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The muon g-2 Experiment

CNR-INO
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CONSIGLIO NAZIONALE DELLE RICERCHE

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CNR-INO & INFN Italy & CERN

on behalf of the g-2 collaboration

IPA2022, Vienna
8 September 2022

INFN
Istituto Nazionale di Fisica Nucleare

Fermilab

www.ino.cnr.it

The muon g-2 Experiment at Fermilab

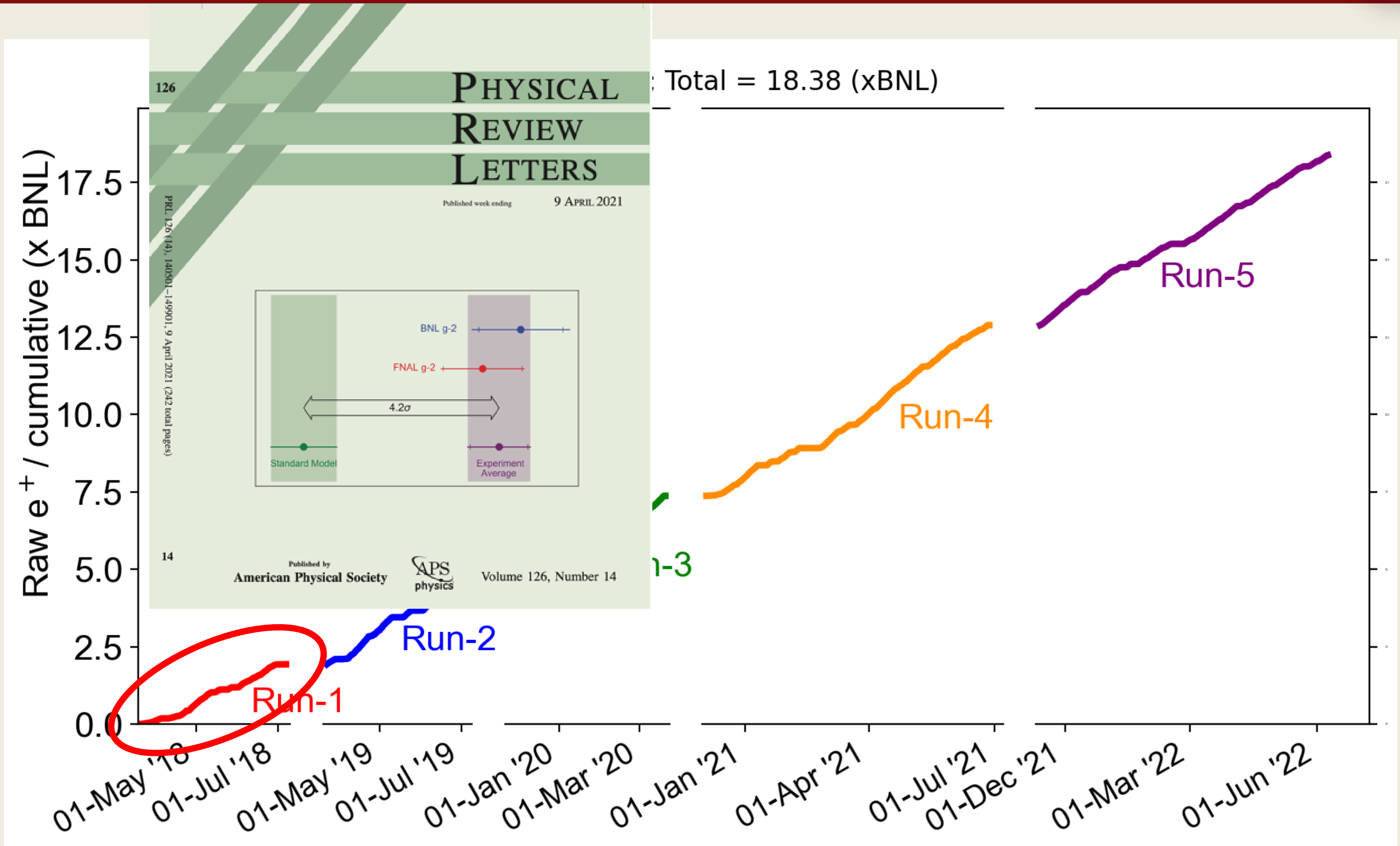
8 Countries, 35 Institutions, 190 Collaborators

- Low energy, high Intensity experiment
- Small scale detectors and collaborations, very high statistics
- Precision measurements, looking for deviations from theory

Outline:

- Brief introduction to a_μ
- Experiment description
- Calculating the a_μ
- Status and outlook

The data



126

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14

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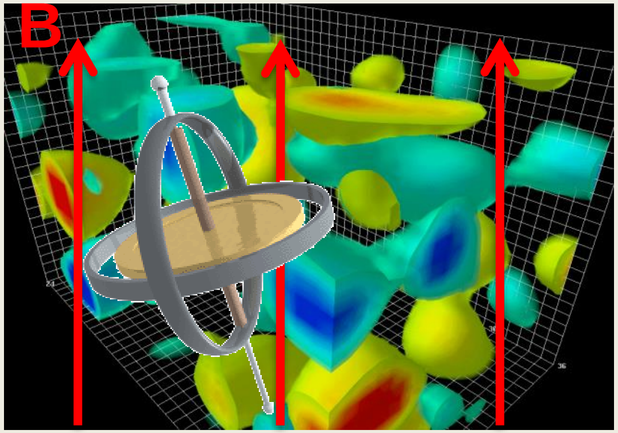
1948: Triumph of QED

g is the proportionality factor between spin and magnetic moment for particle p:

$$\overrightarrow{\mu_p} = -g_p \frac{e}{2m_p} \vec{S}$$

Image Credits: [Derek Leinweber]



- Classical physics: g = 1
- Relativistic quantum mechanics prediction for a point-like particle (Dirac, 1928): g = 2
- For electron, experimentally found to be (Foley & Kush, 1948): $g_e = 2.00119(5)$
- Schwinger figured out why: QED

$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$

1948: Triumph of Quantum Field Theory

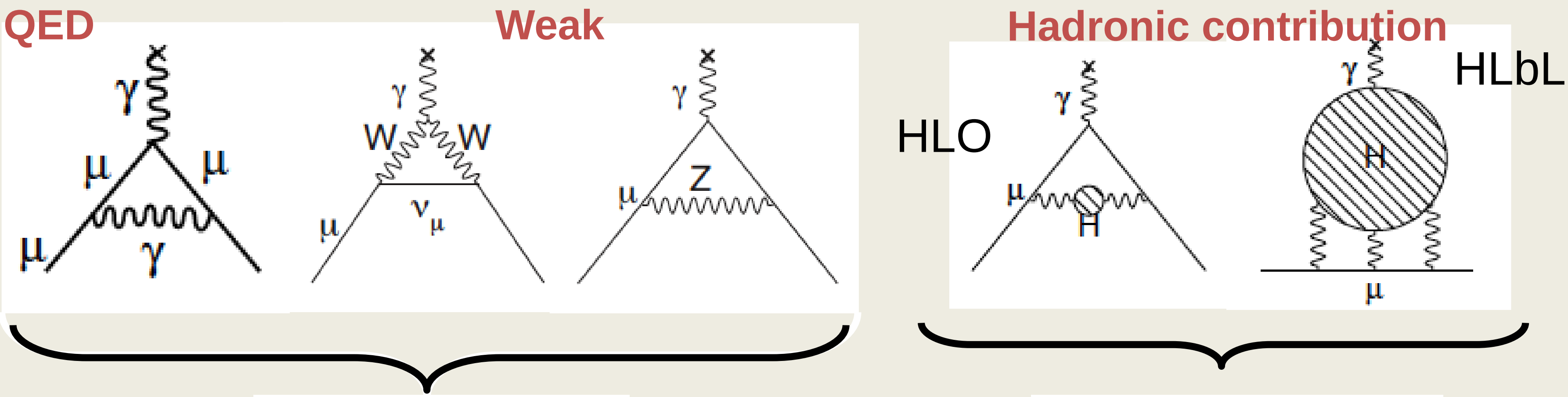
$g_{e,meas}$ = 2.00231930436182(52) [0.25 ppt]

The most precise prediction ever confirmed by experiment [Rev.Mod. Phys. 88, 035009]

Weak and hadronic interaction have small impact on the g_e result

Muons: most interactions are proportional to $(m_\mu / m_e)^2 \approx$ 43.000

a_μ is a better probe for new physics



QED

Weak

Hadronic contribution

HLO

HLbL

Precisely known

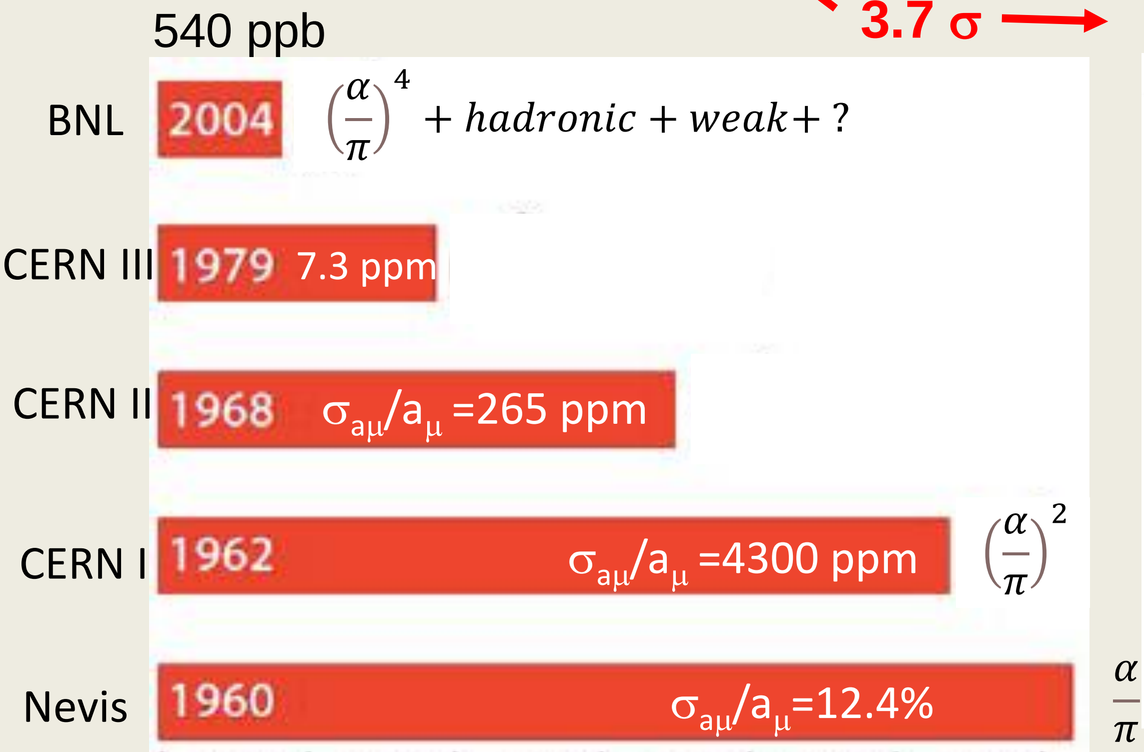
Large uncertainty

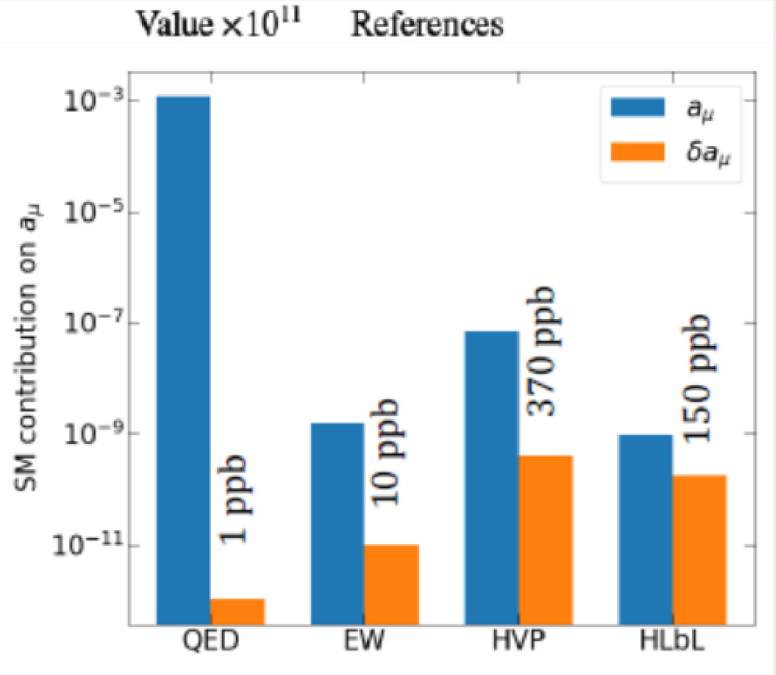
Muon g-2 experiments

$$a_\mu^{BNL} = 116\,592\,089\,(54)_{stat}(33)_{syst}(63)_{Tot} \times 10^{-11}$$ (2001)

3.7 σ

$$a_\mu(\mathrm{SM}) = 116\,591\,810(43) \times 10^{-11}$$

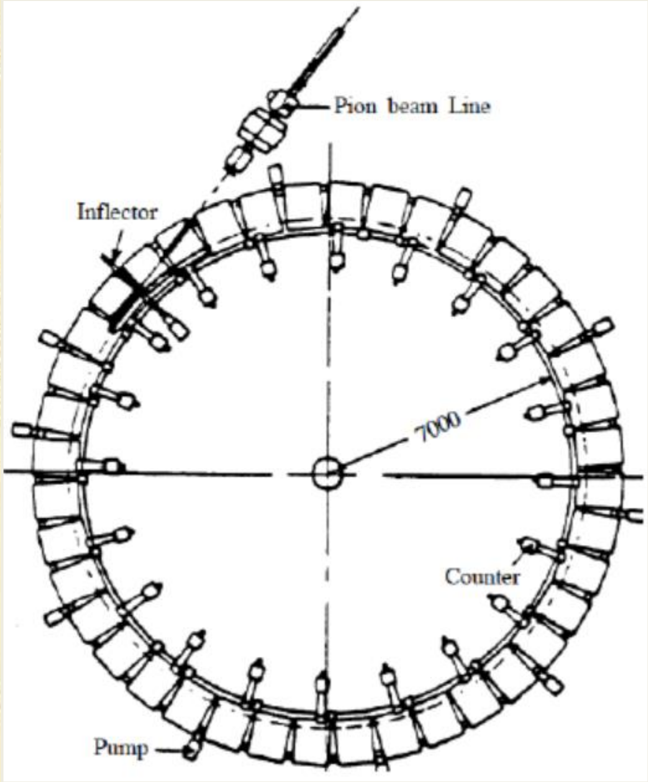




Goal of the E989 experiment at Fermilab:

Reduce the experimental error bar in a_μ by a factor 4 (to 140 ppb)

g-2 muon experiment at CERN (CERN III)

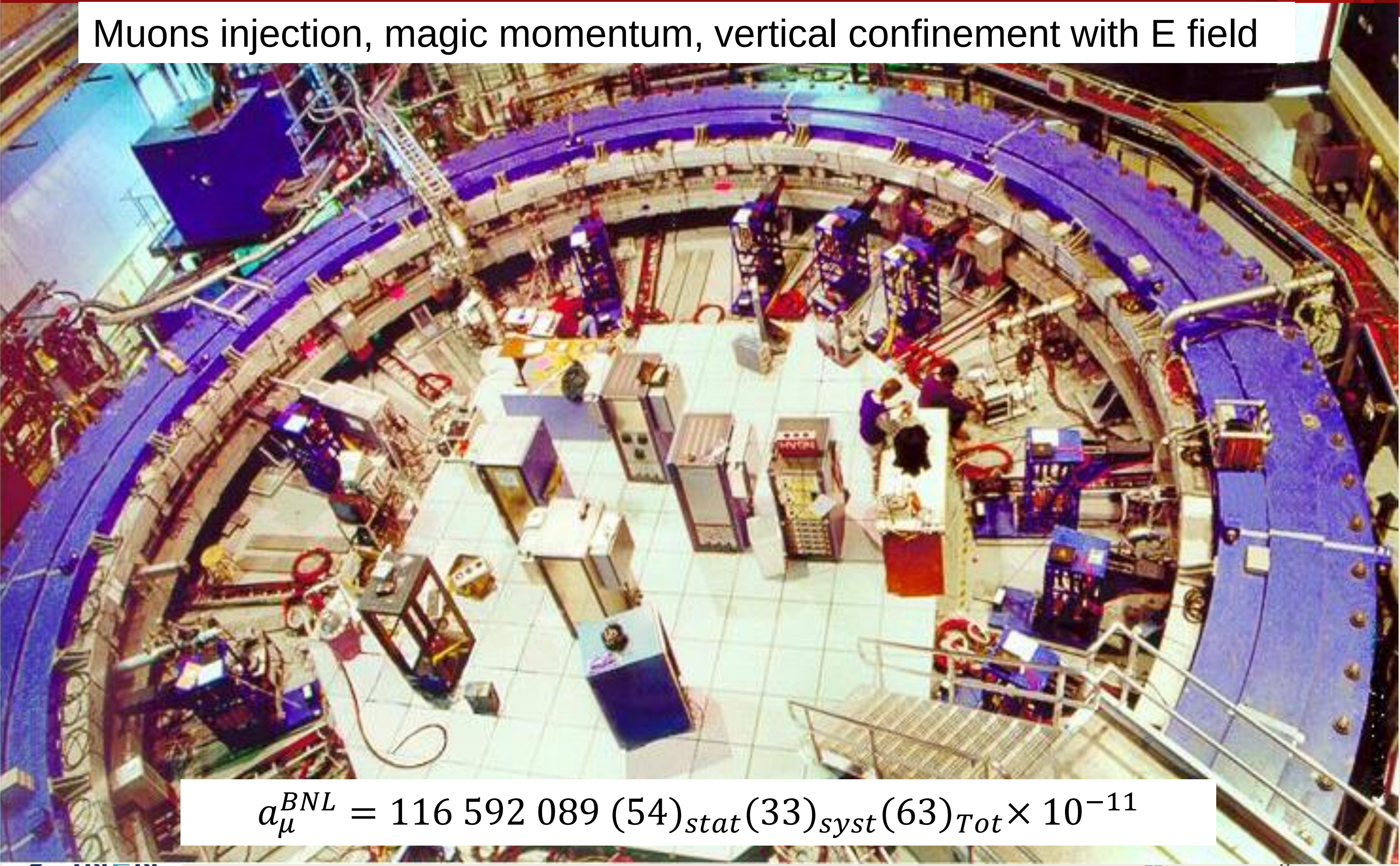


Pions injection, magic momentum, vertical confinement with E field

$$a_\mu = 1\ 165\ 924\ (8.5) \times 10^{-9}\ (7\ \text{ppm}).$$

g-2 muon experiment at Brookhaven (2000’s)

Muons injection, magic momentum, vertical confinement with E field



$$a_\mu^{BNL} = 116\,592\,089\,(54)_{stat}(33)_{syst}(63)_{Tot} \times 10^{-11}$$

The Big Move of the Ring (2013)

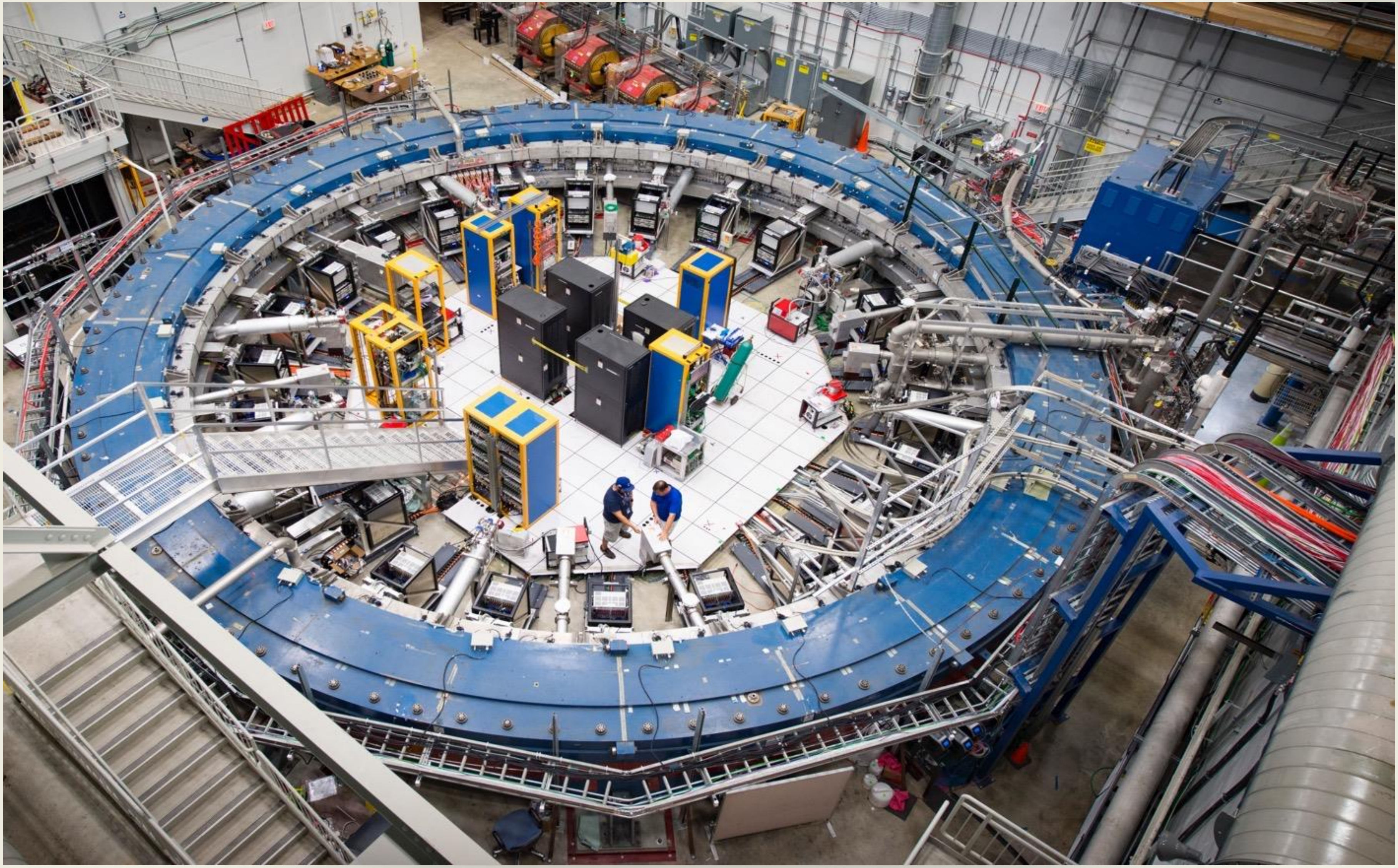
Including 30 miles of Chicago suburbs

Photos


EMMERT
EMMERT

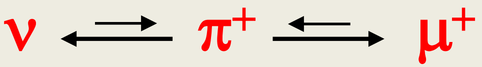

OVERSIZE LOAD
EMMERT
Driving Discovery in Particle Physics

Muon g-2 Storage Ring at Fermilab



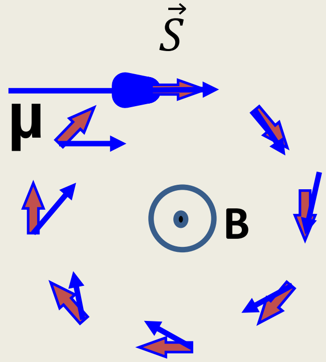
Key ingredients

1) Polarized muons (parity violation in weak decays)



~97% polarized for forward decay

2) Anomalous precession in a B field, proportional to (*g*-2)

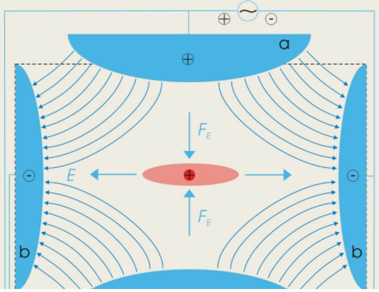


$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

Measure 2 quantities

$$a_\mu = \left(\frac{m}{e}\right)\frac{\omega_a}{B}$$

3) P_m magic momentum = 3.09 GeV/c

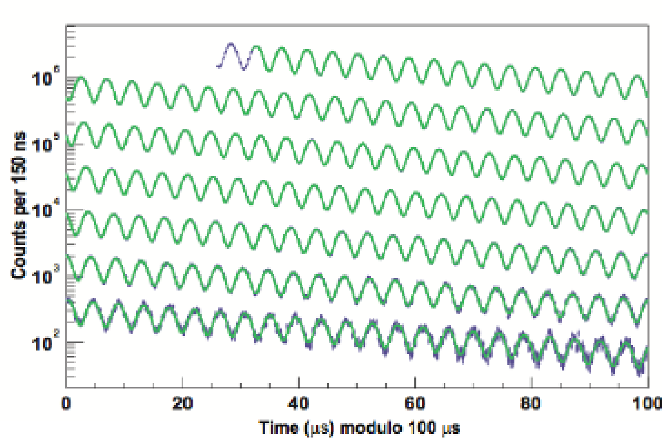


$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \cancel{\frac{1}{\gamma^2-1}}\right)\vec{\beta}\times\vec{E}\right]$$

***E* field doesn't affect muon spin when γ = 29.3**

4) High energy decay e^+ are emitted preferably in spin direction of the muon

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



Towards Fermilab

E821 at Brookhaven

$$\left.\begin{array}{l}\sigma_{stat} = \pm\ 460\text{ ppb}\\ \sigma_{syst} = \pm\ 280\text{ ppb}\end{array}\right\}\ \sigma = \pm\ 540\text{ ppb}$$

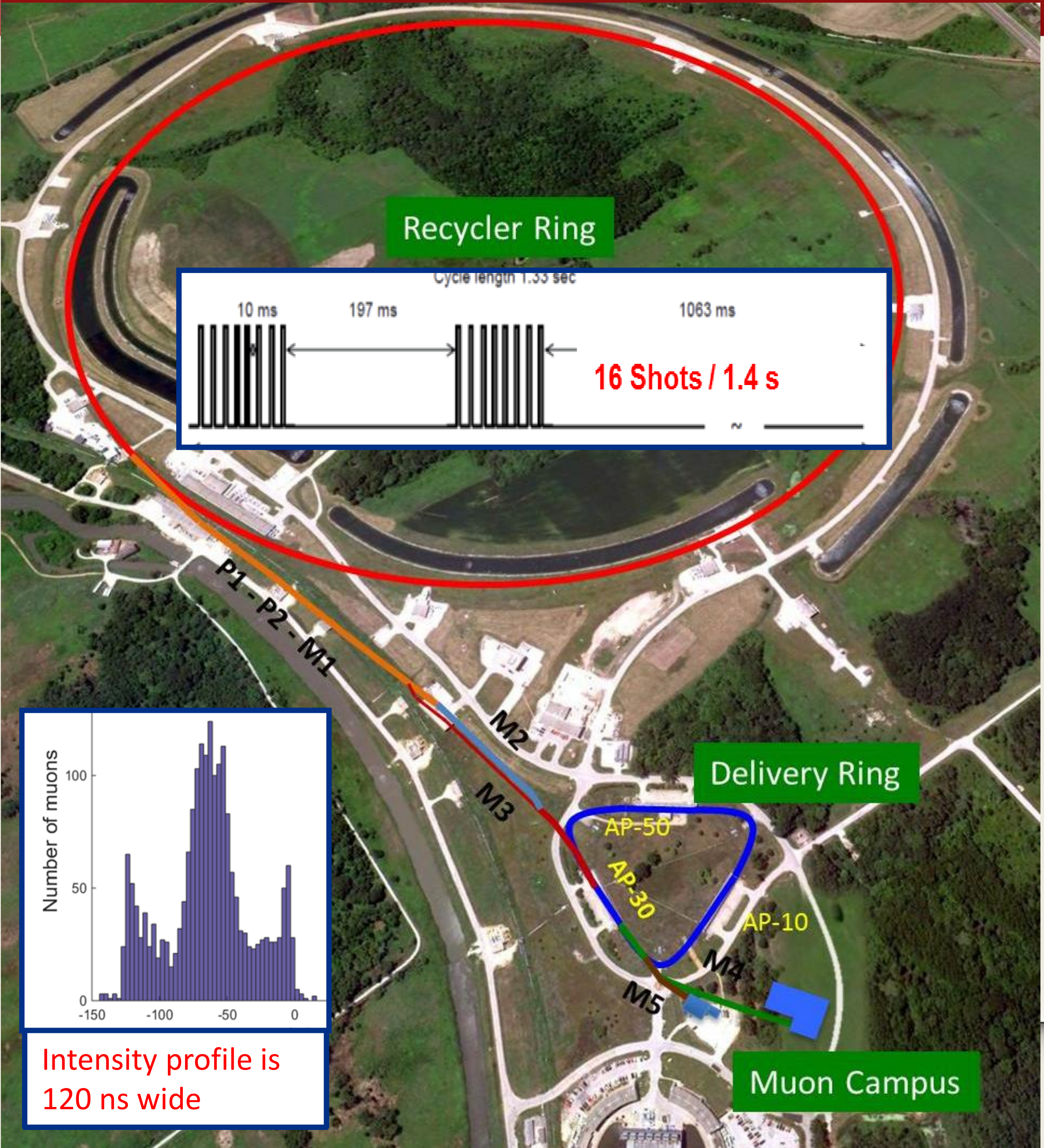
E989 at Fermilab

$$\left.\begin{array}{l}\sigma_{stat} = \pm\ 100\text{ ppb}\\ \sigma_{syst} = \pm\ 100\text{ ppb}\end{array}\right\}\ \sigma = \pm\ 140\text{ ppb}$$

Improvements

- More statistic (positrons x21)
- Improved beam (much less hadronic contamination)
- Improved detectors (segmented calorimeters, SiPM, trackers)
- Laser calibration system (SiPMs gain changes at 1 part in 10^4)
- 800 MHz waveform digitizers sample (twice the rate BNL)
- Simulation tools (Ringsim, GEANT4, COSY, BMAD)
- Magnetic field measurement

Muon beam production

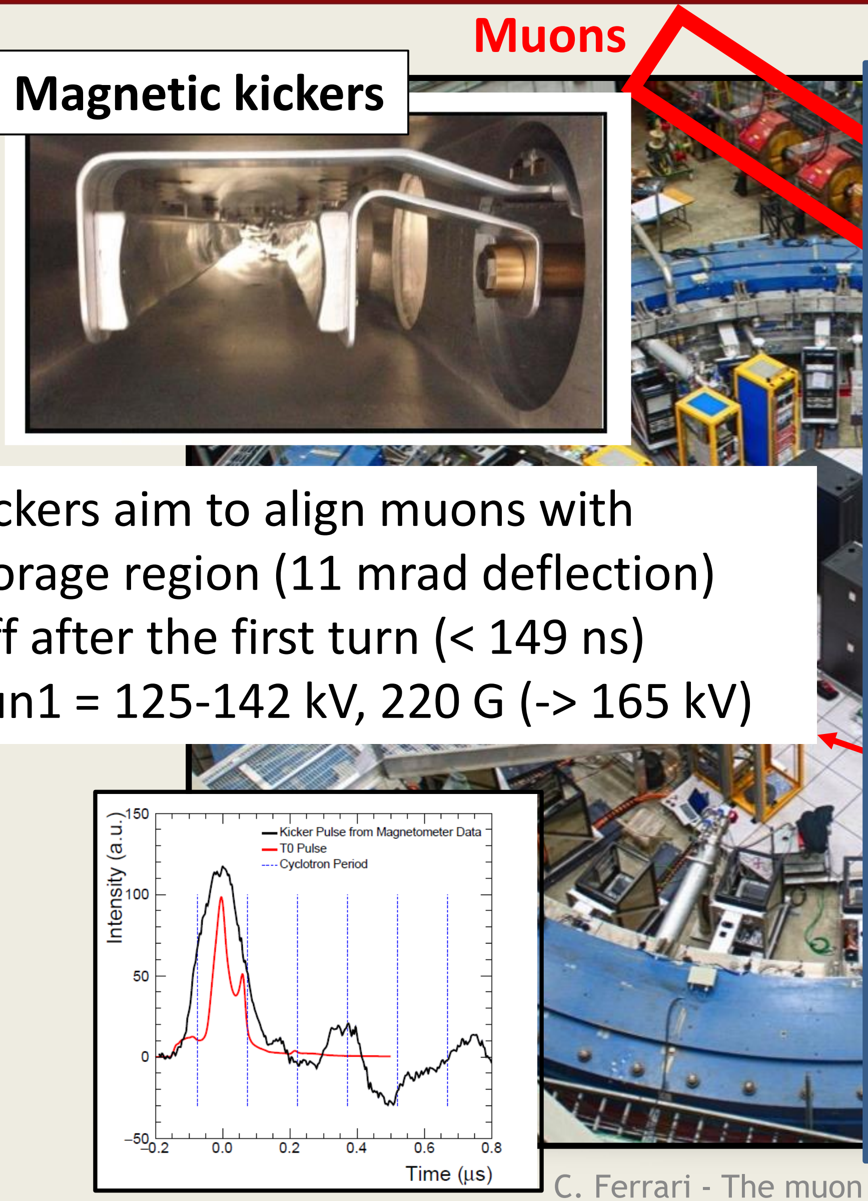


Intensity profile is 120 ns wide

- 10^{12} protons per pulse (~ 9 GeV) batch into Recycler Ring
- hit the production target
- Pion production
- Pion decay to Muons: $\pi^+ \rightarrow \mu^+ \nu_\mu$
- p/π/m beam enters DR; protons kicked out
- Fermilab's Muon Campus beamlines transport ~ 3.1 GeV/c muons to storage ring
- μ enter storage ring and decay to e^+, 700 μs fill, at 15 Hz

The ring

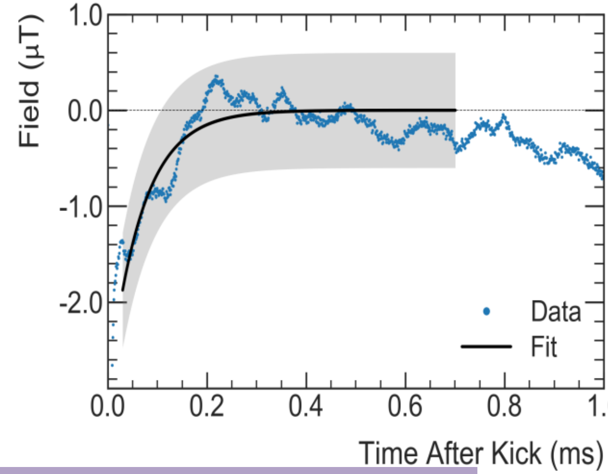
3 Magnetic kickers



Kickers aim to align muons with storage region (11 mrad deflection)
Off after the first turn (< 149 ns)
Run1 = 125-142 kV, 220 G (-> 165 kV)

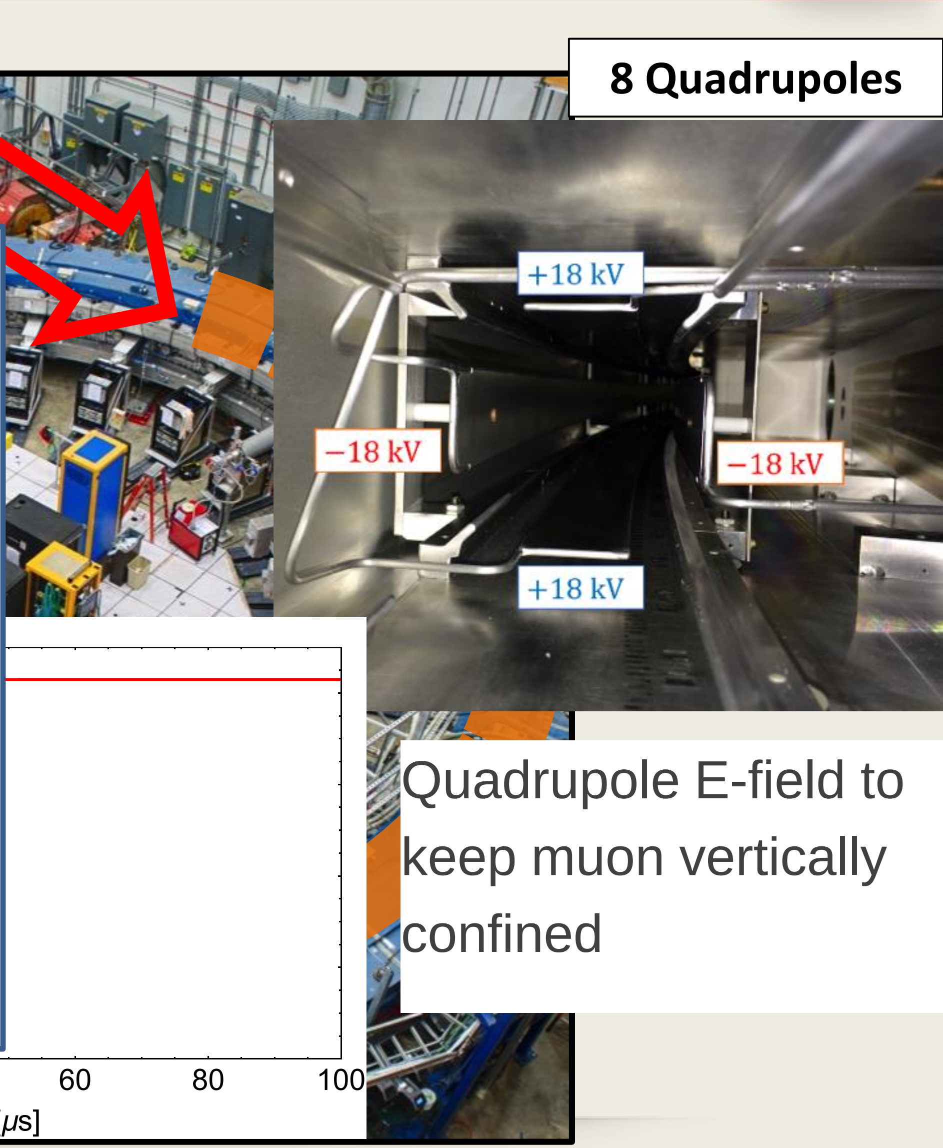
Kicker transient field

- Fast kicker pulses impedance mismatch induces Eddy currents.
- Faraday magnetometer using fibers measured the kicker transient field (laser polarization rotates in TGG crystal in presence of the magnetic field).



$B_k = -27(37)$ ppb for Run-1

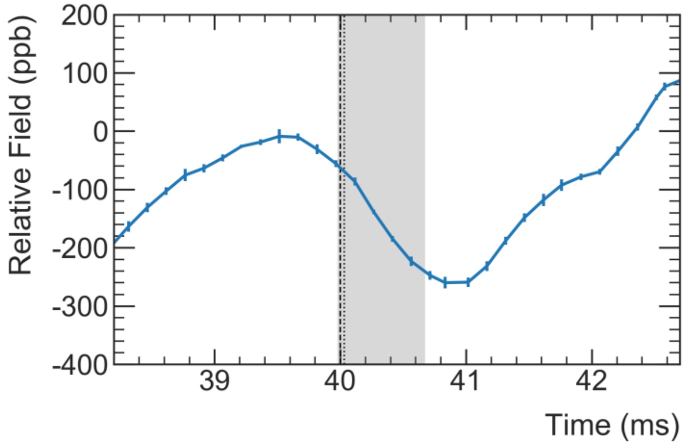
The ring



Quadrupole E-field to keep muon vertically confined

Quad plates mechanical vibration

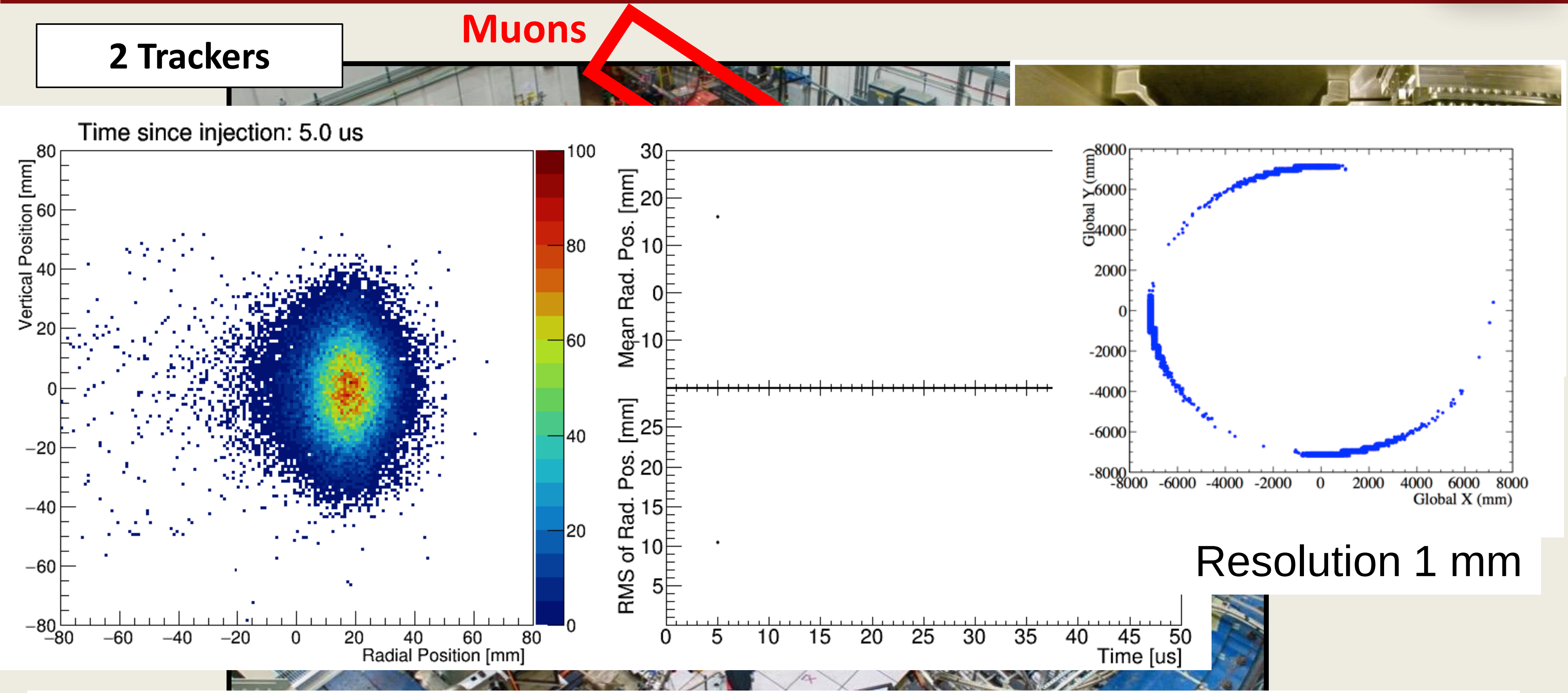
- The ESQ plates are pulsed at 100 Hz.
- Mechanical vibrations induce a magnetic field transient in the storage region.



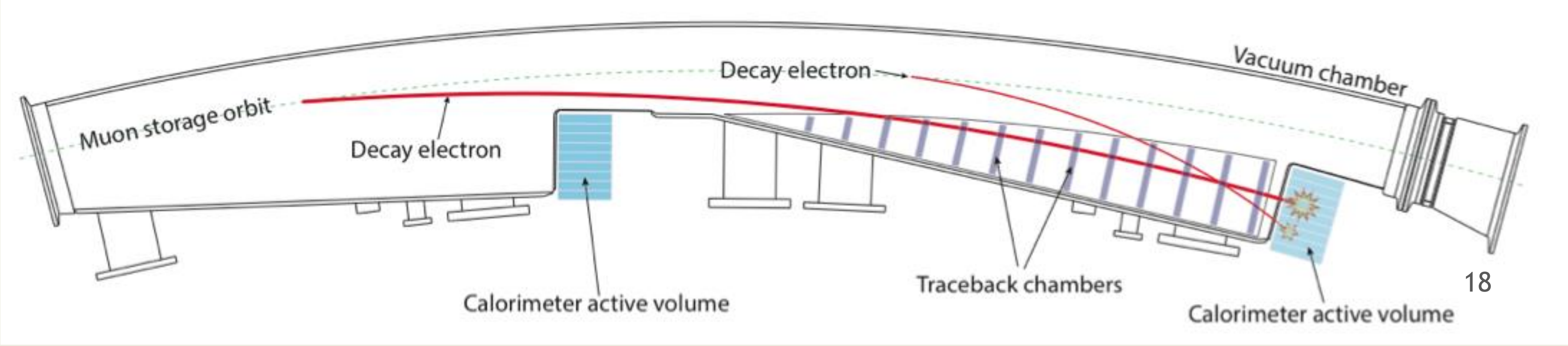
$B_q = -17(92)$ ppb for Run-1

The ring

2 Trackers

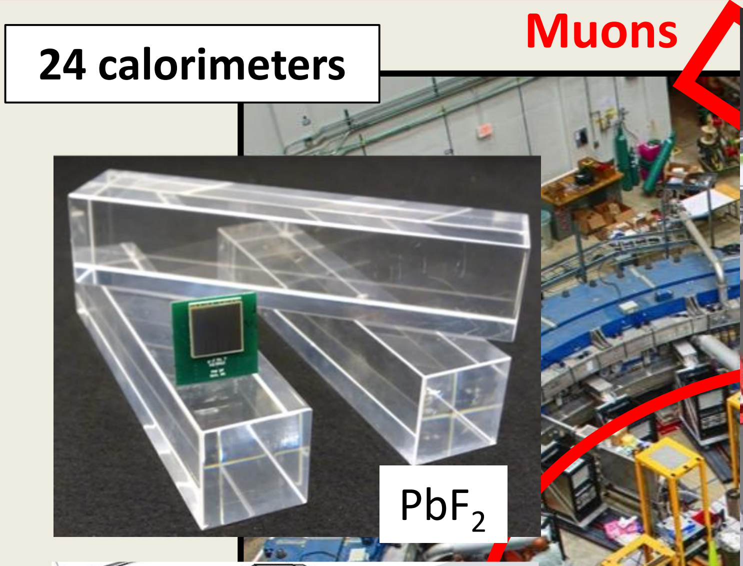


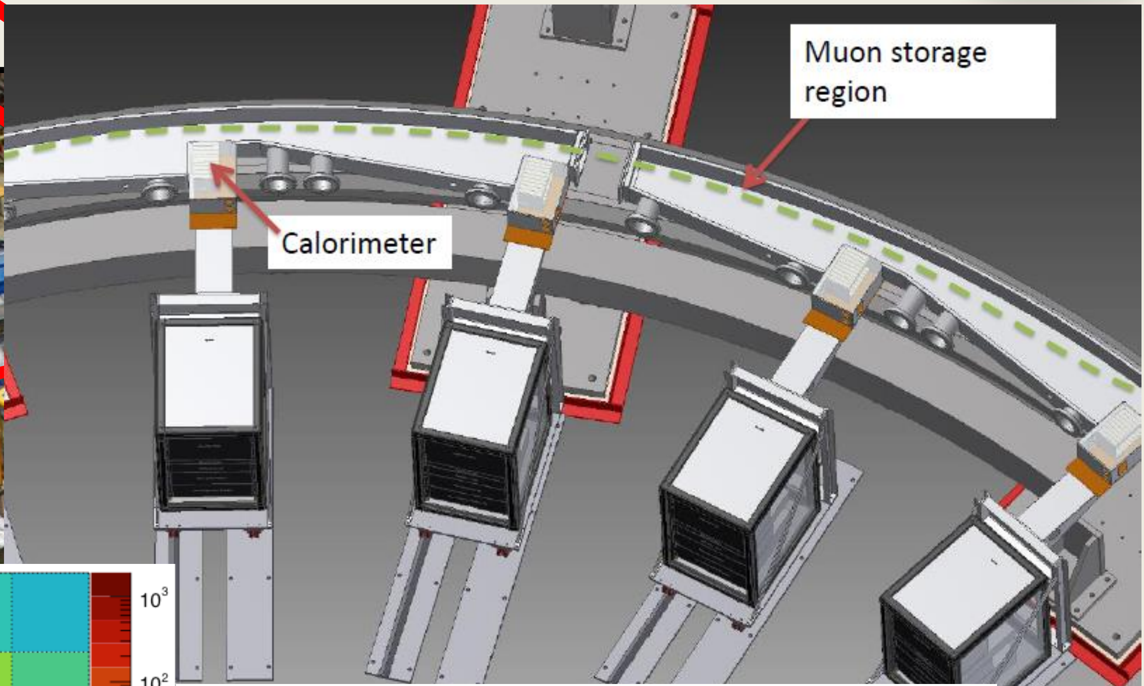
Resolution 1 mm

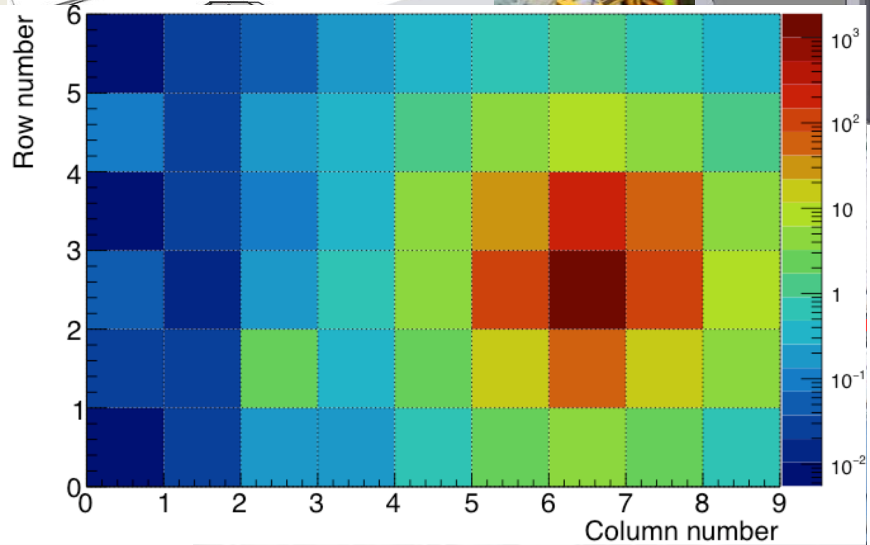


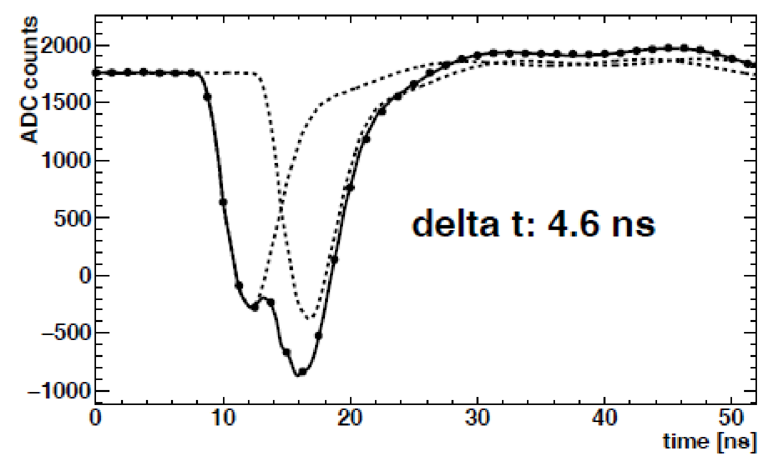
The ring

24 calorimeters





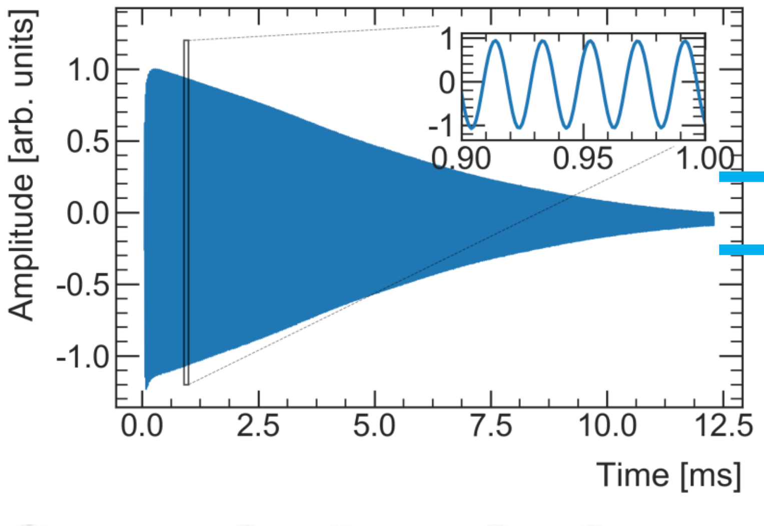


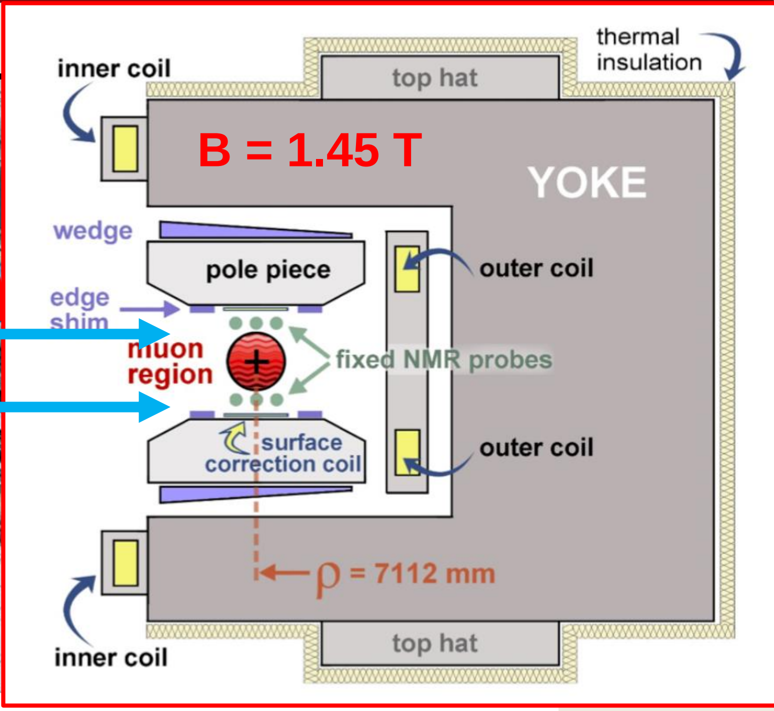


The magnet

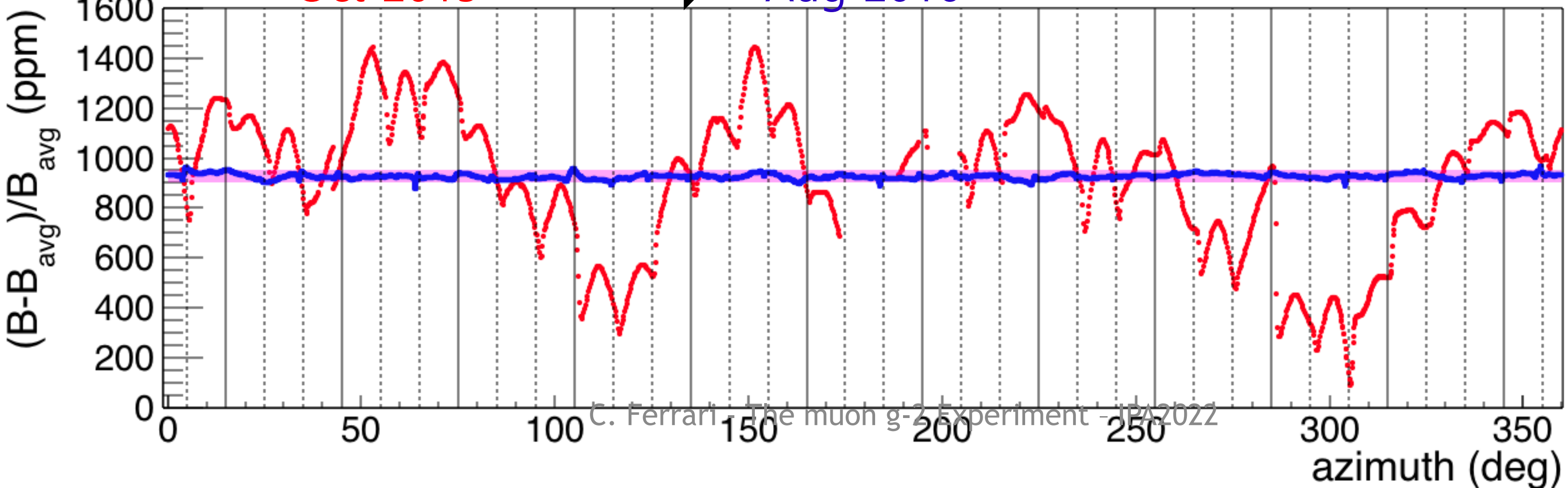
Muons

FID signals from 378 NMR probes





Oct 2015 → Aug 2016

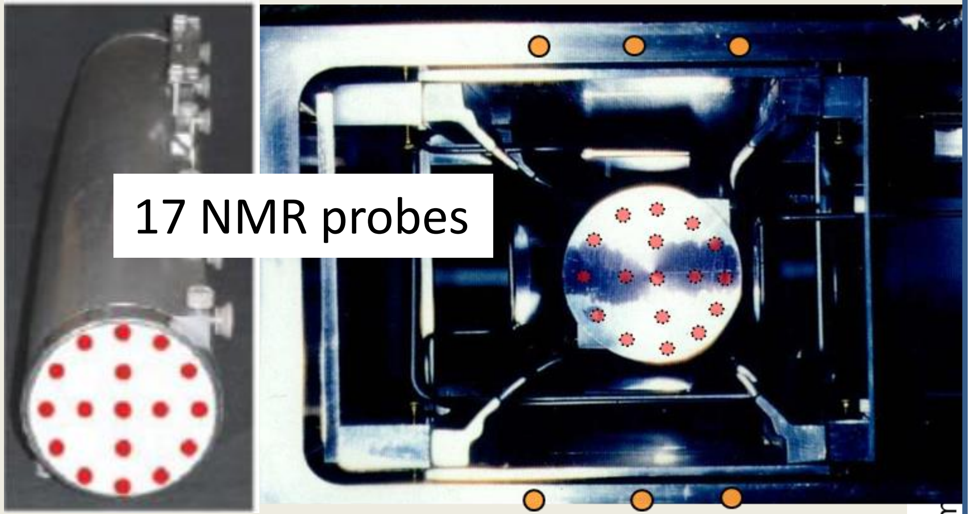


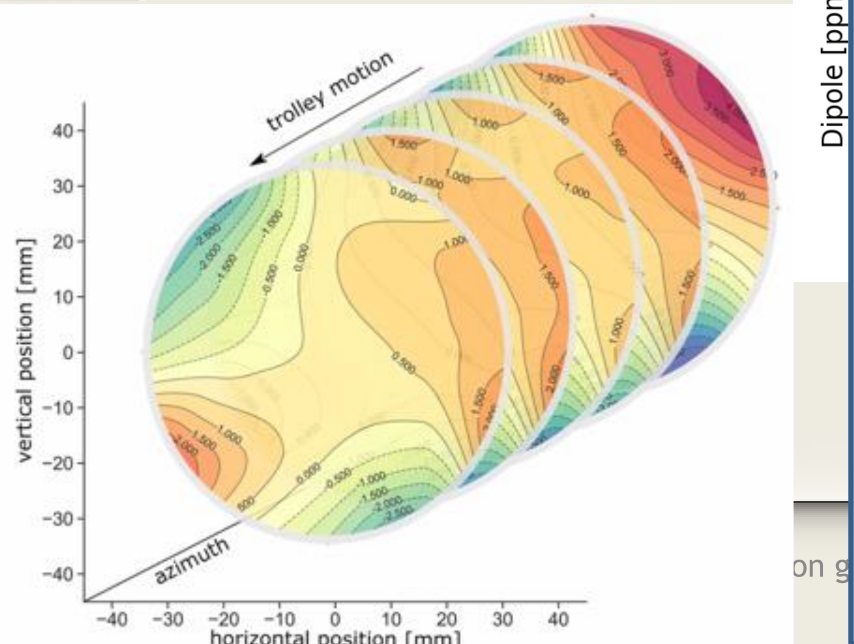
50 ppm

3X BNL

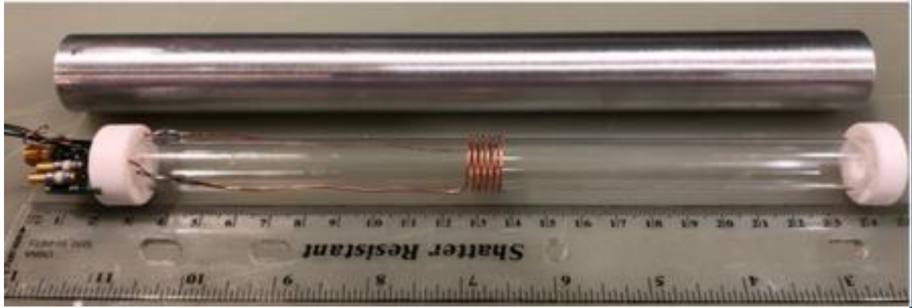
The NMR probes calibration

NMR trolley maps field every 3 days





Trolley absolute calibration:
plunging probe with water sample



Absolute probes all cross-calibrated at the ANL test magnet

Consistent with BNL probe to 6 ppb and with new ^{3}He probe to 38 ppb

The magnetic anomaly $a_\mu = (g - 2)/2$

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T, T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

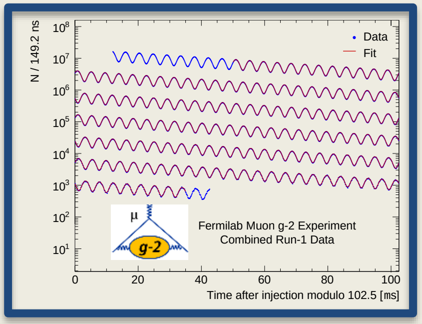
Measured quantities

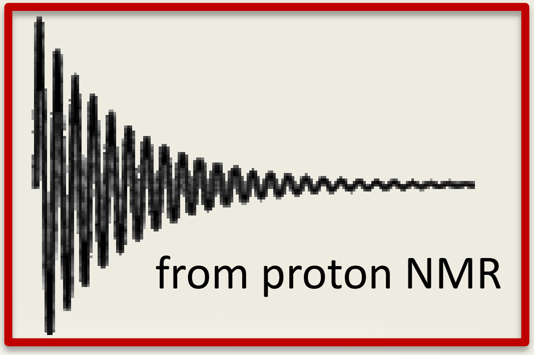
External data, total uncertainties: 25 ppb

$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \approx$$

ω_p= **Larmor precession frequency of protons in water (mapping B)**

ω_a





Precession of muons and protons in the same B field

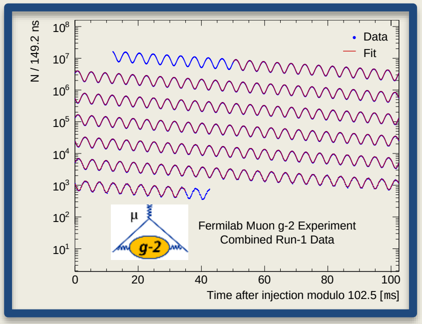
The magnetic anomaly $a_\mu = (g - 2)/2$

$$a_\mu = \boxed{\frac{\omega_a}{\tilde{\omega}'_p(T, T_r)}} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

Measured quantities

External data, total uncertainties: 25 ppb

ω_a



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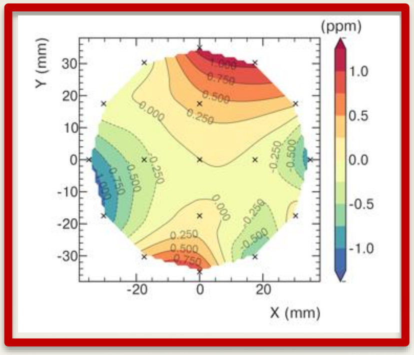
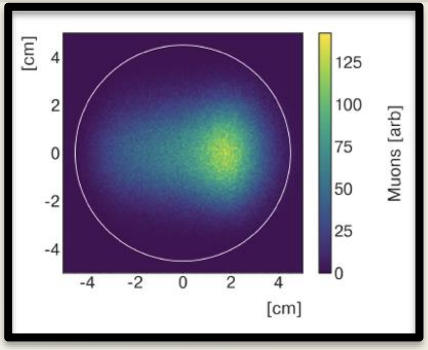


$\otimes$



M = Muon distribution in the storage ring

$$\tilde{\omega}_p = \omega_p(x, y, \varphi) \otimes M(x, y, \varphi)$$

The master formula

Measured $g-2$ frequency

Corrections from the beam dynamics systematic effects

Unblinding conversion factor

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\;\omega_a^m\,(1+\overbrace{C_e+C_p+C_{ml}+C_{pa}})}{f_{\text{calib}}\;\underbrace{\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle}(1+\underbrace{B_k+B_q})}$$

NMR probe calibration factor

Magnetic field weighted over the muon distribution and azimuthally averaged

Corrections from the transient magnetic field

$\boldsymbol{\delta \sim 38\,ppb}$

$\boldsymbol{\delta_{\omega_p} \sim 48\,ppb}$

$\boldsymbol{\delta_{Bk} \sim 37 ppb}$

$\boldsymbol{\delta_{Bq} \sim 92\,ppb}$

Both ω_a^m and ω_p frequencies are measured by a single 10 MHz, GPS master clock.
A $(40-\epsilon)$ MHz blinded frequency (± 25 ppm) is used for ω_a^m.

Uncertainty due to:
1. Temperature Corrections
2. Configuration Corrections
3. Trolley Map Systematics
4. Fixed Probe Systematics
5. Tracking Drift Uncertainty

The ω_a^m analysis strategy

- 6 independent analysis groups using different Reconstruction algorithms and different Fit methods
- Q-method is completely different from all others: it has a larger error
  → used as crosscheck
- 2 Independent Reconstruction algorithms developed (East, West)

Team	Reconstruction	Analysis
CU (Cornell)	East	T, E
UW (Washington)	West	T, A
Europa (INFN+UK)	West/Europa	T, A
SJTU (Shangai)	West	T, E
BU (Boston)	West	T, R
Uky (Kentucky)	Q	Q

T-method: count all positrons with E>1.7GeV and plot them vs time to get the «*Wiggle plot*» ; reference method

E-method (Energy binned): fit each energy slice, combine the resulting values for ω_a

A-method (Asimmetry weighted): weight each event with its own contribution to asimmetry A(E). From the statistical point of view, this method uses most information.

Ratio method: randomly split dataset in 2 subsets shifted by ±half a g-2 period, build combinations of the 2 subsets which eliminates the exponential behavior and leaves just a sinusoidal term

Q method No clustering: just integrate energy above threshold. The total energy per event fluctuates with ω_a frequency

The ω_a^m fit equation (22 parameters)

$$N_0\, e^{-\frac{t}{\gamma\tau}}\, (1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$\phi_{\mathrm{BO}}(t) = 1 + A_\phi \cos(\omega_{\mathrm{CBO}}(t) + \phi_\phi) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{CBO}}(t) = 1 + A_{\mathrm{CBO}} \cos(\omega_{\mathrm{CBO}}(t) + \phi_{\mathrm{CBO}}) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

$$N_{2\mathrm{CBO}}(t) = 1 + A_{2\mathrm{CBO}} \cos(2\omega_{\mathrm{CBO}}(t) + \phi_{2\mathrm{CBO}}) e^{-\frac{t}{2\tau_{\mathrm{CBO}}}}$$

$$N_{\mathrm{VW}}(t) = 1 + A_{\mathrm{VW}} \cos(\omega_{\mathrm{VW}}(t) t + \phi_{\mathrm{VW}}) e^{-\frac{t}{\tau_{\mathrm{VW}}}}$$

Red = free parameters

Blue= fixed parameters

$$N_y(t) = 1 + A_y \cos(\omega_y(t) t + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

Muon Loss term

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

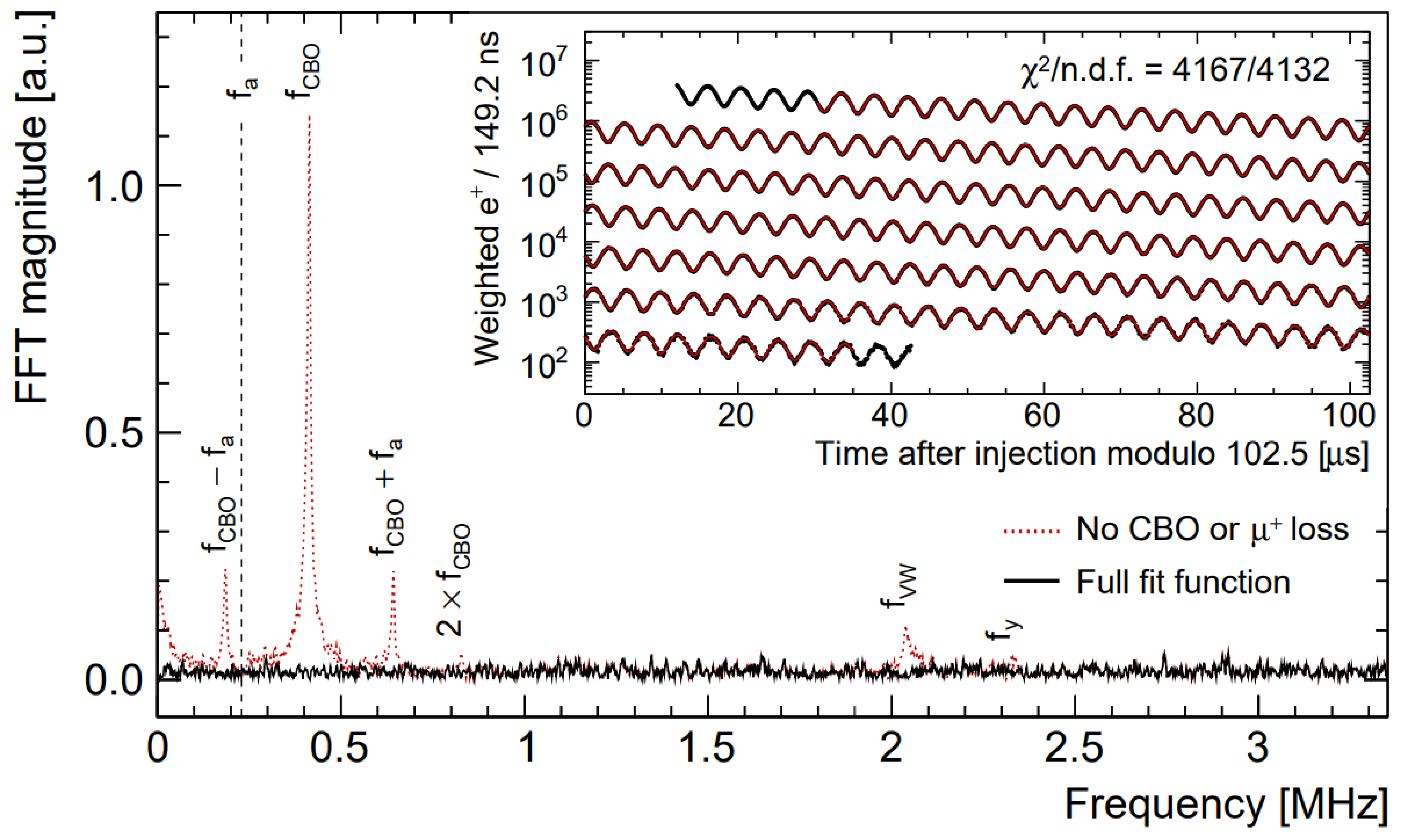
$$\omega_y(t) = F \omega_{\mathrm{CBO}(t)} \sqrt{2\omega_c / F \omega_{\mathrm{CBO}}(t) - 1}$$

$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

ω_y, ω_{vw} vertical oscillations

ω_{CBO}, $\omega_{2\mathrm{CBO}}$, radial oscillation

The ω_a^m fit equation: residuals



The ω_a^m Run 1 results

- First beam injected into ring on May 31, 2017
- Run 1 (FY18): Total statistics = 8.2B e^+ ~ 1.2 x BNL
- Conditions not stable, fragmented data sets taken in different Quad and Kicker conditions, while optimizing Storage Ring operations

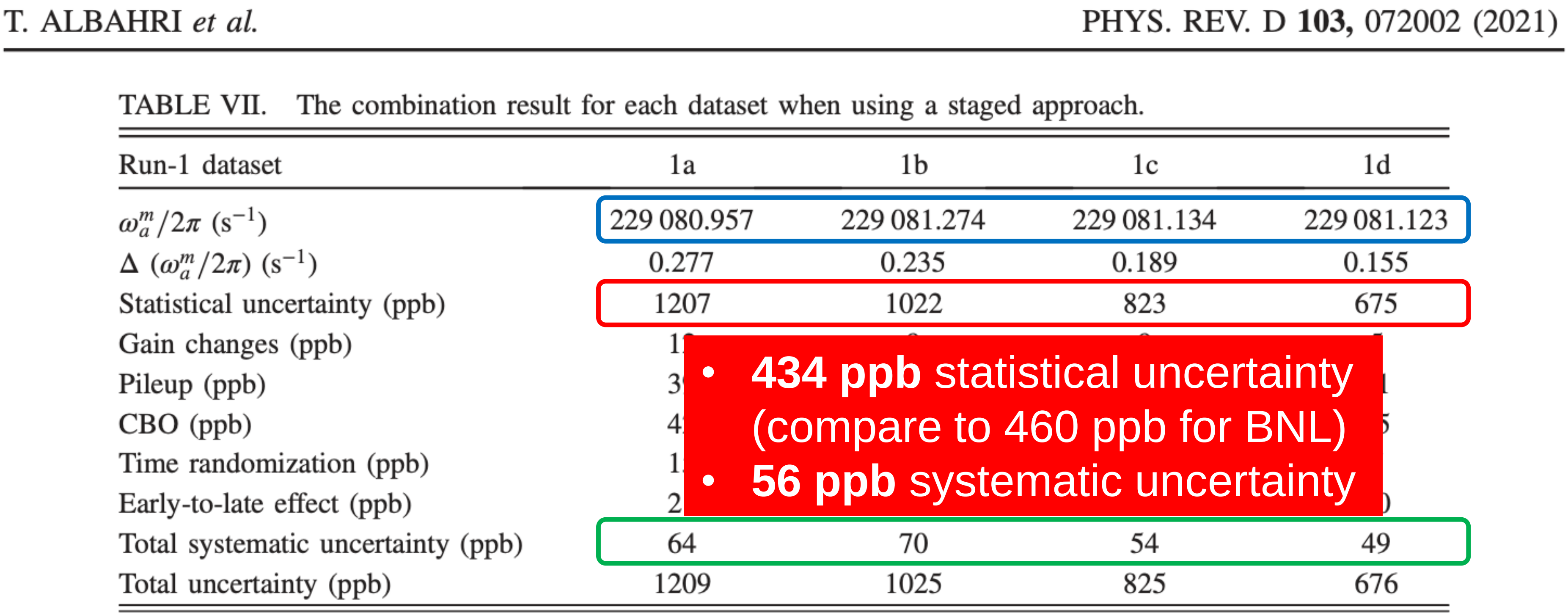


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TABLE VII. The combination result for each dataset when using a staged approach.

Run-1 dataset	1a	1b	1c	1d
$\omega_a^m/2\pi$ (s^{-1})	229 080.957	229 081.274	229 081.134	229 081.123
Δ ($\omega_a^m/2\pi$) (s^{-1})	0.277	0.235	0.189	0.155
Statistical uncertainty (ppb)	1207	1022	823	675
Gain changes (ppb)	[illegible]	[illegible]	[illegible]	[illegible]
Pileup (ppb)	[illegible]	[illegible]	[illegible]	[illegible]
CBO (ppb)	[illegible]	[illegible]	[illegible]	[illegible]
Time randomization (ppb)	[illegible]	[illegible]	[illegible]	[illegible]
Early-to-late effect (ppb)	[illegible]	[illegible]	[illegible]	[illegible]
Total systematic uncertainty (ppb)	64	70	54	49
Total uncertainty (ppb)	1209	1025	825	676

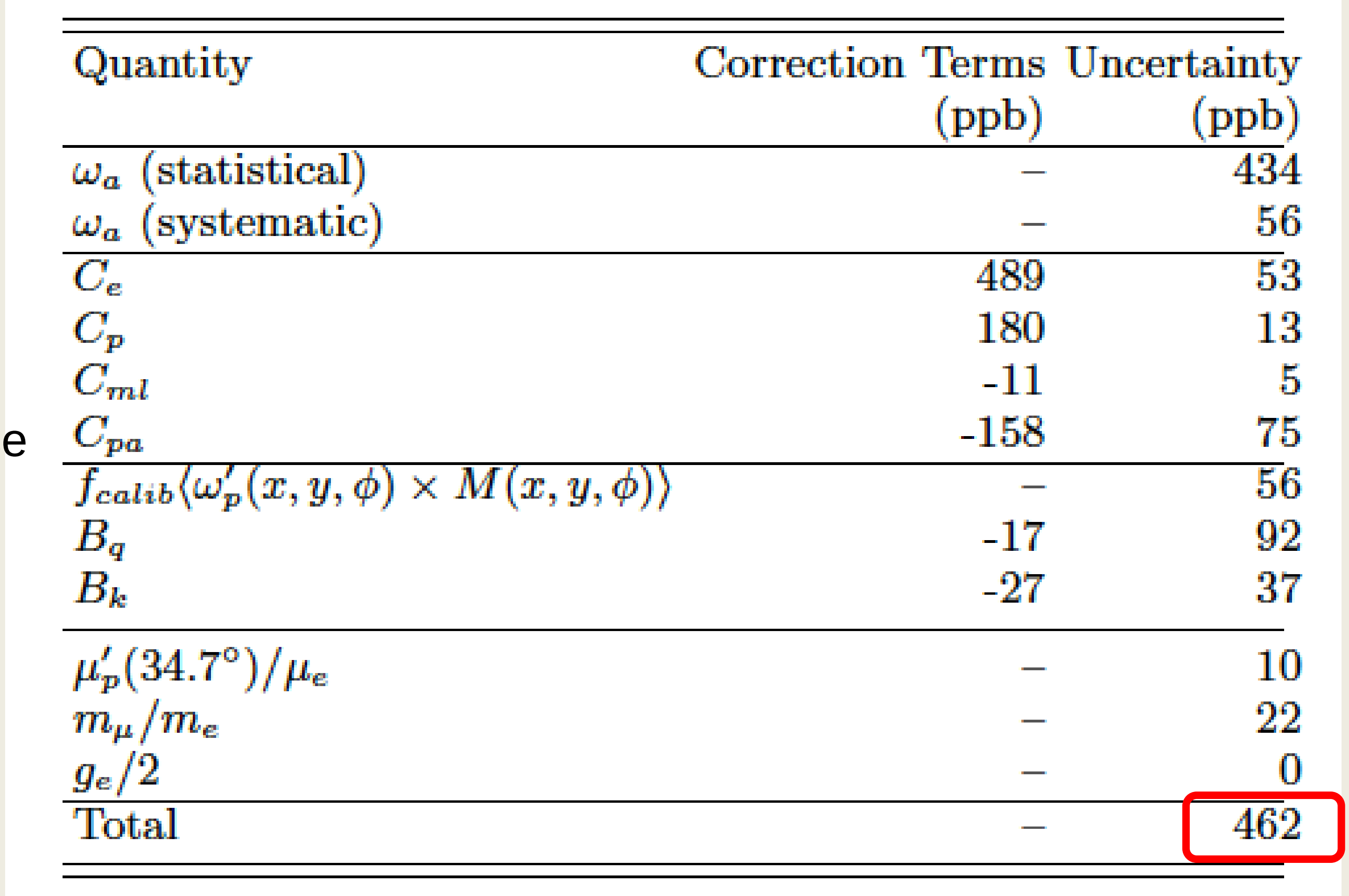
- **434 ppb** statistical uncertainty (compare to 460 ppb for BNL)
- **56 ppb** systematic uncertainty

The a_μ Run 1 results

Taking into account the other corrections: $a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11}$

E-field correction
Pitch correction
Muon loss
Phase-Acceptance

Enhanced by the Run 1 conditions



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

434 ppb stat ⊕ 157 ppb syst error

References

PRAB

Beam dynamics

Phys. Rev. Accel. Beams **24**, 044002

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

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PRA

B field determination

Phys. Rev. A **103**, 042208

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

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PRD

Muon precession

Phys. Rev.D **103**, 072002

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

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PRL

Phys. Rev. Lett. **126**, 141801

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

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C. Strohman,[6] T. Stuttard,[36] H. E. Swanson,[48] G. Sweetmore,[40] D. A. Sweigart,[6] M. J. Syphers,[22,7]
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(The Muon $g-2$ Collaboration)

Comparison with theory

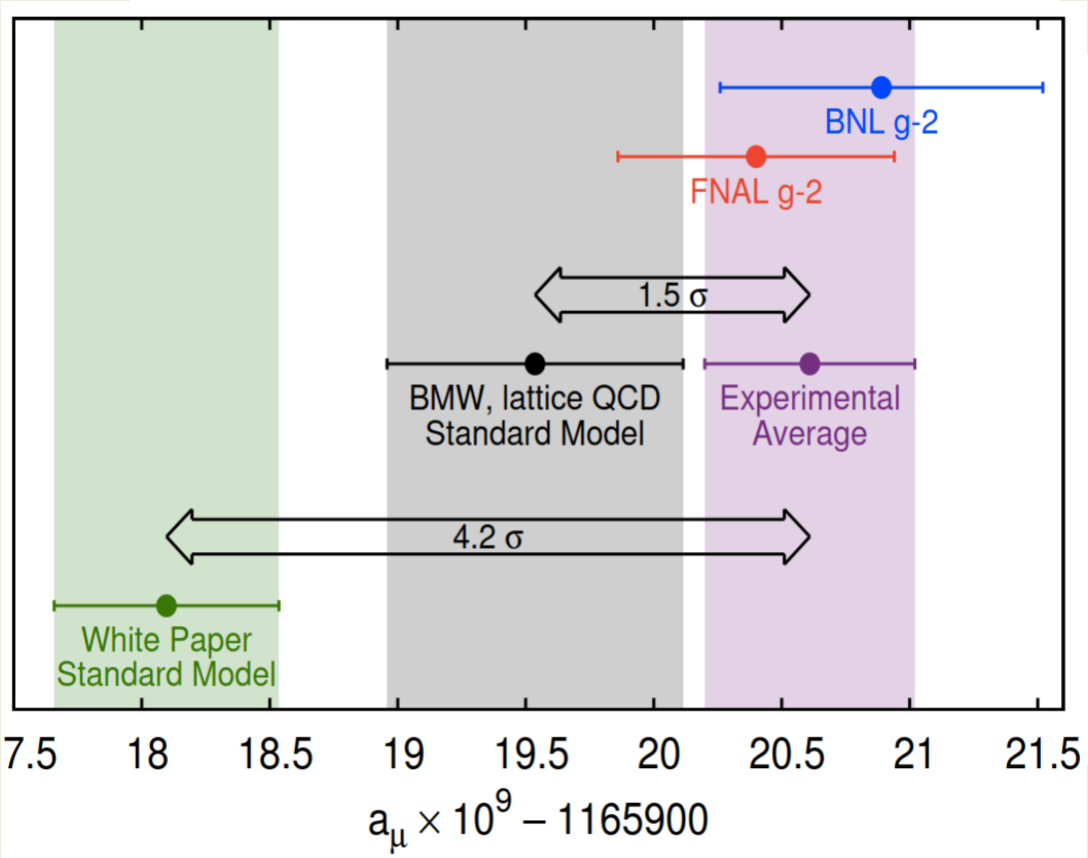
Combining BNL/FNAL and comparing to e+e- based theory by the Theory Initiative → 4.2σ tension with the SM

Lattice QCD (blue band) are becoming competitive

Recent evaluation(s) of HVP from lattice (BMW20) in tension with the e^+e^- evaluation (WP20), at 2σ

Data-driven evaluation (R-ratio) on firm ground. Unlikely to be wrong…

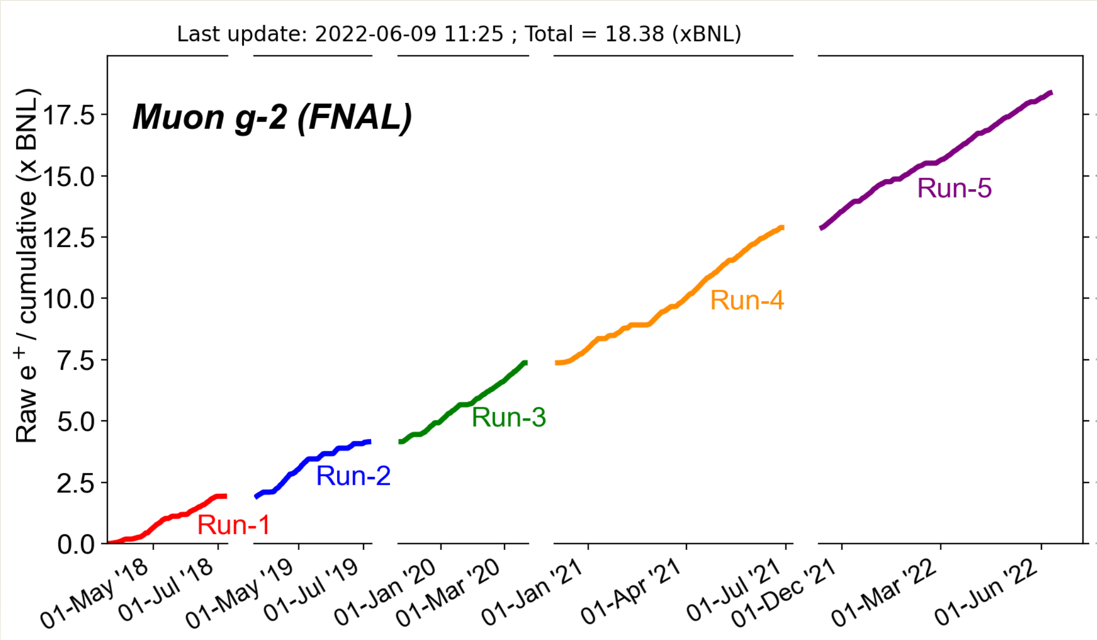
New experiment: MUonE



Conclusion

- We have determined a_μ to an unprecedented 460 ppb precision
- The Run 1 result $a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11}$
  - 6% of ultimate data sample
  - confirm the BNL experimental results
  - 15% smaller error than BNL
  - 3.3σ tension with e+e- SM
- Next year release of Run 2&3
- Analysis of Run 4&5 ongoing
- Run 6 (opportunistic) approved
- New experiment: J-PARC

We have collected ~19 x BNL over the last 5 years



The *g*-2 Collaboration (experiment E989)

Thank you for your attention

Backup slides

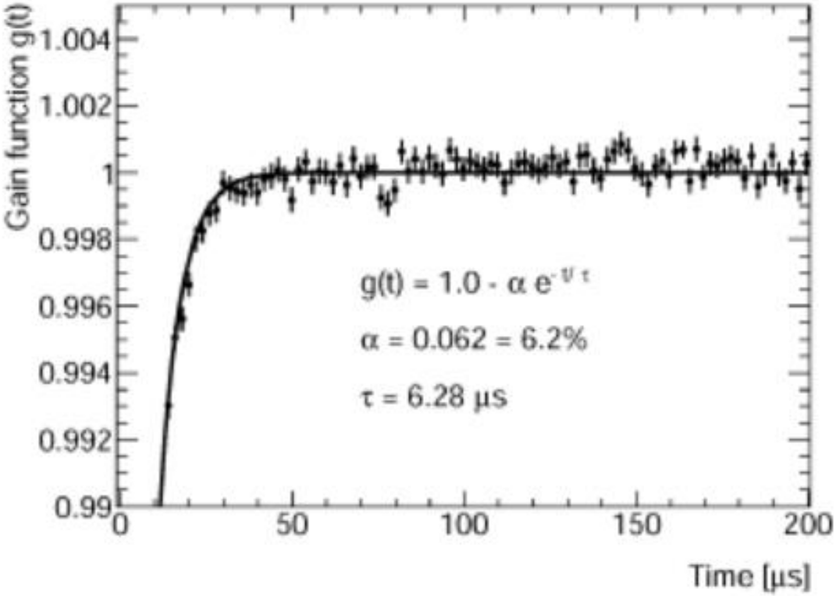
Backup

Laser calibration system

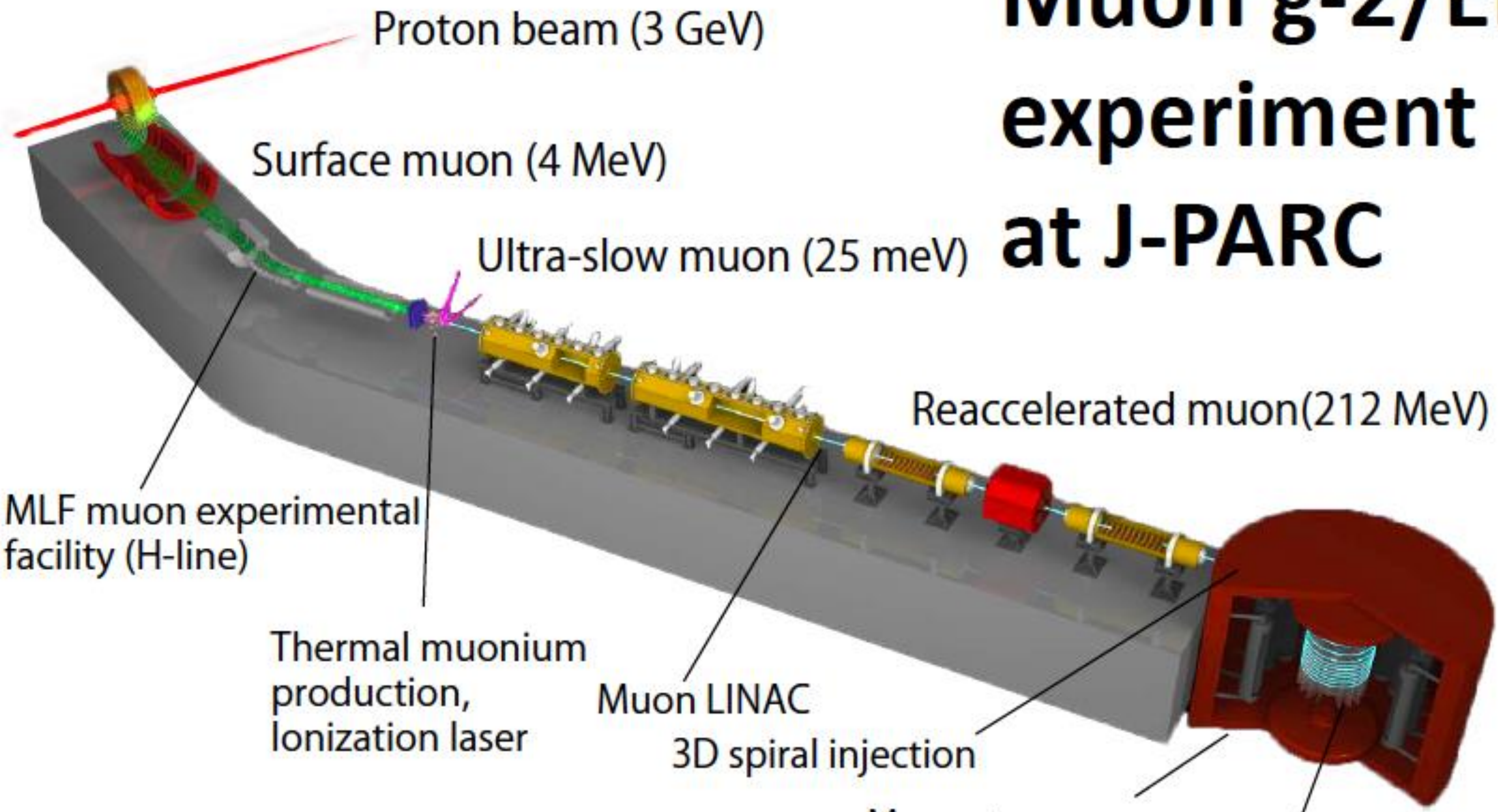
Systematic	Improvements	BNL [ppb]	FNAL [ppb]
Gain changes	Laser gain calibration	120	20
Pileup	Segmented Čerenkov calorimeter	80	40
Lost Muons	Beam Collimation	90	20
Betatron Oscillations	High n value, beamline match	70	<30
E-field and Pitch	Better tracking, improved simulation	50	30
Quadrature sum		180	70

SiPM gain issues:

- Gain sag at the beginning of the fill (beam splash) ~ μs
- Pixel recovery after one hit ~ ns
- SiPM aging and temperature/bias voltage slow drift (affect energy threshold)



Muon g-2/EDM experiment at J-PARC

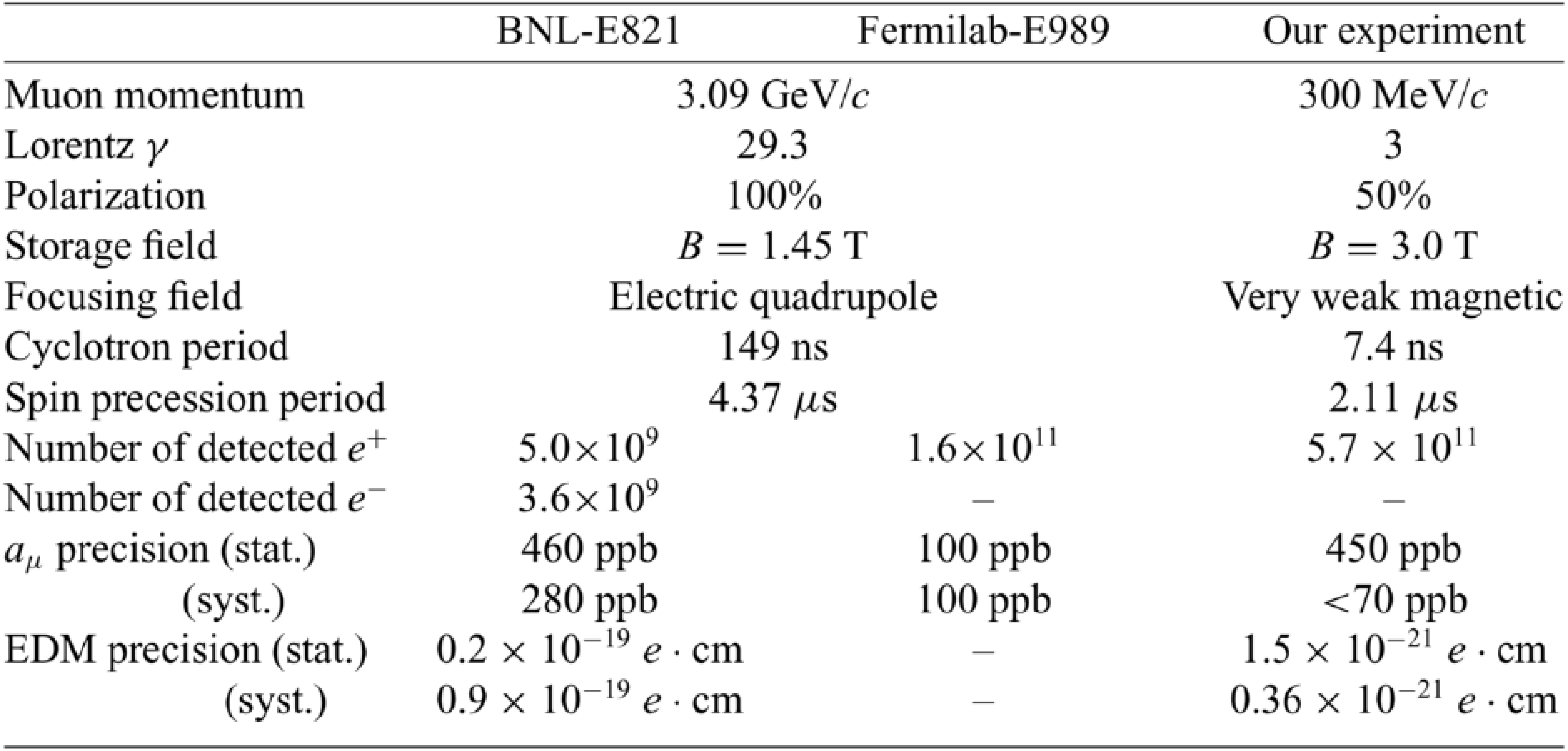


Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

Comparison of g-2 experiments

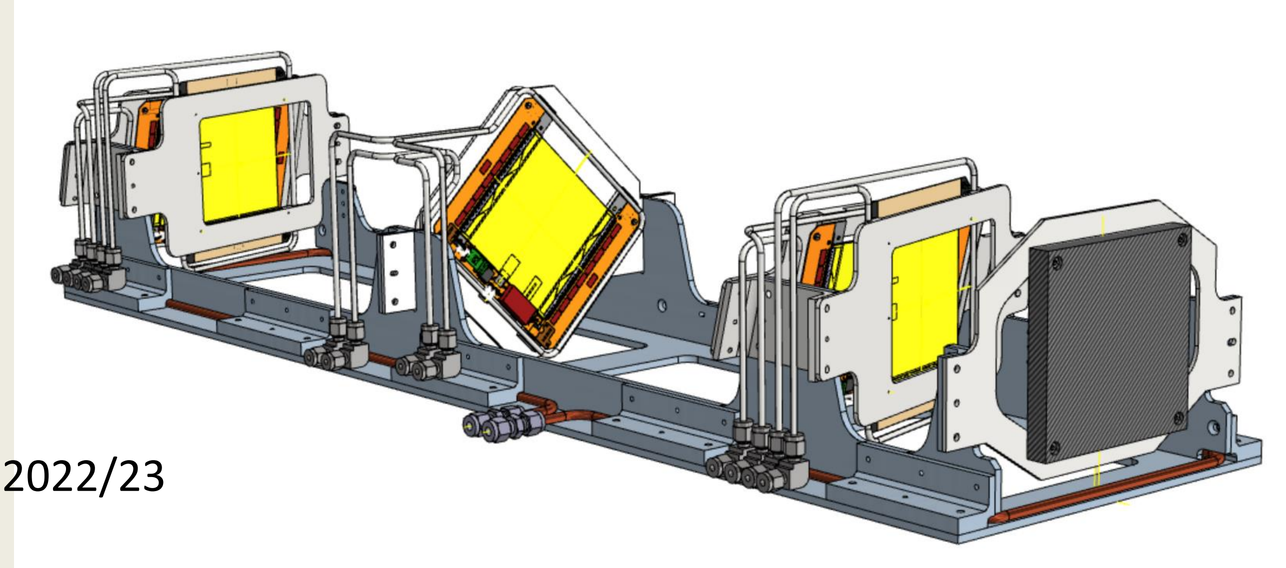
Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)



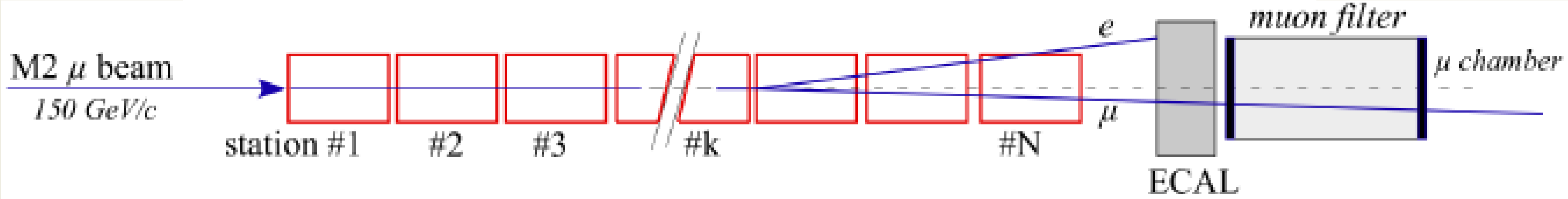
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	$0.2\times10^{-19}\ e\cdot$cm	–	$1.5\times10^{-21}\ e\cdot$cm
(syst.)	$0.9\times10^{-19}\ e\cdot$cm	–	$0.36\times10^{-21}\ e\cdot$cm

Completed **Running** **In preparation**

A third way for HVP…MUonE at CERN



Test RUN 2022/23



Alternative measurement of HVP for a_μ

-*C. M. Carloni Calame et al PLB 746 (2015) 325*

-*G. Abbiendi et al Eur.Phys.J.C* 77 (2017) 3, 139

-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf