The muon g-2 experiment: overview and prospects

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Lepton magnetic dipole moments

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 moment:

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$$a_{\mathrm{e}} = 0.001\,159\,652\,181\,64\,(76) \text{ (theory, 10}^{\text{th}}\text{ order)}$$

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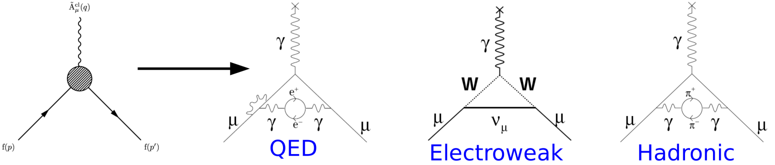
However, a_μ is much more sensitive than $a_{\rm e}$ to massive particle loops as:

$$(m_\mu/m_{\rm e})^2 \approx 43,000 .$$

Muon anomalous magnetic moment



$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$

Snowmass white paper survey [T. Blum et al., arXiv 1311.2198]

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [Davier 11]	$6\,923 \pm 42$
HVP(lo) [Hagiwara 11]	$6\,949 \pm 43$
HVP(ho) [Hagiwara 11]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [Davier 11]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [Hagiwara 11]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

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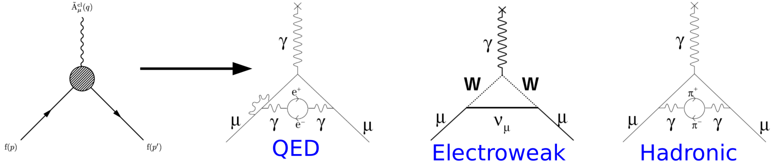

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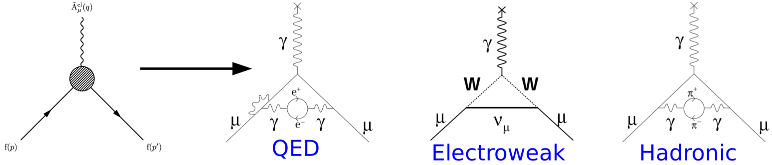

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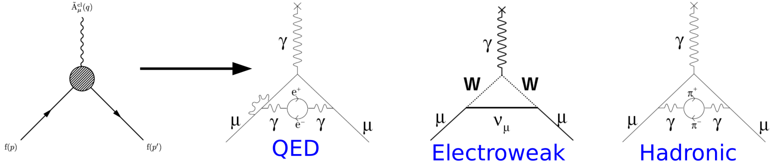

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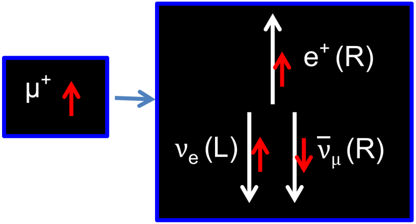
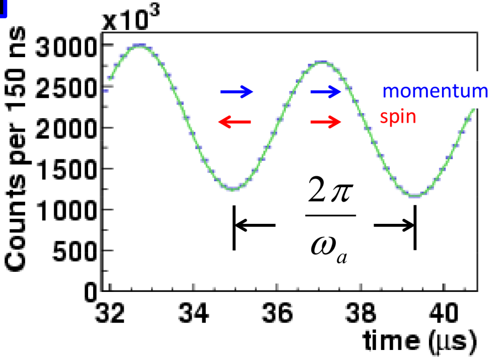
Recent advances: 1st Workshop of the Muon g-2 theory initiative, FNAL, June 2017.

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



Positron direction follows muon spin

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



high energy positrons versus time

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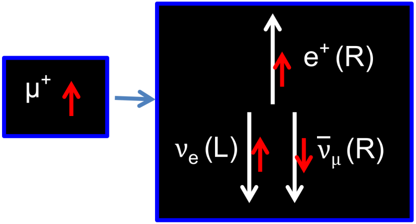

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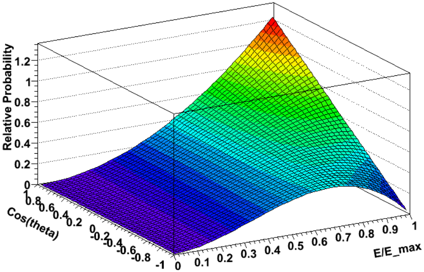
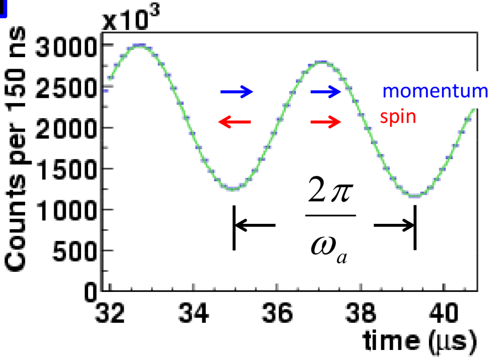


$\theta = \angle(\vec{p}_e, \vec{p}_\mu)$

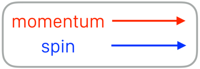


high energy positrons versus time

Measuring ω_a through correlation with p_μ

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

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

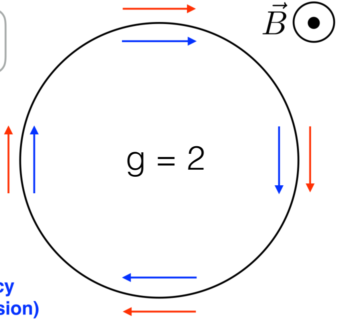


$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

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

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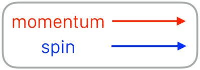
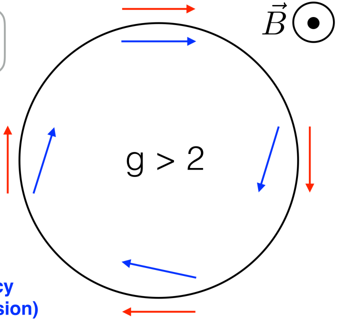




$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

cyclotron frequency

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

spin precession frequency (Larmor, Thomas precession)

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

0 for γ = 29.3 (p = 3.1 GeV)

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

Muon $g-2$: experimental status

Dominated by results of BNL E821:

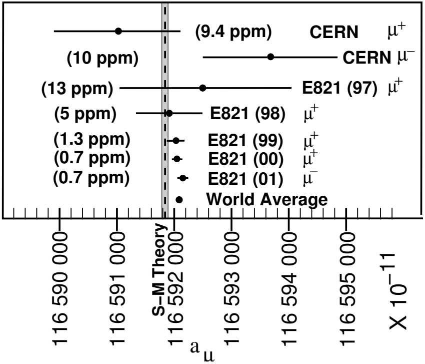
$$a_\mu^{\text{exp}} = 116\,592\,089\,(54)_{\text{stat}}\,(33)_{\text{syst}} \times 10^{-11}\text{, or}$$

$$a_\mu^{\text{exp}} = 116\,592\,089\,(63)_{\text{tot}} \times 10^{-11}\,,$$

i.e., a 0.54 ppm result. Note:

statistical uncertainty dominates.

How to improve?



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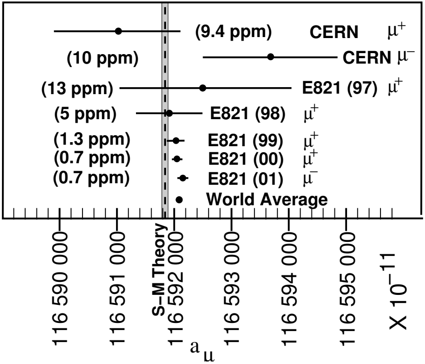

How to improve?

- Use a more intense beam at Fermilab: 21 × statistics of BNL E821,
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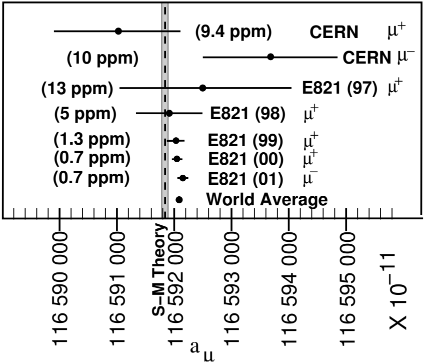

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Goal for Fermilab E989:

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

Ultimate goal of E989

From 2013 Snowmass white paper:

(values given in units of 10^{-11})

Uncertainty	Dav11	Hag11	Future
δa_μ^{SM}	49	50	35
δa_μ^{HLO}	42	43	26
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$\delta(a_\mu^{EXP} - a_\mu^{SM})$	80	80	40

2017 updates:

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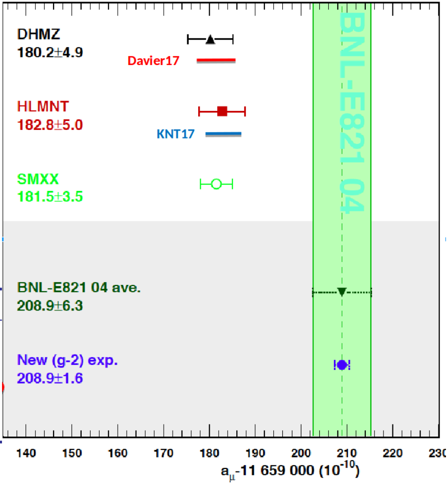

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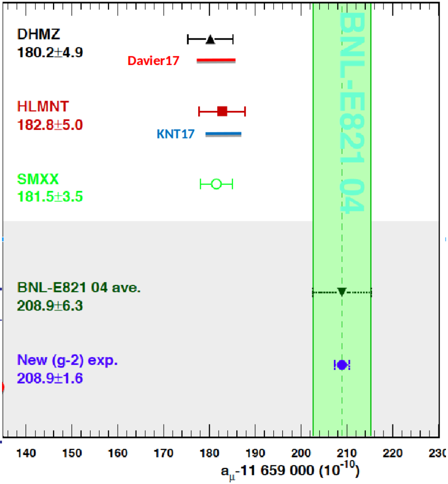


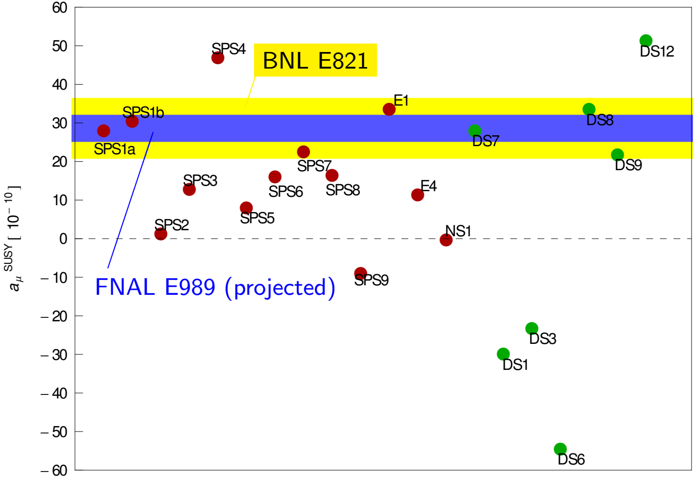
I.e., for the same SM and EXP central values, the discrepancy would increase from $\sim 3.5\,\sigma$ to $\sim 7\sigma$.

New physics reach of a_μ

Much literature & many results produced. We touch on two topics.

Supersymmetry: $a_\mu^{\text{SUSY}} \approx 130 \times 10^{-11} \tan\beta \; \text{sgn}(\mu) \, (100\,\text{GeV}/M_{\text{SUSY}})$,

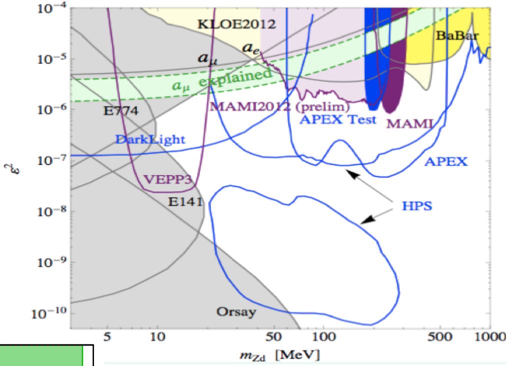
where $\tan\beta = v_2/v_1$ (or v_u/v_d); μ is the strength of $\hat{H}_1 \hat{H}_2$ term ...

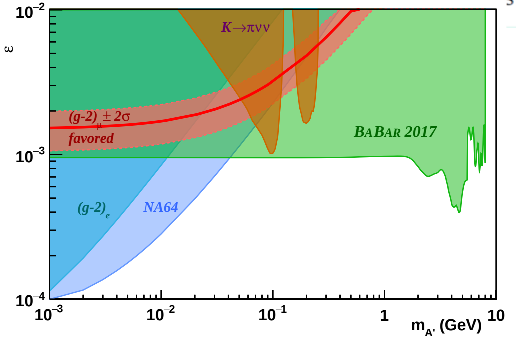


SUSY contributions to a_μ for several benchmark parameter sets [Stöckinger 2014].

Dark photons:

status circa 5 years ago ⟶

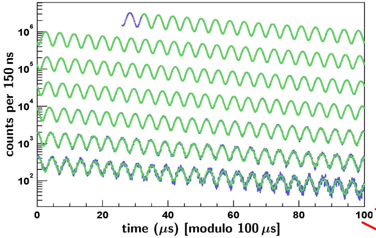


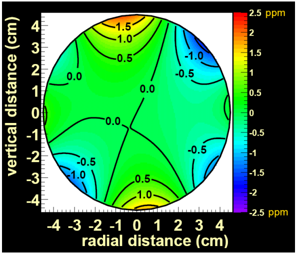


⟵ 2017 BaBar results

Determining a_μ

Rewriting B in terms of free proton precession frequency ω_p:

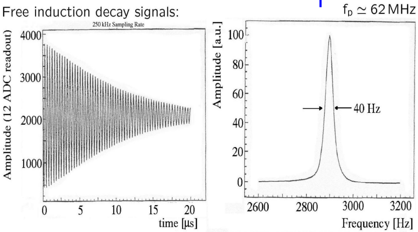




$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

From muonium hyperfine measurements;
25 ppb contribution to a_μ

Free induction decay signals:



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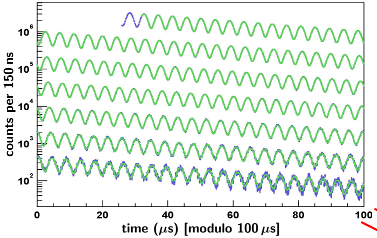

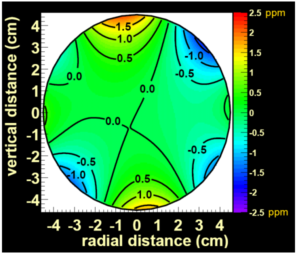

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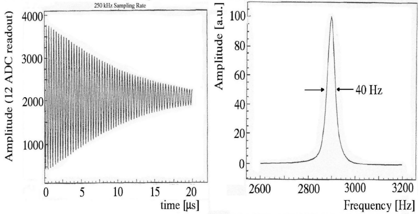
Thus, two independent measurements required!

Free induction decay signals:

$f_p \simeq 62\,\text{MHz}$



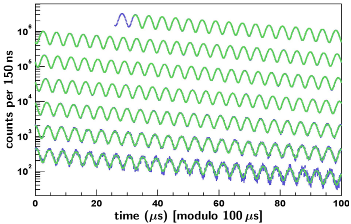
Key points of the experimental method

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: $p_\mu = 30.4\,\mathrm{GeV}/c$
   No effect of $\vec{E}$ on precession when $\gamma_\mu = 29.3$,

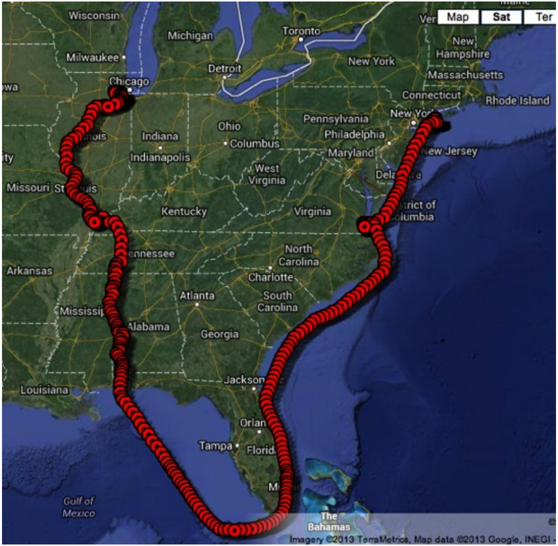
4. EW chiral symmetry breaking (PV) gives lab access to average muon spin direction
   Number of high energy positrons modulated by ω_a (wiggle plot):



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

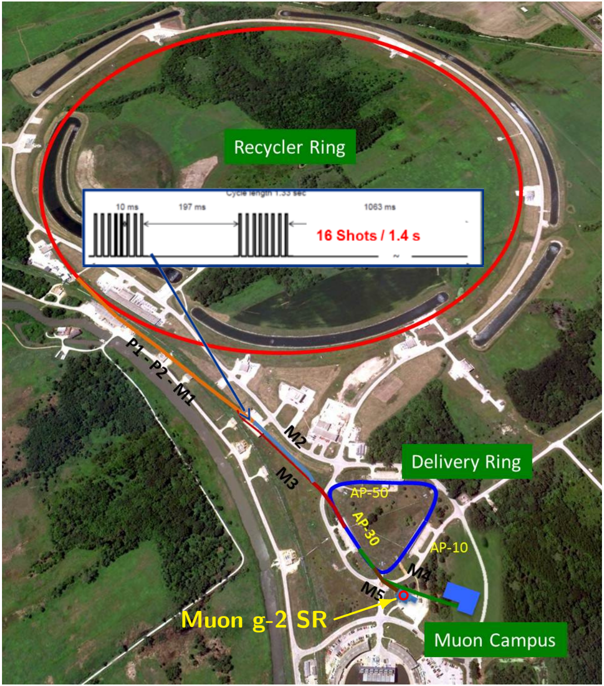
Fermilab E989 collaboration

The big SR magnet move (2013)

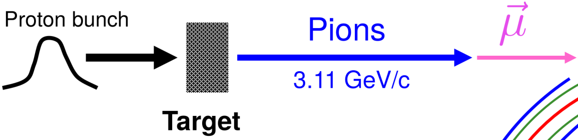


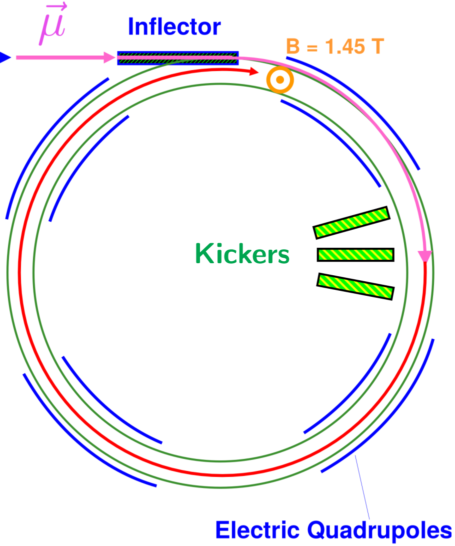
Accelerator complex

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



Muon beam and storage





- 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)

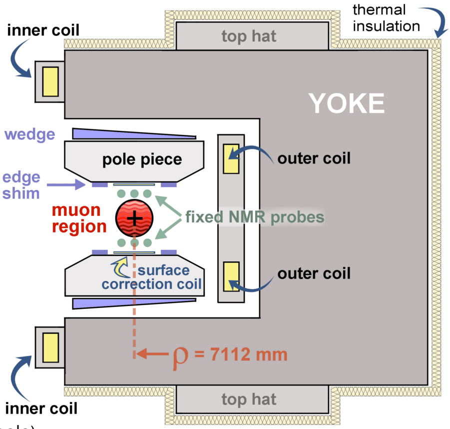
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 poles per yoke
- 72 total poles

Shimming knobs

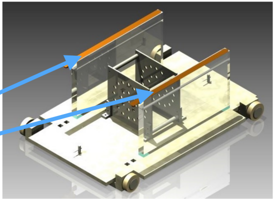
- Poles: shape field
- Top hats (30 deg,dipole)
- Wedges (10 deg, dipole, quadrupole)
- Edge shims (360 deg, quadrupole, sextupole)
- Laminations (360 deg, dipole, quadrupole, sextupole)
- Surface coils (360 deg, quadrupole, sextupole,...)



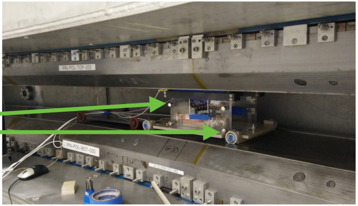
g-2 Magnet in Cross Section

Magnet shimming

Shimming cart



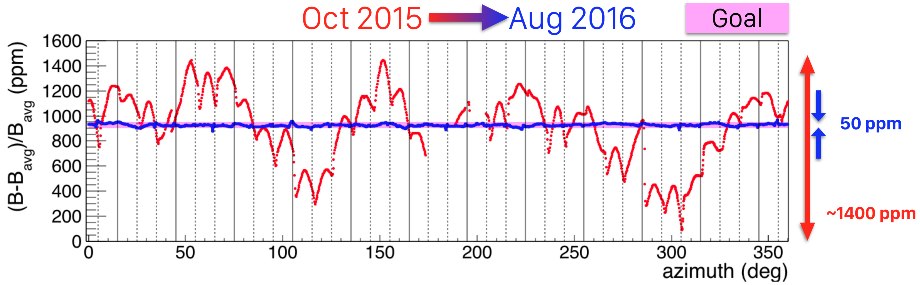
- Lattice of 25 NMR probes (field measurements)
- 4 capacitive gap sensors (pole-pole alignment/ separation), 70-nm resolution
- 4 corner-cube retroreflectors (position), ~25 μm resolution



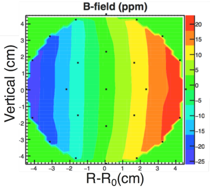
Laser tracker

- Cart position (r, φ, z)

Shimming results

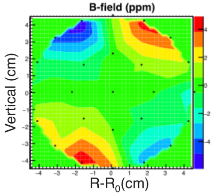


Azimuthally-Averaged Map



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

Oct 2015

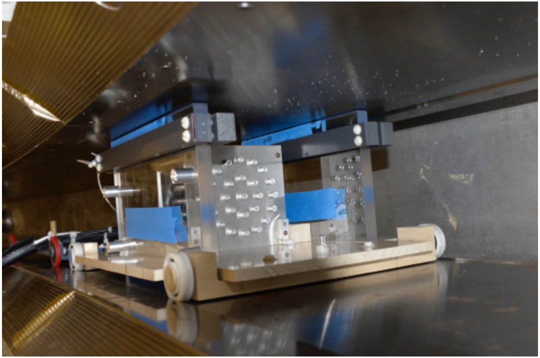


	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

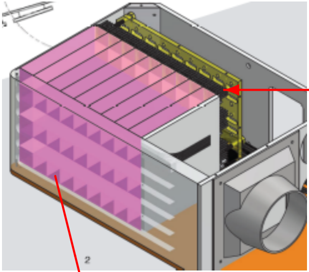
Trolley

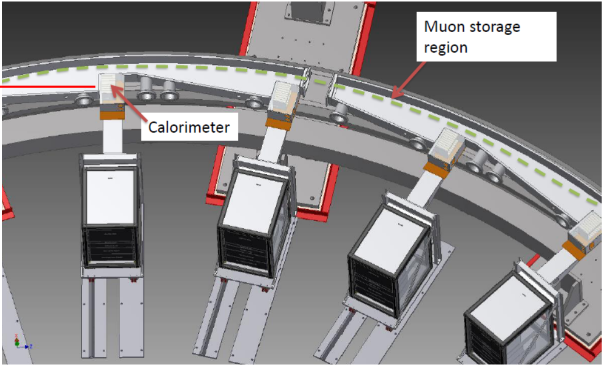
- Map B at regular intervals with NMR probe trolley
- Monitor B during DAQ with fixed probes
- B measured with pulsed proton NMR (< 10 ppb single shot precision)

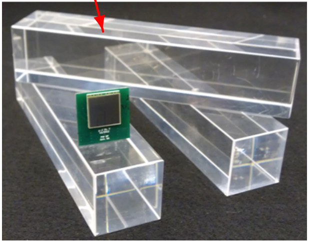


- BNL E821 result:
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989 goal:
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

Calorimeters (ω_a measurement)

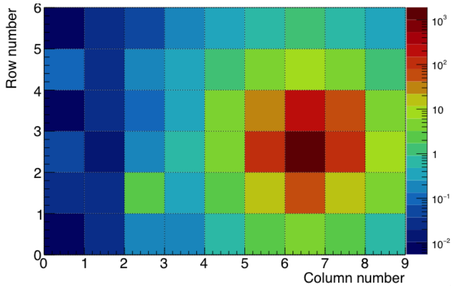


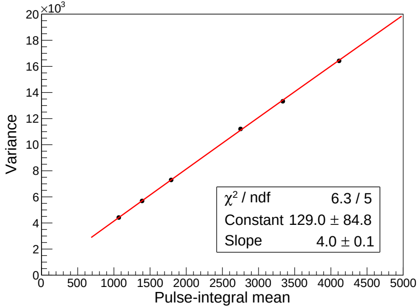


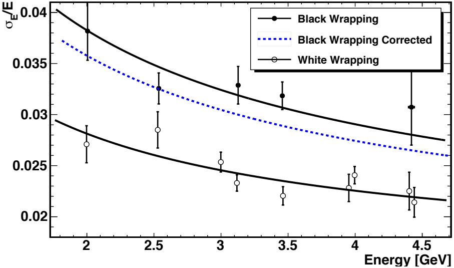


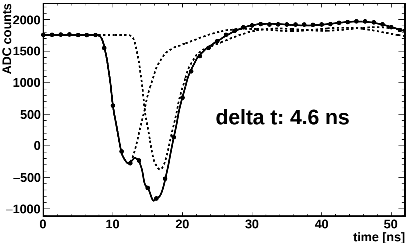
Individual positrons from muon decays are detected in 24 calorimeters; E and t extracted from waveforms. Each calo. segmented into 6×9 channels: Each PbF_2 crystal is read out by a Geiger-mode avalanche photodiode (SiPM).

Calorimeter performance





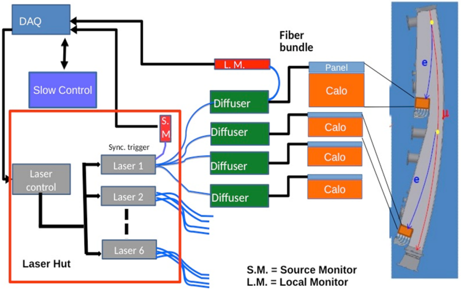


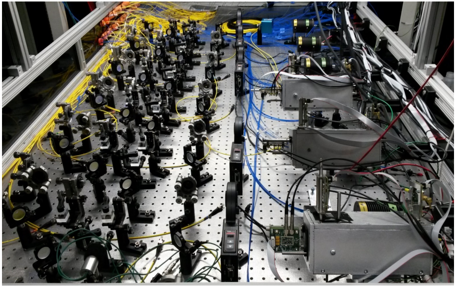


Laser calibration system

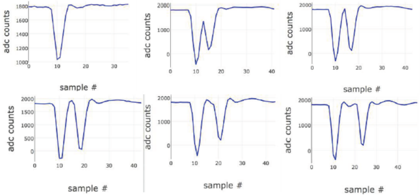
Sends trains of laser pulses on known intensity synchronously on all calorimeters channels; provides:

- 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.

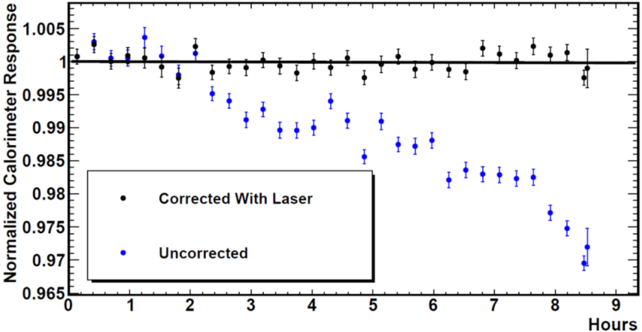




Laser calibration system performance

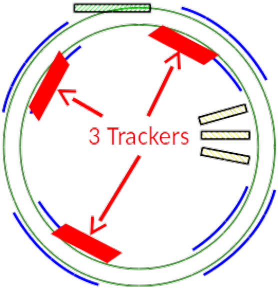


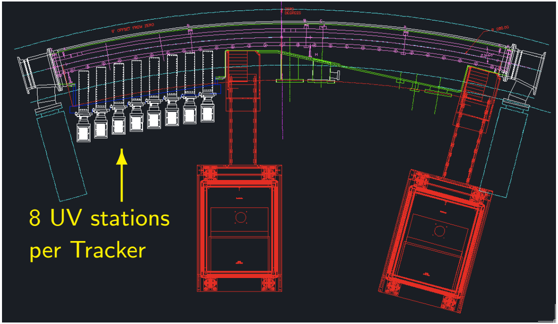
⇐ tuneable individual pulses, tuneable pulse pairs, and "flight simulator" mode.

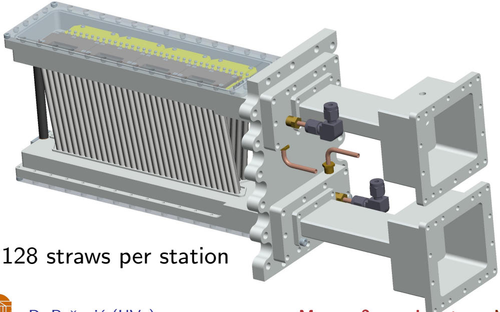


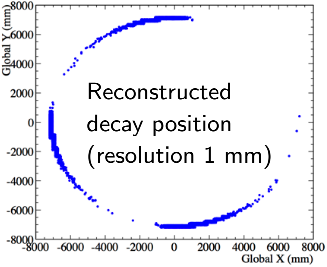
10^{-4}/h stability demonstrated with monoenergetic test beam at SLAC!

Straw tube Trackers



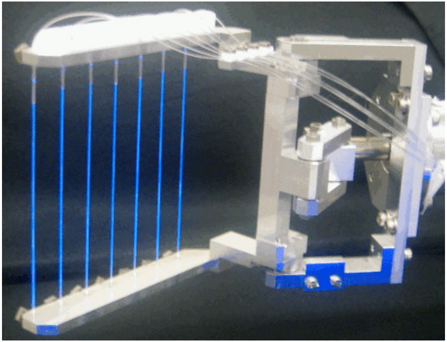






Auxiliary detectors: Fiber harps and IBMS

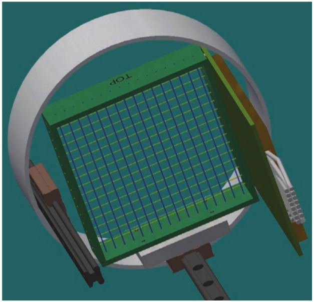
Fiber harps:



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:

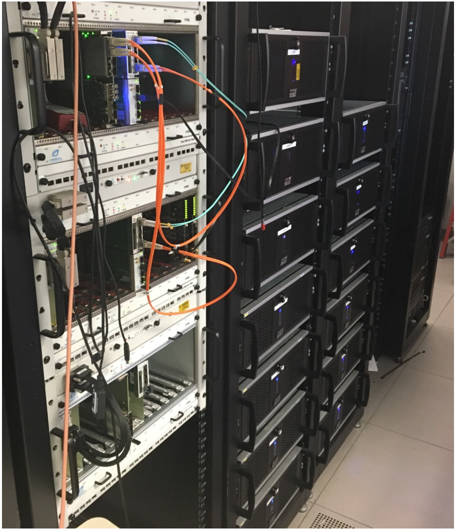


3 det's, each with 2 planes of scint. fiber, located outside the inflector:

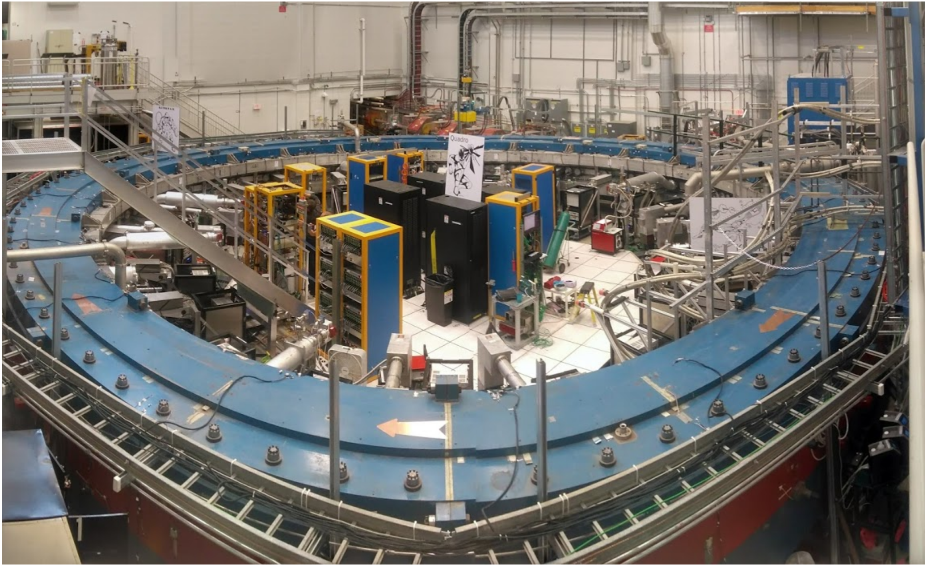
- primary diagnostic tool to develop & verify beam optics tune at injection,
- give relative intensity of each fill,
- timing of the fill (resolution $\ll 150\,\mathrm{ns}$, cyclotron period)

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.



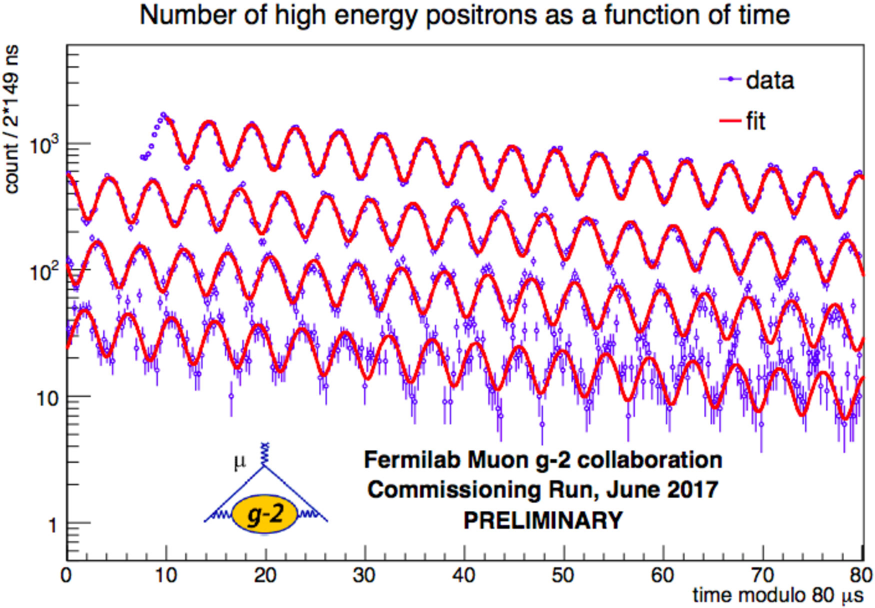
Experiment on the floor (October 2017)



Present status of the experiment

- Practically all sub-systems installed and operational,
- First beam injected into storage ring on 31 May 2017,
- Beam (protons and muons) stored for several hundred turns,
- in July 2017 completed commissioning run (10^{16} proton on target, 3×10^9 muons delivered to ring),
- first wiggle plot recorded at FNAL!
- July through mid-October shut-down for beam and systems tune-up,
- new commissioning run under way since 16 October.

Results of the June 2017 commissioning run



Conclusions and plans

- The Fermilab E989 experiment will improve the BNL E821 muon anomaly a_μ result by a 4-fold improvement in precision (from 0.54 to 0.14 ppm).
- If the BNL value holds, this would provide a 7σ discrepancy with the SM, and ample room for New Physics.
- A 5 weeks summer commissioning run just completed successfully (first "wiggle" plot measured at FNAL); a fall 2017 run is under way.

Our goals are:

- reach the BNL level precision by end 2018, and
- reach the final 0.14 ppm result measurement in 2020.
  This will require a total of 1.5×10^{11} collected events.

Extra slides

Improvements in systematic uncertainties:

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07