The Muon g-2 Experiment at Fermilab

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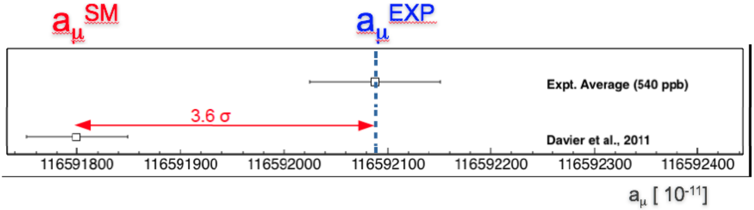
Outline

Measurement Status of Muon g-2

The anomalous magnetic moment of the muon ($a_\mu \equiv \frac{g-2}{2}$) was last measured by the Brookhaven experiment E821 in 1999-2001, resulting in a 3.6σ discrepancy with the Standard Model of particle physics G. Bennett, *et al.*, Phys.Rev.D73, 072003 (2006)]

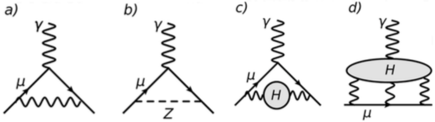


Is this discrepancy an indication of new physics beyond the standard model?

Muon g-2

- The muon has a magnetic dipole moment of $\vec{\mu} = g\frac{q}{2m}\vec{s}$, with $g = 2$ for a pointlike particle (Dirac)
- The Standard Model predicts effects from QED, electroweak theory, and QCD.
  $g_{SM} = 2_{Dirac} + \mathcal{O}(10^{-3})_{QED} + \mathcal{O}(10^{-9})_{EW} + \mathcal{O}(10^{-7})_{QCD}$
- If a discrepancy with the standard model value is found, beyond standard model contributions to g-2 could come from SUSY, dark photons, extra dimensions, or other new physics (NP).

$$a_\mu = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD} + a_\mu^{NP}$$

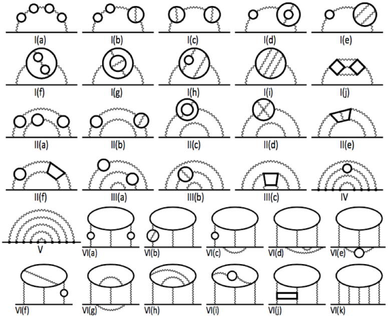


QED Contributions

$$a_\mu = 11659208 \times 10^{-11}$$

- Leading contribution to a_μ, and smallest uncertainty.
- Recent calculations to 5 loops reduce QED uncertainty to 5×10^{-11}.
- 99.99% of a_μ
- 0.001% δa_μ

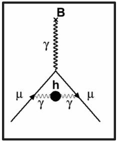
10th
12672
diagrams

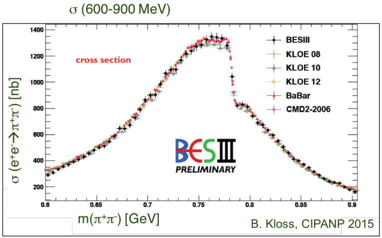


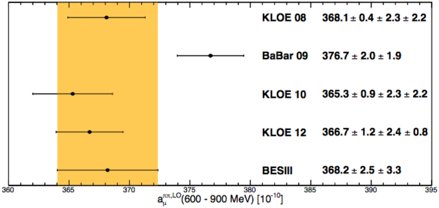
Hadronic Contribution (experiment)

$$a_\mu = 11659208 \times 10^{-11} \; (73\% \; \delta a_\mu)$$

Hadronic Vacuum Polarization contribution determined from $e^+e^- \rightarrow \textit{hadrons}$ measurements at BESIII, CMD3 (soon), BaBar, KLOE.



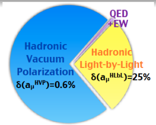




Phys.Lett. B753 (2016) 629-638

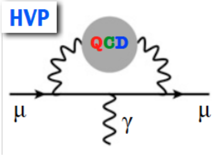
Dispersion Relation: $a_\mu^{HVP} \approx \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \rightarrow \textit{hadrons})ds$

Hadronic Contribution (Lattice QCD)



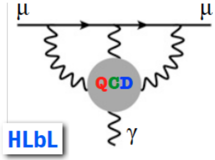
Lattice QCD is being used to compute contributions from HVP and hadronic light-by-light.

Target: $\delta(a_\mu^{HVP}) < 0.2\%$



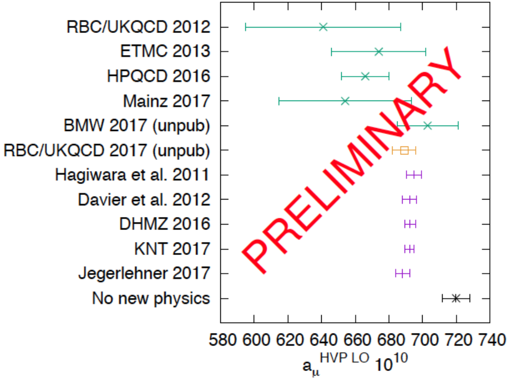
- The vacuum polarization $\hat{\Pi}(K^2)$ is calculated on the lattice. [Blum, PRL 91 (2003)]
- Effect of $\mathcal{O}(\alpha^2)$
- Recent results of the disconnected contribution calculated, $a_\mu^{HPV,LO} = -9.6(3.3)(2.3) \times 10^{-10}$ Blum *et al*, PRL 116 (2016)
- The strange quark connected contribution calculated to 2%, $a_\mu^{had} = 53.1(9)(^{+1}_{-3}) \times 10^{-10}$ Blum *et al.* JHEP 1604 (2016)
- Uncertainties match those given by the experimental measurements. Sub-percent precision will require the inclusion of QED and isospin-breaking.

Target: $\delta(a_\mu^{HLBL}) < 10\%$



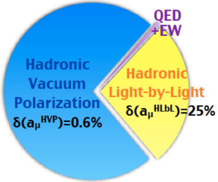
- Unknown how to measure this contribution experimentally.
- Effect of $\mathcal{O}(\alpha^3)$
- Calculated for nearly real pion mass. Blum, *et al.*, PRD93 (2016)
- HLbL contribution to g-2 of $(132.1 \pm 6.8) \times 10^{-11}$. Errors are statistical.
- Better precision requires more computing time.

New Contributions from Lattice



From talk by C. Lehner at Lattice 2017

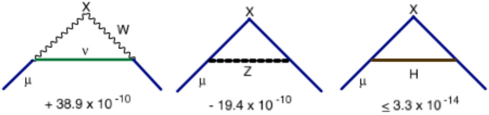
- Significant effort to compute contributions to a_μ from HVP (see left) and hadronic light-by-light (Blum *et al.* 2017) on the lattice.
- HVP uncertainties comparable to those from experiments.



Electroweak Contribution

$$a_\mu = 11659208 \times 10^{-11}$$

- Electroweak contribution calculated to 2-loops.
- Higgs Mass reduces uncertainty by factor of 2
- 0.2% of δa_μ

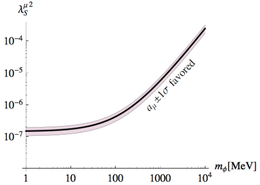


New Physics

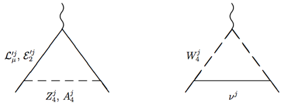
All standard model particles contribute to the anomalous magnetic moments of the electron, muon, and tau via vacuum fluctuations. Compared to electrons, the influence of higher mass particles have a higher impact on a_μ by a factor of $(m_\mu/m_e)^2 \approx 4 \times 10^4$.

If the discrepancy from the Standard Model holds, it could be accounted for with several models, including:

- Dark Matter
- Supersymmetry
- Extra dimensions
- Additional Higgs Bosons
- Something else?



Yukawa coupling parameter vs mass of dark Higgs. Band is 1σ for BNL measurement of muon g-2. Chen *et al*, Phys.Rev.D93 (2015)



Contributions to g-2 from gauge fields polarized in extra dimensions. Appelquist & Dobrescu, Phys.Lett.B516 (2001)

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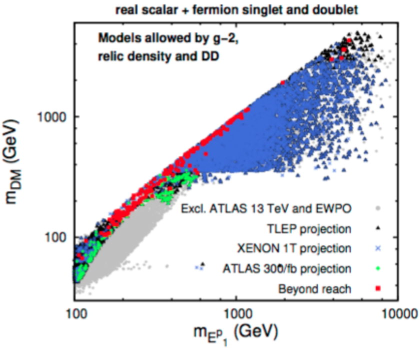


Dark matter model allowed at 2σ from the BNL g-2, Kowalska and Sessolo, 2017

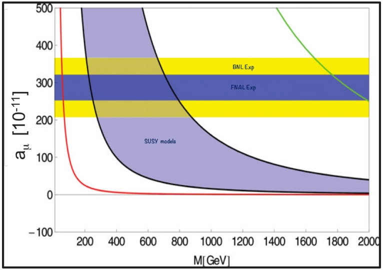
SUSY

$$a_\mu(SUSY) \approx (sgn(\mu)130 \times 10^{-11} tan(\beta)(\frac{100GeV}{\tilde{m}})^2)$$

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\tilde{u}_L\ \tilde{u}_R\ \tilde{d}_L\ \tilde{d}_R$	(same)
			$\tilde{s}_L\ \tilde{s}_R\ \tilde{c}_L\ \tilde{c}_R$	(same)
			$\tilde{t}_L\ \tilde{t}_R\ \tilde{b}_L\ \tilde{b}_R$	$\tilde{t}_1\ \tilde{t}_2\ \tilde{b}_1\ \tilde{b}_2$
sleptons	0	−1	$\tilde{e}_L\ \tilde{e}_R\ \tilde{\nu}_e$	(same)
			$\tilde{\mu}_L\ \tilde{\mu}_R\ \tilde{\nu}_\mu$	(same)
			$\tilde{\tau}_L\ \tilde{\tau}_R\ \tilde{\nu}_\tau$	$\tilde{\tau}_1\ \tilde{\tau}_2\ \tilde{\nu}_\tau$
neutralinos	1/2	−1	$\tilde{B}^0\ \tilde{W}^0\ \tilde{H}_u^0\ \tilde{H}_d^0$	$\tilde{N}_1\ \tilde{N}_2\ \tilde{N}_3\ \tilde{N}_4$
charginos	1/2	−1	$\tilde{W}^\pm\ \tilde{H}_u^+\ \tilde{H}_d^-$	$\tilde{C}_1^\pm\ \tilde{C}_2^\pm$
gluino	1/2	−1	$\tilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\tilde{G}$	(same)

- Complimentary to direct searches at the LHC
- Sensitive to sgnμ and tanβ.
  - g-2 contributions arrise primarily from charginos and sleptons.
  - LHC is most sensitive to squarks and gluinos.

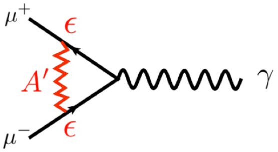
D. Hertzog, Ann.Phys.2015 (image D. Stöckinger)

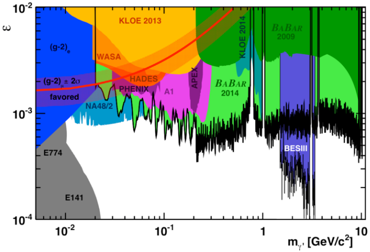


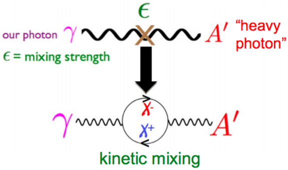
- The grey band shows SUSY models for tan $\beta \approx 5 - 50$.
- The green line indicates radiative muon mass generation.
- The red line shows Z, W, universal extra dimensions, or Littlest Higgs models.

Dark Photon

- The dark photon, A', would demonstrate a new $U(1)$ symmetry and would be a be a contributor to the muon g-2 discrepancy with the standard model.
- A kinetic mixing term where the photon mixes with a new gauge boson (i.e. dark photon) through the interactions of massive fields induces a weak coupling to electric charge

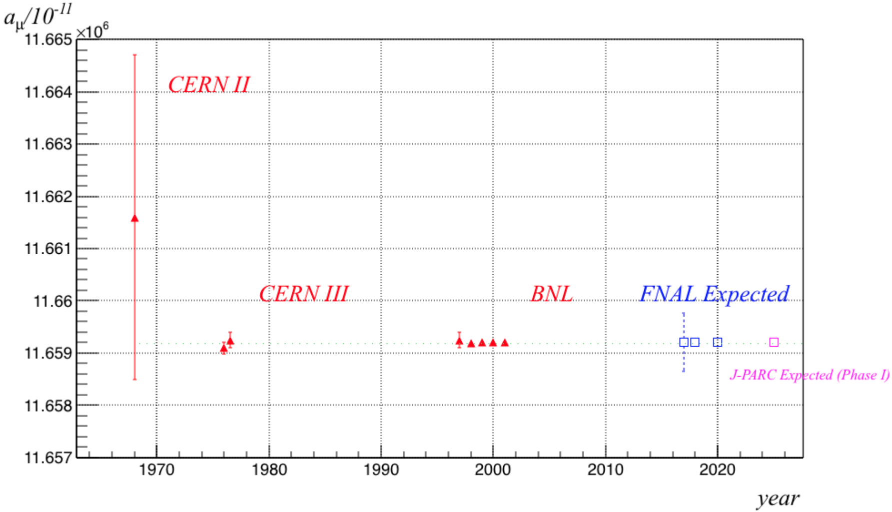




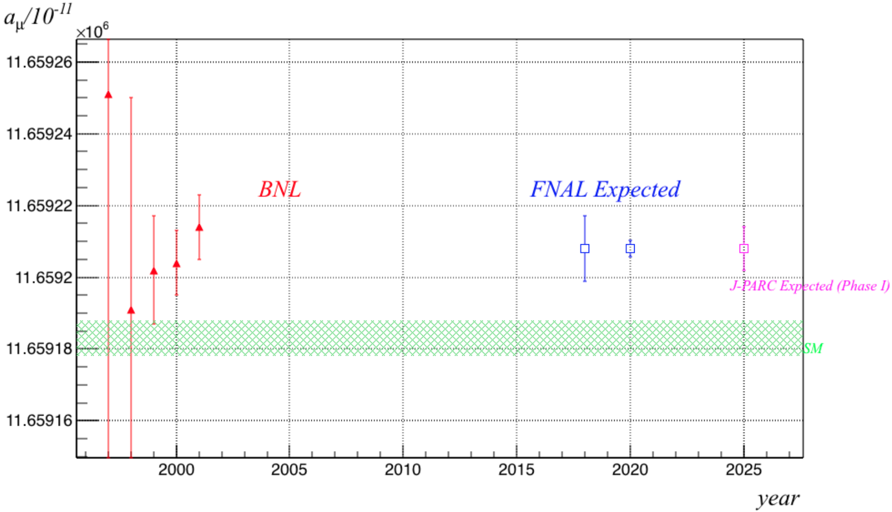


The red band shows the phase space preferred by the current measurement of a_μ.

Measurement history

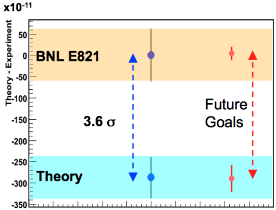


Measurement history



Current status

Contribution	a_μ ($\times 10^{-11}$)	$\delta(a_\mu)$ ($\times 10^{-11}$)
QED ($\gamma + 1$)	116 584 718.951	$\pm$ 0.1
QCD: HVP (lo)	6 949	$\pm$ 43
QCD: HVP (ho)	-98.4	$\pm$ 0.7
QCD: HLbL	132.1	$\pm$ 6.8
EW	154	$\pm$ 1
Total SM	116 591 828	$\pm$ 50

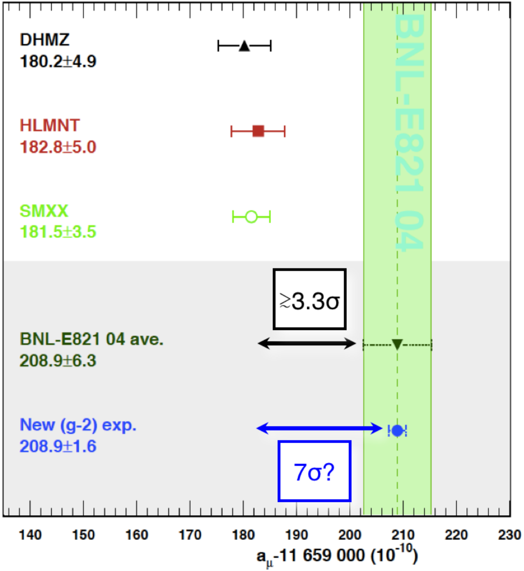


Many possible BSM contributions at $\mathcal{O}(10^{-11})$.

A measurement to this precision could provide a $> 7\sigma$ discrepancy from the standard model, which would provide clear evidence of new physics.

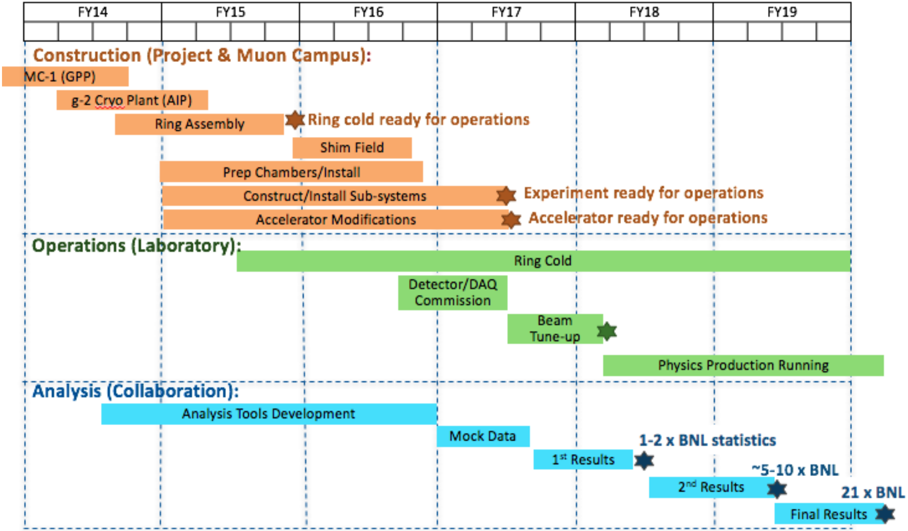
Muon g-2 Experiment at Fermilab

Experimental goal: 5σ



- BNL E821 measured a_μ to have a 3.3σ discrepancy from the standard model (2006).
- Fermilab E989 will measure 21 times the number of muons.
- Without theory improvements, discrepancy could reach $> 5\sigma$.
- Will also perform most precise measurement of muon EDM.

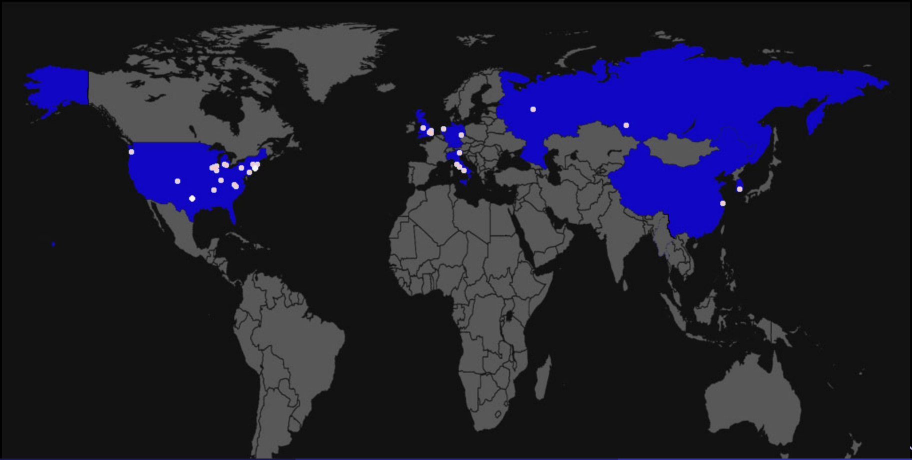
Installation Schedule



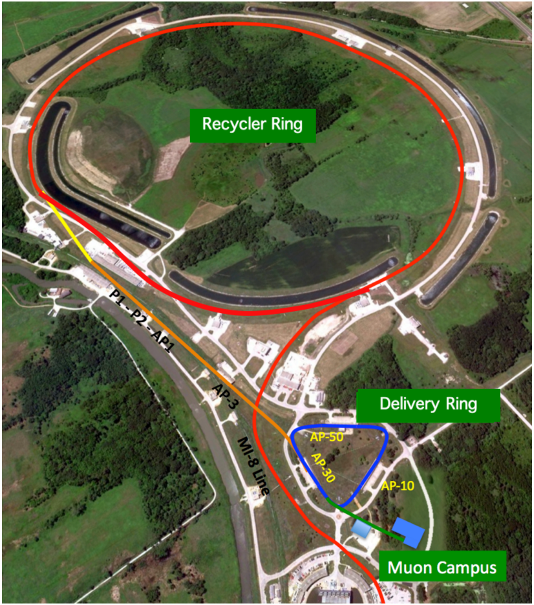
Collaboration

E989 Muon g-2 Collaboration

8 Countries, 33 Institutions



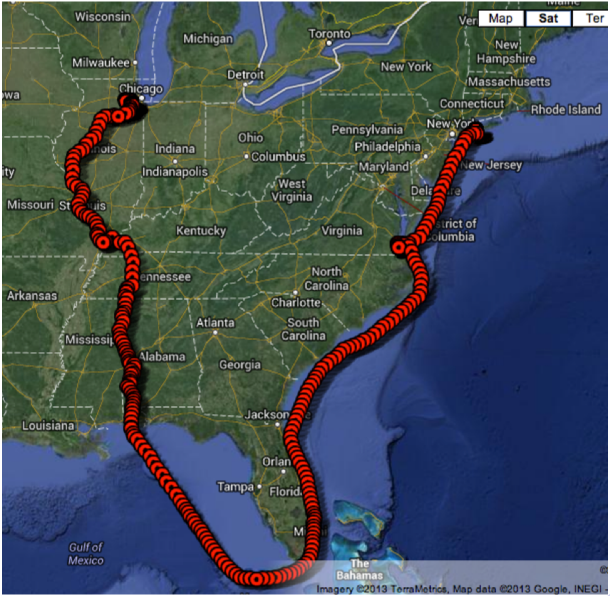
Accelerator



- Fermilab antiproton source was repurposed to serve as polarized muon source, and new tunnels have been built.
- Beamline became operational in May, 2017.

Muon Campus at Fermilab

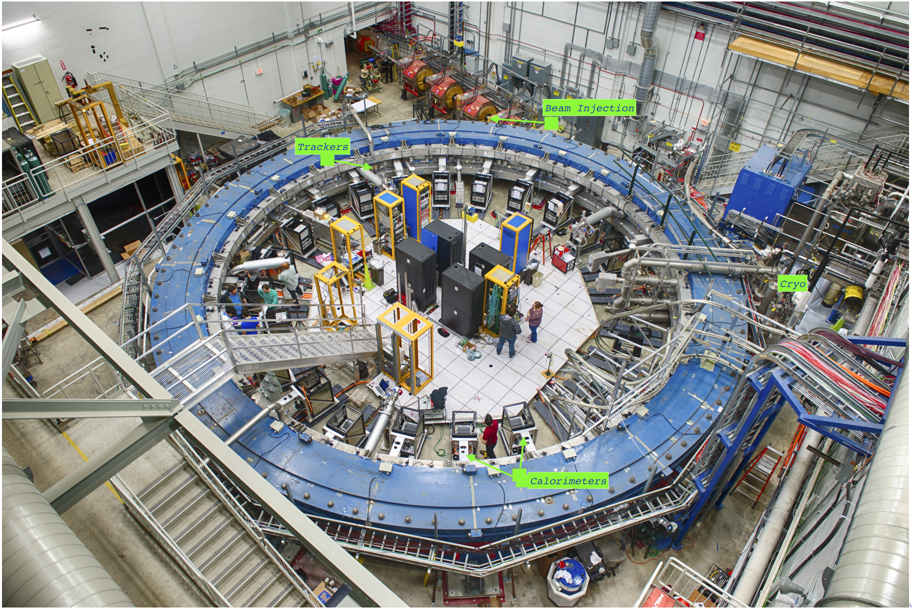
The Big Move



The 50' magnetic storage ring that was used in BNL experiment E821 was moved from New York to Chicago by barge and truck, and has been installed in our new building at Fermilab.

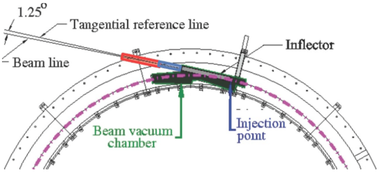
The Big Move

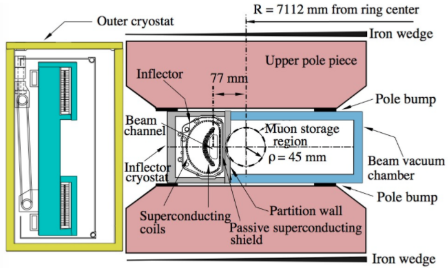
The Ring Installation in MC-1

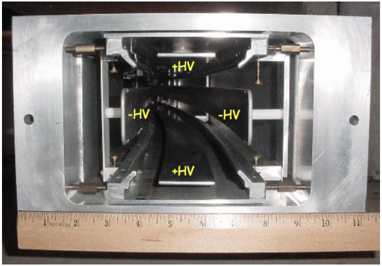


Muon storage

- The inflector allows muons to be injected into the ring.
- Electrostatic quadrupoles contain the beam vertically.
- Kicker plates steer injected muons onto a closed orbit.

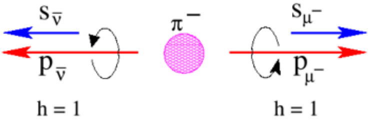


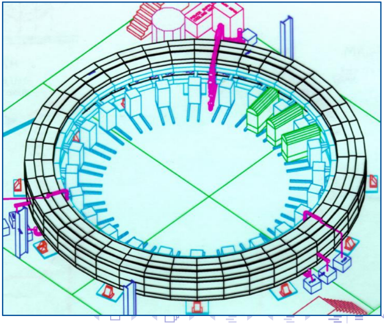




Measurement procedure

- Inject polarized muons into a magnetic storage ring.
- Muons will precess in the magnetic field.
- Measure the precession frequency via the timing of muon decays to positrons.
- Measurements of the precession frequency and magnetic field lead to a_μ.





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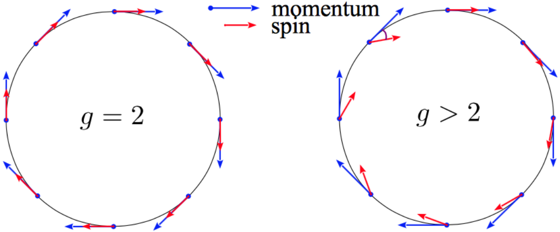

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Magic momentum at $\gamma = 29.3$.

$$\vec{\omega}_a = -\frac{Qe}{m}[a_\mu \vec{B} - (a_\mu - (\frac{mc}{p})^2)\frac{\vec{\beta}\times\vec{E}}{c}]$$

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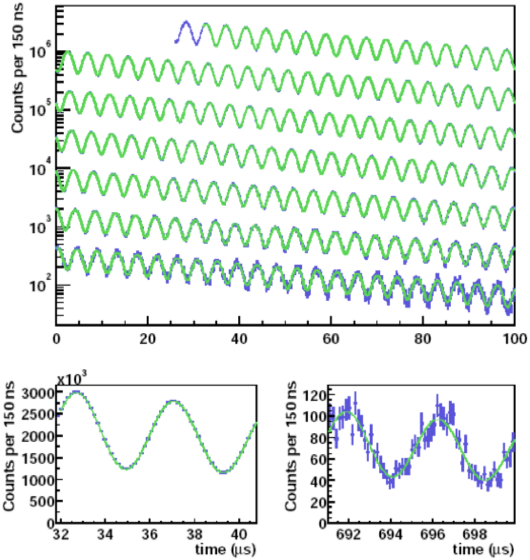
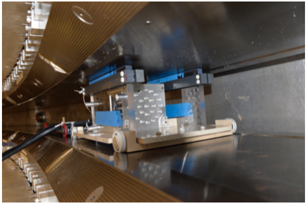
ω_a Measurement

- Cyclotron frequency: $\omega_c = \frac{e}{m\gamma}B$
- Spin precession frequency: $\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$
- We measure $\omega_a = \omega_s - \omega_c = \frac{e}{m}a_\mu B$.
- Measurements of ω_a and B provide a_μ.



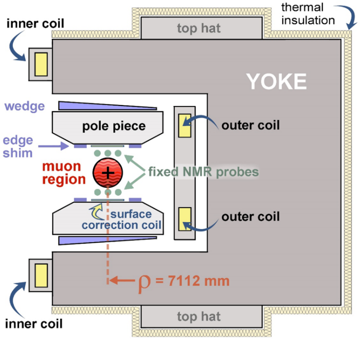
Field Measurement

- The proton precession frequency ω_p is measured as a proxy for $\vec{B}$. Measure ω_p using NMR.
  $\omega_a = \frac{eB}{m} a_\mu \rightarrow a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$
- Fixed NMR probes measure time variations of the field during data taking.
- A trolley with mounted NMR probes periodically circumnavigates the interior of the ring to perform precision measurements of the field in the muon storage region, performing 6000 magnetic field measurements per trolly run.
- Probes are calibrated to provide measurement to 35 ppb using a 1.45 T MRI magnet.



- Shimming trolly outfitted with 25 NMR probes.
- A laser tracking system records the trolly position as it travels around the ring.
- The trolly is pulled by a system of cables, as an on-board motor would disturb the magnetic field.

Field Uniformity



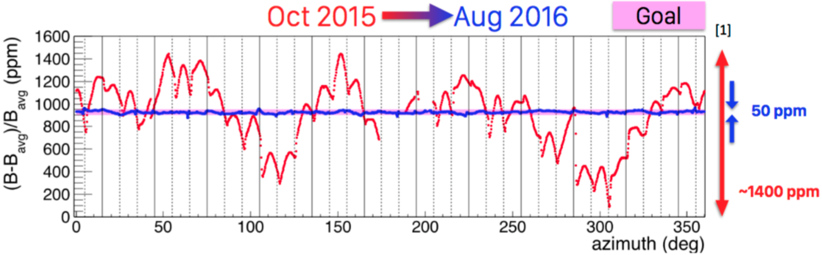
g-2 Magnet in Cross Section

- B field is 1.45 T, 5200 A.
- The magnetic field must be constant in the muon region to ±0.5 ppm.
- The field is homogenized by:
  - Adding iron shims removes quadrupole and sextapole asymmetries.
  - Adjusting the top hats changes the effective mu.
  - Surface correction coils add average field moments.

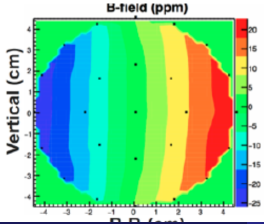
Field measurement

Azimuthal measurement:

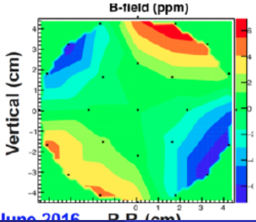
(pink band signifies goal precision of 50 ppm)



Azimuthal average:



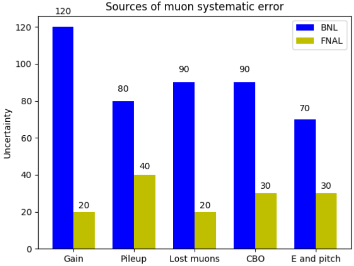
	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

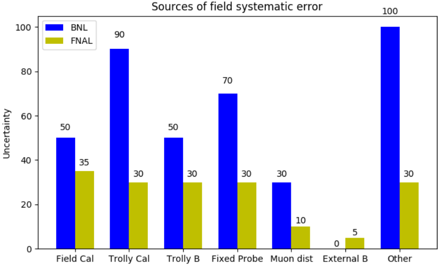


	Norm	Skew
Quad	-1.00	0.56
Sext	-2.83	5.99
Octu	-1.24	-0.20
Decu	1.25	0.18

Systematics Improvements

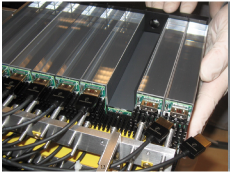
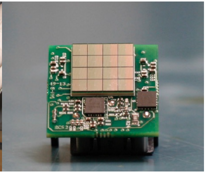
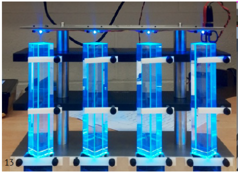
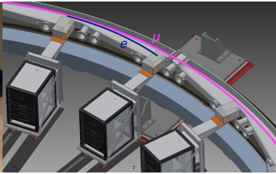
- Accelerator facilities reduce beam power, have p_π closer to magic momentum, utilize a longer decay channel, and increase injection efficiency.
- Systematics on ω_a will be decreased from 180 ppb in E821 to 70 ppb.
- Systematics on ω_p will be decreased from 170 ppb in E821 to 70 ppb..





Calorimeters

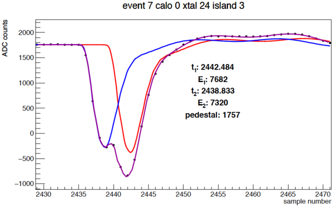
- The interior of the ring is lined with 24 calorimeters, which provide the ω_a measurement.
- Each calorimeter is composed of 54 PbF_2 crystals with SiPMs and read out by custom 800 MSPS waveform digitizers.
- A laser calibration system actively provides calibration signals to the calorimeters in between muon fills.

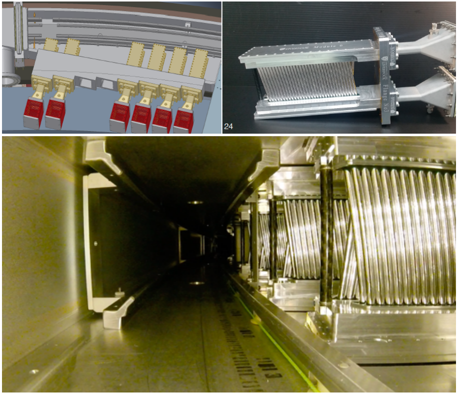
SLAC test beam

In June, 2016, one full calorimeter with 54 crystals, SiPMs, 800 MSPS μTCA WFDs, MIDAS/GPU DAQ, and laser calibration system, was tested in a SLAC test beam.

- Timing resolution of 25 ps at 3 GeV.
  - Allows for electron angle determination based on time-differences between neighboring SiPMs.
- Pileup separation at 4.5 ns.
- 50 MeV resolution at 2 GeV

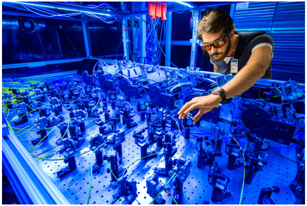


Tracking detectors

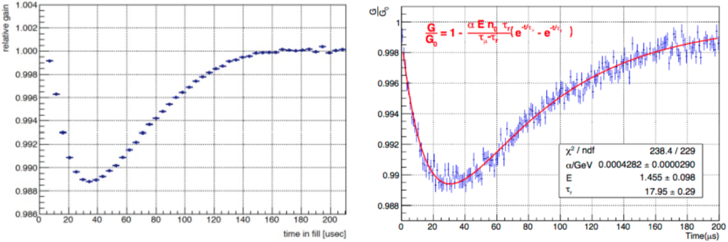


- Plan for three tracking stations – currently have one.
- Tracker sits in front of a calorimeter.
- Each tracker consists of eight modules of 64-128 straws filled with Ar:CO_2 gas.

Laser Calibration System



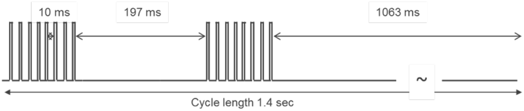
- A state-of-the-art laser calibration system is used to calibrate the calorimeters.
- Fibers cary laser shots to each of the 1296 calorimeter crystals.
- Used for timing and gain calibrations at the subpermil level.

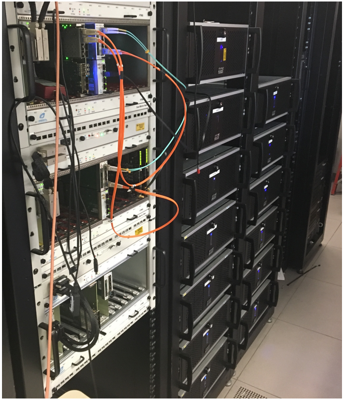


Gain fluctuations from SiPM measurement (left) and simulation (right).

Data Acquisition with GPUs

- The DAQ must produce a deadtime-free record of each 700 μs muon fill. We get 12 fills per second, providing a total data rate of 20 GB/s.
- Data from each calorimeter is processed by an NVidia Tesla K40 GPU, which processes 33M threads per event.
- Data is 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 with CUDA for GPU processing.

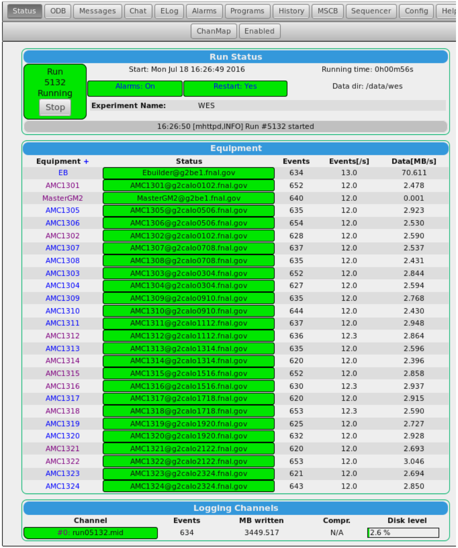




DAQ is fully operational and performed well during commisioning.

MIDAS

- MIDAS is a data acquisition software developed at PSI and also used extensively at TRIUMF.
- Includes web interface for easy control.
- Frontend acquisition code written in C/C++ with CUDA.
- Javascript based analyzer for online data monitoring via a web gui.
- Data will be written to tape as MIDAS datafiles.

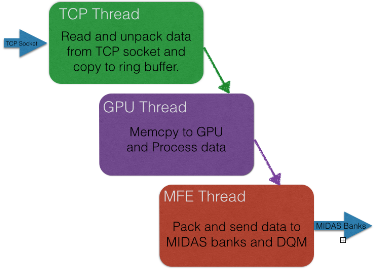


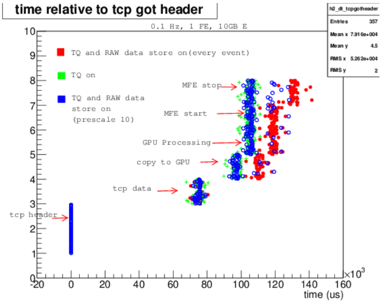
Equipment +	Status	Events	Events[/s]	Data[MB/s]
EB	Ebuilder@g2be1.fnal.gov	634	13.0	70.611
AMC1301	AMC1301@g2calo0102.fnal.gov	652	12.0	2.478
MasterGM2	MasterGM2@g2be1.fnal.gov	640	12.0	0.001
AMC1305	AMC1305@g2calo0506.fnal.gov	635	12.0	2.923
AMC1306	AMC1306@g2calo0506.fnal.gov	654	12.0	2.530
AMC1302	AMC1302@g2calo0102.fnal.gov	628	12.0	2.590
AMC1307	AMC1307@g2calo0708.fnal.gov	637	12.0	2.537
AMC1308	AMC1308@g2calo0708.fnal.gov	635	12.0	2.431
AMC1303	AMC1303@g2calo0304.fnal.gov	652	12.0	2.844
AMC1304	AMC1304@g2calo0304.fnal.gov	627	12.0	2.594
AMC1309	AMC1309@g2calo0910.fnal.gov	635	12.0	2.768
AMC1310	AMC1310@g2calo0910.fnal.gov	644	12.0	2.430
AMC1311	AMC1311@g2calo1112.fnal.gov	637	12.0	2.948
AMC1312	AMC1312@g2calo1112.fnal.gov	636	12.3	2.864
AMC1313	AMC1313@g2calo1314.fnal.gov	635	12.0	2.596
AMC1314	AMC1314@g2calo1314.fnal.gov	620	12.0	2.396
AMC1315	AMC1315@g2calo1516.fnal.gov	652	12.0	2.858
AMC1316	AMC1316@g2calo1516.fnal.gov	630	12.3	2.937
AMC1317	AMC1317@g2calo1718.fnal.gov	620	12.0	2.915
AMC1318	AMC1318@g2calo1718.fnal.gov	653	12.3	2.590
AMC1319	AMC1319@g2calo1920.fnal.gov	625	12.0	2.727
AMC1320	AMC1320@g2calo1920.fnal.gov	632	12.0	2.928
AMC1321	AMC1321@g2calo2122.fnal.gov	620	12.0	2.693
AMC1322	AMC1322@g2calo2122.fnal.gov	653	12.0	3.046
AMC1323	AMC1323@g2calo2324.fnal.gov	621	12.0	2.694
AMC1324	AMC1324@g2calo2324.fnal.gov	643	12.0	2.850

Channel	Events	MB written	Compr.	Disk level
#0: run05132.mid	634	3449.517	N/A	2.6 %

Code structure

CPU multithreading with mutex locks





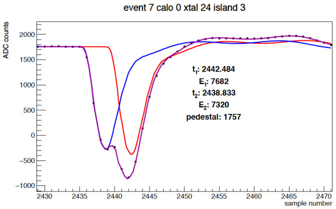
CUDA kernel routines: Data is copied to GPU memory in GPU thread, and then accessed by the following functions to identify and save islands, which are copied back to the computer memory and sent to the event builder.

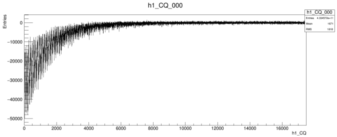
Function	Number of threads	Execution time (ms)
Compute pedestals as average of first 100 samples	54	0.1
Determine if threshold is passed for each sample	560k	1.7
Add pre-samples and post-samples to each island	560k	0.1
Check to see if any islands have merged	560k	0.2
Save an array of identified islands	560k	0.2
Sum all waveforms	560k	1.2
Decimate the sum for the Q-method	17.5k	0.3
Make a fill-by-fill sum of waveforms	30M	2.4

T and Q Methods

CUDA routines process data with two complimentary methods.

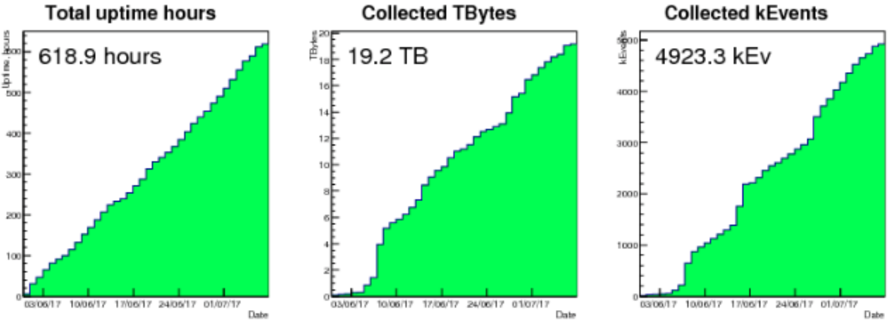
- T-method
    - Positron events in the calorimeter are individually identified, sorted and fit to obtain time and energy.
    - All events above an energy threshold are included.
    - $\vec{\omega}_a$ is determined from a fit to a pileup-subtracted histogram.
    - This was the method used in BNL E821.
- Q-method
    - Individual positron events are not identified.
    - Detector current is integrated as a proxy for event energy.
    - Pileup has a smaller impact.





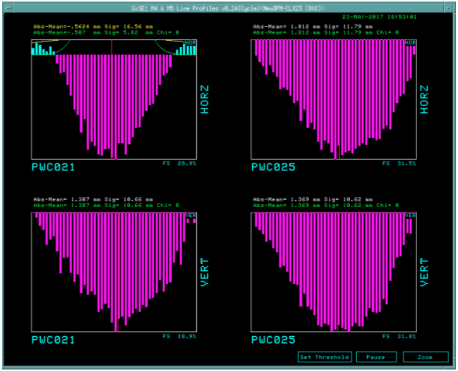
Commissioning Run 2017

- Received 5 weeks of beam during June-July 2017.
- Mostly protons with $\mathcal{O}(1\%)$ muons.
- Fill rate of 0.1 Hz (nominal rate of 12 Hz expected)

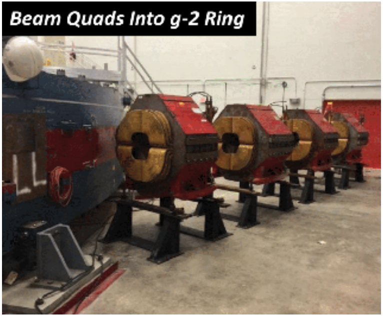


First beam injected

First beam injected into ring on May 31, 2017



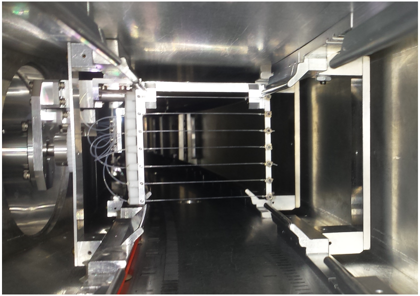
- Beam profile from last upstream beam monitor.

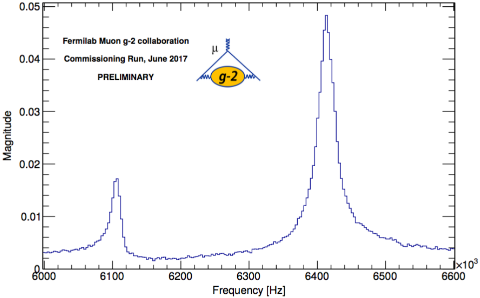


- Beam quadrupoles deliver beam to g-2 ring.

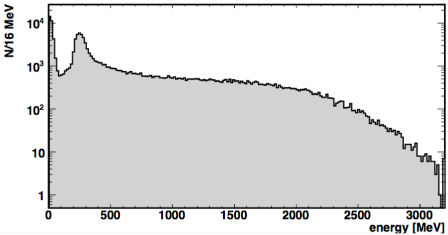
Beam Storage in Ring

- Beam (protons and muons) stored for several hundred turns.
- Fiber harps measure stored beam.
- FFT shows proton cyclotron frequency and betatron frequency of stored protons.

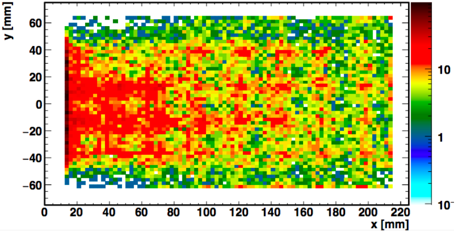




Calorimeter Beam Data

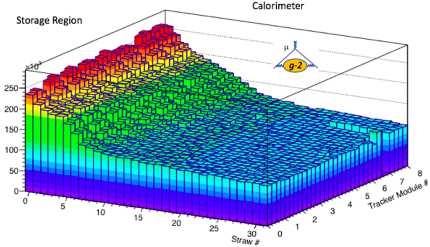


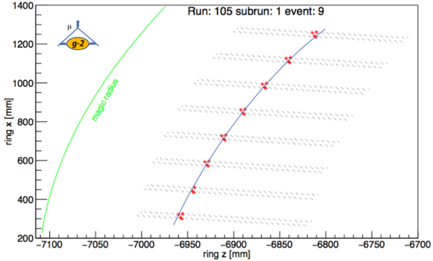
Energy distribution from June 2017 data recorded in the calorimeter. The peaks are from protons and lost muons



Spatial distribution of calorimeter clusters from June 2017 data recorded in the calorimeter. The muon storage region is to the left of the plot.

First tracks





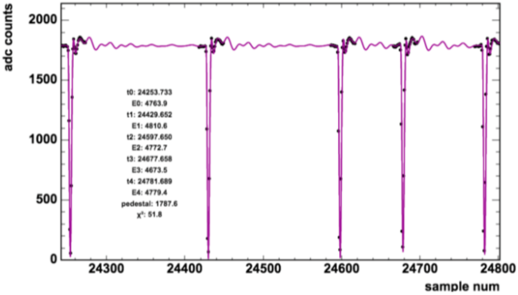
Distribution of recorded hits in the 8 tracking modules. The hit density peaks closer to the storage region.

One of the first tracks recorded by the tracker showing the hits from a single charged particle (likely a proton).

Extracting ω_a

T-method (pulse fitting)

- Using template fits to SiPM pulses and clustering algorithms to extract time of each positron hit on the calorimeter.
- Sensitive to pileup systematics.

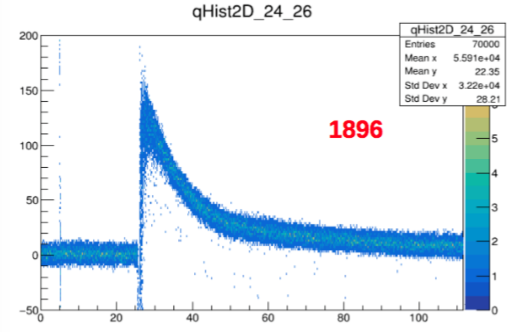


- The tail of one island could affect the baseline of another island.
- If multiple islands fall within the template length of one island, a chained fit is used.

Extracting ω_a

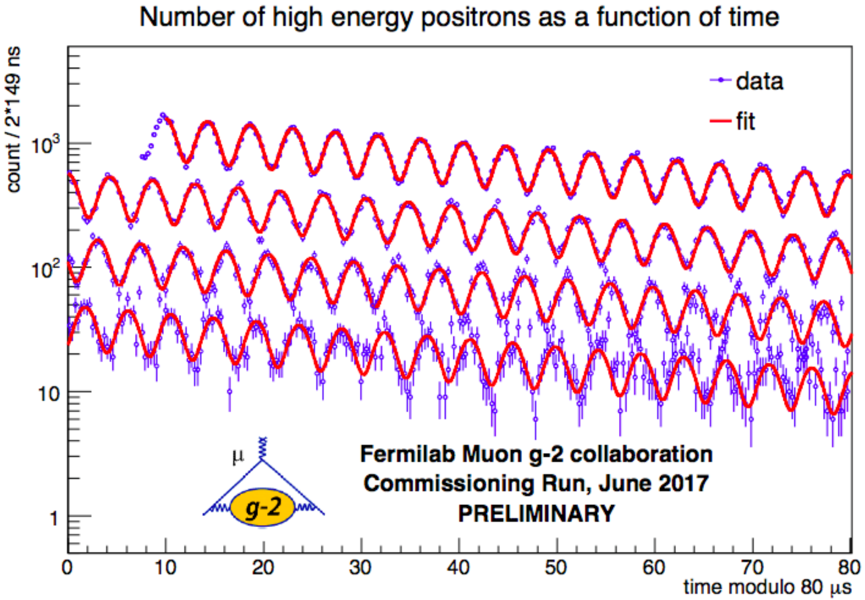
Q-method (charge integration)

- Integrated detector current as a proxy for positron energy, which produces a frequency spectrum.
- Less sensitive to pileup, but more sensitive to pedestal variations.



Pedestal variation in Q-method flushes from one run.

First E989 Wiggle Plot



Conclusion

- The new Muon g-2 experiment at Fermilab will measure the anomalous magnetic moment of the muon to 4 $\times$ the precision of the previous BNL measurement.
- If the previously measured value holds, this could provide a 7σ discrepancy from the standard model.
- We had a successful commissioning run in June of 2017 and will continue running this November.

- The 2017 run provided 10^{-5} of the required stats, which is between the total statistics of CERN II and CERN III.
- Our goal is for a BNL level result in 2018, and a 140 ppb measurement in 2020.

Appendix

Simulation

- An end-to-end simulation of the ring and detectors is being used to explore potential systematic errors and to refine analysis code.
- Strong sources of systematics include pileup, muon loss and coherent betatron oscillation, which can all be explored in our simulation.
- Mock data at the level of the BNL statistics has been generated and analyzed, and our next challenge is to generate a full E989 statistics.