The Anomalous Magnetic Moment of the Muon as a Test of the SM

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	≈ 10^{-7}	0	W, G	< 10^{-20} m	1/2

Forces and Symmetries circa 1970s
$SM = SU(3) \times SU(2) \times U(1)$

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

Weak Force

- Free neutron lifetime = 14 minutes $n \to pe\bar{\nu}$
- If earth to sun filled with Pb, most neutrinos would still get through.
- Strong $N^* \to p\,\pi$ 10^{-22} sec
- Electromagnetic $\pi \to \gamma\,\gamma$ 10^{-18} sec
- How does the sun make energy?
- $p\,e \to n\,\nu$
- The strength of the weak force determines the lifetime of the sun.
- Why don't neutrons in nucleus decay?

Quantum Mechanics

- Developed 1910 – 1970 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: $\Psi(x,y,z,t)$
- Let's rotate by an angle Θ:
- $\Psi' = (\cos(\Theta S) + i \sin(\Theta S))\Psi$
- Spin ½ are matter particles!
- Spin 0, 1, 2 are force particles!
- Without spin we wouldn't be here.

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.

SM Spin ½ Particles
Three Generations!

Particle	Mass	Particle	Mass	Particle	Mass
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 1960s

- C symmetry – changes particle to anti-particle.
- P symmetry – changes *x* to –*x*.
- T symmetry – changes *t* to –*t*.
- QM: CPT is a good symmetry.
- Discovered at BNL 1965, T, and CP are broken symmetries in the weak interaction.
- $K^0 \rightarrow \pi^{\pm} e^{\mp} v$

CP and T Symmetry Violation 1970s

- Theorists: 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 one imaginary.
- 1 is a real number, $\sqrt{-1}$ is an imaginary number.
- 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, H/photon ≈ 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 is zero classically.
- QM: *dE* x *dt* = *h*
- The problem with zero is that it has no uncertainty.

Quantum Electrodynamics

What about Einstein's cosmological constant?

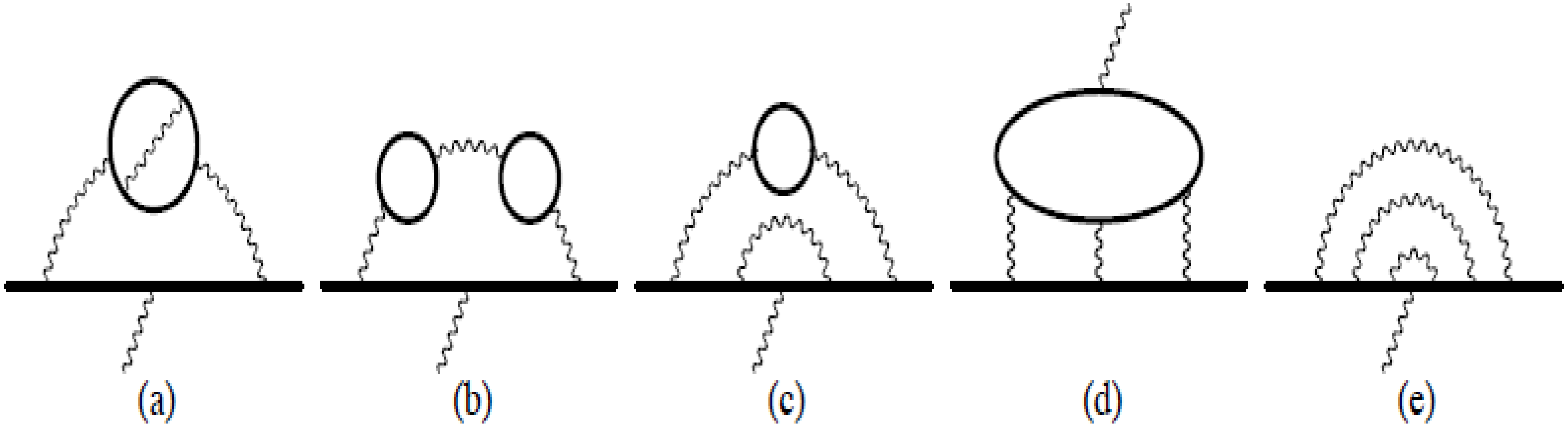


Figure 97: Sixth-order vertex diagrams. There are 72 diagrams in total, and they are divided into five gauge-invariant sets. Typical diagrams from

Strong Interaction

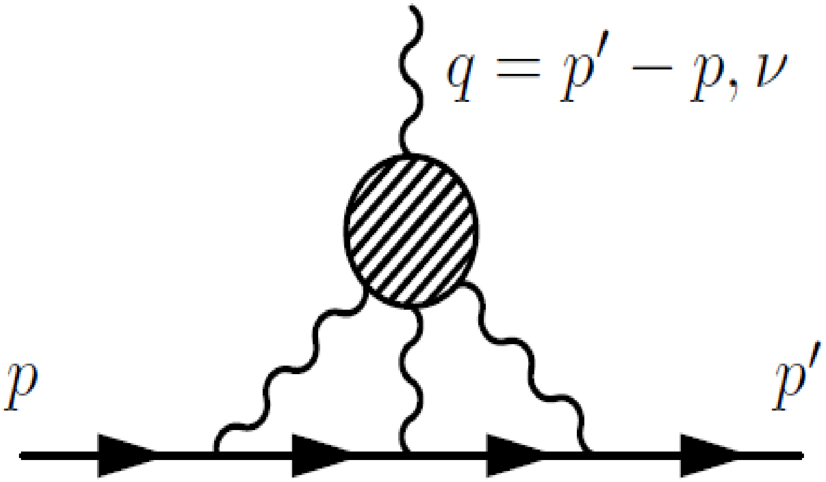


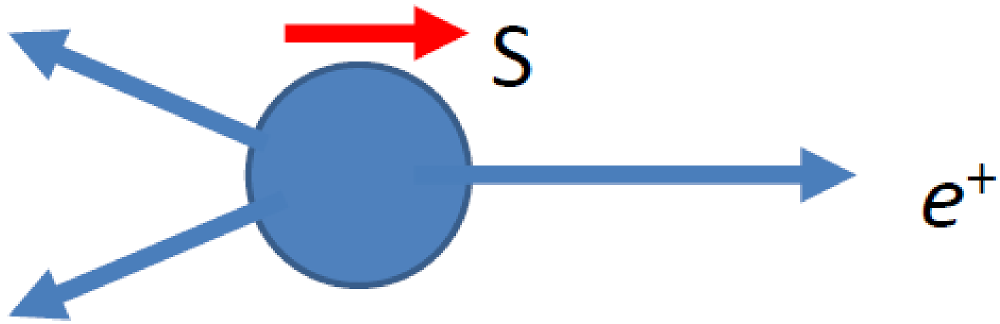
Figure 73: HLbL contribution to the muon $g - 2$. The shaded blob represents all possible intermediate hadronic states.

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[21,22], A. X. El-Khadra[23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

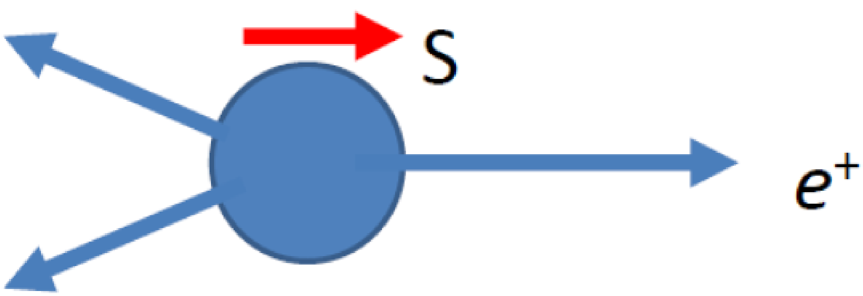
$$\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$$

- $RF: \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$ $\quad$ $Lab: \vec{\omega} = -\frac{ea}{m}\vec{B}$
- 

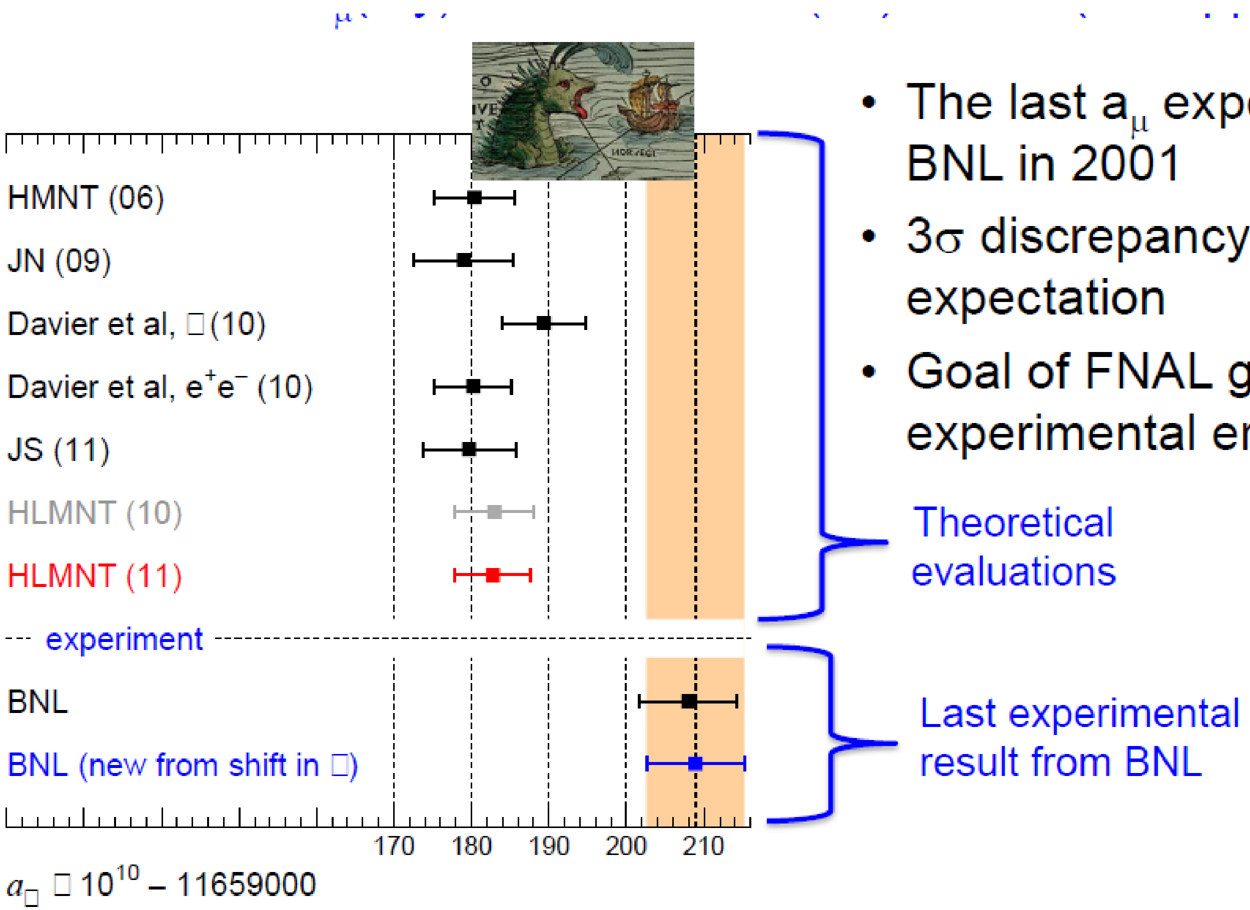
$$\mu^+ \to e^+ \nu_e \overline{\nu_\mu}$$

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$

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



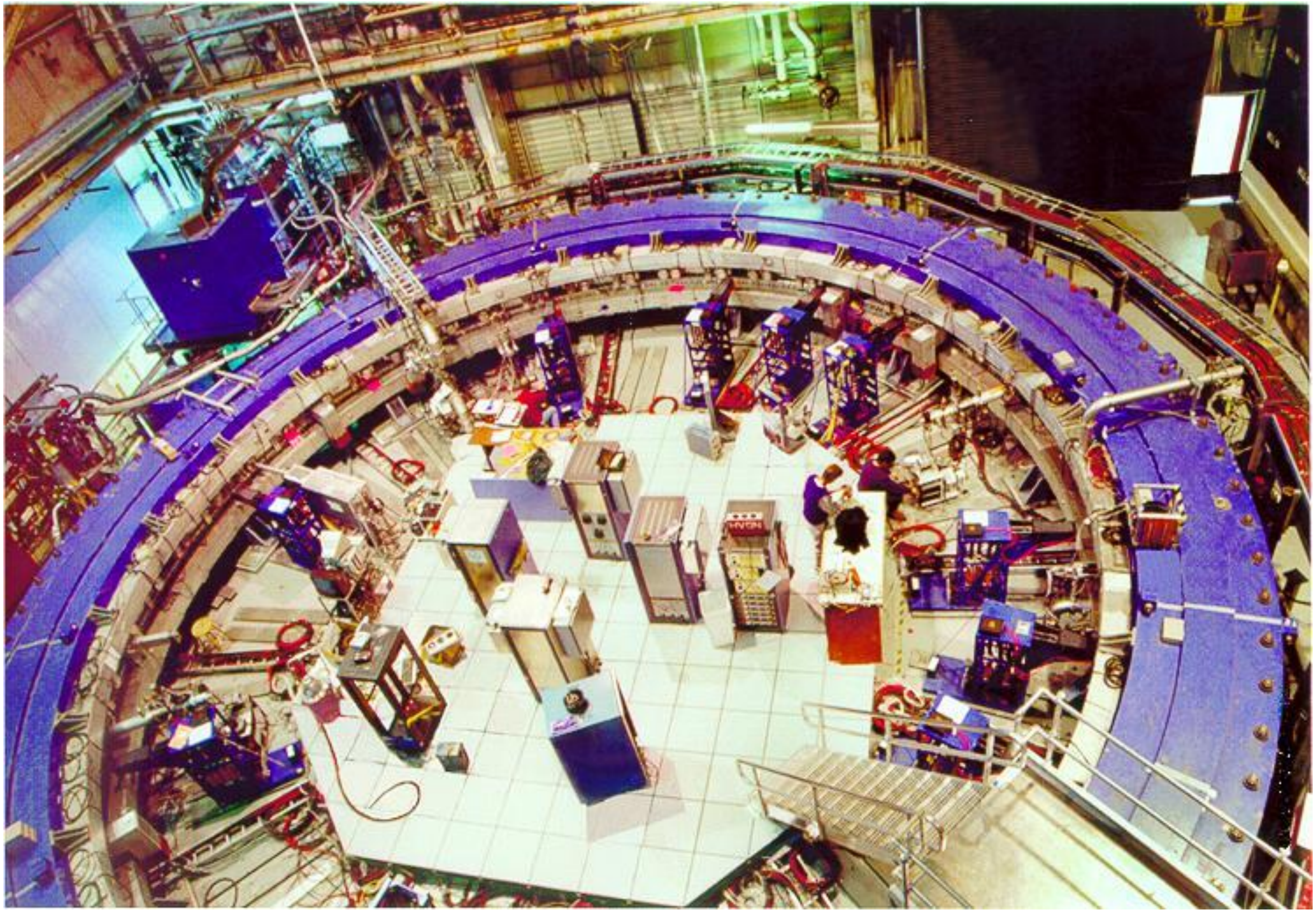
BNL E821



- 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

$$a = 0.0011659000$$

BNL 1983 - 2004



Move from BNL to FNAL

Smith Point Marina

Around FL, and up Miss. River

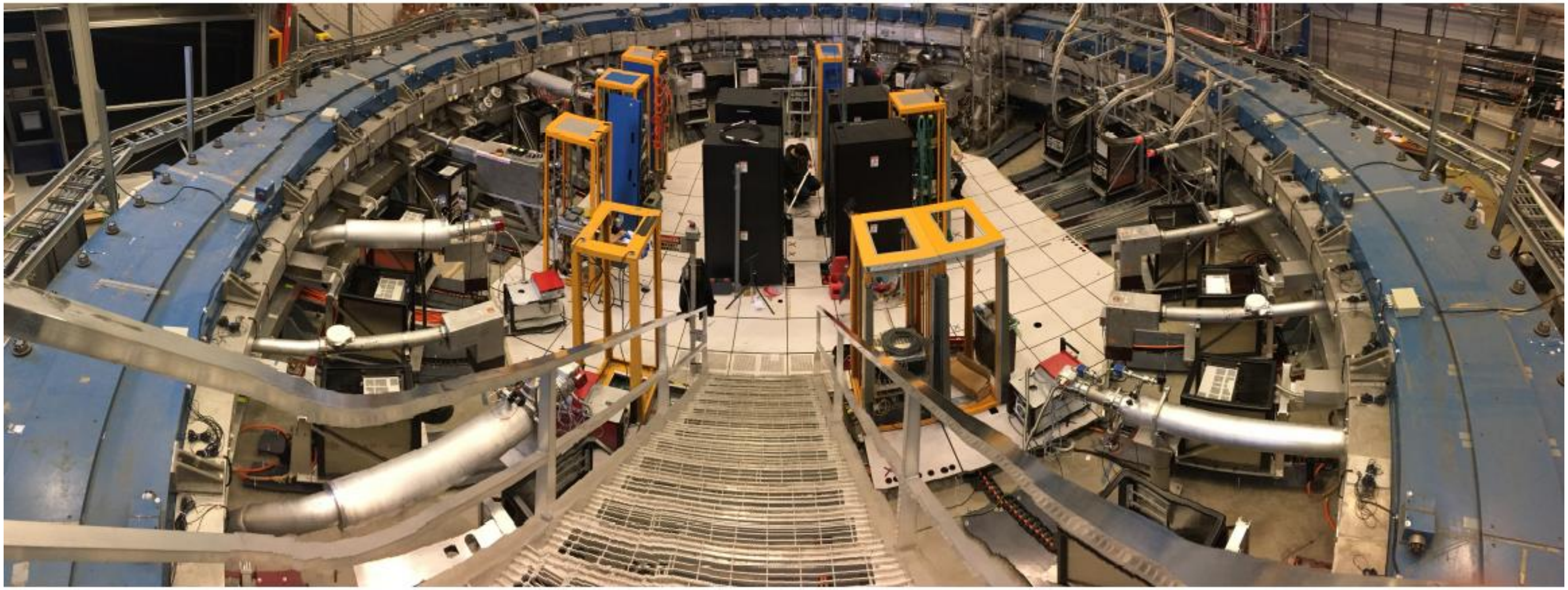
Up Illinois River

Entrance Ramp to Interstate 88

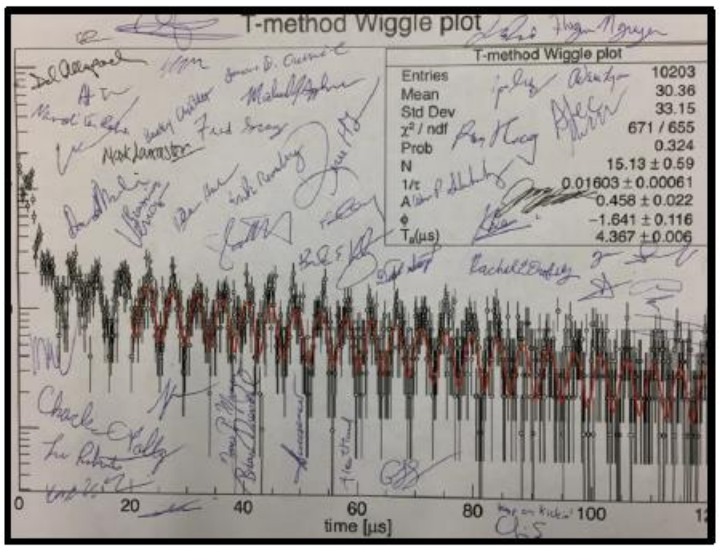
Interstate 88

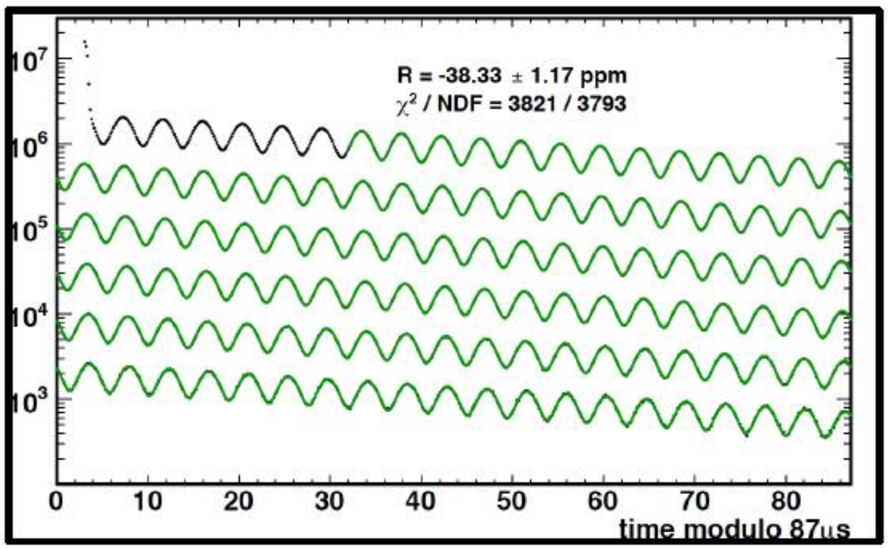
Arriving at FNAL 2013

FNAL 2017



Data 2017 and 2018





Data Taking

- Data Taking 2018 – 2022.
- Analysis finished for 2018 data in 2020.
- 2018 data same accuracy as BNL experiment.