The Anomalous Magnetic Moment of the Muon

W. Morse - BNL

Matter Particles circa 1930s

Particle	Mass (MeV)	Charge	Force	Size	Spin (h)
Proton p	938.3	+	S, E, W, G	10^{-15} m	1/2
Neutron n	939.6	0	S, W, G	10^{-15} m	1/2
Electron e	0.511	-	E, W, G	$< 10^{-20}$ m	1/2
Neutrino ν	$\approx 10^{-7}$	0	W, G	$< 10^{-20}$ m	1/2

Forces and Symmetries circa 1970s
SM = SU(3) × SU(2) × U(1)

Force	Carrier	Spin
Strong	Gluon	1
Electro-Magnetic	Photon	1
Weak	W	1
Gravity	Graviton	2
Mass	H	0

Weak Force

- Free neutron decay half-life = 10 minutes $n \rightarrow pe\bar{\nu}$
- If earth to sun filled with Pb, most neutrinos would still get through.
- Strong N* → p π 10^{-22} sec
- Electromagnetic π → γ γ 10^{-18} sec
- Hydrogen p e → n ν
- Without the weak interaction, there would be no energy from the sun, no elements but H, He.
- The strength of the weak force determines the lifetime of the sun.
- Why don't neutrons in nucleus decay?

Quantum Mechanics

- Developed 1910 – 1950 by:
- Niels Bohr – “Anyone who thinks they understand QM, and is not deeply disturbed by it, doesn’t understand QM.”
- Albert Einstein – “God doesn’t play dice.”
- Erwin Schroedinger – “I wish I never discovered these damn wave functions.”

Quantum Mechanics

- Electron is described by Schroedinger wavefunction: Ψ
- Let's rotate by an angle Θ:
- $\Psi' = e^{iS\theta} = \big(cos(S\theta) + i\ sin(S\theta)\big)\Psi$
- Spin ½ are matter particles!
- Spin 0, 1, 2 are force particles!

Magnetic Moment

- Particle is spinning,
- Particle is charged,
- Spinning charge creates a magnetic field:
- $\mu = \frac{gQS}{M}$
- Dirac Equation: g = 2 for a spin ½ point particle.
- Proton: g = 5.6, finally explained by quark model.
- Electron: g = 2.0
- Oppenheimer et al. calculated the first order correction to 2 to be infinity.

Spin ½ Particles
Three Generations!

Particle	Mass (MeV)	Particle	Mass (MeV)	Particle	Mass (MeV)
u	312	c	1750	t	171200
d	313	s	490	b	5620
e	0.5	$\mu \rightarrow e\nu\bar{\nu}$	105	τ	1777
ν_e	10^{-8}	ν_μ	10^{-7}	ν_τ	10^{-7}

More Symmetries

- C symmetry – changes particle to anti-particle.
- P symmetry – changes x to $-x$.
- T symmetry – changes t to $-t$.
- Discovered in 1950 – 60s: P, T, C, CP are broken symmetries in the weak interaction.

Theory 1970s

- In SM we can only get this if there are three, or more, ways for a given reaction to go, and get QM interference with the three amplitudes, with at least one imaginary.
- Need at least three generations.
- In the big bang all the non-neutrino particles/anti-particles should have finally annihilated to photons.
- Due to symmetry breaking, p/photon $\approx 10^{-9}$.

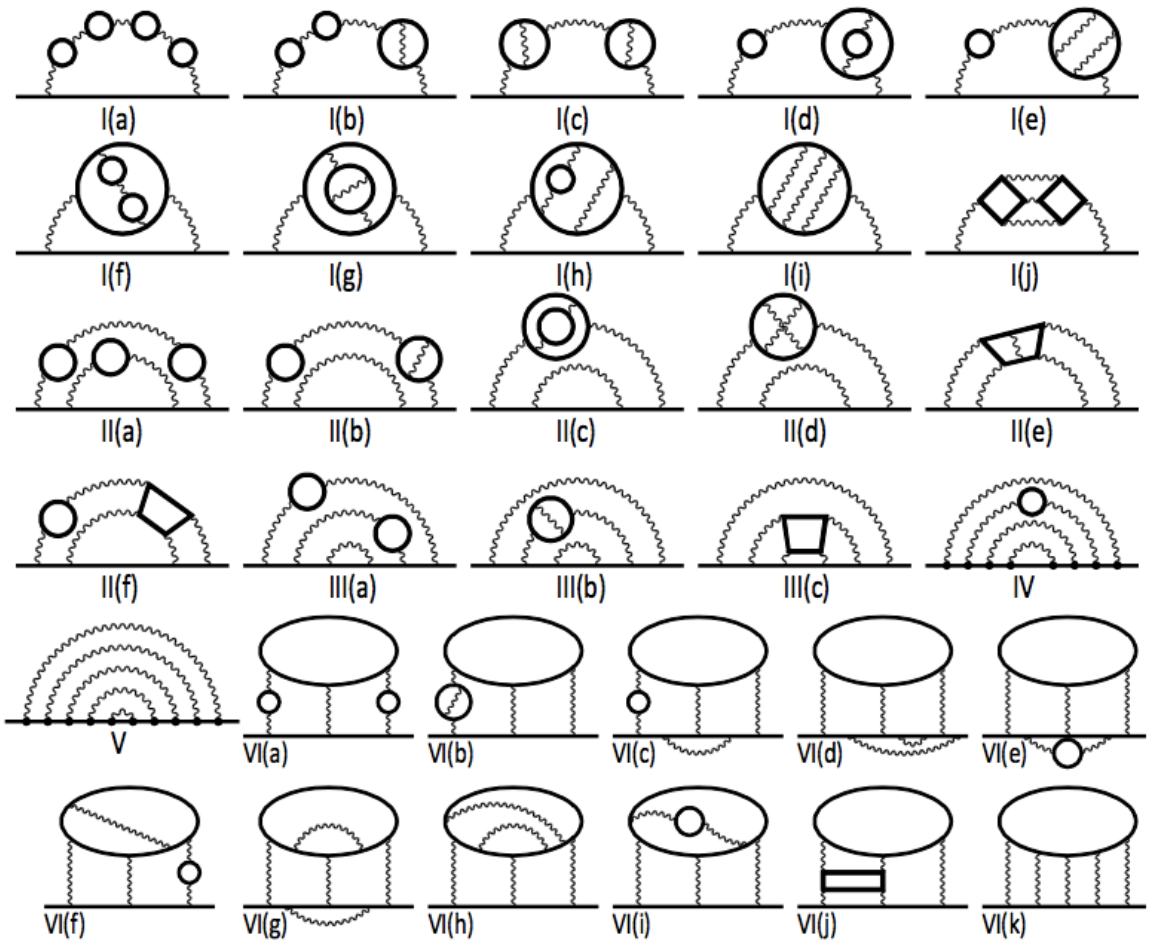
$$a = \frac{g-2}{2} = 0.0011$$

- 1948 I.I. Rabi, Conference at Shelter Island
- Schwinger, Renormalization, QED.
- Anomalous magnetic moment of the muon is due to QM.
- The energy of the vacuum should be zero.
- QM: $dE \times dt = h$
- The problem with zero is that it has no uncertainty.

Quantum Electrodynamics

10th
12672
diagrams

$dE \times dt = h$

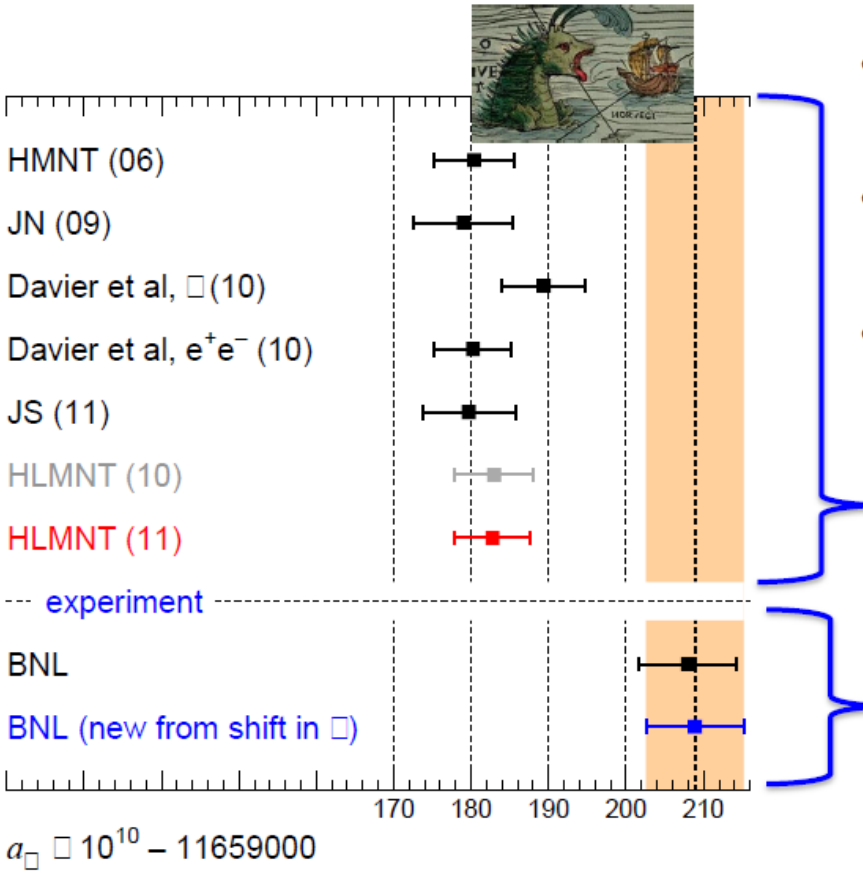


What about Einstein's cosmological constant?

Quantum Mechanics

- All particles exist in the vacuum: $dE \times dt = h$.
- All particles contribute to the anomalous magnetic moment.
- Are there new particles?
- Super-symmetry?

BNL E821

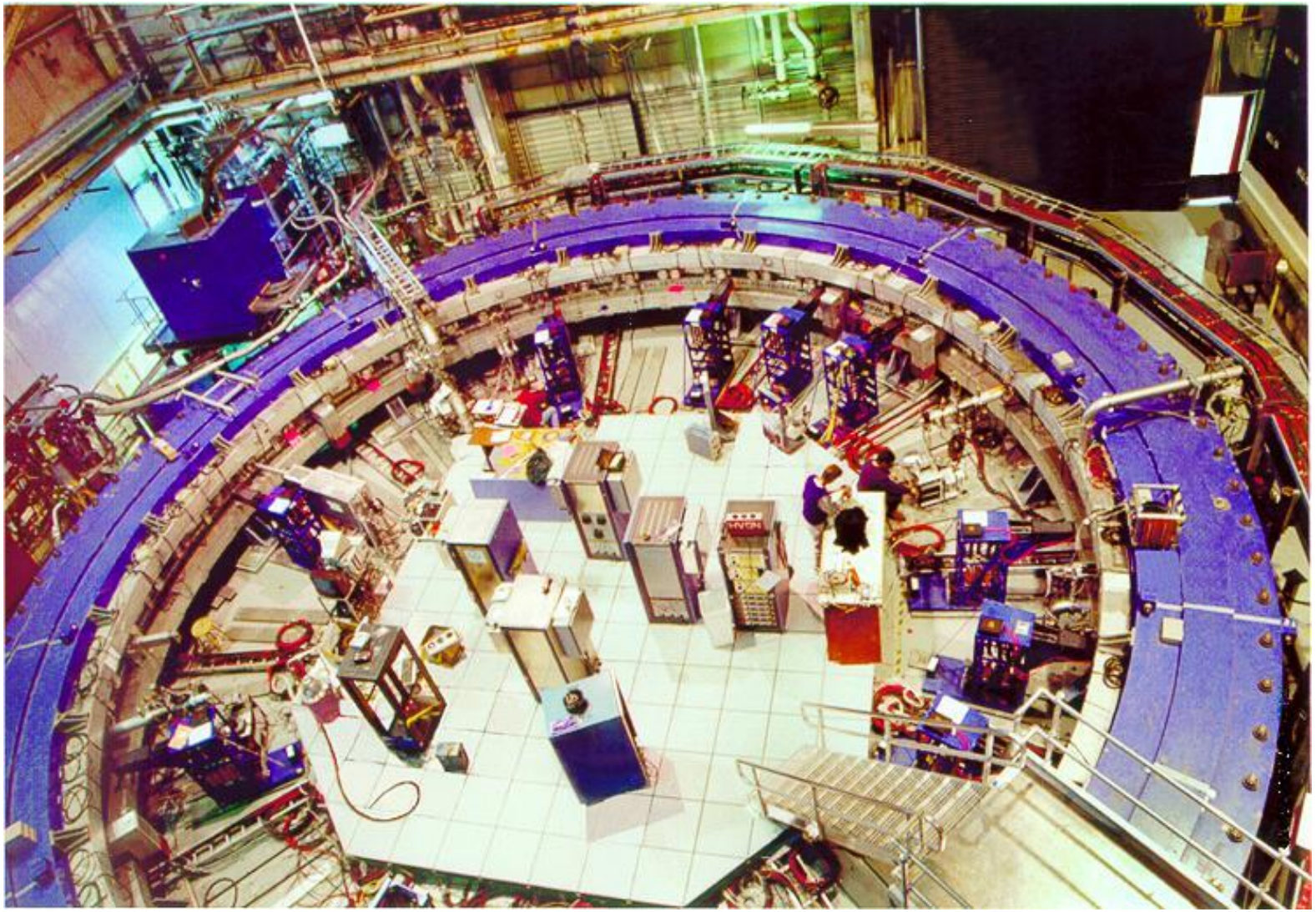


- The last a_μ experiment ended at BNL in 2001
- 3σ discrepancy with the theoretical expectation
- Goal of FNAL g-2 is to reduce the experimental error by a factor of 4

Theoretical evaluations

Last experimental result from BNL

BNL 1983 - 2004



Move from BNL to FNAL

Smith Point Marina

Around FL, and up Miss. River

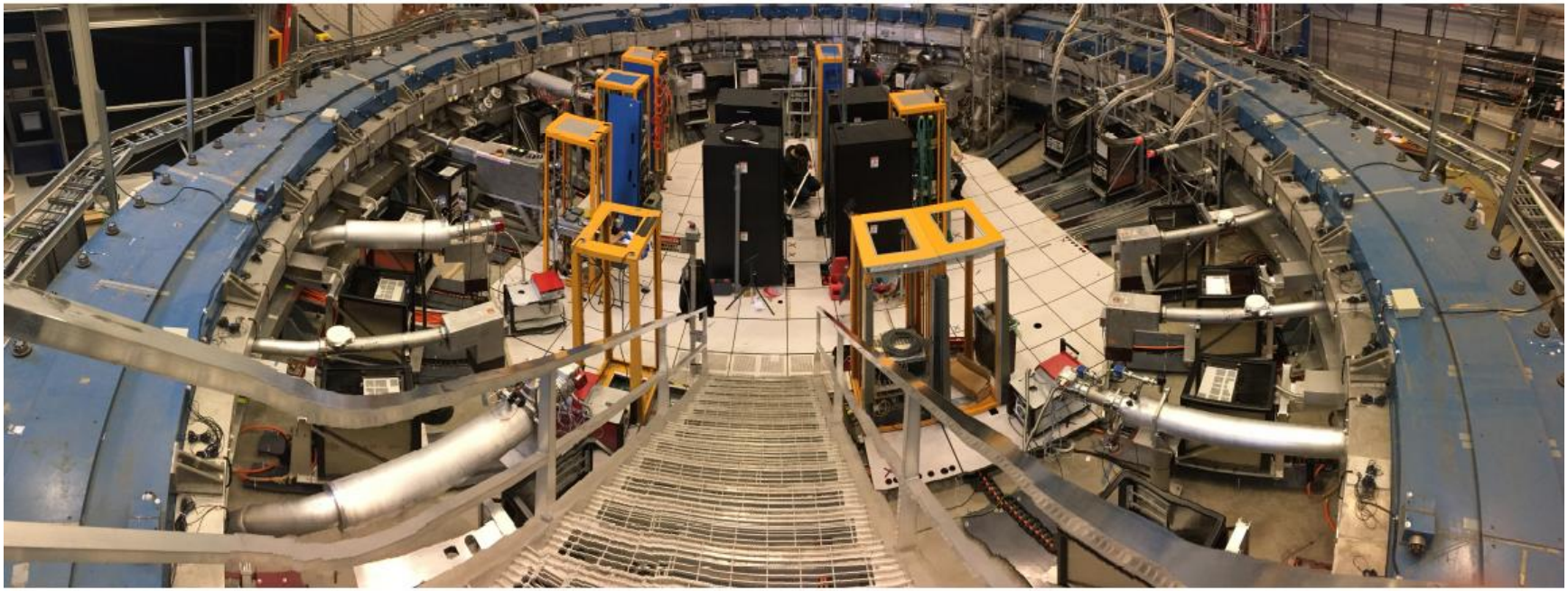
Up Illinois River

Entrance Ramp to Interstate 88

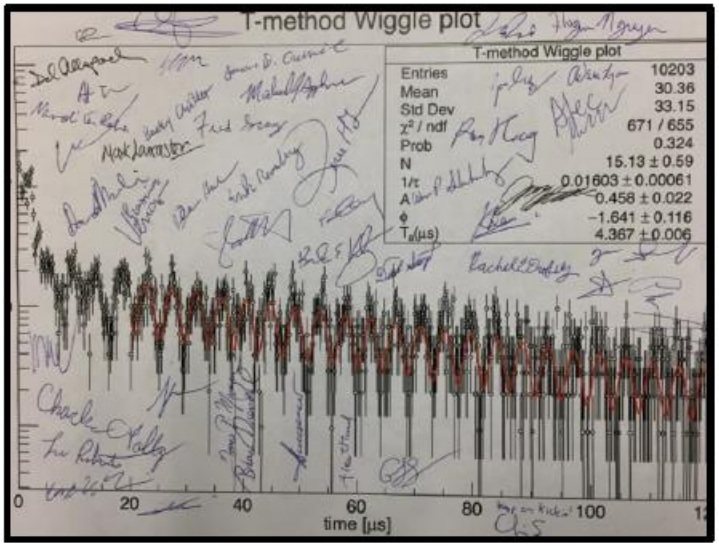
Interstate 88

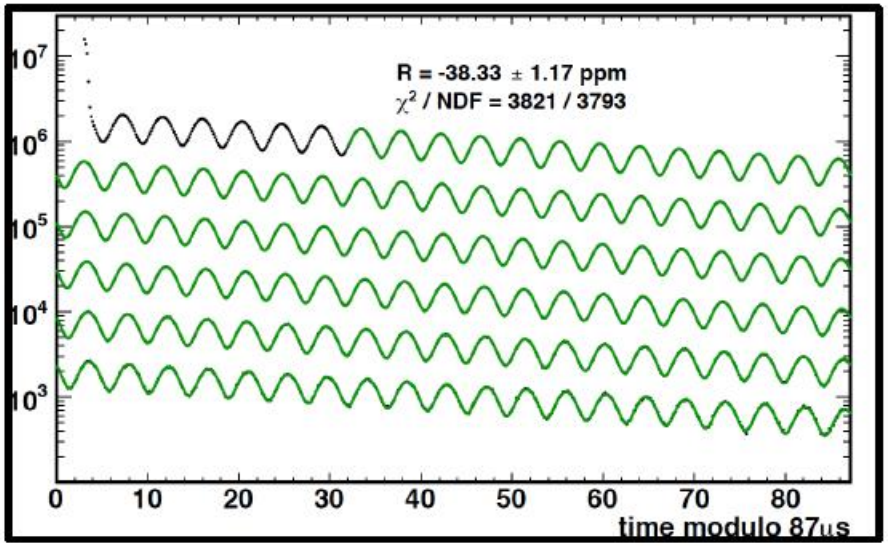
Arriving at FNAL 2013

FNAL 2017



Data 2017 and 2018





Data Taking and Analysis

- Data Taking 2017 – 2021.
- Analysis finished for 2018 data summer or fall 2019. ≈10B muon decays on tape. Same as BNL experiment.
- 2021, 0.2T muon decays on tape.