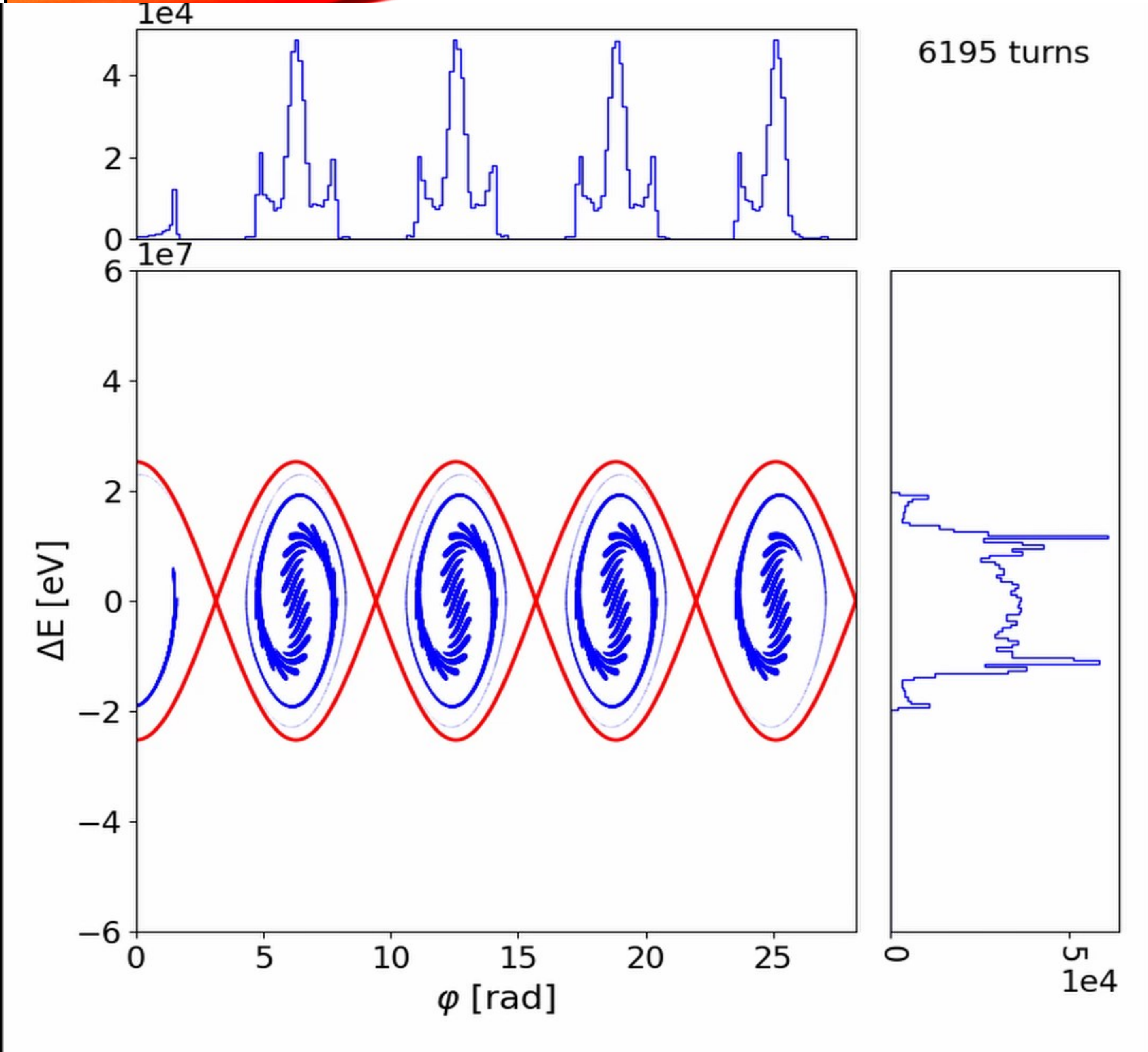
BUILDING AT FERMILAB

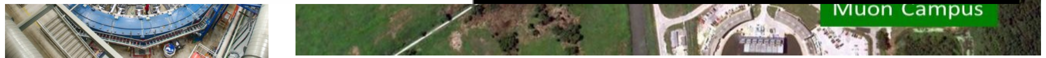
- **Physicists love tension… finding it… resolving it…**
  - The Universe is the most imaginative thing in the room. How imaginative is it?
- **After ~20 years, Fermilab Muon g-2 formed to try to answer the underlying questions from BNL**
  - Fermilab experiment aims to make 140 ppb measurement
- **Why the move? Lots of muons!**
  - 8 GeV protons extracted from Recycler Ring






40
10^{-10}
BNL E821 Value


1e4
6195 turns
1e7
ΔE [eV]
φ [rad]
1e4


Muon Campus