Experimental status of the muon g-2 (and prospects for CLFV measurements)

Dinko Počanić, (for the Muon g-2 Collaboration)

University of Virginia

18th Int'l. Conf. on B-physics
BEAUTY 2019
Ljubljana, Slovenia
30 Sep.–4 Oct. 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:

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

Lepton magnetic dipole moments

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

$$\left.\begin{aligned} a_e &= 0.001\,159\,652\,181\,61\,(23) \text{ [SM, } (\alpha/\pi)^5 \text{ order]}^{*} \\ a_e &= 0.001\,159\,652\,181\,28\,(18) \text{ [experiment, 0.15 ppb]}^{\dagger} \end{aligned}\right\} \text{agreement: } \sim 1.1\sigma$$

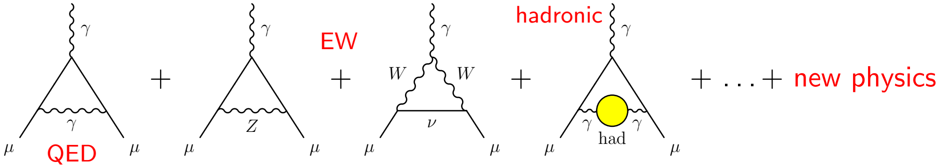
insensitive to massive particle loops ($\Rightarrow$ a_e provides an alternative measurement of α_{em})

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.

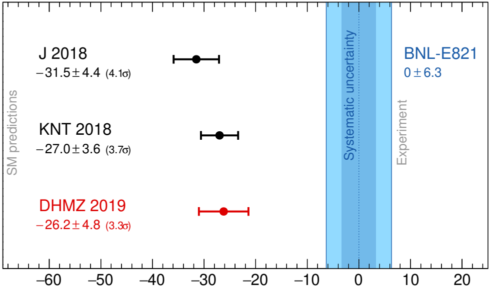
† Mohr et al., CODATA 2018, posted online 20 May 2019, to be published.

LO diagrams:



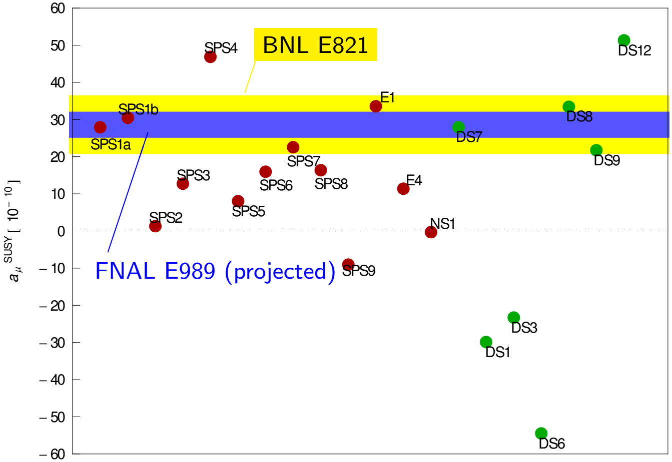
Term	Value ($\times 10^{-11}$)
QED $(\gamma + \ell)^*$	$116\,584\,718.95 \pm 0.08$
HVP(lo) [Davier et al 19]	$6\,939 \pm 40$
HVP(nlo) [Davier et al 19]	-98.7 ± 0.9
HVP(nnlo) [Kurz et al 14]	12.4 ± 0.1
HLbL [Prades et al 09]	105 ± 26
EW [Gnendinger et al 13]	154 ± 1
Total SM [Davier et al 19]	$116\,591\,829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

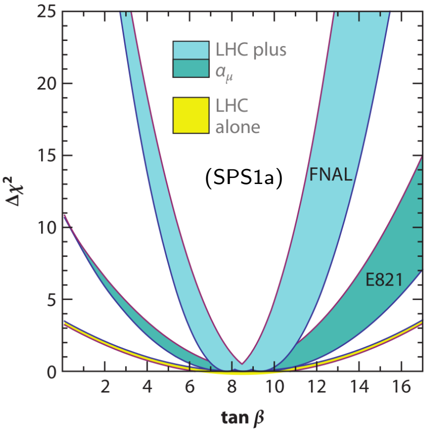
* Kinoshita et al 04-12, Kurz et al 16, Kataev 06, Passera 05



from Davier et al, arXiv:1908.00921 $a_\mu - a_\mu^{exp}$ [$\times 10^{-10}$]

$a_\mu^{\rm SUSY} \approx 13 \times 10^{-10} \tan\beta \; {\rm sgn}(\mu) \left(\frac{100\ {\rm GeV}}{M_{\rm SUSY}}\right)$, w. $\tan\beta = \frac{v_2}{v_1}$ (or $\frac{v_u}{v_d}$); μ is the strength of $\hat{H}_1\hat{H}_2$ term ...

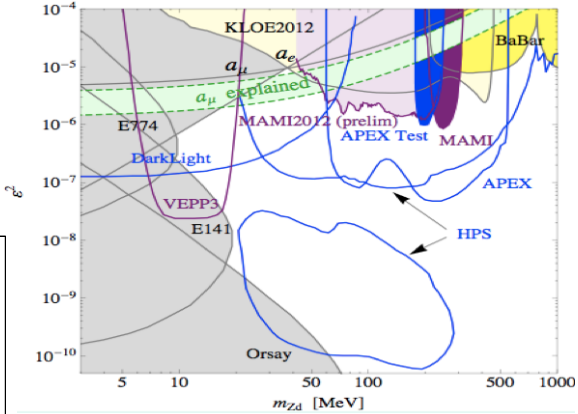


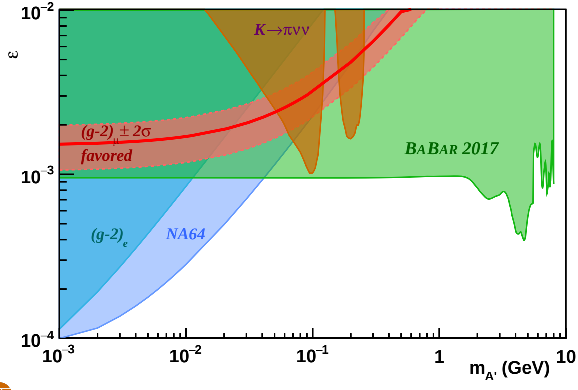


SUSY contributions to a_μ for select parameter sets [after C. Adam et al., EPJ C 171 (2011) 1520, and M. Alexander et al., arXiv:0802.3672].

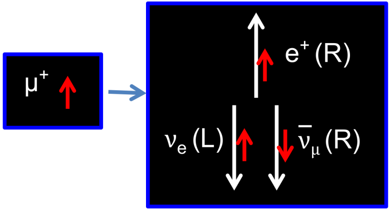
Dark photons:

status circa 2012 ⟶



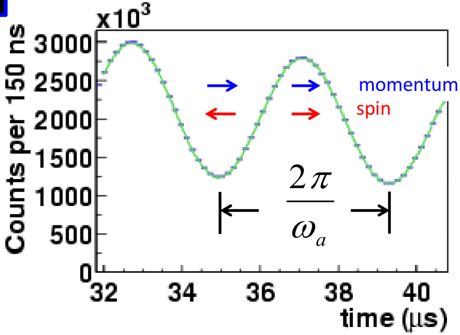


⟵ 2017 BaBar results



Positron direction follows muon spin

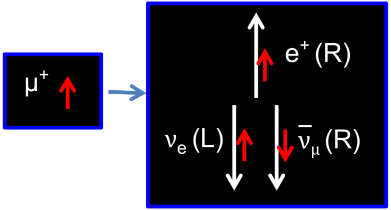
Highest energy positrons occur when muon spin and momentum are aligned (decay is boosted)



high energy positrons versus time

courtesy D. Hertzog

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



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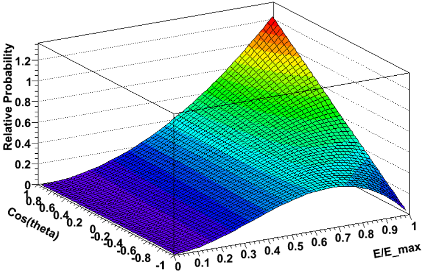
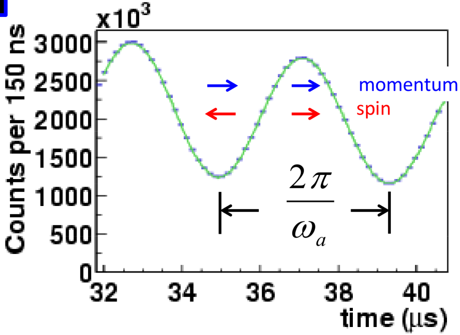


$$\theta = \angle(\vec{p}_e, \vec{p}_\mu)$$

courtesy D. Hertzog

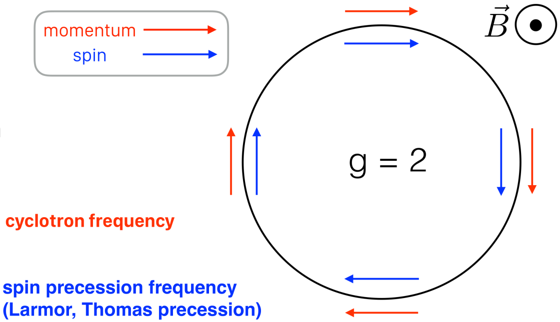


high energy positrons versus time

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

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

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



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

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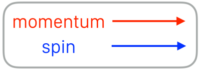
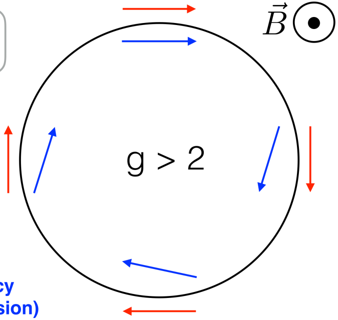




$$\vec{\omega}_C = -\frac{e}{\gamma m}\vec{B}$$

cyclotron frequency

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

spin precession frequency (Larmor, Thomas precession)

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

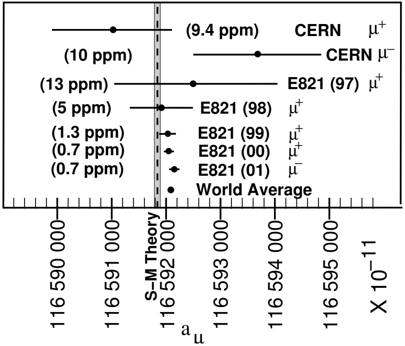
Dominated by results of BNL E821:

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

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

0.54 ppm result : statistical uncertainty dominates .

How to improve this result?



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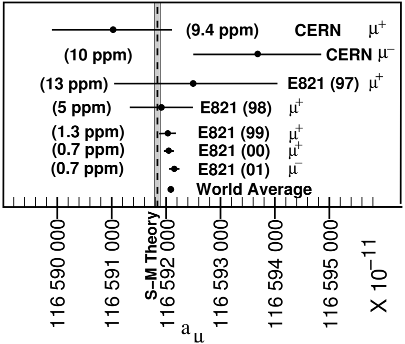

How to improve this result?

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

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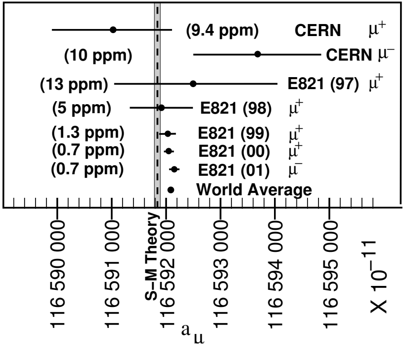

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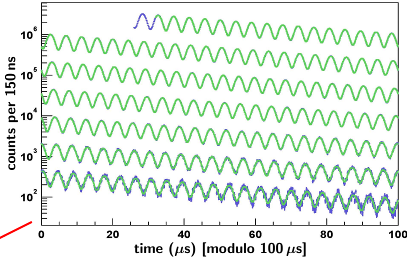
- Use a more intense beam at Fermilab: 21 × statistics of BNL E821,
- improve a number of contributing systematics factors.

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:



$$a_\mu = \frac{g_e}{2}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle\omega_p\rangle}$$

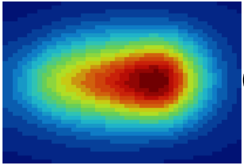
From 2018 CODATA (Mohr et al., May 2019):

$g_e = -2.002\,319\,304\,362\,56\,(35)$ [0.17 ppt] [$(g-2)_e$, QED]

$\mu_p/\mu_e = -0.001\,519\,270\,377\,10\,(46)$ [0.3 ppb] [H maser]

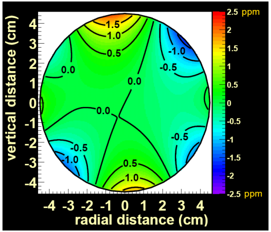
$m_\mu/m_e = 206.768\,2830\,(46)$ [22 ppb] [muonium HFS] MuSEUM/J-PARC

Recall: E989 goal is **140 ppb** overall!



beam profile in μSR

$\otimes$



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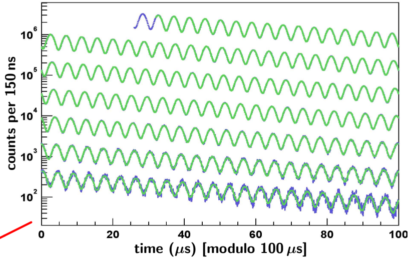

Two independent measurements required!

$$a_\mu = \frac{g_e}{2}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{\omega_a}{\langle\omega_p\rangle}$$

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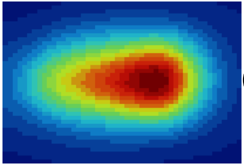

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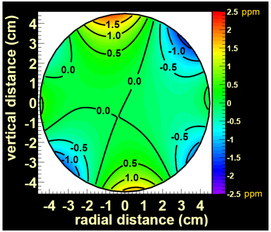
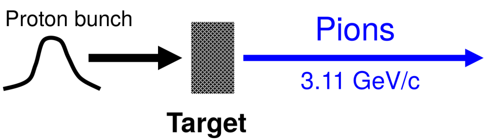
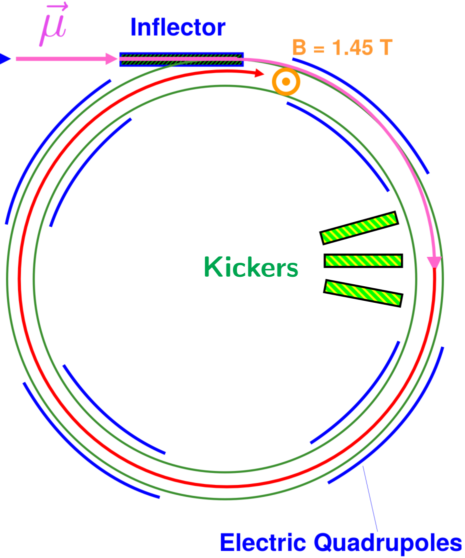




- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Kicker magnets move the orbit to the centre of the storage ring
- Muons focussed vertically with electrostatic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



Magnet anatomy

B = 1.4513 T (~5200 A)

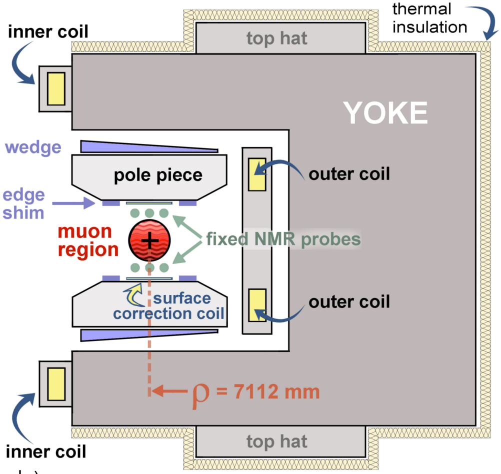
- Non-persistent current: fine-tuning of field in real time

12 C-shaped yokes

- 3 poles per yoke
- 72 total poles

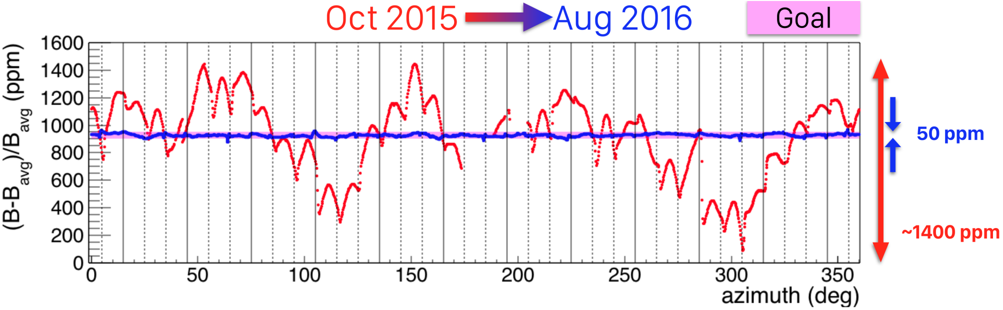
Shimming knobs

- 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,...)

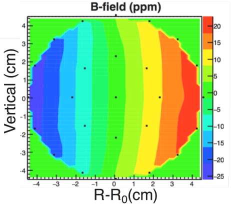


g-2 Magnet in Cross Section

Shimming results:

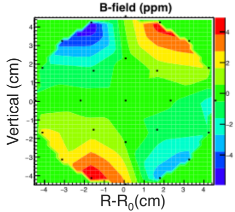


Azimuthally-Averaged Map



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

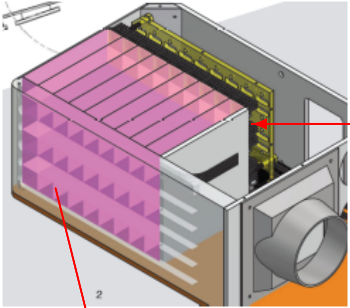
Oct 2015

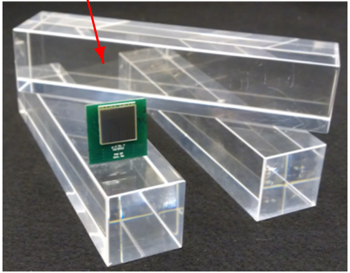


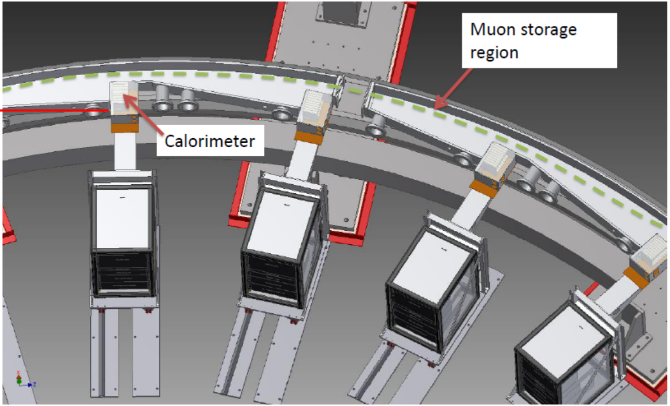
	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

Calorimeters (ω_a measurement)

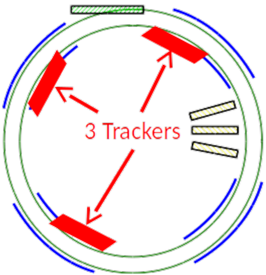


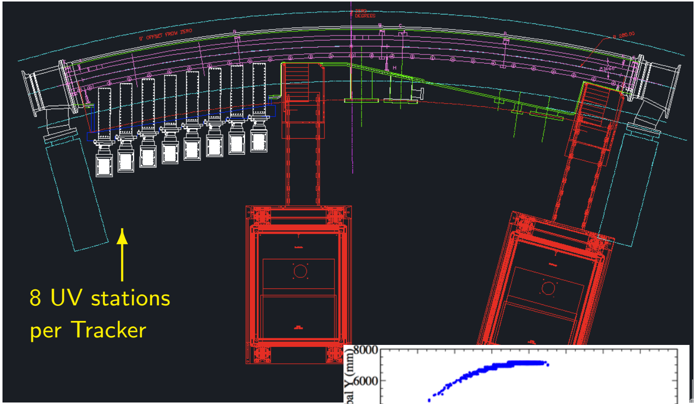


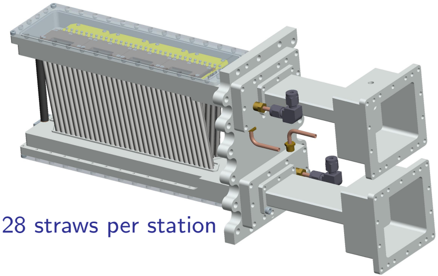


Individual positrons from muon decays are detected in 24 calorimeters; E and t extracted from waveforms. Each calo. segmented into 6×9 channels: Each PbF_2 crystal is read out by a Geiger-mode avalanche photodiode (SiPM).

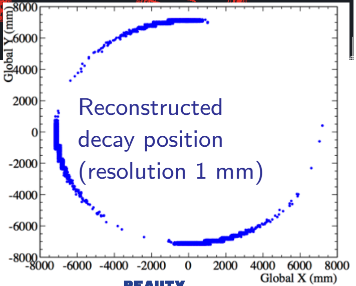
Straw tube Trackers







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



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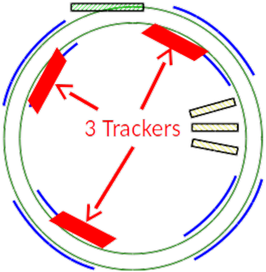

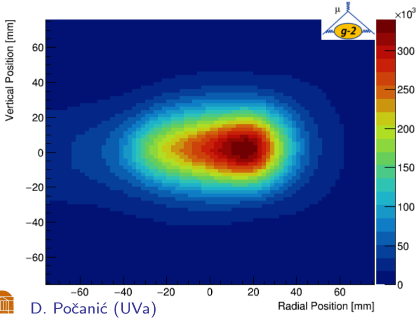

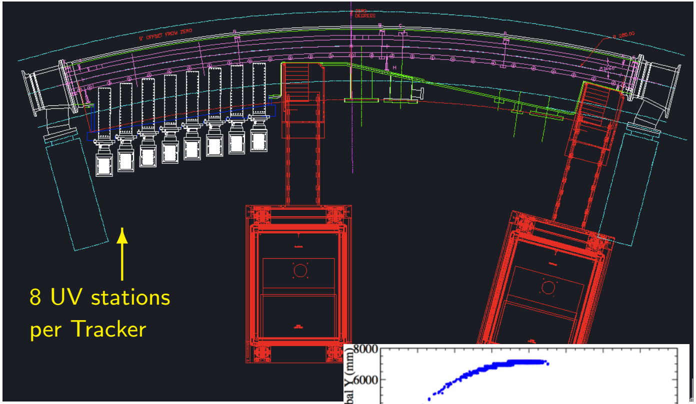

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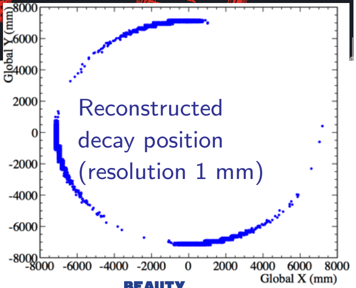
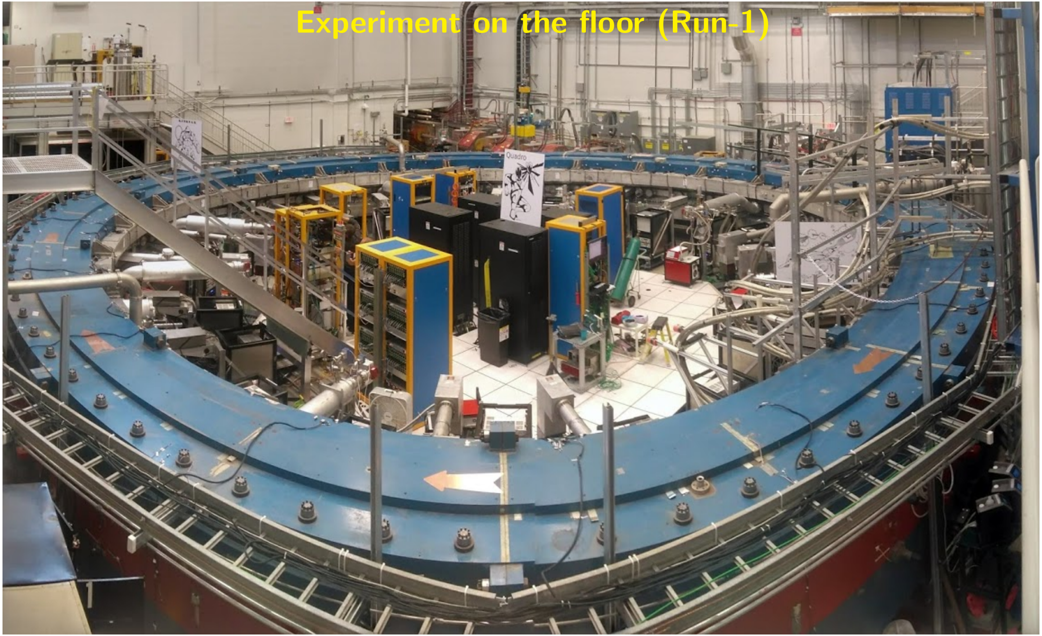
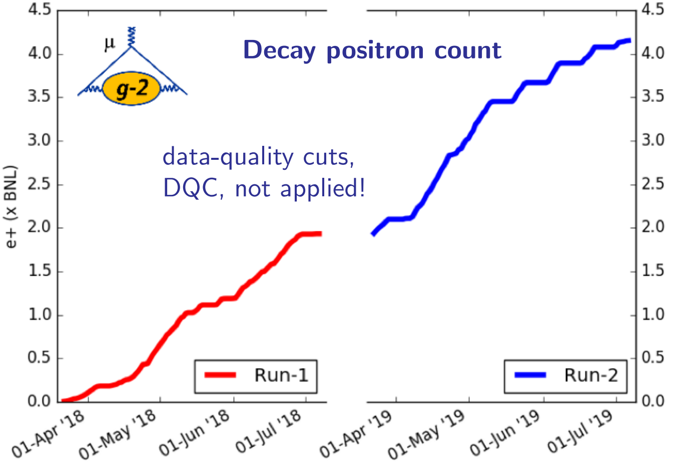


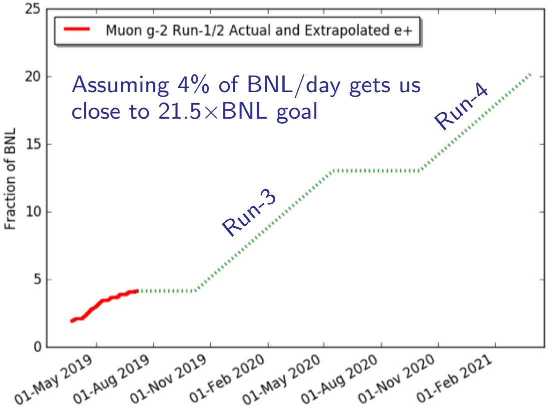
Experiment on the floor (Run-1)

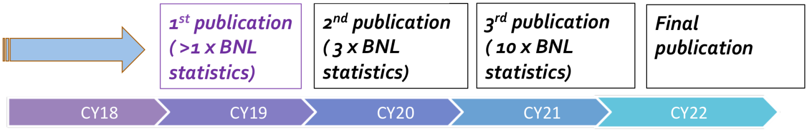


- Finished Run-1 and Run-2; analyzing data!
- After DQC we expect:
  - $\sim 1.4\times$ BNL for Run-1,
  - $\sim 1.8\times$ BNL for Run-2.
- Currently ending shutdown & preparing for Run-3.
- Goal: publish results of Run-1 by end of 2019.



- 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:





Different approach: reaccelerated low-emittance muon beam and MRI-type storage ring

Fermilab E989 $p = 3.1$ GeV$/c$ J-PARC sets $E \equiv 0$.

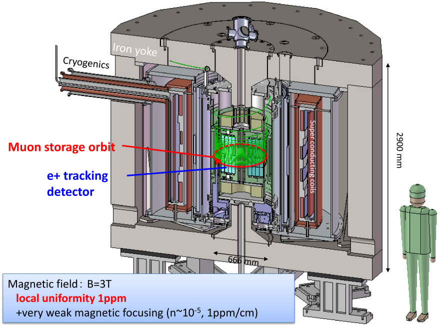
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right]$$

$(g-2)_\mu$ μEDM

Status and plans:

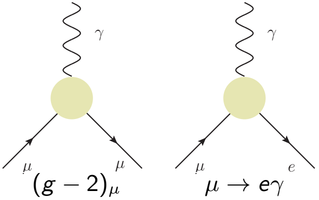
- 2019 continuing R&D; funding request;
- 2020-23 construction;
- 2023 commissioning;
- 2024-26 data run.

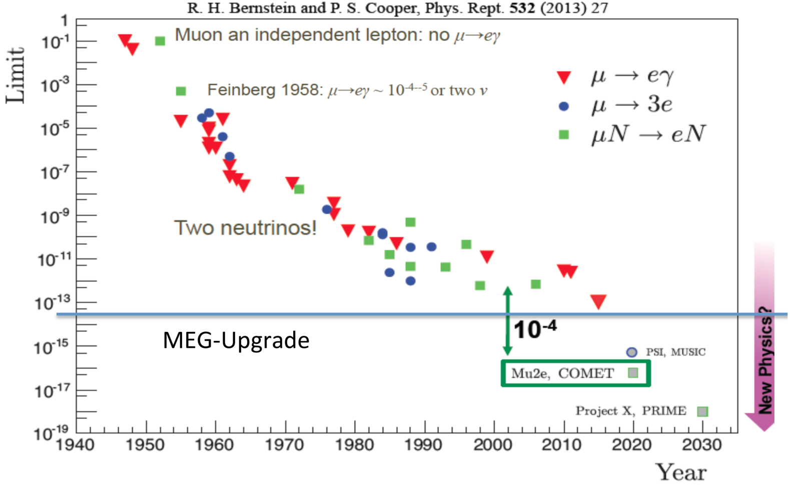
Muon storage magnet and detector



Goal uncertainties: similar to Fermilab E989, but very different systematics and likely higher sensitivity to muon EDM.

CLFV processes are highly suppressed in the SM. Muon $g-2$ and LFV processes share some of the same physics:



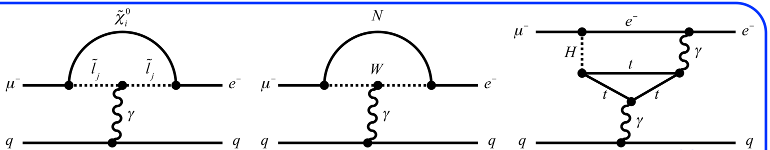


Current and planned experiments:

- MEG and MEG II at PSI: $\mu \to e\gamma$ search;
- Mu2e at Fermilab and COMET at J-PARC: μ to e conversion search;
- Mu3e at PSI: $\mu^+ \to e^+e^-e^+$ search.

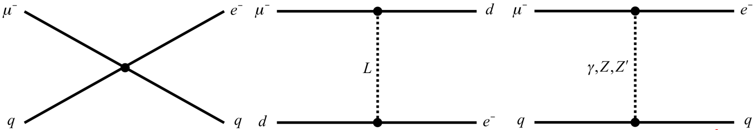
$$L^{[1]}_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \text{h.c.}}_{\text{Loop Terms}} + \underbrace{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L \gamma_\mu e_L \left(\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L\right) + \text{h.c.}}_{\text{Contact Terms}}$$

Loop Terms



Supersymmetry — Heavy Neutrinos — Two Higgs Doublets

Contact Terms



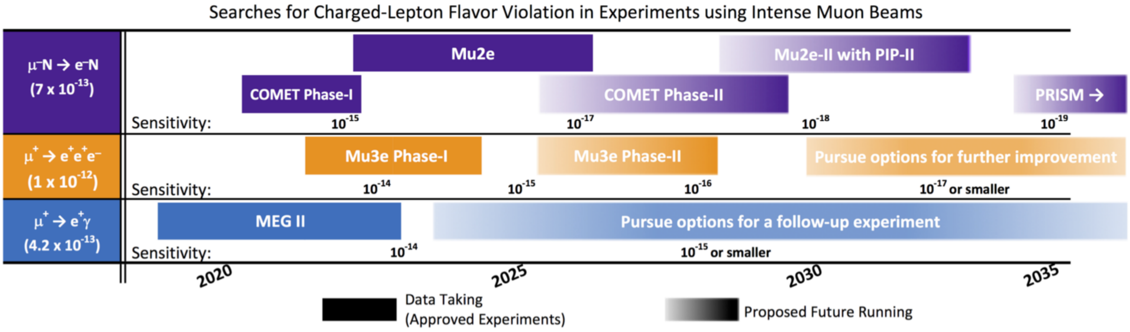
Compositeness — Leptoquarks — New Heavy Bosons / Anomalous Couplings

[1] A. de Gouvea and P. Vogel, Prog. Part. Nucl. Phys. **71**, 75 (2013). doi:10.1016/j.ppnp.2013.03.006 [arXiv:1303.4097 [hep-ph]]

5

κ . . . relative coupling strength; Λ . . . effective mass scale.

CLFV experimental prospects:



Extra slides

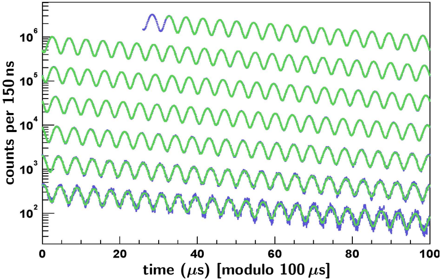
Key points of the experimental method

1. Large quantity of highly polarized muons stored in storage ring:
   97 % polarized $\Rightarrow$ 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 $\gamma_\mu = 29.3$,

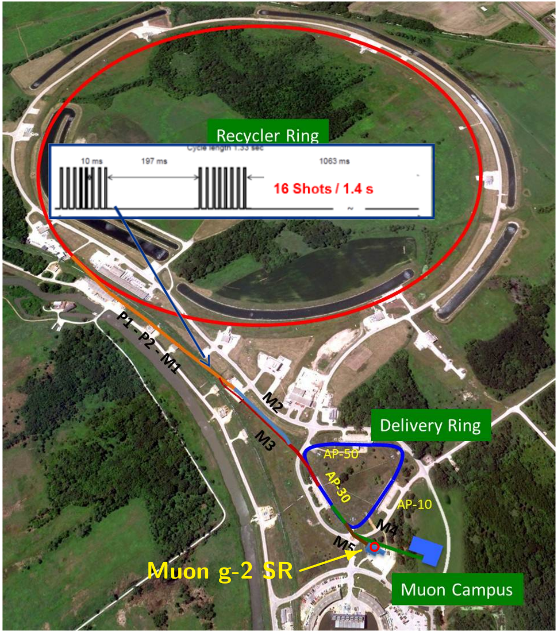
4. EW chiral symmetry breaking (PV) gives lab access to average muon spin direction
   Number of high energy positrons modulated by ω_a (wiggle plot):



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

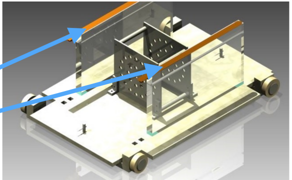
The accelerator complex:

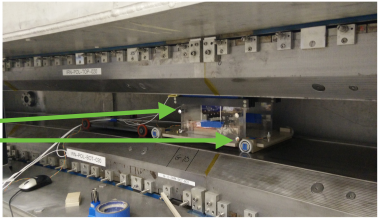
- 8 GeV p batch into Recycler,
- split into 4 bunches,
- extract 1 by 1 to strike target,
- long FODO channel (alternating focusing and defocusing quads) to collect $\pi \to \mu\nu$,
- $p/\pi/\mu$ beam enters DR;
  protons kicked out;
  π's decay away,
- μ enter storage ring.



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



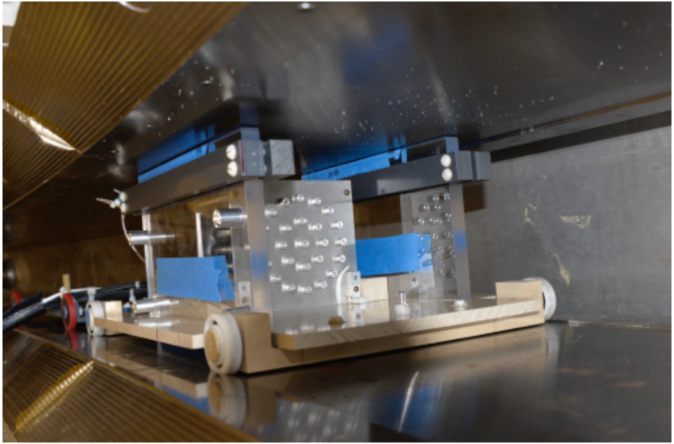


Laser tracker

- Cart position (r, φ, z)

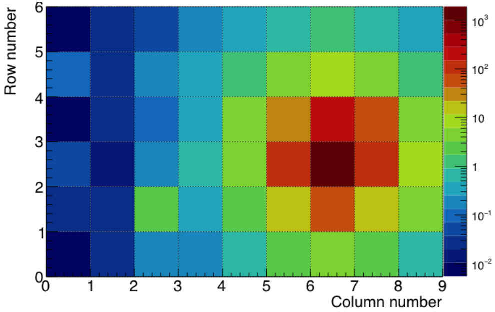
Magnetic field monitoring

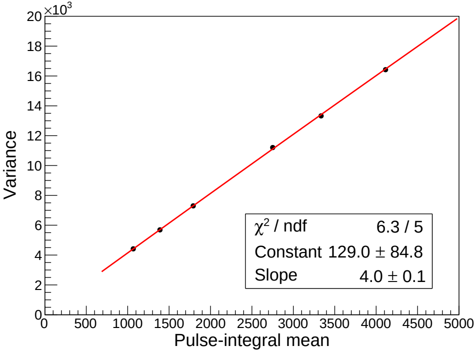
- Map B at regular intervals (about every two days), with NMR probe trolley: 17 proton NMR probes,
- monitor B during DAQ with 378 pNMR fixed probes in 72 stations;
- pulsed pNMR measure B with < 10 ppb single shot precision.

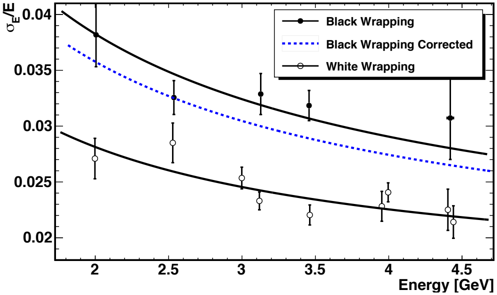


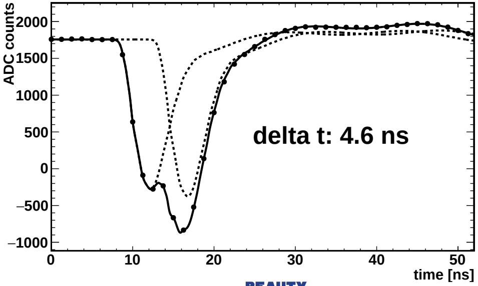
- BNL E821 result:
  - 1 ppm (azimuth average)
  - 100 ppm (local variations)
- FNAL E989 goal:
  - 1 ppm (azimuth average)
  - 50 ppm (local variations)

Calorimeter performance



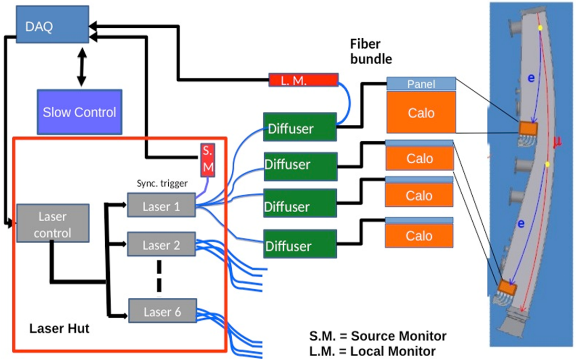


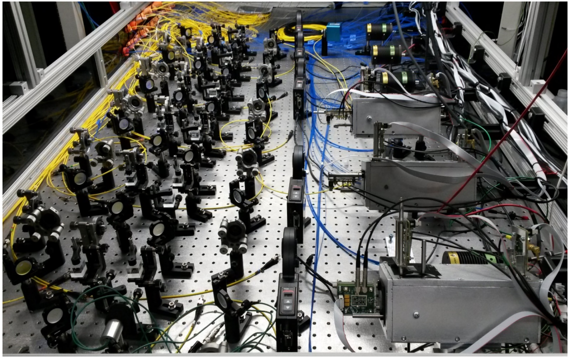




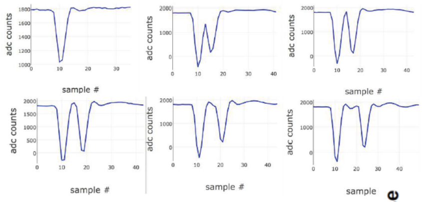
Sends trains of laser pulses of known intensity synchronously on all calo. channels; provides:

- 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.



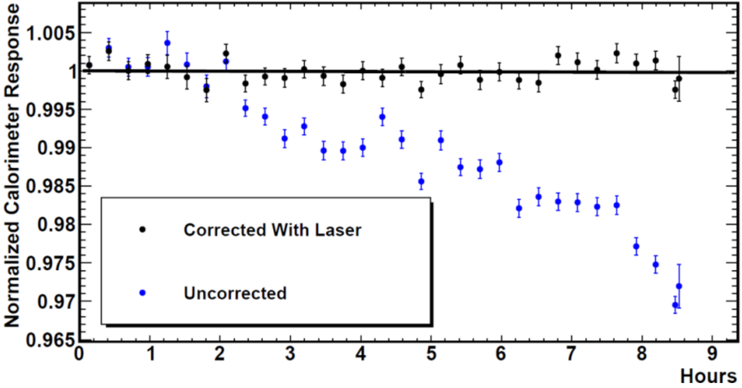


Laser calibration system performance



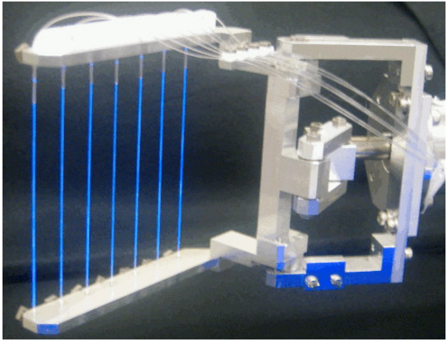
⇐ tuneable individual pulses, tuneable pulse pairs, and "flight simulator" mode.

10^{-4}/h stability demonstrated:



Auxilliary detectors:

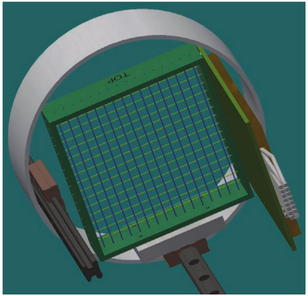
Fiber harps:



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):

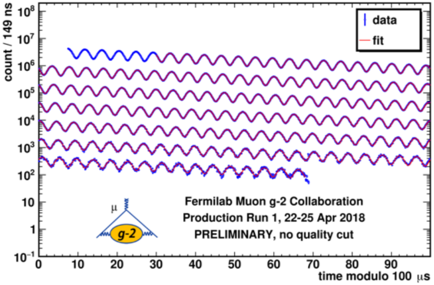
- primary diagnostic tool to develop & verify beam optics tune at injection,
- give relative intensity of each fill,
- timing of the fill (resolution $\ll 150\,$ns, cyclotron period)

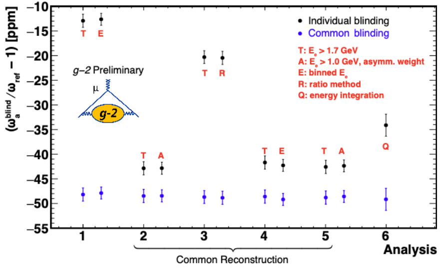
Data acquisition system

- 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 . . .





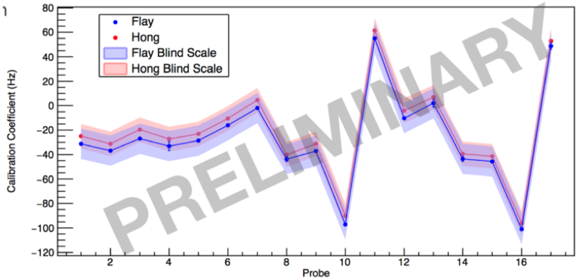
Run-1 ω_a analysis:

- 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.:

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

Run-1 $\langle \omega_p \rangle$ (B-field) analysis



- 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.

$\langle\omega_p\rangle$ (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

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

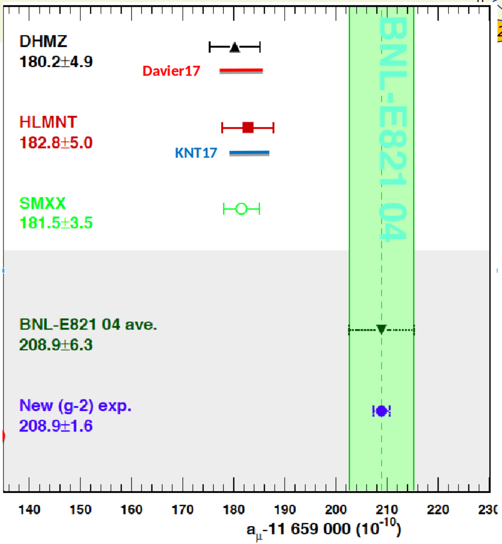
Ultimate goal of E989

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
δa_μ^{HLbL}	26	26	25
$\delta(a_\mu^{EXP} - a_\mu^{SM})$	80	80	40

2017 updates:

Uncertainty	DHMZ17	KNT17	Future
δa_μ^{SM}	42	37	35
δa_μ^{HLO}	33	26	26
δa_μ^{HLbL}	26	26	25
$\delta(a_\mu^{EXP} - a_\mu^{SM})$	76	73	40



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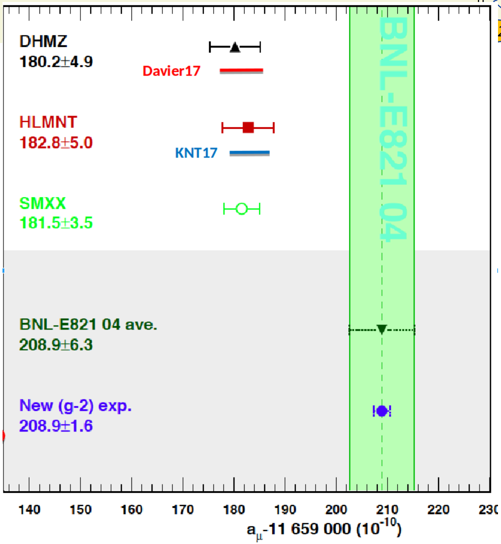
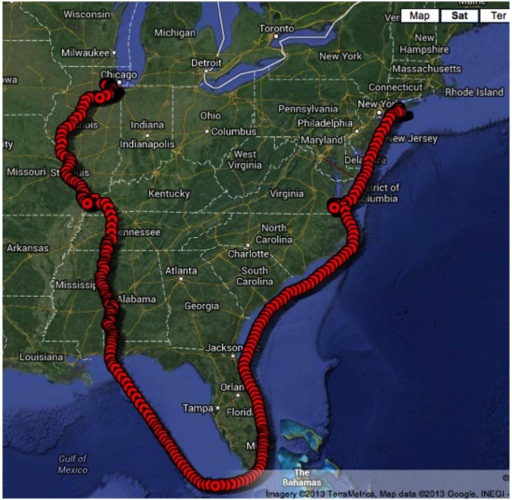
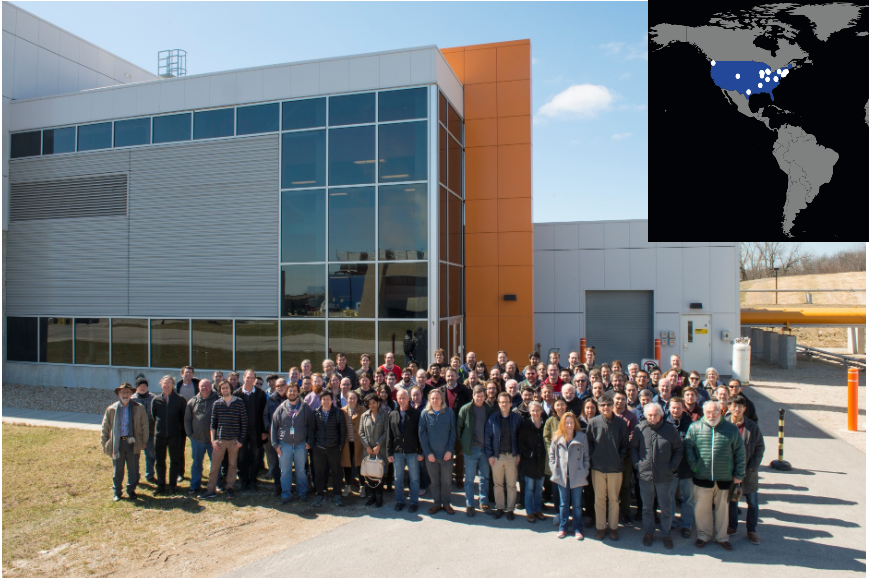


For the same SM and EXP central values, the discrepancy would increase from $\sim 3.5\,\sigma$ to $\sim 7\sigma$.

The big SR magnet move (2013)



Fermilab E989 collaboration



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- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

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- Argonne
- Brookhaven
- Fermilab

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