Muon g-2 Expt Status and Outlook

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Exotic Hadrons and Flavor Physics

1 June 2018

Worldwide Effort in Precision Muon Physics

- Extensive effort underway to utilize muons as probes of new physics
  - Hunting for ultra-rare decays
  - Precision measurements
- Spans many muon sources
  - TRIUMF, PSI, Fermilab, J-PARC
- Today's talk
  - Fermilab muon program
  - Muon g-2
    - Which aspects are the same as BNL
    - How the experiment differs
    - Outlook for first physics results

Fermilab Muon Program

Fermilab Muon Campus Vision, circa 2012

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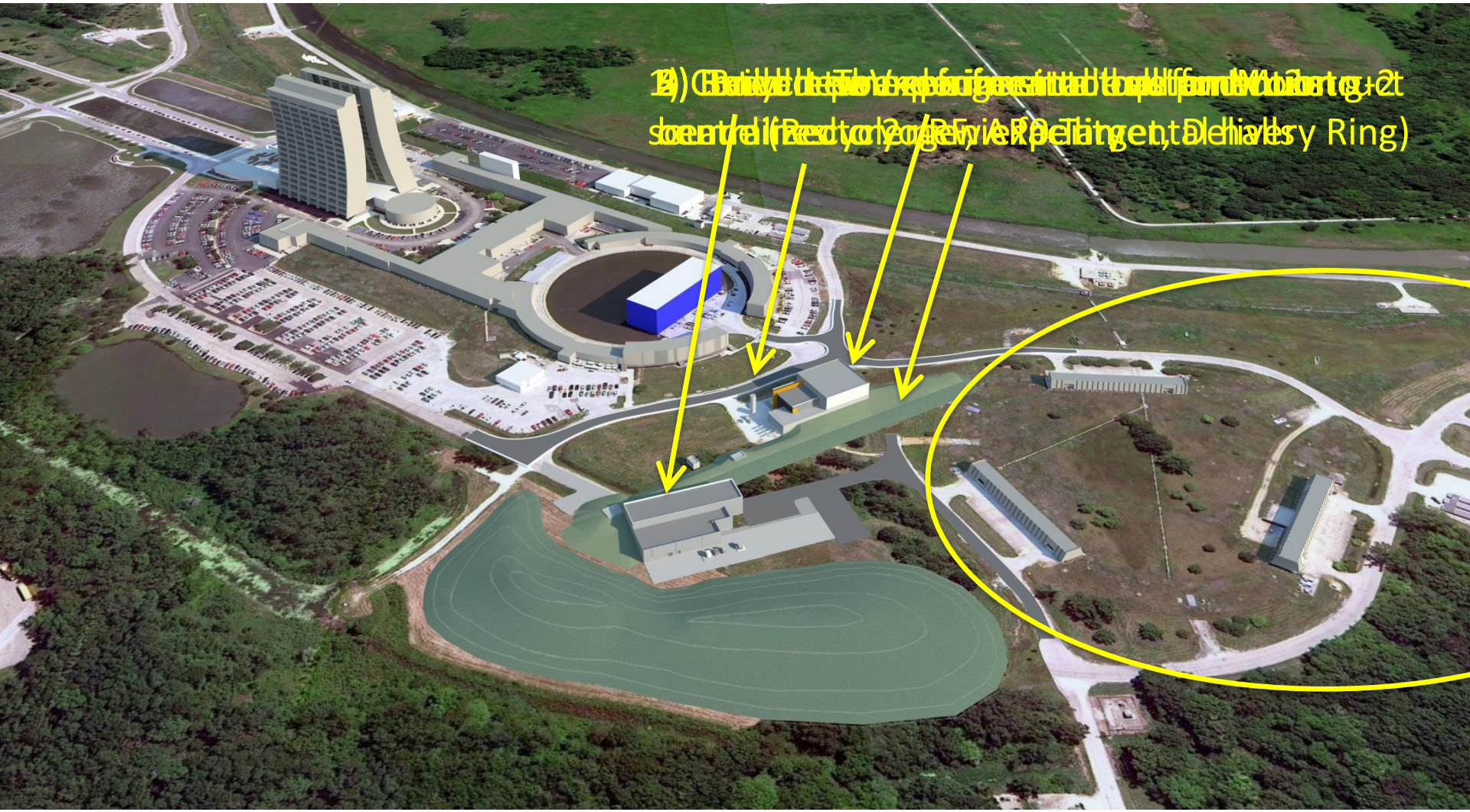
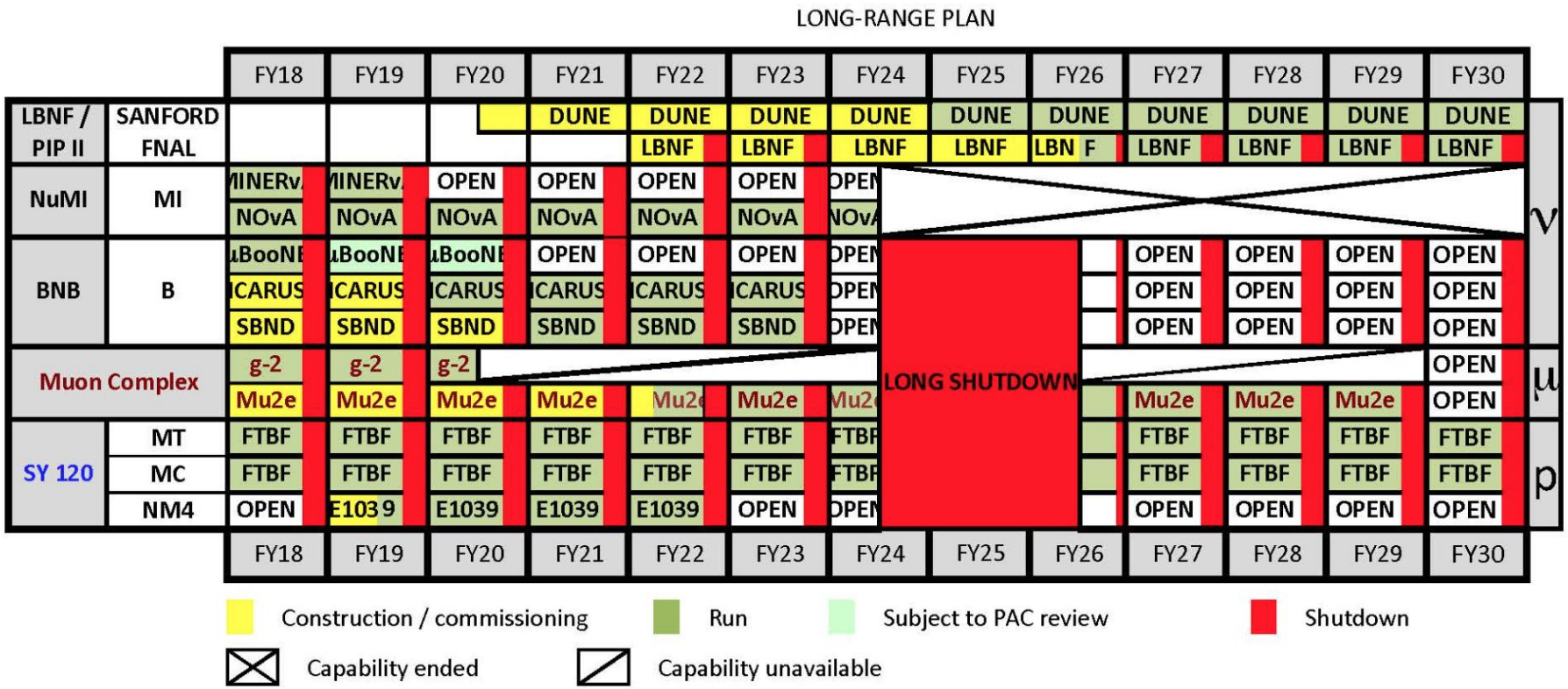


Muon Campus Reality, Oct 2016

Muon Campus Program Plan

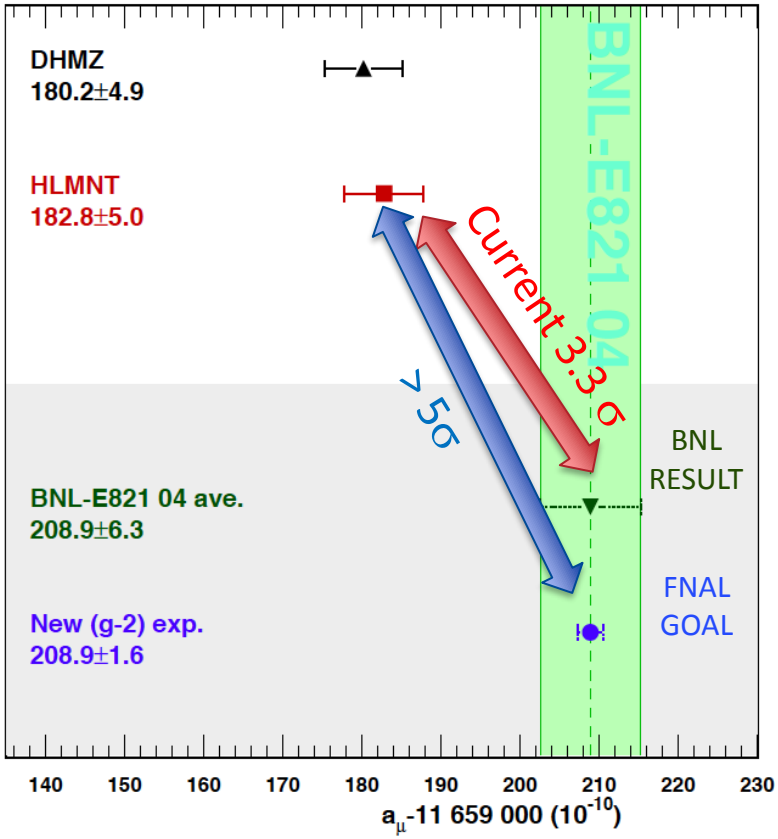


- Muon g-2 taking data 2018-2020
- Mu2e finish commissioning in 2021 for physic running in 2022
- Two experiments cannot take data simultaneously

Muon g-2

FNAL Muon g-2 Goal

http://arxiv.org/pdf/1311.2198v1.pdf



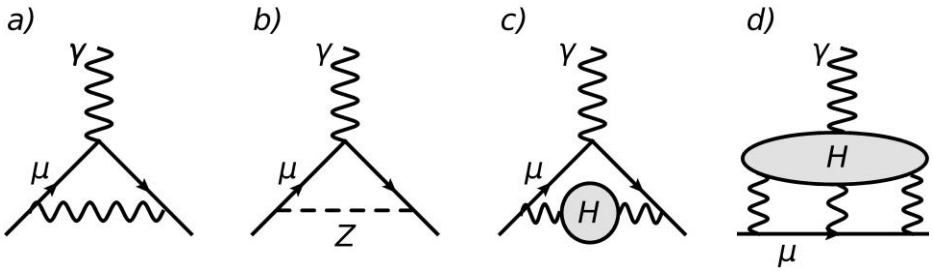
Reduce the experimental error on a_μ by 4 and resolve the long-standing BNL g-2 discrepancy

- Requires 21 x BNL statistics and better control of key systematics

If discrepancy persists, experiment improvement alone → anomaly would grow to > 5σ

Muon g-2 Theory

Theoretical status of a_μ

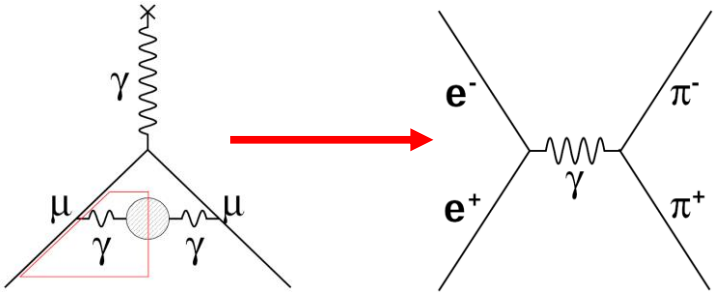


Source	Value (a_μ x 10^{-11})	Error
a) QED	116 584 718.95	0.08
b) EW	154	1
c) HVP	6850.6	43
d) HLBL	105	26

See Muon g-2 TDR and references therein

Summary	(a_μ x 10^{-11})
$a_\mu^{(EXP)}$	116 592 089(63)
$a_\mu^{(SM)}$	116 591 828(49)
$a_\mu^{(EXP)}$- $a_\mu^{(SM)}$	261(80) → 3.3σ

- QED/EW uncertainties are tiny, e.g.
  - Recent calculation to 5th order in α contributes 5x10^{-11} to a_μ
  - Known Higgs mass reduces error on EW from 2 to 1x10^{-11}
- Error dominated by hadronic terms
  - HVP can be determined from e^+e^- → hadrons data
  - HLBL smaller overall error, but calculation model-dependent

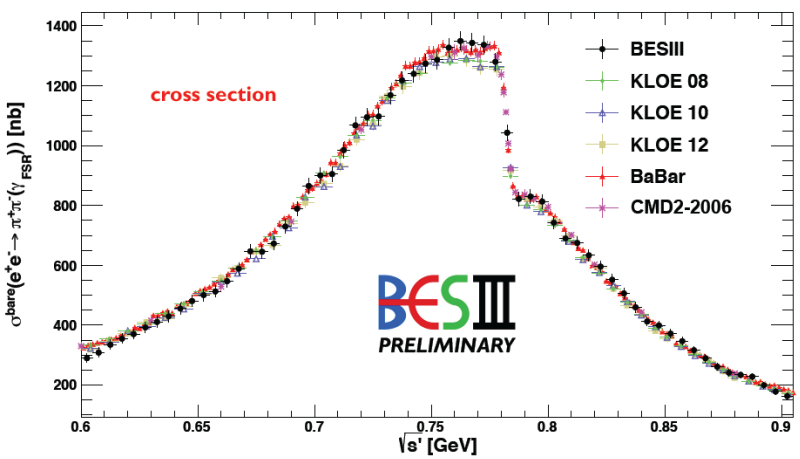


$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Theoretical status of a_μ

- New e^+e^- data for HVP continues to contribute
  - BESIII latest to map crucial 2π contributions
  - Multi-hadron final states from b-factories
  - CMD3 at VEPP2000
- Data driven approaches to HLBL
  - LE tagger at KLOE to measure $\gamma^*\gamma^*$ physics related to 70% of HLBL.
  - New data-driven evaluation of the pion-pole contribution spot on (Hoferichter et al. arXiv:1805.01471)
- Lattice progress looks very promising for both HVP and HLBL…see next talks…



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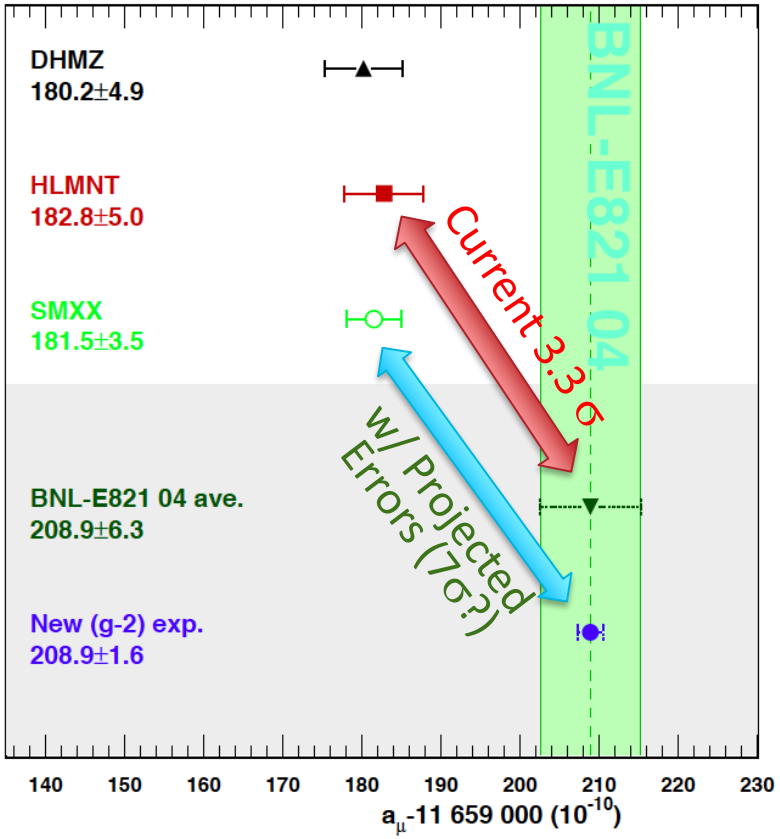
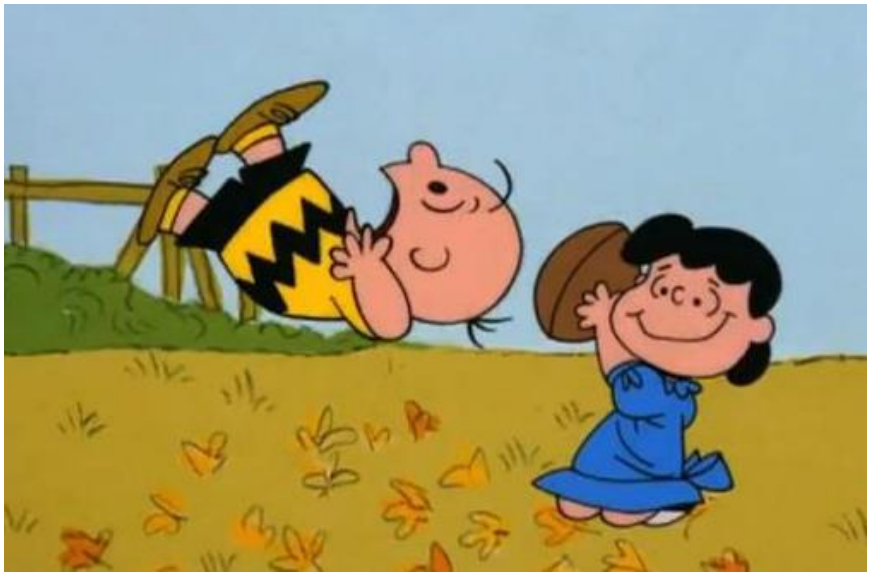
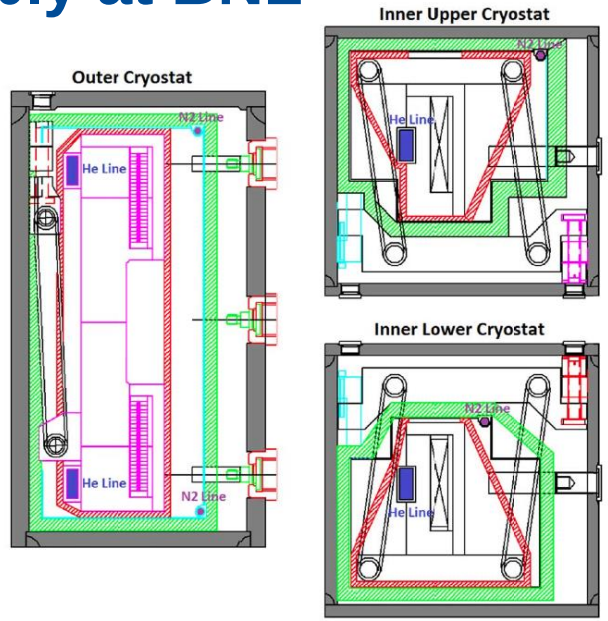


Projecting a factor of 2 reduction in theory error over course of experiment!

Muon g-2 @ FNAL… what's the same?



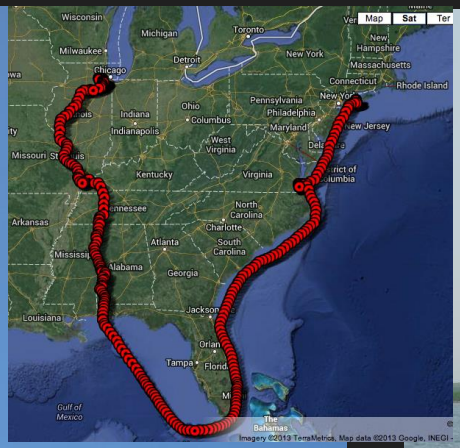
Using the same container – disassembly at BNL



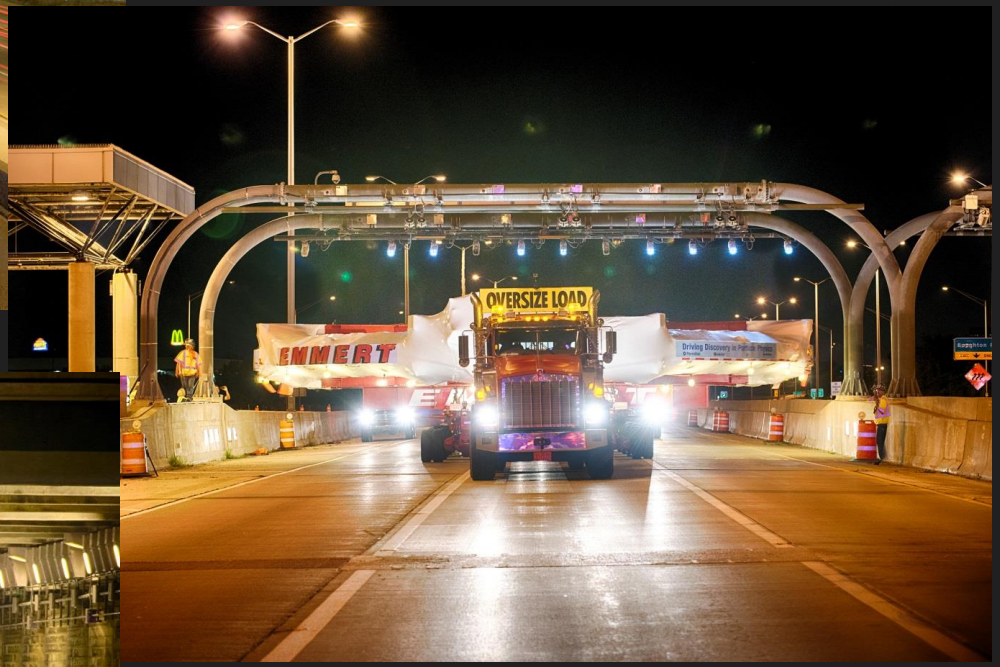
- The big pieces of steel (return yoke) come apart
  - Ship one 26T piece/flatbed
- The superconducting coils do not
  - Can't be cut and can't be unwound
  - $20M and 2 year delay to make from scratch

Moving 50 ft diameter Al rings without flexing by >1/8”

Journey by barge

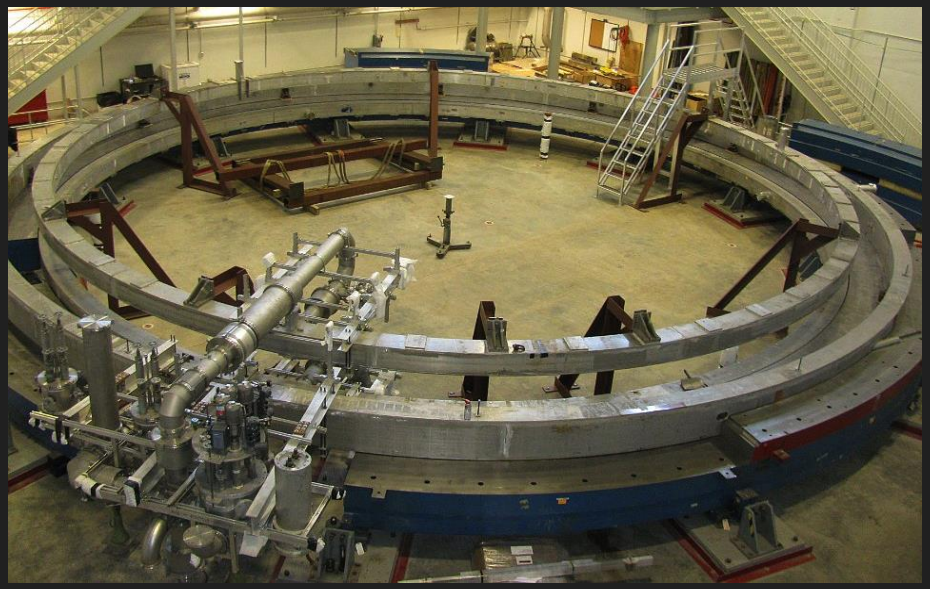


Traveling around Chicago…

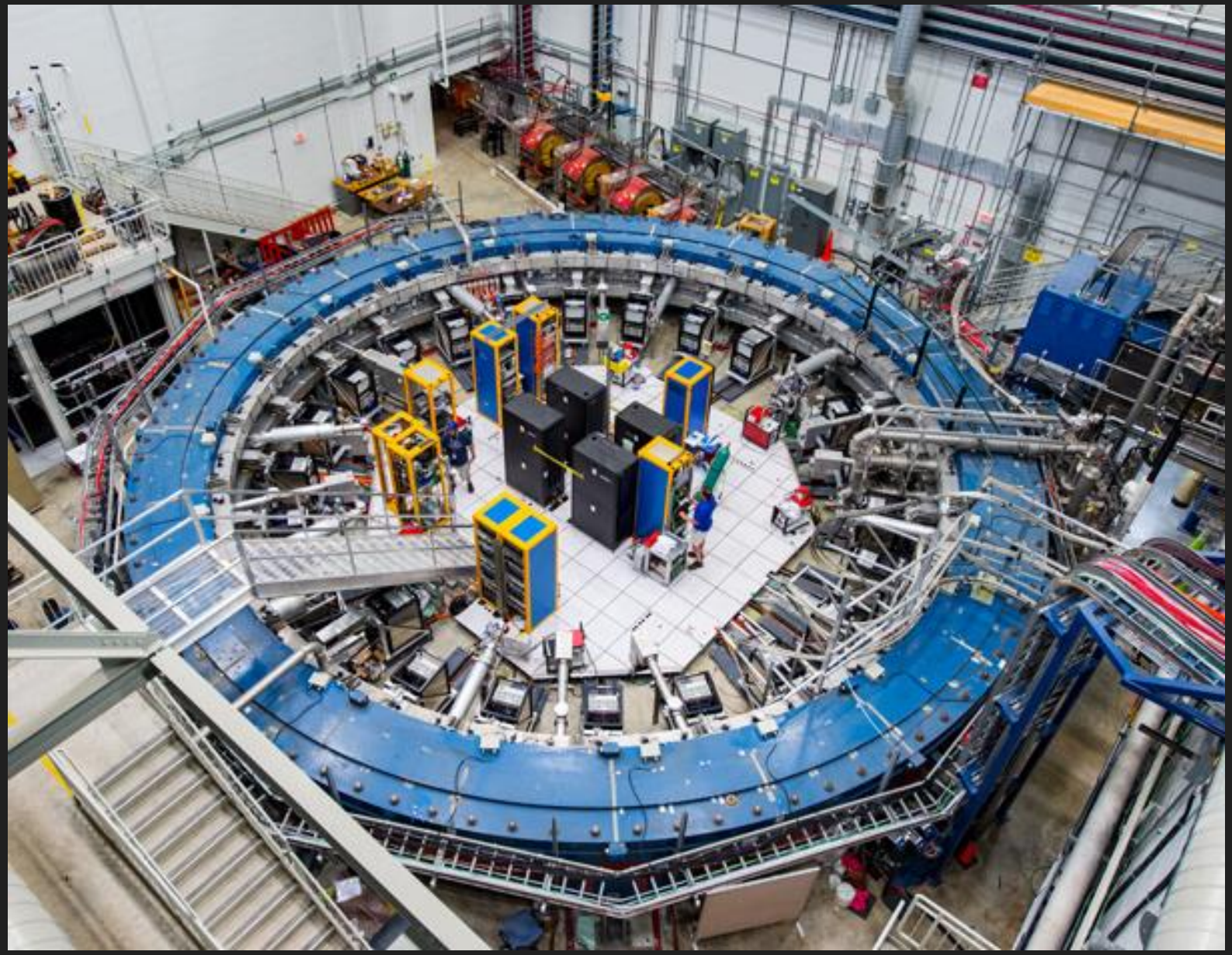


Arrival at Fermilab (July 2013)

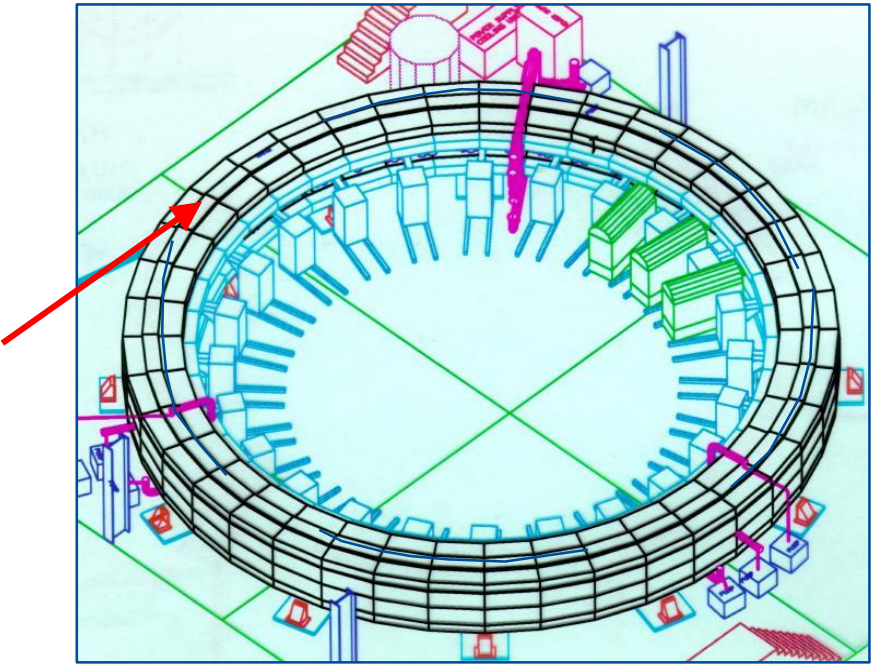
Magnet moved into hall (Summer 2014)



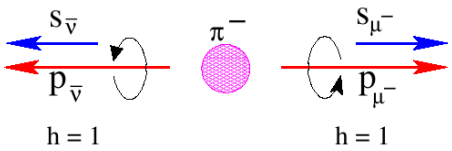
Muon g-2 storage ring today



Experimental principles still the same (CERN III/BNL/FNAL)



1) Inject polarized muon source



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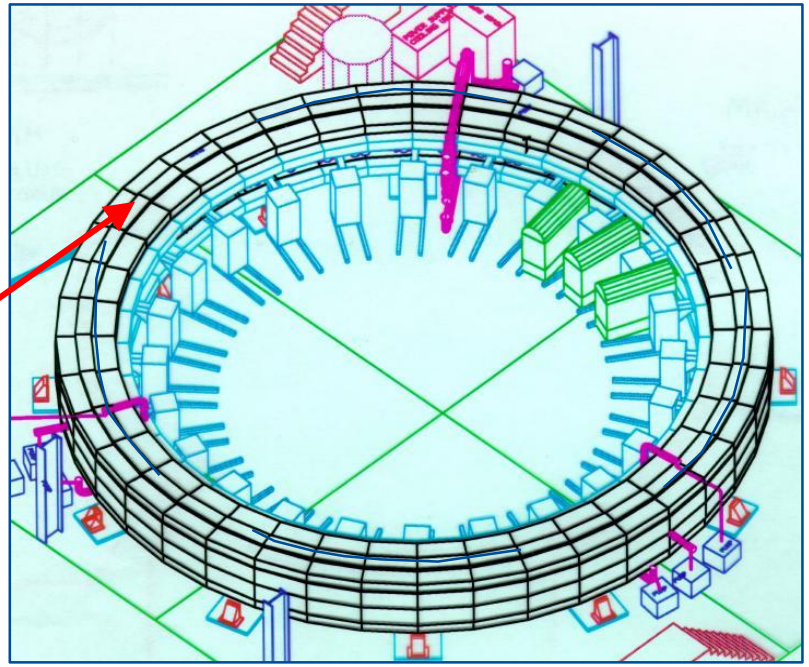

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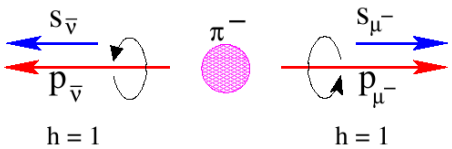

2) γ=29.3 muons allow E-field vert. focusing

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

~0

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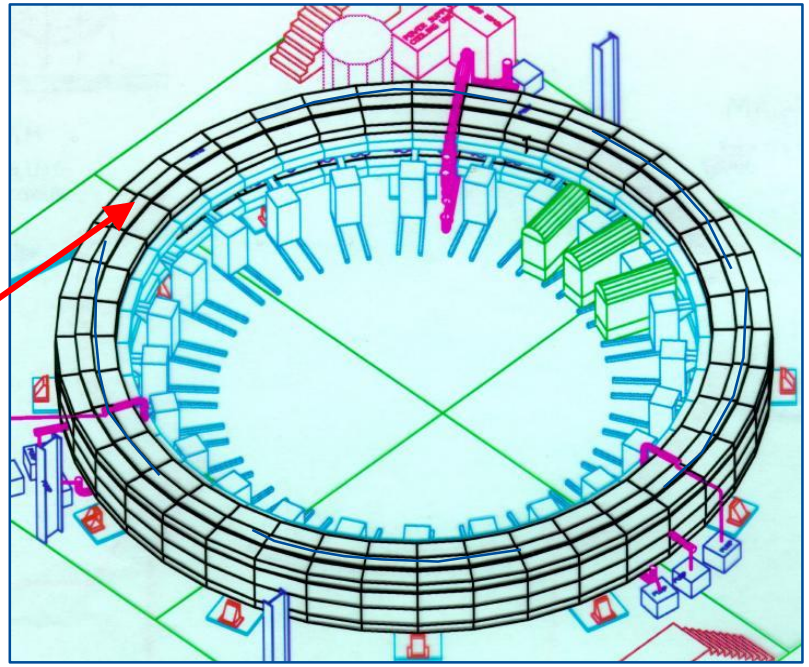

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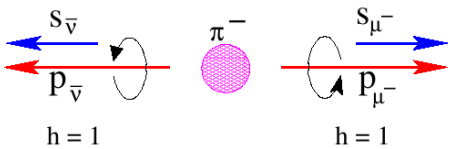

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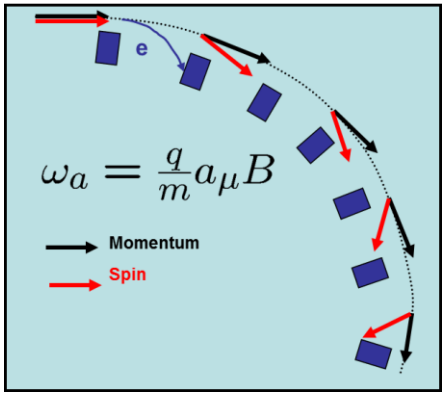

3) Muon spin precession relative to momentum in cyclotron is directly proportional to a_μ

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$

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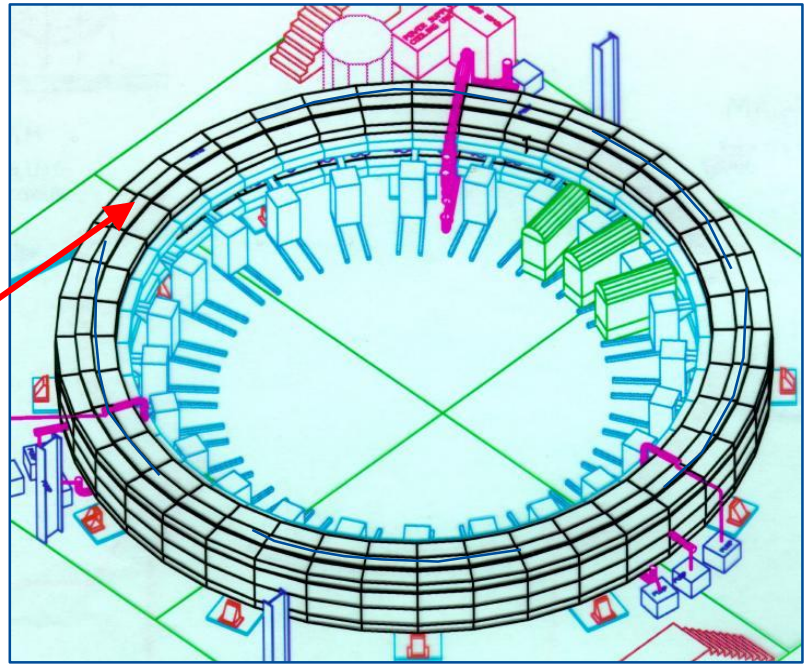

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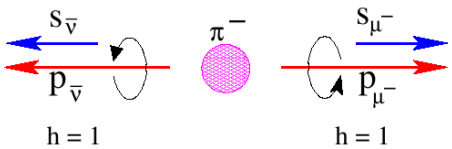

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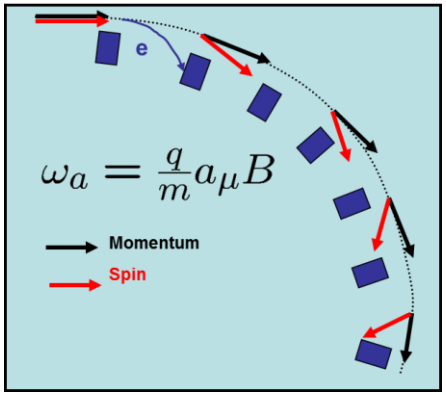

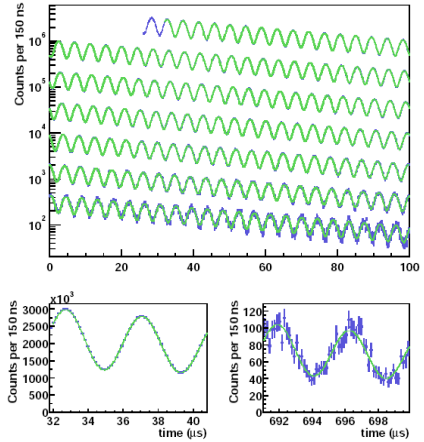

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4) Highest energy decay electrons emitted when spin and momentum vectors parallel

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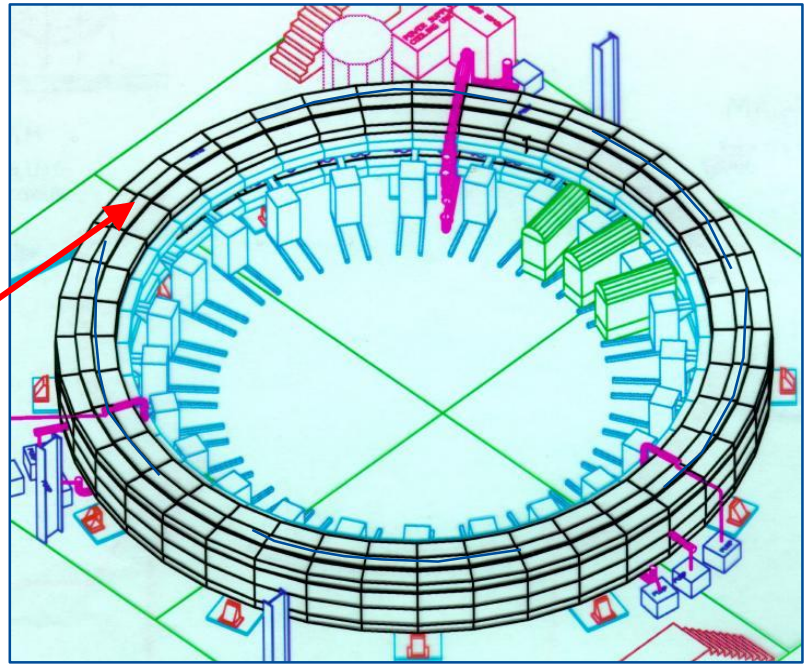

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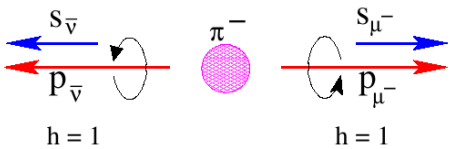

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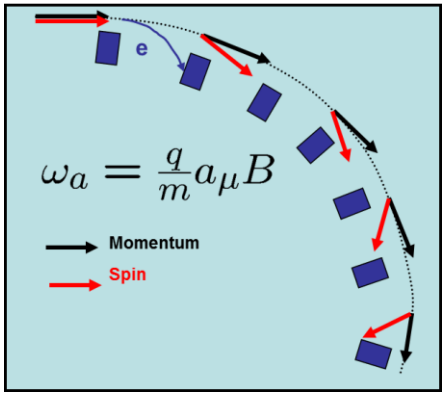

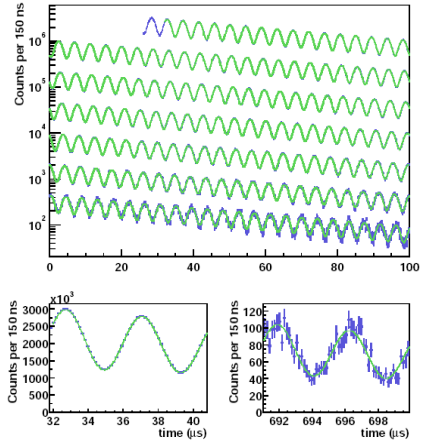

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Measure 2 quantities in Muon g-2

4) Highest energy decay electrons emitted when spin and momentum vectors parallel

Extracting a_μ

FNAL Projected Errors:
140 ppb (total) =
100 (stat)⊕ 100 (syst)

2017 CODATA

-0.001 519 270 380(5) [3 ppb] Hydrogen Maser

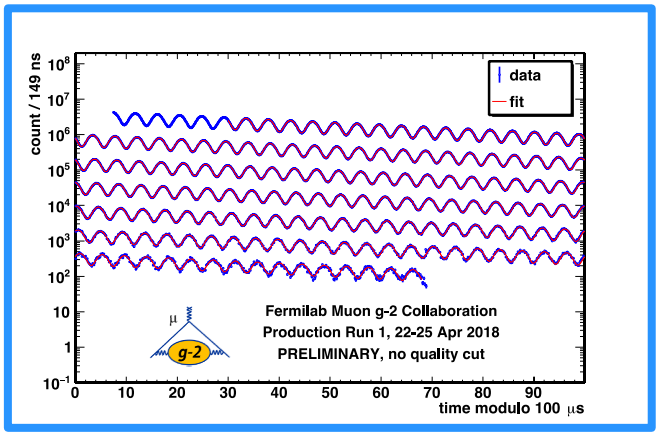
206.768 2826(46) [22 ppb] Muonium Hyperfine

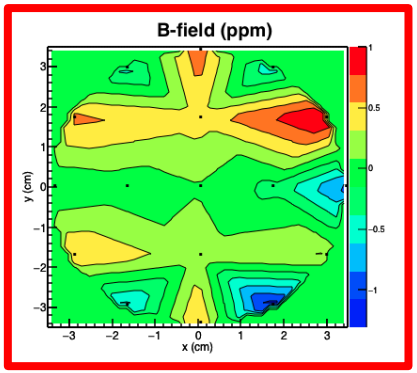
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$$\Downarrow$$

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





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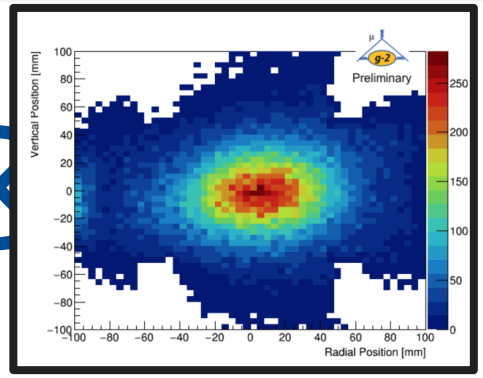
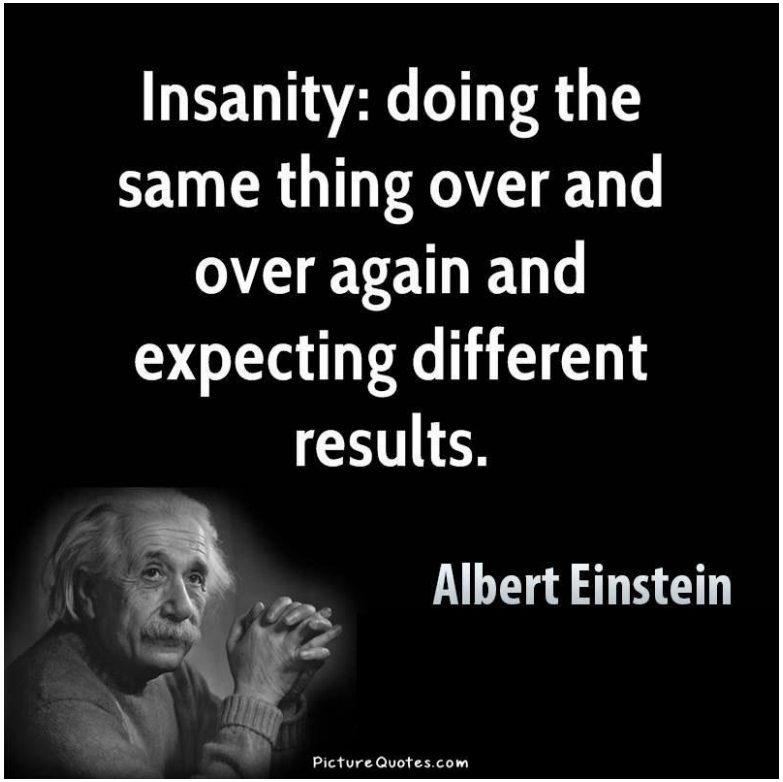
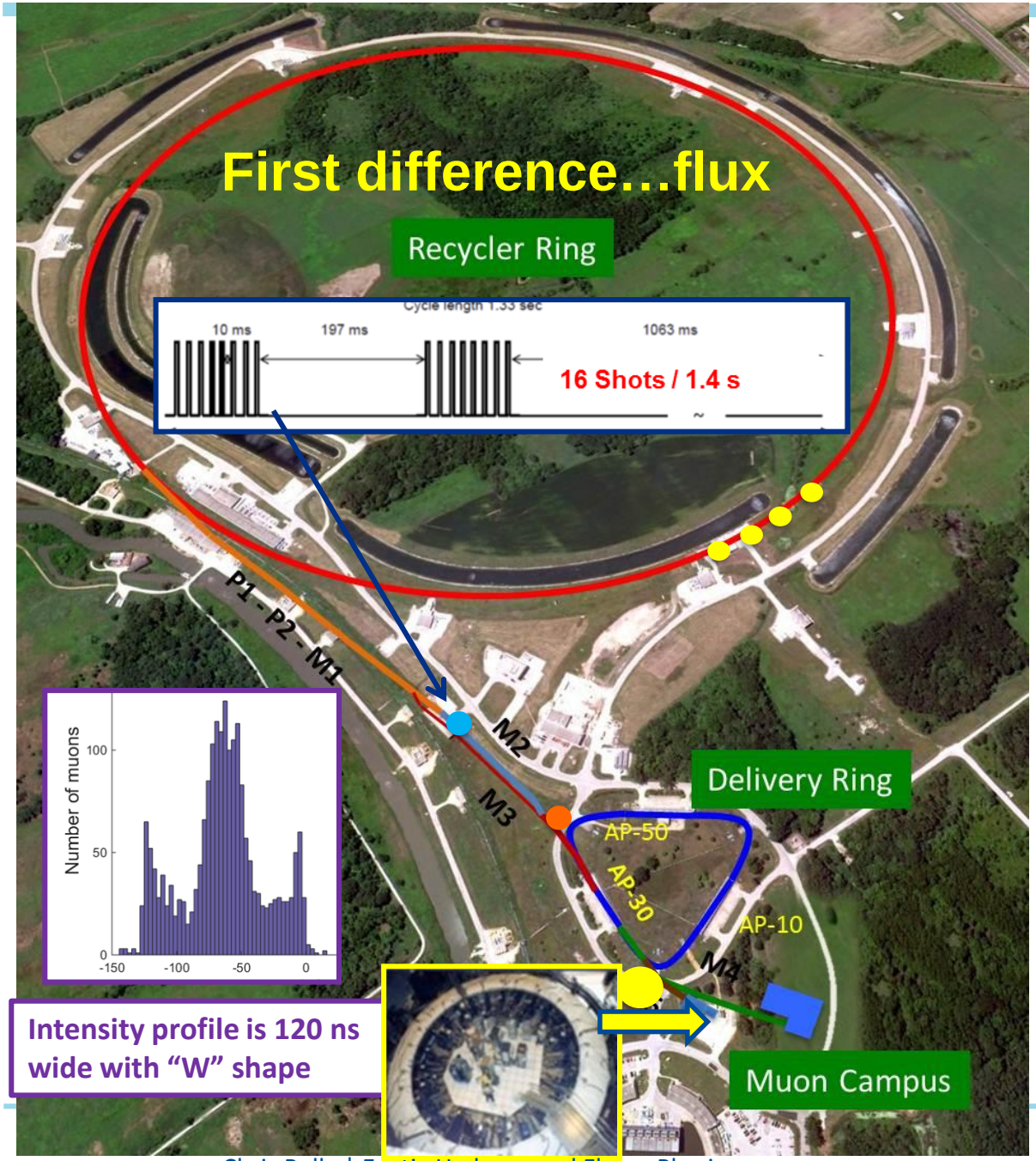




Muon g-2 @ FNAL… what's different?



Intensity profile is 120 ns wide with "W" shape

Delivers 10^{12} 8-GeV proton batches to the Main Injector Recycler.

Batches are split into four bunches.

Each bunch collides with a fixed target.

3.1 GeV pions are selected and focused to the delivery ring as they decay to muons.

Several passes around Delivery Ring to remove protons by time-of-flight.

Muons are focused and injected into the Muon g-2 storage ring.

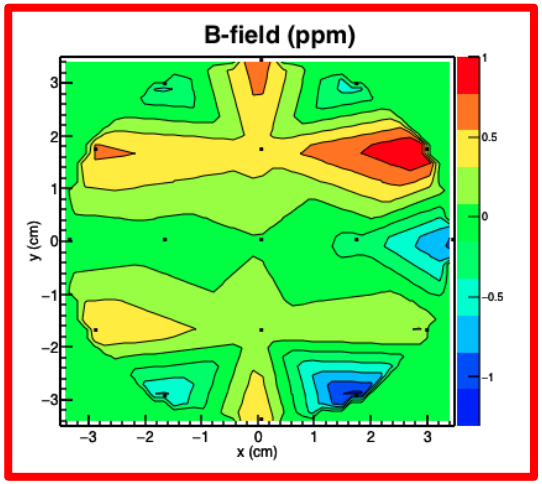
Relative to BNL E821:

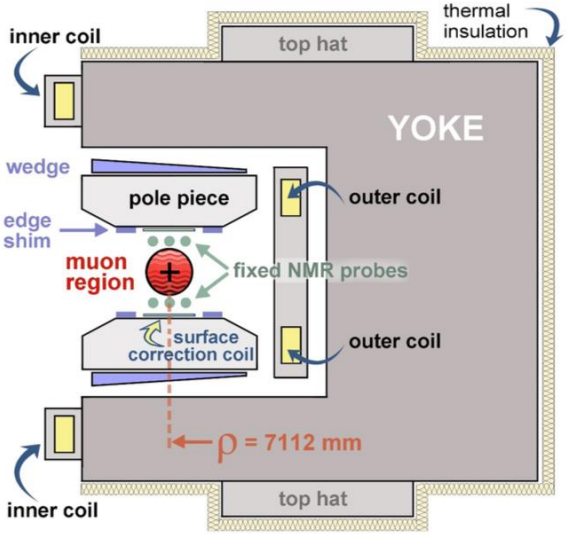
- Rep rate x 3
- Overall muon rate x6
- No hadronic flash
  - π all decay
  - protons removed

Improvements to field systematics

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

70 ppb error budget!!





g-2 Magnet in Cross Section

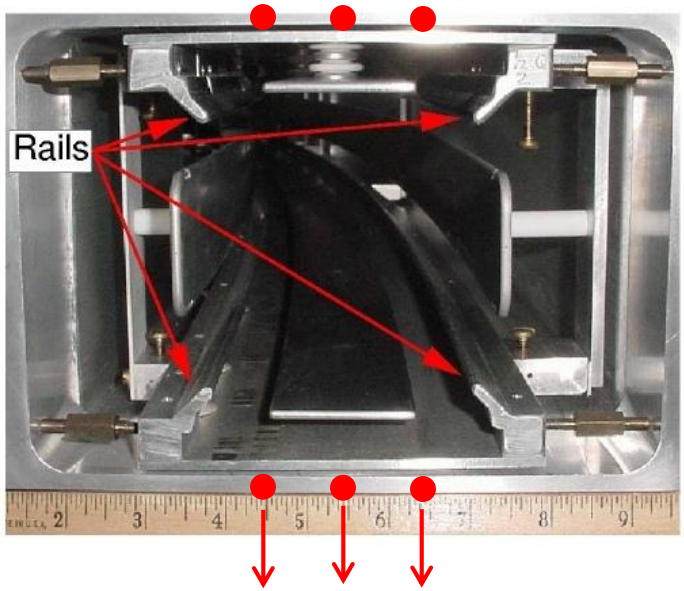
- Environment
  - Improved floor stability
  - Temperature control of hall to +/- 1C

Improvements to field systematics – shimming

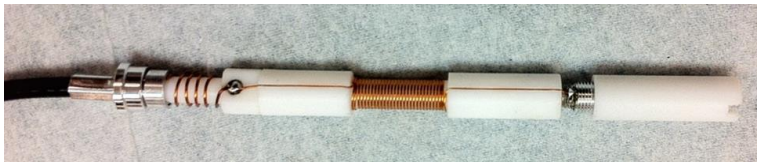
- Starting with field as uniform as possible is key to 70 ppb

Improvements to field systematics – field tracking

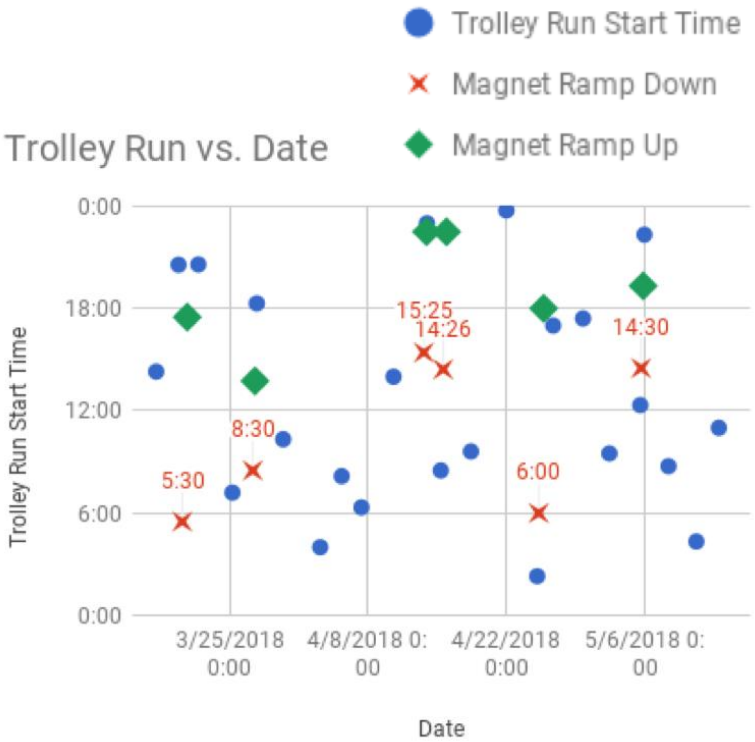
- Map the storage field regularly during beam off periods with trolley
  - Increase frequency of trolley runs to reduce interpolation errors
- Monitor the field with 400 fixed NMR probes around the ring
  - Only about half of the probes were operational at BNL



trolley



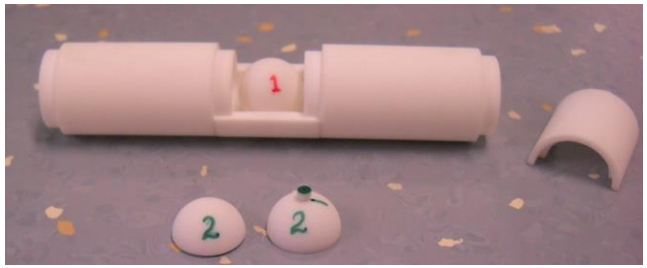
Fixed NMR probes



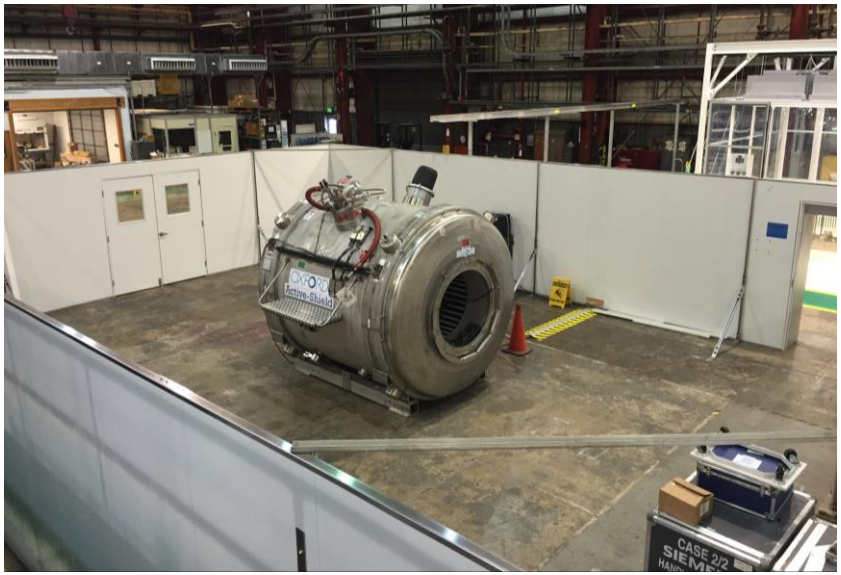
Improvements to field systematics – absolute calibration

- At BNL one historical H_2O probe was used
  - Same probe used in LANL muonium hyperfine
- Developed new probe
  - Holder has less magnetic impurities
  - More spherical, easier to correct for diamagnetism of H_2O (26 ppm correction!)
- Developing He3 as new standard
- Dedicate facility at ANL for cross-calibration

Original H_2O probe



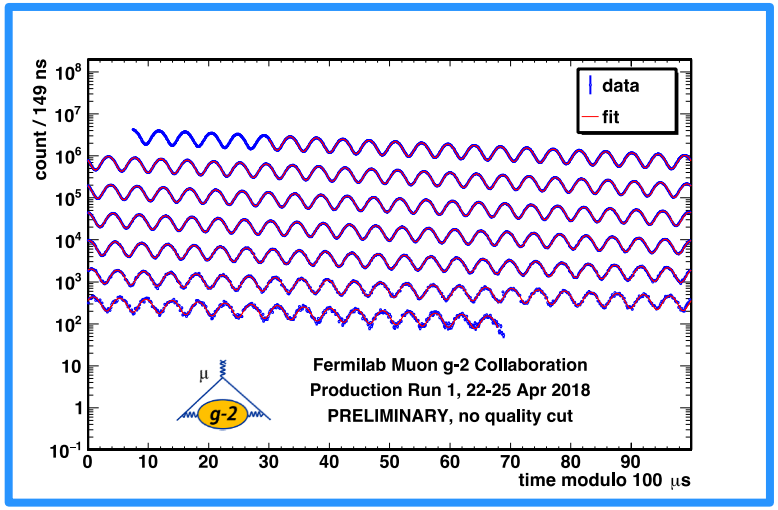
Improved H_2O probe



Developing He3 as a new standard

Improving ω_a systematic

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70



$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$

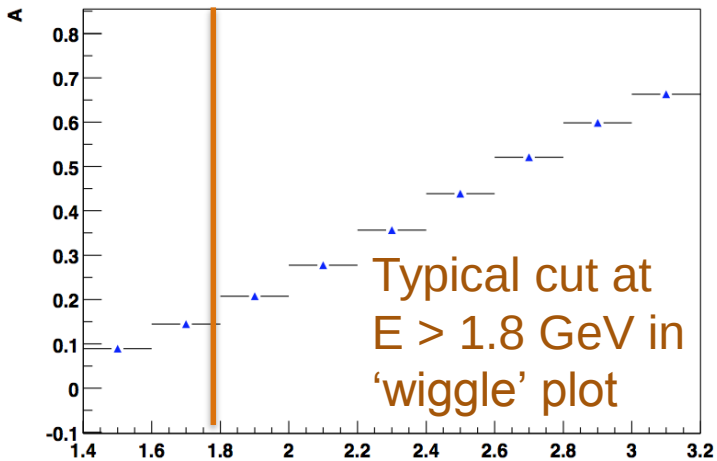
Any systematics that change the g-2 phase during the fit period are very dangerous

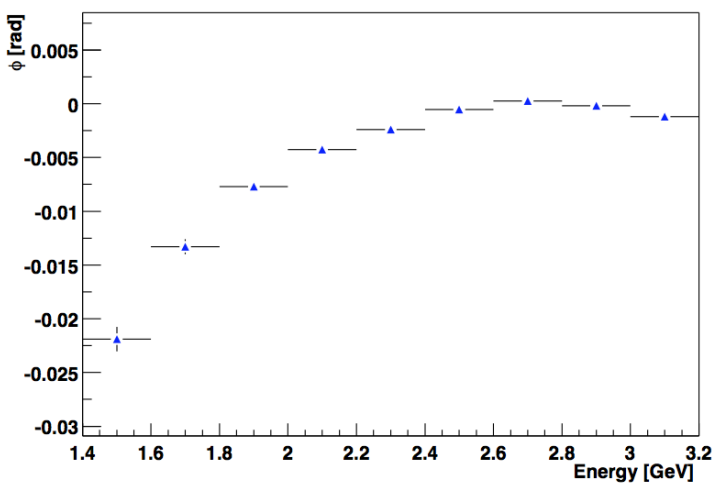
$$f(t) = f_0 + at + bt^2 \;\; » \; f_0 + at$$

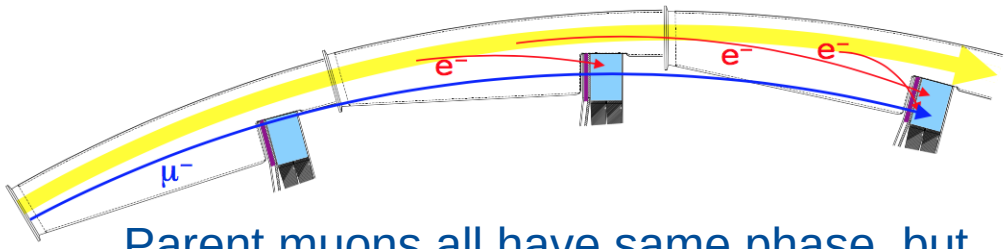
$$\cos(w_a t + f(t)) » \cos((w_a + a)t + f_0)$$

Changes in E scale during muon lifetime → phase change

$$N(t) = N_0 e^{-t/\tau}[1 + A_\mu \cos(\omega t + \phi)]$$

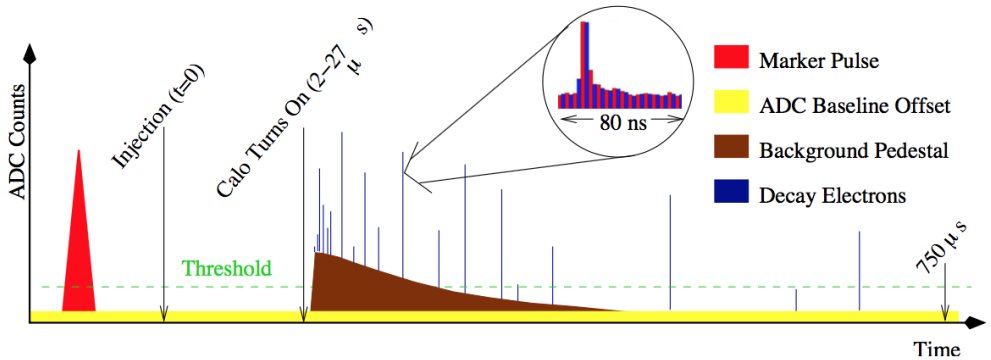




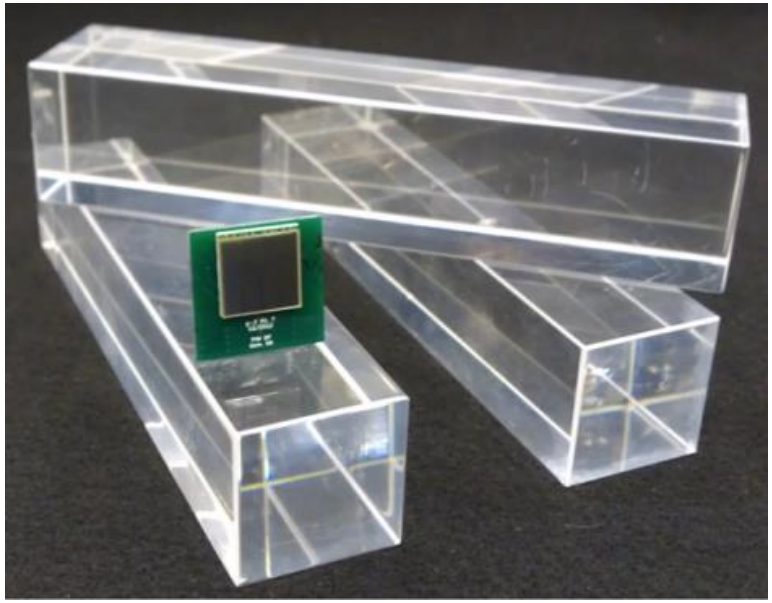


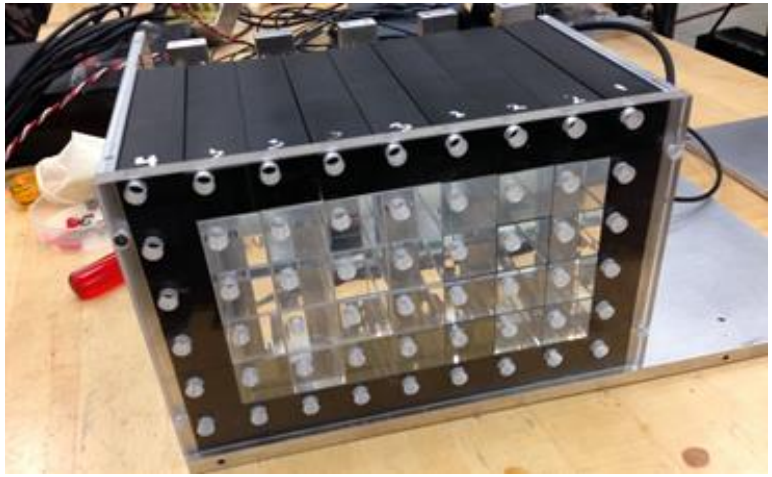
Parent muons all have same phase, but decay electrons have different tof → many ways to acquire a phase shift

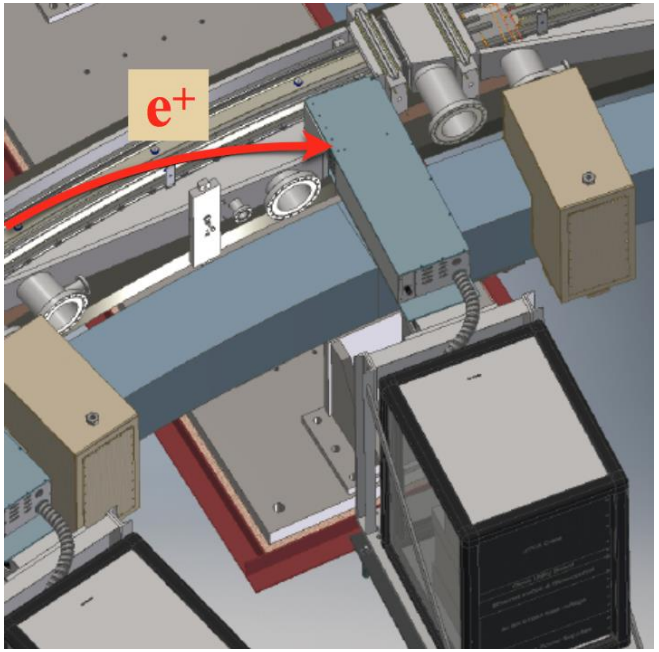
- Bias in pedestal subtraction from hadronic bkgs (removed at FNAL)
- Gain shifts
- Pileup



Upgrades to control phase systematics– segmented calos

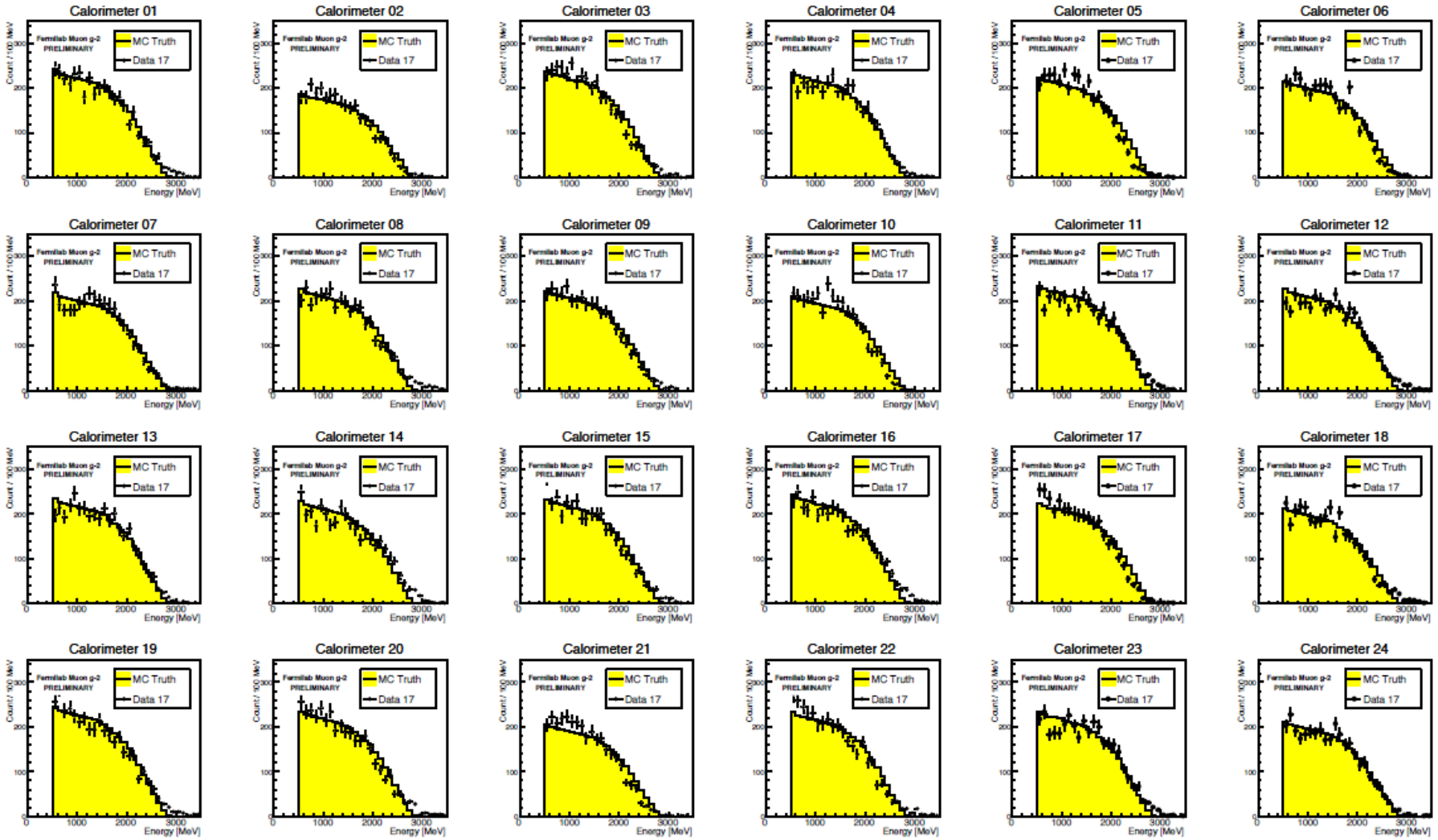




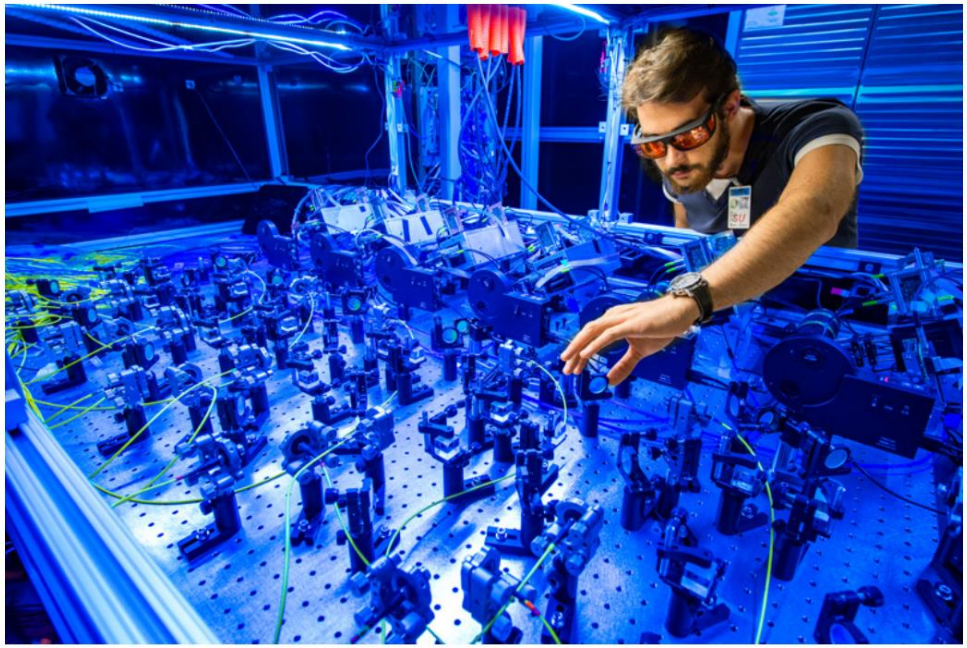


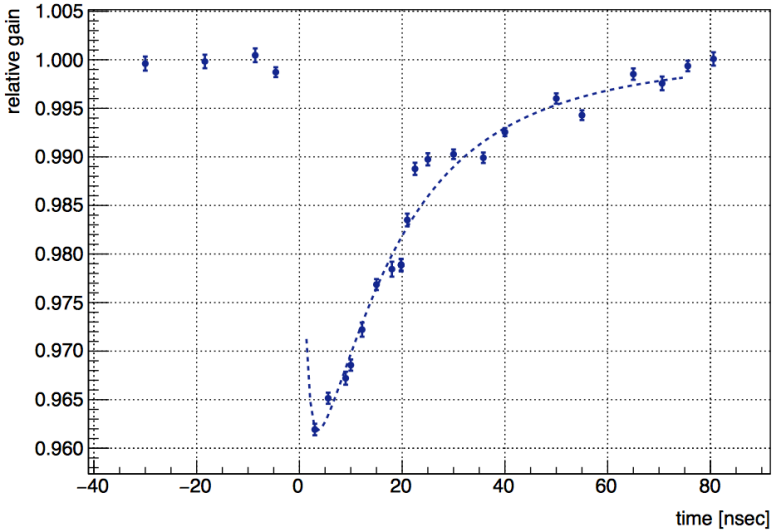
- Segmented calorimetry allows for spatial separation of pileup
  - PbWO4 with SiPM readout
  - 6x9 array for each of 24 calorimeters
- No segmentation at BNL

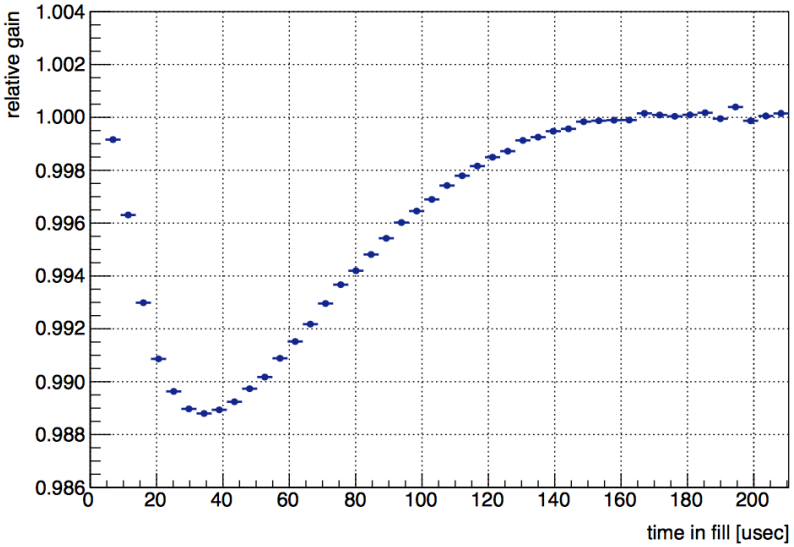
Decay e+ energy spectrum in each calorimeter



Upgrades to control phase systematic – laser calibration







- State-of-the-art laser calibration system from INFN
- Shown to achieve 10^{-4} gain correction
- BNL relied on end point spectrum of decay electrons

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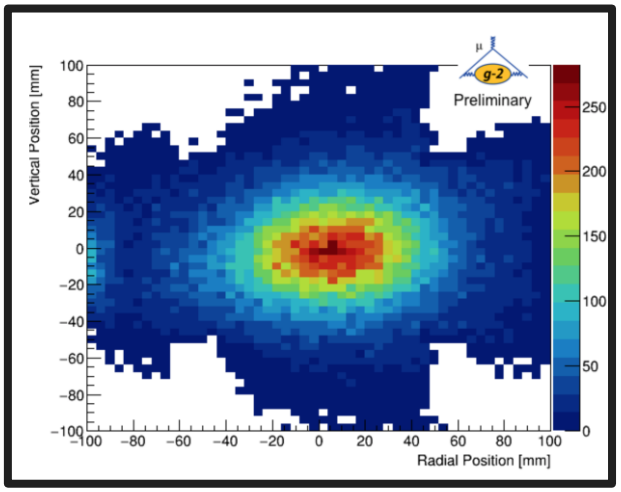
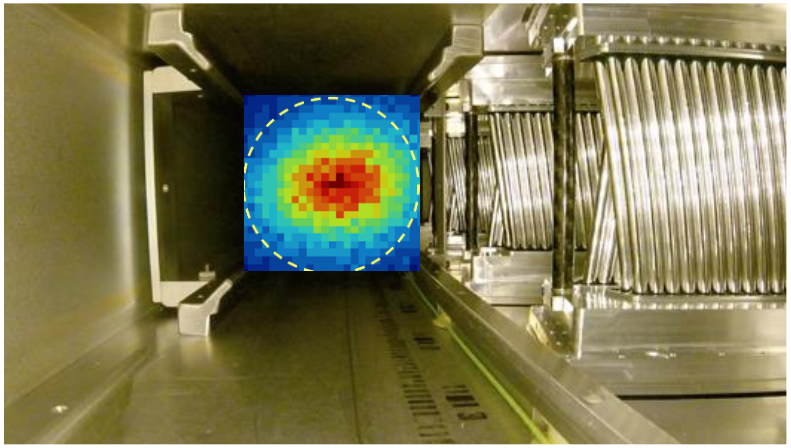
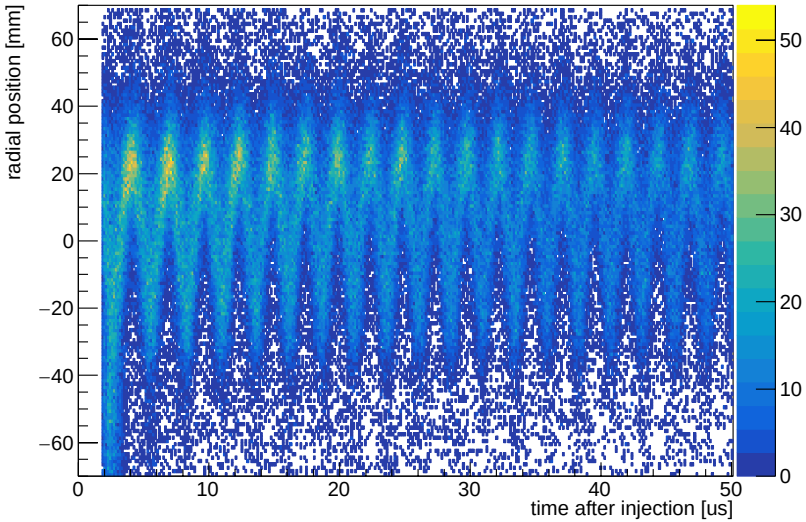
Major improvements to tracking

- In situ straw trackers installed at two locations around ring
- Useful diagnostic for many systematic
  - Muon convolution with B-field
  - Beam dynamics in ring, e.g. CBO
- BNL had one tracker outside vacuum volume with smaller acceptance w/ a number of issues







Trackers also provide E-field and pitch corrections

$$\vec{\omega}_a = -\frac{e}{mc}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}_{\text{E-field}} - \underbrace{a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}_{\text{Pitch}}\right]$$

- E-field and pitch corrections arise from additional spin precession terms in the BMT equation
  - E-field arise due to momentum spread of injected muons
  - Pitch correction is due vertical oscillations of beam
- Both come down to having to know physical properties of the stored beam

$$C_E = \frac{\Delta\omega}{\omega} = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

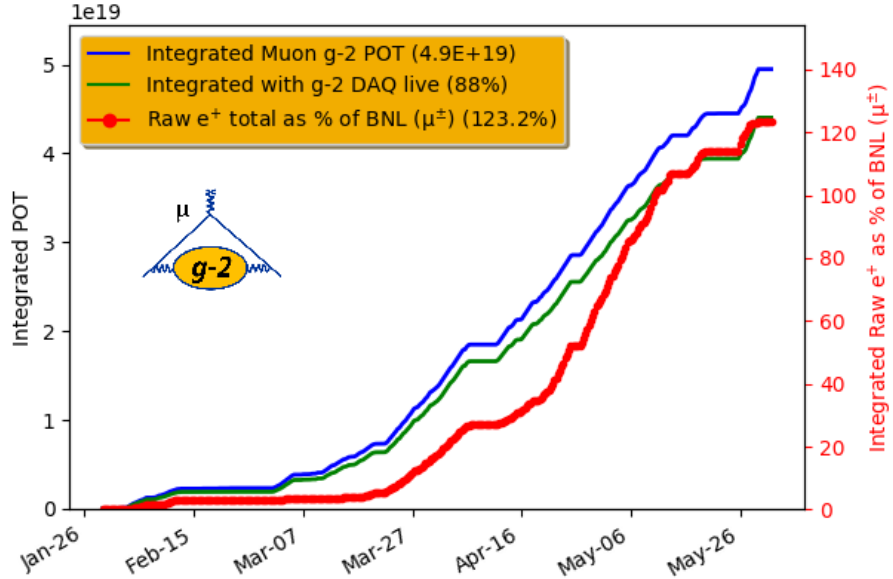
$$C_p = -\frac{n}{4}\frac{\langle y^2\rangle}{R_0^2}$$

BNL	Value	Error
E-field	470 ppb	54 ppb
Pitch	270 ppb	36 ppb

Muon g-2 outlook

We are burning up the tape farm with new data!

- After spending most of year finalizing commissioning, started physics production running in early April
- Have > 1.2 x BNL on tape
- Collecting a BNL-sized data sample every 6 weeks!
  - 5 weeks left in this run
- Aiming to publish results exceeding BNL precision by Summer 2019



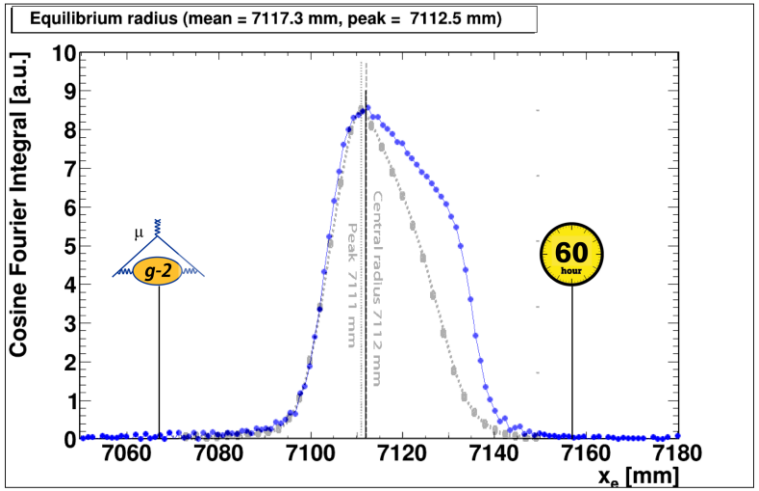
1st publication (>1 x BNL statistics)

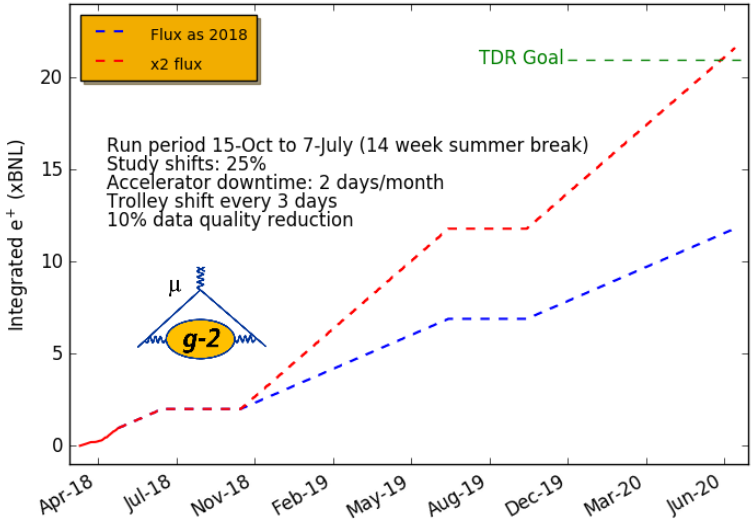
2nd publication (5-10 x BNL statistics)

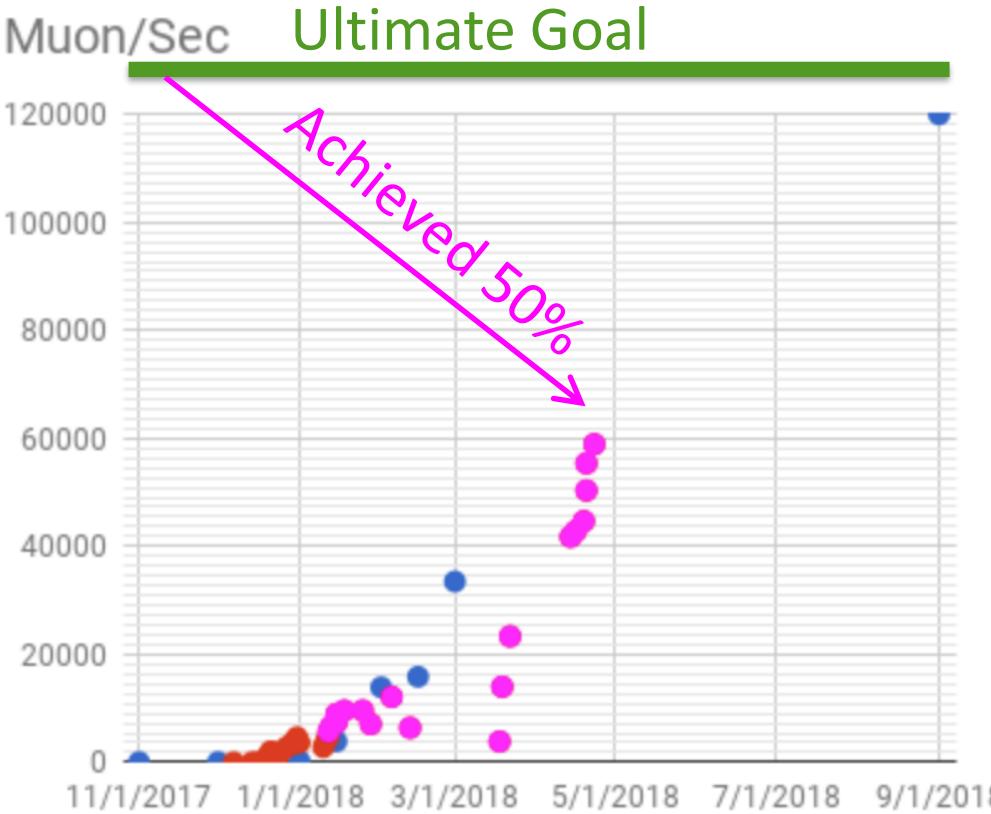
3rd publication (>20 x BNL statistics)

CY18 | CY19 | CY20 | CY21

Still work to do this summer



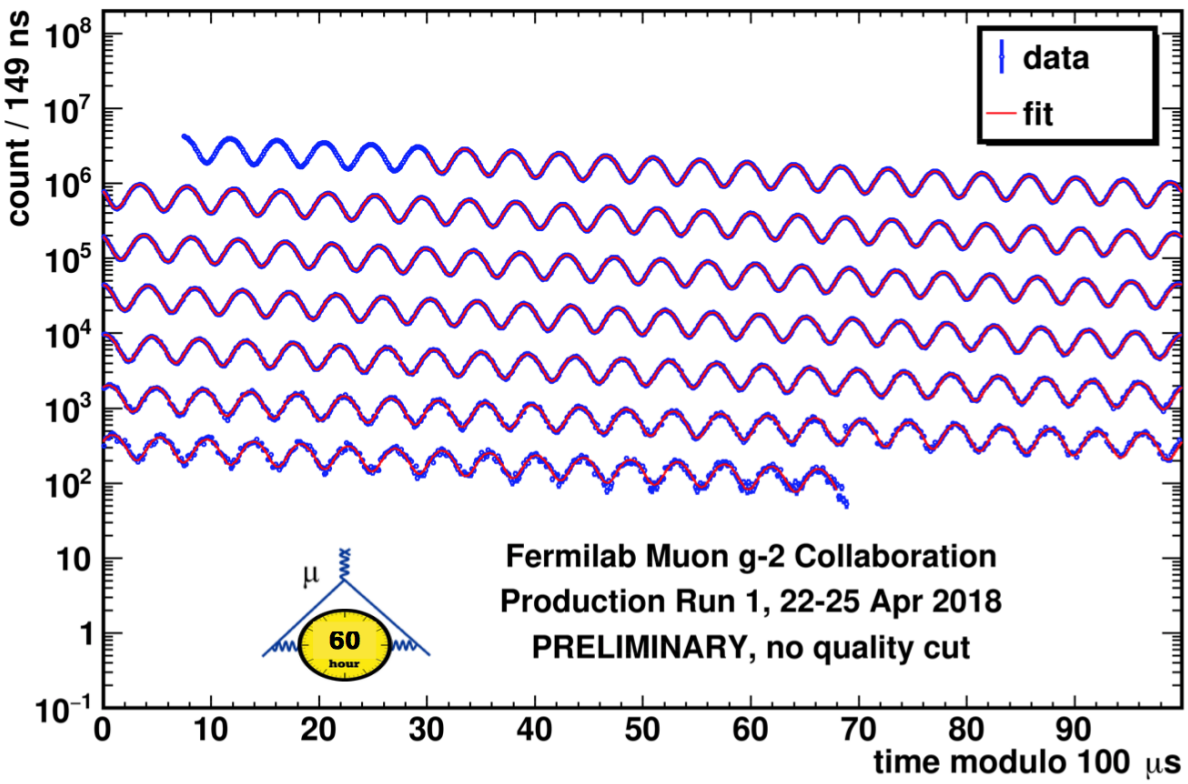




- Still only at about half of TDR design goal for rates…need to improve flux
- Momentum distribution is skewed to higher p…need to improve muon injection dynamics
- Will address both over July 7 – Oct 1 Fermilab accelerator shutdown

60-hour data challenge

- Analyzers encourage to complete full analysis of 60 hour data set as large sample (~2PB) is reprocessed
- Analysis comparable to BNL sophistication level is nearly complete
  - still needs gain correction and final DQ cuts



- Results already very encouraging
  - 1.2 ppm stat error
  - χ^2/ndf = 3797/3785
- Still much work to be done before unblinding, but so far no obvious showstoppers

Conclusions

- After 5 years of design, construction, and commissioning Muon g-2 at Fermilab is up and running
- Aiming for statistics 20 x BNL with a significantly upgraded experiment
- Expecting published results surpassing BNL precision no later than Summer 2019 conferences…pushing for Winter

Muon g-2 results are coming soon!