Overview of the Fermilab Muon g-2 experiment

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Flavour changing and conserving processes
FCCP2019
Anacapri, Island of Capri, Italy
29 – 31 August 2019

We recall g, the g-factor (or dimensionless gyromagnetic ratio):

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

- Dirac theory gives $g \equiv 2$ for a point particle.
- Quantum fluctuations give rise to the anomalous magnetic moments:

$$a = \frac{g-2}{2} \neq 0.$$

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- Quantum fluctuations give rise to the anomalous magnetic moments:

$$a = \frac{g-2}{2} \neq 0.$$

E.g., electron anomaly is extremely well reproduced by QED:

$$\left.\begin{array}{l} a_e = 0.001\,159\,652\,181\,61\,(23)\ \text{[SM, } (\alpha/\pi)^5 \text{ order]}^* \\ a_e = 0.001\,159\,652\,180\,91\,(26)\ \text{[experiment, 22 ppb]}^\dagger \end{array}\right\}\ \text{agreement: } \sim 2.2\sigma$$

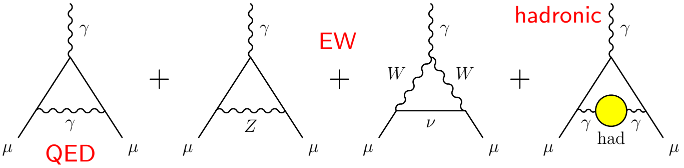
insensitive to massive particle loops ($\Rightarrow$ a_e provides an alternative measurement of α_{em})

But, a_μ is much more sensitive than a_e to massive loops as: $(m_\mu/m_e)^2 \approx 43,000$.

* Aoyama, Kinoshita & Nio, Atoms **7** (2019) 1.

† Mohr, Newell & Taylor, Rev. Mod. Phys. **88**(2016) 035009 — CODATA 2014.

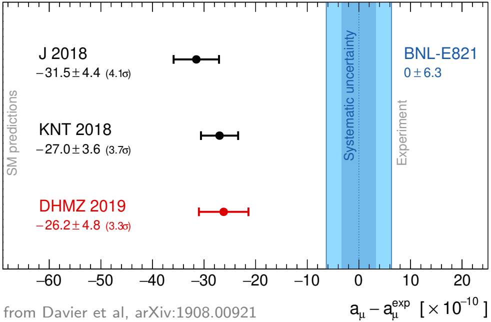
LO diagrams:



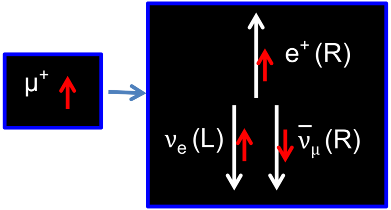
$+\ \ldots + $ new physics

Term	Value ($\times 10^{-11}$)
QED $(\gamma + \ell)^*$	$116\,584\,718.95 \pm 0.08$
HVP(lo) [Davier et al 19]	$6\,939 \pm 40$
HVP(nlo) [Davier et al 19]	-98.7 ± 0.9
HVP(nnlo) [Kurz et al 14]	12.4 ± 0.1
HLbL [Prades et al 09]	105 ± 26
EW [Gnendinger et al 13]	154 ± 1
Total SM [Davier et al 19]	$116\,591\,829 \pm 49_{\text{tot}}$

* Kinoshita et al 04-12, Kurz et al 16, Kataev 06, Passera 05

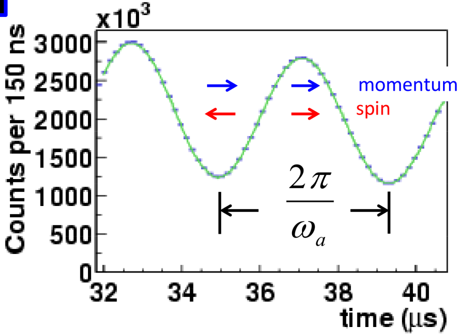


from Davier et al, arXiv:1908.00921



Positron direction follows muon spin

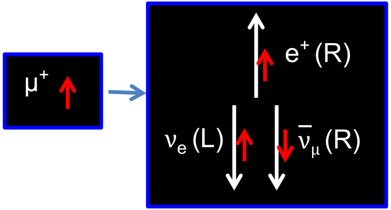
Highest energy positrons occur when muon spin and momentum are aligned (decay is boosted)



high energy positrons versus time

courtesy D. Hertzog

Experiment: use properties of $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ decay



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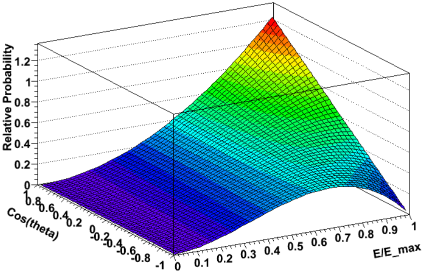
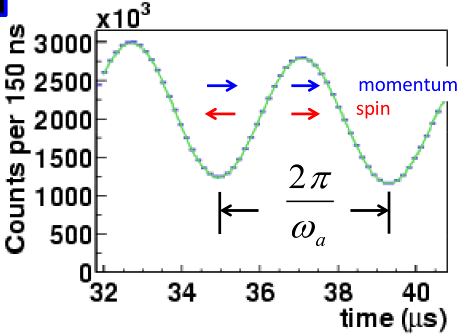


$$\theta = \angle(\vec{p}_e, \vec{p}_\mu)$$

courtesy D. Hertzog



high energy positrons versus time

- Inject polarized muon beam (from pion decay) into ring

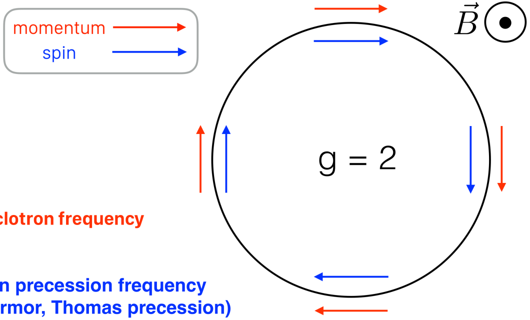
- Measure **difference** between spin precession and cyclotron frequencies

$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

cyclotron frequency

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}$$

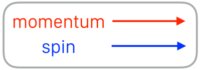
spin precession frequency
(Larmor, Thomas precession)

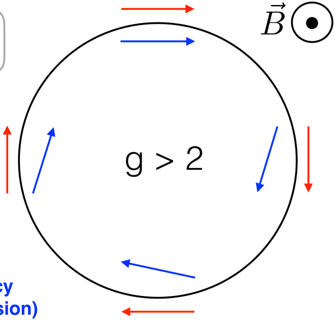


- If g = 2, difference of spin precession and cyclotron frequencies is zero

courtesy D. Flay

- Inject polarized muon beam (from pion decay) into ring
- Measure **difference** between spin precession and cyclotron frequencies





$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

cyclotron frequency

$$\vec{\omega}_S = -\frac{e}{\gamma m}\vec{B}\,(1+\gamma a_\mu)$$

spin precession frequency (Larmor, Thomas precession)

0 for γ = 29.3 (p = 3.1 GeV)

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

E-field vertical focusing allowed at p = 3.1 GeV (higher-order a_μ contribution cancelled)

courtesy D. Flay

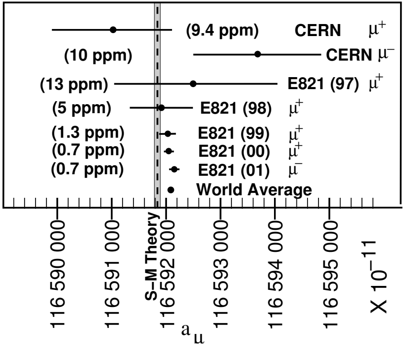
Dominated by results of BNL E821:

$$a_\mu^{\rm exp} = 116\,592\,089\,(54)_{\rm stat}\,(33)_{\rm syst} \times 10^{-11}$$, or

$$a_\mu^{\rm exp} = 116\,592\,089\,(63)_{\rm tot} \times 10^{-11},$$ i.e., a

0.54 ppm result : statistical uncertainty dominates .

How to improve this result?



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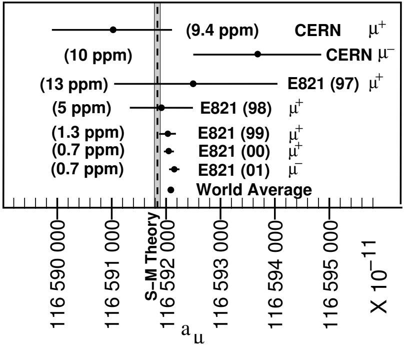

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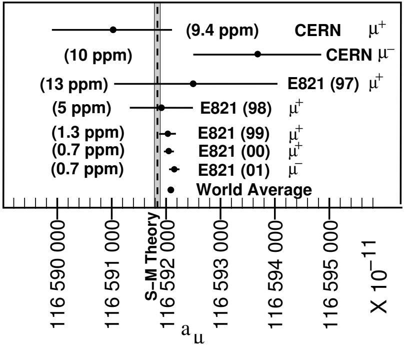

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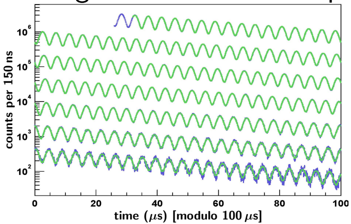
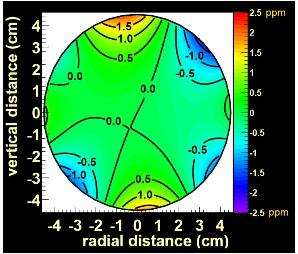
- Use a more intense beam at Fermilab: 21 × statistics of BNL E821,
- improve a number of contributing systematics factors.

Goal for Fermilab E989:

- obtain overall 4× reduction in uncertainty, i.e., 0.14 ppm (total).

Rewriting B in terms of free proton precession frequency ω_p:



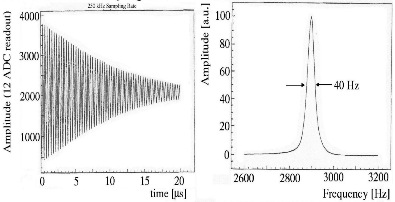


$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

From muonium hyperfine measurements;
25 ppb contribution to a_μ

Free induction decay signals:

$f_p \simeq 62$ MHz



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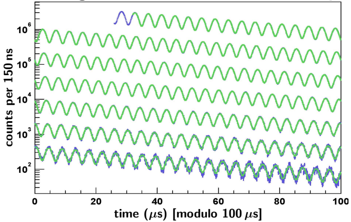

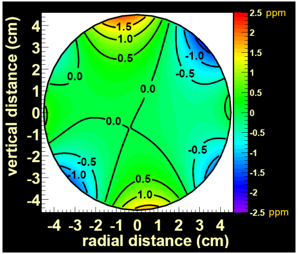

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

From muonium hyperfine measurements;
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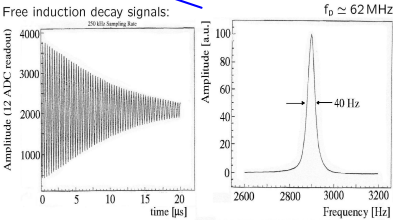
Thus, two independent measurements required!

Free induction decay signals:

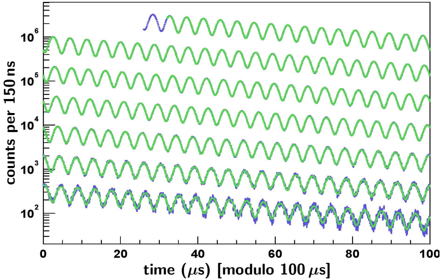


1. Large quantity of highly polarized muons stored in storage ring:
   97 % polarized ⇒ forward decays,

2. Muon spin precession in magnetic field, ω_a is determined by $g_\mu - 2$,

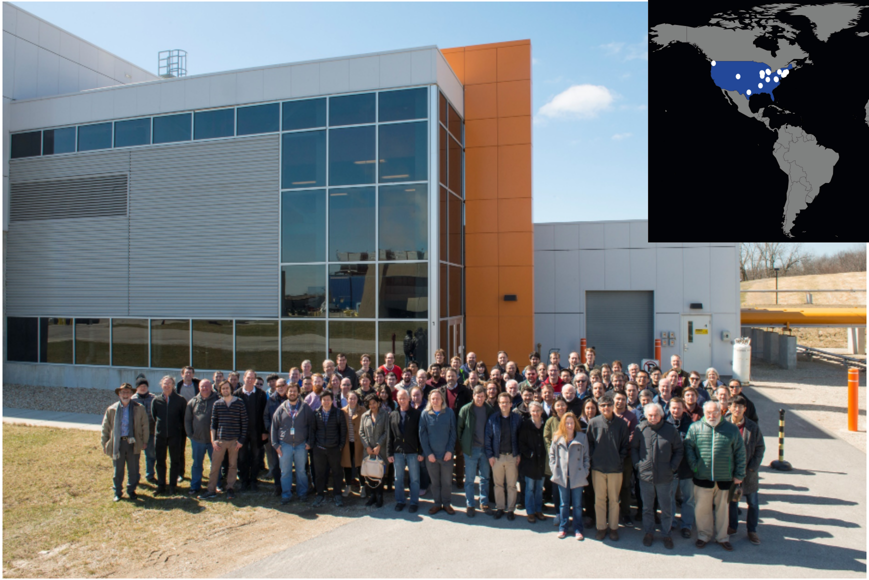
3. Magic momentum: $p_\mu = 3.09\,\mathrm{GeV}/c$
   No effect of $\vec{E}$ on precession when $\gamma_\mu = 29.3$,

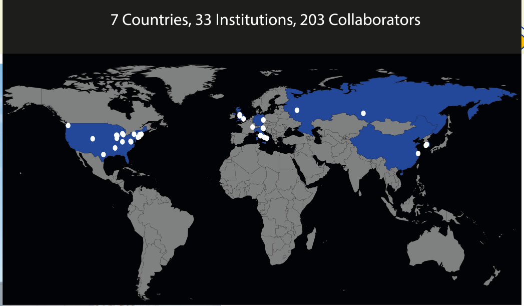
4. EW chiral symmetry breaking (PV) gives lab access to average muon spin direction
   Number of high energy positrons modulated by ω_a (wiggle plot):



5. To interpret ω_a in terms of g_μ, an independent precise measurement of muon beam averaged $\langle B \rangle$ is critical.

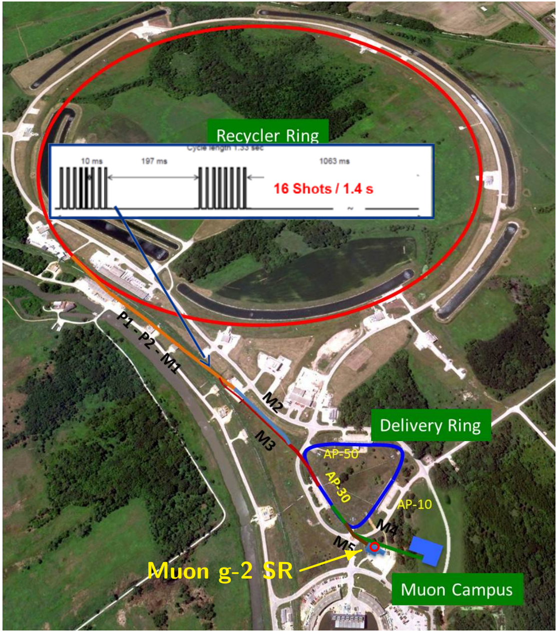
Fermilab E989 collaboration

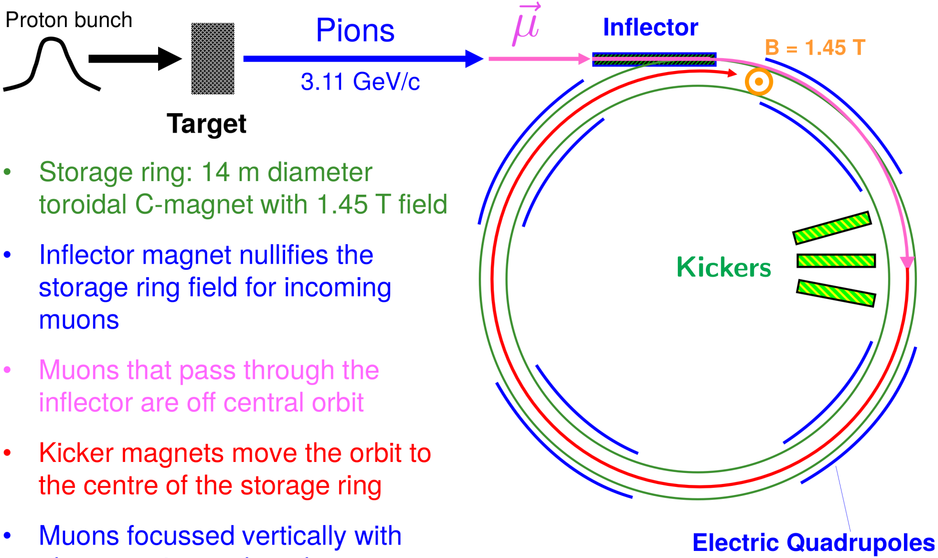




The accelerator complex:

- 8 GeV p batch into Recycler,
- split into 4 bunches,
- extract 1 by 1 to strike target,
- long FODO channel (alternating focusing and defocusing quads) to collect $\pi \to \mu\nu$,
- $p/\pi/\mu$ beam enters DR; protons kicked out; π's decay away,
- μ enter storage ring.





- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Kicker magnets move the orbit to the centre of the storage ring
- Muons focussed vertically with electrostatic quadrupoles

Magnet anatomy

B = 1.4513 T (~5200 A)

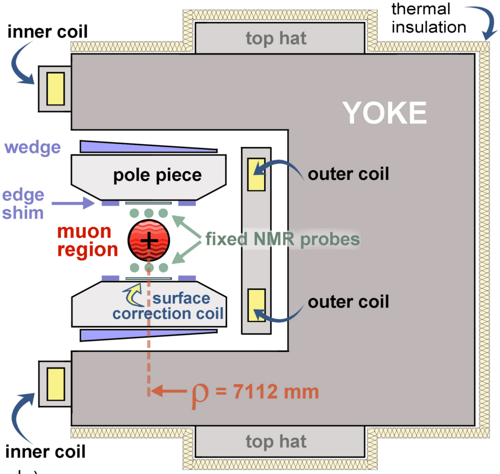
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 poles per yoke
- 72 total poles

Shimming knobs

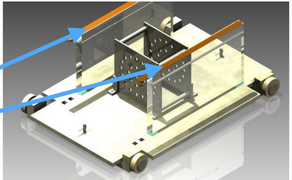
- Poles: shape field
- Top hats (30 deg,dipole)
- Wedges (10 deg, dipole, quadrupole)
- Edge shims (360 deg, quadrupole, sextupole)
- Laminations (360 deg, dipole, quadrupole, sextupole)
- Surface coils (360 deg, quadrupole, sextupole,...)

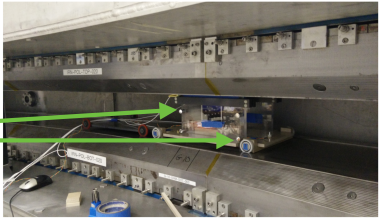


g-2 Magnet in Cross Section

Shimming cart

- Lattice of 25 NMR probes (field measurements)
- 4 capacitive gap sensors (pole-pole alignment/ separation), 70-nm resolution
- 4 corner-cube retroreflectors (position), ~25 μm resolution

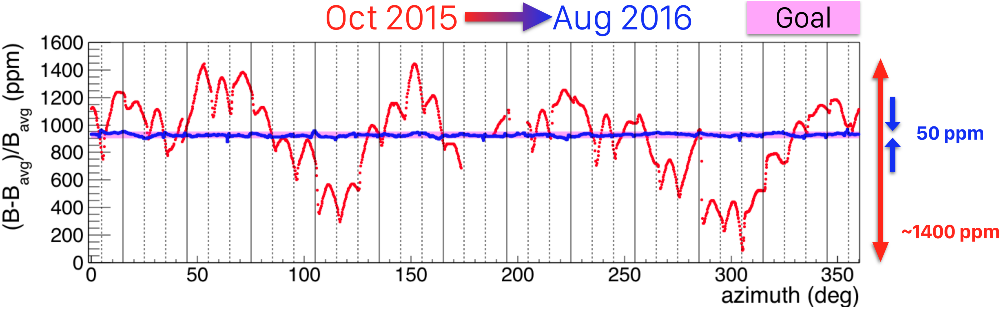




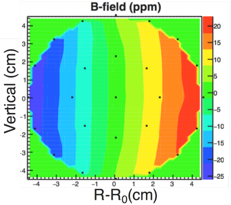
Laser tracker

- Cart position (r, φ, z)

Shimming results:

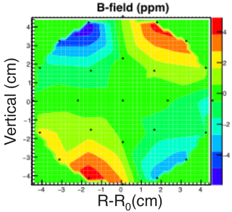


Azimuthally-Averaged Map



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

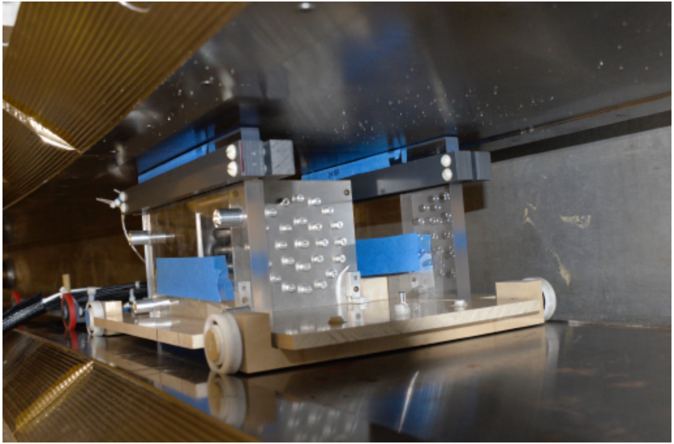
Oct 2015



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

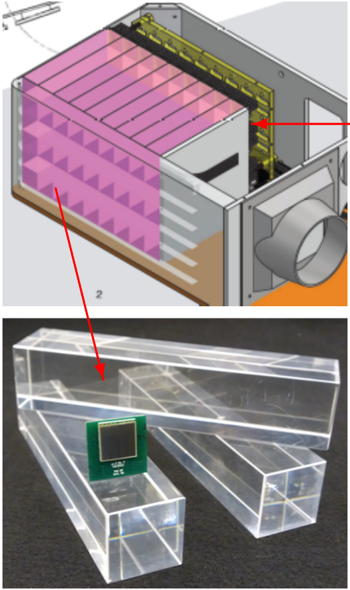
Aug 2016

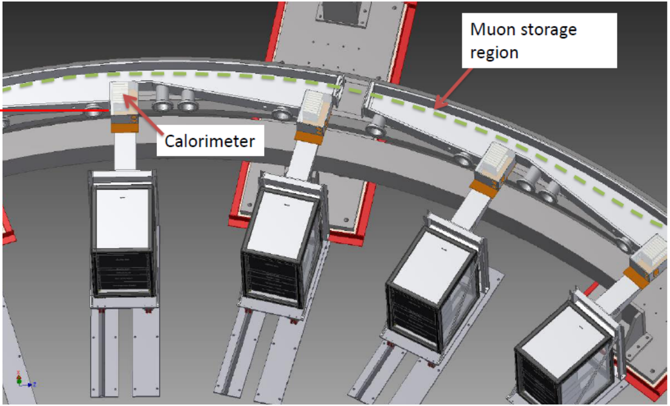
- Map B at regular intervals (about every two days), with NMR probe trolley: 17 proton NMR probes,
- monitor B during DAQ with 378 pNMR fixed probes in 72 stations;
- pulsed pNMR measure B with $< 10\,\text{ppb}$ single shot precision.



- BNL E821 result:
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989 goal:
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

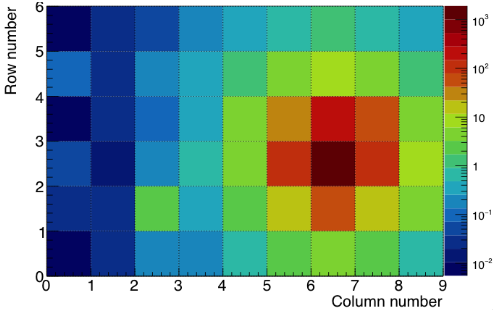
Calorimeters (ω_a measurement)

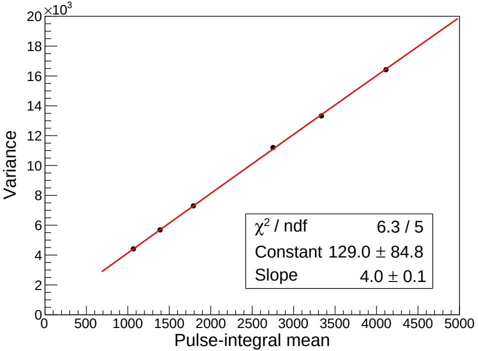


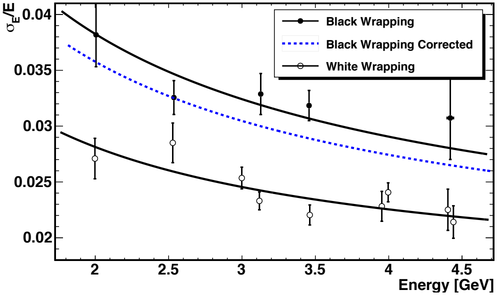


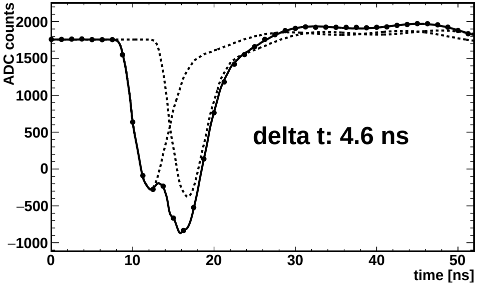
Individual positrons from muon decays are detected in 24 calorimeters; E and t extracted from waveforms. Each calo. segmented into 6×9 channels: Each PbF_2 crystal is read out by a Geiger-mode avalanche photodiode (SiPM).

Calorimeter performance



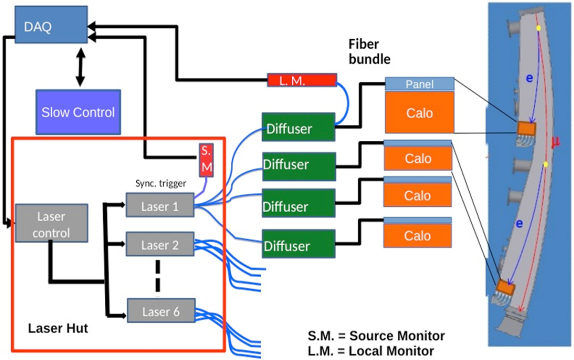


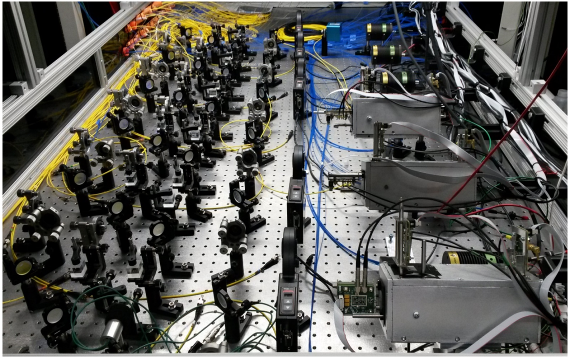


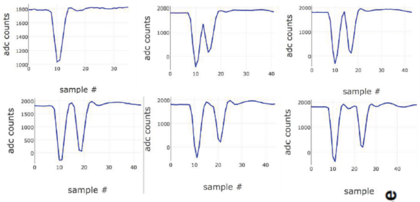


Sends trains of laser pulses of known intensity synchronously on all calo. channels; provides:

- absolute calibration of the SiPMs response,
- short and long term calibration of the of the SiPM gain function,
- debugging of Calo and DAQ systems,
- additional synchronization signals.

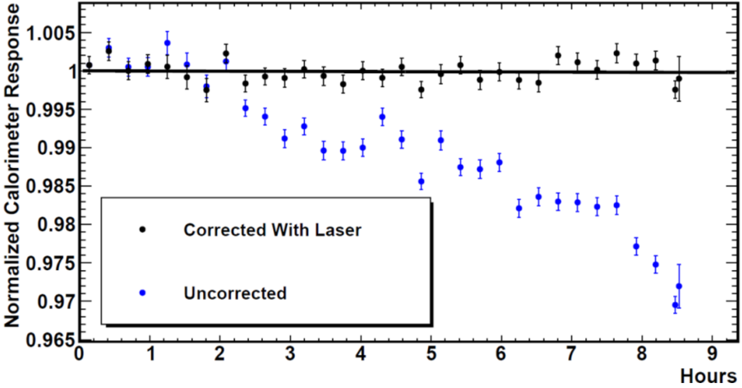




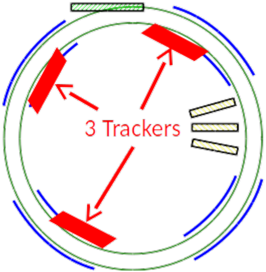


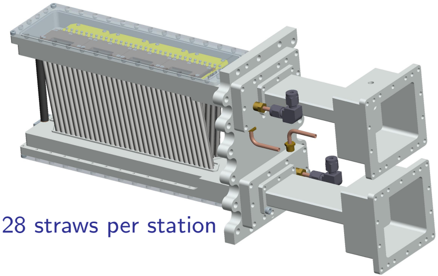
⇐ tuneable individual pulses, tuneable pulse pairs, and "flight simulator" mode.

10^{-4}/h stability demonstrated:

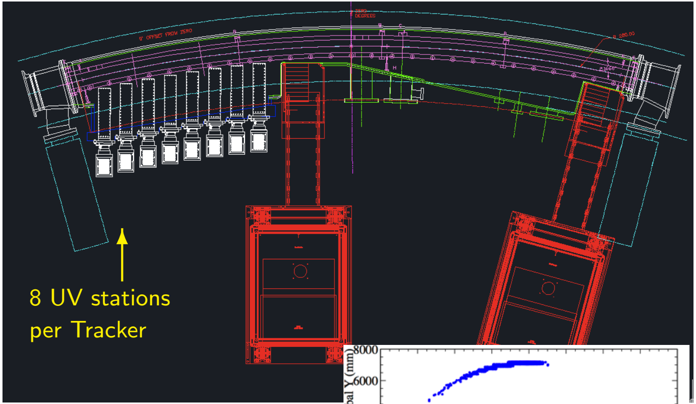


Straw tube Trackers

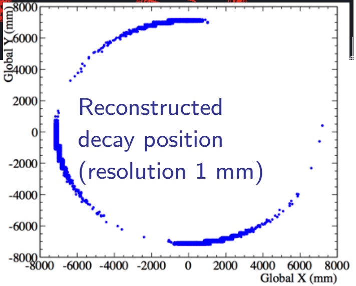




128 straws per station



New for Fermilab E989 (did not exist in BNL E821); provide critical beam phase space and dynamics data.



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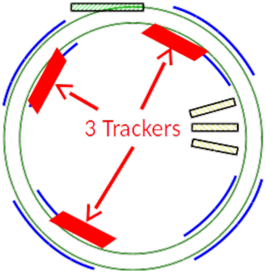

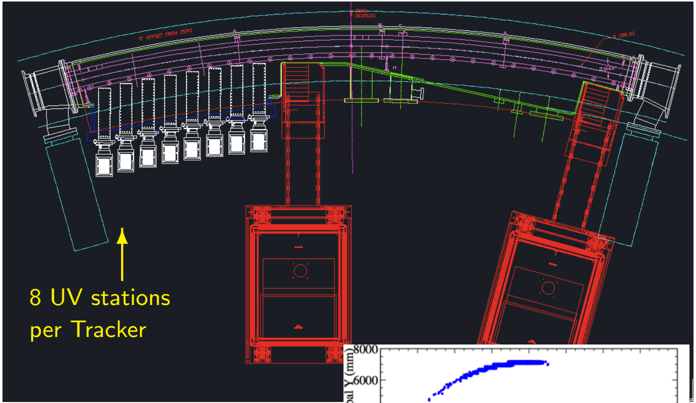

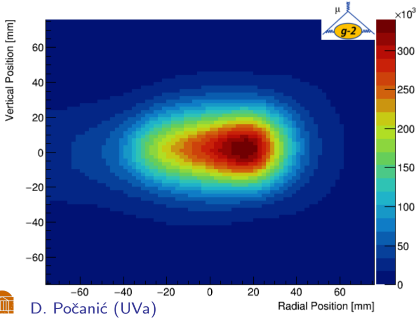

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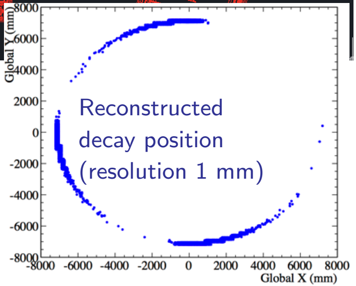
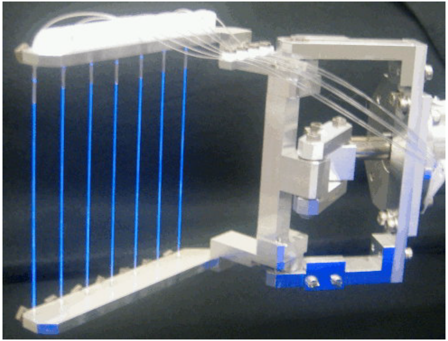


Auxilliary detectors:

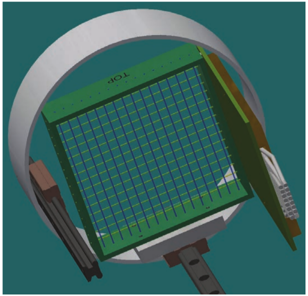
Fiber harps:



2 locations, 2-axis,

- monitor the muon beam entrance position and angle during commissioning,
- periodically measure betatron oscillations during data taking runs.

Inflector beam monitoring system (IBMS):



2 det's with 2 planes/each (scint-iber), upstream of inflector; 1 vertical plane (x) downstram of inflector (retracted during data taking):

- primary diagnostic tool to develop & verify beam optics tune at injection,
- give relative intensity of each fill,
- timing of the fill (resolution $\ll 150$ ns, cyclotron period)

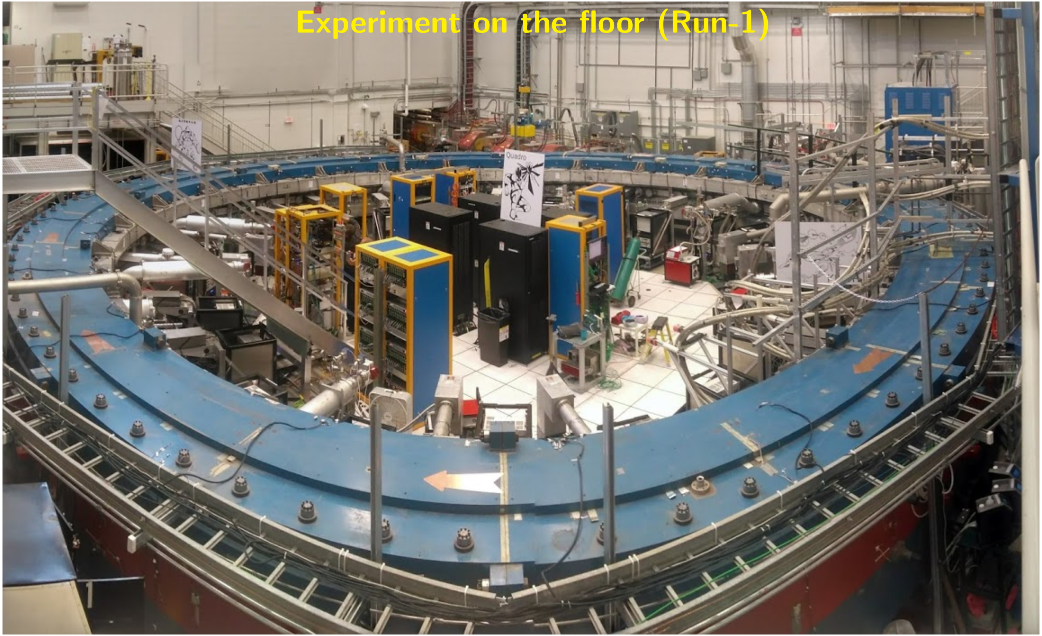
Data acquisition system

- Calorimeters, trackers and the laser monitoring system are read out by custom 800 MSPS waveform digitizers.
- The DAQ produces a deadtime-free record of each 700 μs muon fill. We get 12 fills per second, for a total data rate of 20 GB/s.
- Data from each calorimeter processed by an NVidia Tesla K40 GPU, which processes 33M threads per event.
- Data are sorted by T-method (chopped islands) and Q-method (current integrated) data, from which timing info can be extracted.
- The DAQ software is MIDAS based.

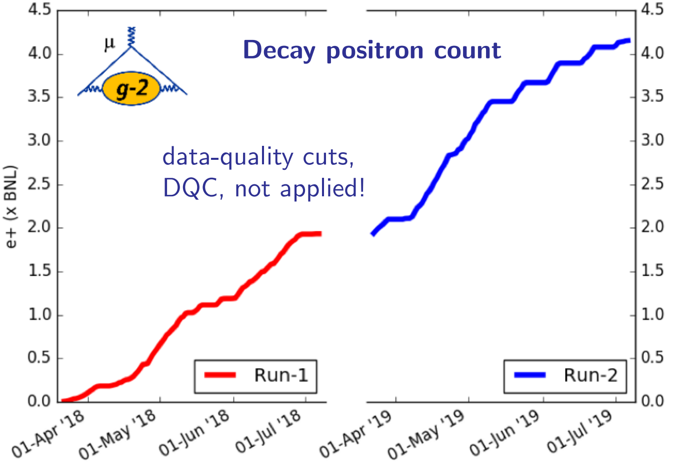
Subprojects not discussed here in detail — each presenting great challenges, with a huge effort invested to solve them:

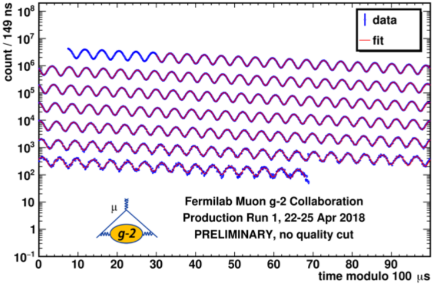
- Beam transport, optics and optimization through the accelerator complex (enormous and impressive effort by FNAL accelerator group);
- Inflector magnet optimization (a new one has been built);
- Kicker system improvements;
- Electrostatic quadrupole system improvements;
- Beam dynamics analysis;
- many more . . .

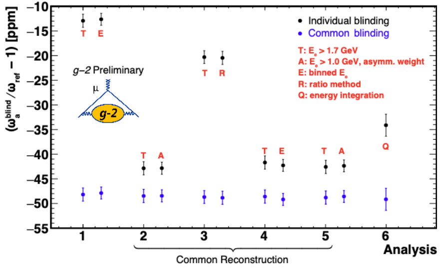
Experiment on the floor (Run-1)



- Finished Run-1 and Run-2; analyzing data!
- After DQC we expect:
  - $\sim 1.4\times$ BNL for Run-1,
  - $\sim 1.8\times$ BNL for Run-2.
- Currently in a summer shutdown preparing for Run-3.
- Goal of publishing results of Run-1 by end of 2019.





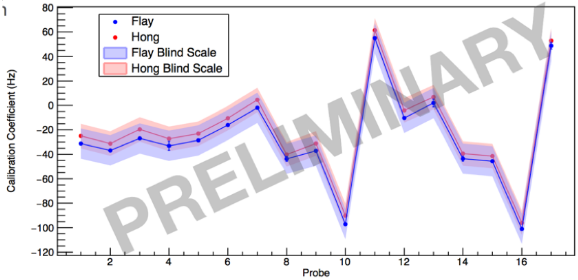


Run-1 ω_a analysis:

- data are hardware blinded (clock tick frequencies known only to 2 external people);
- Each analysis has own private software frequency offset.
- Run-1 has 4 primary data subsets with different Kicker & el-stat Quad settings;
- 6 groups fitting the frequency with multiple methods;
- 3 independent event reconstruction efforts;
- data are corrected for gain & pile-up, binned, and randomized with respect to the cyclotron frequency;
- full fit functional forms are producing excellent χ^2 and clean residuals.

Sample fit fn.:

$$N(t) = N_0 \Lambda(t) N_{cbo}(t) N_{vw} e^{-t/\tau} \{1 + A_0 \cdot A_{cbo}(t) \cos[\omega_a(R) \cdot t + \phi_0 + \phi_{cbo}(t)]\}$$



- Fixed probes provide continuous data (outside of muon storage ring volume, SRV) for interpolation between trolley runs.
- Trolley probe measurements (every ~ 2 days) provide detailed mapping of μSRV field (multipole expansion).

- Calibration of trolley probes (TPs) is performed via a special "plunging probe" in the μSRV, as TPs experience $\vec{B}$ perturbations due to trolley materials, electronics, enclosures.
- Absolute calibration of plunging probe by two methods:
  - using spherical-shaped H_2O sample (as was done in BNL E821), and
  - using polarized ^{3}He (an independent technique newly implemented in FNAL E989).
- Two(+) independent blinded analyses; they agree within the blinding bands; a preliminary Run-1 estimate of $\langle B \rangle$ is imminent.

FNAL Muon $g-2$ experiment final uncertainty goals

ω_a systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Gain Changes	120	20
Pileup	80	40
Lost Muons	90	20
CBO	70	< 30
E-field & Pitch Corrections	50	30
Total (Quadrature Sum)	190	70

a_μ uncertainty summary[1,2].

Category	BNL [ppb]	FNAL Goal [ppb]
Total Statistical Uncertainty	460	100
Total Systematic Uncertainty	280*	100
Total (Quadrature Sum)	540*	140

* The net systematic is across 3 running periods.

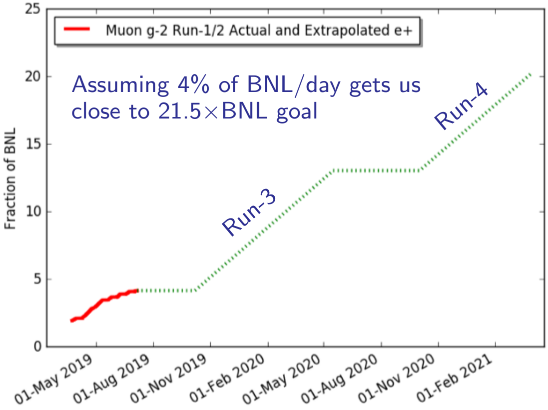
[1] J. Grange et al. [Muon g-2 Collaboration], arXiv:1501.06858 [physics.ins-det].

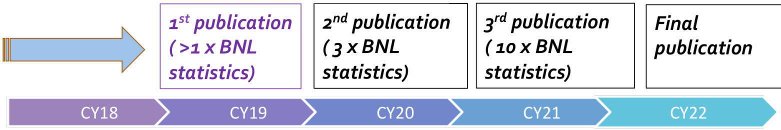
[2] M. Tanabashi et al. (PDG), Phys. Rev. D **98** (2018) 030001.

<ω_p> (B-field) systematic uncertainty summary[1].

Category	BNL [ppb]	FNAL Goal [ppb]
Absolute Field Calibration	50	35
Trolley Probe Calibrations	90	30
Trolley Measurements Of B_0	50	30
Fixed Probe Interpolation	70	30
Muon Distribution	30	10
Time-dependent External Magnetic Fields	-	5
Others (Collective Smaller Effects)	100	30
Total (Quadrature Sum)	170	70

- FNAL E989 is on track to improve the BNL E821 a_μ precision 4-fold: from 0.54 to $\sim$0.14 ppm .
- Run-3 starts 3-Oct-19, ends 15-May-20.
- Run-4 will share beam with Mu2e commissioning: 6 months for Muon $g-2$, 3 months for Mu2e.
- Goal to publish Run-1 result by end of 2019:





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- North Central
- Northern Illinois
- Regis
- Virginia
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