Northern Illinois University

An Opportunity at Fermilab — *Muon g-2 at the Muon Campus*

Mike Syphers

Northern Illinois University

Fermilab

Fundamental Particle Spin

Northern Illinois University

- For a spin ½ point particle, classically the expectation is $g = 1$
- Stern-Gerlach and atomic spectroscopy experiments in the 1920s, became apparent **$g_e = 2$** for the electron.
- Dirac's famous equation in 1928

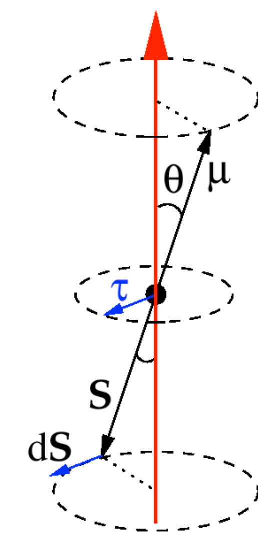
$$\left(\frac{1}{2m}(\vec{P}+e\vec{A})^2+\frac{e}{2m}\vec{\sigma}\cdot\vec{B}-eA^0\right)\psi_A=(E-m)\psi_A$$

So, for an elementary spin ½ particle in Dirac's theory, *g*=2!

- Deviations from the value $g = 2$ for the electron, muon, etc. accounted for by quantum field theory

spin $\vec{S}=\frac{\hbar}{2}\vec{\sigma}$

magnetic moment $\vec{\mu}=g\frac{q}{2m}\vec{S}$



Set $g = 2(1+a)$

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

For the muon, *a* is approximately 0.001166.

The Thomas BMT Equation and the Magic Momentum

Northern Illinois University

- For electromagnetic fields in the lab frame, the precession of the spin vector in the rest frame of the particle is given by the Thomas-BMT eq.*:

$$\frac{d\vec{S}}{dt} = \vec{\omega}_s \times \vec{S} = -\frac{e}{\gamma m}\left[(1+a\gamma)\vec{B}_\perp + (1+a)\vec{B}_\parallel + \left(a\gamma + \frac{\gamma}{\gamma+1}\right)\frac{\vec{E}\times\vec{\beta}}{c}\right]\times\vec{S}$$

- The momentum vector of the particle will precess with

$$\frac{d\vec{p}}{dt} = \vec{\omega}_c \times \vec{p} = -\frac{e}{\gamma m}\left[\vec{B}_\perp + \frac{\gamma^2}{\gamma^2-1}\frac{\vec{E}\times\vec{\beta}}{c}\right]\times\vec{p}$$

* citations:
— Thomas L H 1927 Philos. Mag. 3 1–22
— Bargmann V, Michel L and Telegdi V L, 1959 Phys. Rev. Lett. 2 435–6

- For ideal condition of **purely** perpendicular magnetic field, and with electric fields:

$$\vec{\omega_a} \equiv \vec{\omega_s} - \vec{\omega_c} = -\frac{e}{m}\left[a\vec{B}_0 + (a - \frac{1}{\gamma^2-1})\frac{\vec{E}\times\vec{\beta}}{c}\right]$$

The Thomas BMT Equation and the Magic Momentum

- 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

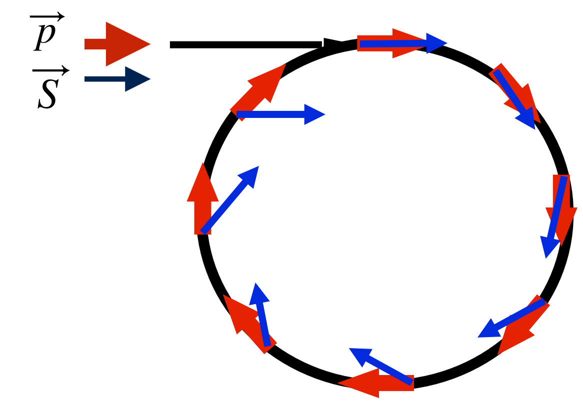
$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B}_0 + \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{E}\times\vec{\beta}}{c}\right]$$

$$p_{magic} = mc/\sqrt{a}$$

~3.094 GeV/c for the muon

- Then, ideally, rates observed at a detector at one location in the ring would contain frequency:

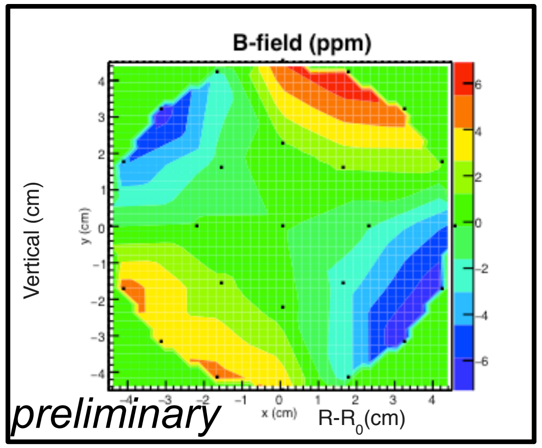
$$\omega_a = \frac{e}{m}\cdot B_0 \cdot a$$



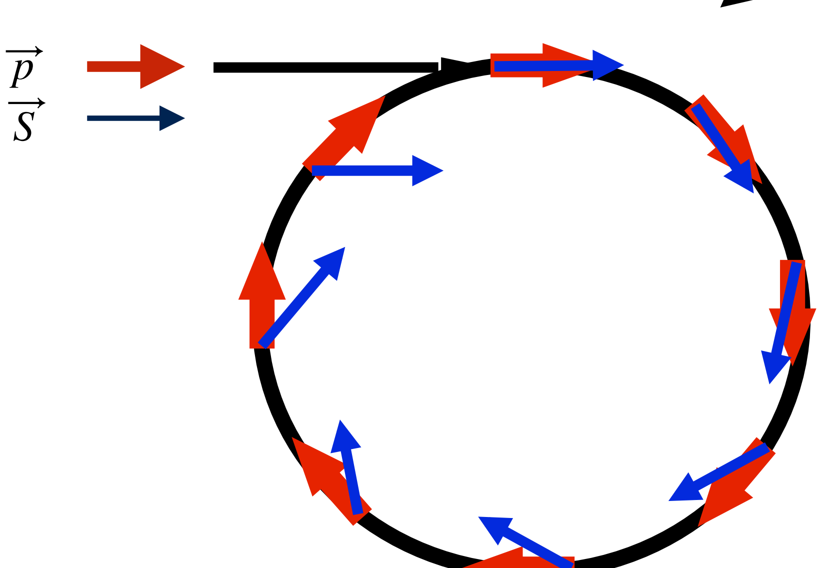
- So, send highly polarized beam of muons at the magic momentum into a highly uniform magnetic field, focused with electrostatic fields
- Detect positrons from muon decays; kinematics show those with highest energies emerge in direction of the muon’s spin

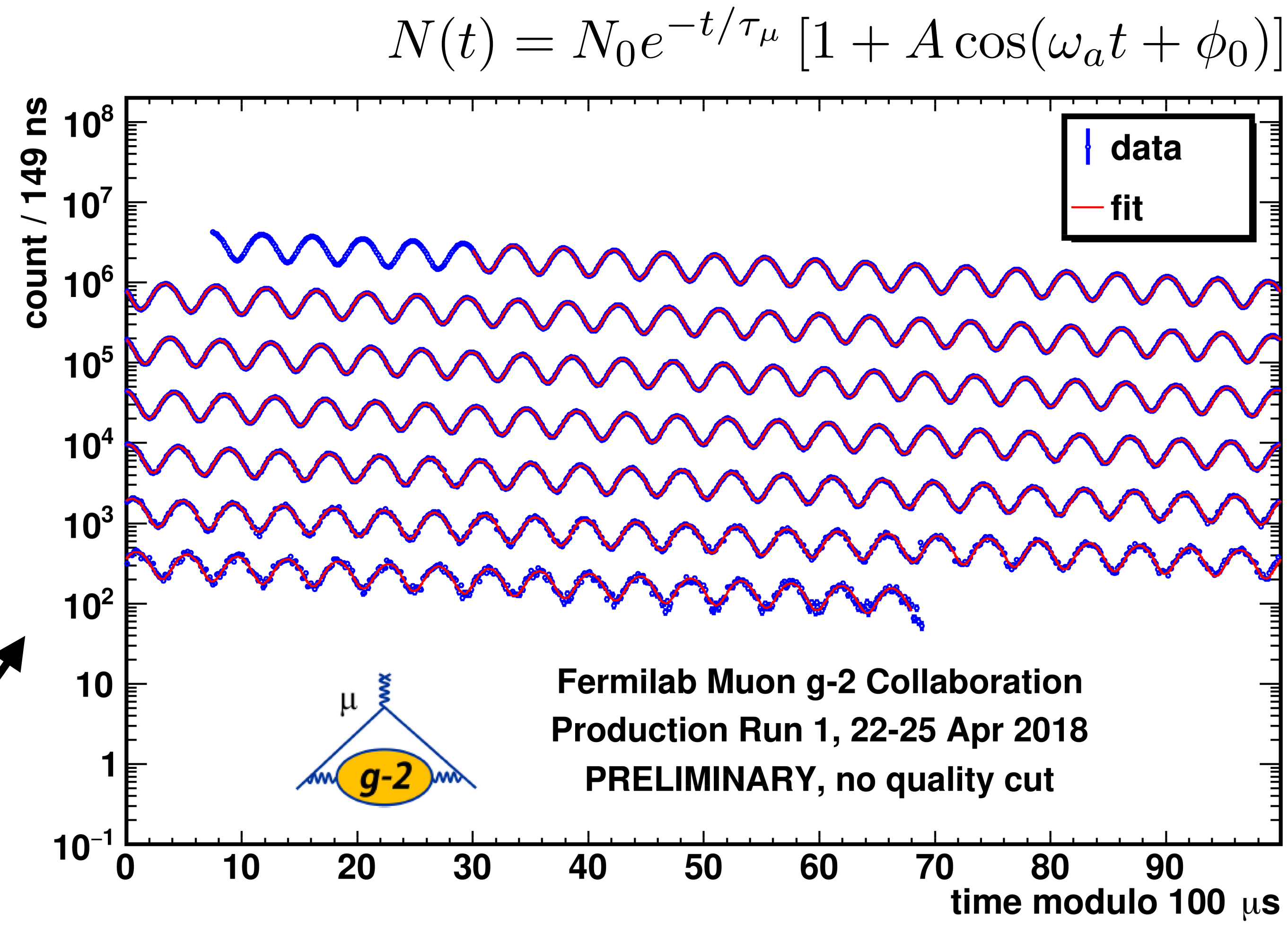
Wiggle Plots

- Fixed detector in the ring would observe the rate of muon decay “wiggle” with a frequency given by $\omega_a = (e/m) \cdot B_0 \cdot a$



highly uniform B



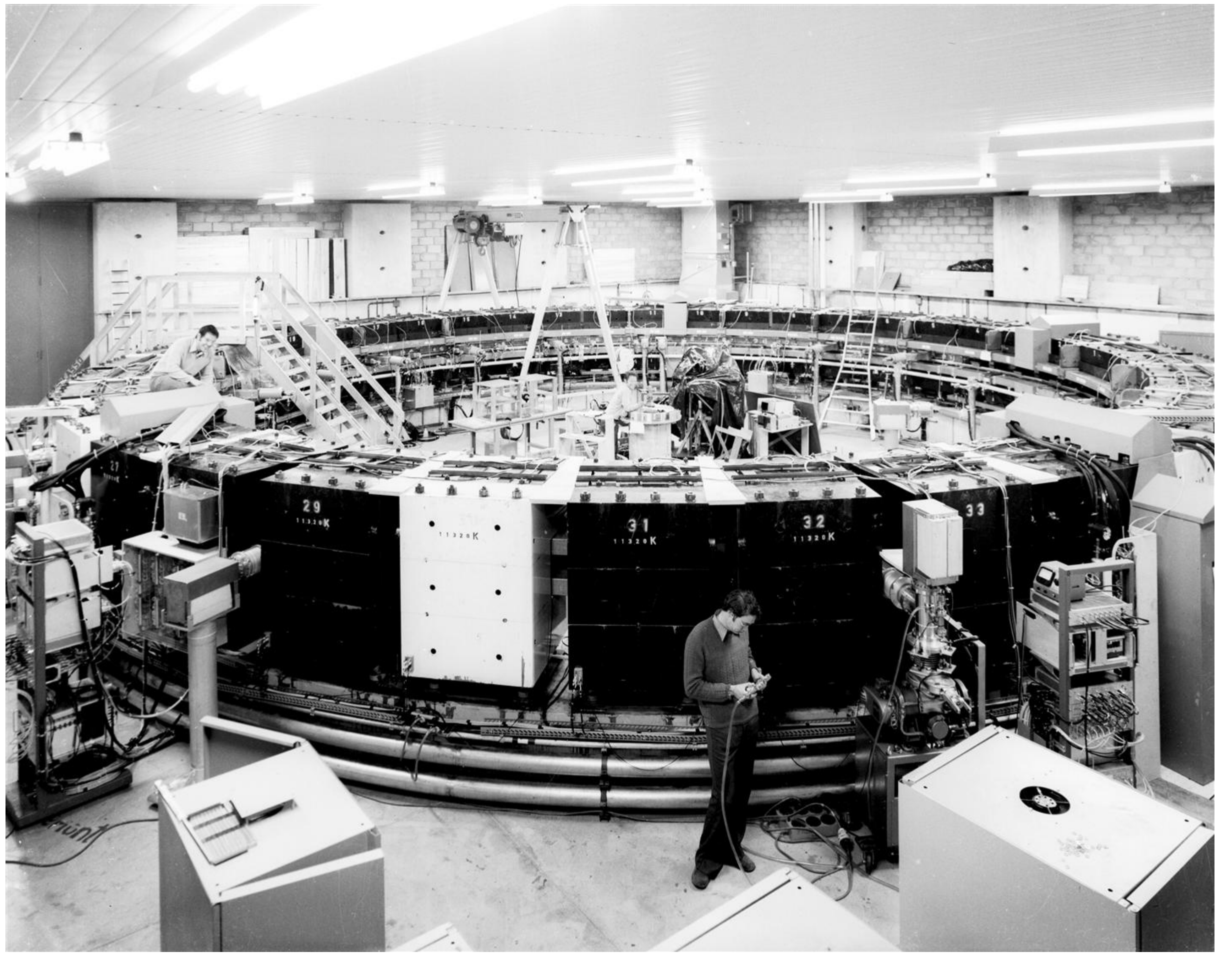


- Fermilab Muon g-2 Experiment uses 24 detector systems around the circumference, measuring positron energies, arrival times, etc.
- repeat the wiggle plot millions of times…

Brief History of Muon *g*-2

Northern Illinois University

- The measurement of $a = (g-2)/2$ for the **muon** 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
  - began running in 1997, final result in 2004
- Since then, theory has improved further
  - » ~3.5σ discrepancy, between E821 and SM



CERN g-2 storage ring, 1974

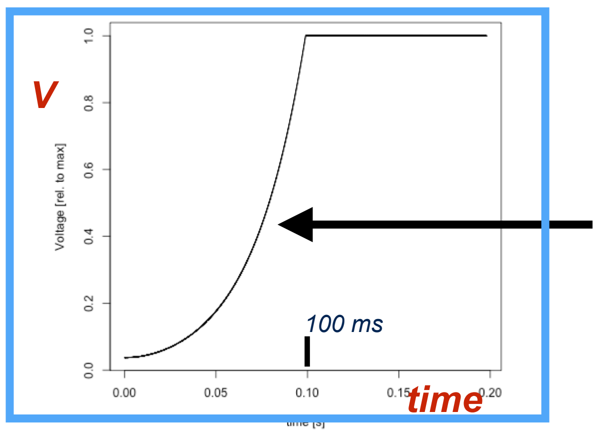
Brief History of Muon *g*-2 [cont'd]

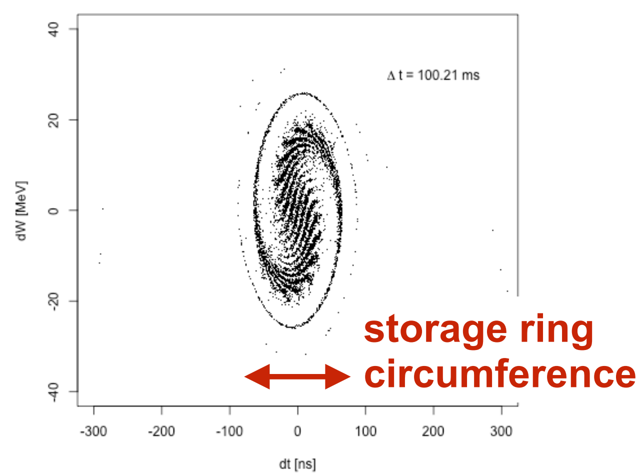
Northern Illinois University

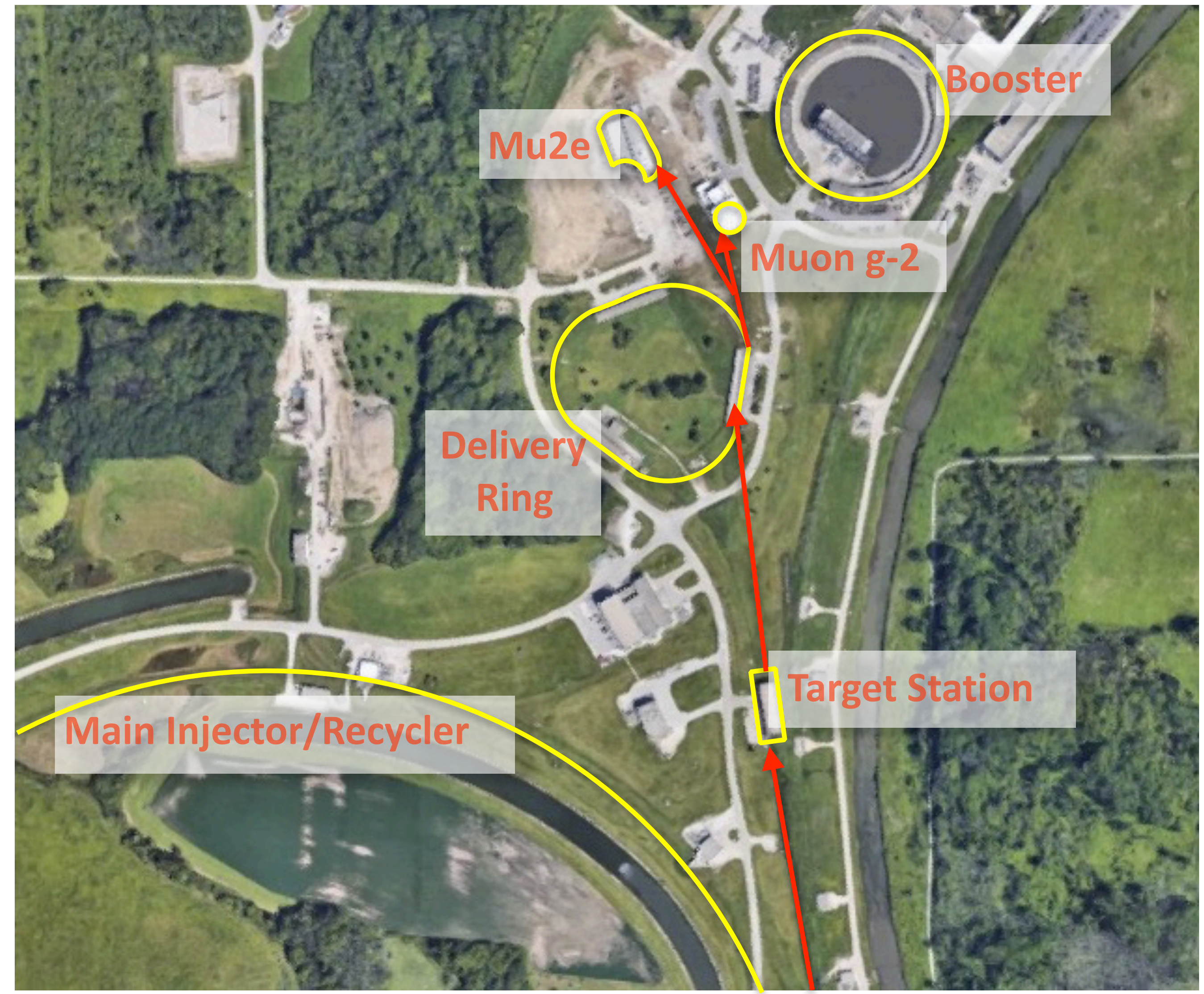
- Following the 2004 publication of the E821 result, next steps explored
- BNL beam was no longer supported by HEP — RHIC is NP
- Fermilab was biggest source of high intensity proton beams
- Tevatron was on its way to being shut off in ~2011; g-2 collaborators began discussions with FNAL
- Many options 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

- 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

Northern Illinois University

Fermilab Rings for the *Intensity* Frontier

Northern Illinois University

kinetic energies indicated here

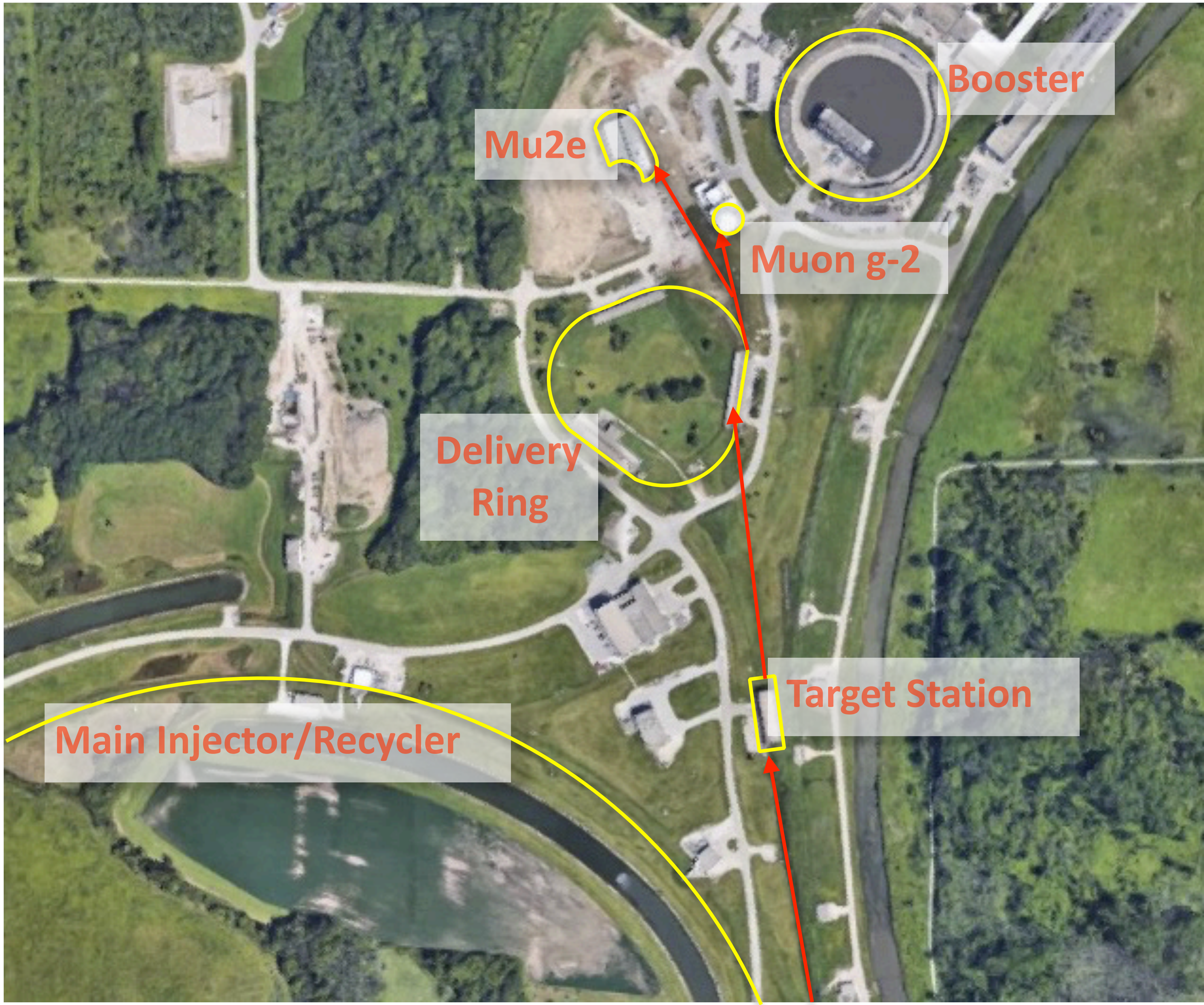
Rings at the Intensity Frontier

- 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**

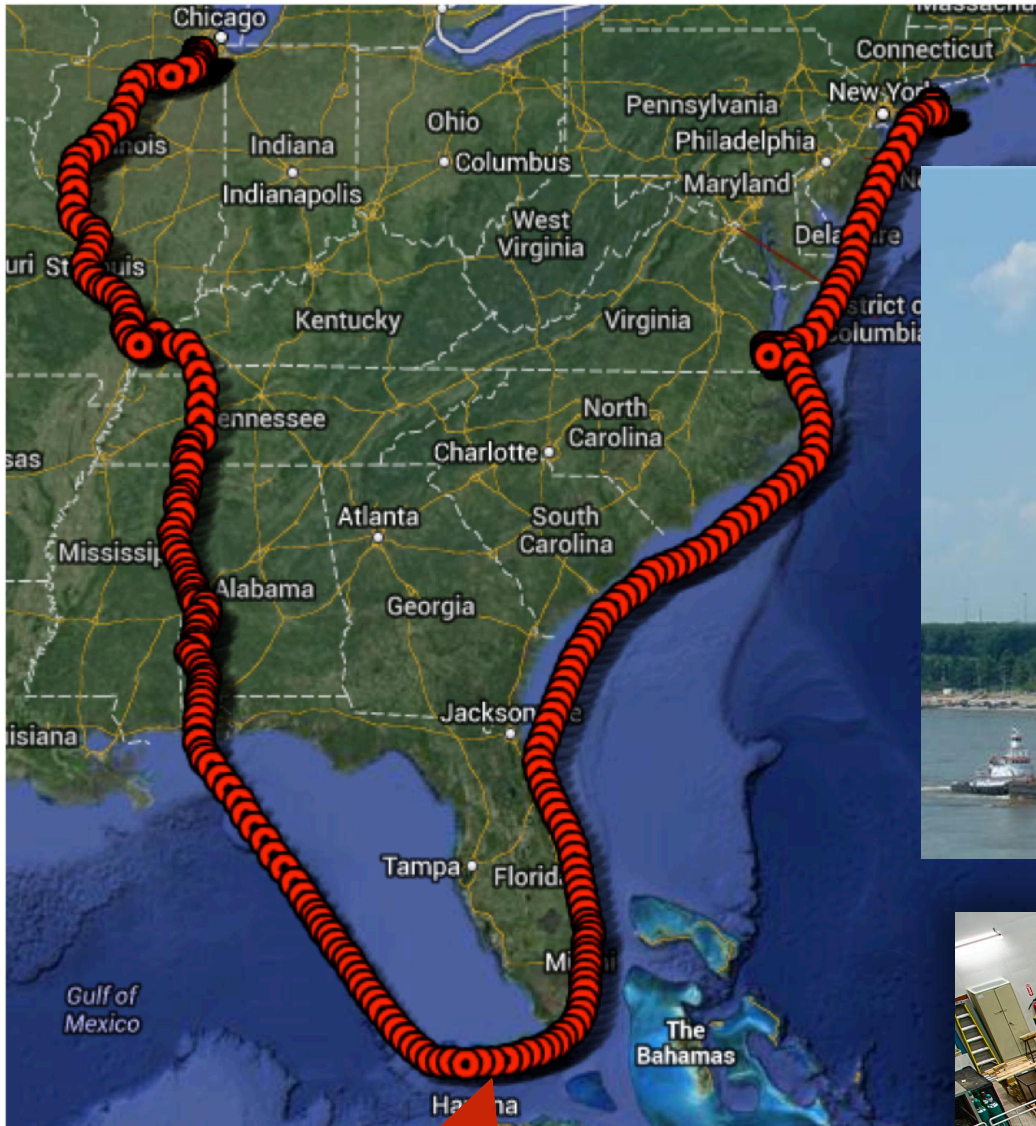
The Muon Campus

- 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



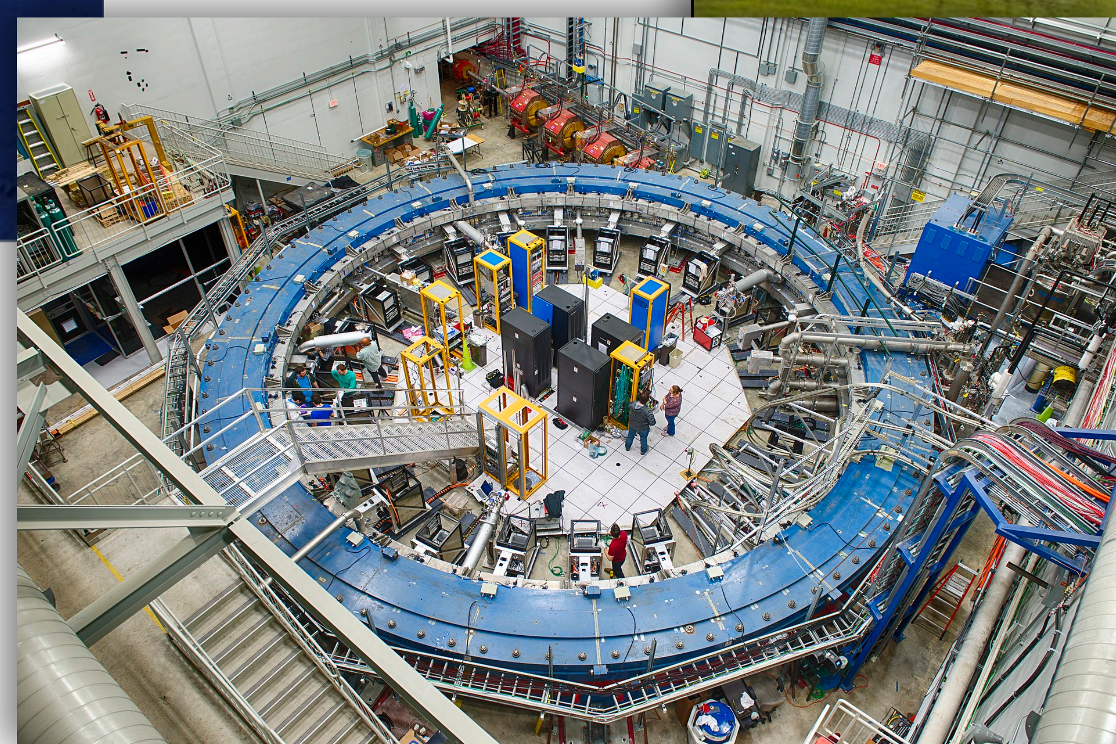
Fermilab E989 — Next Incarnation

Northern Illinois University



Key West, FL

moved magnet to Fermilab in 2013…

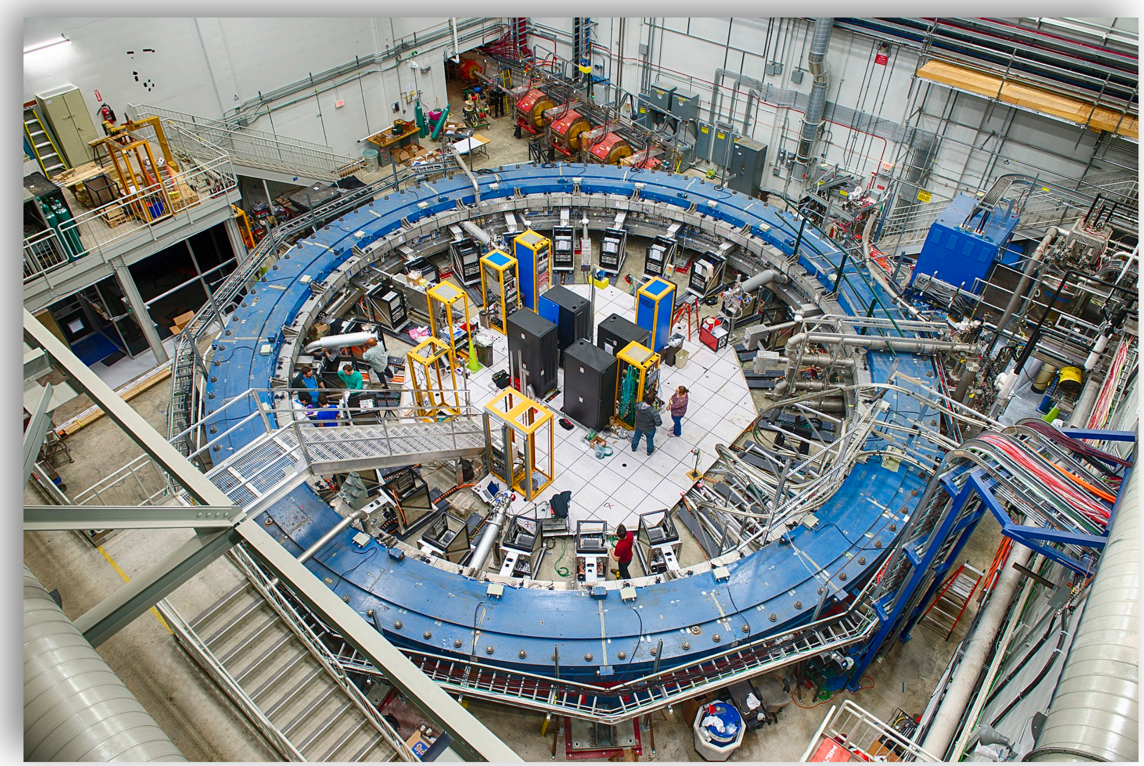


Fermilab data taking started in 2017…

The Muon *g*-2 Storage Ring

Northern Illinois University

- The storage ring is a precision-field high energy physics experiment with 24 detector stations in order to detect and identify charged particles and their time of arrival, momenta
- However, no **direct** beam measurements, *per se* — i.e., no BPMs or wire scanners or current monitors, etc.
  - all information about the beam is inferred from the detector data
- From reconstructed data, the equilibrium horizontal (momentum) distribution, vertical beam distribution and other quantities can be inferred for each injection/store.
  - these important quantities are necessary for reducing systematic errors in the final analyses of the anomalous spin frequency
- Unique opportunity for beam physics to help guide the understanding of signals and processing of data

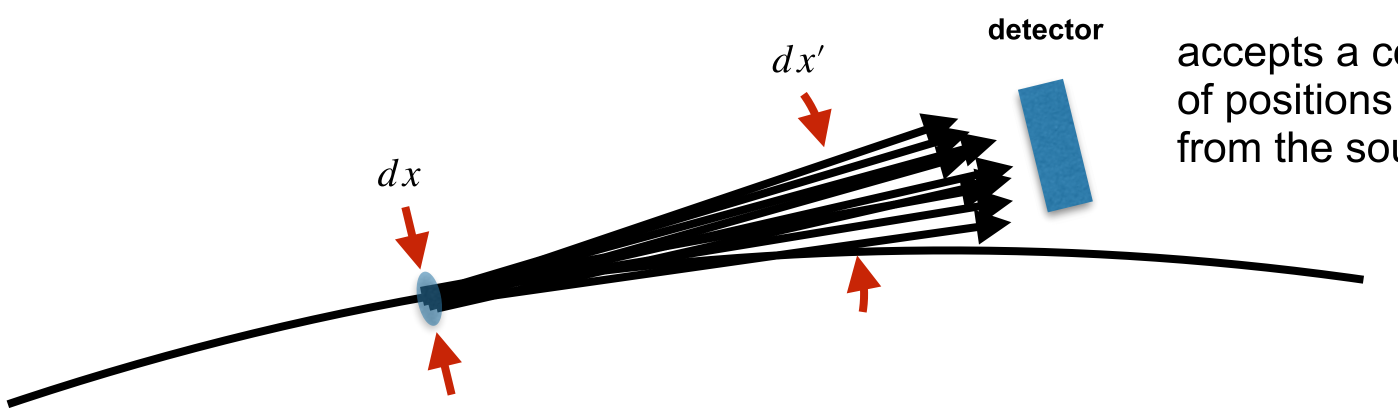


E989, Fermilab

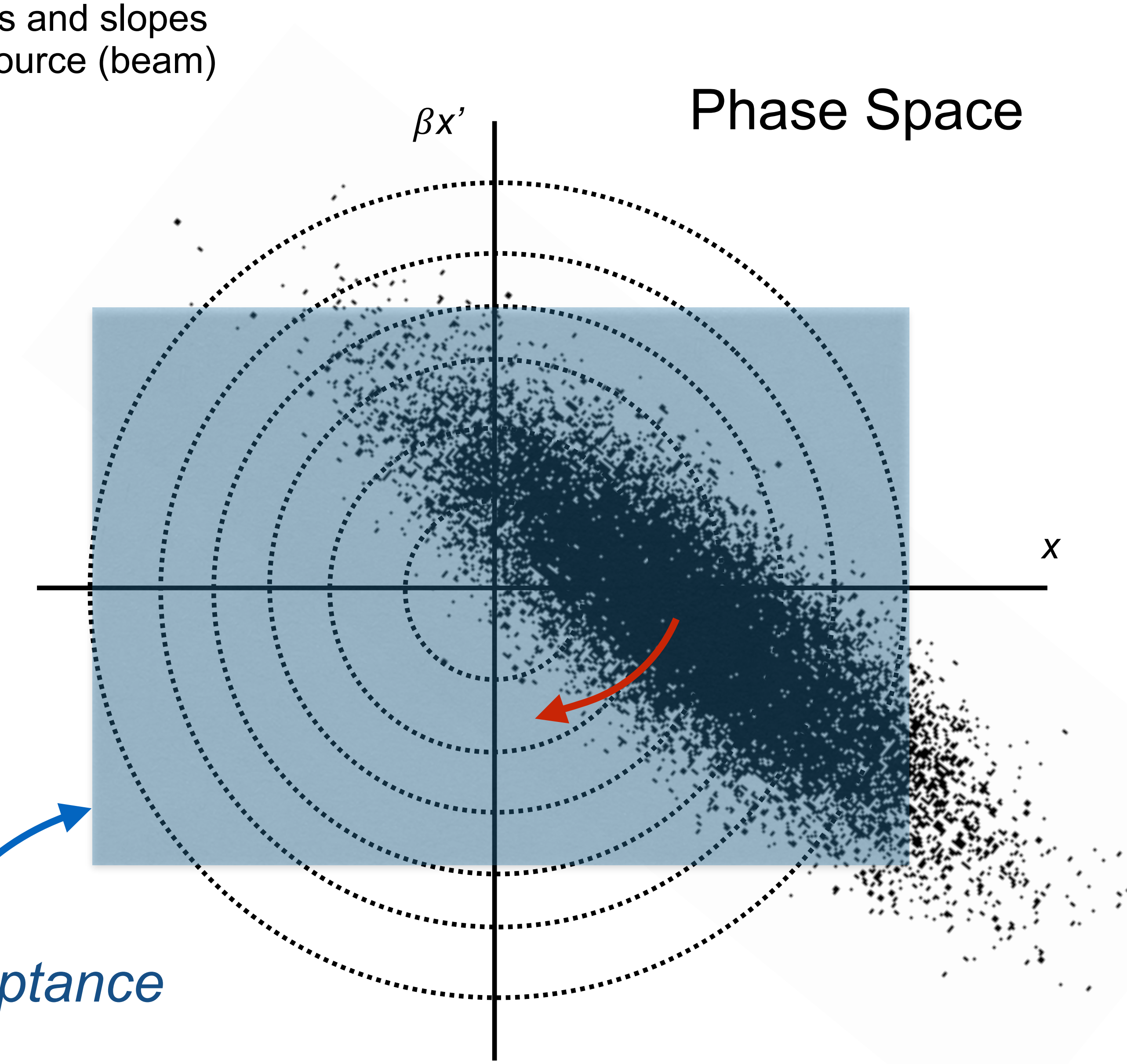
Phase Space and Acceptance

Northern Illinois University

- Detectors have a certain acceptance that is mapped onto the beam phase space; hence, due to beam dynamics, many other frequencies come into play in the particle rates other than ω_a :



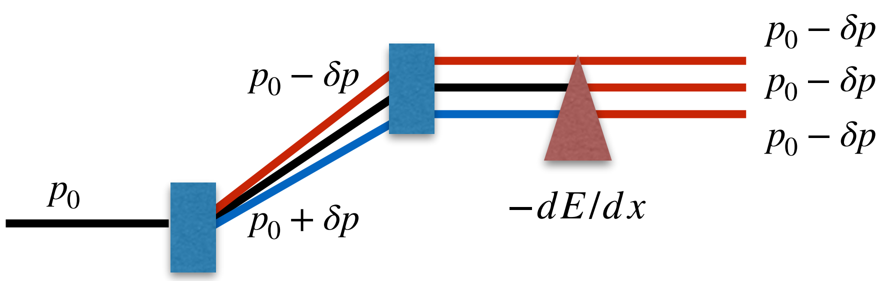
- coherent betatron oscillation tunes
- twice those, due to quad mismatches
- tune spread from chromaticity
  - » decoherence and detuning
    - i.e., apparent frequency shifts
- *etc.*



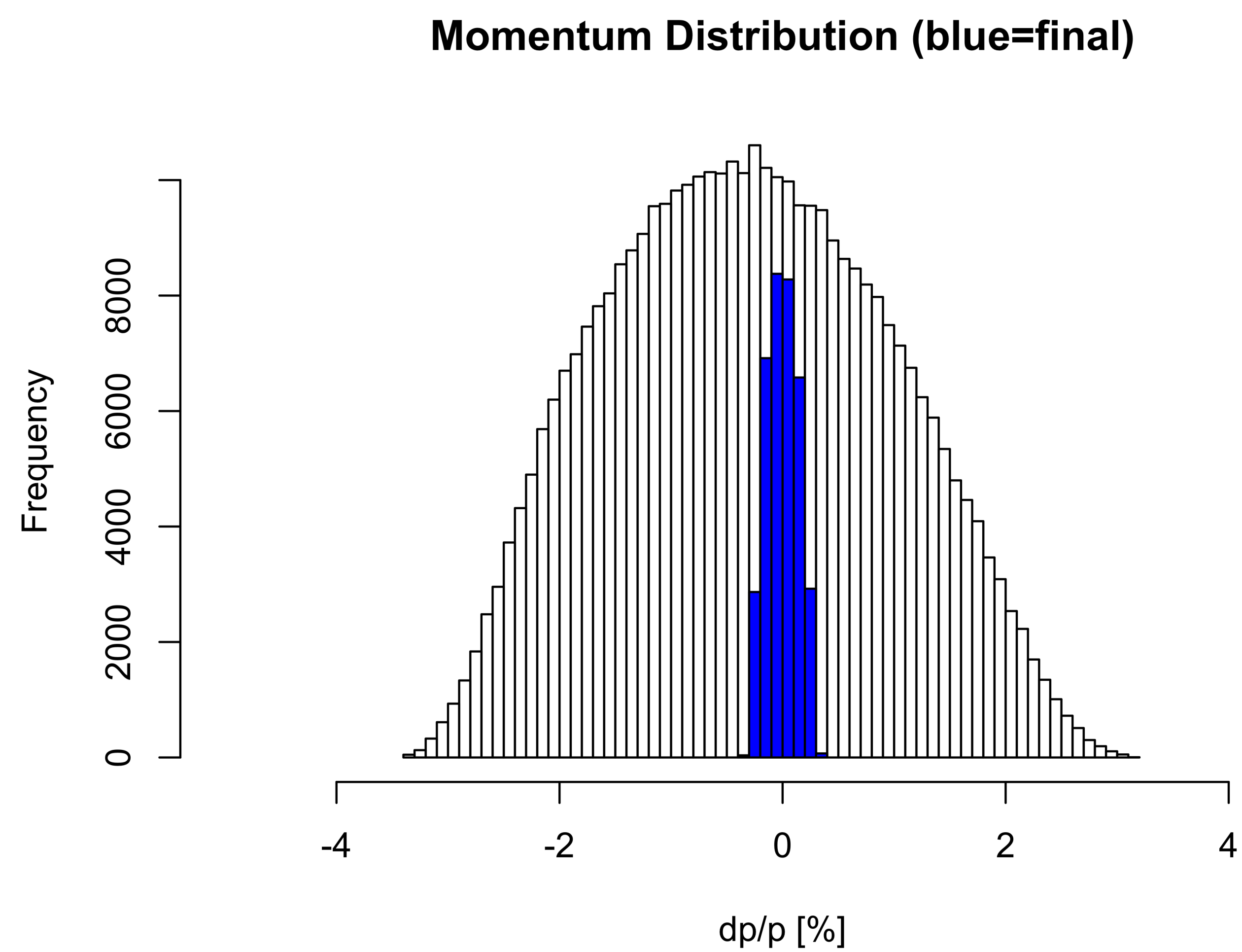
Outlook

Northern Illinois University

- This important HEP measurement not only relies upon high flux to the apparatus, but also ***heavily*** on particle beam dynamics, including spin dynamics
  - important contribution to high-profile experiment
- Have generated ~2x BNL data set
  - looking for factor of 20 or more
  - Approx. 1-2 years more to run
- How to improve the muon flux?
  - Momentum Cooling using *wedges*



  - System in place for current run



- ***Continue running***!

Fermilab LDRD Funding, *Stratakis, Syphers*