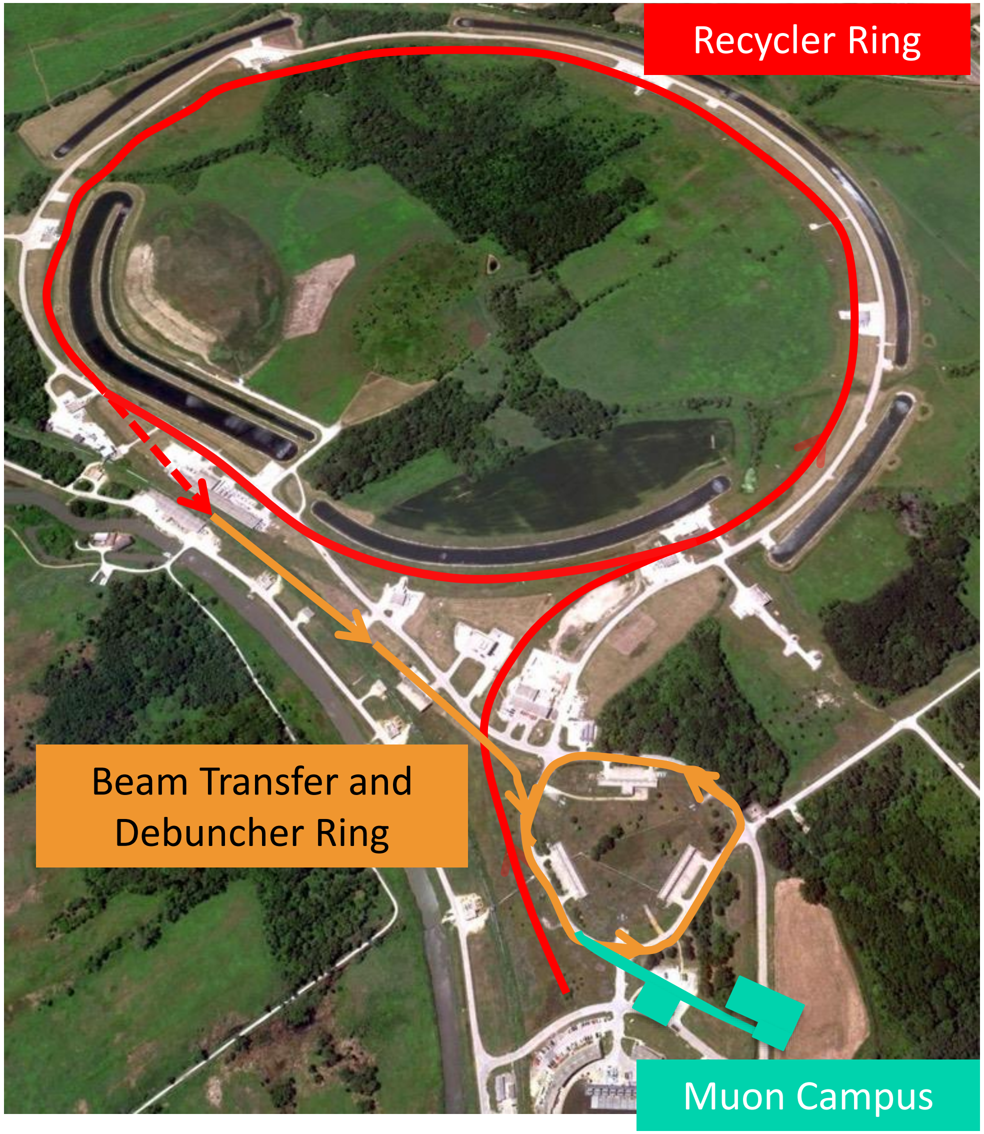
Overview of the Muon g-2 Experiment at Fermilab

Summer Student Lecture
August 18, 2019

Chris Polly

The Fermilab Muon Program



- Starting in 2009, several groups started looking at what could be done at Fermilab after the impending shut down of the Tevatron
- Suddenly, several $100M worth of equipment and accelerators available for first time in decades
- In particular, the facility use for generating the anti-matter proton (pbar) beam could be used to make other particles, e.g. muons
- In 2011, the Tevatron saw its last collisions, but the stage was set for the construction of a new muon program
- Muon Campus to house 2 new experiments
  - Mu2e
  - Muon g-2

Muon Campus vision, circa 2013

Muon g-2

- New facility at Fermilab
  - Two new experimental halls and the tunnel infrastructure to connect to the complex
  - Capability of produce and deliver high intensity customized muon beams

Muon Campus vision, circa 2013

Muon g-2

Why muons?

Muons can be extremely good probes of the Standard Model

- Can be produced copiously

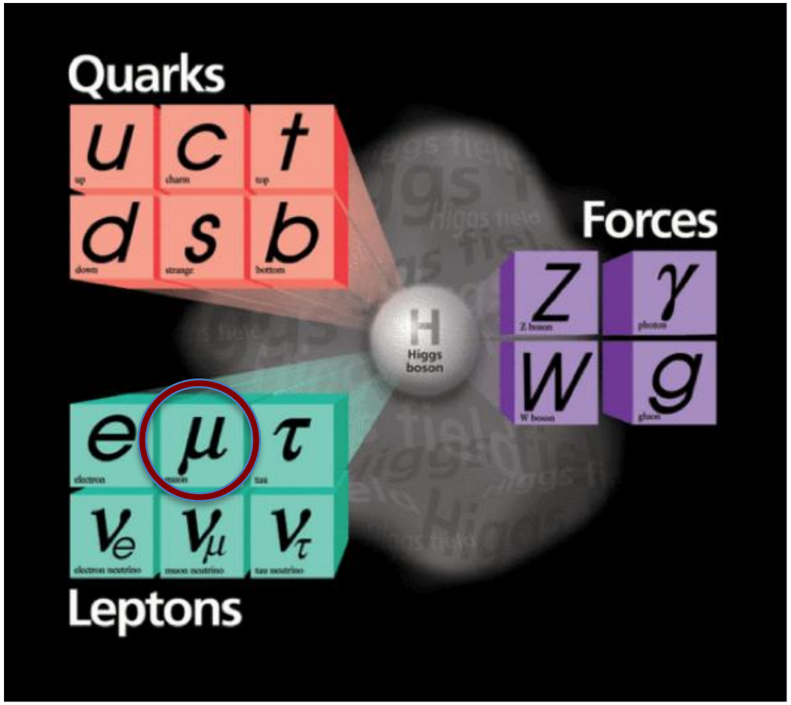
  $BR(\pi^\pm \to \mu^\pm \nu) = 99.9877\%$

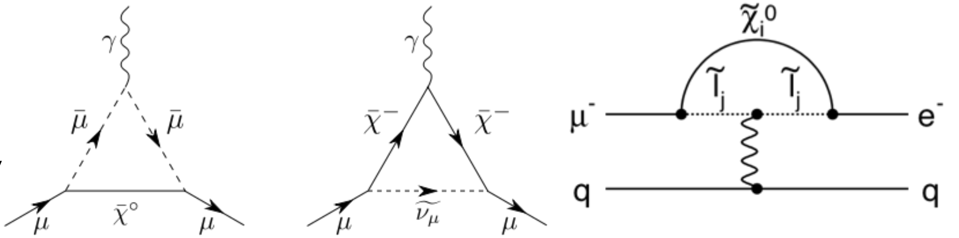
- Don't get ensnared by the strong force
- Relatively long life time 2.2 μs
- Relatively heavy $(m_\mu/m_e)^2 = 40000$

Developing a program at Fermilab based on using muons as tools

- Muon g-2 experiment (data 2017)
- Mu2e experiment (data 2020)
- Future possibilities for other muon-based experiments, e.g. muon EDM, other CLFV channels

The Standard Model





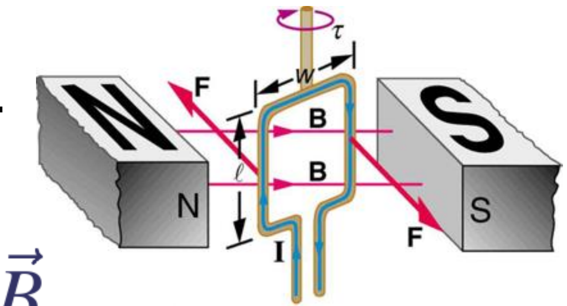
Windows into new physics…

Magnetic moments

Magnetic moments…classical

- Magnetic moments have been an invaluable tool for probing basic physics for a very long time!
- For a system of classical charged particles…

$$\vec{\mu} = \sum_i \frac{q_i}{2m_i c}\vec{L}_i$$

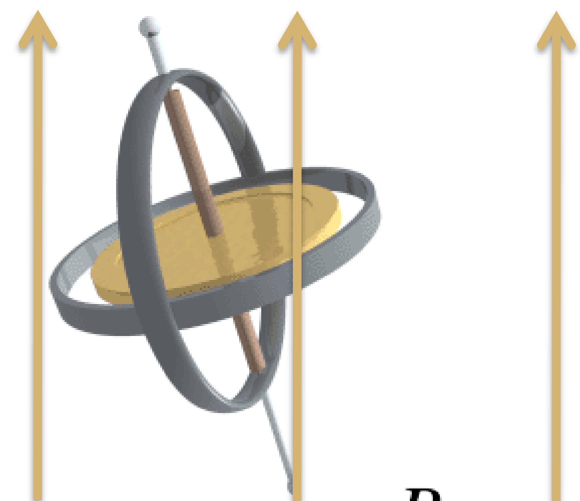


$$\vec{\tau} = \vec{\mu} \times \vec{B}, \;\; U = -\vec{\mu}\cdot\vec{B}$$

- For particles with spin

$$\vec{\mu} = g\frac{q\hbar}{4mc}\vec{\sigma} \qquad \vec{S} = \frac{\hbar}{2}\vec{\sigma}$$

- The Landé g factor is a proportionality constant describing the strength of the magnetic moment and how rapidly a particle will Larmor precess



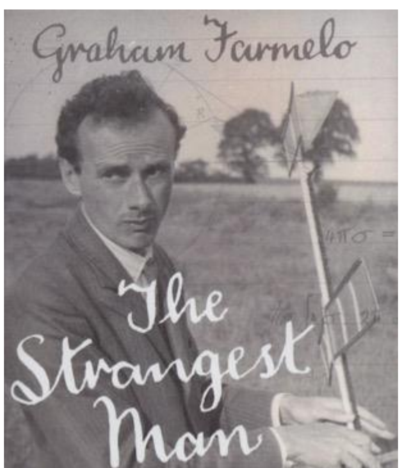
$$\omega_s = g\frac{eB}{2mc}$$

Magnetic moments…classical to quantum

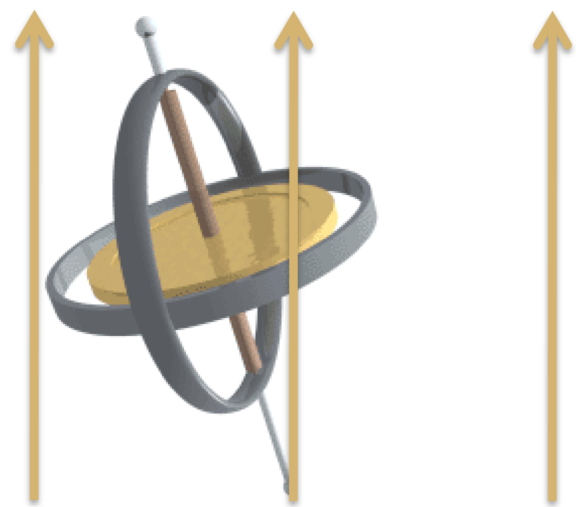
Muon g-2

- For a spin ½ point particle, classically the expectation is g = 1
- With Stern-Gerlach and atomic spectroscopy experiments in the 1920s, it became apparent that $g_e = 2$.
- An electron (or muon) precesses twice as fast
- Solution to the g problem appeared in 1926 with a relativistic treatment by Thomas
- Incorporated in Dirac's famous equation by 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!



$$\omega_s = g\,\frac{eB}{2mc}$$

Moments testing BSM for a century

- The success of Dirac's theory got people excited about making a measurement of the g-factor for the proton
- Stern and Estermann set out to make the measurement in 1933

"Don't you know the Dirac theory? It is obvious that g_p=2.", Pauli to Stern

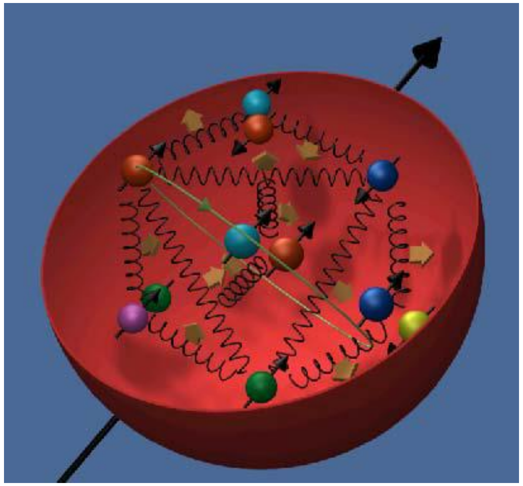
$g_p \approx 5.6$

The first 'anomalous' magnetic moment!

- Same year, Rabi inferred g_n = -3.8 from measurements on the deuteron

How does a neutral particle develop a magnetic moment?

30 more years to develop quark model



Can see how powerful magnetic moments are for exploring new physics!

Proof that nature abhors a vacuum

- At least for the electron, things were in good shape with Dirac's new theory until 1948 when gains in precision revealed another 'anomaly'
- Kusch and Foley employed atomic spectroscopy to precisely measure g_e

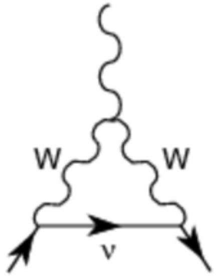
Thus the anomalous magnetic moment was discovered, fractionally g differs from 2 by (g-2)/2 = 0.1%

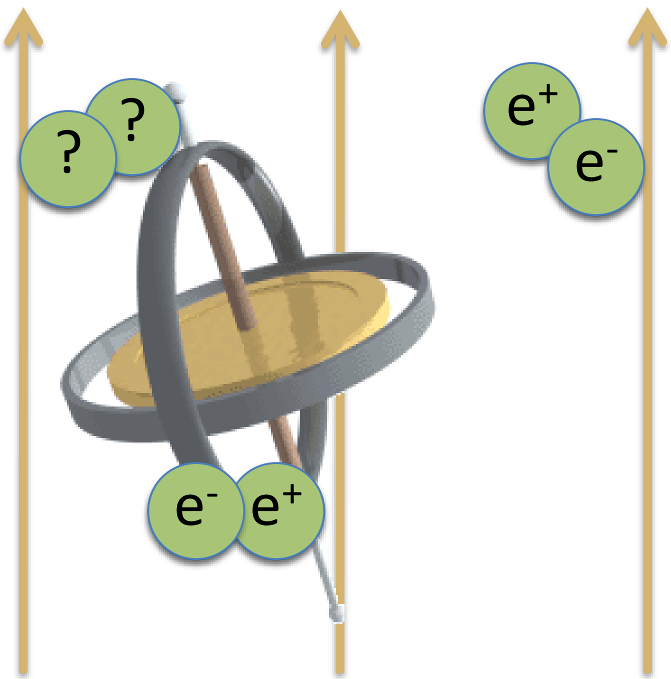
$g_e = 2.00238(6)$

Enter the world of phantom particles

- In reality, particles are never really alone…virtual particles continually fluctuate in and out of the vacuum
- In fact, the more massive the particle, the more mass it has to lend and the probability for friends appearing unexpectedly is enhanced
- These virtual particles effectively screen the magnetic field and alter the bare muon's interaction, changing the g factor
- The extent to which g differs fractionally from 2 is what we call the anomalous magnetic moment

$$a_\mu = \frac{g-2}{2}$$

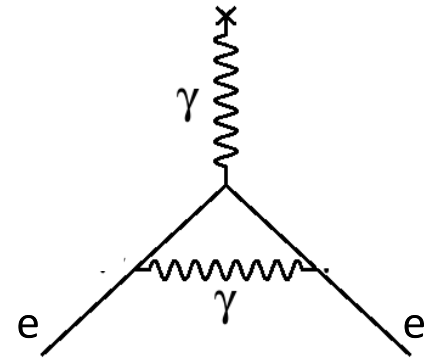




QED discovered

- Schwinger takes one look at the anomaly in the g-factor and immediately knows what's up

$g_e = 2.00238(6)$



Schwinger term describing 1st order electron self-interaction

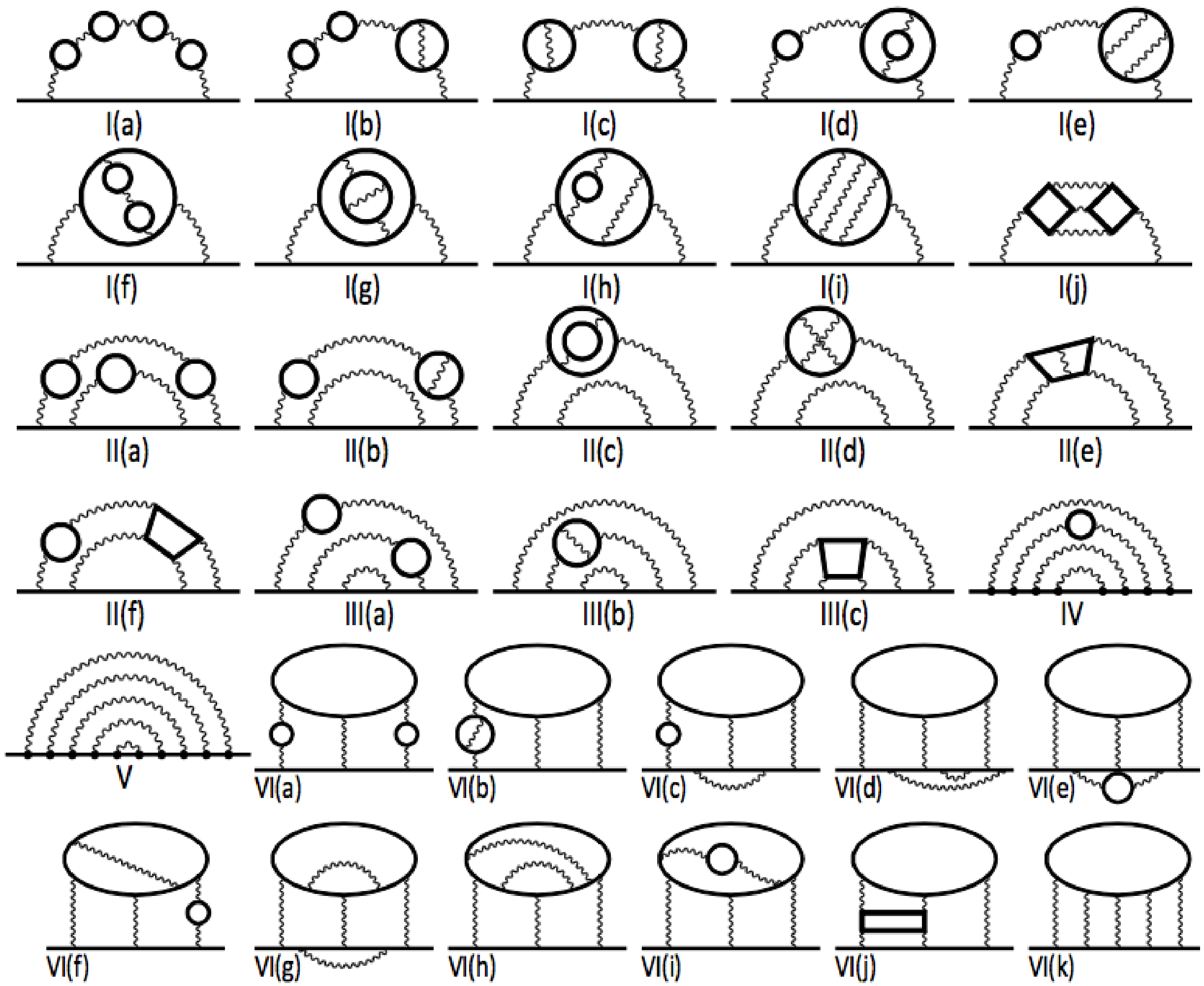
$$g_e \approx 2\left(1 + \frac{\alpha}{2\pi}\right) \approx 2.00232$$

Calculation agrees well with experiment, and that is how we build confidence in new physics models!

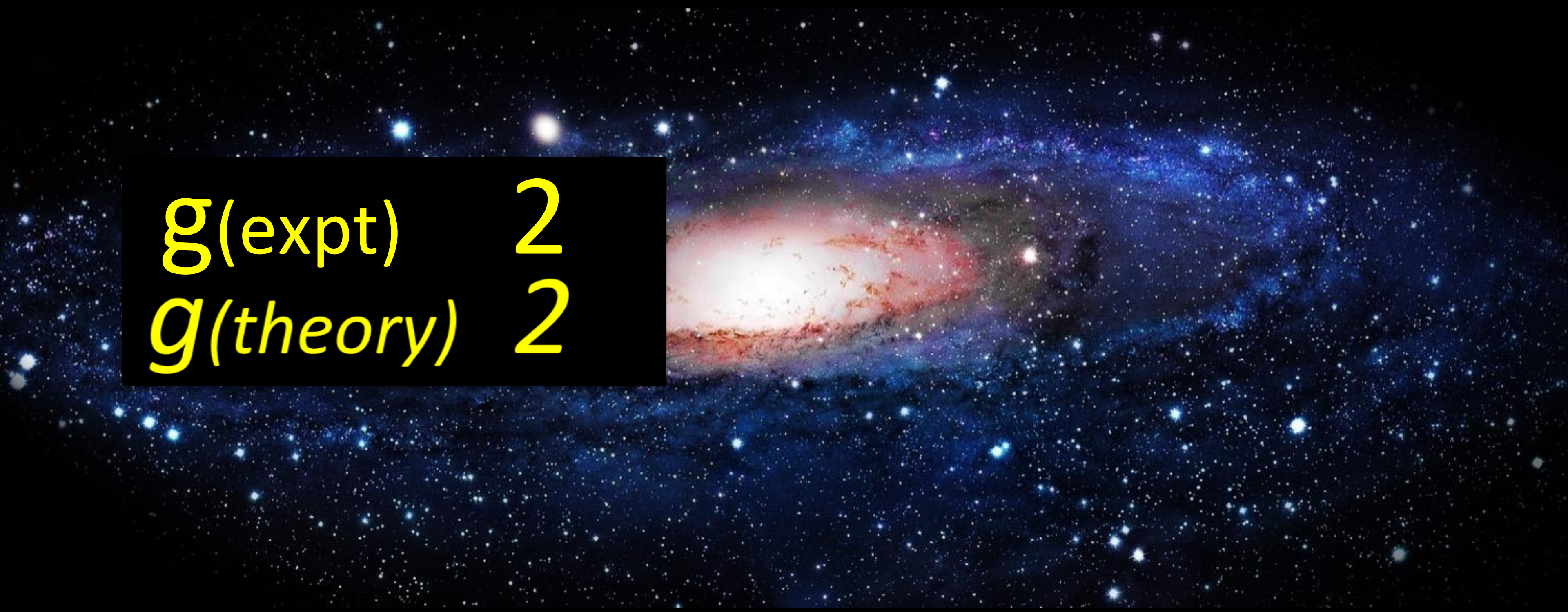
QED calculation now out to 5 loops

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

10th
12672
diagrams



To fairly high precision (unlike the proton and neutron) the g-factor of the electron is consistent with the QED expectation

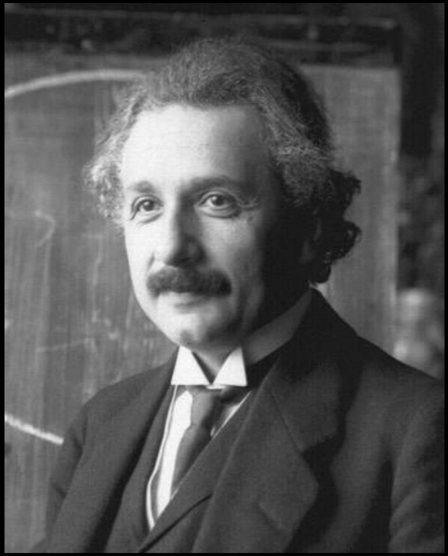


g(expt) 2

g(theory) 2

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

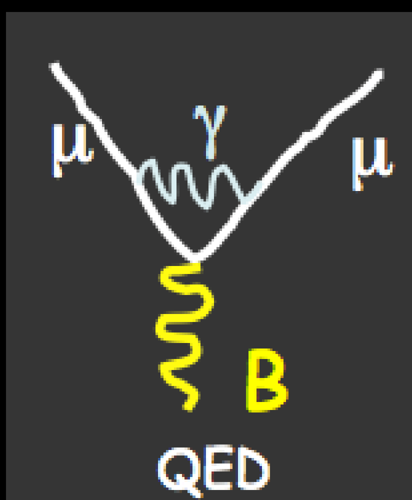
Quantum mechanics meets relativity -> anti-matter




g(expt) 2.00
g(theory) 2.00

g(expt) 2.002331

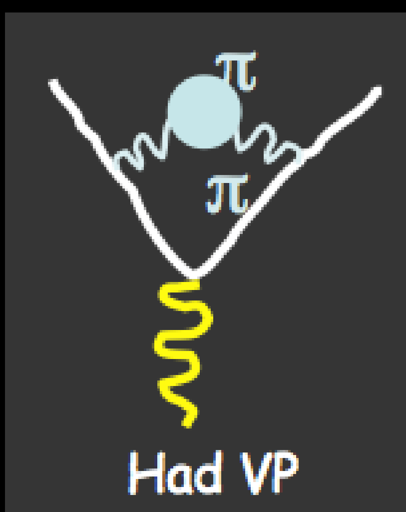
g(theory) 2.002331



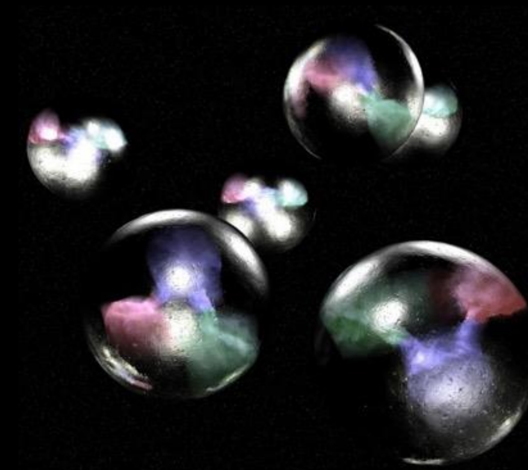
Quantum Electrodynamics -> Electricity & Magnetism

g(expt) 2.00233184

g(theory) 2.00233183

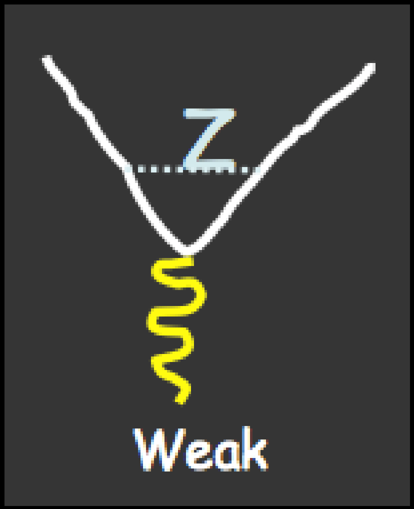


Quantum Chromodynamics -> Strong force that binds nuclei

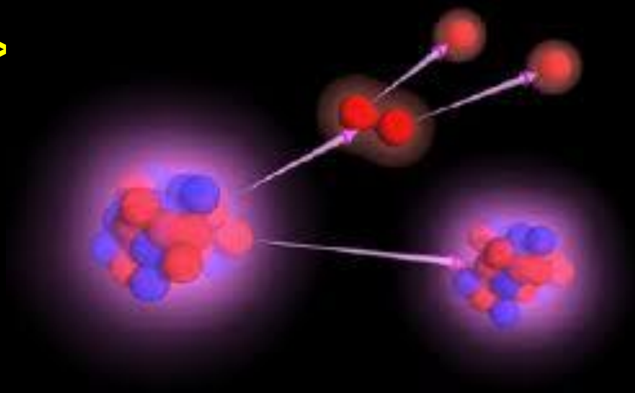


g(expt) 2.002331841

g(theory) 2.002331836

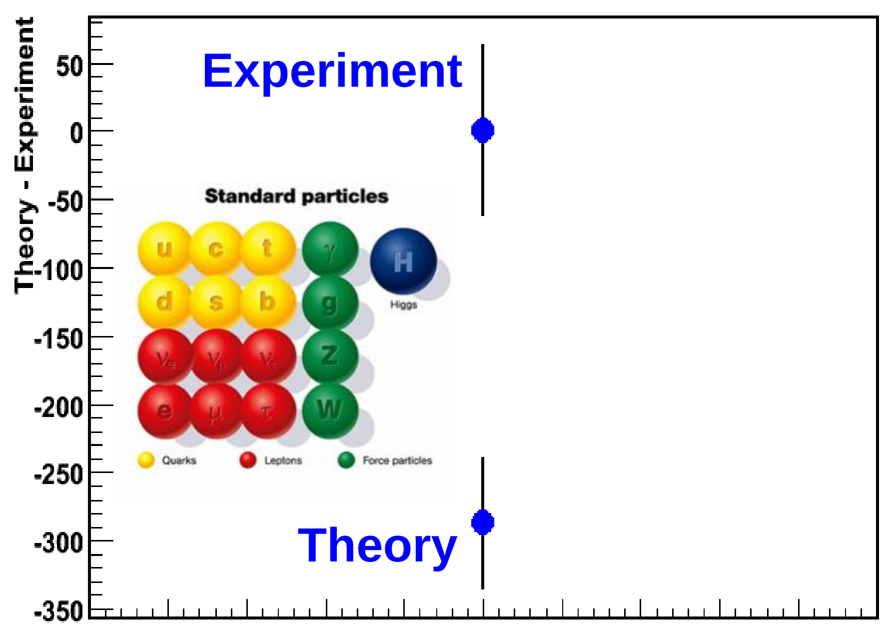


Electroweak Theory->
Weak force that
makes nuclei (and
muons) unstable



g(expt) 2.00233184178

g(theory) *2.00233183630*



Recap...the physics of muon g-2

- Special relativity
- Quantum mechanics
- Electricity and magnetism (QED)
- Strong force (QCD)
- Weak force (EW theory)
- Supersymmetry?
- Dark Matter?

Not bad for a single number!

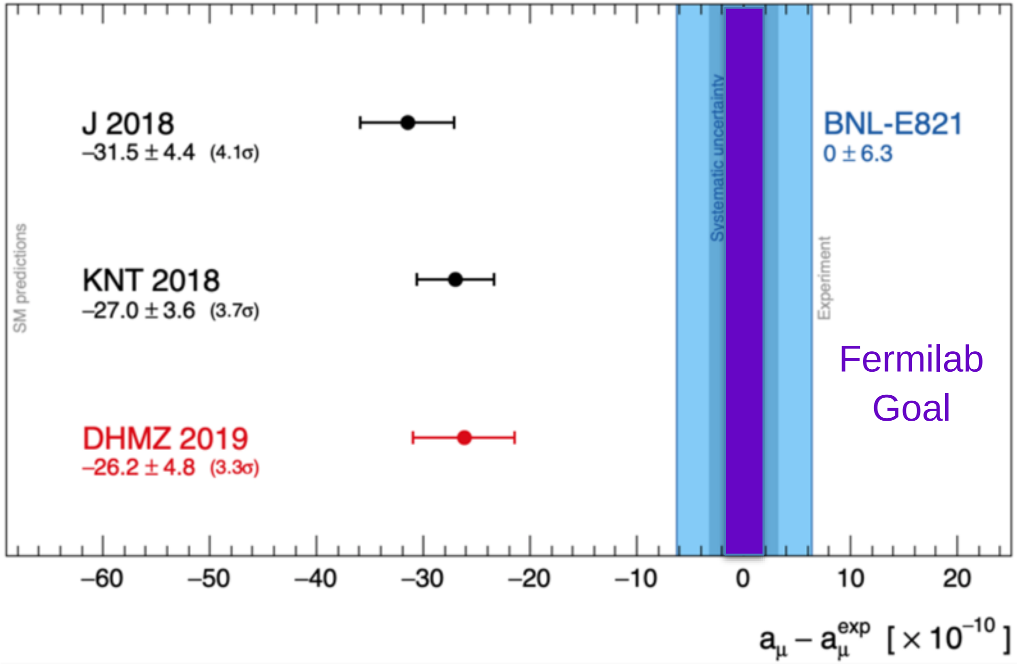
Goal at FNAL: Repeat with 20x muons

Theory vs Experiment Status

Current theory/experiment confrontation

- Last time Muon g-2 was measured was in 1999-2001 at Brookhaven National Lab
- Results showed an intriguing >3σ difference with the theory calculation
- For 20 years people have wondered if this was a hint of new particles or forces at play

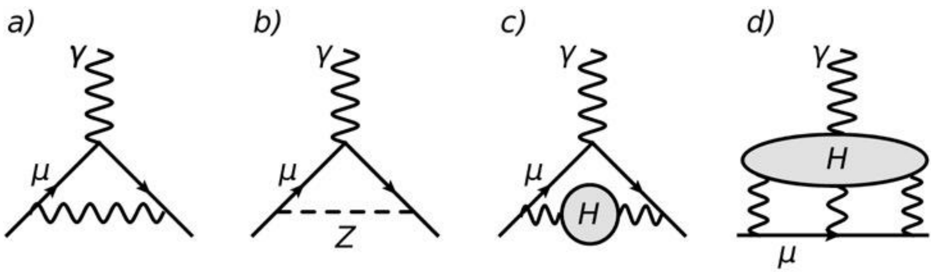
Z. Zhang – EPS 2019



Goal is to repeat experiment with 20x more muons (200B) generated at Fermilab...reduce experimental error by a factor of 4

If discrepancy is really due to new physics then final result would be 5-7σ signficant

Theoretical status of a_μ

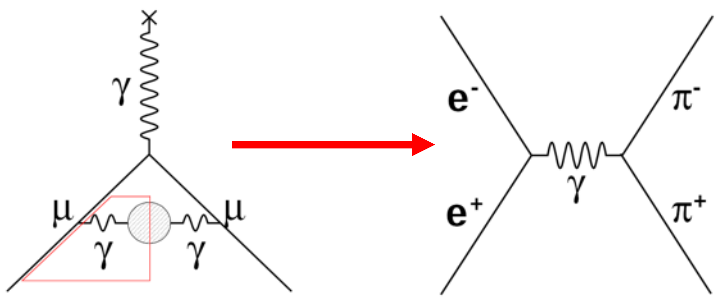


Source	Value (a_μ x 10^{-11})	Error
a) QED	116 584 718.95	0.08
b) EW	154	1
c) HVP	6850.6	43
d) HLBL	105	26

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 $5\text{x}10^{-11}$ to a_μ
  - Known Higgs mass reduces error on EW from 2 to $1\text{x}10^{-11}$
- Error dominated by hadronic terms
  - HVP can be determined from e^+e^- → hadrons data
  - HLBL smaller overall error, but calculation model-dependent



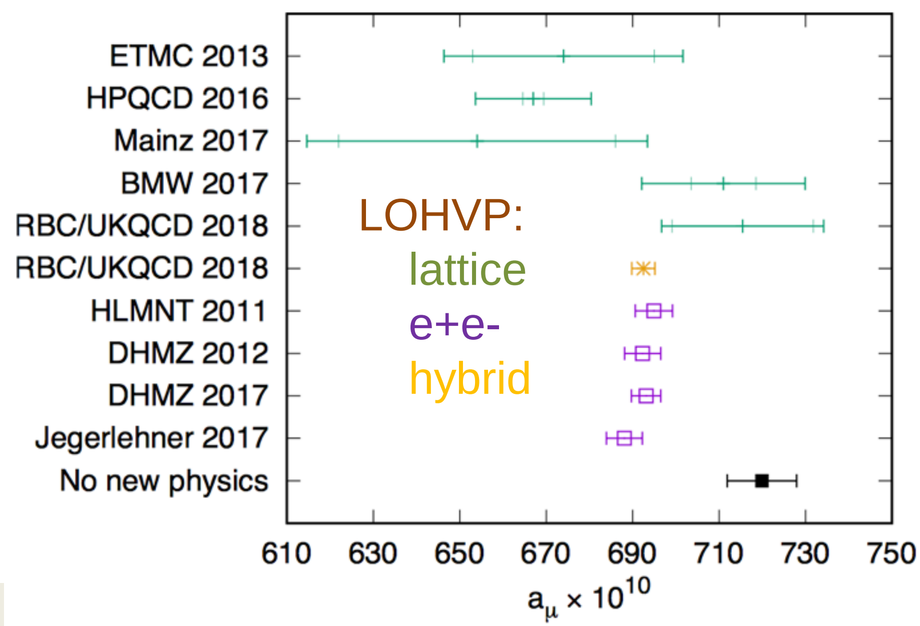
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

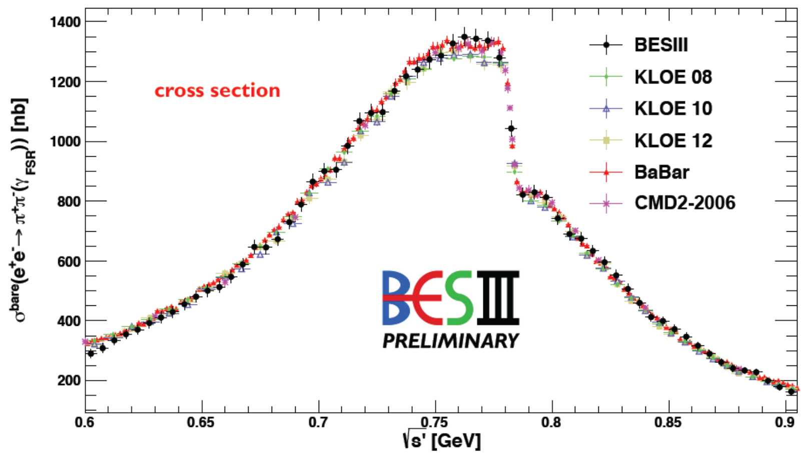
$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Theoretical status of a_μ

https://arxiv.org/pdf/1801.07224.pdf

- 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



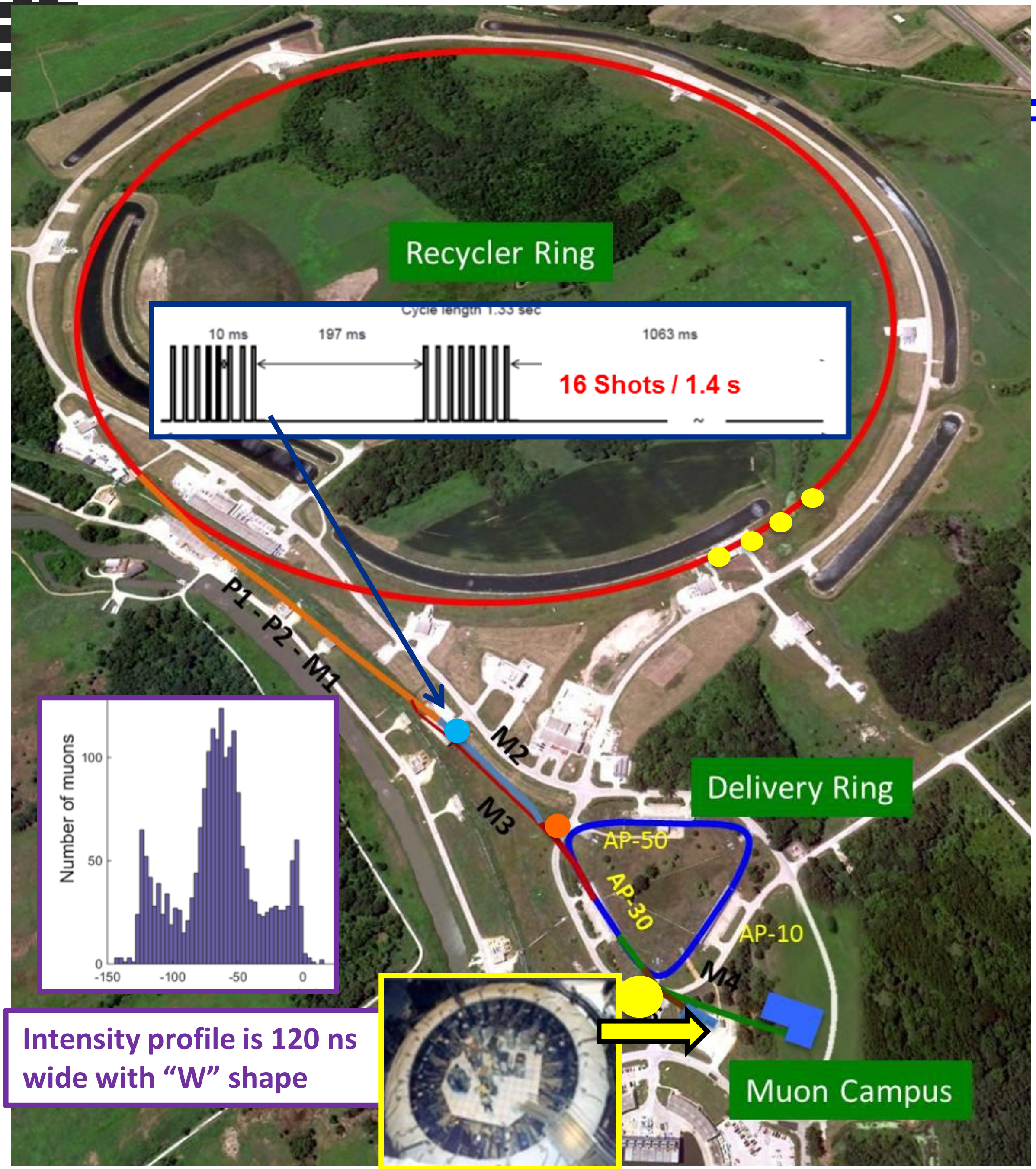


- For hadronic light-by-light
  - From lattice (arXiv 1907.00864)
    - $a_\mu(\text{HLBL}) = (7.4 \pm 6.3) \times 10^{-10}$
  - Analytic
    - $a_\mu(\text{HLBL}) = (10.5 \pm 2.6) \times 10^{-10}$
  - T. Blum "It appears that this contribution can not "rescue" the Standard Model (or the E821 experiment)"

Muon g-2 Theory Initiative Working Group preparing summary to be released ahead of experimental results.

Muon g-2

Principles of Muon g-2 Expt



Muon g-2

Beam delivery

Deliver two 4 ×10^{12} 8-GeV proton batches to the Main Injector Recycler (graphic shows one)

Batches are split into four bunches

One bunch extracted every 10 msec to AP0 target hall

3.1 GeV pions are selected and focused by Li lens

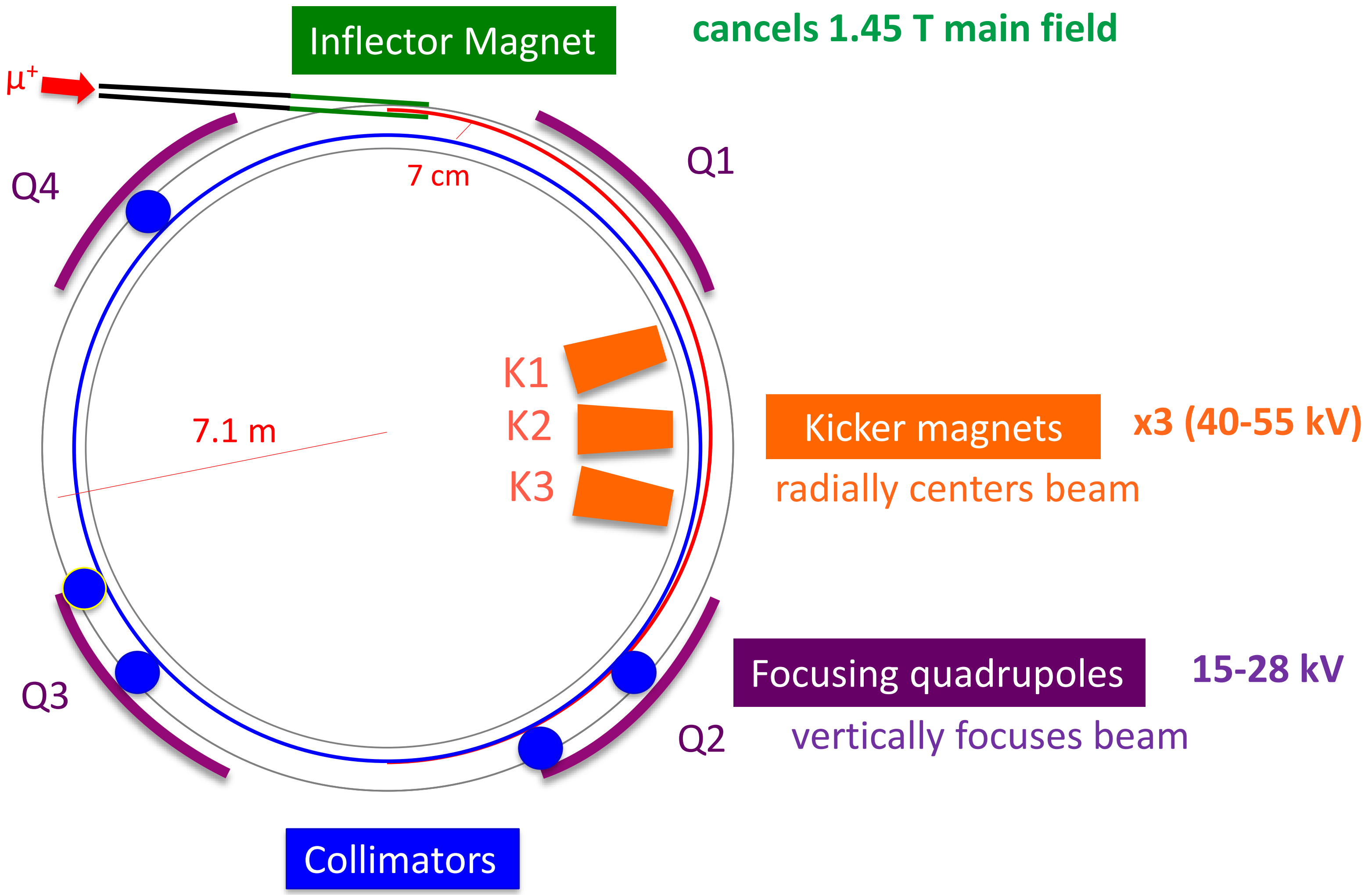
Transported through dense FODO lattice to Delivery Ring

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

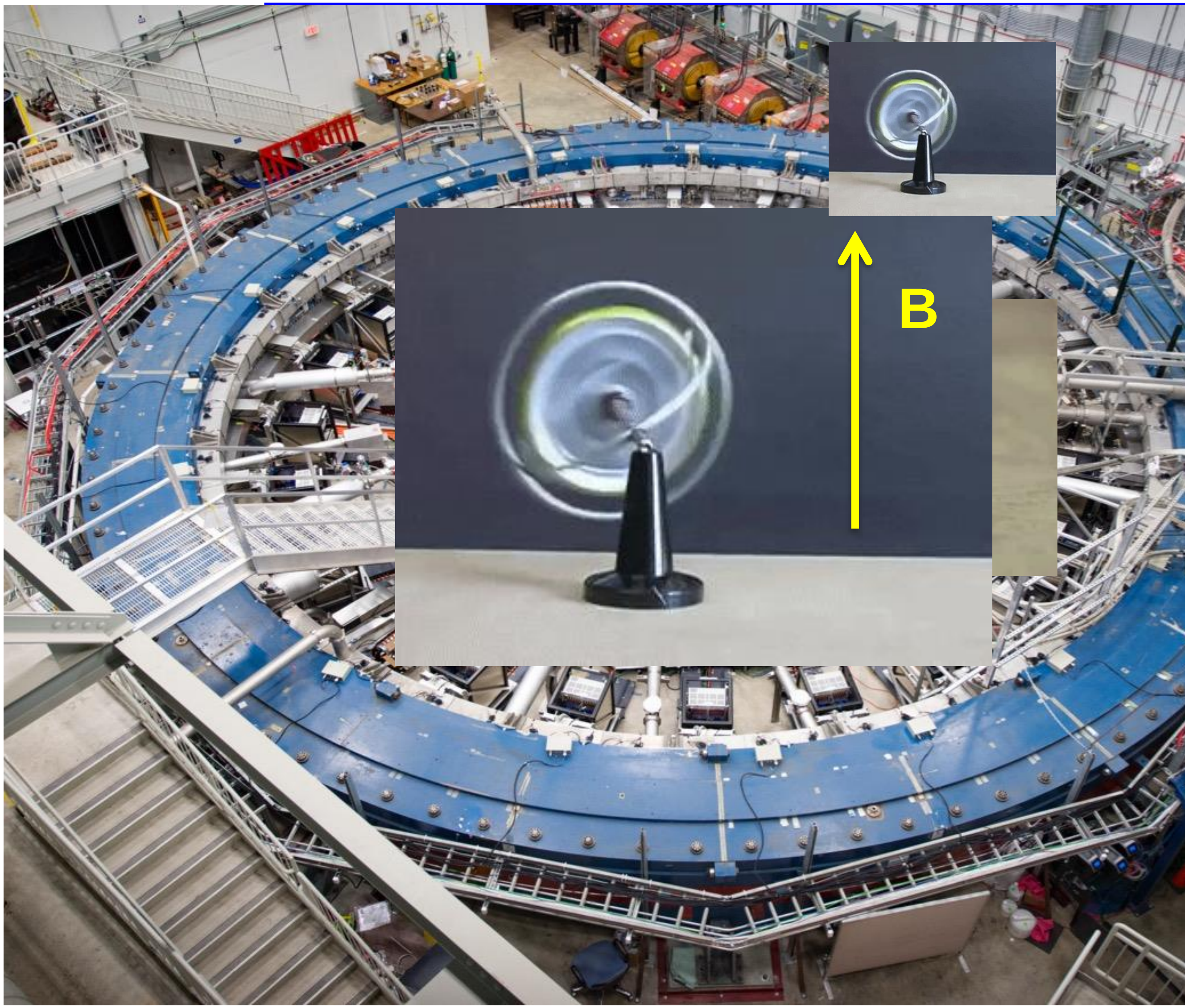
Muons are focused and injected into the Muon g-2 storage ring

Whole cycle repeats twice every 1.4s

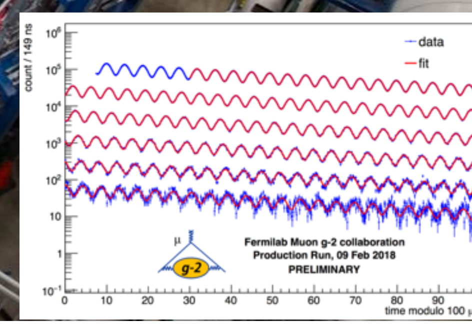
Determining the precession frequency, ω_a



Determining the precession frequency, ω_a



Goal: Measure the revolution frequency…to very high precision



Muon spin dynamics in a storage ring

Muon g-2

$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad\qquad \omega_C = \frac{eB}{mc\gamma}$$

The Spin frequency relative to the Cyclotron frequency is the "anomalous precession frequency", ω_a

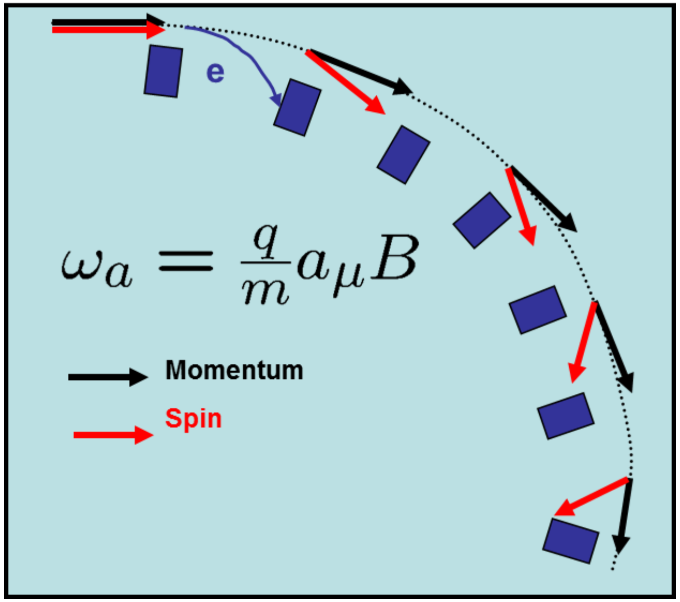
Does NOT depend on γ !

Proportional to g - 2 and *B* !

$$\gamma \equiv \frac{1}{\sqrt{1-\beta^2}} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{c}{\sqrt{c^2-v^2}}.$$

$$\omega_a = \omega_S - \omega_C$$

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

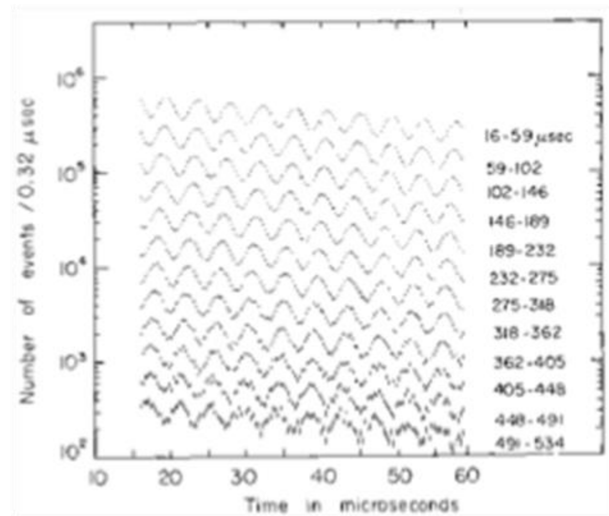


E field needed for vertical focusing

But … it looks like a B field to a moving particle !

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

The CERN III Miracle : choose $\gamma = 29.3$ ($P_\mu = 3.094$ GeV/c)
and an E-field can be used without having to know E at sub-ppm

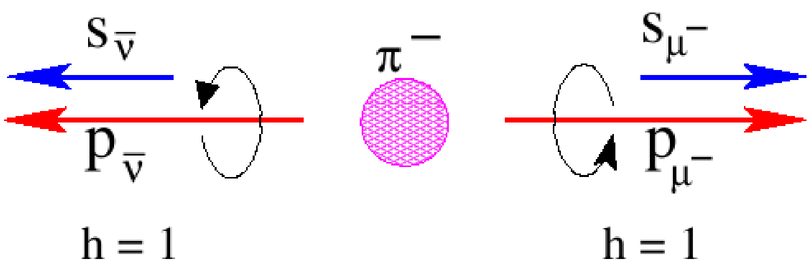


$a_\mu = 0.001\ 166\ 924(8.5)$ (± 7 ppm)
(sensitive to HVP)

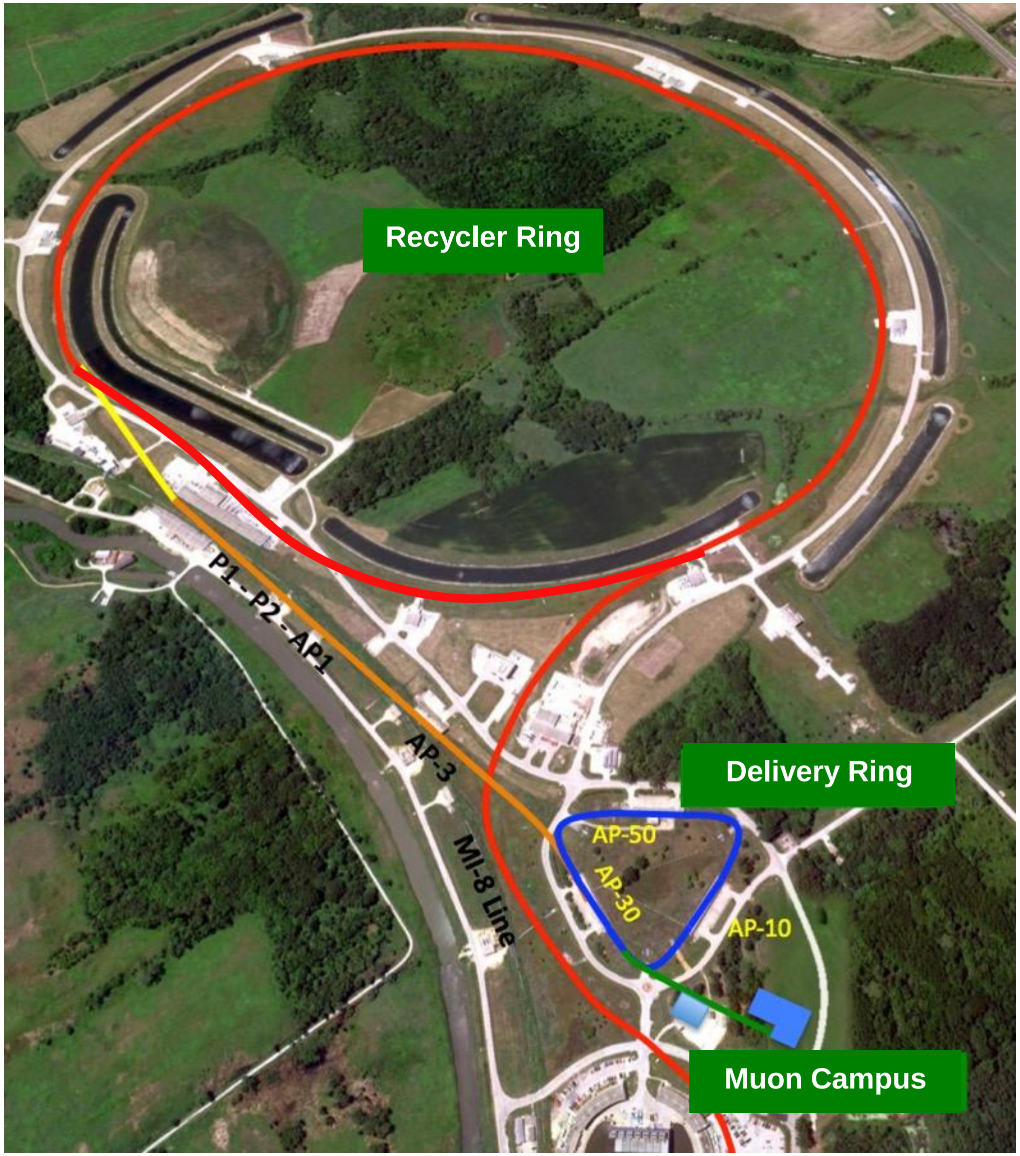
Need a polarized muon source

- Hit a target with a proton beam and copious amounts of pions are produced, which then decay to muons

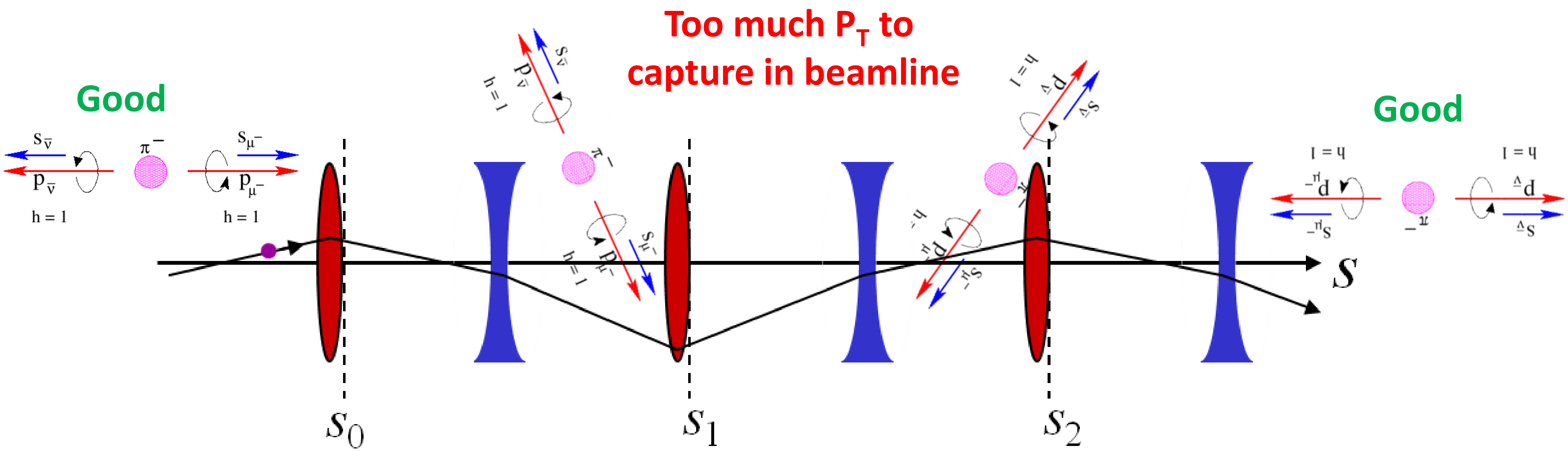
Pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$



- To high order, nature only makes left-handed neutrinos (right-handed anti-neutrinos)



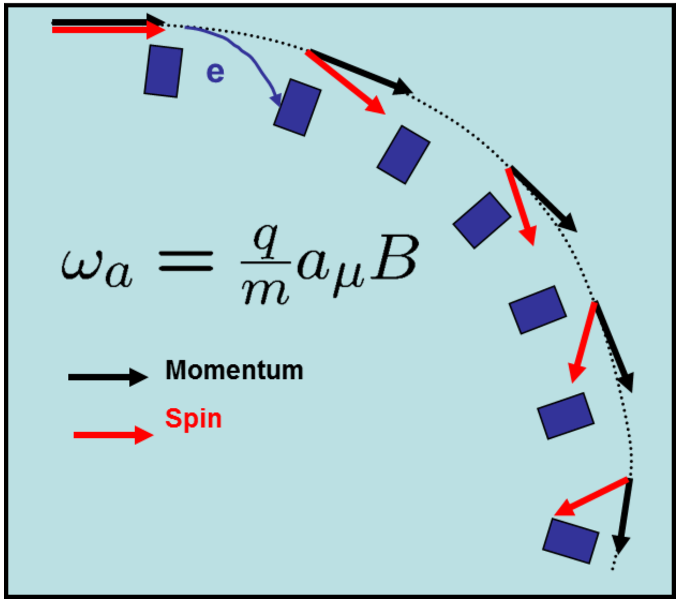
Need a polarized muon source



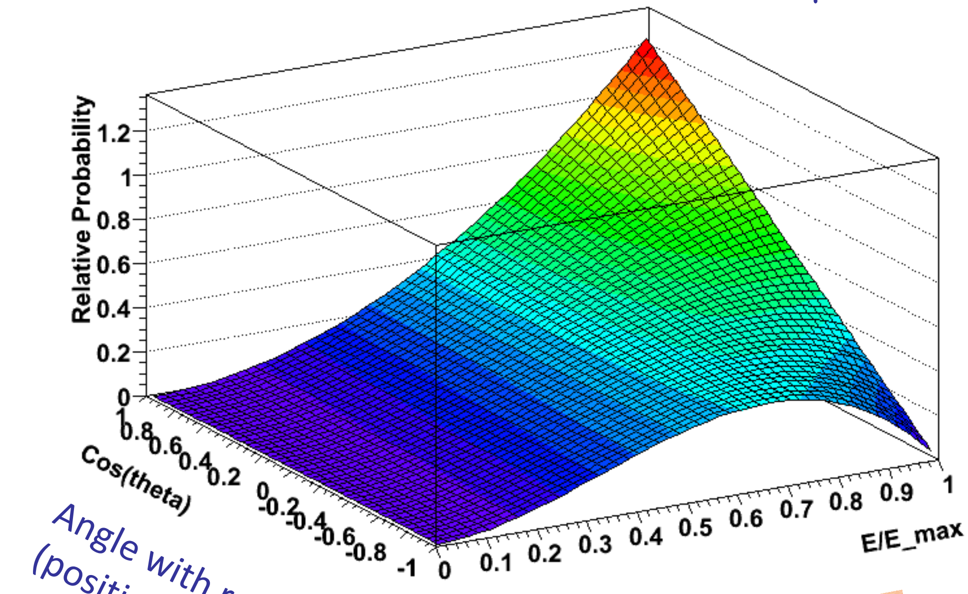
- A beamline of magnetic quadrupoles acts as a series of lens, keeping particles focused
- As the pions decay, muons are produced in random direction in the pion rest frame
- Decay with the muon not parallel (or anti-parallel) to the direction of motion have too much transverse momentum to stay in the beamline
- The result is that you only capture the highest or lowest energy muons
- Parity violation in pion decay gives us a 97% polarized muon source for free

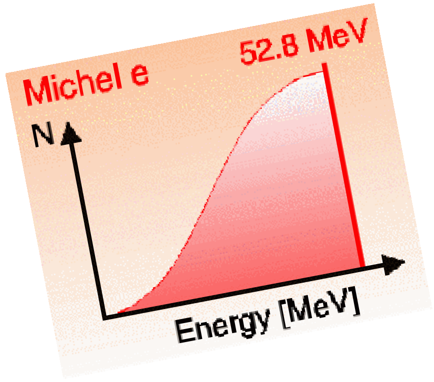
PV in muon decay is how we ‘see’ the muon spin

- Parity violation in muon decay → highest energy decay electron emitted in direction of muon spin
- When spin is aligned with momentum, the boost adds, anti-aligned and the decay electron energy is reduced in the lab frame
- Results in a modulation of the energy spectrum at the g-2 frequency



Muon decay $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$





Extracting a_μ from experiment

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

2017 CODATA

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

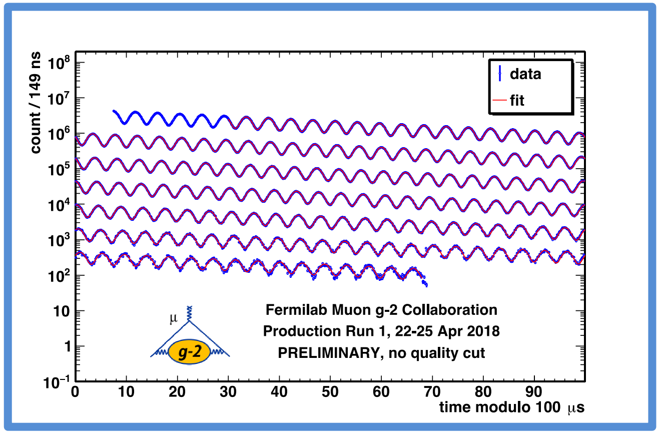
206.768 2826(46) [22 ppb] Muonium Hyperfine

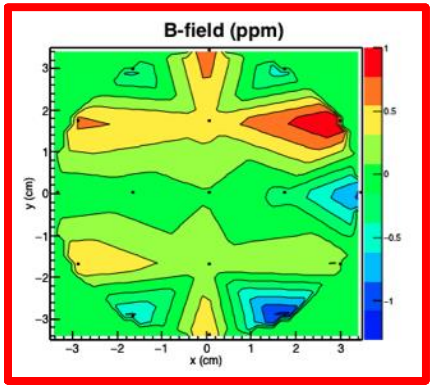
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

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

$$\Downarrow$$

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





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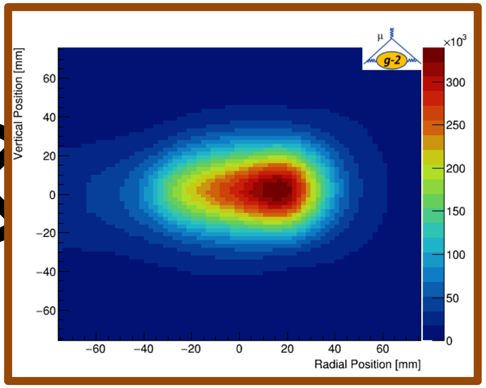
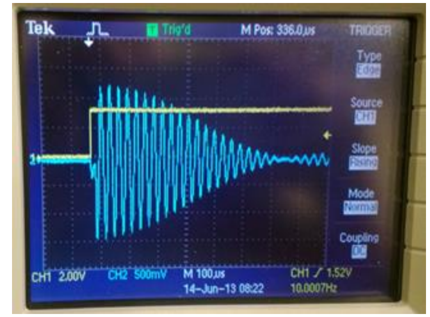
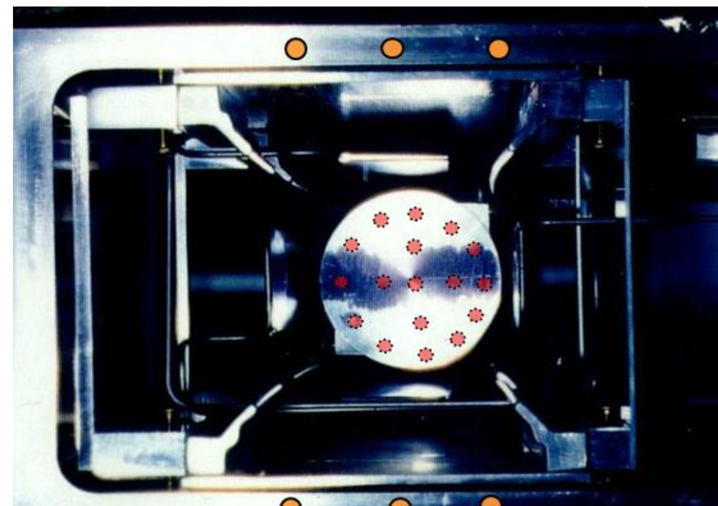


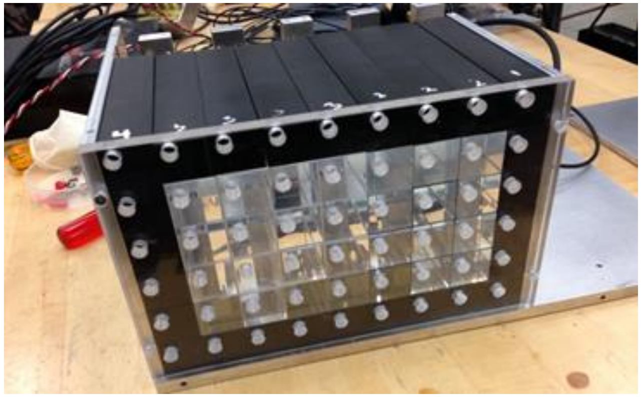
Determining the field strength

- We use a series of proton NMR (nuclear magnetic resonance) probes to determine the strength of the field in the storage ring, ω_p
- To determine B to sub-ppm precision requires making the field as uniform as possible
- Final step require an absolute calibration procedure that is at the limit of the ability of human's to absolutely determine B-fields

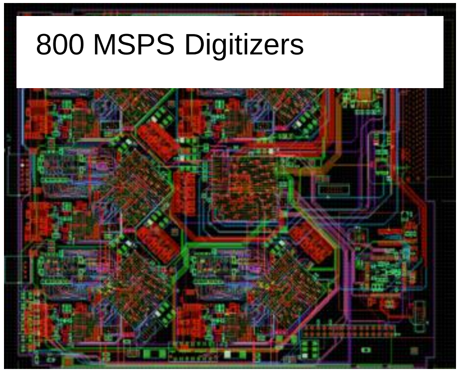


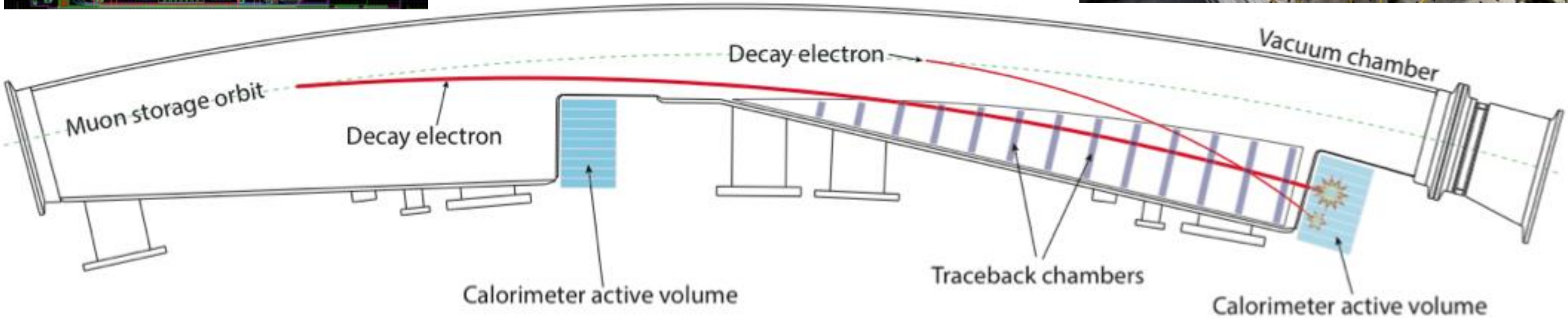


Determining the precession frequency, ω_a

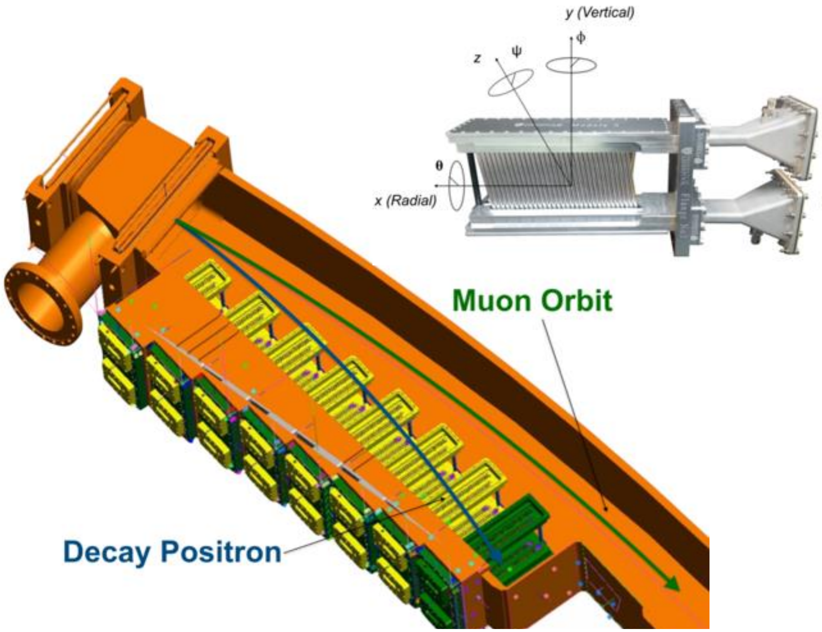


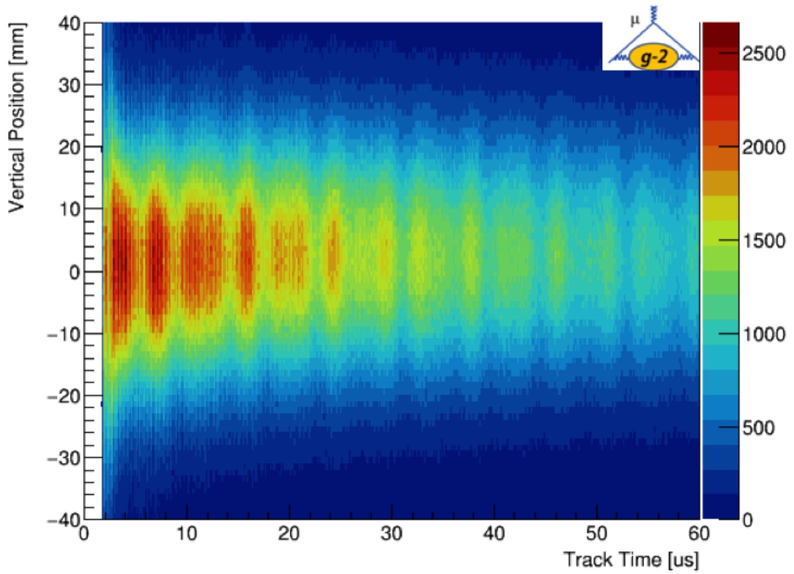
- Calorimeters 24 6x9 PbF2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- New laser calibration system from INFN crucial for untangling gain from other systematics



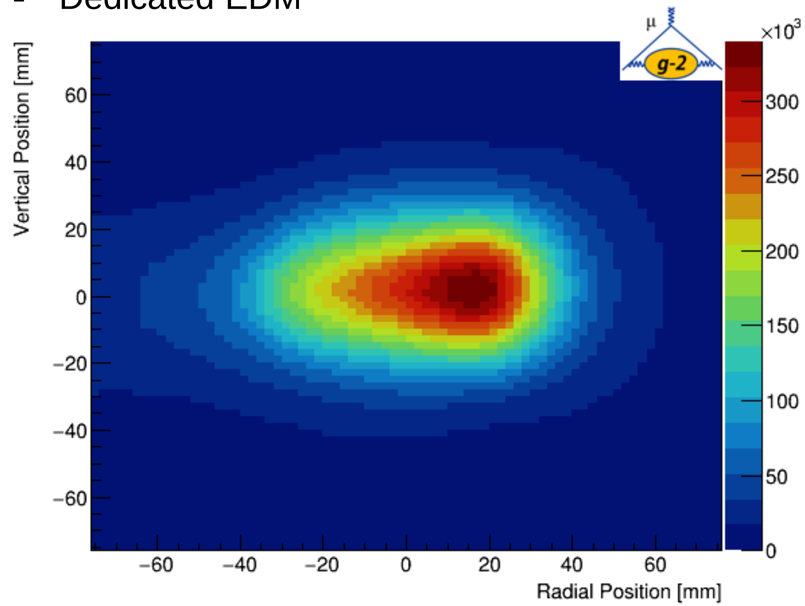


Tracking





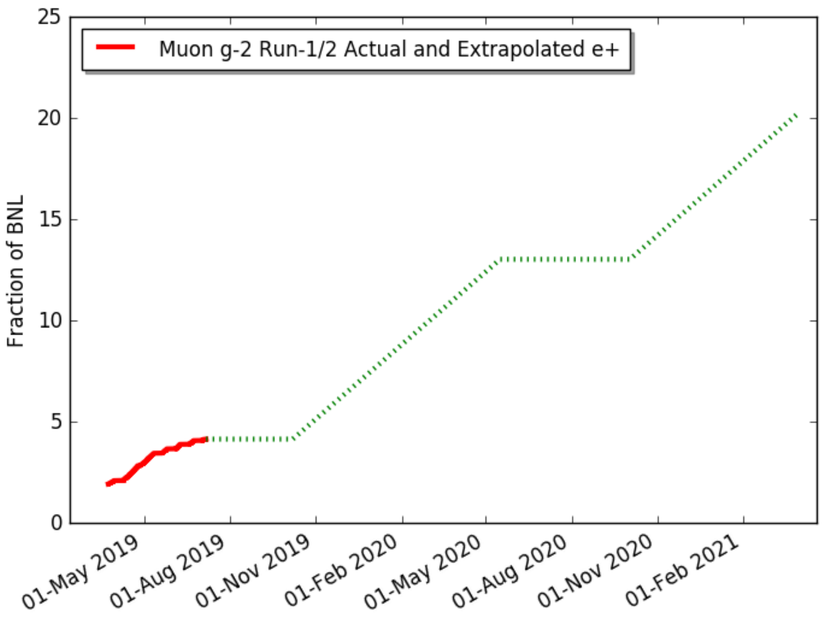
- Tracking stations installed at 2 azimuthal locations in storage ring
- Each composed of 16 U/V planes with a total of 1024 straws
- Used for many functions
  - Measure muon distribution for convolution with field
  - Determine beam dynamics parameters to feed into muon spin precession analysis and establish corrections
  - Dedicated EDM

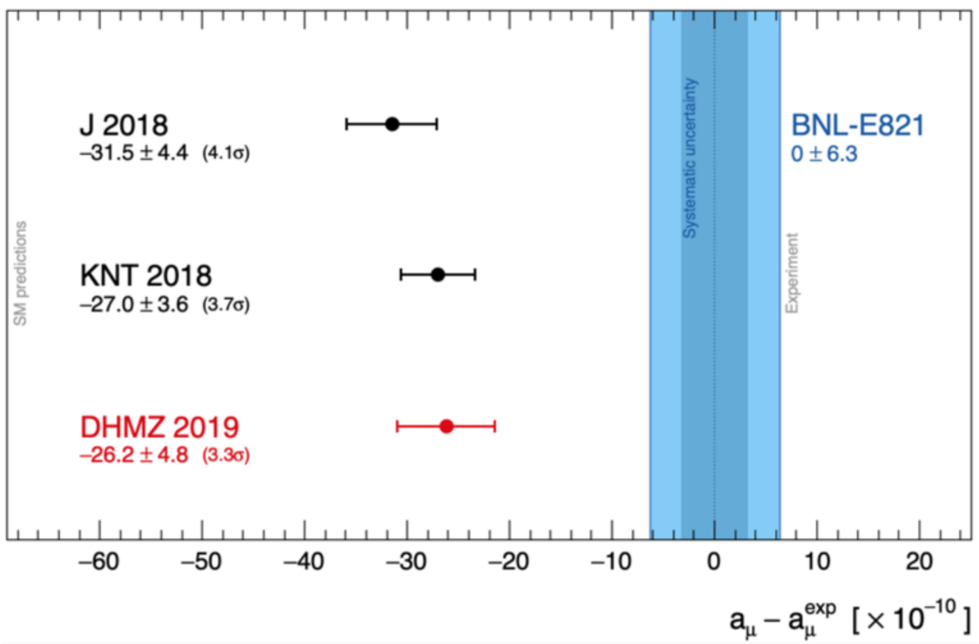


Several other beam monitoring systems as well...IBMS detectors monitor injected beam profiles and retractable fiber harps that can plunge into muon beam in ring

Outlook

- Experiment has been taking data
  - Collected 1.3xBNL in FY18, 2xBNL in FY19
  - Anticipate 8xBNL in next year
- Wrapping up analysis of the Run 1 data, anticipate a 1st publication by the end of the year!





The end…thank you!