First Results from the New Muon g-2 Experiment at Fermilab

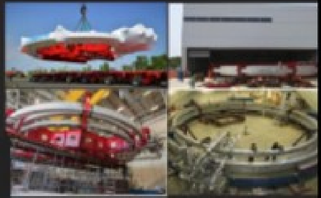
μ

g-2

James Stapleton
for the Muon g-2 Collaboration
Sep 30, 2021

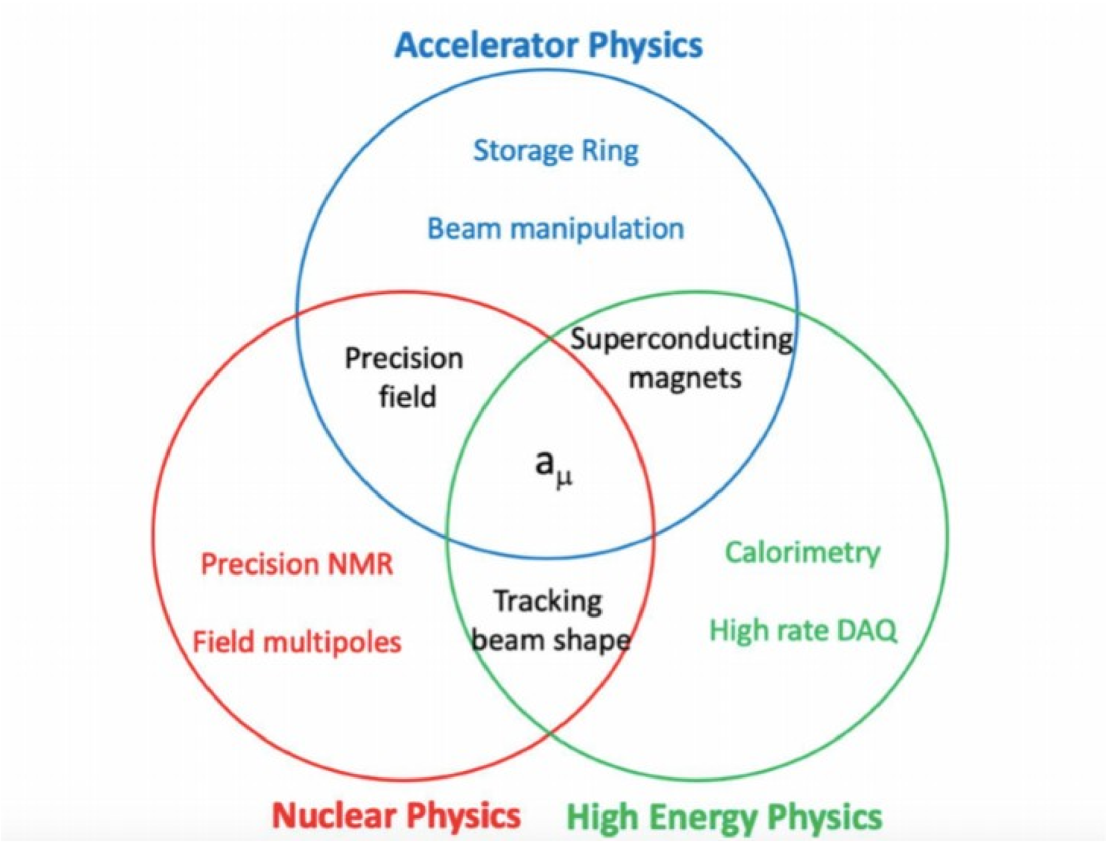
Fermilab

Muon g-2 Collaboration



7 Countries, 35 Institutions, 203 Collaborators

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Budker Institute of Nuclear Physics
CAPP/IBS Korea
Cornell University
Fermi National Accelerator Lab
INFN, Sezione di Napoli
INFN, Sezione di Pisa
INFN, Sezione di Roma Tor Vergata
INFN, Sezione di Trieste
James Madison University
Johannes Gutenberg Univ. Mainz
JINR Dubna
KAIST
Laboratory Nazionali di Frascati
Lancaster University
Michigan State University
North Central College
Northern Illinois University
Regis University
Shanghai Jiao Tong University
Technische Universitat Dresden
Universita di Molise
Universita di Udine
University College London
University of Illinois at Urbana-Champaign
University of Kentucky
University of Liverpool
University of Manchester
University of Massachusetts Amherst
University of Michigan
University of Mississippi
University of Virginia
University of Washington


Accelerator Physics
Storage Ring
Beam manipulation
Precision field
Superconducting magnets
a_μ
Precision NMR
Field multipoles
Tracking beam shape
Calorimetry
High rate DAQ
Nuclear Physics
High Energy Physics

Muon g-2 Measurement (April 2021)

Fermilab Run 1

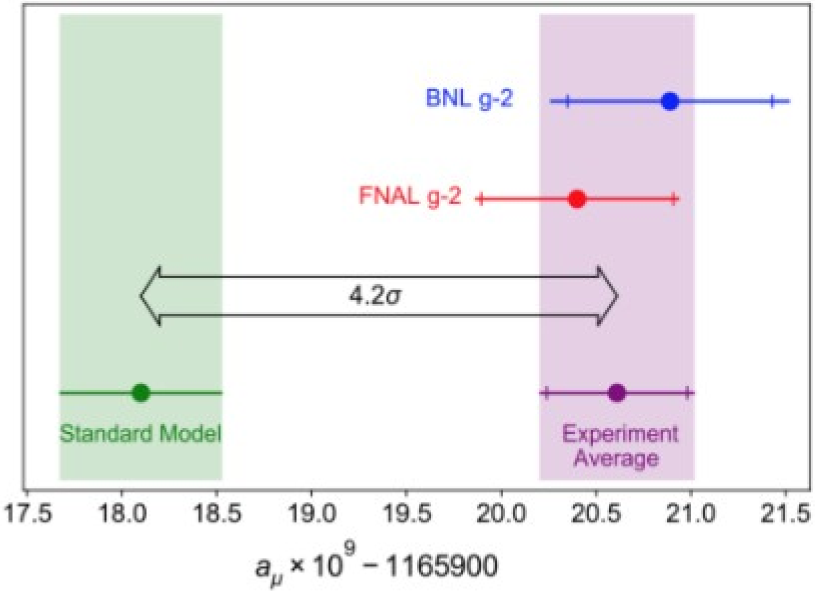
$$a_\mu = 0.001\,165\,920\,40\,(54)$$

magnetic moment: $g\frac{e}{2m}\overline{S}$

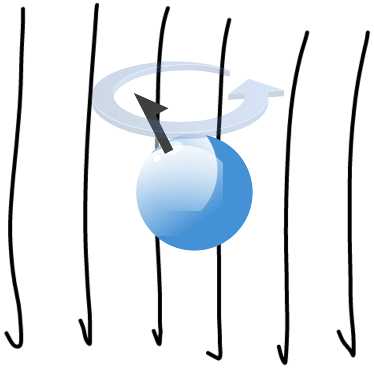
spin ½ pointlike particle: $g = 2$

enhanced by quantum-loop-level processes!

$$g = 2 \times (1 + a)$$



How It's Done



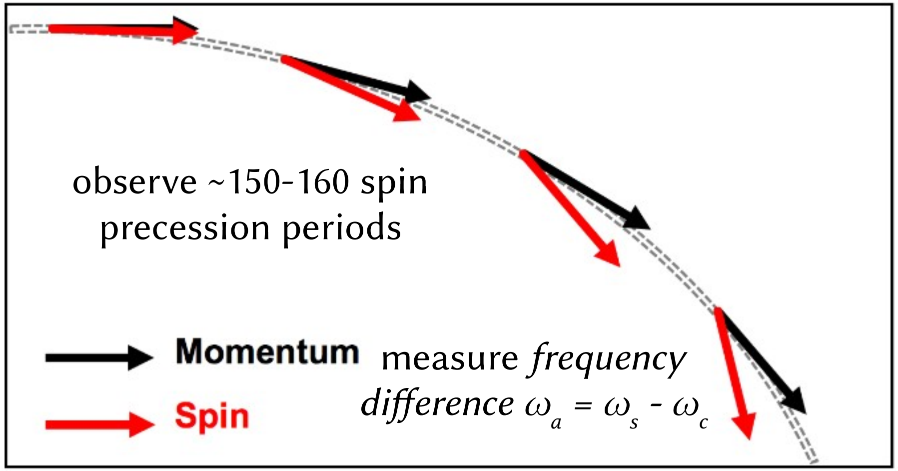
- We trap polarized muon bunches in a magnetic field & watch spin precession
- Precession *speed* depends only* on dipole moment & magnetic field

$$\omega \sim g\overline{B}$$

- Very clean: measuring g-factor to high precision depends only on **these two factors**
  - B field strength
  - spin precession frequency
- Same lesson is true in more complex treatments: this is how we squeeze more precision out of the measurement

The Muon Storage Ring

Inject muons into 'ring'
& trap with dipole field



Observed frequency difference is proportional to anomalous factor a_μ!

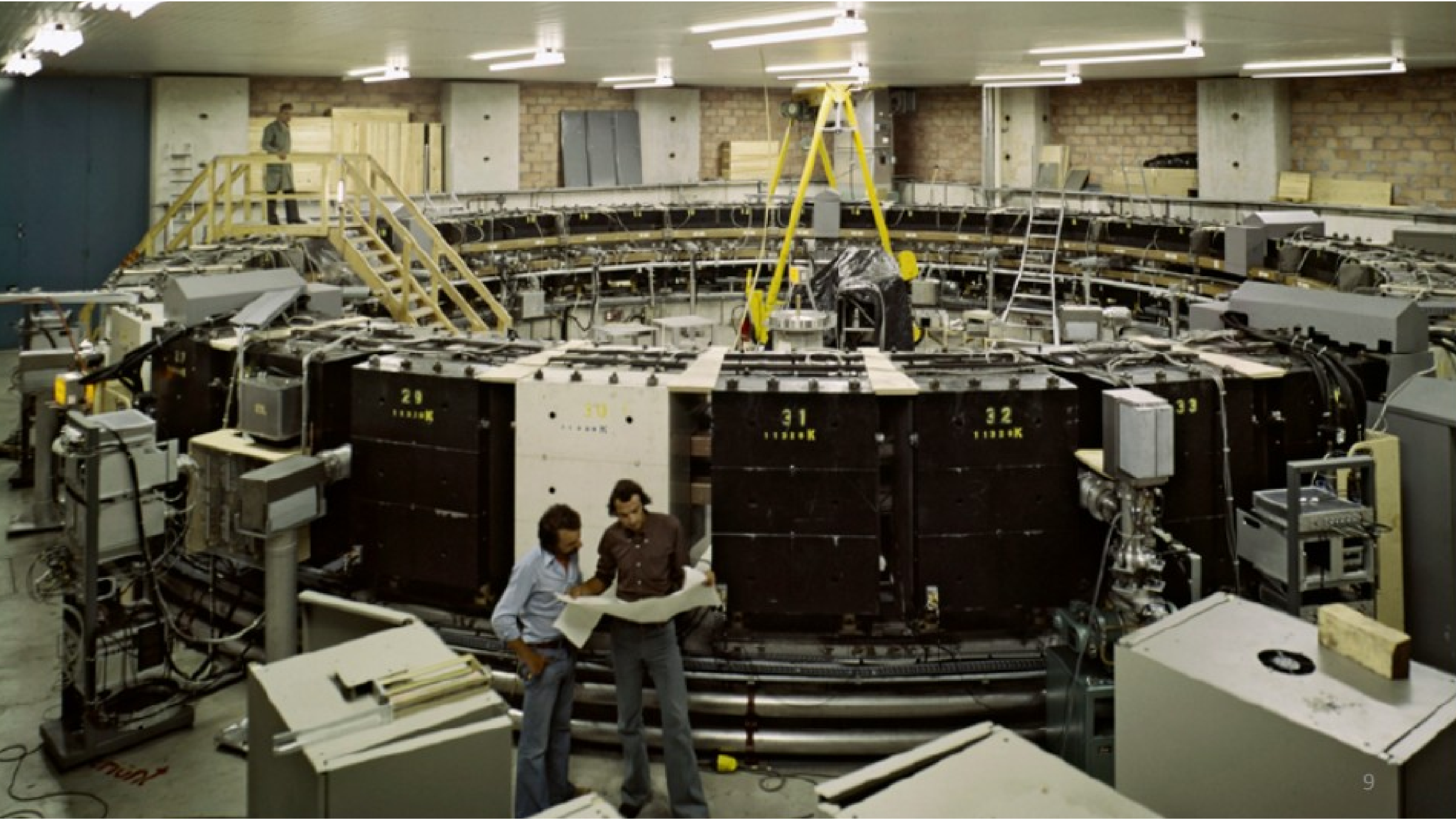
- Over the years the CERN experiment developed a new design linking spin precession & momentum
  - dynamically store muon bunches (cyclotron)
  - Larmor & Thomas precession, minus cyclotron frequency ⟶ a_μ!

measure angular velocity of spin vs. momentum for a μ^- rotating in uniform magnetic field B

$$\omega_s - \omega_c = \omega_a$$

$$\left[-g_\mu \frac{eB}{2m_\mu} - (1-\gamma)\frac{eB}{m_\mu \gamma}\right] - \left[-\frac{eB}{m_\mu \gamma}\right] = \left[-a_\mu \frac{eB}{m_\mu}\right]$$

Larmor + Thomas precessions — cyclotron frequency — no γ!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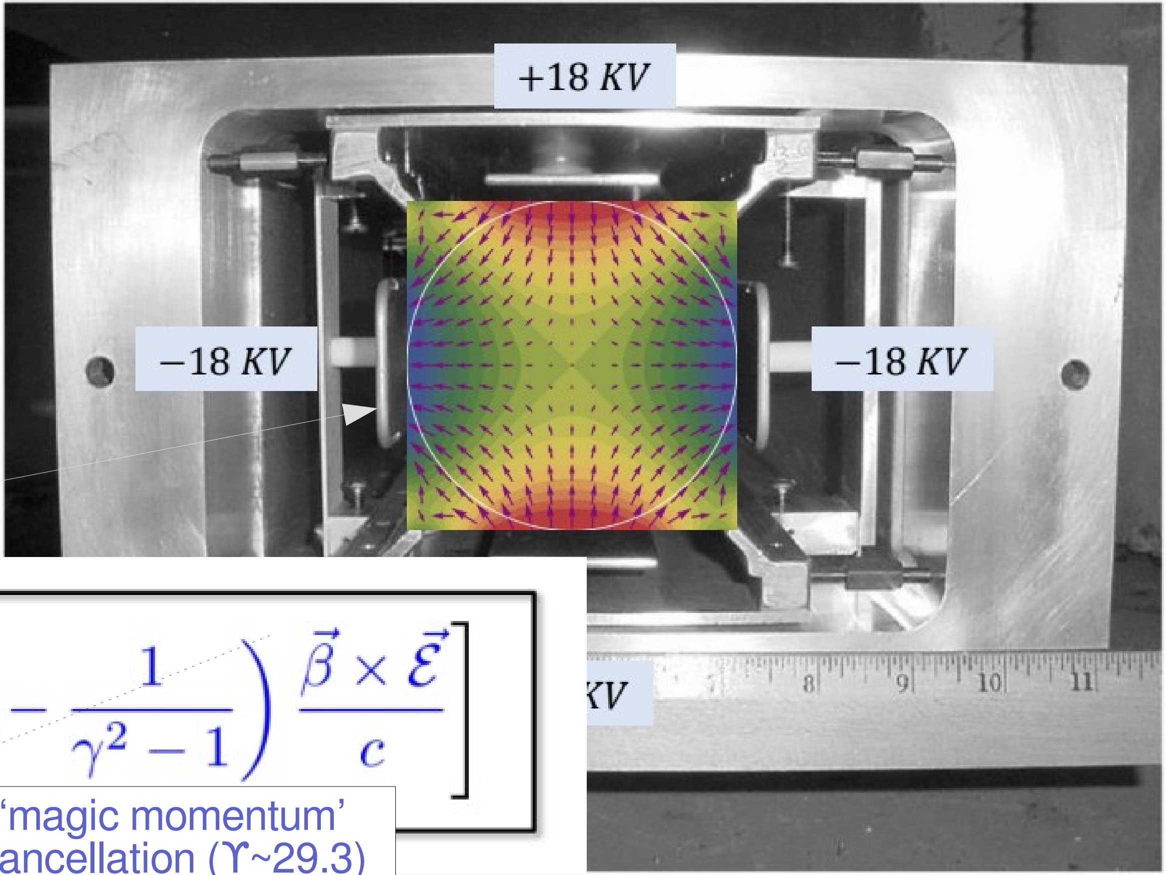
The Magic Momentum Technique

Can use Electrostatic Quadrupoles (ESQs) with only a small penalty

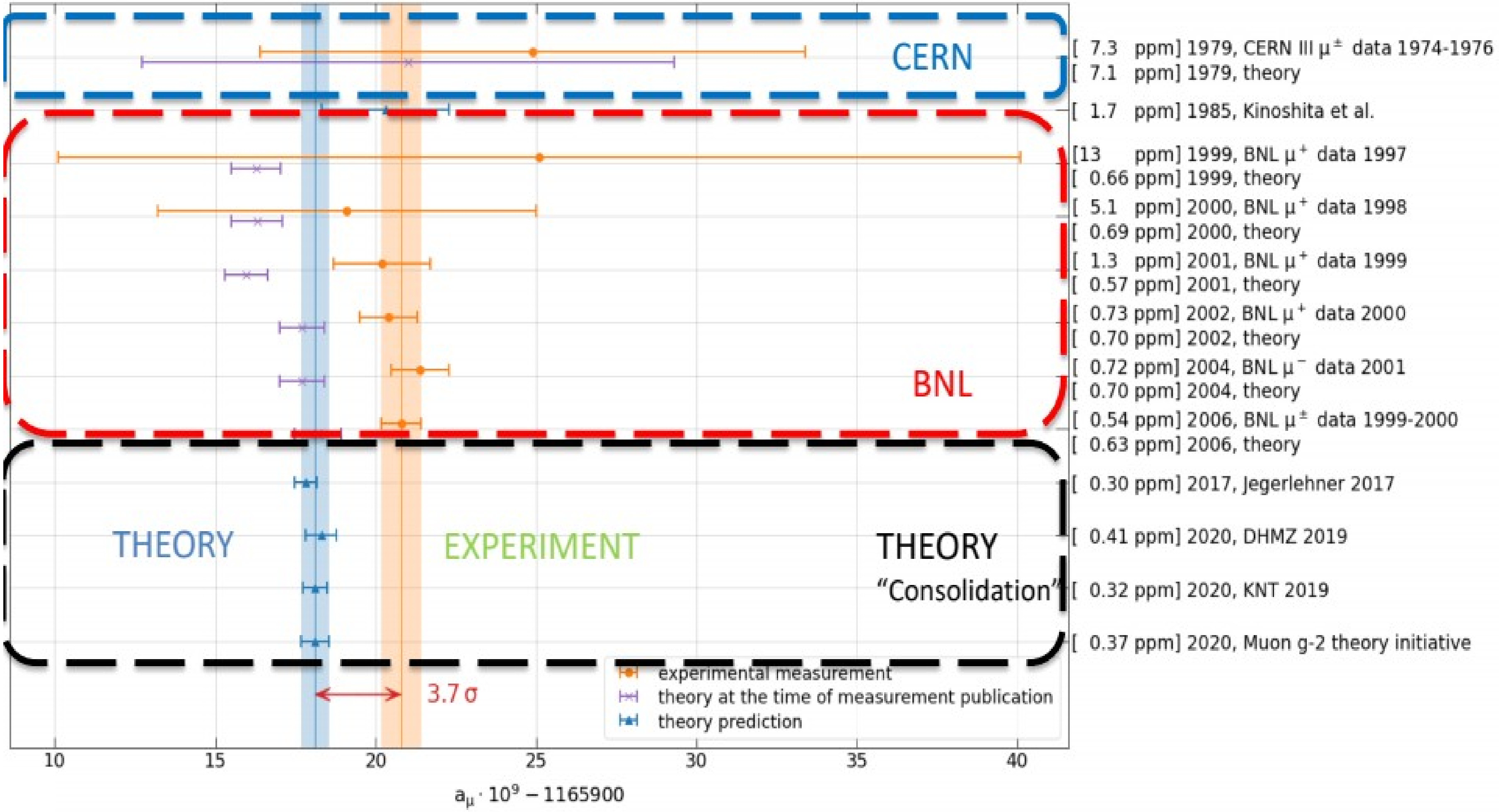


Vertical Focusing

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

'magic momentum' cancellation (ϒ~29.3)

Slow but Steady Progress



Bringing g-2 to Fermilab

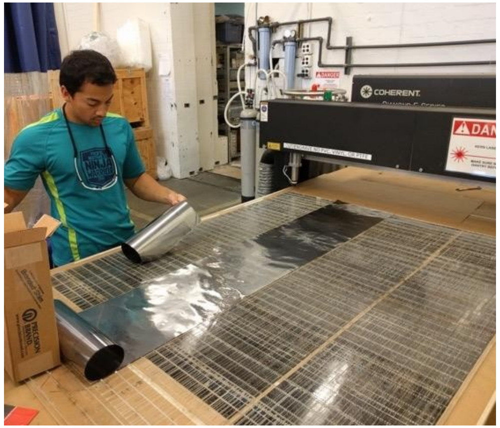
- Goal: Bring the container used to hold the muons from BNL and couple it to Fermilab's powerful accelerator beam

- 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!!

Storage ring transported by land/sea in 2013

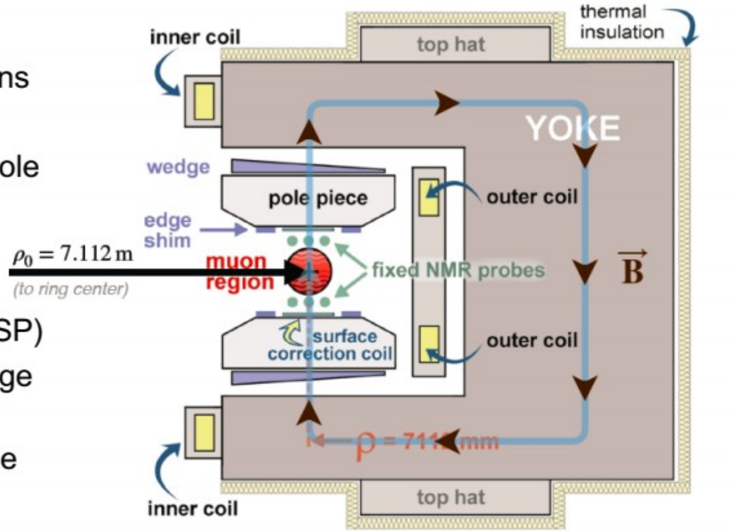


Shimming tools for the Magnetic Field

INFN Istituto Nazionale di Fisica Nucleare

Muon g-2

- **B Field** 1.45T
- **12 Yokes**: C shaped flux returns
- **72 Poles**: shape field
- **864 Wedges:** angle - quadrupole (QP))
- **24 Iron Top Hats**: change effective mu
- **Edge Shims**: QP, sextupole (SP)
- **8000 Surface iron foils**: change effective mu locally
- **Surface coils**: will add average field moments (360 deg)



G. Venanzoni, CERN Colloquium, 8 April 2021

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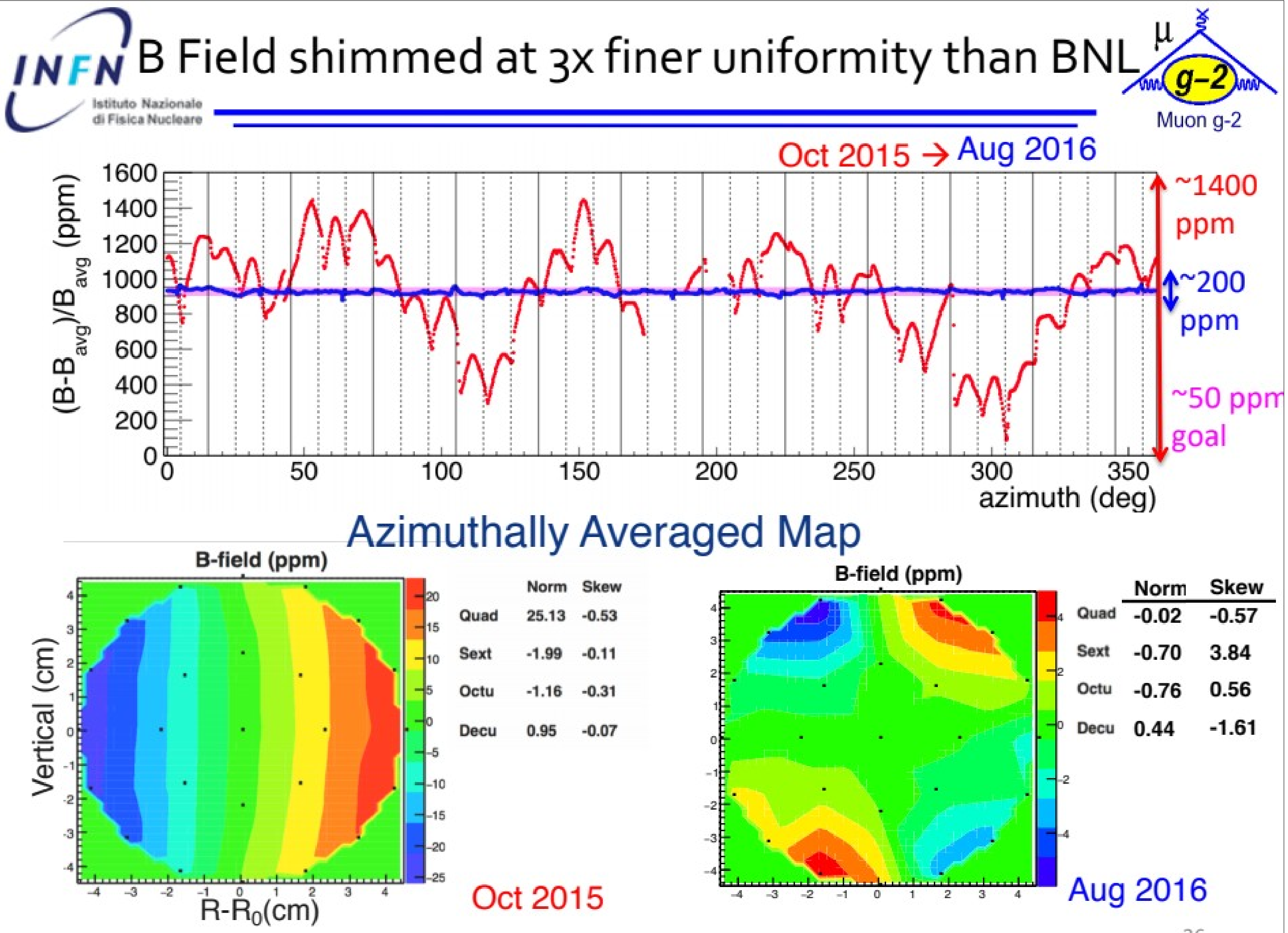
B Field shimmed at 3x finer uniformity than BNL



Oct 2015:

	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

Aug 2016:

	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

G. Venanzoni, CERN Seminar, 8 April 2021

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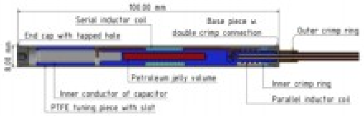
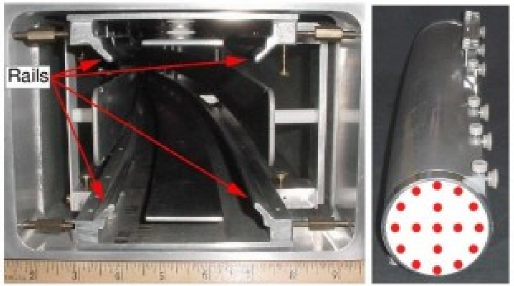
Precision Monitoring (<100ppb)

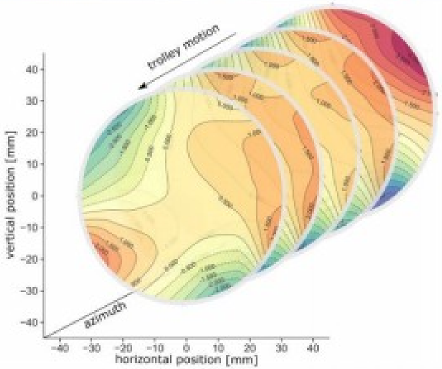
- Use NMR to find B-field in terms of proton precession frequency ω_p (comagnetometer)

378 fixed probes monitor 24/7

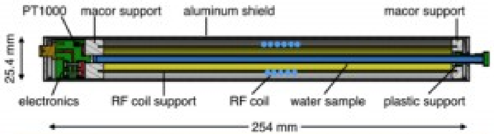


NMR trolley maps field every 3 days





Trolley cross-calibrated to absolute probes



Absolute probes all cross-calibrated at ANL test magnet

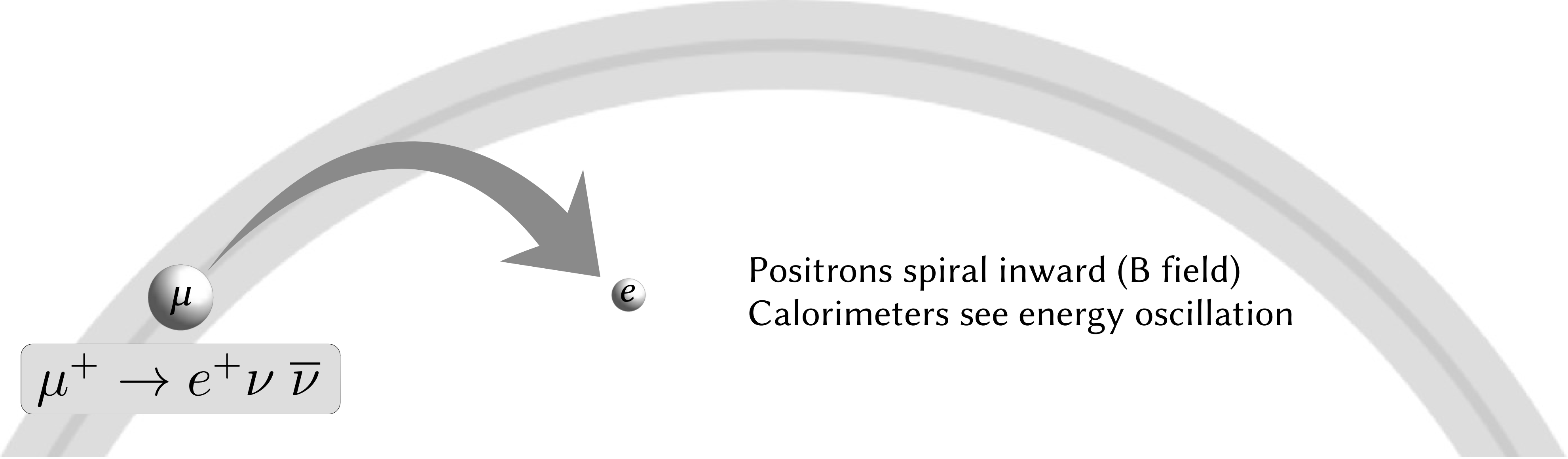
Observing the Spin Precession

CM Frame

parity-violation in muon decay
gives $\overline{p}_{e^+} \sim \overline{s}_{\mu^+}$

Lab Frame

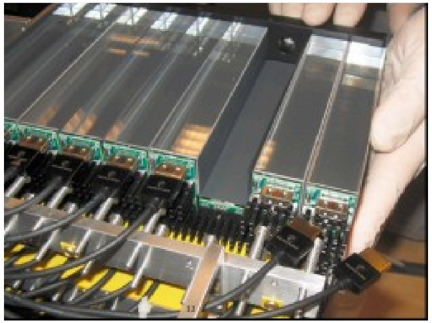
forward momentum (& energy)
oscillate with spin precession



Positrons spiral inward (B field)
Calorimeters see energy oscillation

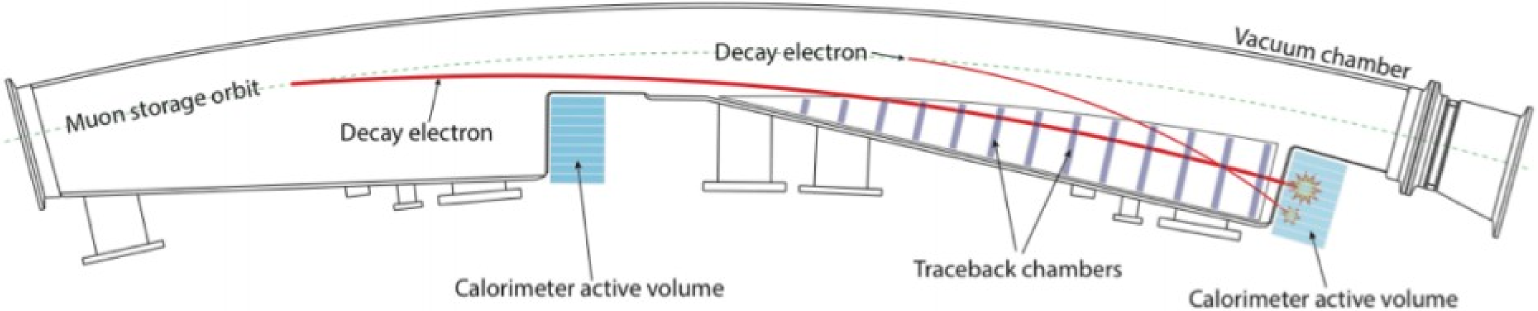
$$\mu^+ \rightarrow e^+ \nu \, \overline{\nu}$$

Detector systems



- Calorimeters: fast PbF_2 crystal arrays with SiPM readout → greatly reduce pileup
- State of the art laser calibration system
- WFD electronics → greatly reduced energy threshold
- Two straw tube trackers to precisely monitor properties of stored muons

Top view of 1 of 12 vacuum chambers



a_μ, obtained from our **2 frequency measurements** and well-known fundamental factors

We measure these 2 frequencies

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

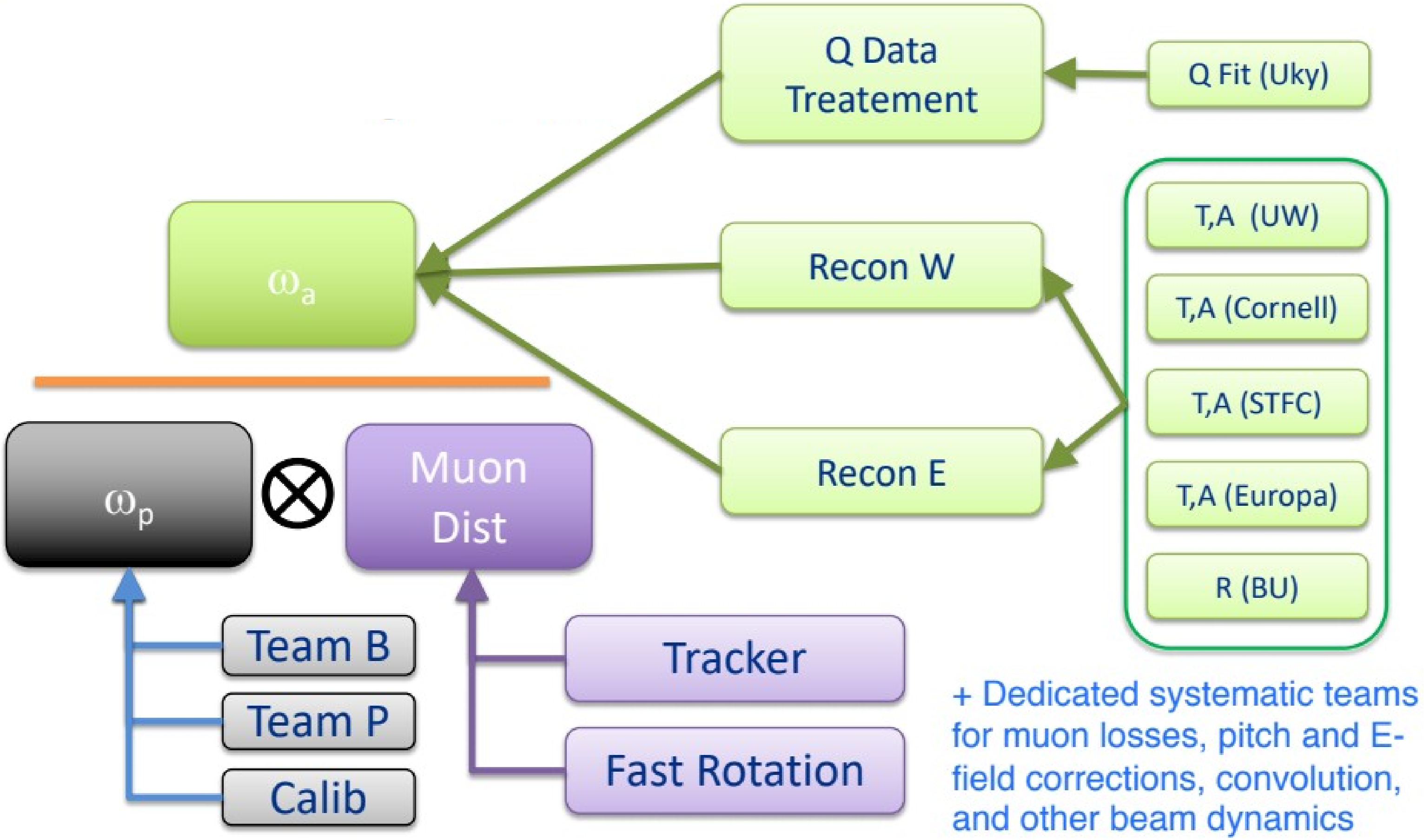
$\frac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb at T = 34.7℃
Metrologia **13**, 179 (1977)

$\frac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting
Phys. Rev. Lett. **82**, 711 (1999)

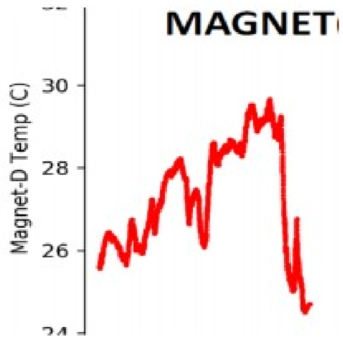
$\frac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)
Rev. Mod. Phys. **88** 035009 (2016)

$\frac{g_e}{2}$ Measured to 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

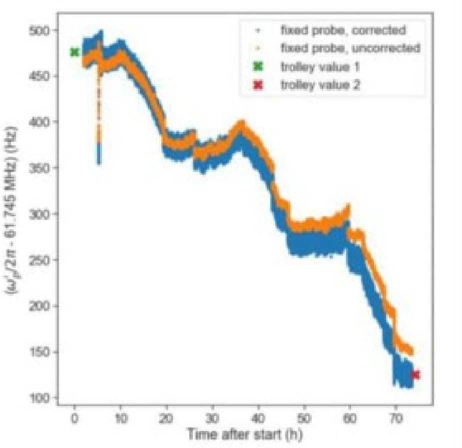
Data Analysis



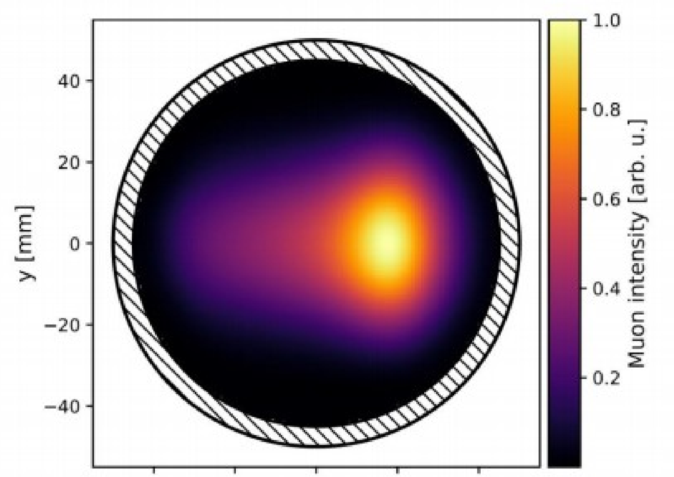
Run-1 commissioning Challenges … (resolved by now)



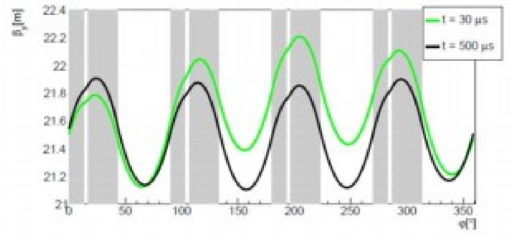
Hall T unstable
→ B changing
→ Gains changing

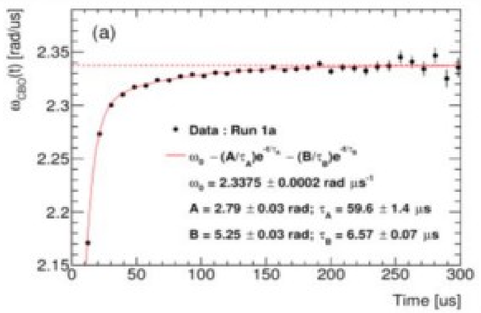


Kicker sparks limited range to below optimum



2/32 ESQ resistors "damaged"



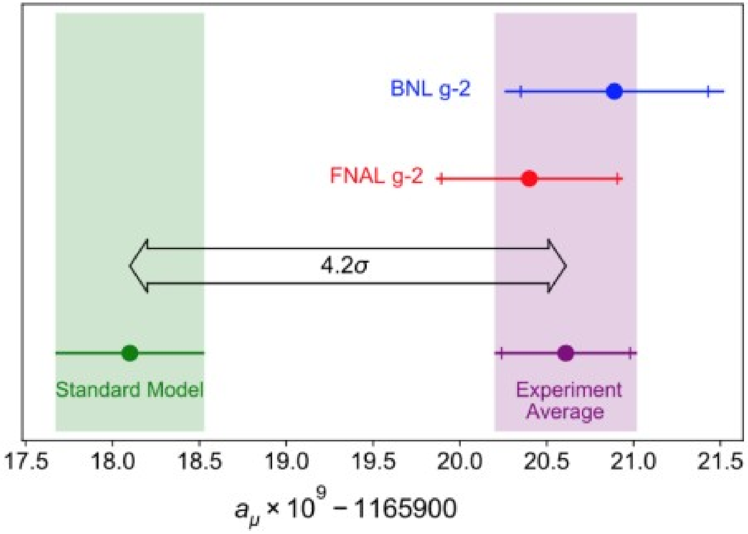


The Run 1 a_μ Result

- 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

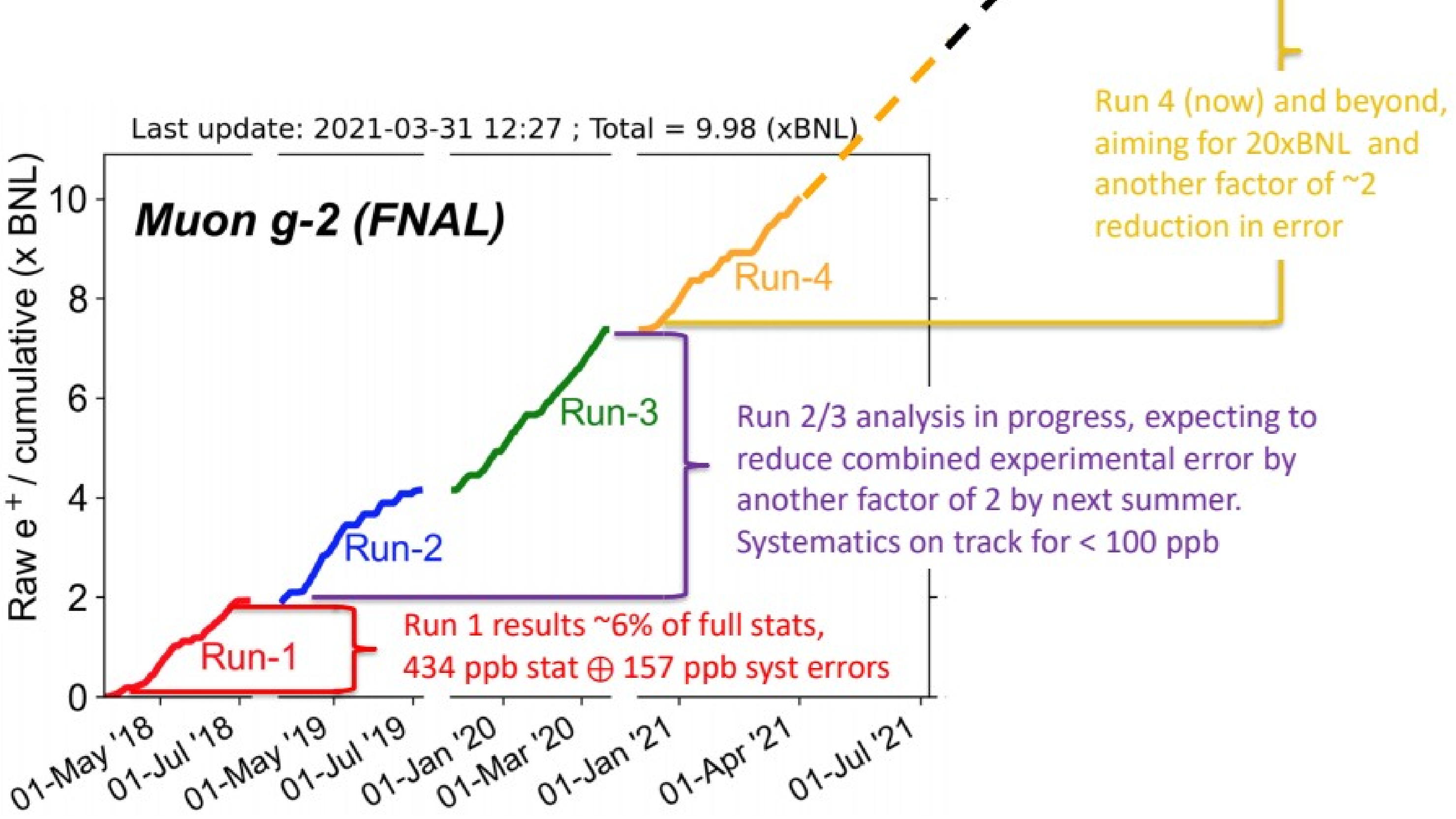
$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11}$$



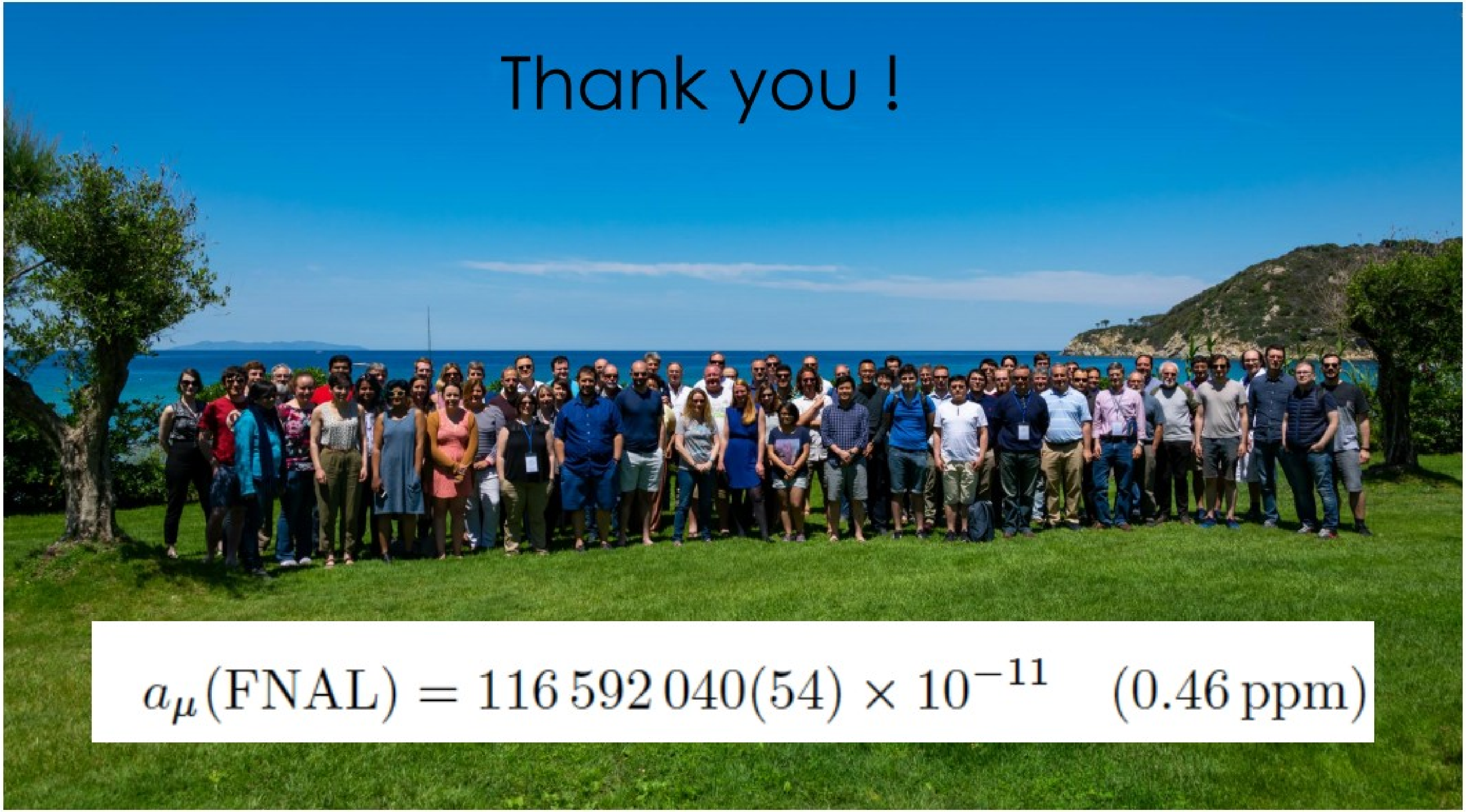
- After 20 years, we confirm the BNL experimental results!
- Combining BNL/FNAL and comparing to theory → 4.2σ tension

Outlook

Much more data to come!



Thank you !



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

Final uncertainties from Run 1

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

- 462 ppb overall error
  - 434 ppb statistical
  - 157 ppb systematic
  - 25 ppb CODATA inputs
- Results for Run 1 are vastly dominated by statistical error
- At 157 ppb systematic error
  - Nearly half of BNL
  - Not quite to 100 ppb goal