The Muon g-2 Experiment at Fermilab

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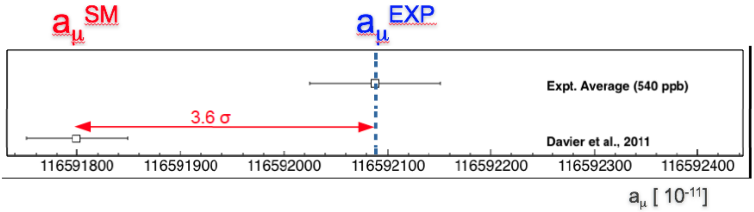
Measurement Status of Muon g-2

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)]

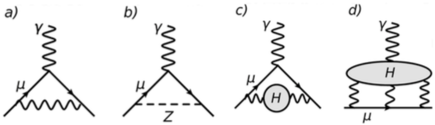


Is this discrepancy an indication of new physics beyond the standard model?

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)
- Additional effects from QED, electroweak theory, and hadronic factors move the standard model prediction of g away from 2, and we measure this difference, g-2.
- 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).

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

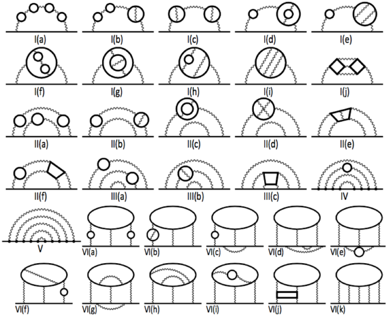


$$g_{SM} = 2_{Dirac} + \mathcal{O}(10^{-3})_{QED} + \mathcal{O}(10^{-9})_{EW} + \mathcal{O}(10^{-7})_{QCD}$$

QED and Electroweak Contributions

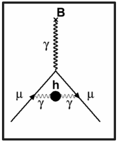
- Leading contribution to a_μ, and smallest uncertainty.
- Recent calculations to 5th order in α reduce QED uncertainty to 5×10^{-11}.
- Measurement of Higgs mass reduces electroweak error from 2×10^{-11} to 1×10^{-11}.

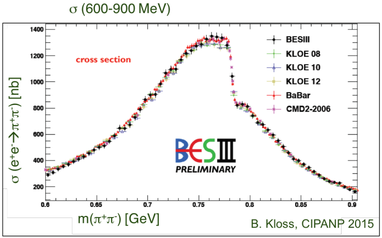
10th
12672
diagrams

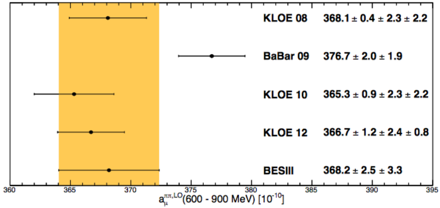


Hadronic Contribution (experiment)

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



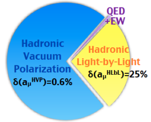




Phys.Lett. B753 (2016) 629-638

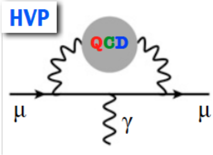
Dispersion Relation: $a_\mu^{HVP} \approx \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to hadrons)ds$

Hadronic Contribution (Lattice QCD)



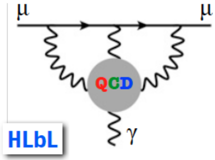
Lattice QCD is being used to compute contributions from HVP and hadronic light-by-light.

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



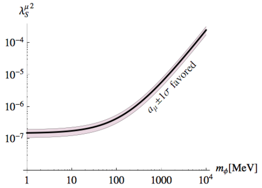
- Unknown how to measure this contribution experimentally.
- Effect of $\mathcal{O}(\alpha^3)$
- Calculated for nearly real pion mass. Blum, *et al.*, PRD93 (2016)
- HLbL contribution to g-2 of $(132.1 \pm 6.8) \times 10^{-11}$. Errors are statistical.
- Better precision requires more computing time.

New Physics

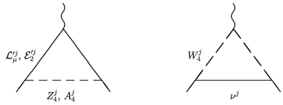
All standard model particles contribute to the anomalous magnetic moments of the electron, muon, and tau via vacuum fluctuations. Compared to electrons, the influence of higher mass particles have a higher impact on a_μ by a factor of $(m_\mu/m_e)^2 \approx 4 \times 10^4$.

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
- ~~A 750 GeV diphoton excess at the LHC~~
- 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)

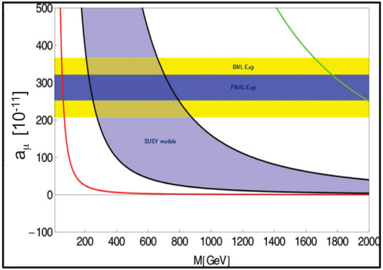
SUSY

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

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.

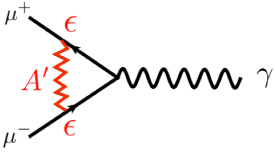
D. Hertzog, Ann.Phys.2015 (image D. Stöckinger)

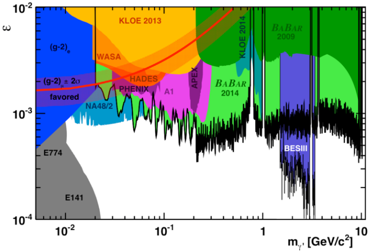


- The grey band shows SUSY models for tan $\beta \approx 5 - 50$.
- The green line indicates radiative muon mass generation.
- The red line shows Z, W, universal extra dimensions, or Littlest Higgs models.

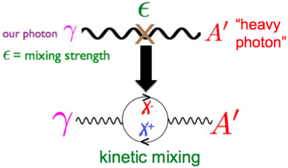
Dark Photon

- 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



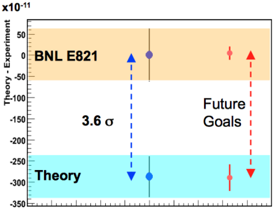


The red band shows the phase space preferred by the current measurement of a_μ.



Theory Summary

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

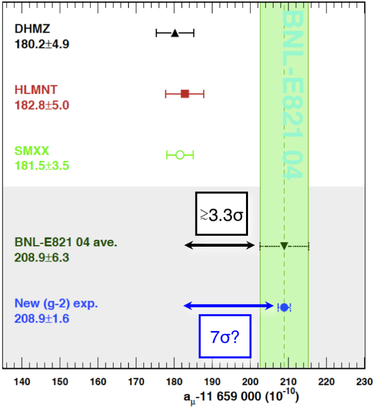


Many possible BSM contributions at $\mathcal{O}(10^{-11})$.

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



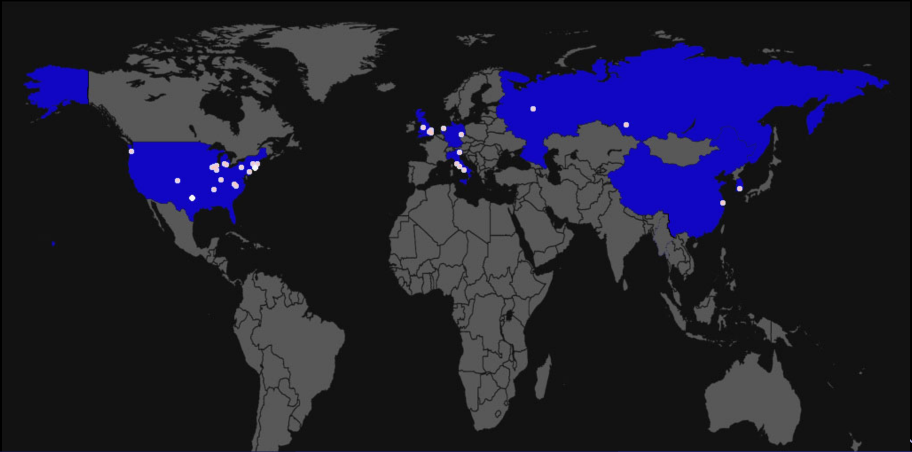
- BNL E821 measured g-2 to have a 3.3σ discrepancy from the standard model (2006).
- Fermilab E989 will measure 20 times the number of muons, reducing the uncertainty on this measurement by a factor of 4.
- Without theory improvements, discrepancy could reach $> 5\sigma$.

Uncertainty $\delta(a_\mu)$	Current value (ppb)	E989 Projection (ppb)
Theory	420	310
Experiment	540	140

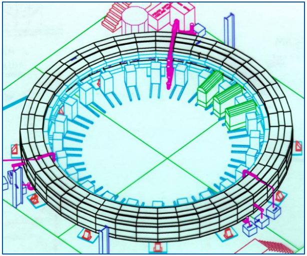
Collaboration

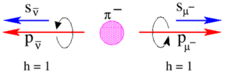
E989 Muon g-2 Collaboration

8 Countries, 33 Institutions



Measurement procedure

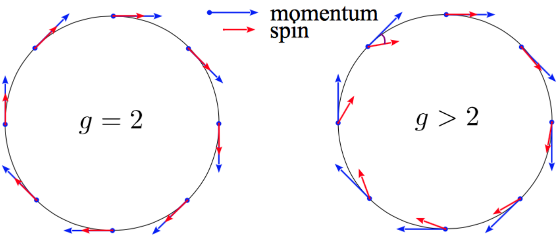




- Inject polarized muons into a magnetic storage ring.
- Muons will precess in the magnetic field.
- Measure the precession frequency via the timing of muon decays to positrons.
- Measurements of the precession frequency and magnetic field lead to a_μ.

Magic momentum at $\gamma = 29.3$.

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



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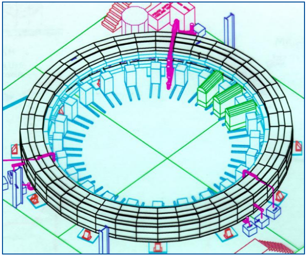

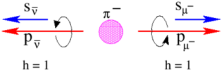

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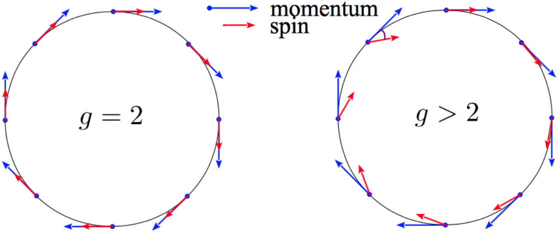
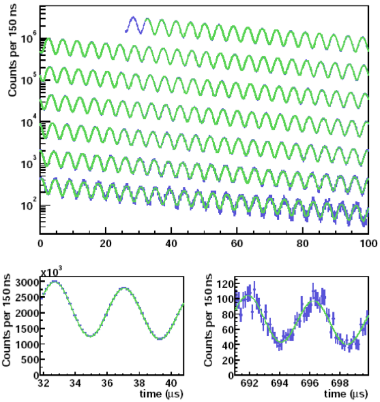


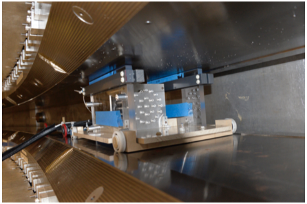
ω_a Measurement

- Polarized muons are produced naturally from pion decay and injected into a storage ring with a uniform magnetic field.
- 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

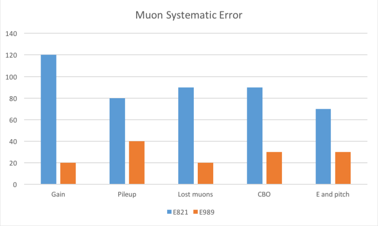
- The proton precession frequency ω_p is measured as a proxy for $\vec{B}$. Measure ω_p using NMR.
  $\omega_a = \frac{eB}{m} a_\mu \rightarrow a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$
- Fixed NMR probes measure time variations of the field during data taking.
- A trolley 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.

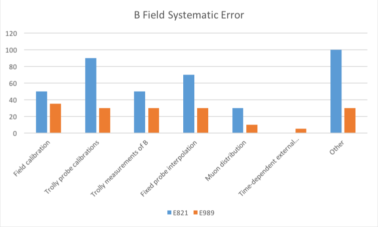


- Shimming trolly outfitted with 25 NMR probes.
- A laser tracking system records the trolly position as it travels around the ring.
- The trolly is pulled by a system of cables, as an on-board motor would disturb the magnetic field.

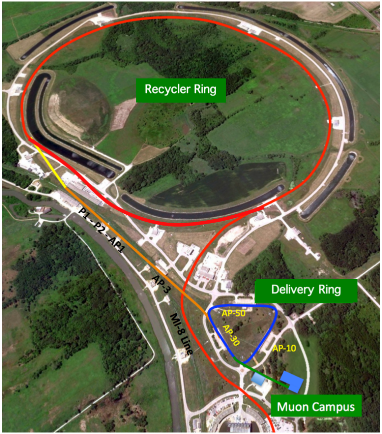
Statistics and Systematics

- We plan to collect 21 times the BNL statistics, which will reduce our statistical uncertainty by a factor of four.
- Improved accelerator facilities will reduce beam power, have p_π closer to magic momentum, utilize a longer decay channel, and increase injection efficiency.
- Uncertainties on ω_a will be decreased from 180 ppb in E821 to 70 ppb in E989 by using an improved laser calibration, a segmented calorimeter, better collimator in the ring, and improved tracker.
- Uncertainties on ω_p will be decreased from 170 ppb in E821 to 70 ppb in E989 by improving the uniformity and monitoring of the magnetic field, increasing accuracy of position determination of trolly, better temperature stability of the magnet, and providing active feedback to external fields.



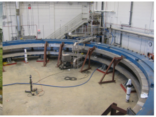


Infrastructure



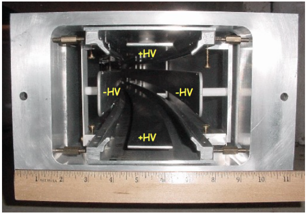
- Fermilab antiproton source was repurposed to serve as polarized muon source, and new tunnels have been built.
- A new experimental hall was built.
- The 50' magnetic storage ring that was used in BNL experiment E821 was moved from New York to Chicago by barge and truck, and has been installed in our new building at Fermilab.

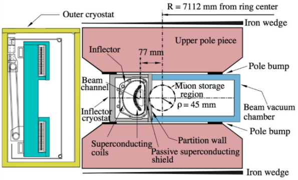


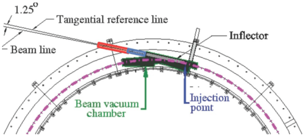


Muon storage

- 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.

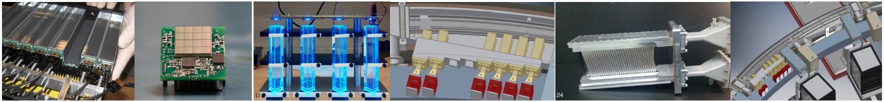






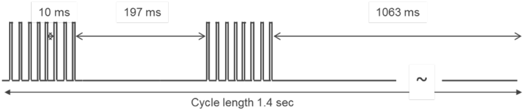
Detectors and DAQ

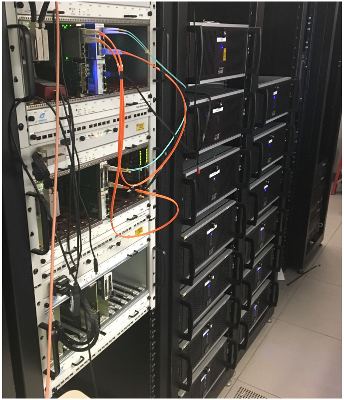
- The interior of the ring will be lined with 24 calorimeters, which perform the ω_a measurement. Each calorimeter is composed of 54 PbF_2 crystals with SiPMs and read out by custom 800 MSPS waveform digitizers.
- Three straw trackers positioned in the positron path will be used for determination of the track position.
- A fiber harp will be used during special calibration runs to measure beam dynamics.
- A laser calibration system is being constructed to actively provide calibration signals to the calorimeters in between muon fills.
- The data acquisition system is being constructed based on GPU technology to provide a deadtime free record of every muon fill.



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 18.6 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.



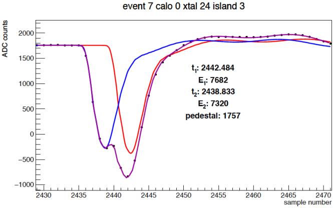


DAQ is fully operational as of July, 2016.

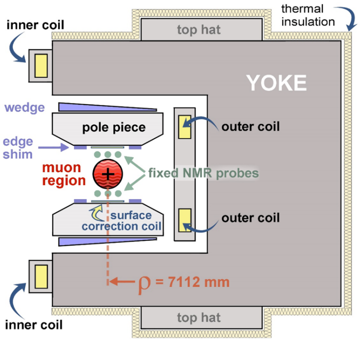
SLAC test beam

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.
- Data is being analyzed using the full *art*-based analysis chain.



Field Uniformity



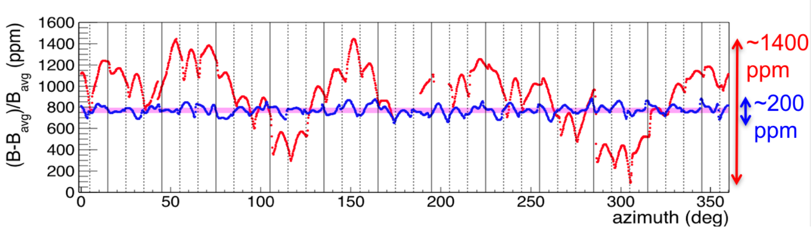
g-2 Magnet in Cross Section

- 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.

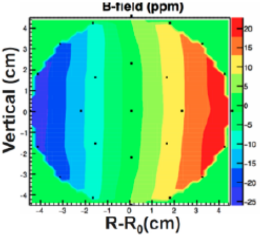
Field status

Azimuthal measurement:

(pink band signifies goal precision of 50 ppm)

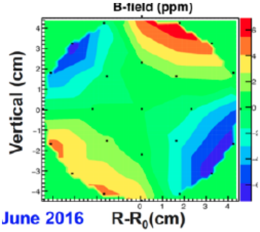


Azimuthal average:



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

Oct 2015

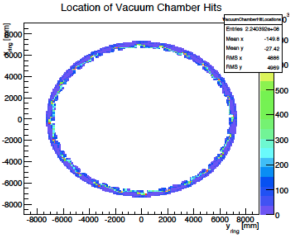


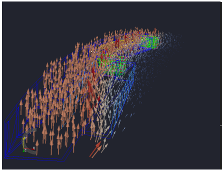
	Norm	Skew
Quad	-1.00	0.56
Sext	-2.83	5.99
Octu	-1.24	-0.20
Decu	1.25	0.18

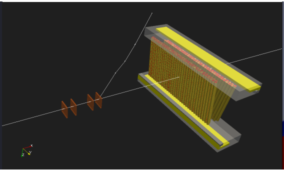
June 2016

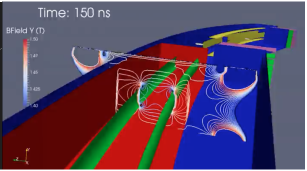
Simulation

- 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.

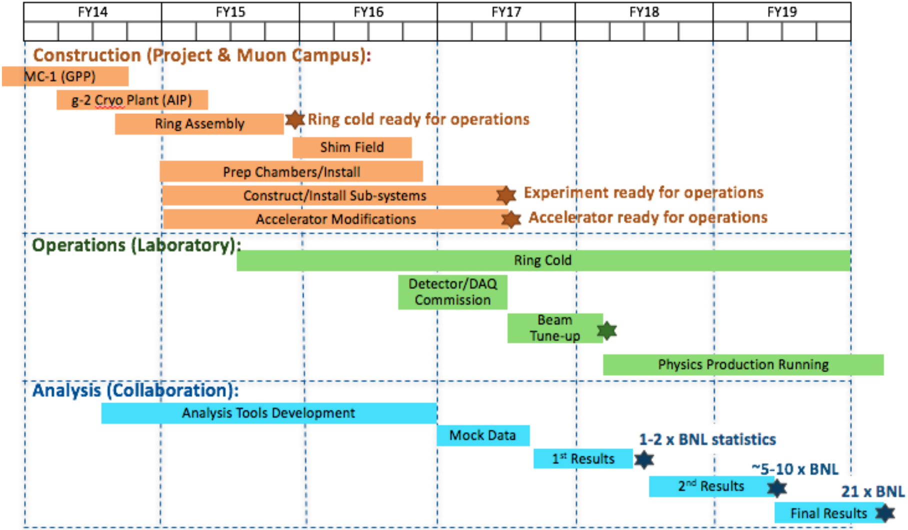








Installation Schedule



Conclusion

- The new E989 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.
- Data taking will begin in Spring of 2017, and will run through 2020.
- Homogenization of the ring's magnetic field is progressing nicely, and installation of detectors will begin in October.

Appendix