Muon *g* – 2 in 10 (ish) minutes

11 June 2019

New Perspectives 2019

Jason Hempstead (on behalf of the Muon *g* – 2 collaboration)

Outline

- The physics of $g_\mu - 2$
  - Magnetic dipole moments
  - Standard model calculation
  - Past experiments
- Fermilab E989
  - Experimental technique
  - Current status

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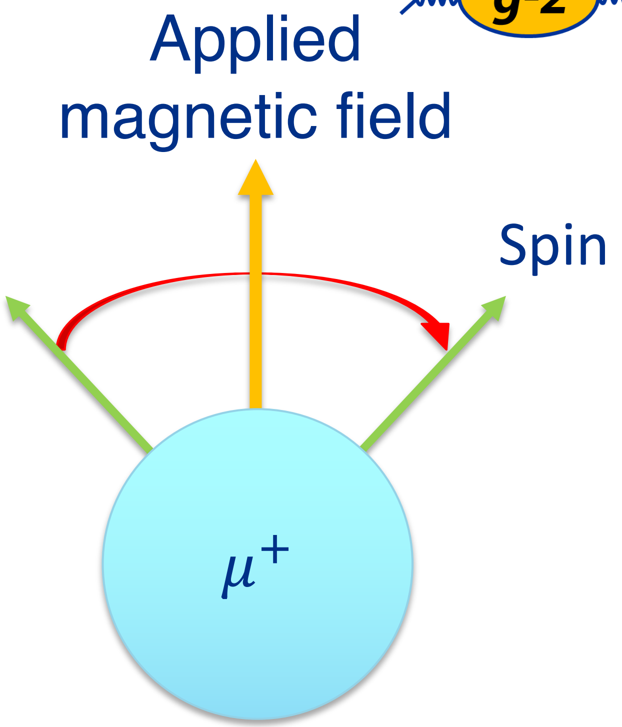
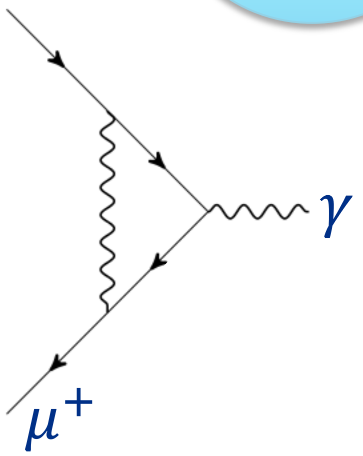
Magnetic dipole moment

- Spin will precess about an external field
  - At a rate dependent on the size of the magnetic moment

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$
$$= \frac{gq}{2mc} \vec{s} \times \vec{B}$$



- Dirac calculated $g = 2$
  - Later, Schwinger calculated a correction due to a photon loop in the vertex



- Define the "magnetic anomaly" – this is what we are measuring

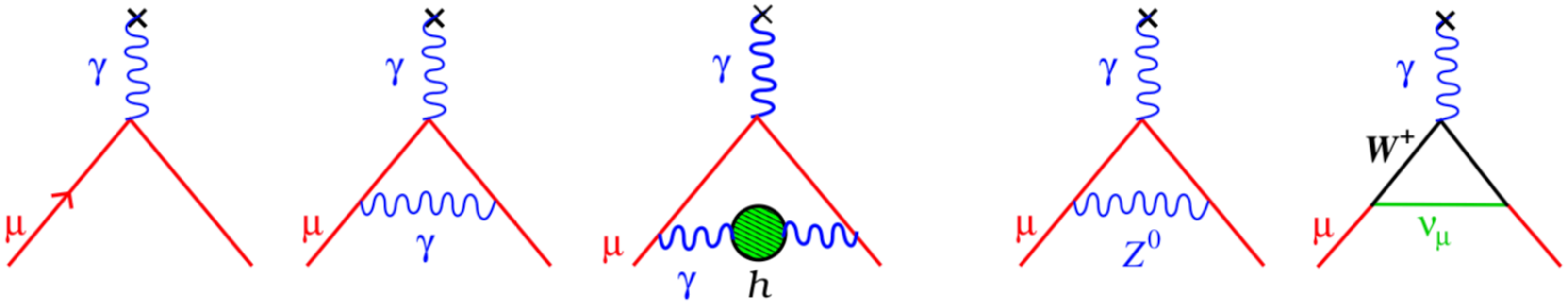
$$a \equiv \frac{g-2}{2}$$

Standard model calculation

- Value of a_μ sensitive to all particles
  - New physics would show up in difference between SM calculation and measurement

- Calculation split into 4 categories, organized by what particles are loopy:
  - QED
    - Leptons and photons
  - Hadronic
    - Vacuum polarization (HVP)
    - Light-by-light (HLbL)
  - Weak
    - Higgs, Z, W

	Contribution ($\times 10^{10}$)	Error ($\times 10^{10}$)
QED	11 658 471.8971	0.007
Weak	15.36	0.10
HVP	684.68	2.42
HLbL	9.8	2.6
Total a_μ^{SM}	11 659 182.04	3.56



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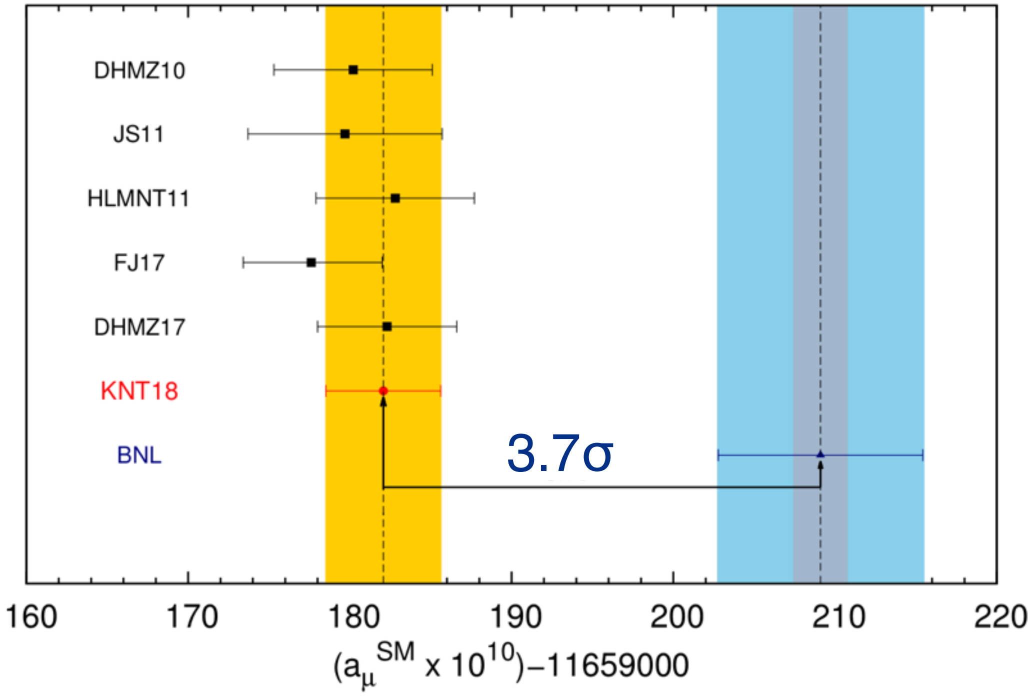
Brookhaven (BNL) E821 measurement

- Results of most recent measurement at Brookhaven E821 hint at something unknown…



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a_μ^{BNL}	11 659 208.0	6.3
Δa_μ	25.96	7.24

Outline

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- Fermilab E989
  - Experimental technique
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To resolve this…

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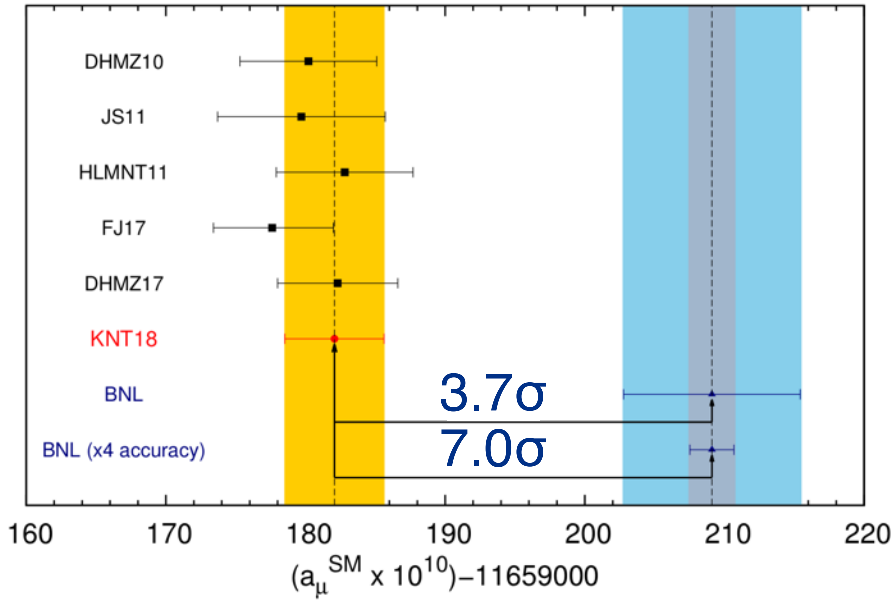
Fermilab E989

- 4x the precision of BNL
  - 540 parts per billion (ppb) → 140 ppb

- 100 ppb statistical uncertainty
  - $\approx 10^{11}$ collected positrons
  - Roughly 21x the statistics taken at BNL

- 100 ppb systematic uncertainty
  - 70 ppb for magnetic field measurement
  - 70 ppb for spin precession frequency



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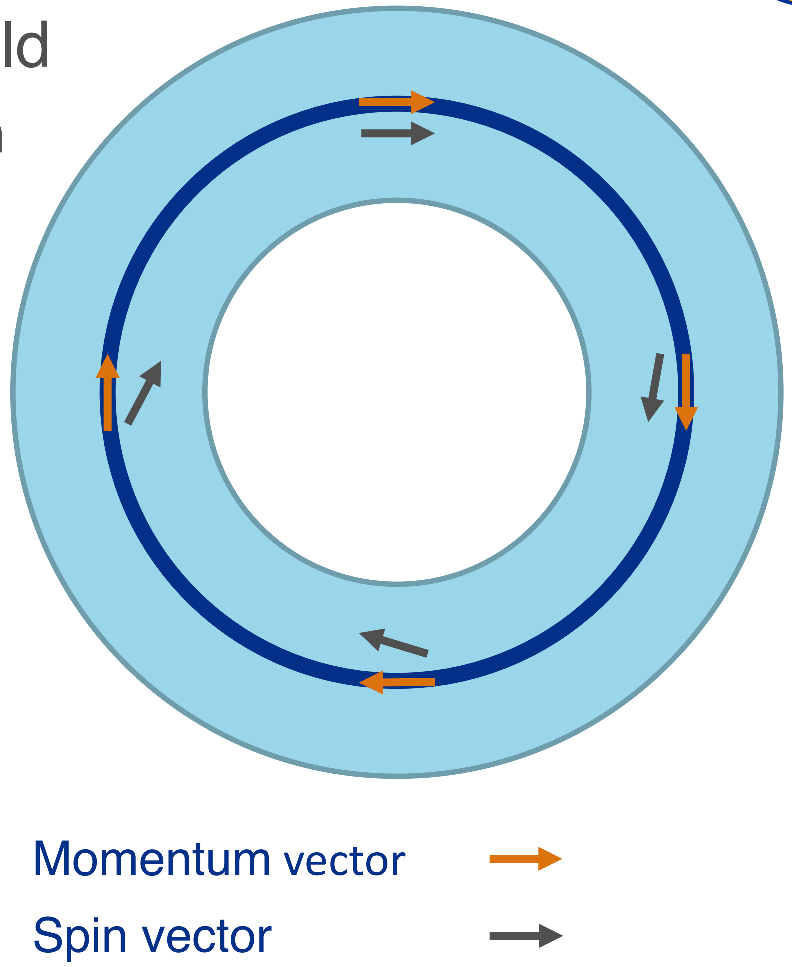
Measuring a_μ with a storage ring

- Inject polarized muons into highly uniform 1.45 T field
  – High energy positrons preferentially emitted in direction of spin

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

≈ 0 for motion transverse to magnetic field

≈ 0 for muons at "magic" momentum 3.1 GeV / c or $\gamma = 29.3$



Measuring a_μ with a storage ring

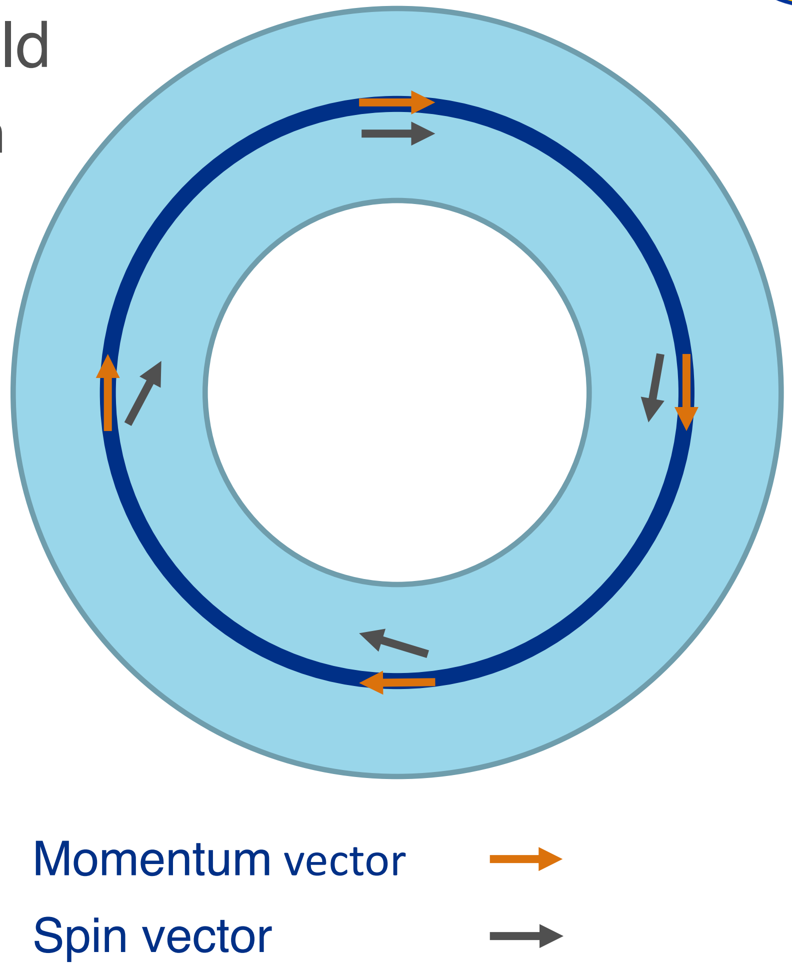
- Inject polarized muons into highly uniform 1.45 T field
  - High energy positrons preferentially emitted in direction of spin

- Record data in 700 μs "fills"
  - 10 (boosted) lifetimes of muon precession data

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c \quad = \quad -\frac{e}{m} a_\mu \vec{B}$$

- Magnetic field measured in terms of the Larmor precession frequency of the free proton, ω_p

$$B \quad = \quad \frac{\omega_p}{\mu_p}$$



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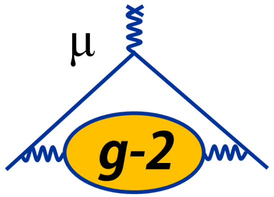
Getting a number for $g_\mu - 2$

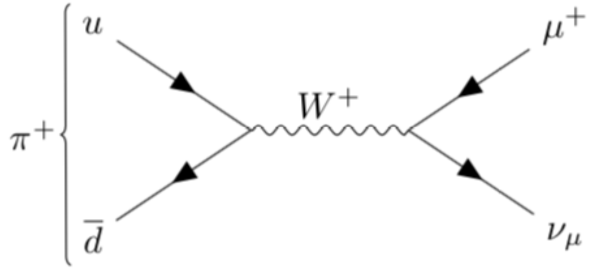
- Combination of constants measured very well

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

	Relative error (ppb)	Experiment
g_e	0.000 26	Quantum electron cyclotron. Hanneke et al. 2008.
μ_e/μ_p	3.0	Hydrogen spectroscopy. Winkler et al. 1972.
m_μ/m_e	22	Muonium hyperfine splitting. Liu et al. 1999.
$\omega_a/\tilde{\omega}_p$	140	Fermilab $g-2$

Fermilab Muon *g* – 2 (E989)





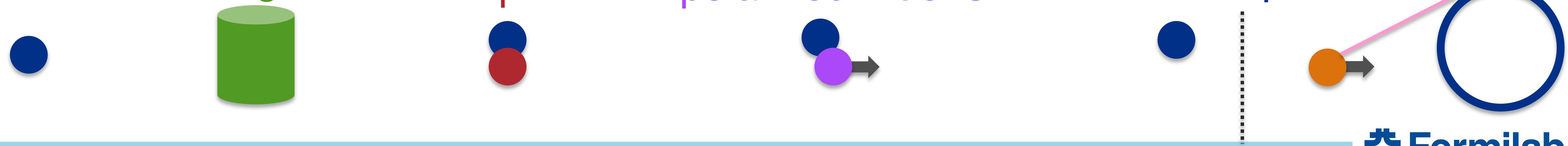
8 GeV protons

Target

3.1GeV protons and pions

Protons and polarized muons

Protons and muons separated



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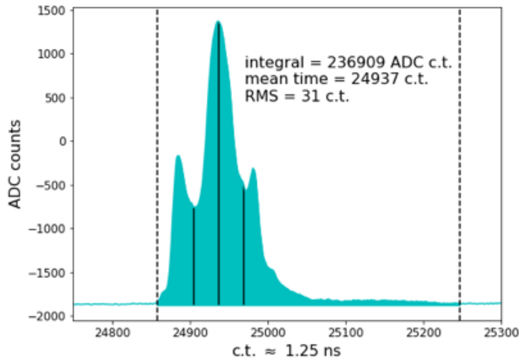
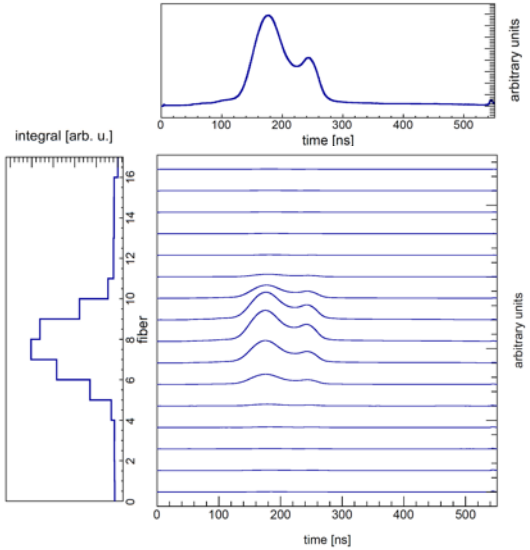
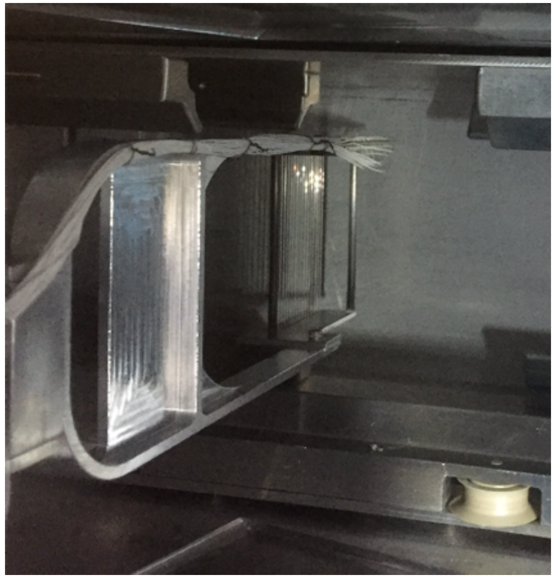
Understanding injection

- Beam entrance counters:
  - T0
    - Scintillating paddle coupled to 2 PMTs
    - Provides absolute injection time
  - Inflector Beam Monitoring System (IBMS)
    - Series of 3 detectors along beam path
    - Scintillating fibers coupled to silicon photomultipliers (SiPMs)
    - Spatial profile of beam

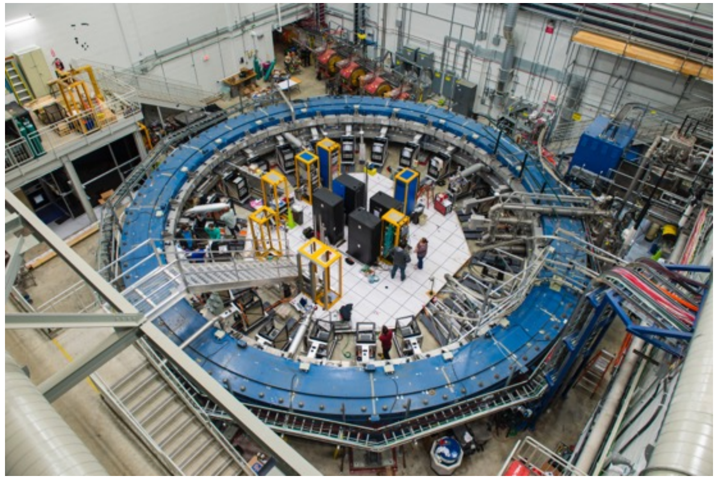


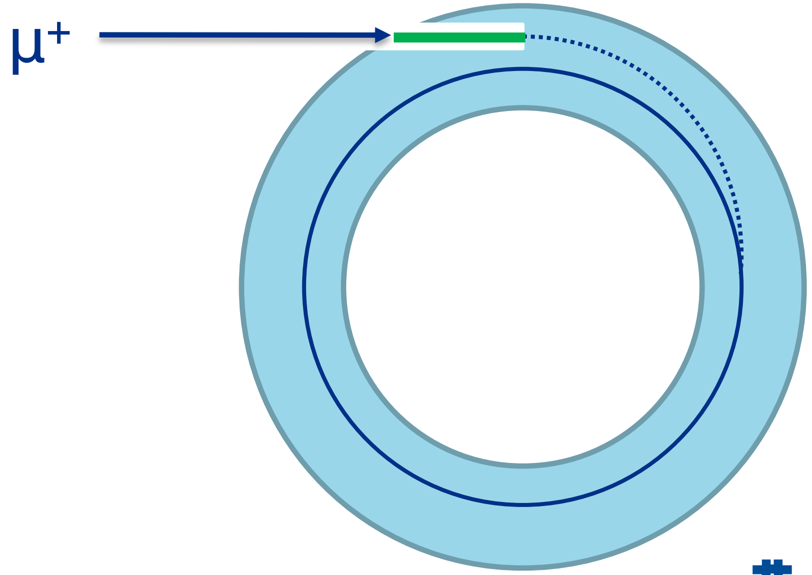




Storing muons to watch them precess

- Superconducting inflector
  - Cancels out magnetic field to allow injection





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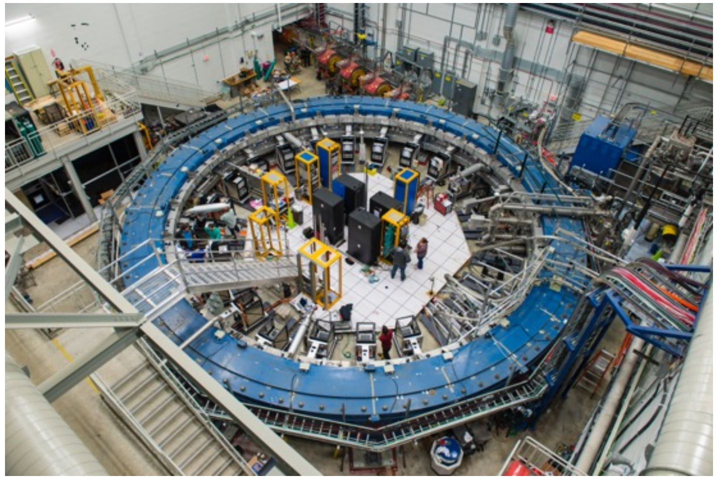
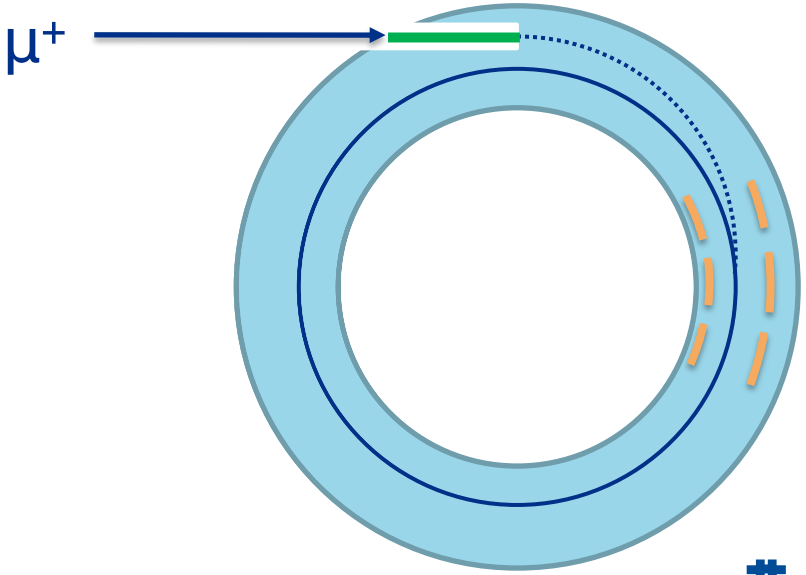
Storing muons to watch them precess

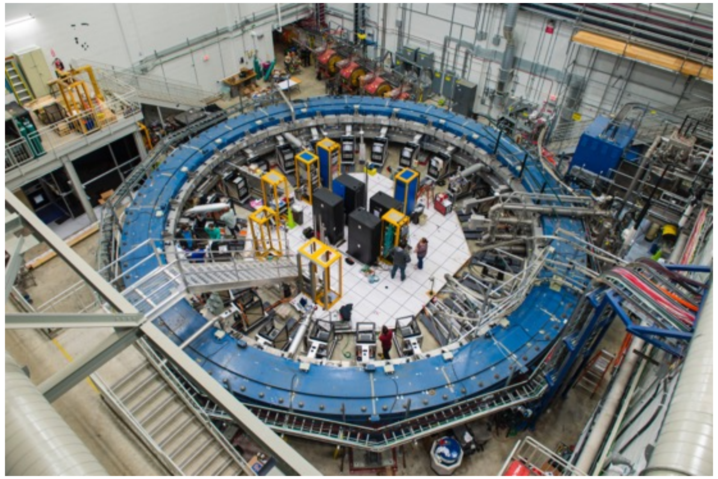
- Superconducting inflector
  - Cancels out magnetic field to allow injection
- Magnetic kickers
  - Deflect muons onto the proper orbit

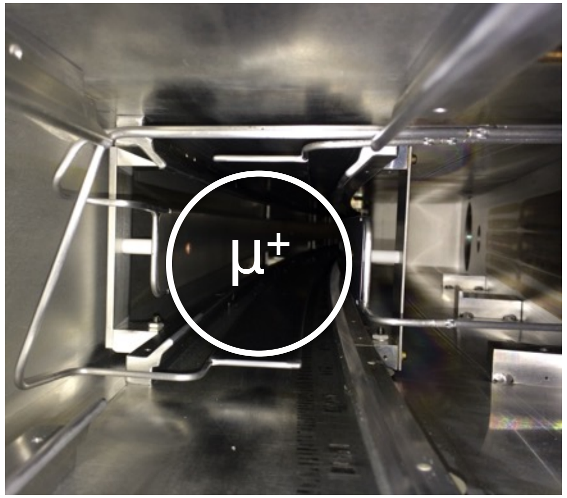




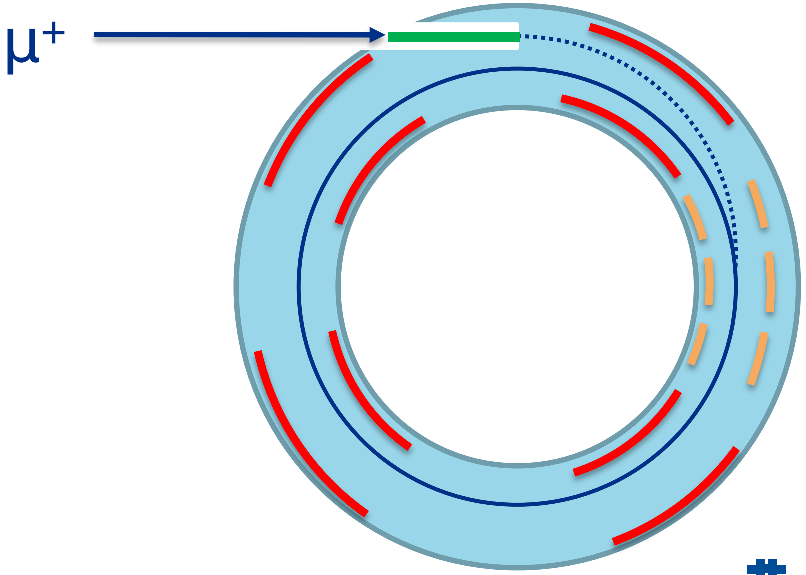
Storing muons to watch them precess

- Superconducting inflector
  - Cancels out magnetic field to allow injection
- Magnetic kickers
  - Deflect muons onto the proper orbit
- Electrostatic quadrupoles
  - Provide vertical focusing

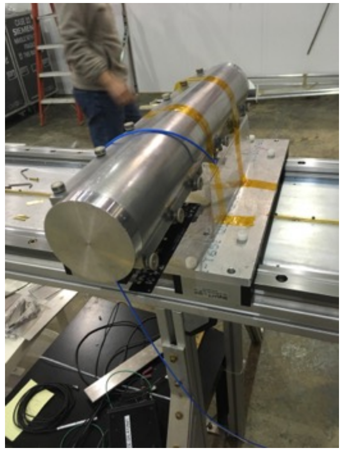


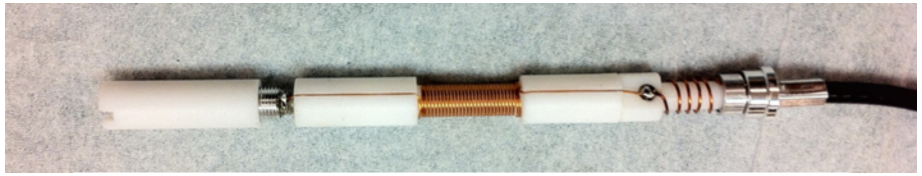


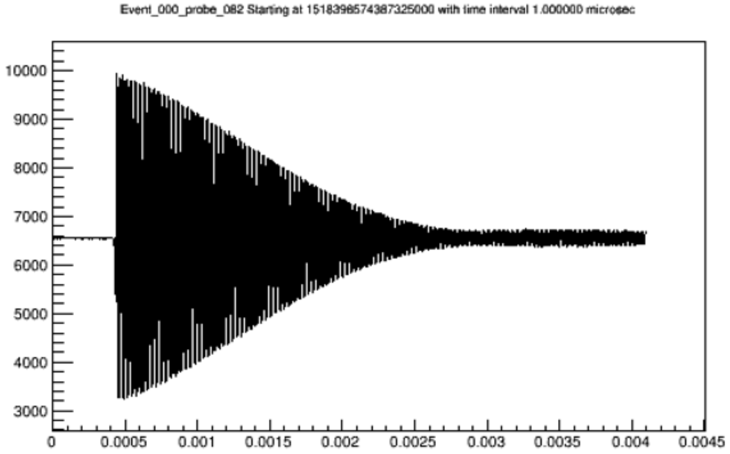
Cross-section of storage region



Measuring the magnetic field (ω_p)







- Nuclear magnetic resonance (NMR) probes (x17) on a trolley to survey the muon storage region periodically
  - When no beam present
  - Measures Larmor precession of the protons in petroleum jelly samples

- 378 additional probes outside the storage region to monitor continuously

- Very well understood water sample to calibrate the trolley probes

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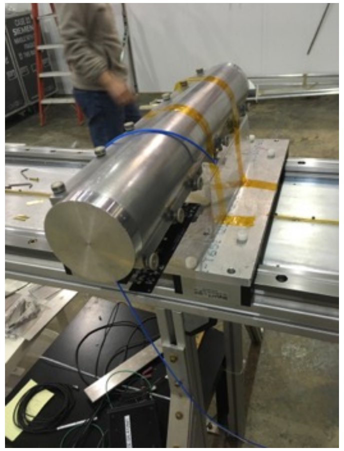

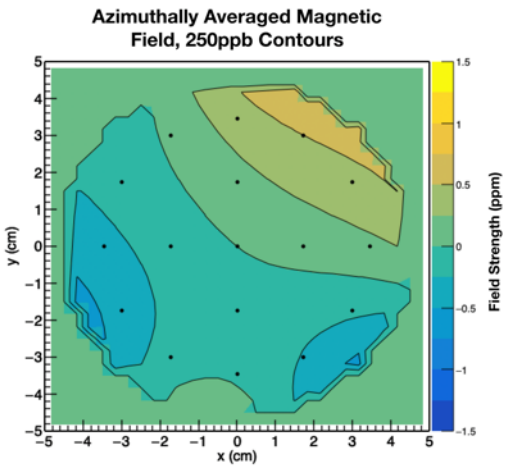

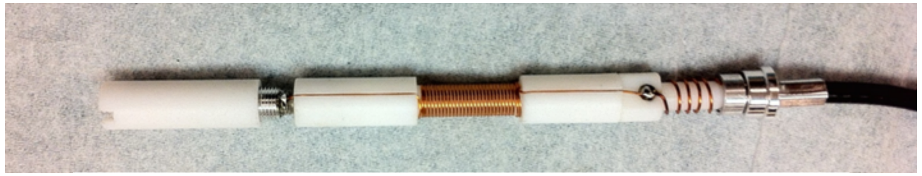

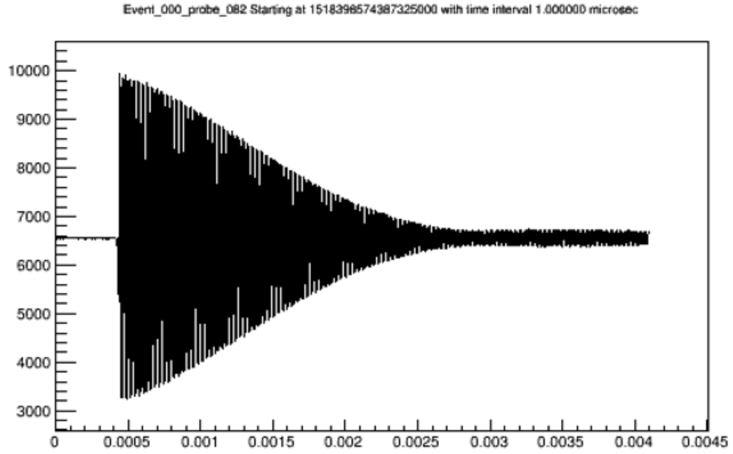

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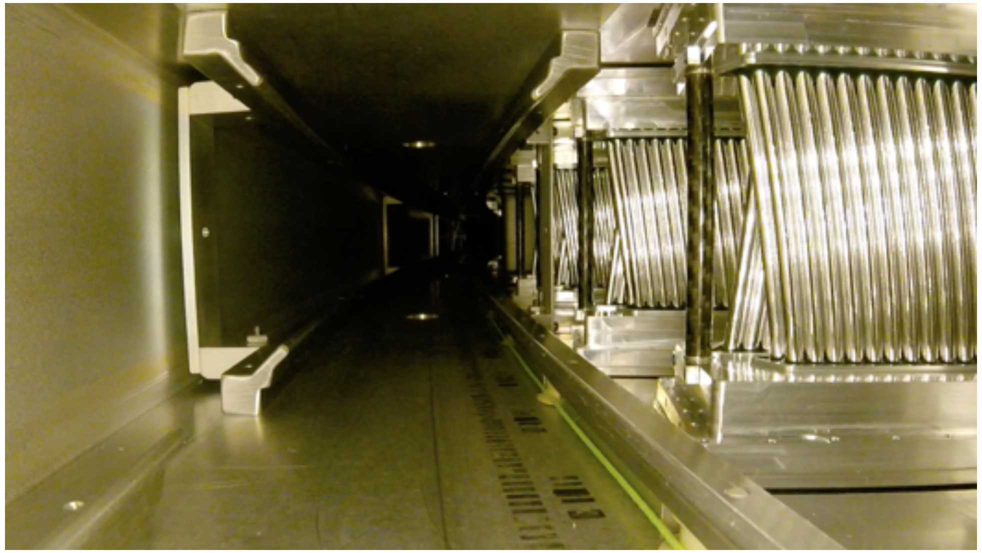
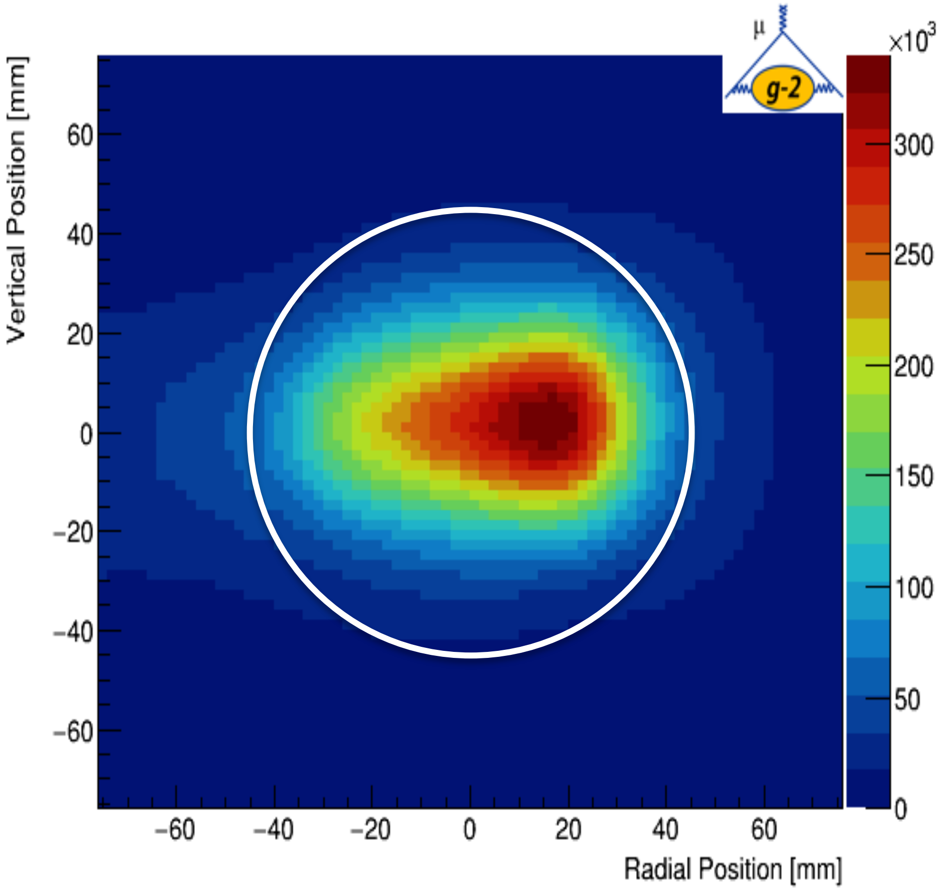
Measuring beam distribution

- 2 stations of straw tracking detectors
  - Extrapolate positron tracks to decay position
- Provide information about location of beam
  - $\omega_p \rightarrow \tilde{\omega}_p$





G. Lukicov. High precision track-based alignment of the tracking detector of the g-2 experiment (poster). Fermilab Users Meeting 2019.

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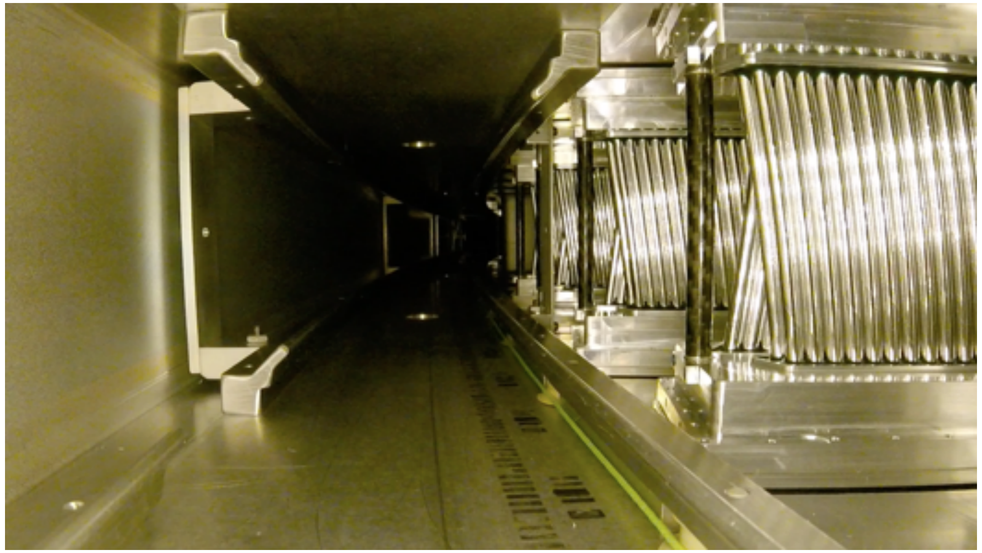

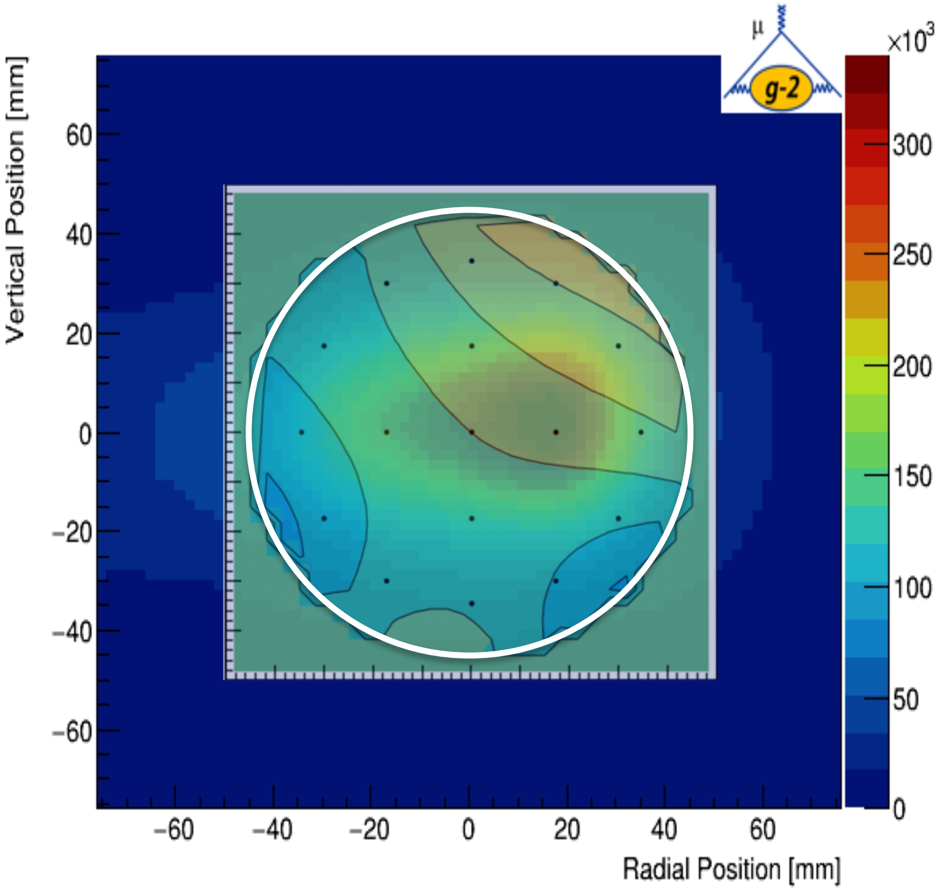

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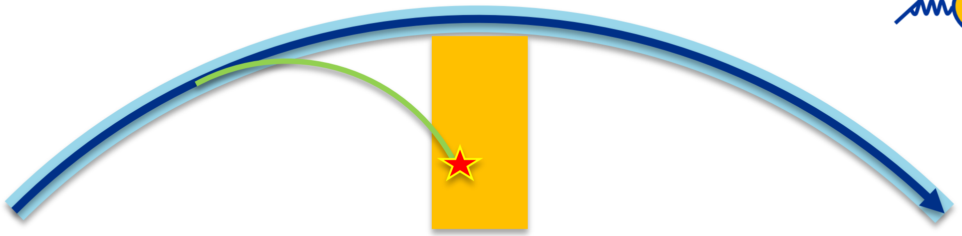
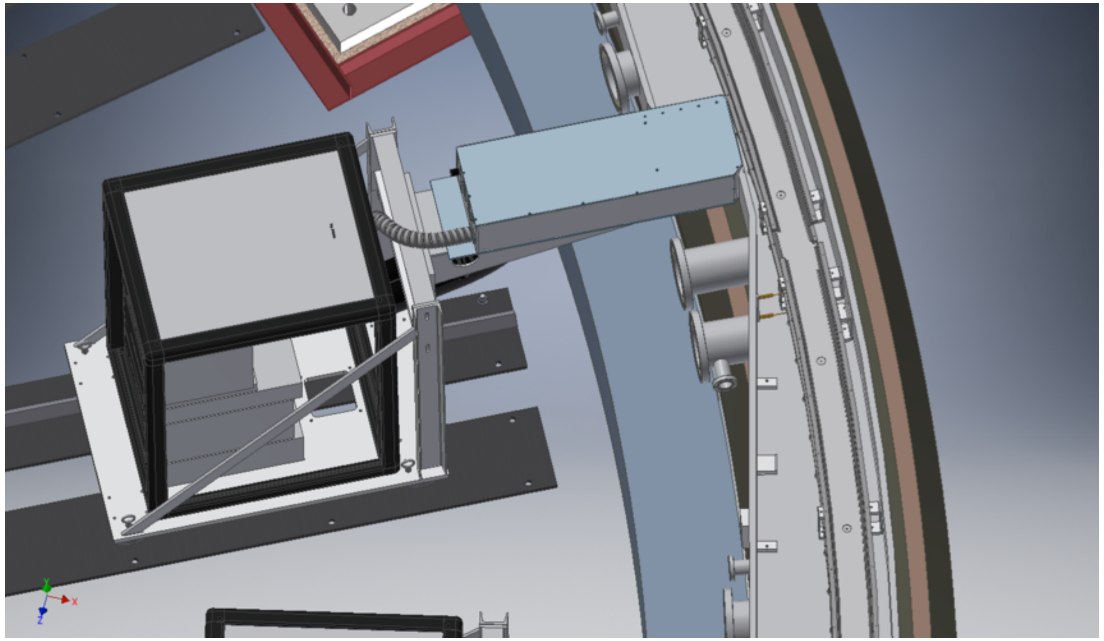
Measuring the precession frequency (ω_a)

- Use electromagnetic calorimeters
  - 24 equally spaced around ring
  - Each is a 9x6 grid of lead fluoride (PbF_2) crystals read out individually by SiPMs



Decay positron curling inward from the muon storage orbit to strike a calorimeter

J. Hempstead. Preparing the Muon $g-2$ calorimeters for Run 2 (poster). Fermilab Users Meeting 2019.



Measuring the precession frequency (ω_a)

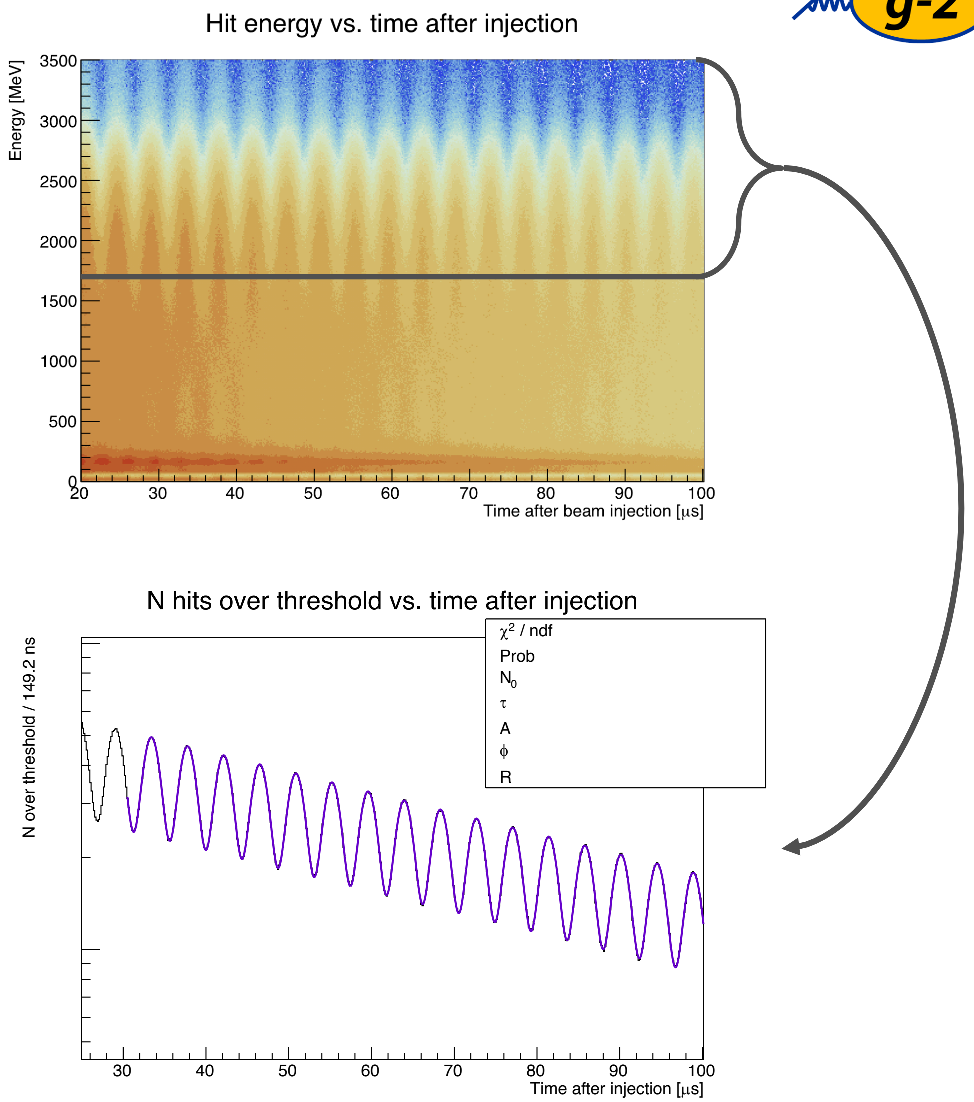
- Use electromagnetic calorimeters
  - 24 equally spaced around ring
  - Each is a 9x6 grid of lead fluoride (PbF_2) crystals read out individually by SiPMs

- $\omega_a = \omega_s - \omega_c$ is imprinted in the number of positrons in a given direction
  - Cut on positron energy

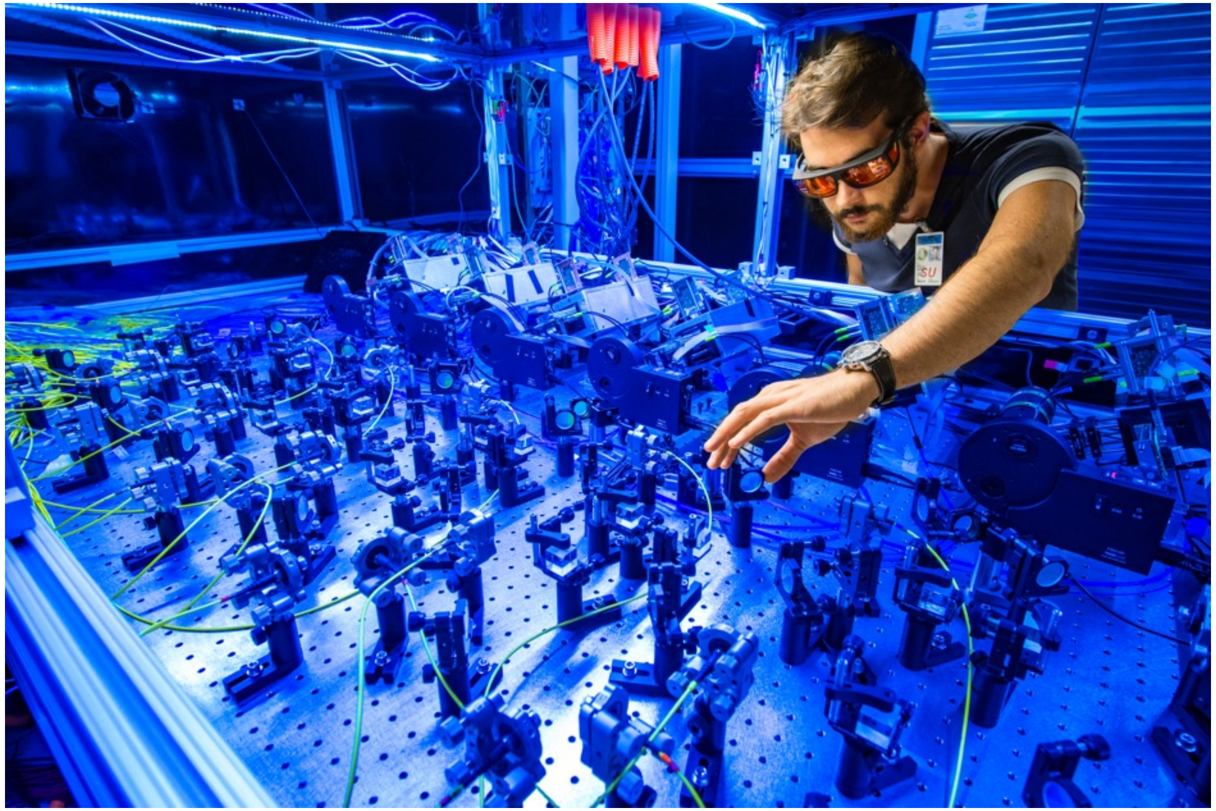
- Fit using

$$N(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 + A\cos\left(\omega_a t - \phi\right)\right]$$

M. Bhattacharya. Pileup Systematic Studies in the Fermilab Muon g-2 Experiment. New Perspectives 2019.



Laser system



- Track and correct gain of individual channels in calorimeters
- Timing alignment of individual channels
  - Synchronization laser pulse at the beginning of every fill

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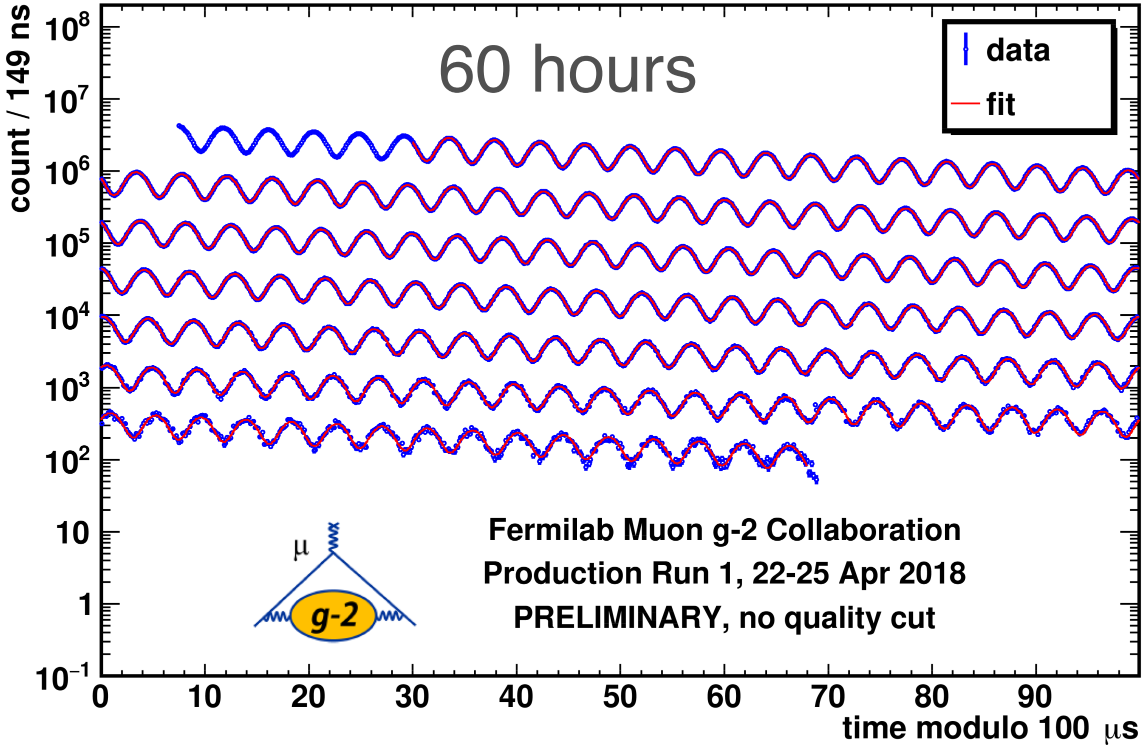
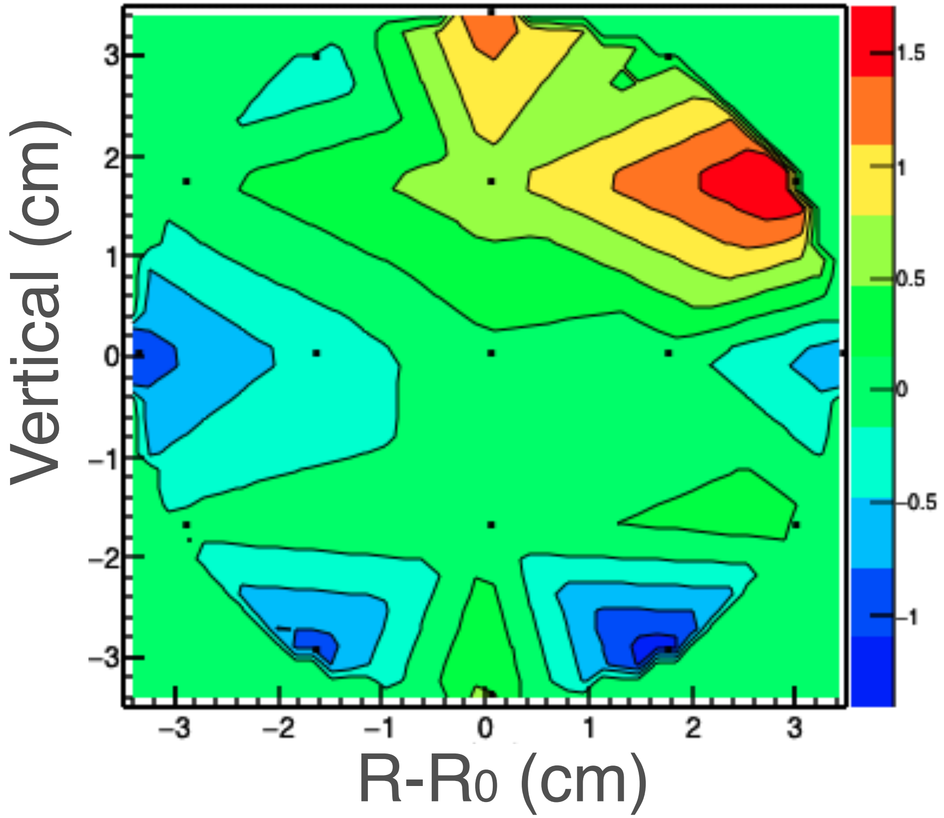
Current status

- Run 1 analysis underway
  - About 1.4x the statistics of the E821 result (in ω_a fit)
  - Magnetic field uniformity about 2x better

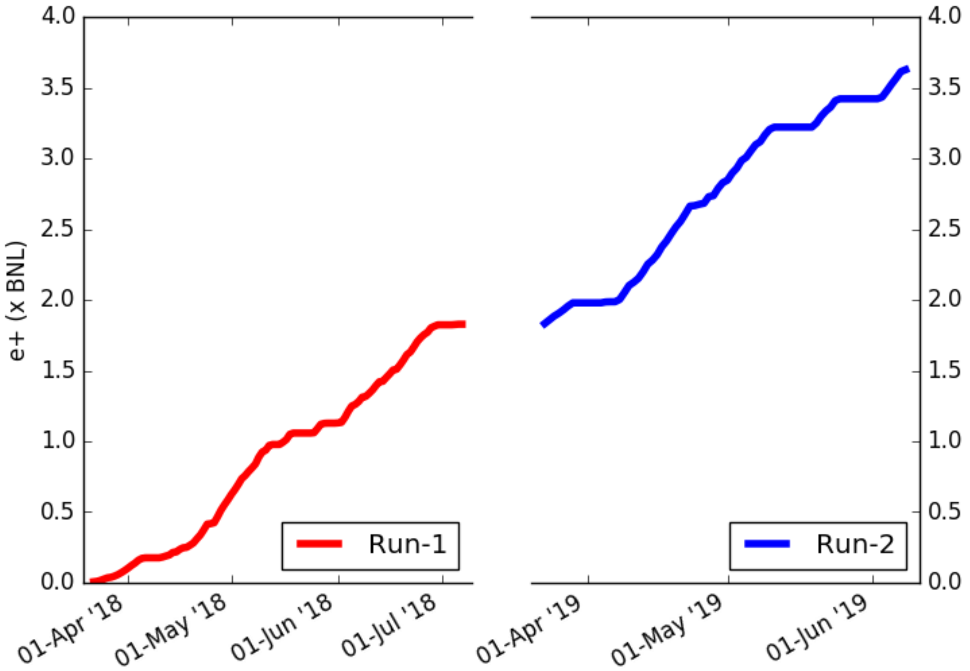




Current status

- Run 1 analysis underway
  - About 1.4x the statistics of the E821 result (in ω_a fit)
  - Magnetic field uniformity about 2x better

- Run 2 in progress
  - Currently collected ~1.8x the statistics of E821
  - Improved stability of run conditions



S. Ganguly. Muon g-2: Measuring the anomalous magnetic dipole moment of a muon to high precision. Fermilab Users Meeting 2019.

Thanks!

Back-up

Various sources

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- B. Lee Roberts. The History of the Muon (g – 2) Experiments. 2018.
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- G. W. Bennett et al. Final report of the E821 muon anomalous magnetic moment measurement at BNL. 2006.
- A. T. Fienberg. Measuring the Precession Frequency in the E989 Muon g – 2 Experiment. 2019.
- P. J. Mohr, D. B. Newell, and B. N. Taylor. CODATA Recommended Values of the Fundamental Physical Constants: 2014. 2016.
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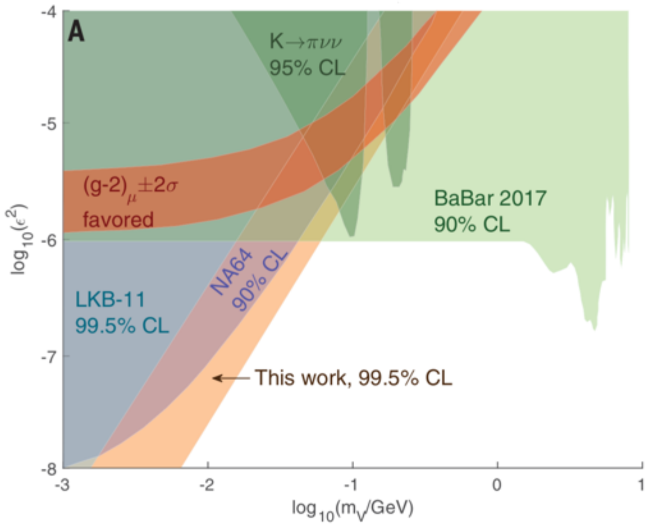
- R. Osofsky. Magnetic Field Status of the Muon g-2 Experiment. New Perspectives 2018.

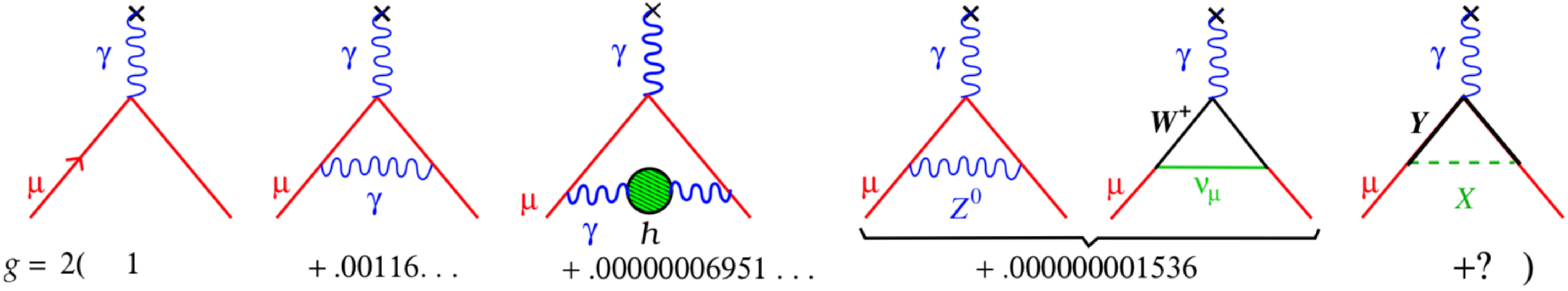
- J. D. Jackson. Classical Electrodynamics, Third Edition. 1998.

- Photos from Fermilab and Wikipedia

Potential new physics?

- SUSY
  – Still no sign at the LHC
- Dark photon
  – Almost completely ruled out by various experiments

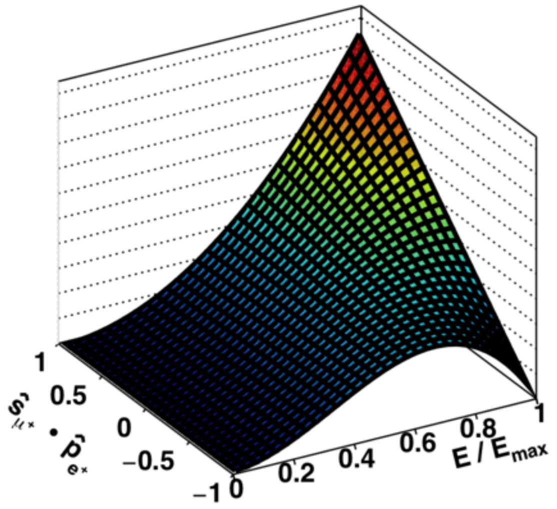


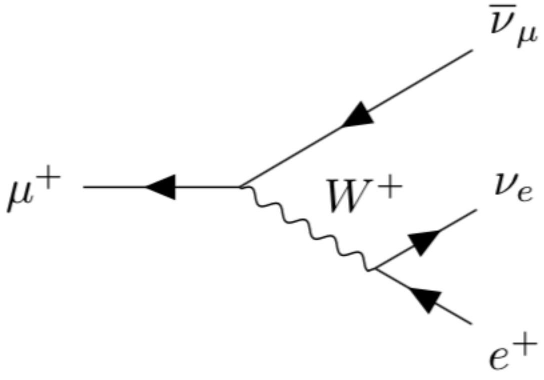


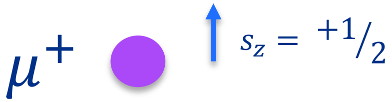
- Parker et al. Measurement of the fine-structure constant as a test of the Standard Model. 2018.
- B. Lee Roberts. The History of the Muon (g – 2) Experiments. 2018.

Measurement technique

- Apply a magnetic field
  - Muons’ spins rotate
- Count decay positrons
  - Preferentially emitted in the direction of the muon’s spin
  - Relies on parity violation in the weak decay







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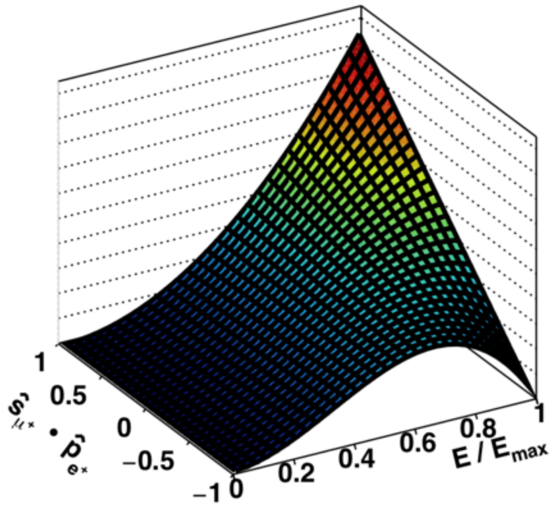

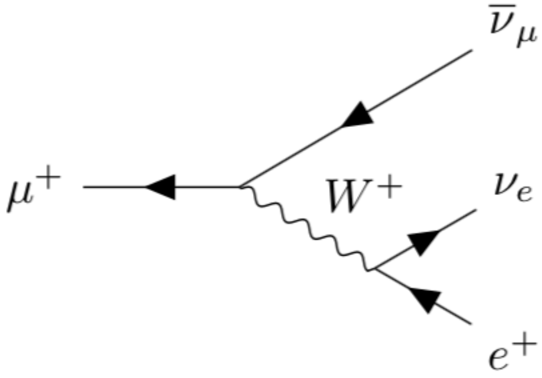

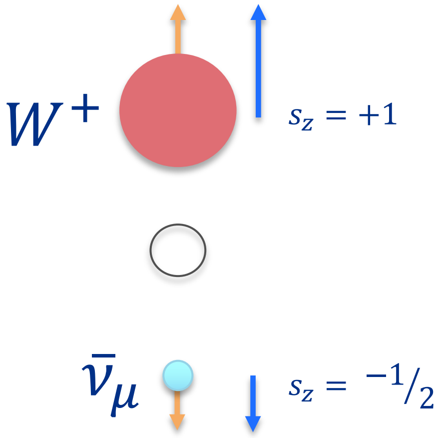

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