An Opportunity at Fermilab
— *The Muon Campus*

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USPAS 2019 Winter Session
January 2019

The Thomas BMT Equation and the Magic Momentum

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- As we need to provide vertical focusing, if we operate at the "magic momentum" where the last term goes to zero, then can use *electrostatic* quadrupoles for this task

$$\vec{\omega_a} = -\frac{e}{m}\left[a\vec{B_0} + (a - \frac{1}{\gamma^2 - 1})\frac{\vec{E} \times \vec{\beta}}{c}\right]$$

- Thus, a detector at one point in the ring would see frequency:

$$\omega_a = \frac{eB_0}{m} \cdot a$$

- So, provide a highly polarized beam of muons at the magic momentum into a highly uniform magnetic field, focus with electrostatic fields, and place detectors around circumference to detect positrons from the muon decays — kinematics show that the positrons with highest energies will emerge in the direction of the original muon's spin
- The rate of decay at these higher energies will oscillate with ω_a

Wiggle Plots

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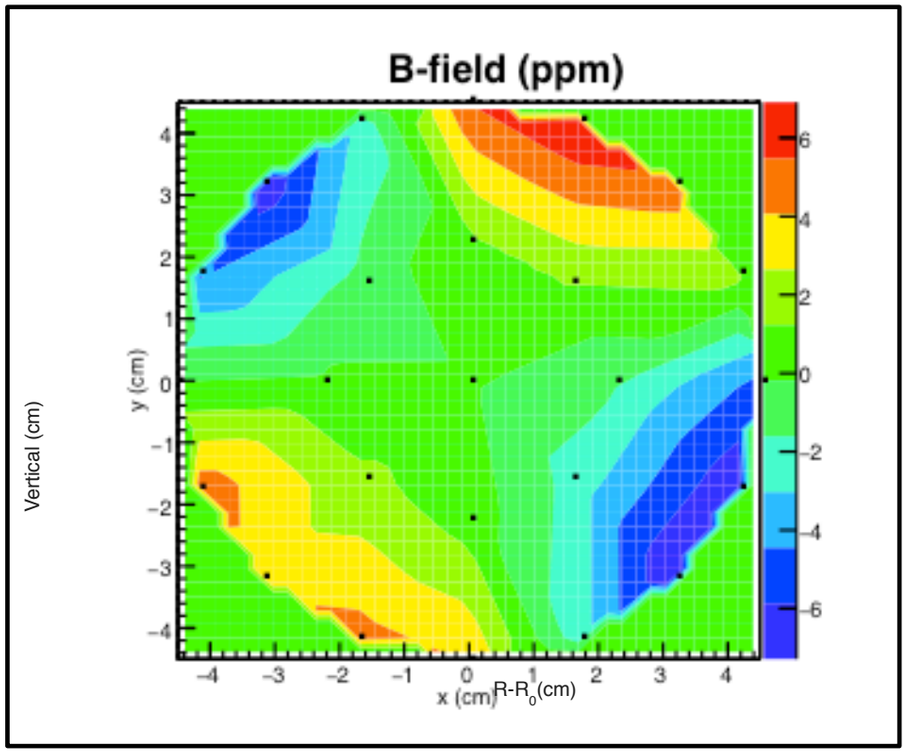
- Fixed detector in the ring would observe the rate of muon decay “wiggle” with a frequency given by

$$\omega_a = \frac{eB_0}{m} \cdot a$$



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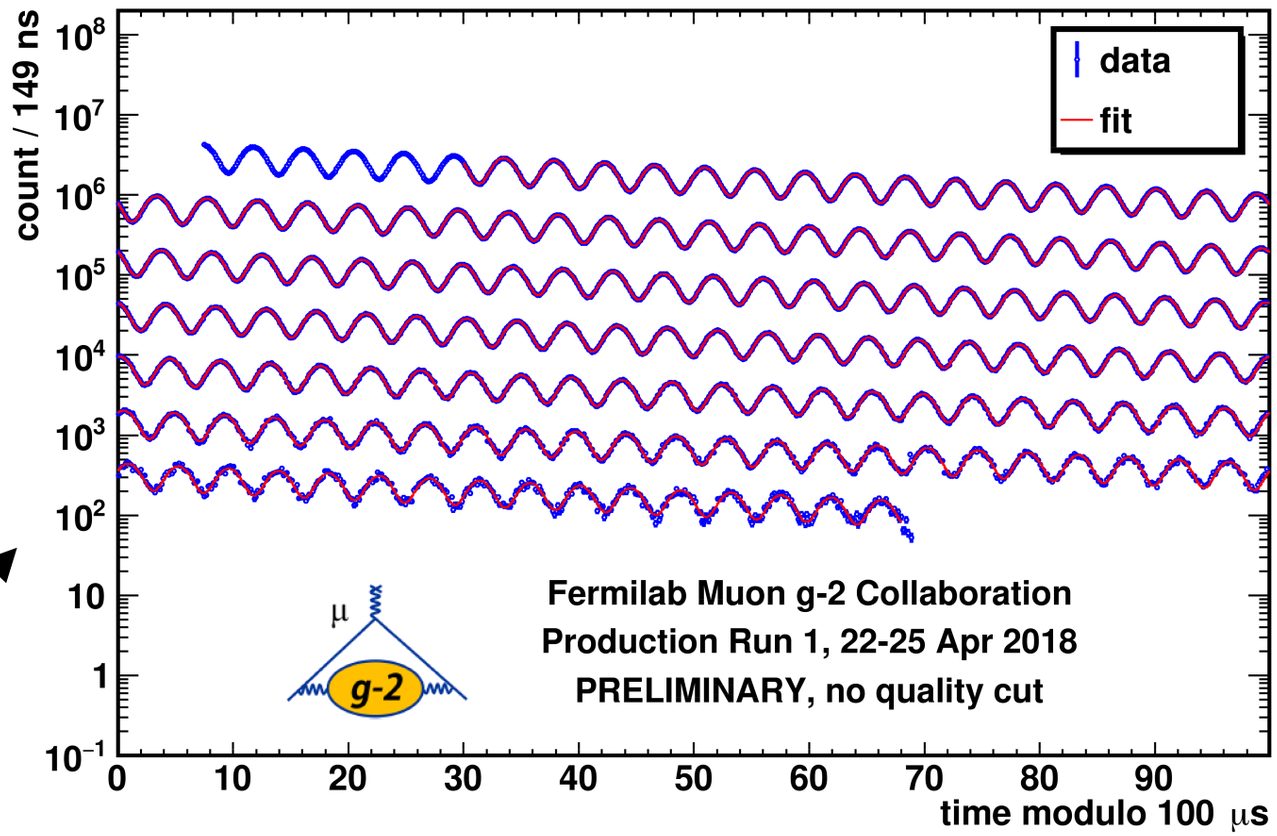

- Muon g-2 Experiment uses 24 detector systems around the circumference, measuring positron trajectories, energies, etc.
- repeat the wiggle plot billions of times…

Short History of the *g*-2 Experiment

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- Started out at CERN
  - 1959 (Lederman, *et al.*), using Synchrocyclotron — 2% result published in 1961, followed by more precise result — 0.4% error — confirming QED calculations at the time
  - 1966, using the CERN Proton Synchrotron (PS)
    - » 25x more accurate, showed inconsistency between experiment and the theory of the day
  - 1969-1979, third iteration of the experiment (still with PS) gave much more accuracy
    - » theory was confirmed to precision of 0.0007%
  - As time went on, theory continued to improve
  - In 1980s, new experiment formed in U.S.
    - » led to BNL g-2 Experiment E821
    - » on toward more precise measurement

CERN g-2 storage ring, 1974

Short History of the *g*-2 Experiment

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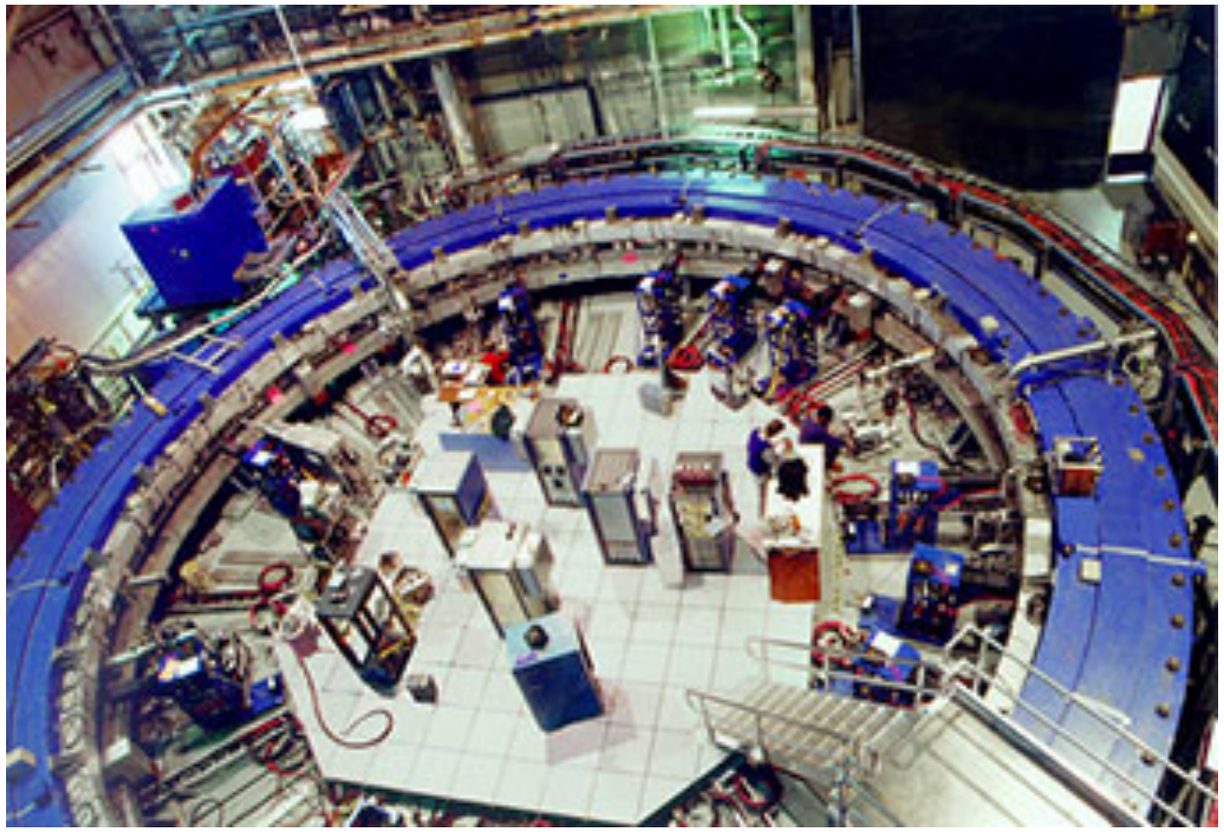
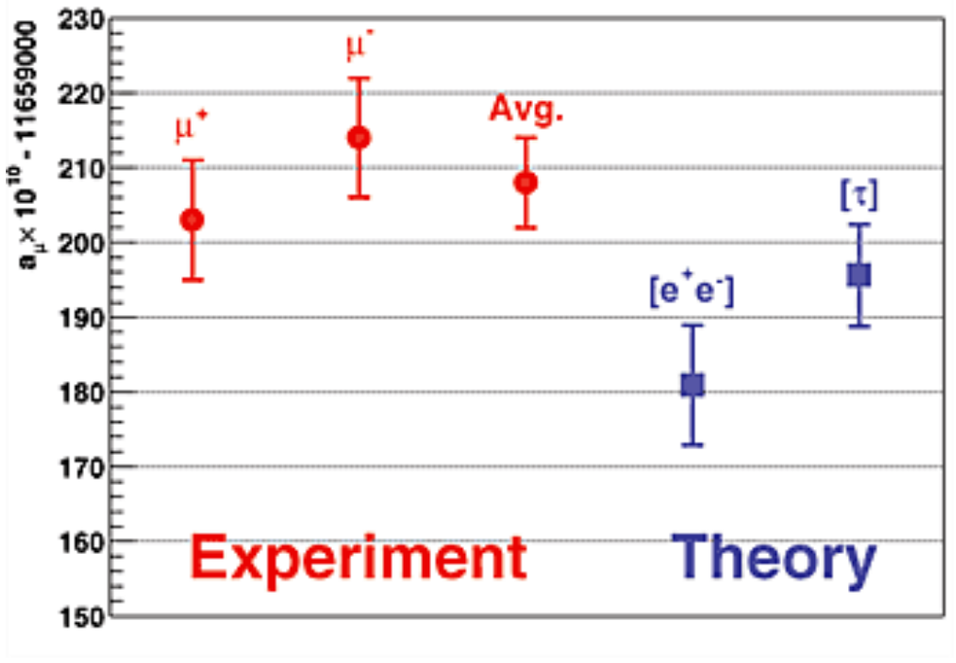
- BNL Experiment E821 began running in 1997, published final result in 2004



a_μ (exp) = 11 659 208 (6) × 10^{-10} (0.5 ppm)



- Since then, theory has improved further
  - Presently: ~3.5σ discrepancy, between E821 and Standard Model calculations

Errors in E821? or Something missing in the Standard Model?

Short History of the *g*-2 Experiment

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- Following the 2004 publication of the E821 result, next steps explored
- BNL beam was no longer supported by HEP — RHIC is NP
- Fermilab was biggest source of high intensity proton beams
- Tevatron was on its way to being shut off in ~2011; g-2 collaborators began discussions with FNAL
- Many options were explored at FNAL — 8 GeV was the energy of choice
  - FNAL Booster was being upgraded to handle higher rep rates; goal was to achieve 15 Hz continuous operation (PIP)
  - Also, the 8 GeV storage rings used for antiproton production and storage *could* become available following Tevatron operations
    - » there was some interest in continuing antiproton operations, but protons won out
  - While other options were considered, decided best option was to perform g-2 with 8 GeV beam from Booster pulses, located somewhere on or near the old antiproton facility
- And then there was also Mu2e…

Fermilab Implementation — E989

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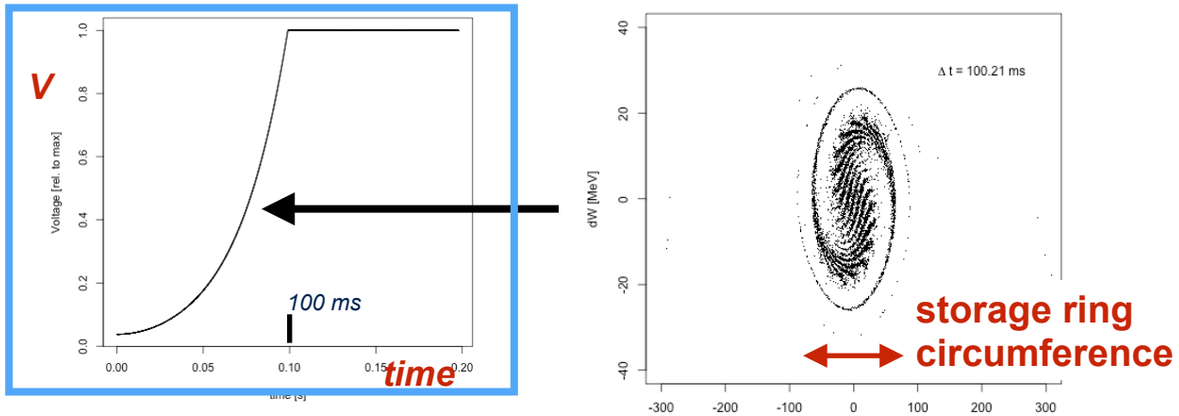
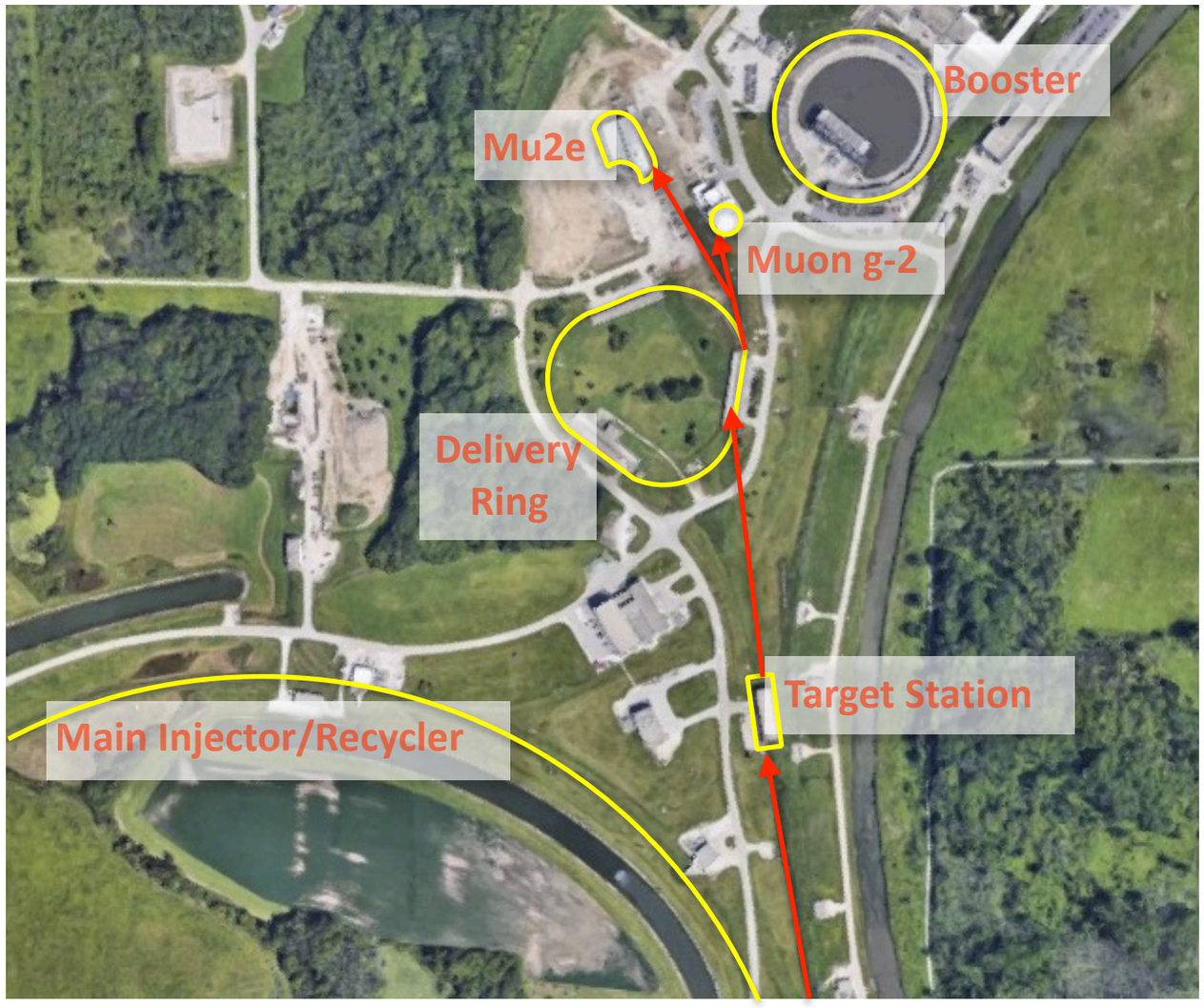
- Fermilab re-purposed its antiproton rings to create the The Muon Campus
- Bunch formation in the Recycler





- System delivers 8 pulses / 1.4 s
- 10^{12} protons on target / pulse
- Roughly 10^{6} muons / pulse to ring
  - ~10^{4} magic muons stored / pulse
- Goal: **20x** the statistics compared to BNL

- *Heavy reliance on modeling of beam production, transport, ring injection and beam storage to reduce systematic errors in the determination of anomalous magnetic moment*

Fermilab Rings for the *Intensity* Frontier

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Fermilab Rings for the *Intensity* Frontier

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kinetic energies indicated here

Rings at the Intensity Frontier

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- Long Baseline Neutrino Facility
  - Main Injector system at Fermilab — will support the DUNE experimental program
  - beam delivery system, targeting and horn
  - Possible future accelerator complex upgrades: PIP-II (linac), PIP-III (ring?)

- **The Muon Campus**
  - two new efforts came on the scene in late 2000's: Mu2e and Muon g-2
  - both are precision measurements/searches, requiring high intensities, muon beams, moderate particle energies
  - Tevatron program was winding down, and the infrastructure for antiproton beams was no longer required for future programs
    - » note: was not clear for a while whether antiproton physics had its own future at the lab
  - decision was made to create a "campus" for the two new experiments, utilizing the tunnel of the antiproton Debuncher and Accumulator rings and associated target station and beam lines
    - » the Accumulator ring was dismantled; the Debuncher ring renamed: **Delivery Ring**

The Muon Campus

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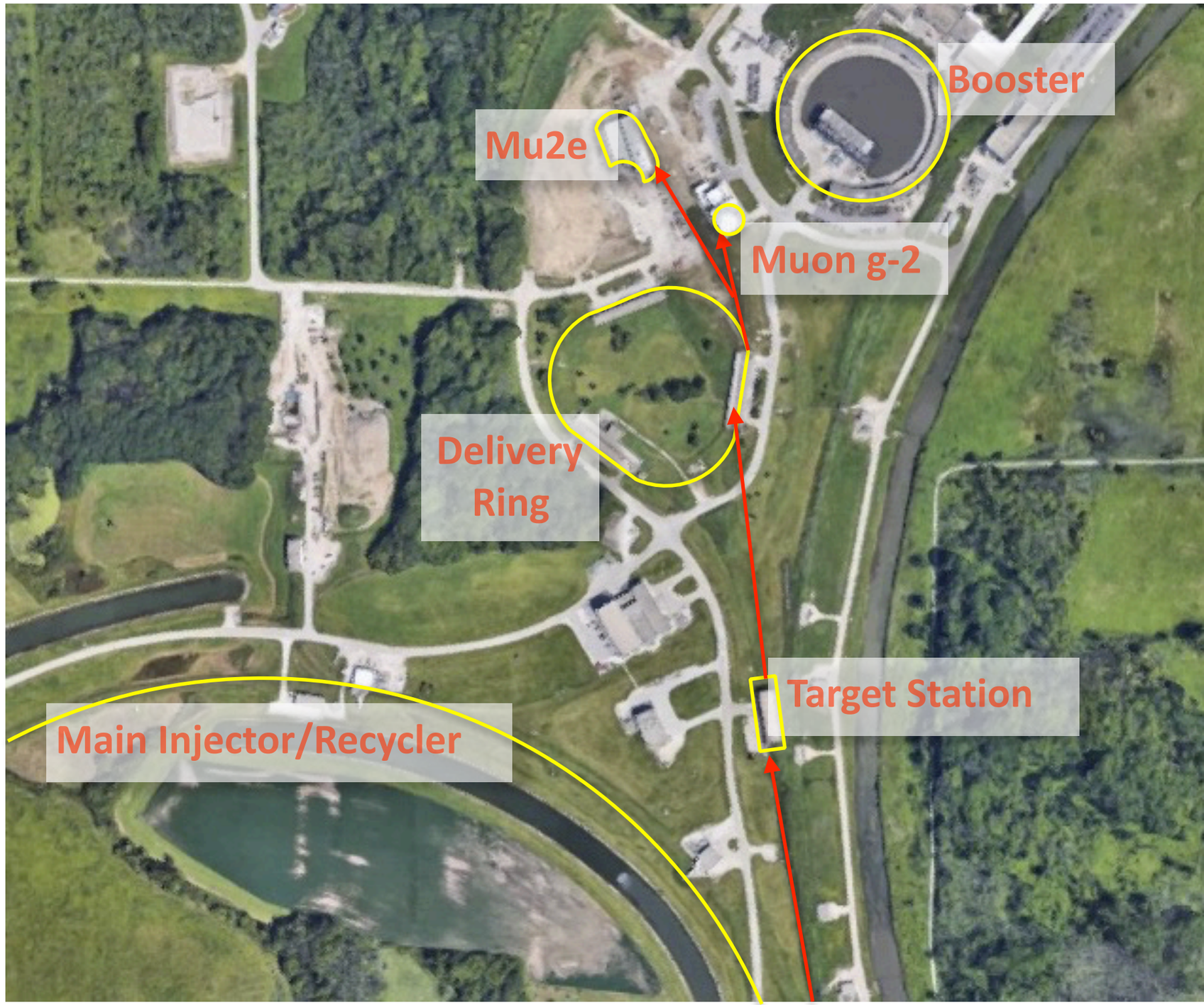
- Delivery Ring has same circumference (slightly larger) than Booster
  - ~500 m
- 8 GeV protons from Booster to Recycler/ Main Injector; manipulate bunches to create time structure appropriate for g-2, Mu2e
- Use (not use) target station for g-2 (Mu2e)
- Fast extract (g-2) or slow spill (Mu2e) particles from DR to experiments



Fermilab E989 — Next Incarnation

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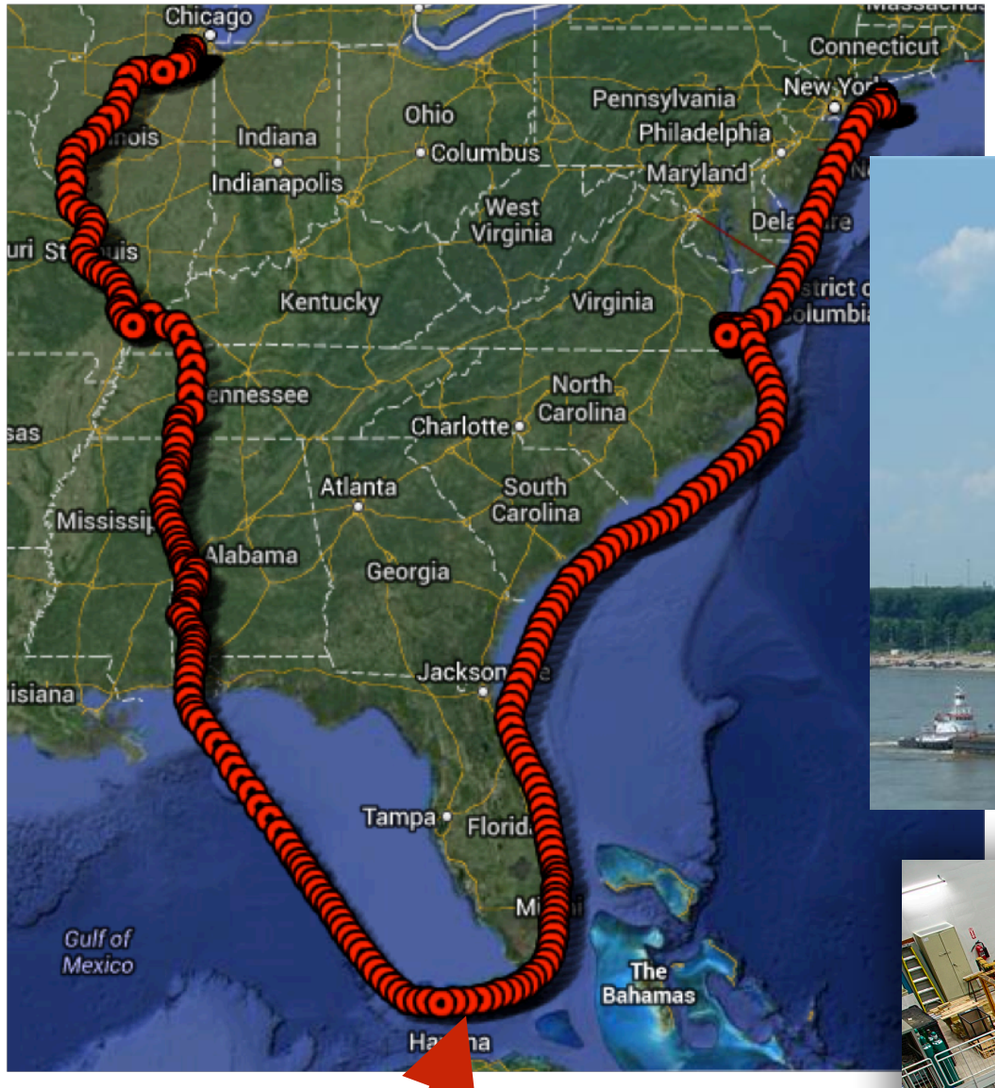
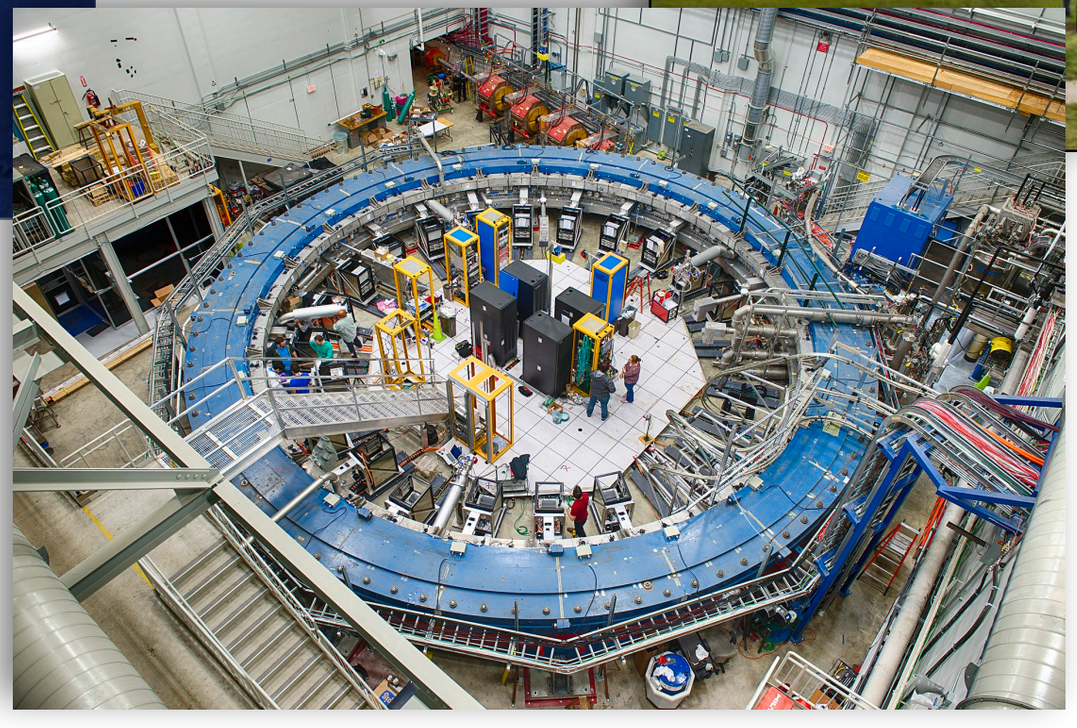


You are Here!

moved magnet to Fermilab in 2013…



Fermilab data taking started in 2017…