Muon g-2

Fermilab Summer Lecture
Aug 2, 2016

Chris Polly

U.S. DEPARTMENT OF ENERGY | Office of Science

Who we are…

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

• National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

D.W. Hertzog, Co-Spokesperson
B.L. Roberts, Co-Spokesperson
C. Polly, Project Manager

England
University College London

Liverpool

Oxford

Korea
KAIST

- 33 institution, 150 members

Muon program at Fermilab

- New facility under construction,
  - Two new experimental halls and the tunnel infrastructure to connect to the complex
  - Capability of producing high intensity customized muon beams

Muons as probes for new physics

Muons can be extremely good probes of the Standard Model

- Can be produced copiously

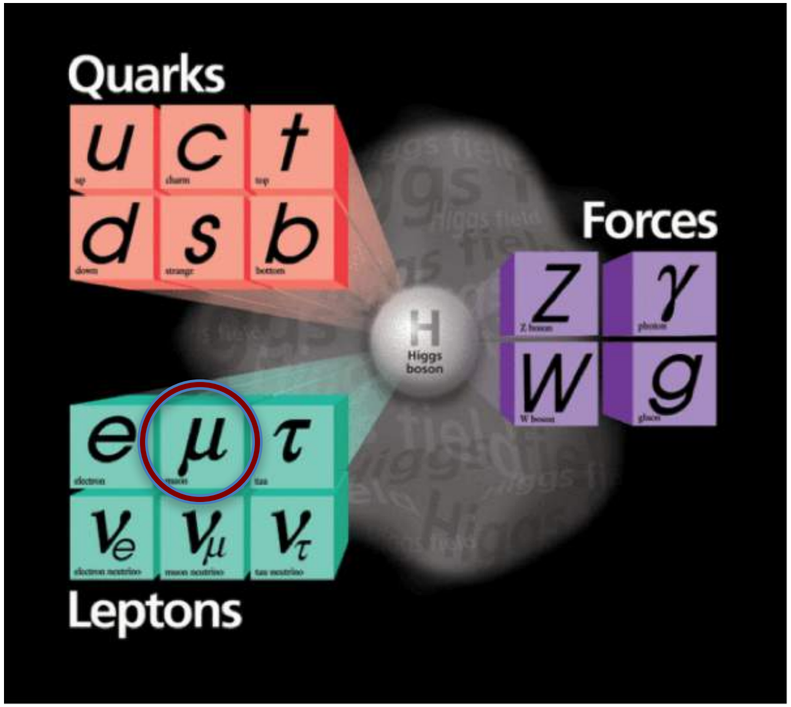
  BR($\pi^{\pm} \to \mu^{\pm} \nu$)=99.9877%

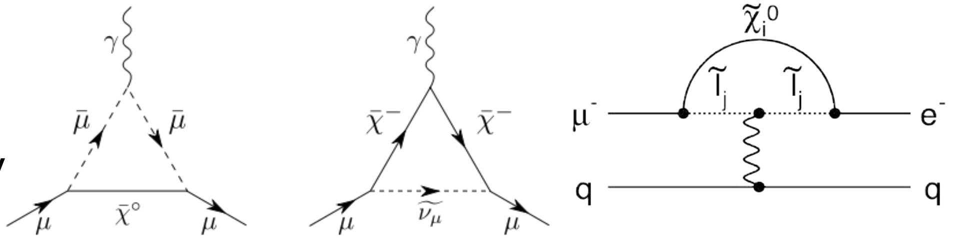
- Don't get ensnared by the strong force
- Relatively long life time 2.2 μs
- Relatively heavy $(m_{\mu}/m_{e})^2 = 40000$

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





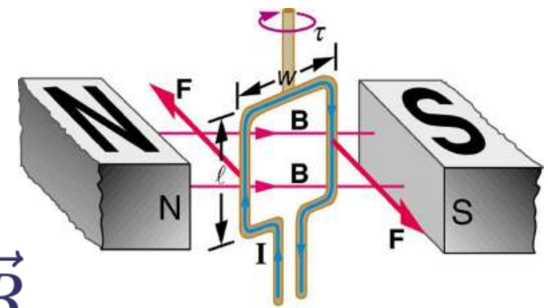
Windows into new physics…

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…

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

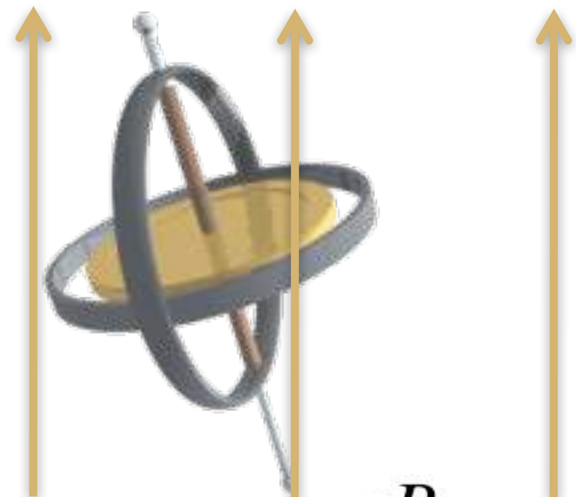


$$\vec{\tau} = \vec{\mu} \times \vec{B}, \quad U = -\vec{\mu} \cdot \vec{B}$$

- 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

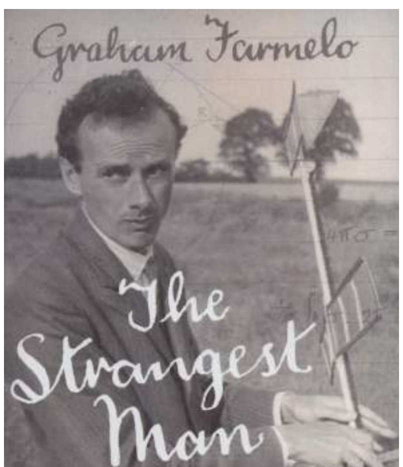


$$\omega_s = g\frac{eB}{2mc}$$

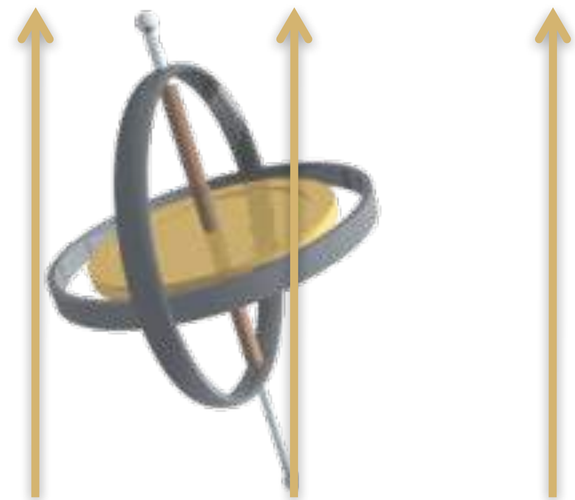
Magnetic moments…classical to quantum

- For a spin ½ point particle 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 have been testing BSM for decades

- 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

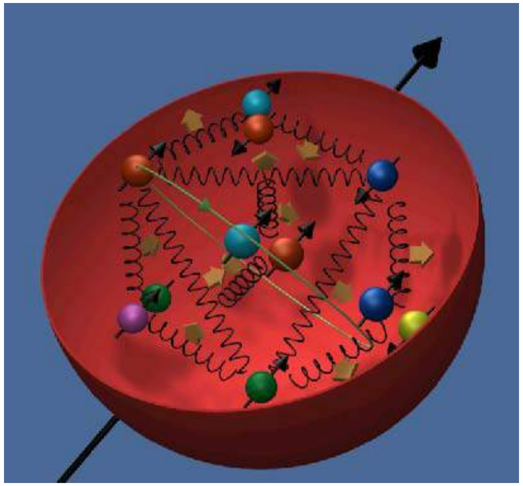
$g_p \approx 5.6$

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

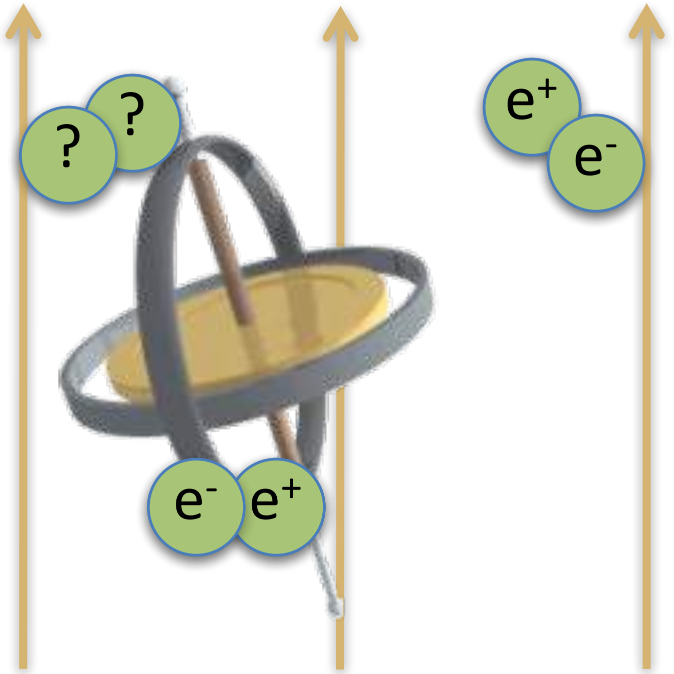
Thus the anomalous magnetic moment was discovered, fractionally g differs from 2 by (g-2)/2 = 0.1%

$g_e = 2.00238(6)$

Enter the world of phantom particles

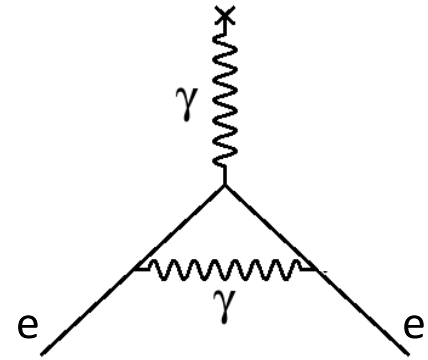
- In reality, particles are never really alone…virtual particles continually fluctuate in and out of the vacuum
- In fact, the more massive the particle, the more mass it has to lend and the probability for friends appearing unexpectedly is enhanced
- These virtual particles effectively screen the magnetic 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

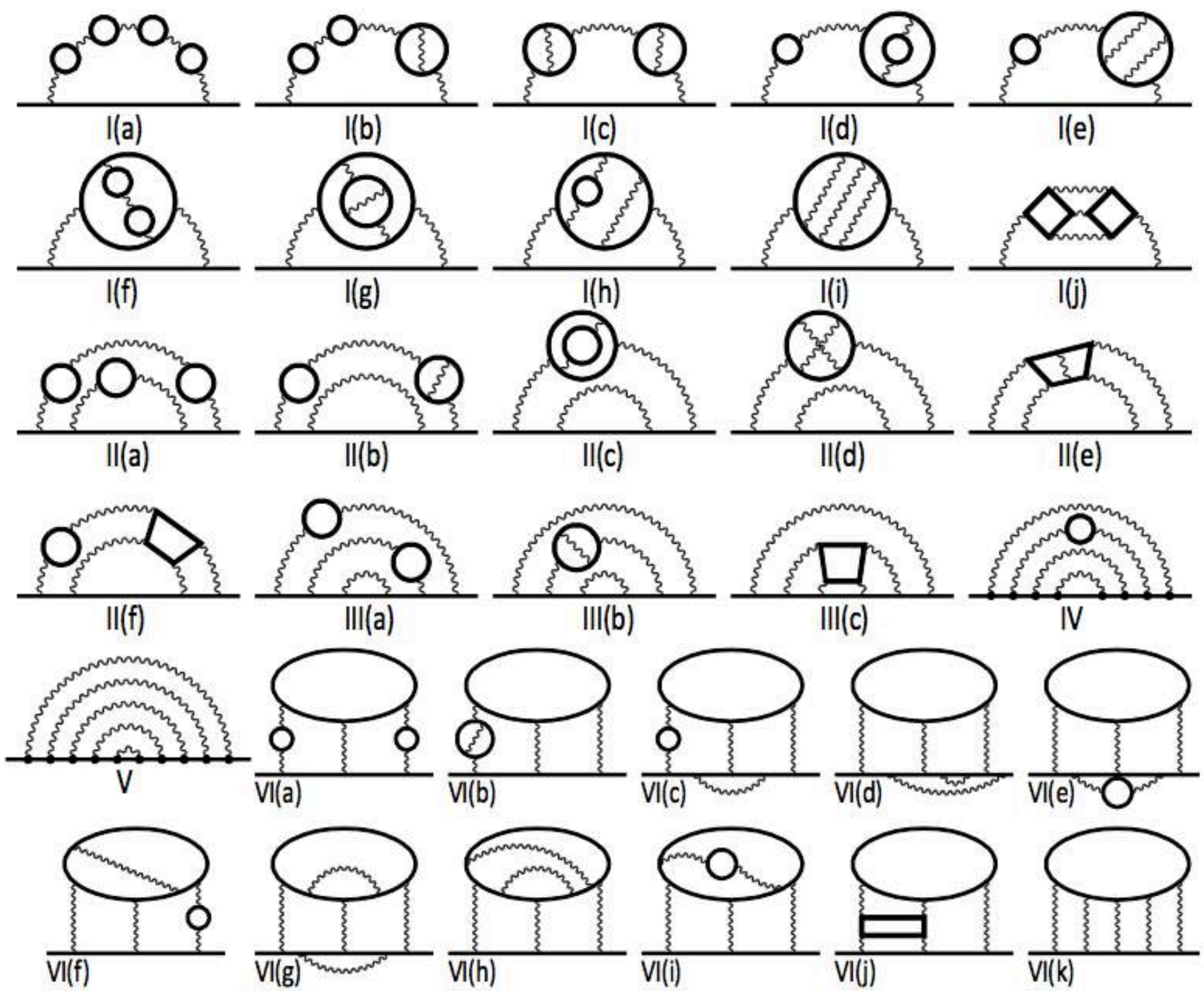
$$g_e \approx 2\left(1+\frac{\alpha}{2\pi}\right) \approx 2.00232$$

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

QED calculation now out to 5 loops

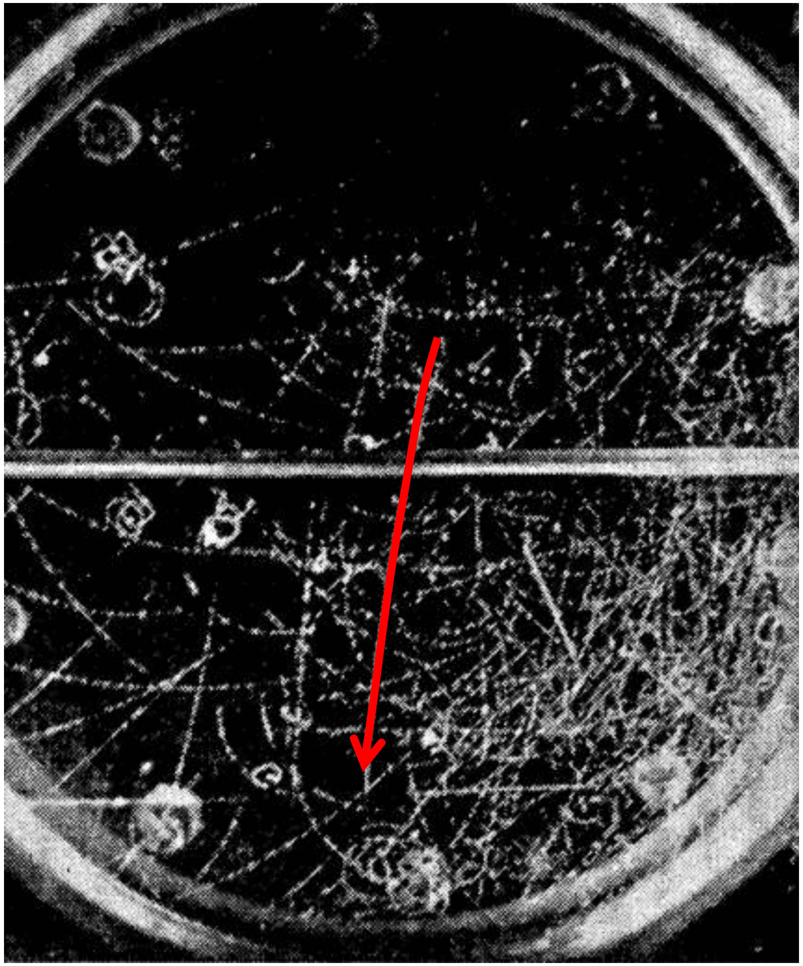
T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

10th
12672
diagrams



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

Muon discovered in 1936



Immediately people were interested in determining its magnetic moment

First g_μ measurements

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

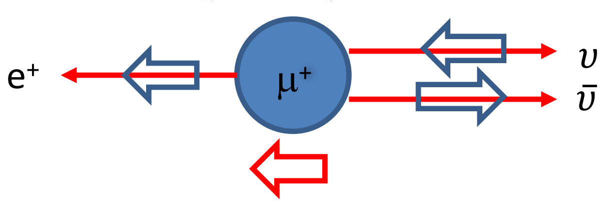
Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

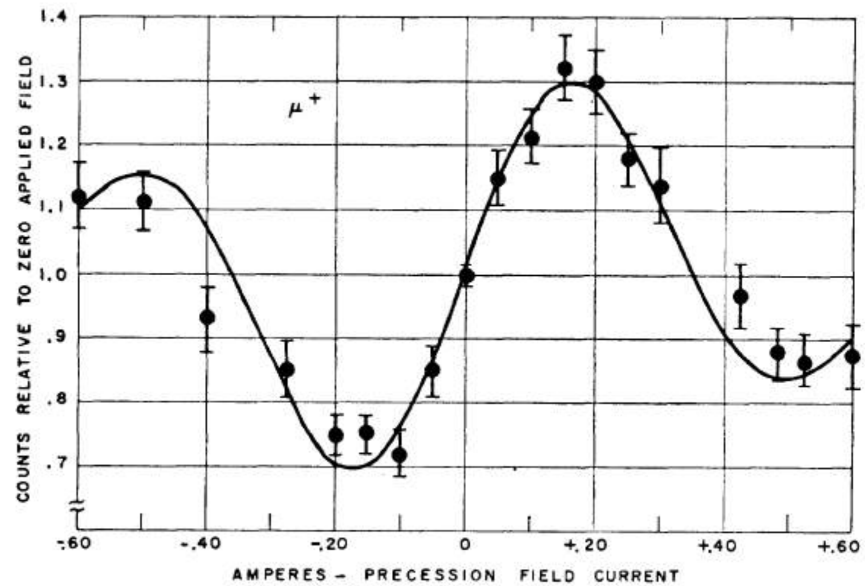
(Received January 15, 1957)

LEE and Yang[1-3] have proposed that the long held space-time principles of invariance under charge conjugation, time reversal, and space reflection (parity) are violated by the "weak" interactions responsible for decay of nuclei, mesons, and strange particles. Their hypothesis, born out of the $\tau-\theta$ puzzle,[4] was accompanied by the suggestion that confirmation should be sought (among other places) in the study of the successive reactions

$$\pi^+ \rightarrow \mu^+ + \nu, \quad (1)$$

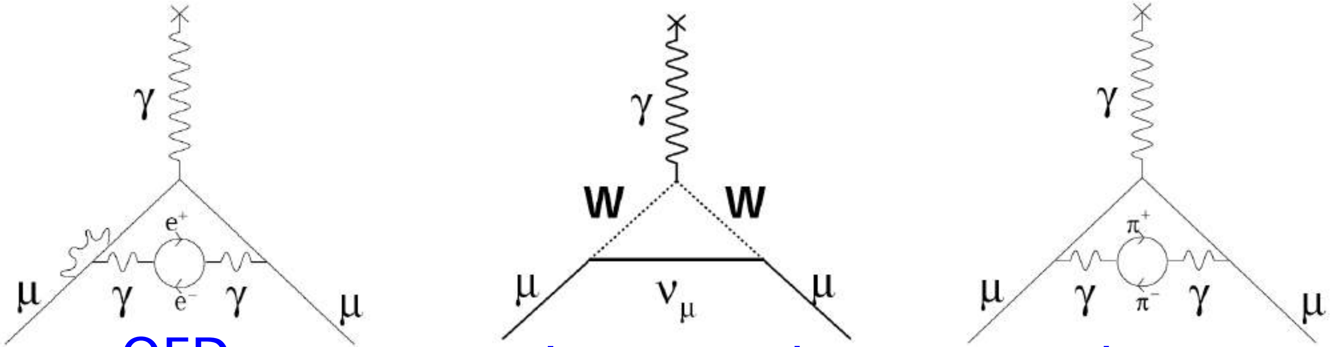
$$\mu^+ \rightarrow e^+ + 2\nu. \quad (2)$$





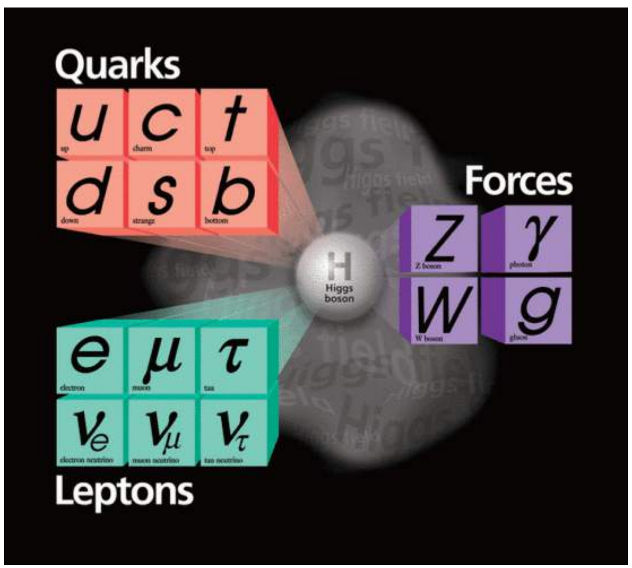
- Place polarized muons in a B-field and make two discoveries
  - Parity violation in the muon decay
  - $g_\mu = 2.01 \pm 0.01$
- More precise results followed which confirmed muons really are like 'heavy' electrons

The motivation for muon g-2 today



QED　　Electroweak　　Hadronic

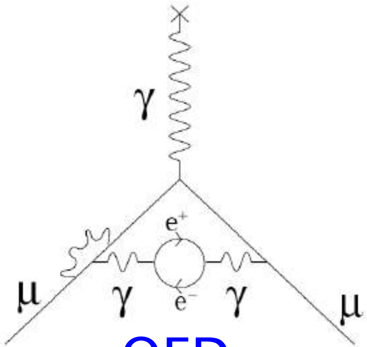
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP}$$



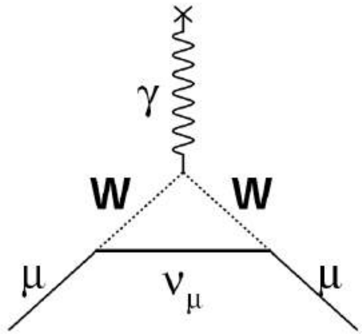
- Any Standard Model particle can contribute
- It is customary to break the calculation into QED, weak, and hadronic impacts on a_μ
- Because the muon is more massive, it is easier for higher mass particles to appear in the loops

$$\lambda_{sens} \propto \left(\frac{m_\mu}{m_e}\right)^2 \approx 40{,}000$$

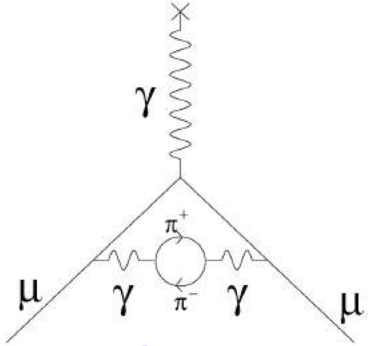
Calculating a_μ (thy)



QED

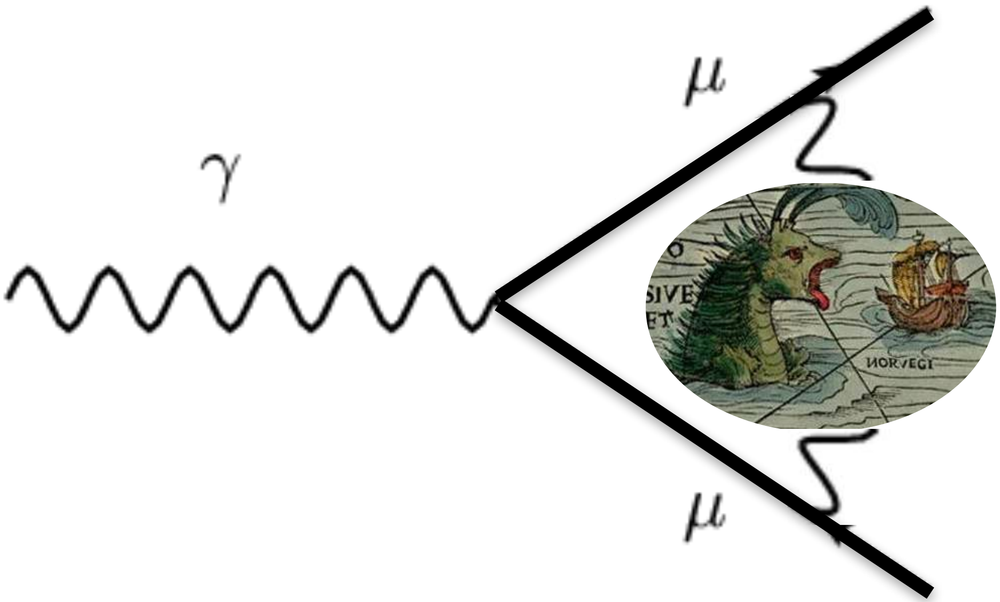


Electroweak



Hadronic

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HLBL} + a_\mu^{HVP} + a_\mu^{HOHVP} + a_\mu(NP)$$

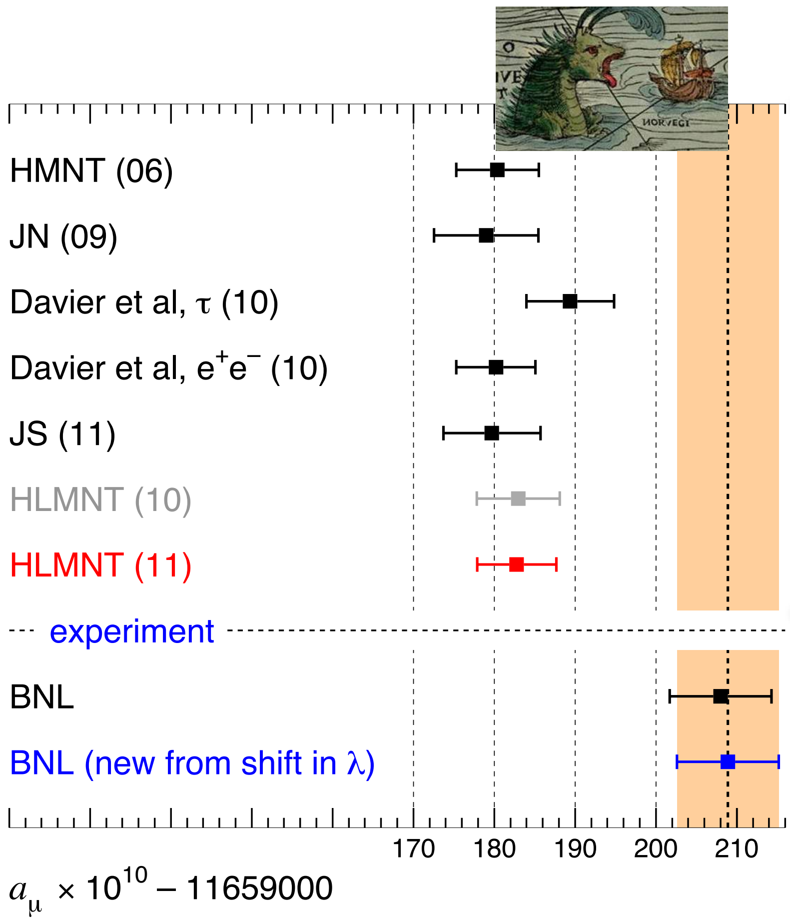


- What we really want to know is if there are any new monsters lurking in the loops

Progress on the hunt, thus far…

$a_\mu(\text{exp}) = 116\ 592\ 089\ (63) \times 10^{-11}$ (0.54 ppm)

$a_\mu(\text{thy}) = 116\ 591\ 802\ (49) \times 10^{-11}$ (0.42 ppm)

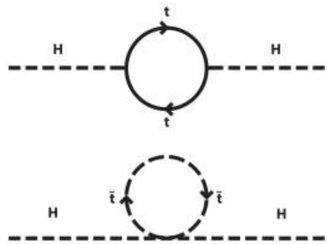


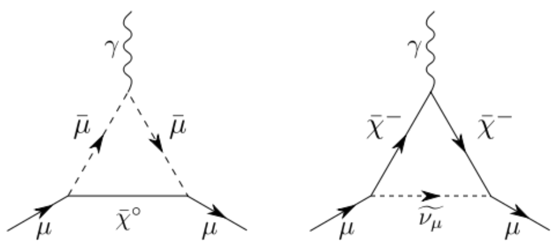
Theoretical evaluations

Last experimental result from BNL

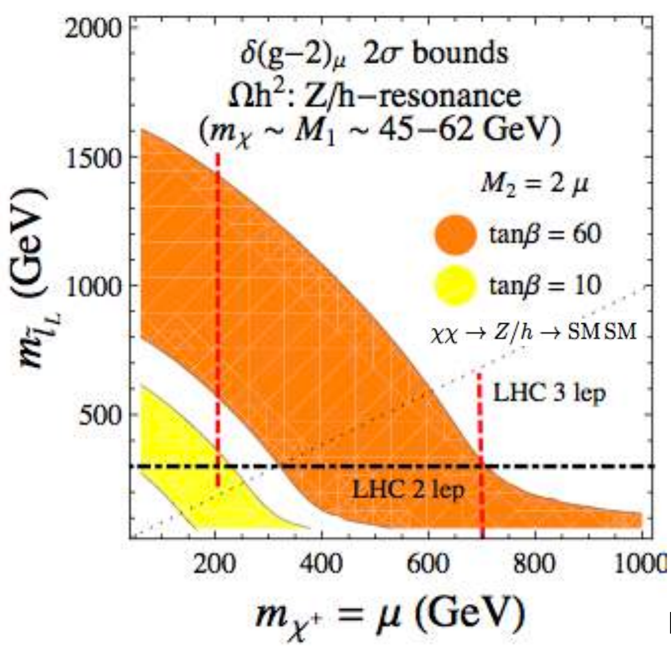
- The last a_μ experiment ended at BNL in 2001
- 3σ discrepancy with the theoretical expectation
- Goal of FNAL g-2 is to reduce the experimental error by a factor of 4

What monsters might there be? SUSY





arXiv:1503.08219v1



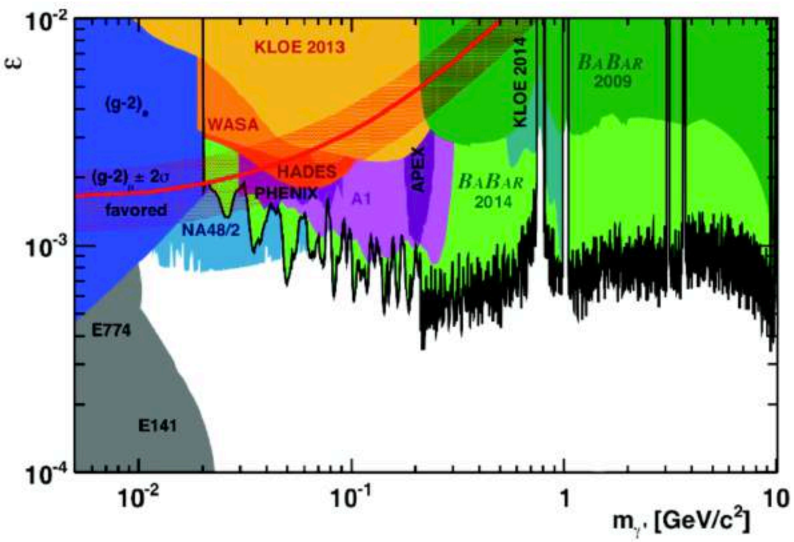
- The Higgs mass has now been measured at the LHC (and predicted long before that due to precision electroweak fits) to be ~125 GeV
- Theoretically, expectation is that the Higgs should acquire a much heavier mass from loops with heavy SM particles, e.g. top quark
- Supersymmetry postulates a new class of particles who can enter the loops and effectively cancel the

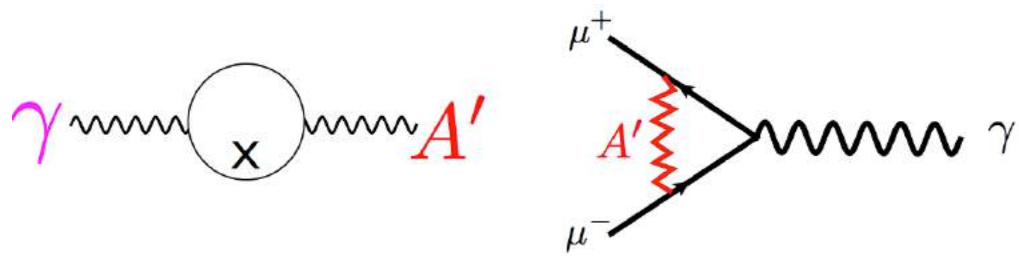
$$a_{\mu}(SUSY) \approx (\mathrm{sgn}\mu) 130 \times 10^{-11} \tan\beta \left(\frac{100\mathrm{GeV}}{\tilde{m}}\right)^2$$

- Complementary to direct searches at the LHC
  - Sensitive to sgn μ and tan β
  - Contributions to g-2 arise from charginos and sleptons while LHC direct searches are most sensitive to squarks and gluinos

What monsters might there be? Dark Matter

- Through cosmological observations, e.g. galaxy rotation curves, lensing, there appears to be much more mass in the universe than expected
- Many theories arising to explain the dark matter
- One example is the dark photon, which is a new U(1) gauge symmetry that would weakly couple standard model particles to dark matter

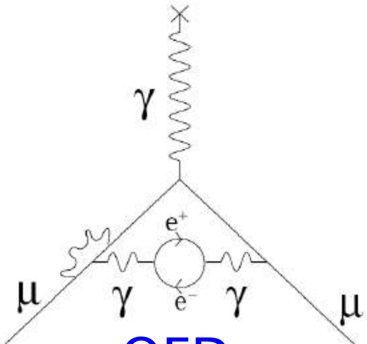




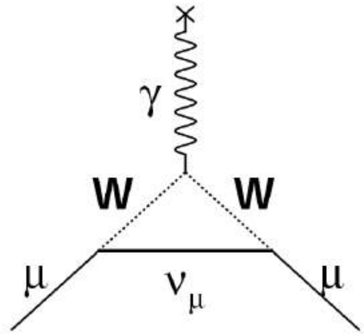
- Dark photon can also impact the magnetic moment of the muon
- Many search underway for direct production
  - Visible decay modes now highly constrained

Standard Model Calculation

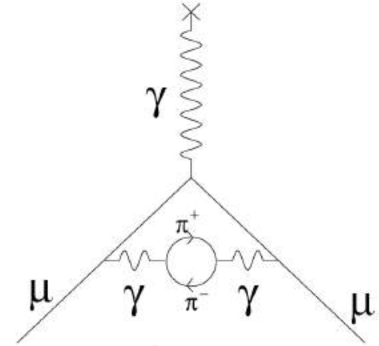
Calculating a_μ (thy)



QED



Electroweak



Hadronic

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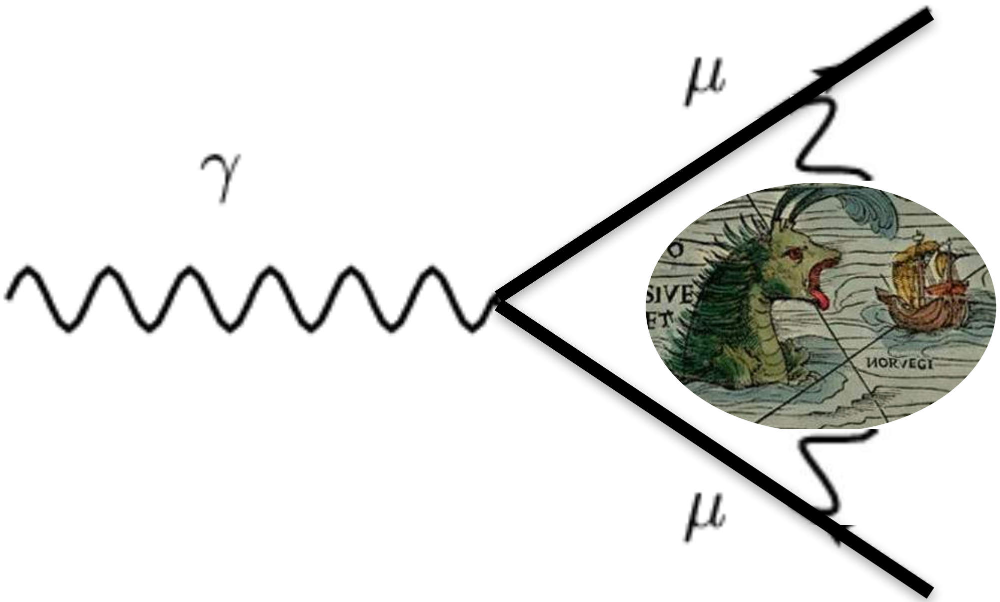


- To determine if there are any new monsters in the loops we first need to understand what the normal creatures contribute

Standard Model contributions to a_μ

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	-98.4 ± 0.7
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

- Theoretical contribution is dominated by QED component
- Error is dominated by hadronic terms (loops with quarks)
- For comparison, the discrepancy is…

$$a_\mu^{\exp} - a_\mu^{SM} = (261 - 287 \pm 80) \times \mathbf{10^{-11}}$$

*Davier et al, Eur. Phys. J. C (2011) 71:1515
**Hagiwara et al, J. Phys. G38, 085003 (2011).
† Prades et al Lepton Moments

QED contributions to a_μ by order

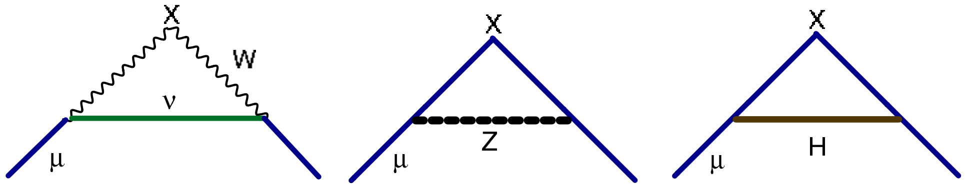
Table: $a_\mu(\text{QED})$ at each order $2n$, scaled by 10^{11}

order $2n$	using $\alpha(\text{Rb})$	using $\alpha(a_e)$
2	116 140 973.318 (77)	116 140 973.213 (30)
4	413 217.6291 (90)	413 217.6284 (89)
6	30 141.902 48 (41)	30 141.902 39 (40)
8	381.008 (19)	381.008 (19)
10	5.0938 (70)	5.0938 (70)
sum	116 584 718.951 (80)	116 584 718.846 (37)

2015 NEW!

- Standard Model QED has now been calculated out to 5 loops...12672 Feynman diagrams
- Non-controversial since the QED is so exact

Electroweak contributions to a_μ



$+38.9 \times 10^{-10}$ -19.4×10^{-10} $\leq 3.3 \times 10^{-14}$

$$a_\mu^{EW(1)} = 195 \times 10^{-11}$$

- 2-loop calculation completed $a_\mu^{EW(1+2)} = (154 \pm 2) \times 10^{-11}$
- Higgs mass now determined…thanks LHC!

$$a_\mu^{EW(1+2)} = (153.6 \pm 1.0) \times 10^{-11}$$

- Error completely negligible
- Interesting to note that discrepancy between SM and BNL result is nearly double the weak contribution

→ Plenty of room for monsters!

Now for the hadronic terms

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_{\alpha}$
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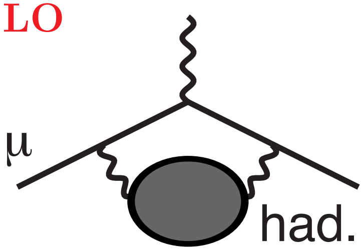
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

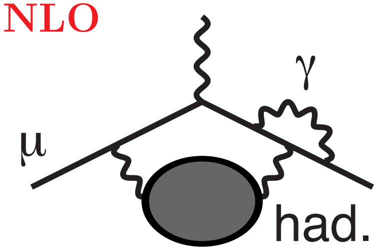
- Hadronic contributions divided into 3 terms

$$= \quad a_\mu^{\text{had,VP LO}} + a_\mu^{\text{had,VP NLO}} + a_\mu^{\text{had,Light-by-Light}}$$

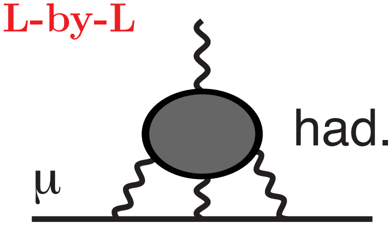
LO



NLO

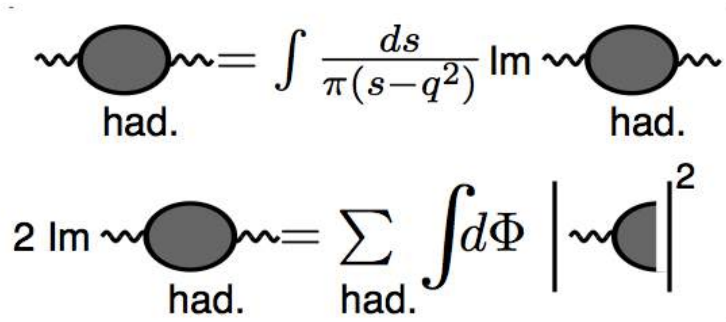


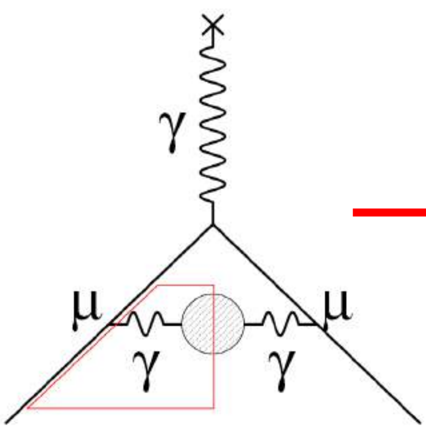
L-by-L

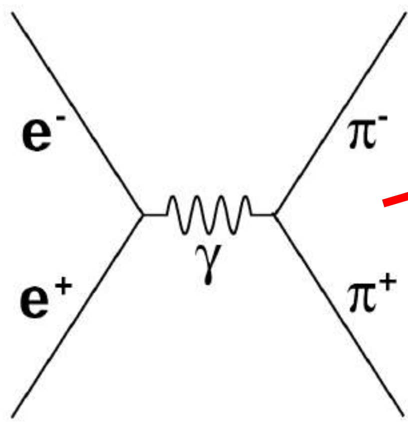


LO hadronic contributions

- Due to non-perturbative nature of QCD at low energies, an analytical calculation is not possible
- Instead, we rely on using the optical theorem and a dispersion integral to calculate the contribution from direct measurements of $e^+e^- \rightarrow$ hadrons
- Contribution heavily weight to low sqrt(s)







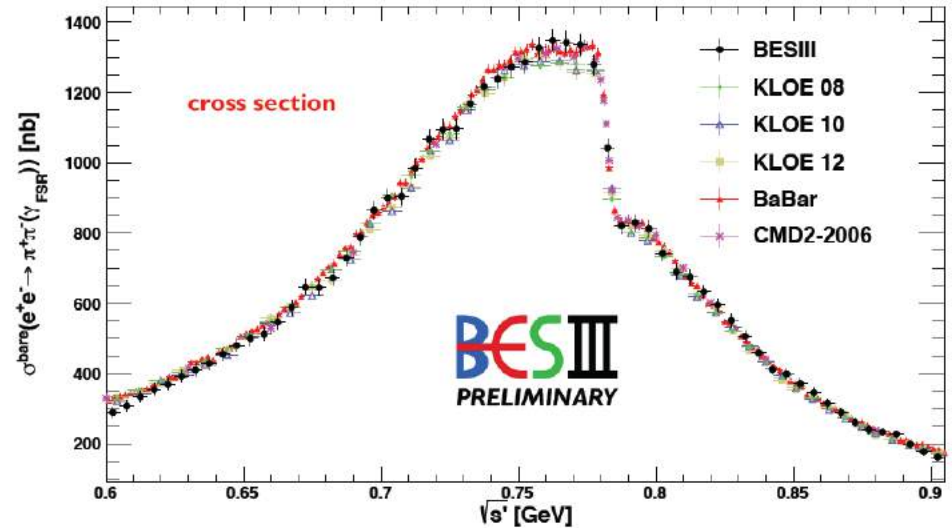
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

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

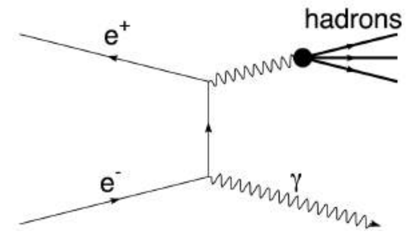
Error is dominated by how well we have determined the cross sections

The 'theory' error on the LOHVP is actually exp

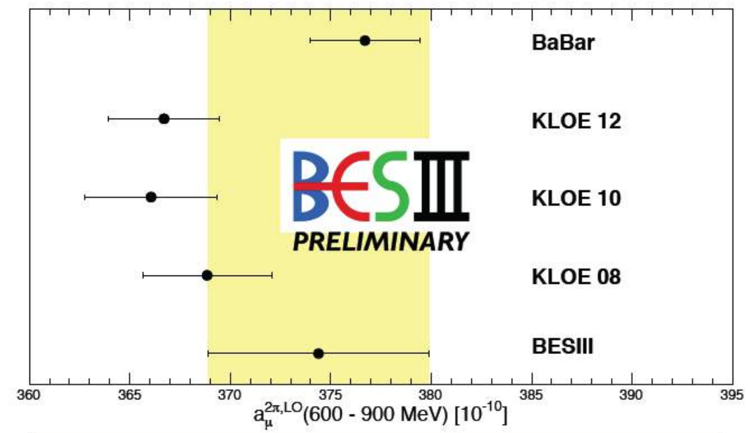
Comparison to other experiments



- KLOE pioneered ISR method



Result for (g-2)



Experiment	$a_\mu^{2\pi,LO}$ (600 – 900 MeV) [10^{-10}]
BaBar	$376.7 \pm 2.0_{stat} \pm 1.9_{sys}$
KLOE 08	$368.9 \pm 0.4_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 10	$366.1 \pm 0.9_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 12	$366.7 \pm 1.2_{stat} \pm 2.4_{sys,exp} \pm 0.8_{sys,theo}$
BESIII (preliminary)	$374.4 \pm 2.6_{stat} \pm 4.9_{sys}$

- Examples of $e^+e^- \to \pi\pi$ data, recent development where BESIII upgraded collider is starting to produce data
- Other data coming from upgrade machines at Novosibirsk, KLOE and Belle

Hadronic light-by-light

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_{\alpha}$
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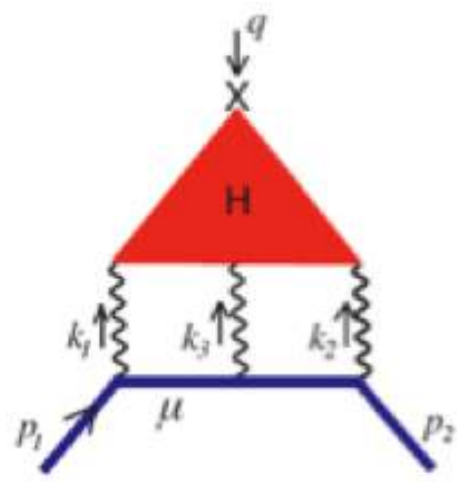
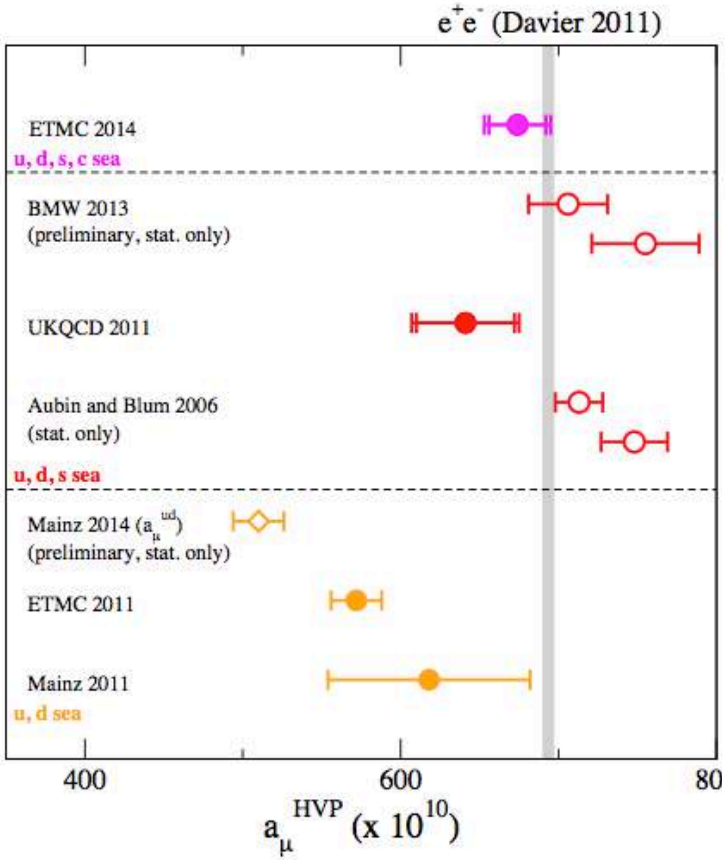
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

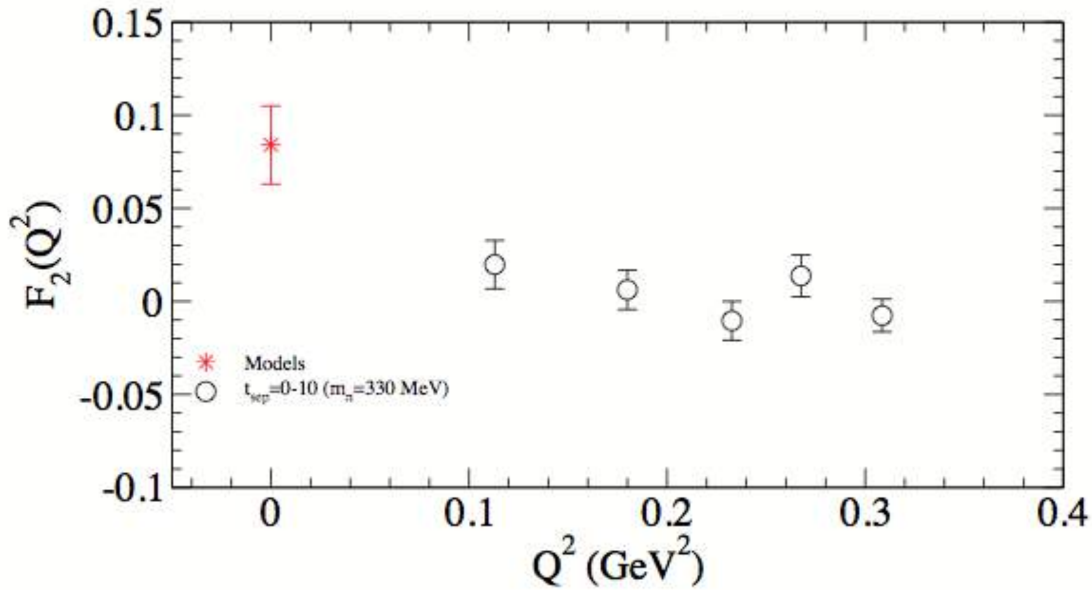
- 2nd largest error in SM calculation
- Cannot be directly related to data in the same way as the LOHVP
- Calculations are model-dependent based on Chiral Perturbation Theory plus short distance constraints
- Probably the limiting term in the future theory, but hope that lattice QCD will be able to produce a first principles calculation



Lattice calculation of g-2



Blum et al. Phys.Rev.Lett. 114 (2015)



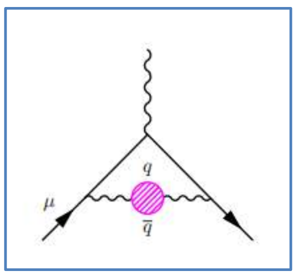
- Can see from plot on left that the LOHVP calculations are converging…expectation is that they will become competitive with e+e-
- On right some initial attempts from Tom Blum to calculate HLBL by factorizing the QED part
- For both LOHVP and HLBL, results from the lattice would have a profound impact

Lattice calculation of g-2

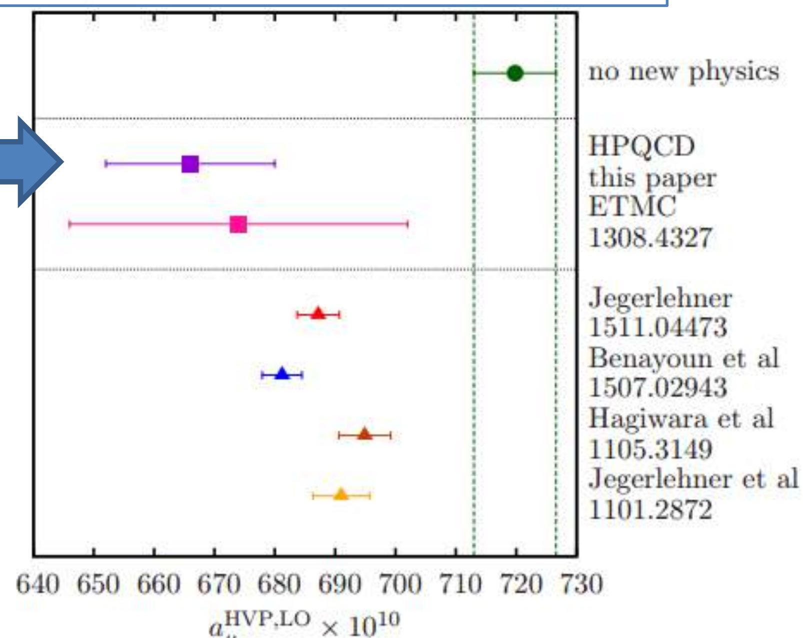
- Jan 2016 publication using physical pions, and u,d,s,c connected loops* → **Precision at 2%** (x4 improvement)
- Can match experimental HVP with currently available routines and computing resources

The hadronic vacuum polarization contribution to a_μ from full lattice QCD

Bipasha Chakraborty,[1] C. T. H. Davies,[1,*] P. G. de Oliveira,[1] J. Koponen,[1] and G. P. Lepage[2]
(HPQCD collaboration),[†]
[1]*SUPA, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK*
[2]*Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, New York 14853, USA*
(Dated: January 14, 2016)



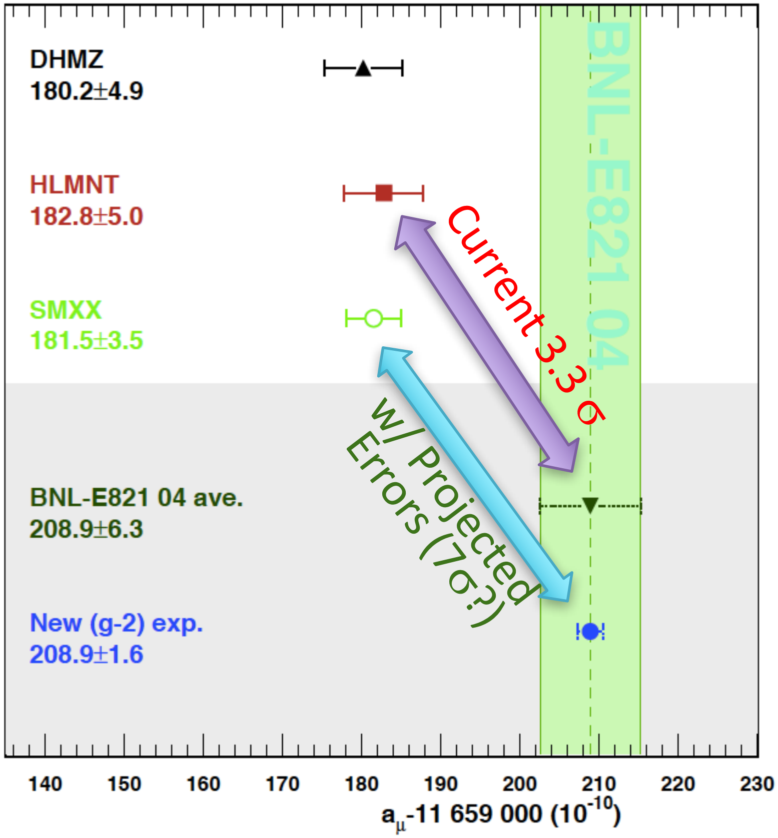
3.5σ from lattice alone



*__connected diagrams__ (which dominate)
2% uncertainty includes an estimate of $(0 \pm 9) \times 10^{-10}$ in error quoted in paper

Projections

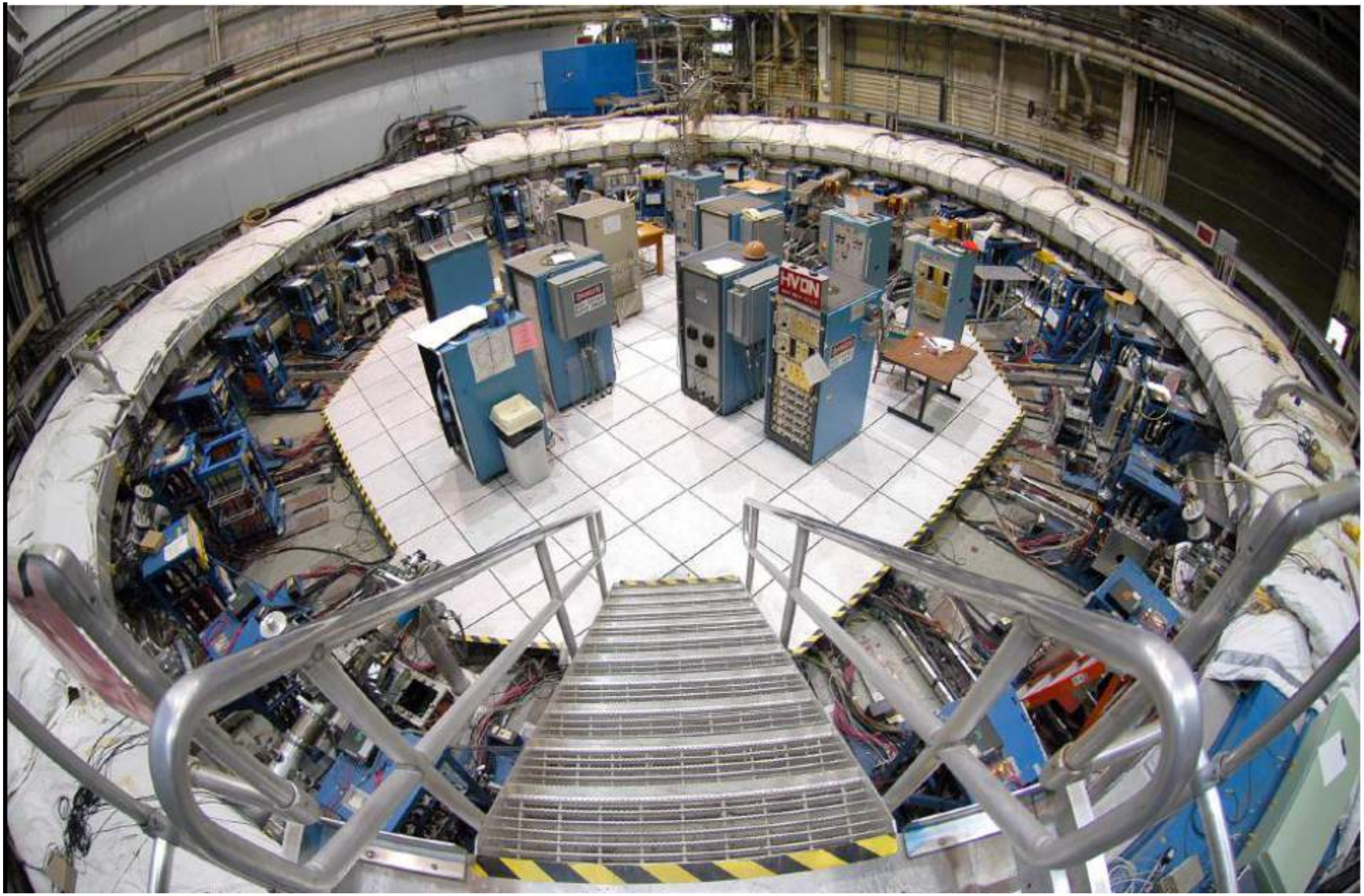
http://arxiv.org/pdf/1311.2198v1.pdf



- With new e+e- → hadrons data samples coming from upgraded machines, it is anticipated that the theory error will come down by about 30% in the next 5 years
- Lattice community getting heavily involved with avenues to independent calculations
- Goal of the new muon g-2 experiment at Fermilab is to reduced the experimental error by a factor of 4
  - If current discrepancy persists, significance will be pushed beyond 5σ discovery threshold
  - Anticipated theoretical improvement could lead to >7σ

Principles of Muon g-2 Expt

For perspective, this is the device at BNL



What we need to do…

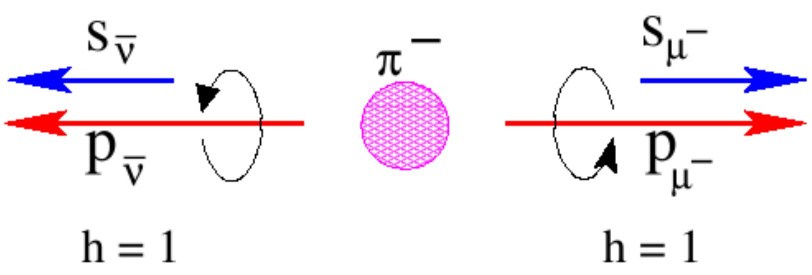
- 4 Major Steps
  - Transport BNL storage ring and associated equipment to Fermilab ✔
  - Construct a new experimental hall to house the storage ring ✔
  - Modify anti-proton complex to provide a high-purity, intense beam of 3.094 GeV/c muons
  - Upgrade various subsystems (injection devices, field monitoring, detectors & DAQ) to meet requirements for rates and systematics

- Overall plan to achieve a factor of four improvement in precision
  - Increase statistics by x 21 to reduce stat error from 0.46 ppm to 0.1 ppm
  - Reduce systematics on ω_a from 0.2 ppm to 0.07 ppm
  - Reduce systematics on ω_p from 0.17 ppm to 0.07 ppm

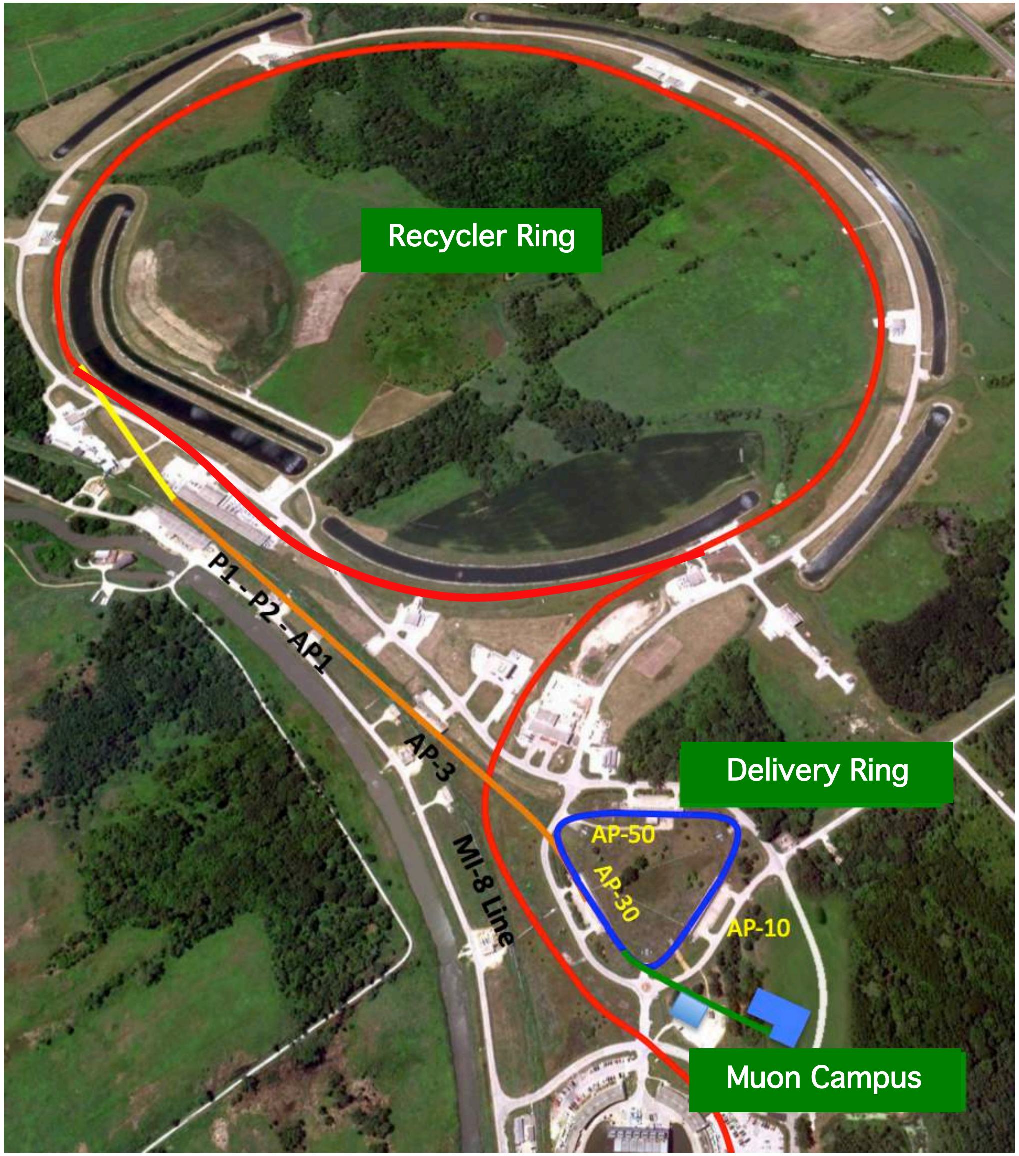
Need a polarized muon source

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

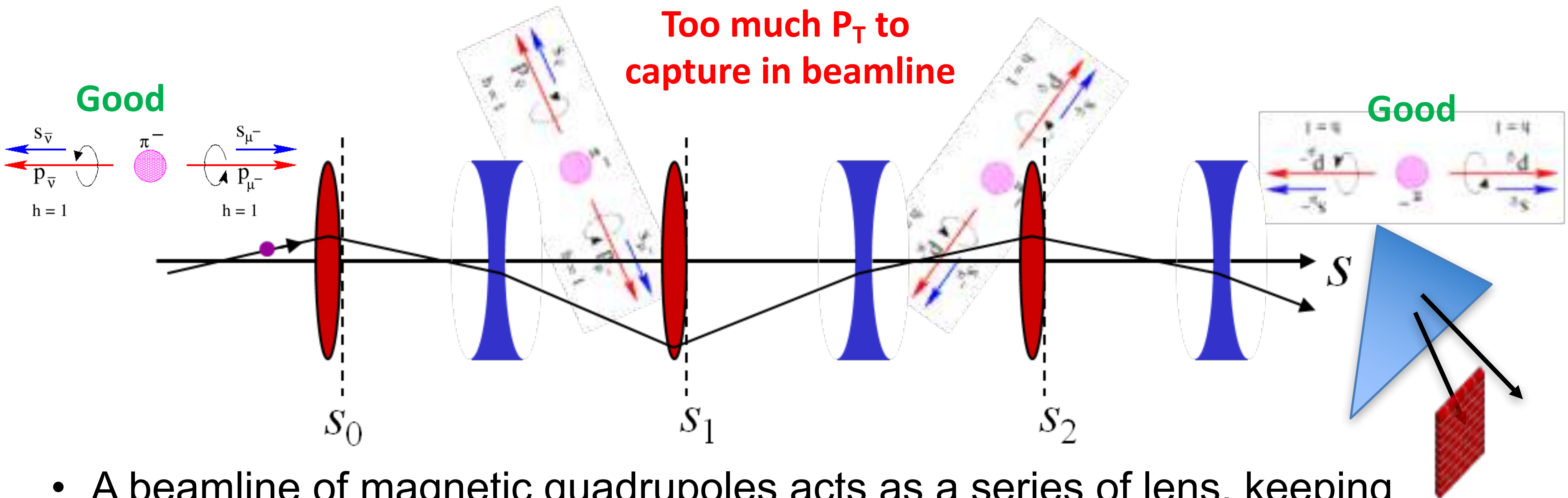
Pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$



- To first 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 highly polarized (+ and -)
- The positive and negative polarized muons have very different momenta → can select which one you want to keep with a bending dipole

Muon spin dynamics in a storage ring

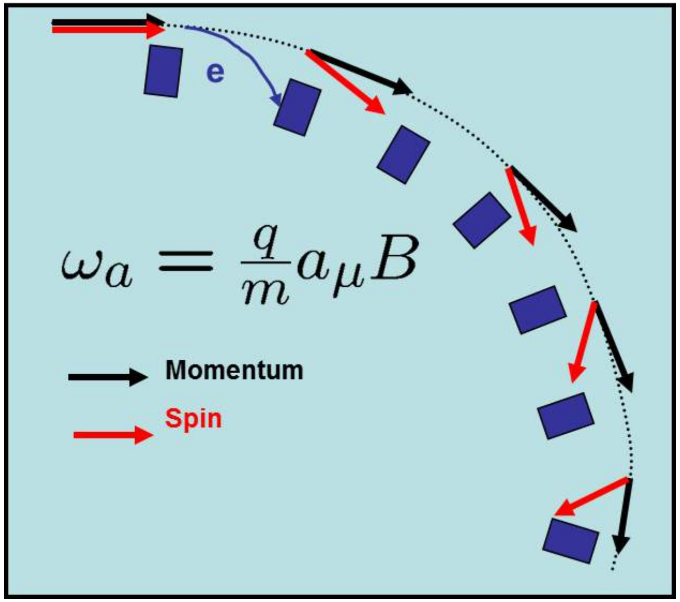
$$\omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc} \qquad \omega_C = \frac{eB}{mc\gamma}$$

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* !

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

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



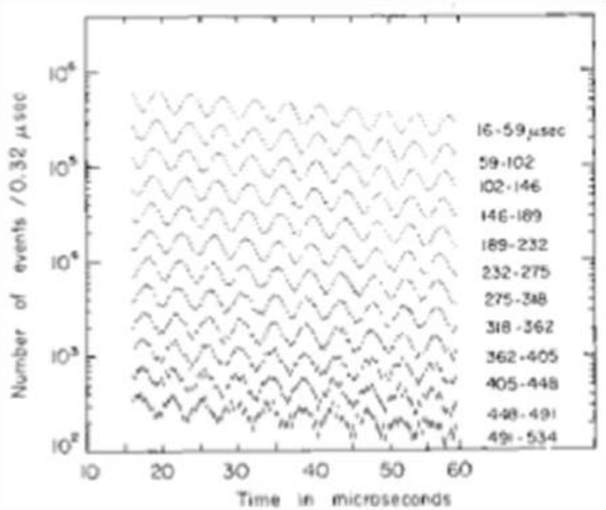
E field needed for vertical focussing

Muon g-2

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)

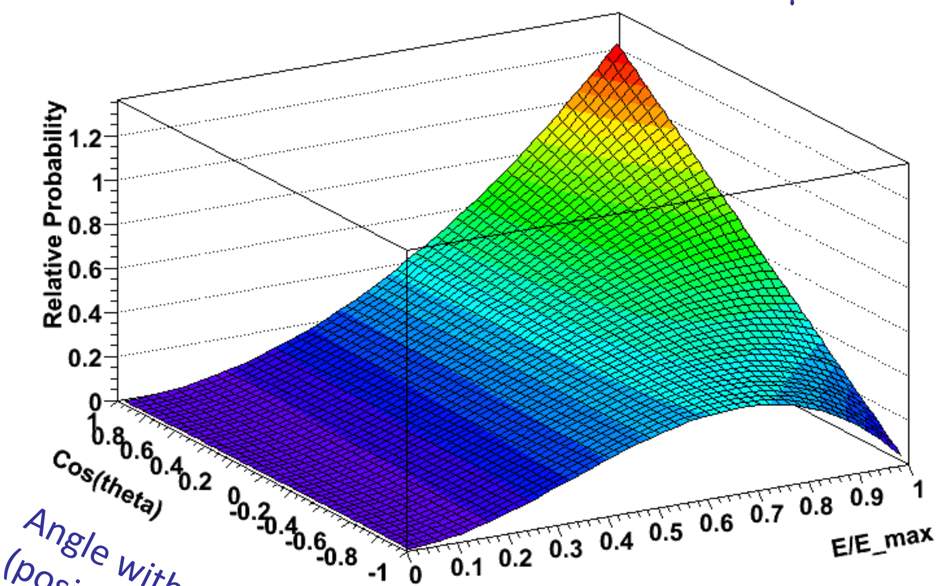


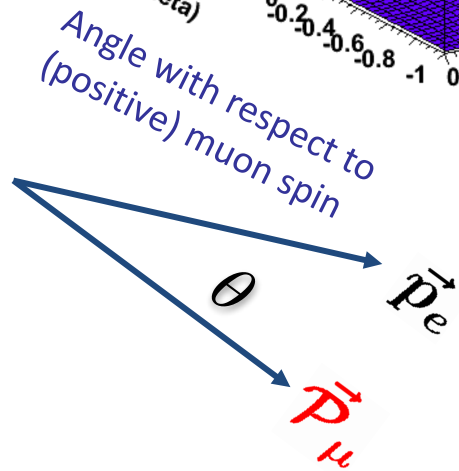
$a_\mu = 0.001\ 166\ 924(8.5)$ (± 7 ppm)
(sensitive to HVP)

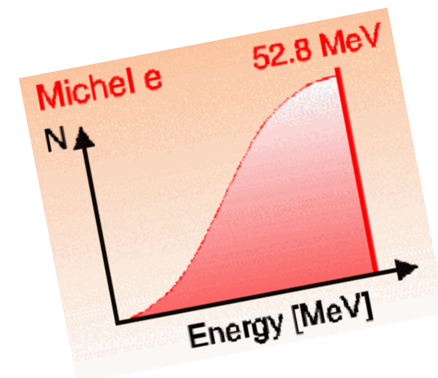
Analyzing the muon spin

Primary decay $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

- 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



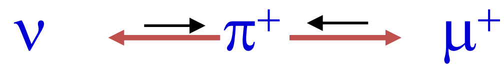


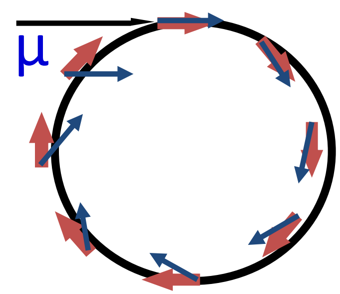


Recap the four key elements

(1) Polarized muons

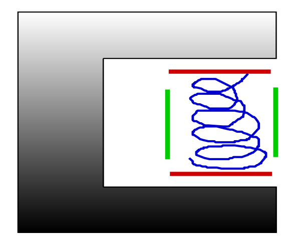
~97% polarized for forward decays



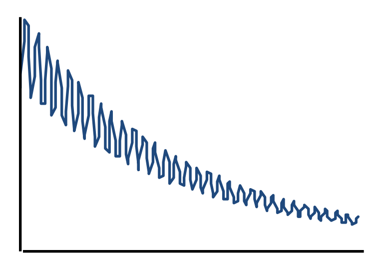


(2) Precession proportional to (g-2)

(3) P_μ magic momentum = 3.094 GeV/c



(4) Parity violation in the decay gives average spin direction



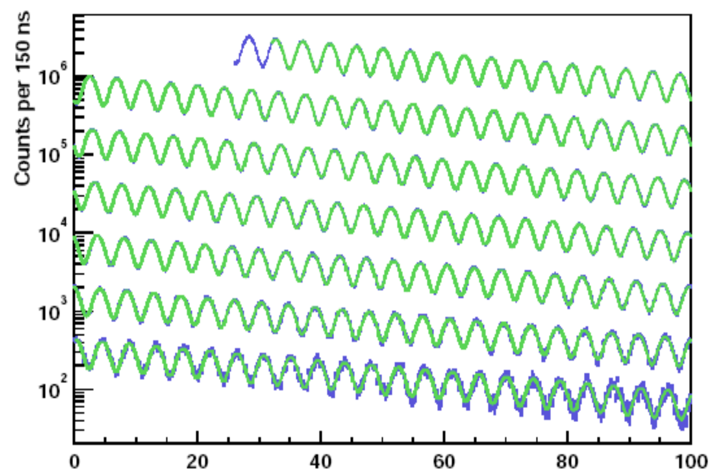
Extracting a_μ from experiment

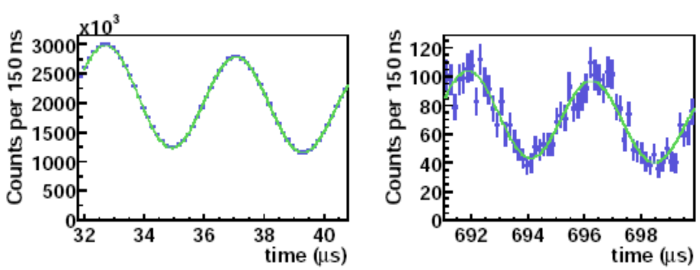
λ

taken from muonium hyperfine ←

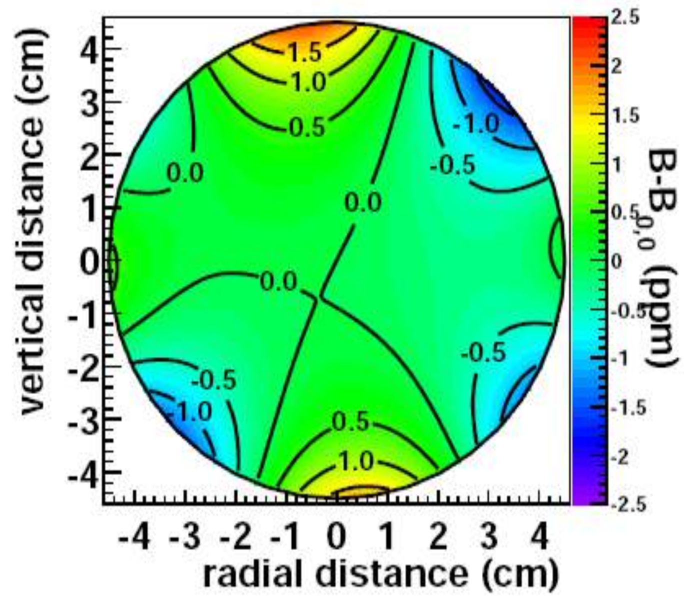
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

$$dN/dt = N_0(t)e^{-t/\tau}\left[1 + A(t)\cos(\omega_a t + \phi_a(t))\right]$$





At BNL stat error dominant!



	2001 [ppm]	2000 [ppm]
Total Syst Error	0.27	0.39
Statistical Error	0.66	0.62
Total Error	0.71	0.73

Combined total BNL error on a_μ 0.540 ppb

First challenge…getting the statistics

Item	Estimate
Protons per fill on target	10^{12} p
Positive-charged secondaries with $dp/p = \pm 2\%$	4.8×10^7
π^+ fraction of secondaries	0.48
π^+ flux entering FODO decay line	$> 2 \times 10^7$
Pion decay to muons in 220 m of M2/M3 line	0.72
Muon capture fraction with $dp/p < \pm 0.5\%$	0.0036
Muon survive decay 1800 m to storage ring	0.90
Muons flux at inflector entrance (per fill)	4.7×10^4
Transmission and storage using $(dp/p)_\mu = \pm 0.5\%$	0.10 ± 0.04
Stored muons per fill	$(4.7 \pm 1.9) \times 10^3$
Positrons accepted per fill (factors 0.15 x 0.63)	444 ± 180
Number of fills for 1.8 $\times 10^{11}$ events	$(4.1 \pm 1.7) \times 10^8$ fills
Time to collect statistics	(13 ± 5) months
Beam-on commissioning	2 months
Dedicated systematic studies periods	2 months
Net running time required	17 ± 5 months

Achieving required statistics is a primary concern

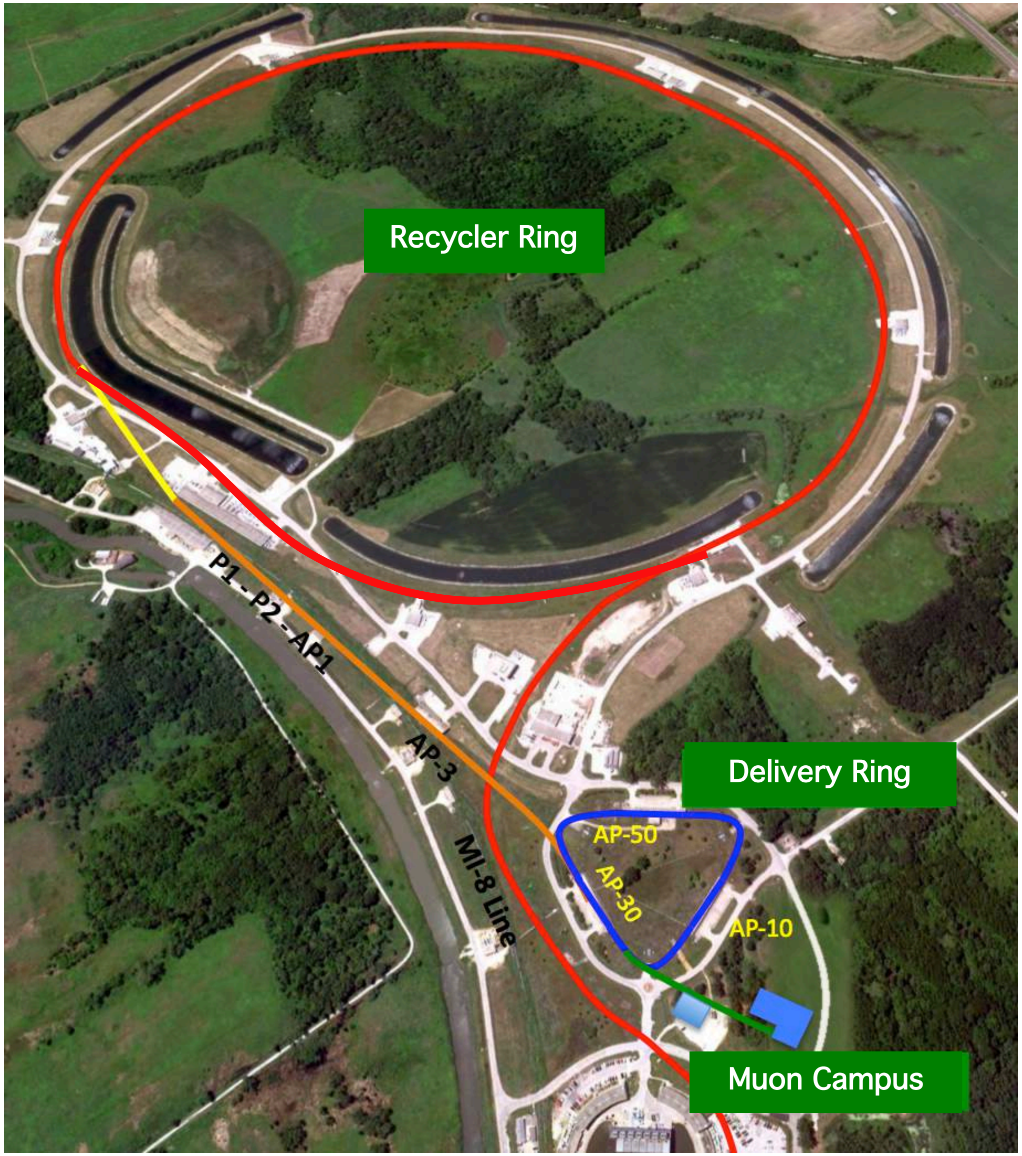
- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

Need a factor of 85 improvement in integrated beam coming from many other factors

Ratio of beam powers BNL/FNAL:

$$\frac{\text{4e12 protons/fill} * (\text{12 fills / 2.7s}) * \text{24 GeV}}{\text{1e12 protons/fill} * (\text{16 fills / 1.3s}) * \text{8 GeV}} = 4.3$$

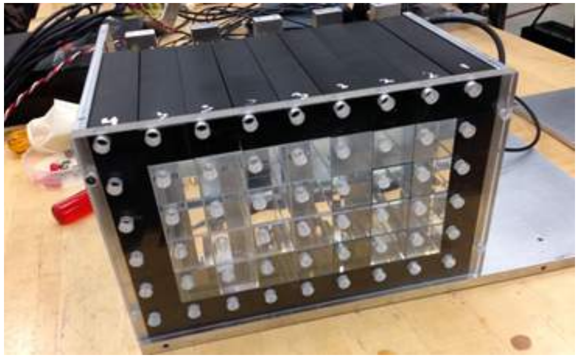
First challenge…getting the statistics

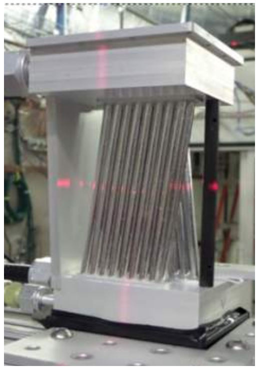


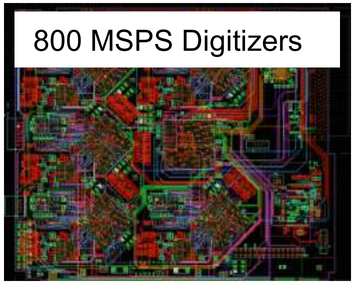
Achieving required statistics is a primary concern
- Need a factor 21 more statistics than BNL
- Beam power reduced by 4

Need a factor of 85 improvement in integrated beam coming from many other factors
- Collection of pions from lens
- Capture of decay muons in FODO channel
- p_π closer to magic momentum
- Longer decay channel
- Increased injection efficiency
- Earlier start time of fits
- Longer runtime

Detectors

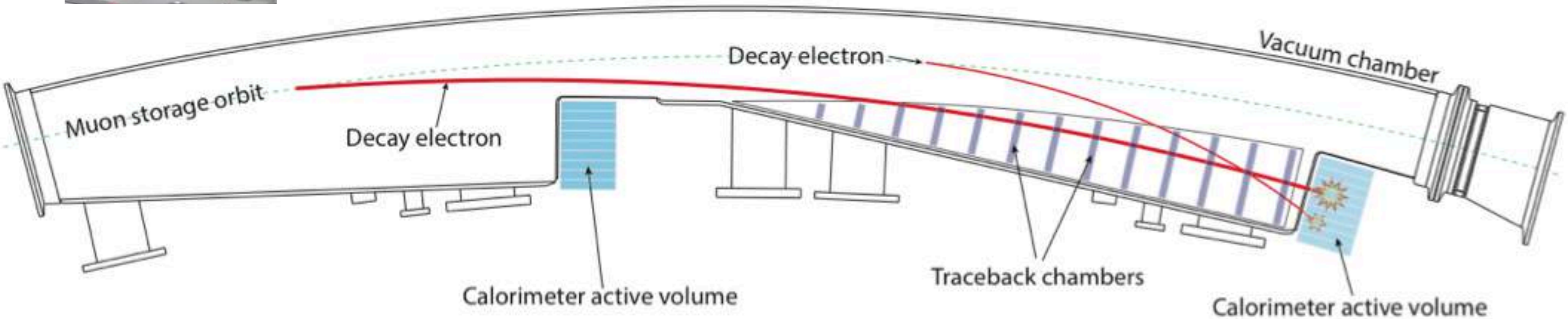






- Calorimeters 24 6x9 PbF_2 crystal arrays with SiPM readout
- New electronics and DAQ
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons
- Auxiliary detectors and slow controls to monitor beam properties and environmental conditions

Top view of 1 of 12 vacuum chambers



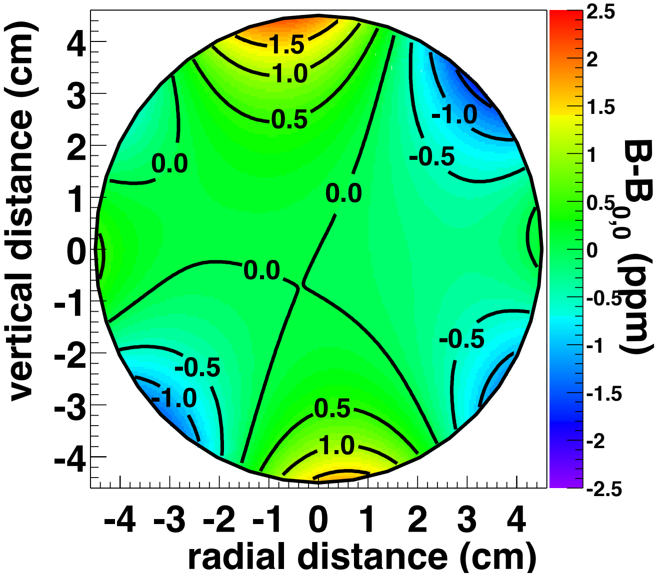
Second challenge..controlling ω_a systematic

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

- Tackling each of the major systematic errors with knowledge gained from BNL E821

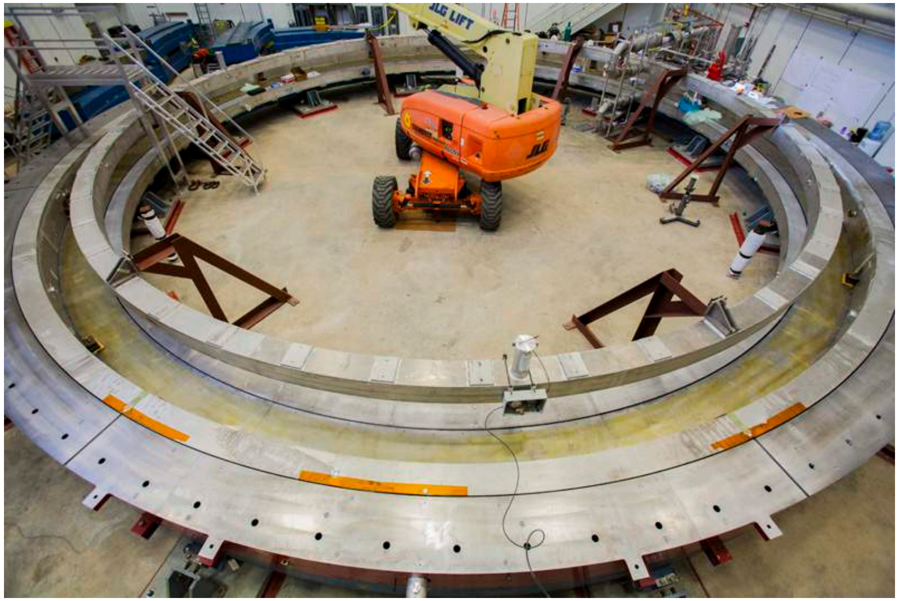
Third challenge…controlling ω_p systematic

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70



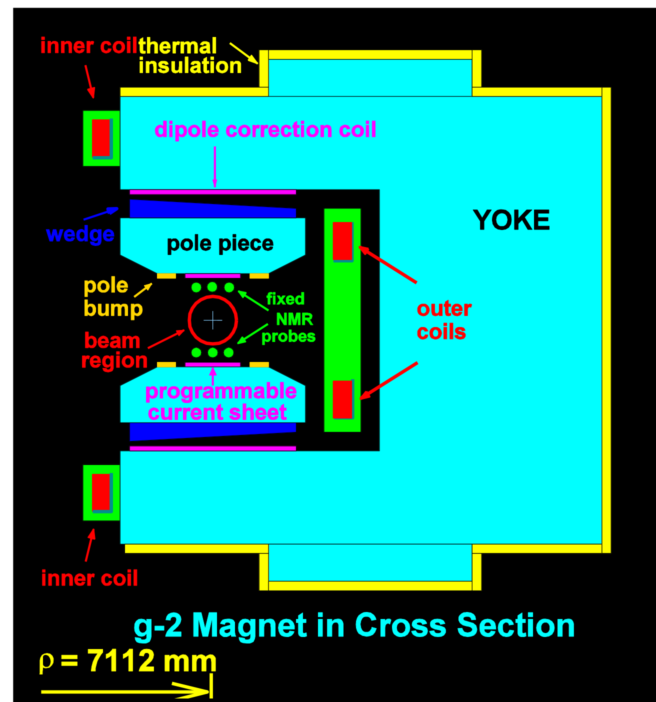
- 3 part plan to achieve 70 ppb
  - Start by making magnetic fields as uniform and stable as possible
  - Continuously monitor the magnetic field with proton NMR
  - Absolutely calibrate the proton NMR

Field stability and uniformity improvements

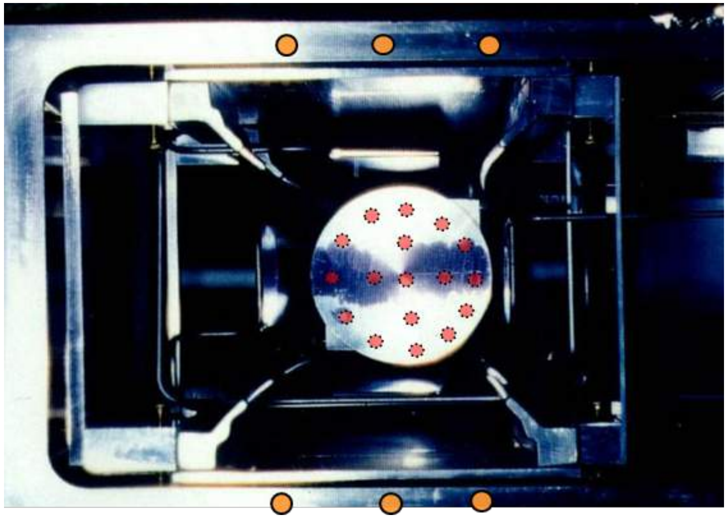


- Environmental
  - 2’9” heavily-reinforced floor installed on 12’ deep excavation of undisturbed soil
  - Temperature control to +/- 1C

- Construction tolerances
  - 26 ton pieces of yoke steel (30 of them) placed to 125 micron tolerance
  - Pole pieces aligned to 25 micron
- 9 months of interactively shimming B-field with bits of steel and current loops

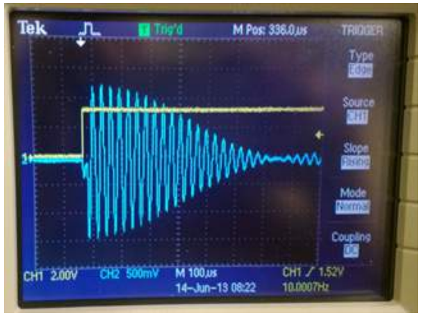


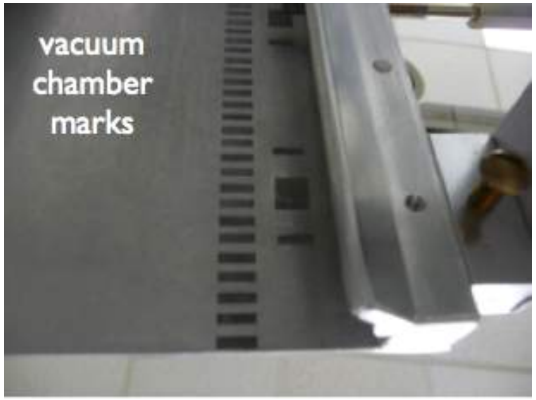
Monitoring magnetic field



- Fixed probes track field at top/bottom of vacuum chamber monitor field 24/7
  - Only half of 400 were used in BNL (primarily due to being in gradients that were too large) → building better NMR probes and in some case adjusting positions

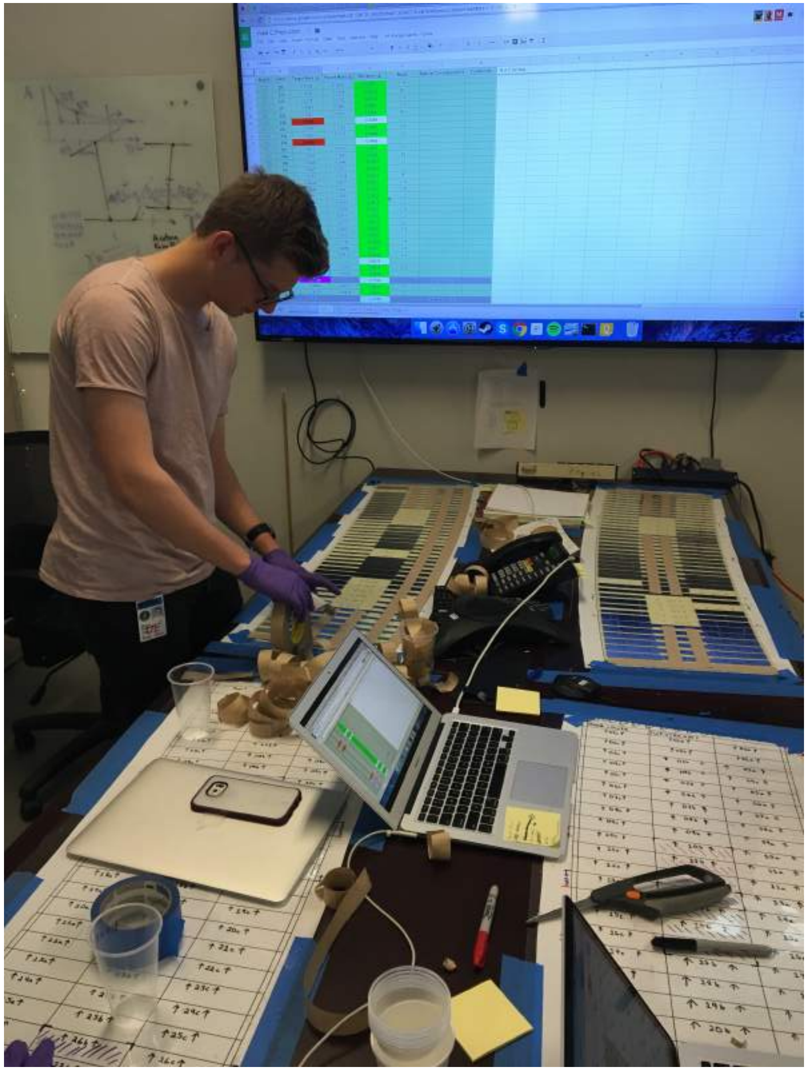
- NMR trolley pulls out of garage every day or two and maps field where muons live
  - More frequent trolley runs (every 2-3 days) to reduce extrapolation error
  - Optical encoders for better position resolution
- Digitizing FID signals





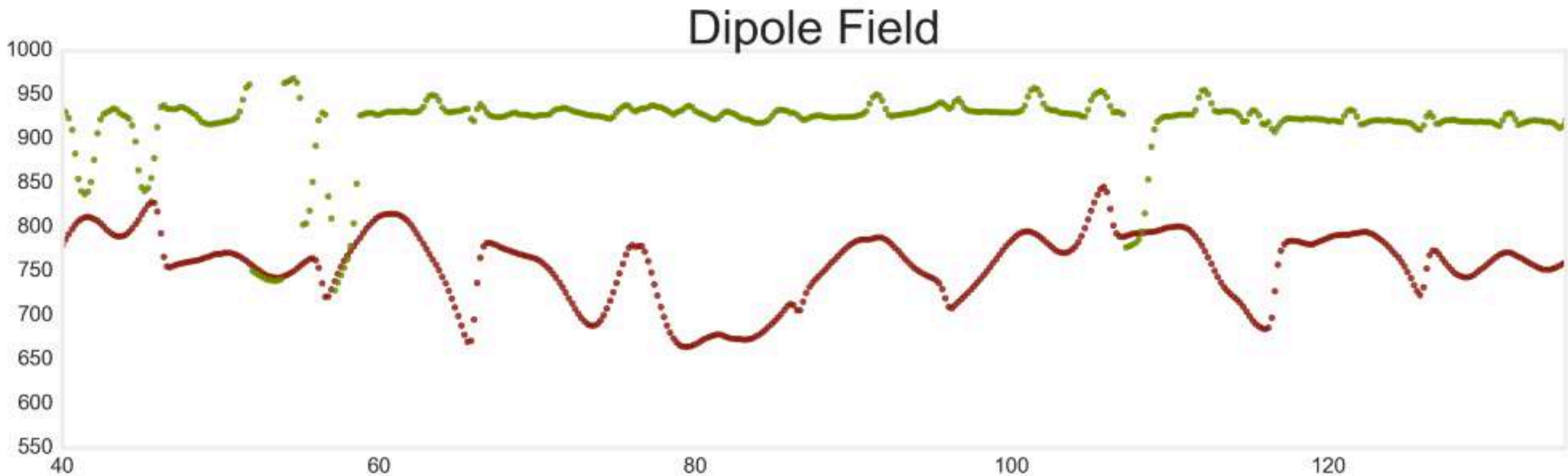
Laminating

- Different templates for
  - Upper vs Lower Poles
  - Left, Center, Right
- Affix to 20 mil G10 sheets
  - 123 slots, 4 inches radially, 1 mil thick, variable width
- Reserve spaces for Picket Fences

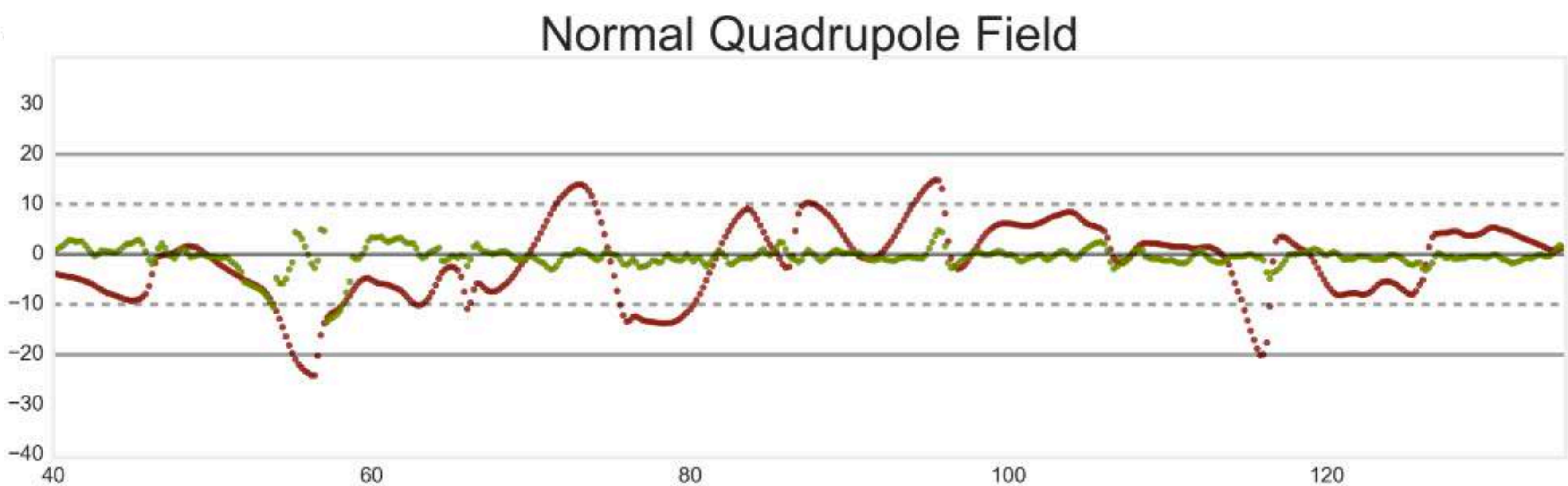


Finished Product → Ready to go

Results



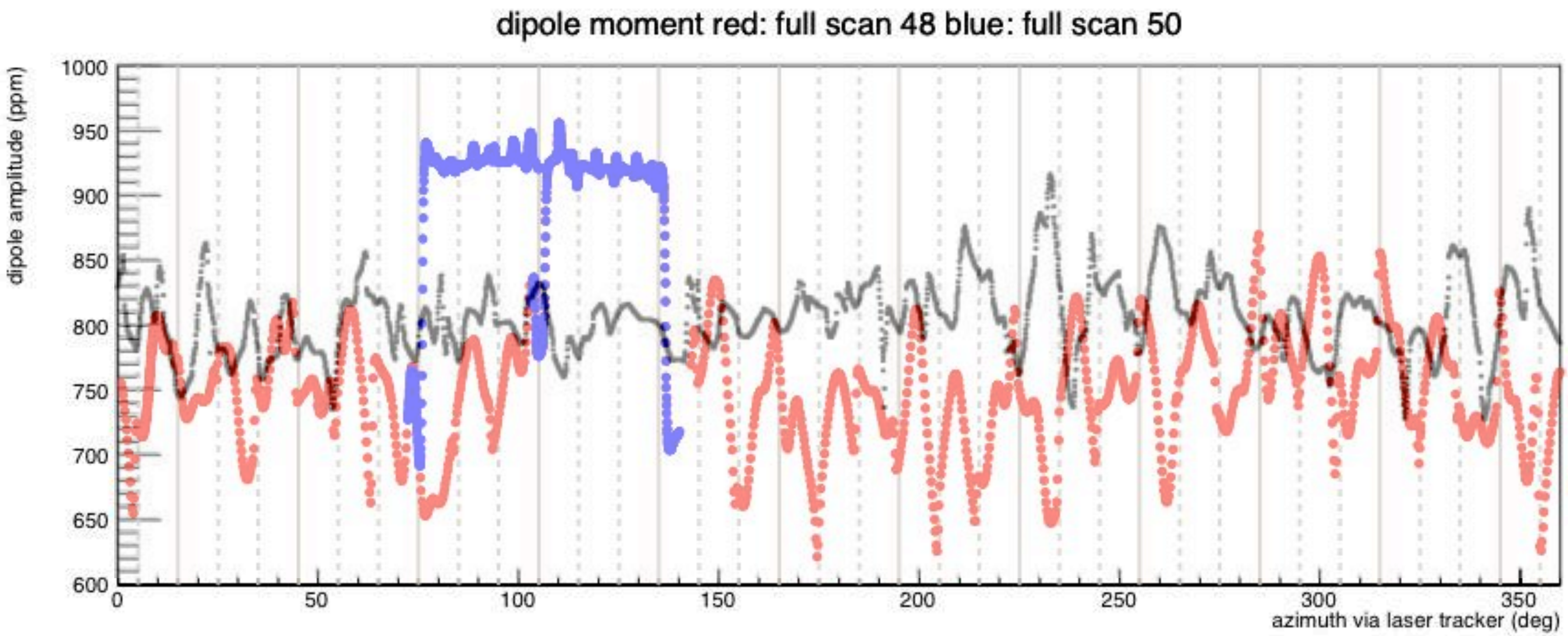
Dipole Field
1000
950
900
850
800
750
700
650
600
550
40
60
80
100
120



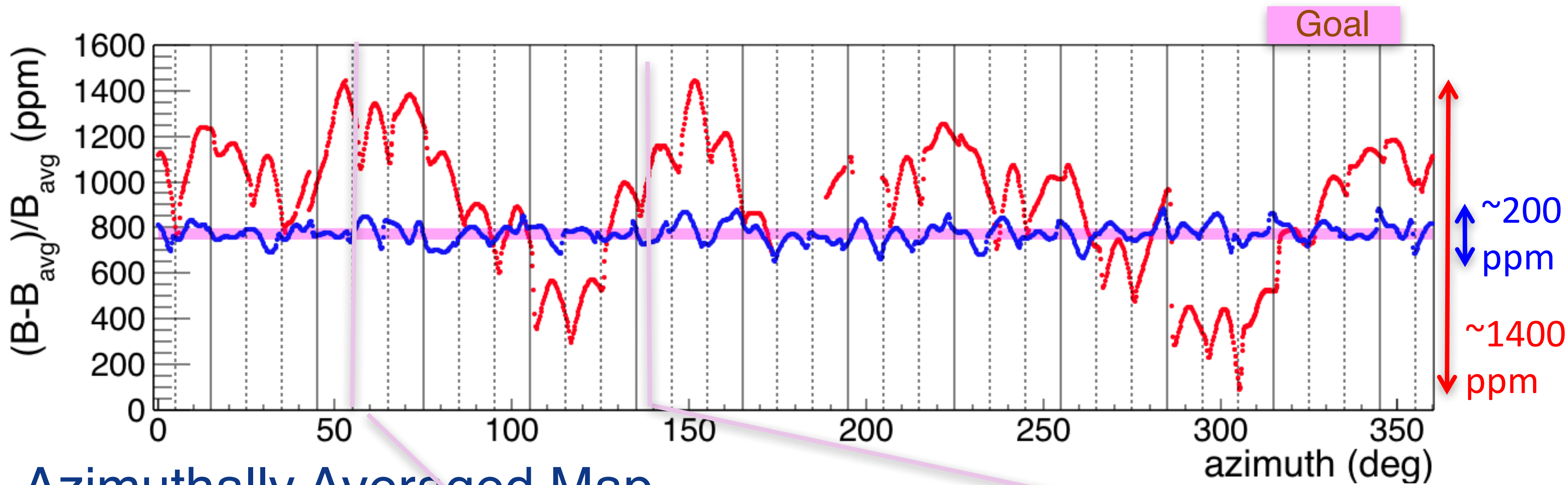
Normal Quadrupole Field
30
20
10
0
−10
−20
−30
−40
40
60
80
100
120

Install and Measure

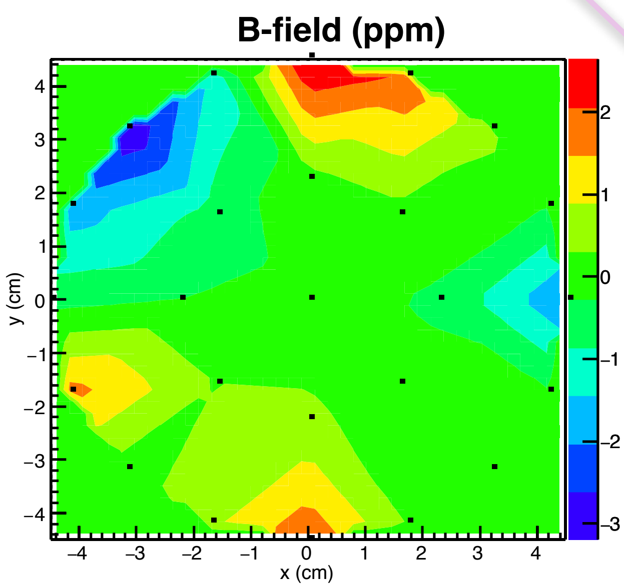
BNL PRD



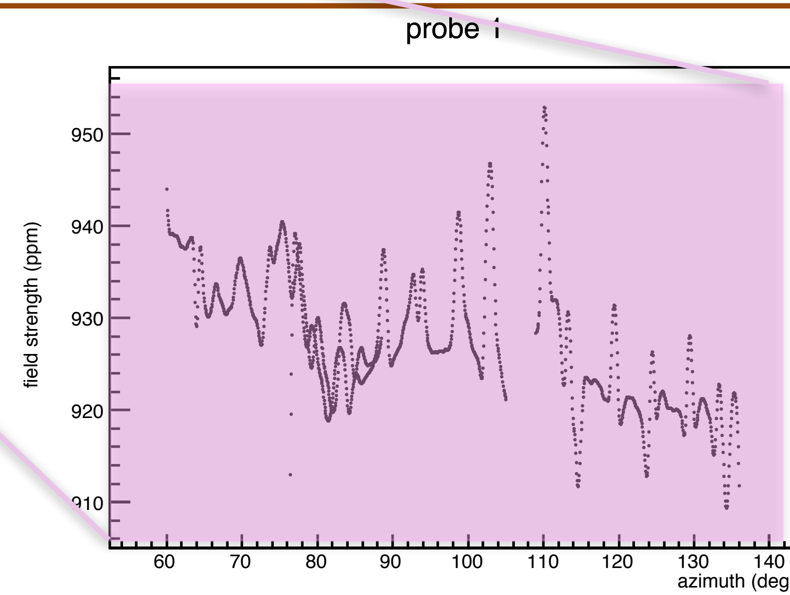
Field Improvements



Azimuthally Averaged Map



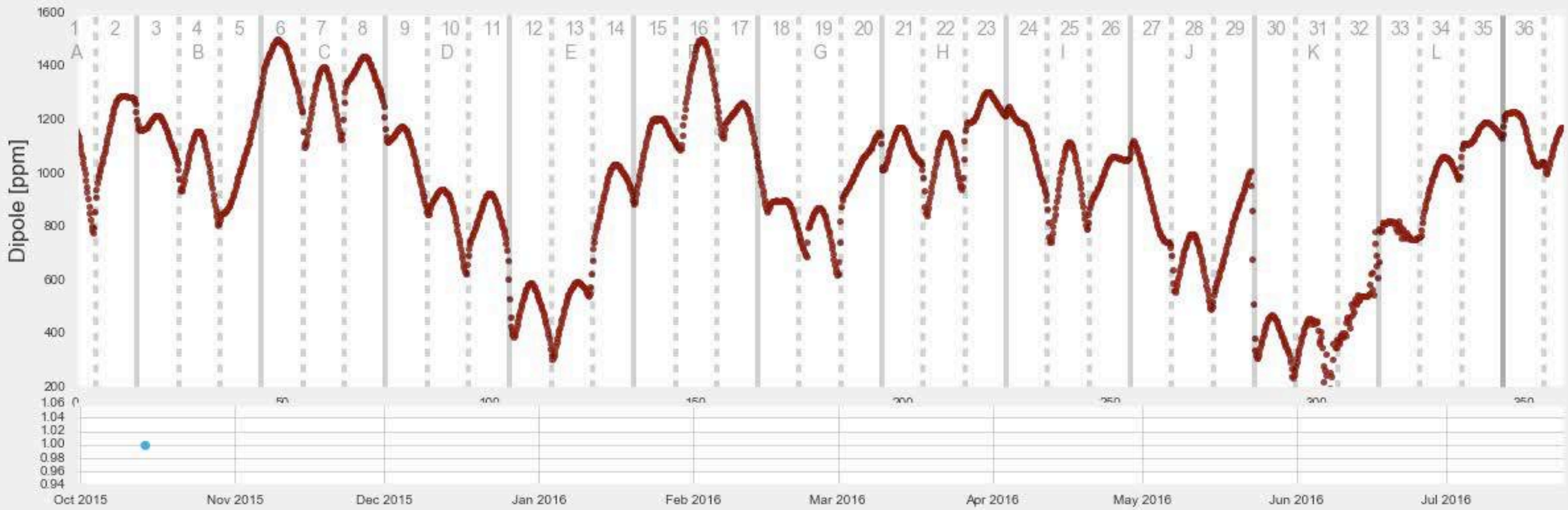
	Norm	Skew
Quad	0.20	-0.35
Sext	-1.11	1.12
Octu	-0.85	-0.72
Decu	0.63	-0.05
Dipole	-0.0	



July 2016

Summary Dipole

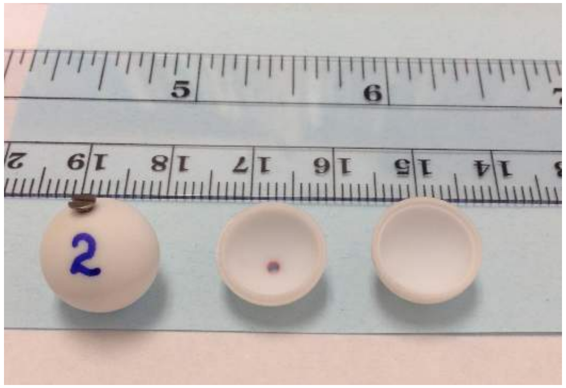
Video: M. Smith



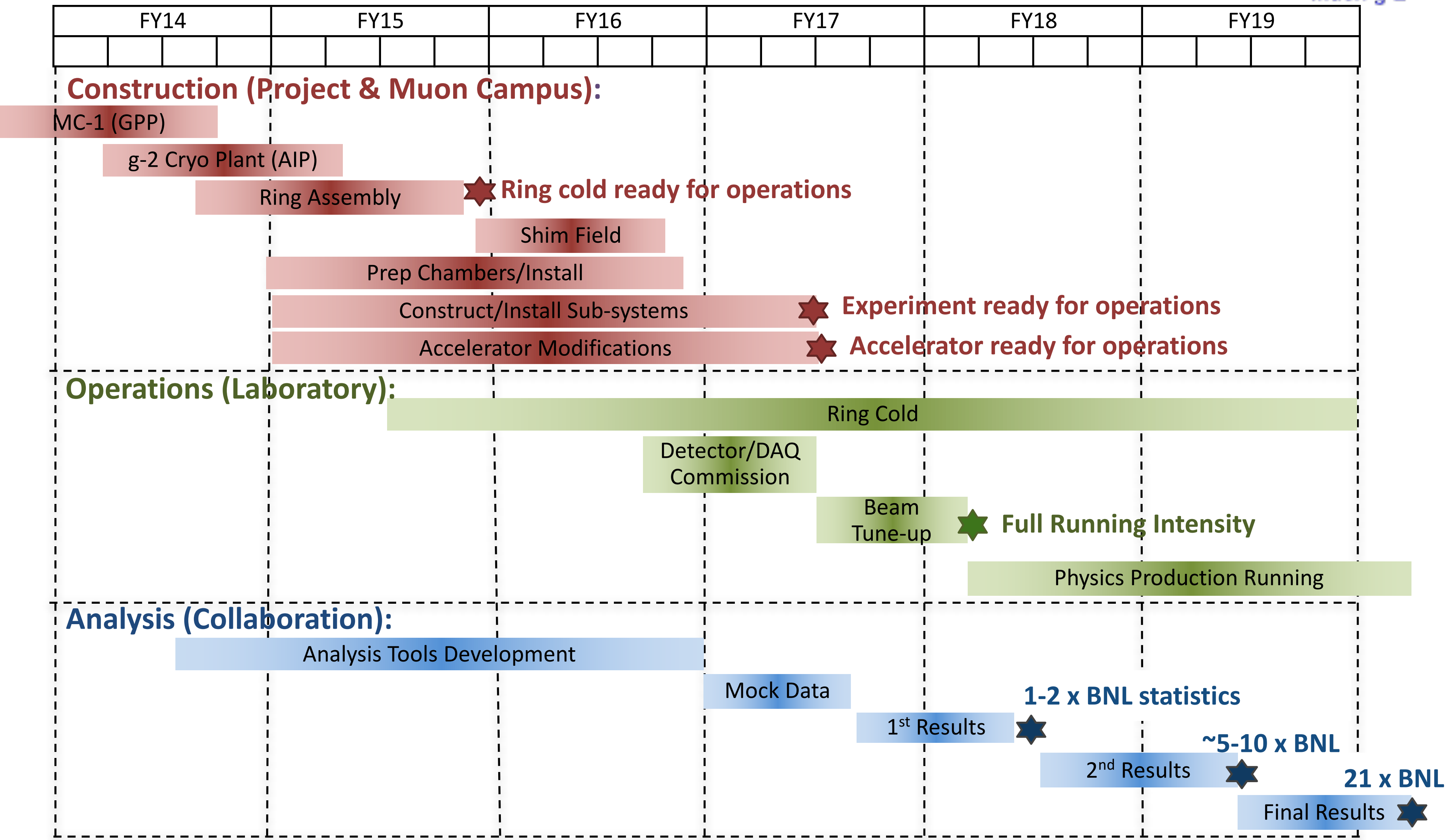
Calibrations Poles Wedges Laminations

Absolute calibration

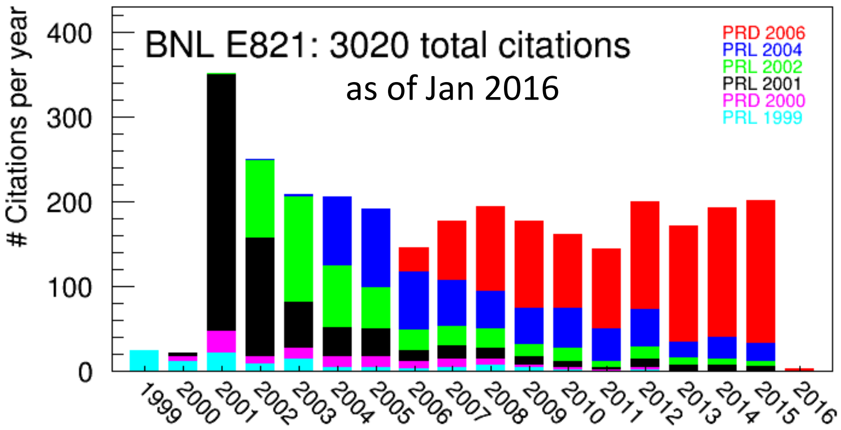
- Setting up a dedicated test facility at ANL to study and develop improved absolute calibration tests
- Learning how to make better spheres… water diamagnetic shielding is 26 ppm
- Developing He3 magnetometry



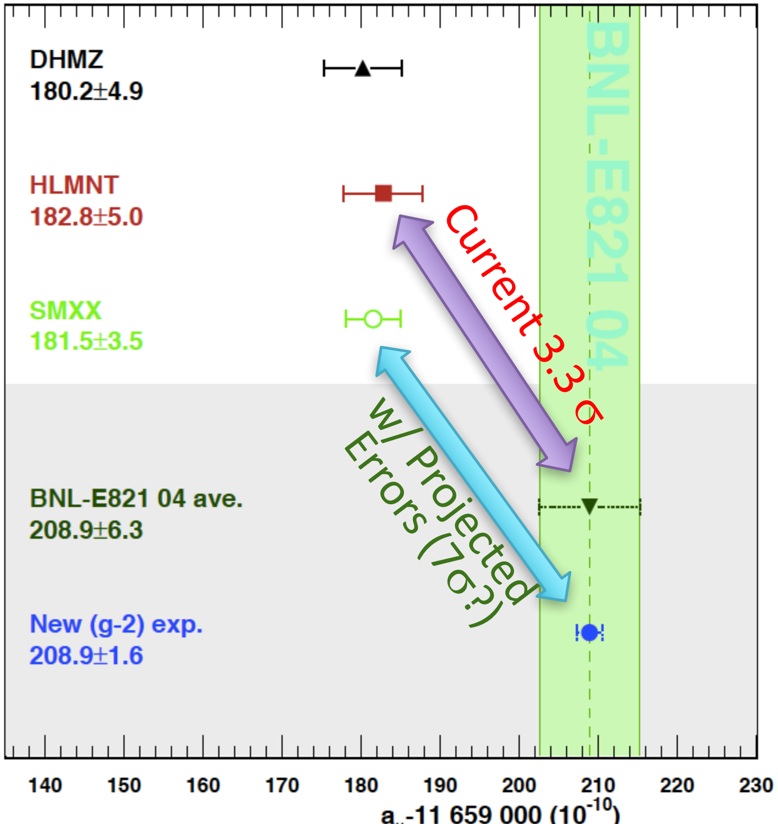
Big Picture Schedule-Project/Ops/Analysis



Conclusion



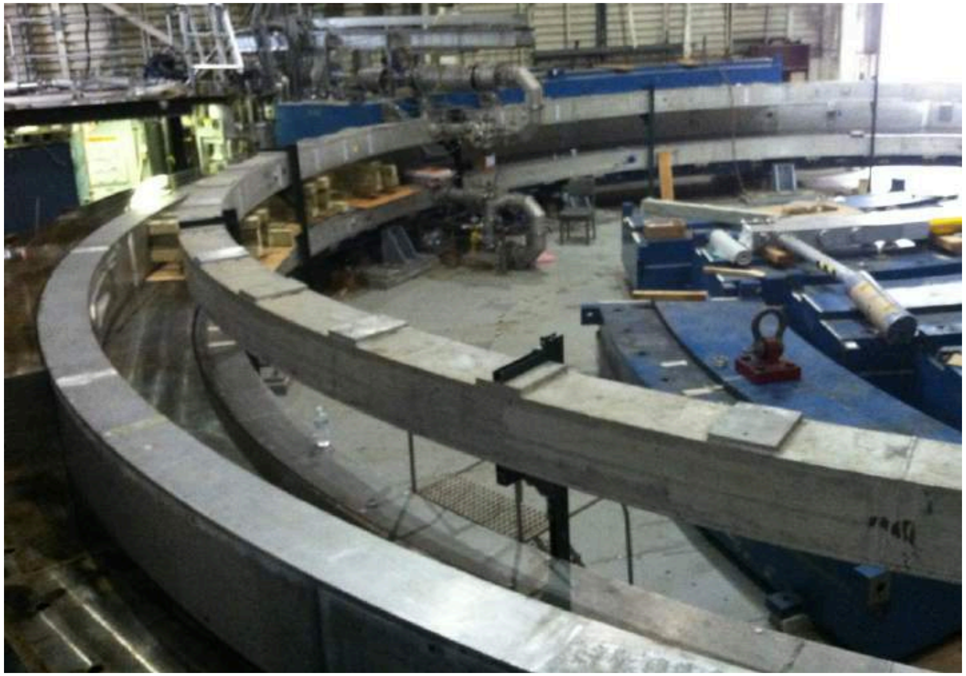
http://arxiv.org/pdf/1311.2198v1.pdf

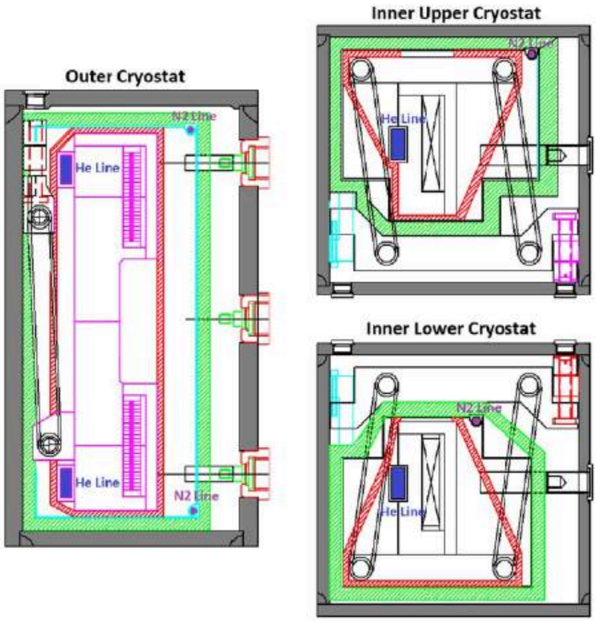


- Muon g-2 remains one of the most highly cited experimental results in particle physics
  - Provides constraints orthogonal to many other experiments in the quest for new physics
- The theoretical error will continue to improve over the next few years
  - 30% reduction from e+e- with high hopes for lattice QCD
- A new muon g-2 is under construction now….data in 2017…stayed tuned for first results in 2018!

Transport

Getting storage ring to FNAL was a challenge



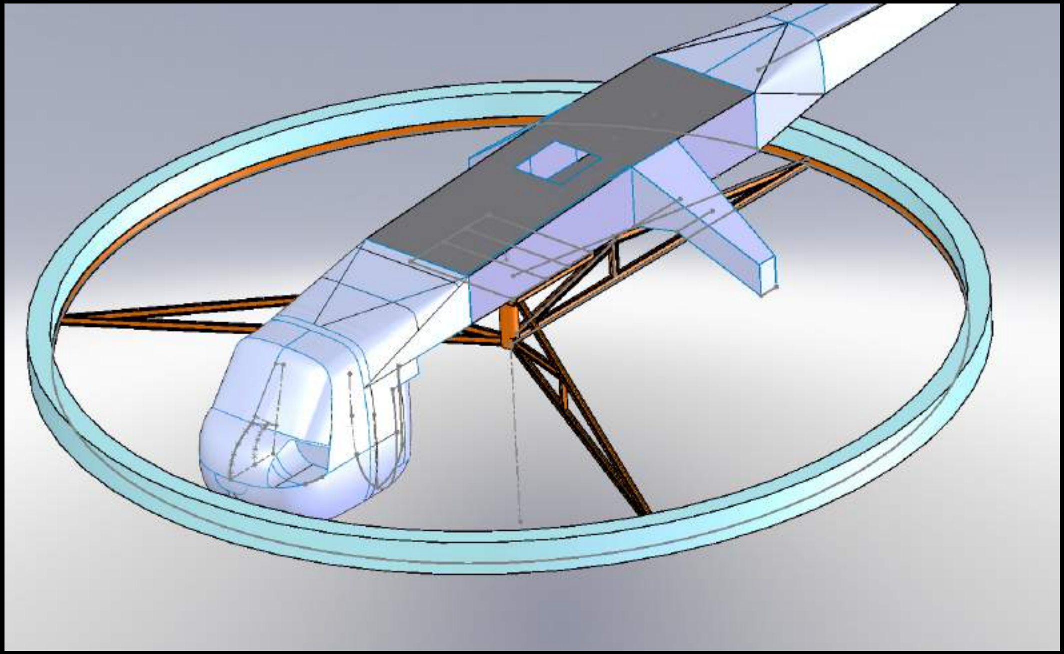


- The big pieces of steel (return yoke) come apart
  - Ship one 26T piece/flatbed
- The superconducting coils do not
  - Can't be cut and can't be unwound
  - $20M and 2 year delay to make from scratch

Can ship by barge most of the way…this is actual GPS during transport

Easiest way to get to Chicago is by barge,
but how to get from lab to barge?

First solution considered…



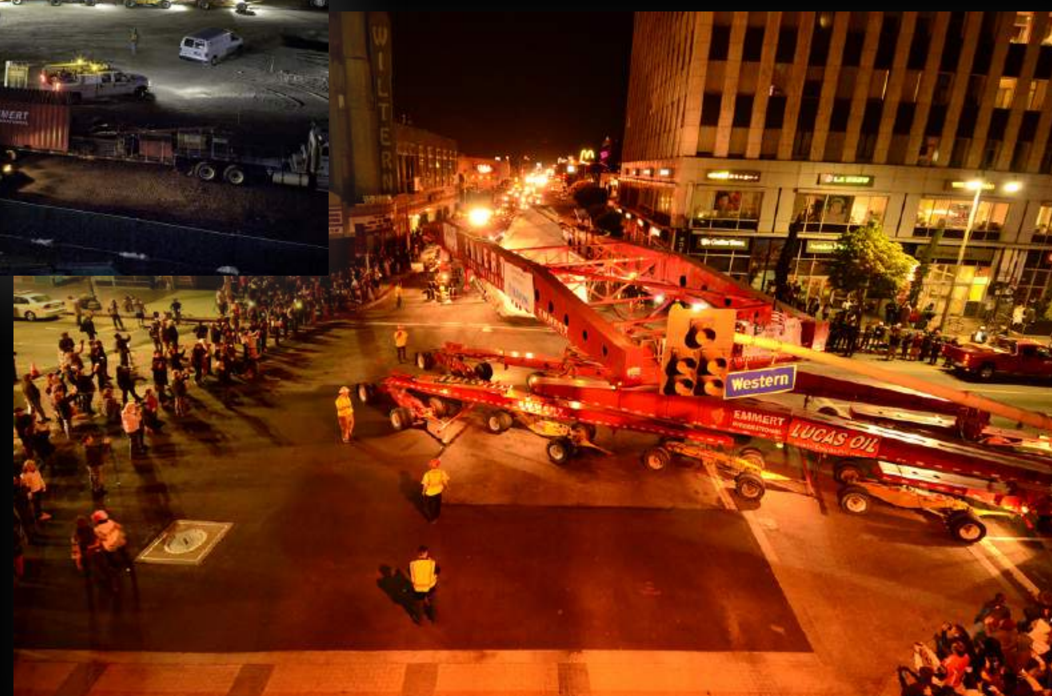
Took helicopter concept through full feasibility study. High risk due to vibrations, need to keep fixture light but coils rigid, and fact that helicopter needs 300 ft clear path (no humans)

Instead we hired Emmert International..

Family started business 40 yrs ago

World leader in specialized hauling

Might have seen them on TV a couple of years ago moving the rock through LA



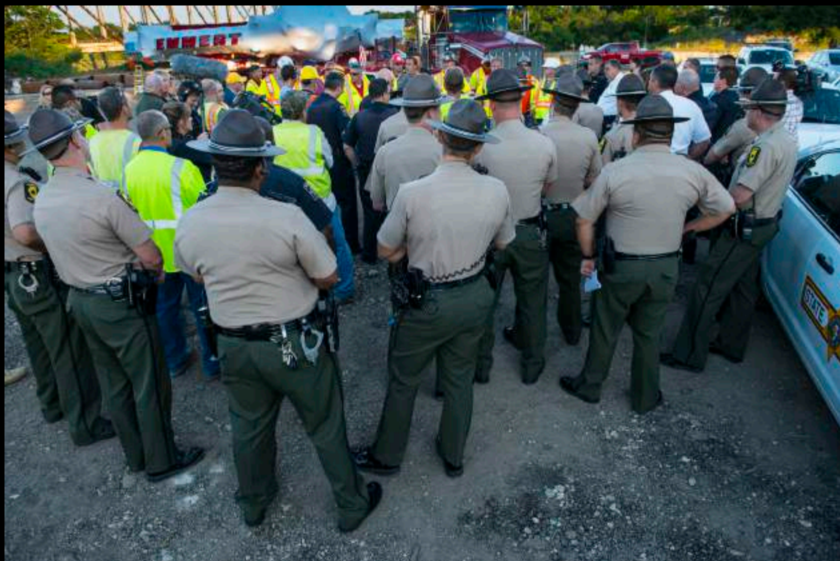
Moving 50 ft diameter Al rings without flexing by >1/8”

The barge deck flexed by way more than the spec on rings

Offloading in Lemont, IL…30 miles from FNAL

Closing two interstates in Chicago…

Enthusiasm…


EMMERT


EMMERT
EMMERT
STOP


Muon Down
The Road!


EMMERT
EMMERT
EMMERT
INTERNATIONAL

After the crowds left…

Science as art

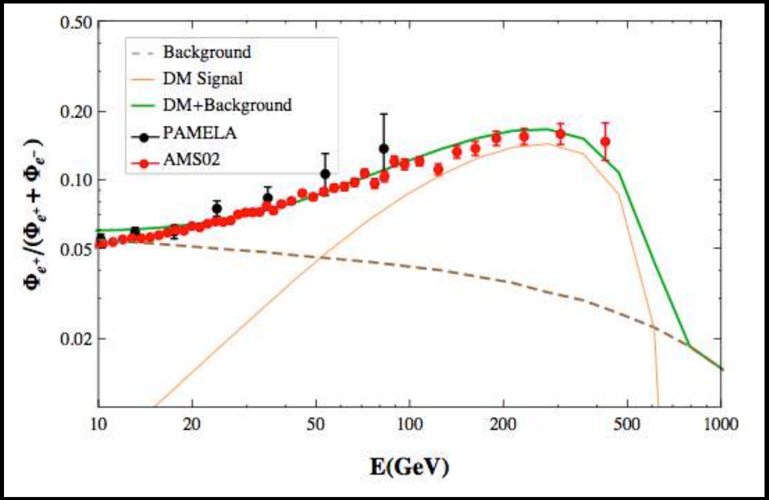
Photo Credit: Connie Sieh

Our local brewery, Two Brothers, created a special beer for the occasion

Cover of the Rolling Stone!

Ironically, there is a GREAT new archive article out that relates dark matter and the AMS positron excess to muon g-2

arXiv:1501.06193 [hep=ph]

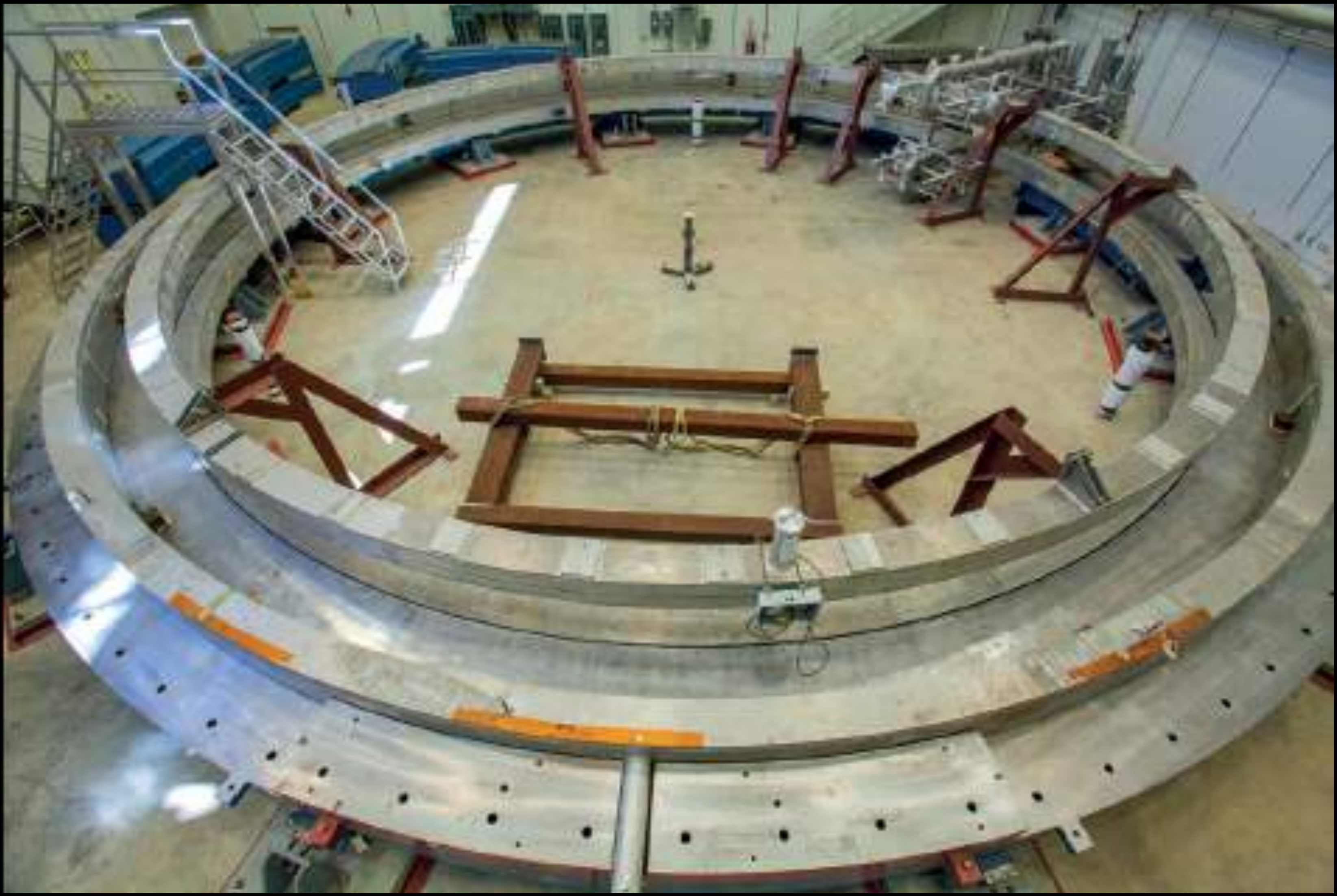


$$\Delta a_\mu = 2.9 \times 10^{-9}$$

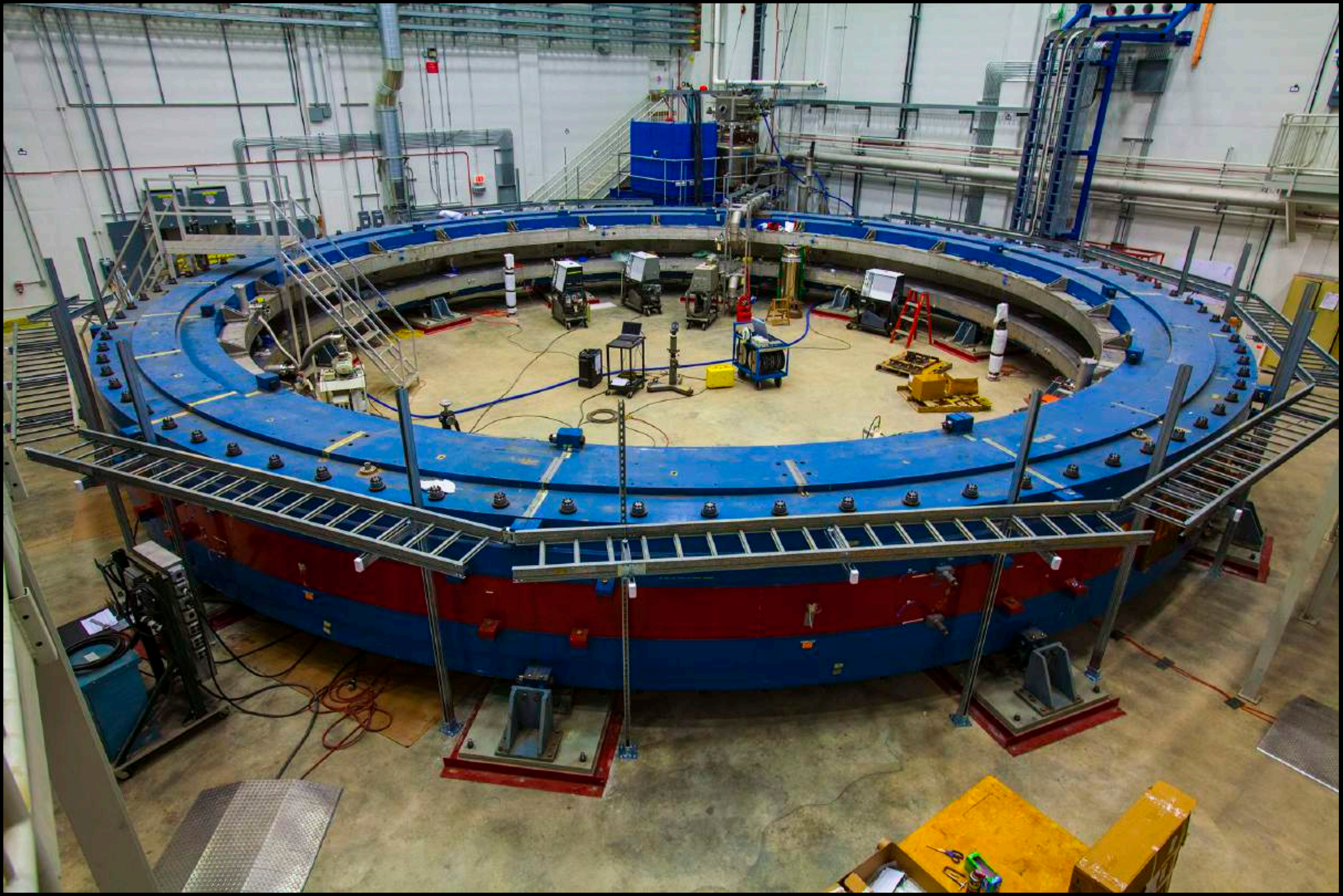
About one year later…the building finished

About one year later…the building

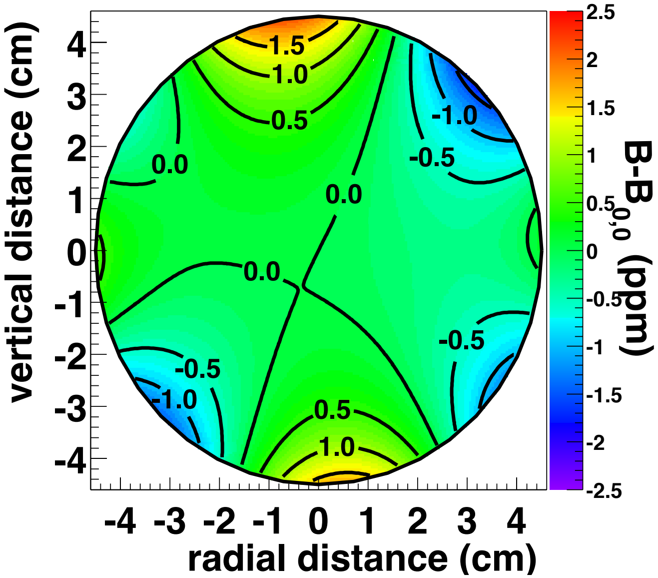
Coils installed last July



Fully-assembled…ready to shim



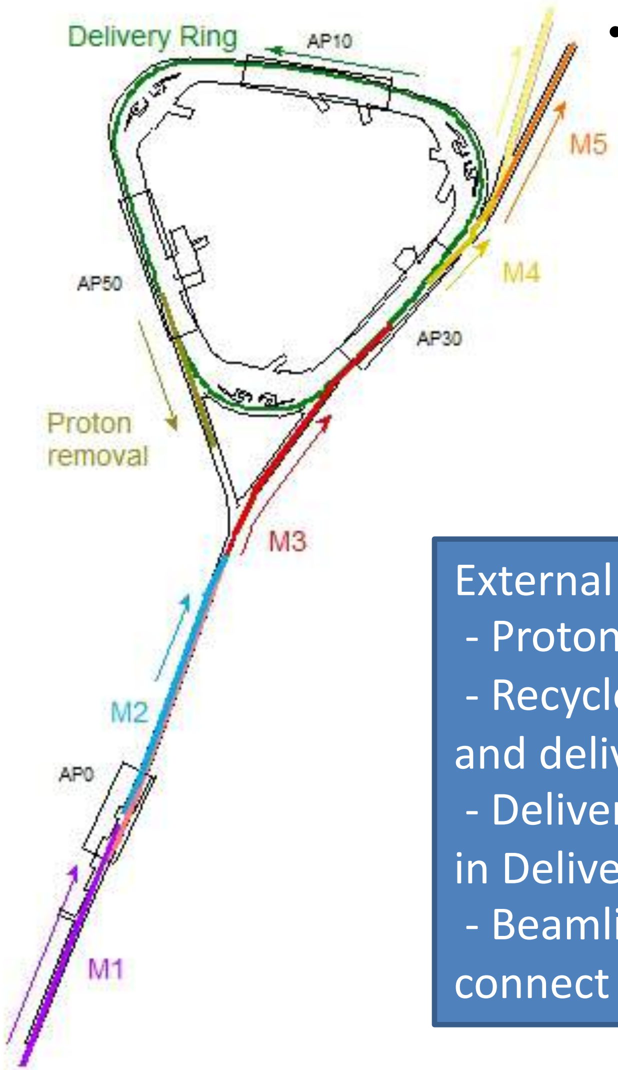
Ring



- Reassembly of E821 storage ring,
- Design, construct, and install upgraded subsystems
  - Refurbishment of ring and modernization to FNAL-compatible controls
  - Upgrades to electromagnetic kickers and electrostatic quadrupoles
  - Reuse of superconducting inflector
    - A new inflector was explored for CD-2 and would provide many benefits. However, due to funding constraints it has been moved into our contingency spend plan
  - Improvements in field monitoring equipment and shimming of magnetic field to attain high uniformity

External Dependencies:
- MC-1 Building GPP to house storage ring
- Muon Campus Cryo Plant to provide liquid He and N cryogens for storage ring and inflector

Accelerators

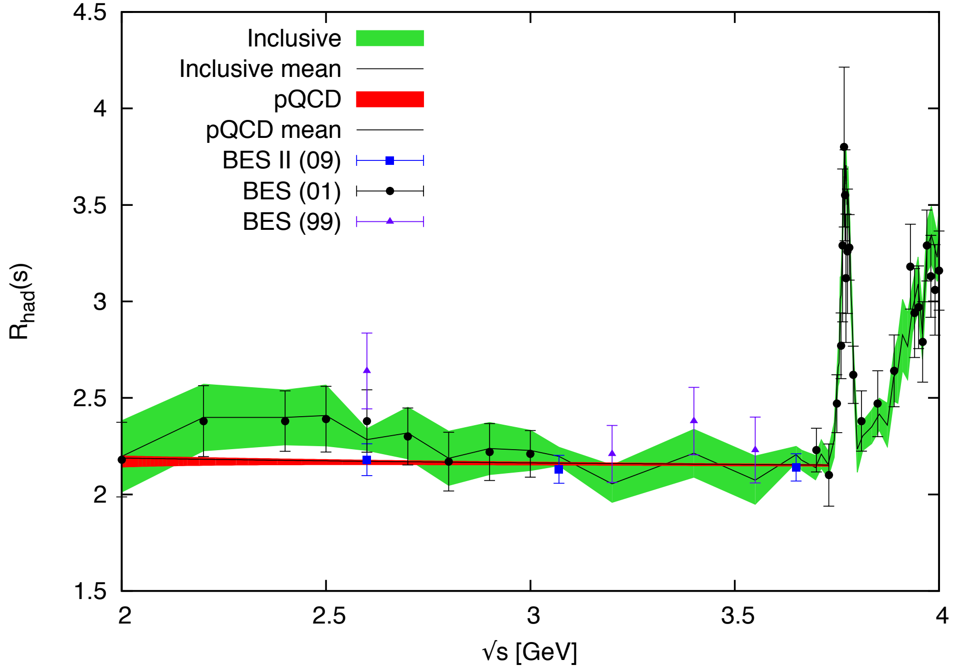


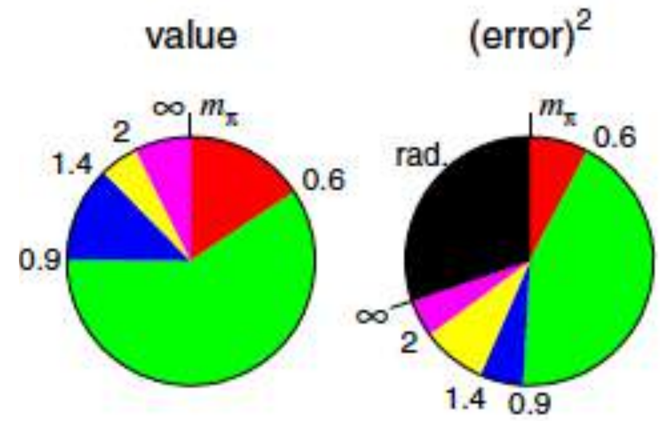
- Convert anti-proton source to a custom muon source
  - Largely reuse of AP0 target hall as-is with some modification and repairs to run at g-2 rep rate
  - Installation of M2, M3, M4, and M5 beamlines to efficiently capture muons and transport to experimental hall
  - Circulation in Delivery Ring for to enough turns (4-7) to remove protons from muon beam
  - Appropriate controls, instrumentation, and safety systems to monitor and steer the beam

External Dependencies:
- Proton Improvement Plan to upgrade Booster to 15 Hz
- Recycler RF and Beam Transport AIPs rebunch Booster beam and deliver to M1 line
- Delivery Ring AIP providing common g-2/Mu2e components in Delivery Ring
- Beamline Enclosure GPP constructs new tunnel system to connect Delivery Ring to g-2 and Mu2e halls

Backup Slides

LO hadronic contributions at sqrt(s) > 2 GeV

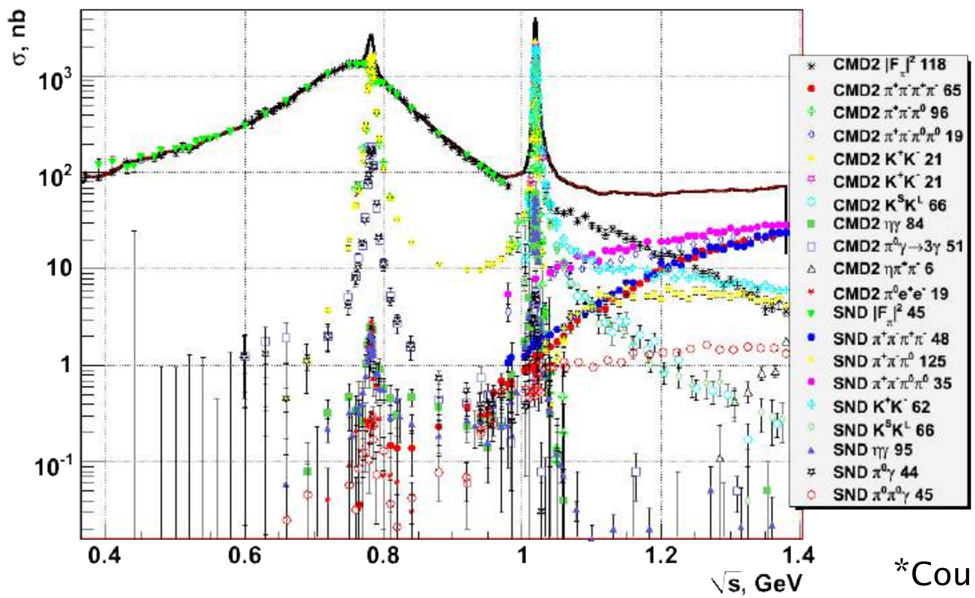


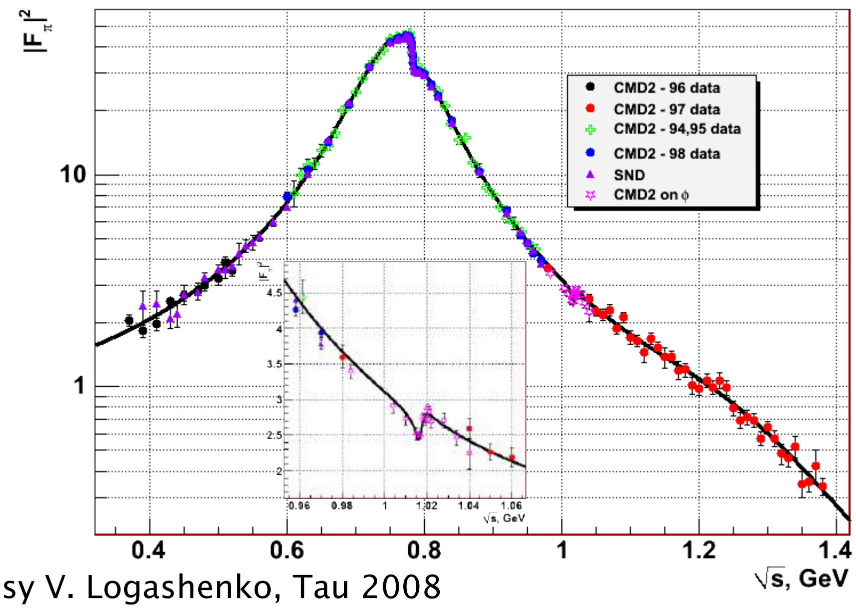


*from Hagiwara et al., J. Phys. G: Nucl. Part. Phys. 38 (2011) 085003

- At larger center-of-mass energies perturbative QCD can be used to calculate e+e- cross-section
  - BES data confirms pQCD calculation in transition region, different groups have slightly different regions where they switch from using data to pQCD (1.8 – 2.4 GeV)
  - Looking forward to higher statistics and center of mass energies from BES III data
- Below 2 GeV, we rely on exclusive measurements, with two pion channel especially important (green portion of pi charts)

Hadronic contributions at lower sqrt(s)

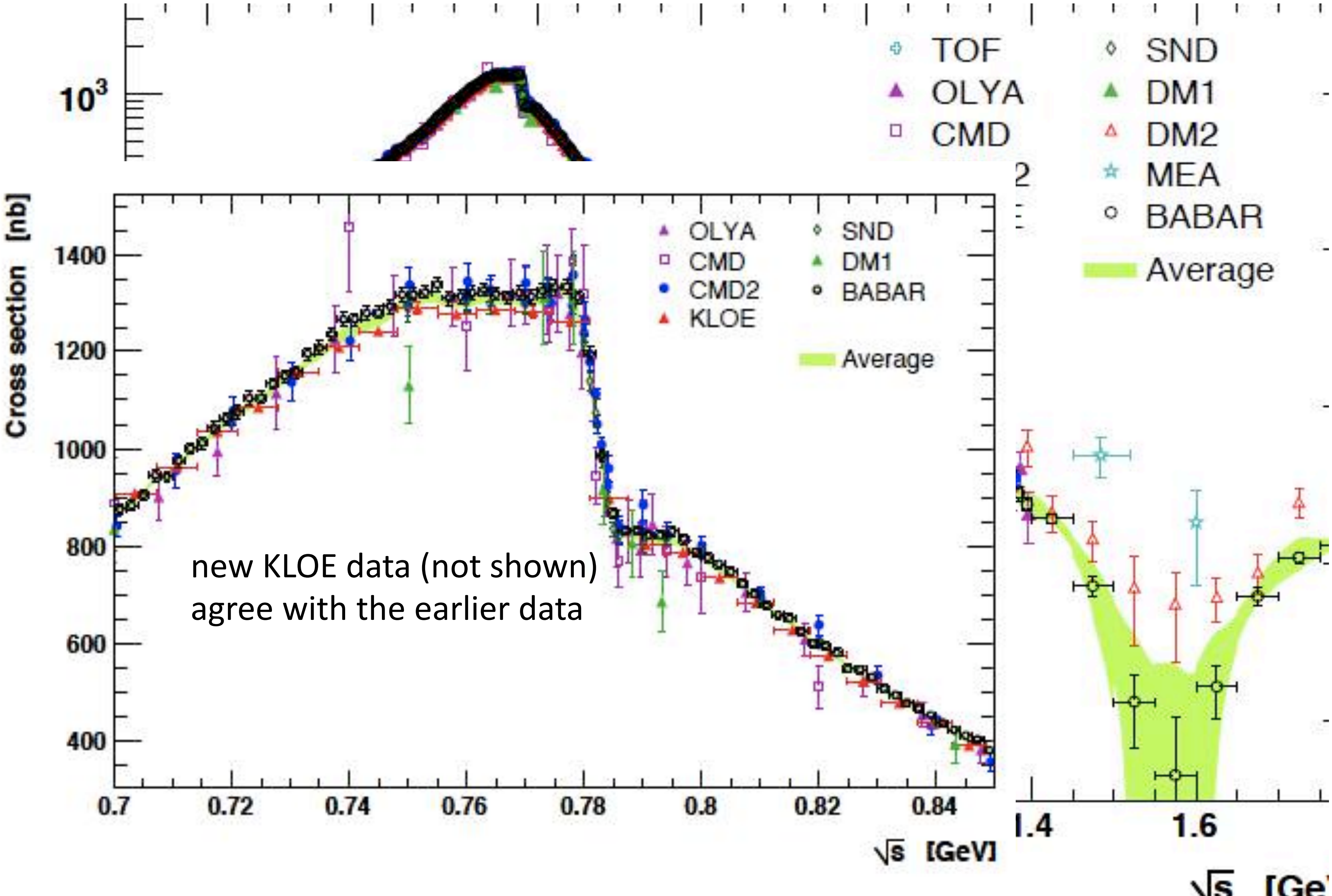




*Courtesy V. Logashenko, Tau 2008

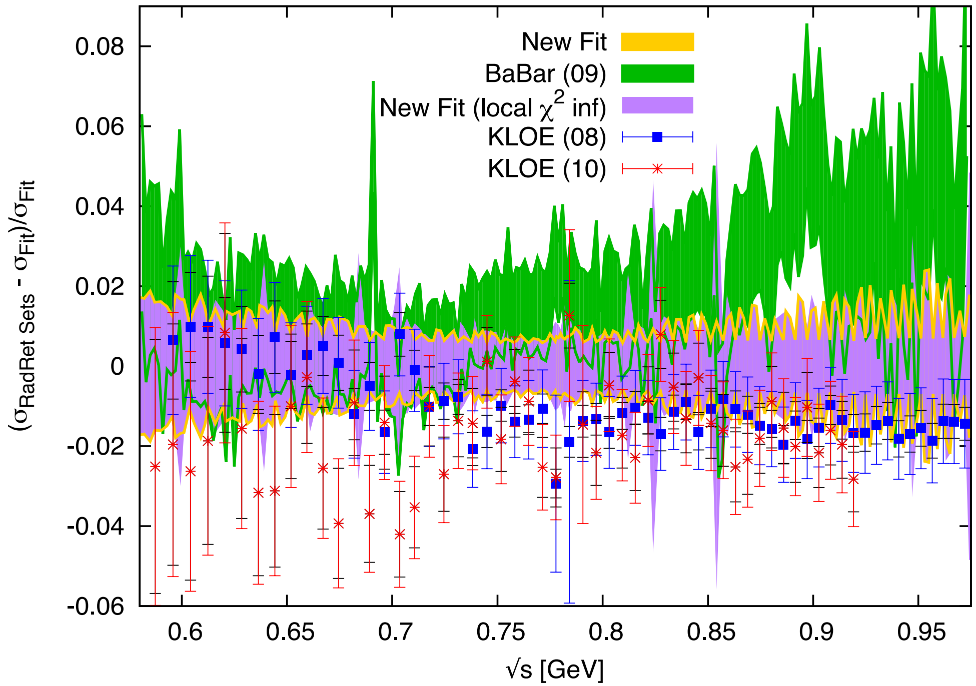
- At the time the BNL data were being analyzed, the only e+e- data with came from Novosibirsk beam energy scans
- Since then, KLOE and Babar have used radiative return to produce very high statistics data sample
- Can see the $\rho-\omega$ mixing peak (2 pion channel) that dominates spectrum along with the turn on of many exclusive channels

Results from the 2 pion channel



new KLOE data (not shown) agree with the earlier data

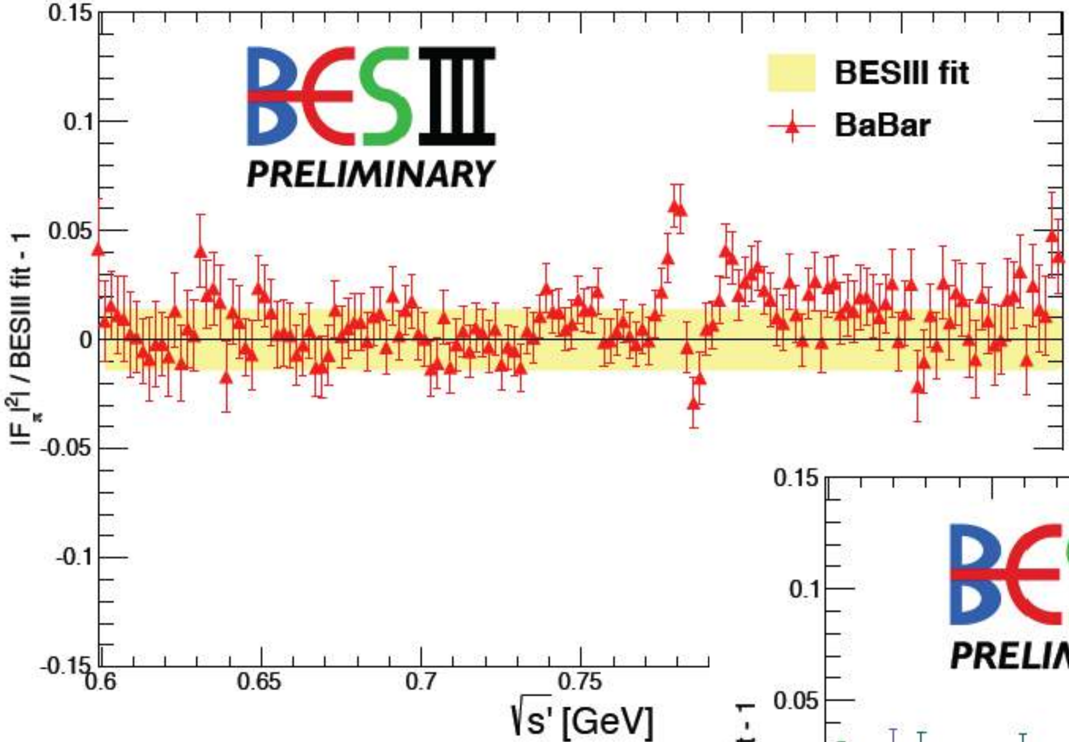
Outlook for ρ–ω mixing region

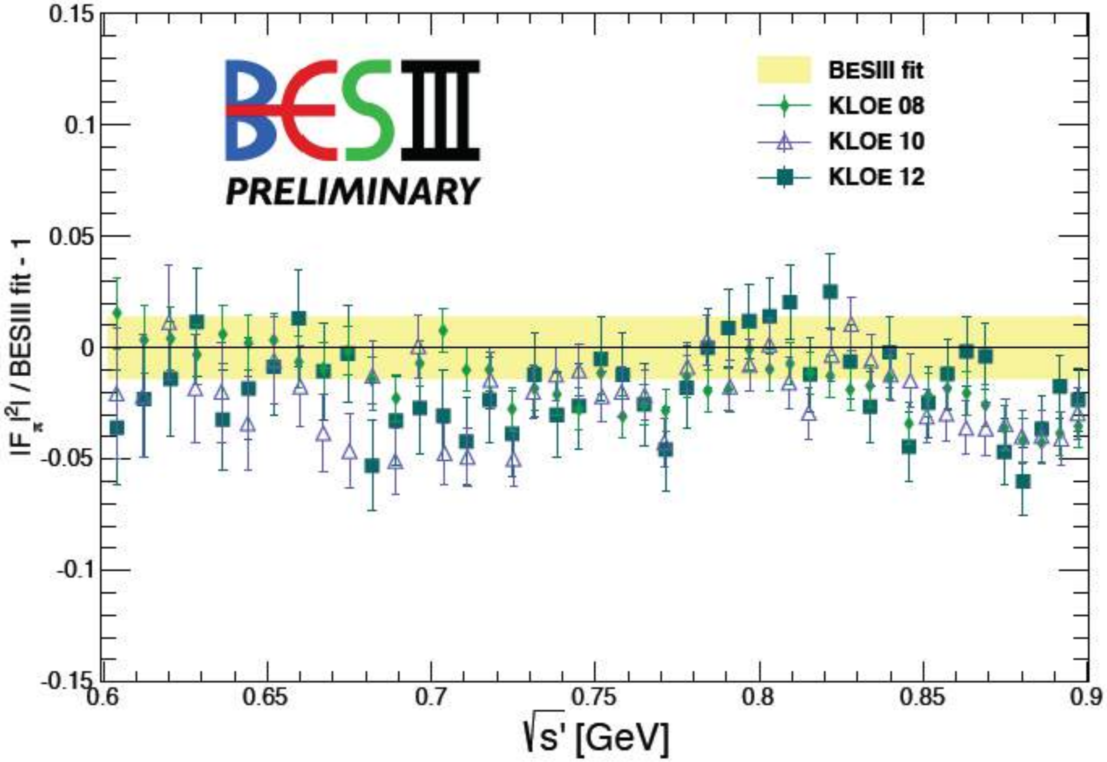


- Can see tension between Babar and KLOE data
- Prevents full reduction in errors from combination

- Avenues for improvement…
  - Understand source of tension, radiative return corrections
  - Bring in more data sets
    - BESIII data already coming in
    - Novosibirsk upgrade to run up to higher center-of-mass energies
  - Calculate LO HVP on the lattice

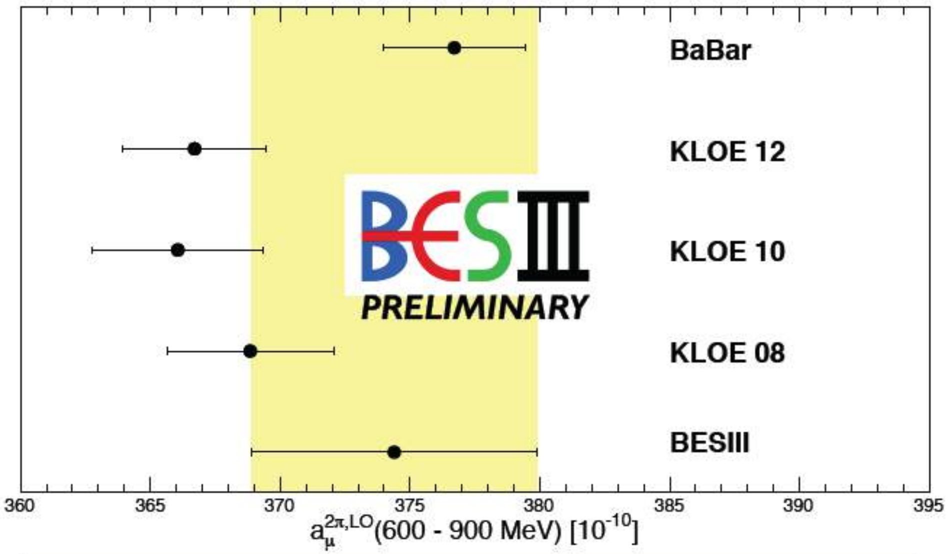
Comparison to BaBar/KLOE





Initial results confirm BaBar/KLOE

Result for (g-2)

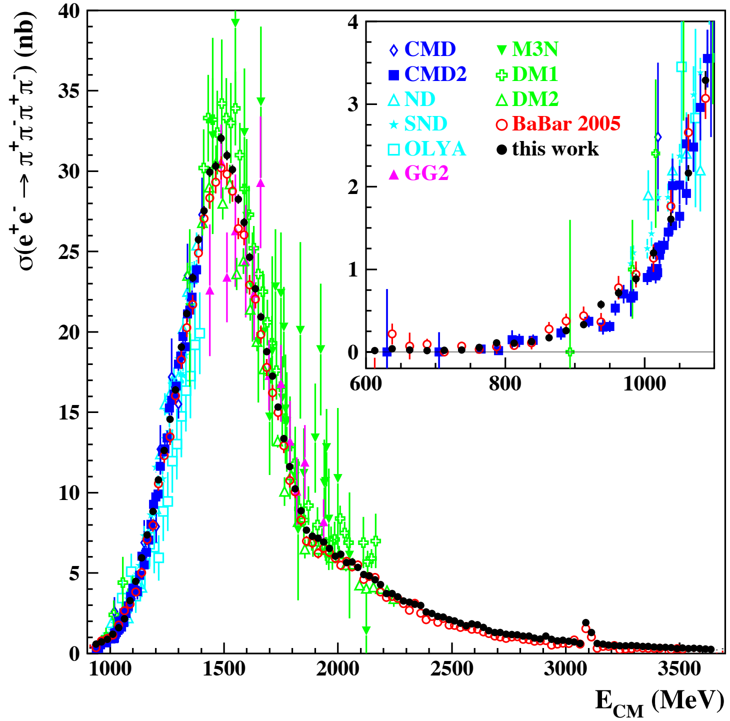


Experiment	$a_\mu^{2\pi,LO}$ (600 – 900 MeV) [10^{-10}]
BaBar	$376.7 \pm 2.0_{stat} \pm 1.9_{sys}$
KLOE 08	$368.9 \pm 0.4_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 10	$366.1 \pm 0.9_{stat} \pm 2.3_{sys,exp} \pm 2.2_{sys,theo}$
KLOE 12	$366.7 \pm 1.2_{stat} \pm 2.4_{sys,exp} \pm 0.8_{sys,theo}$
BESIII (preliminary)	$374.4 \pm 2.6_{stat} \pm 4.9_{sys}$

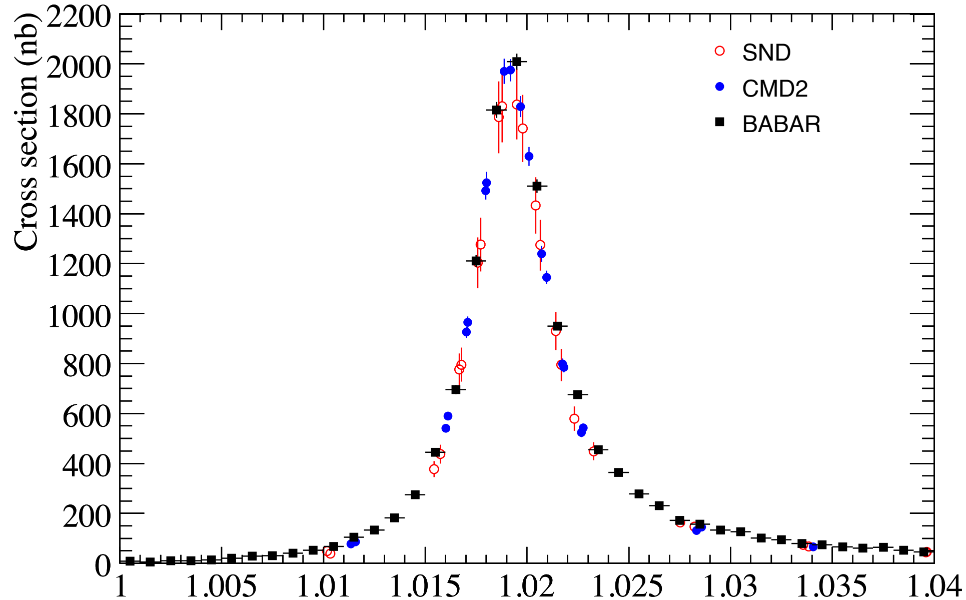
- 3x data already collected
- Anticipate initial publication with 30% smaller errors
- So far, landing right between BaBar and KLOE

Recent data from multi-hadron channels

$K^+K^-(\gamma)$ from BaBar

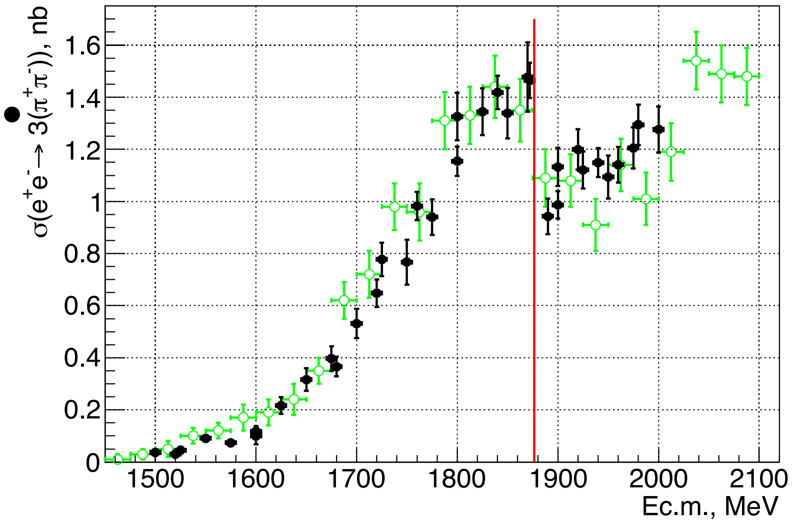


$2\pi^+2\pi^-(\gamma)$ from BaBar



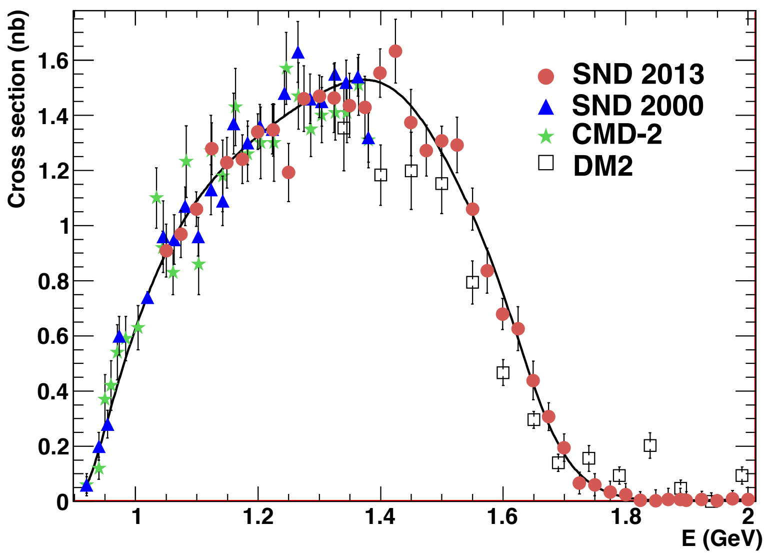
- In region from 2π threshold to 2 GeV…many exclusive channels are used
- More precise measurements coming from BaBar, Belle, & Novosibirsk

Novosibirsk recently upgrade to 2 GeV sqrt(s)



CMD-3 6π charged PLB723(2013)82

- solid black: CMD-3, open green: BaBar
- full analysis will include $2(\pi^+\pi^-\pi^0)$



SND $\omega\pi^0$, arXiv:1303.5198

- many more anlayses reported with preliminary results, incl. 3π, 4π(2n)
- looking forward to rich harvest from SND and CMD-3

Out look for LOHVP data-driven approach

- Much more data coming in from b-factories
- Upgrades to BES and Novosibirsk allowing access to multi-hadron channels with unprecedented precision
- Work has started to reanalyze how BaBar and KLOE handle radiative corrections
- Lattice calculation looks very promising as well.

Thomas Teubner's opinion...echoes sentiment of the community

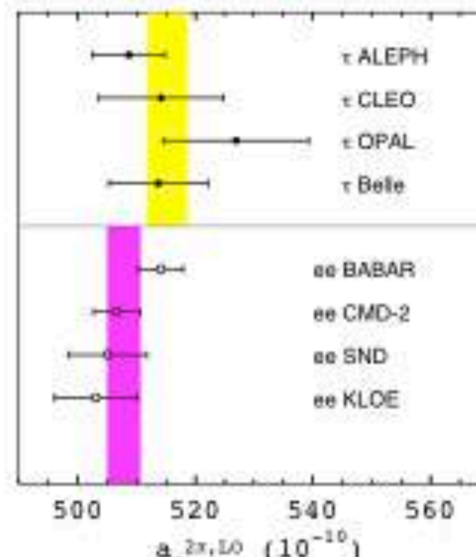
My personal `5 year prognosis':
[expected improvement in error]

- 2π: error down by about 30-50%
- subleading channels: by factor 2-3
- $\sqrt{s} > 2$ GeV: by about a factor 2

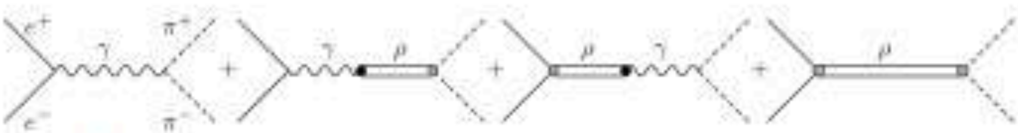
→ I believe we can half the HVP error

Another `puzzle': Use of tau spectral function data?

- Use CVC (iso-spin symmetry) to connect $\tau^- \to \pi^0\pi^-\nu_\tau$ spectral functions to $e^+e^- \to \omega, \rho \to \pi^+\pi^-$ but have to apply iso-spin corrections
- Early calculations by Alemany, Davier, Hoecker: use of τ data complementing e^+e^- data originally resulted in an improvement w.r.t. use of e^+e^- data alone; discrepancy smaller with tau data; later increased tension between e^+e^- and τ
- Recent compilation by Davier et al in BaBar's PRD86,032013:



- Jegerlehner+Szafron: crucial role of γ-ρ mixing:



- They found discrepancy gone but τ data improved e^+e^- analysis only marginally, however BaBar $\pi^+\pi^-$ data not used
- Analyses by Benayoun et al: combined fit of e^+e^- and τ based on Hidden Local Symmetry (HLS): no big tension betw. e^+e^- and τ, but w. BaBar, hence not used; increased Δa_μ of ~ 4.5σ
- Davier+Malaescu refute criticism, claim fair agreement betw. BaBar and their τ comp.
- HLMNT: stick to e^+e^- (and do not use τ data). With e^+e^- (incl. BaBar) discrepancy of 3-3.5σ

The 'Glasgow Consensus'

- Major effort from quite a few experts over the last two decades to produce reliable (but still model-dependent) calculations

Some results for the various contributions to $a_\mu^{\mathrm{LbyL;had}} \times 10^{11}$:

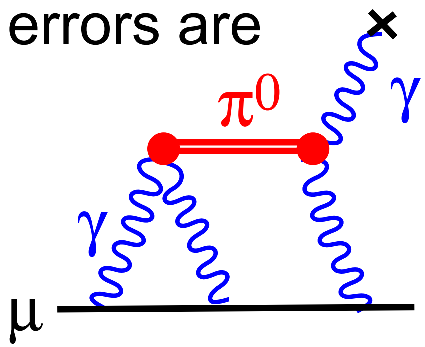
Contribution	BPP	HKS, HK	KN	MV	BP, MdRR	PdRV	N, JN	FGW
π^0, η, η'	85 ± 13	82.7 ± 6.4	83 ± 12	114 ± 10	–	114 ± 13	99 ± 16	84 ± 13
axial vectors	2.5 ± 1.0	1.7 ± 1.7	–	22 ± 5	–	15 ± 10	22 ± 5	–
scalars	-6.8 ± 2.0	–	–	–	–	-7 ± 7	-7 ± 2	–
π, K loops	-19 ± 13	-4.5 ± 8.1	–	–	–	-19 ± 19	-19 ± 13	–
π, K loops +subl. N_C	–	–	–	0 ± 10	–	–	–	–
other	–	–	–	–	–	–	–	0 ± 20
quark loops	21 ± 3	9.7 ± 11.1	–	–	–	2.3	21 ± 3	107 ± 48
Total	83 ± 32	89.6 ± 15.4	80 ± 40	136 ± 25	110 ± 40	105 ± 26	116 ± 39	191 ± 81

BPP = Bijnens, Pallante, Prades '95, '96, '02; HKS = Hayakawa, Kinoshita, Sanda '95, '96; HK = Hayakawa, Kinoshita '98, '02; KN = Knecht, Nyffeler '02; MV = Melnikov, Vainshtein '04; BP = Bijnens, Prades '07; MdRR = Miller, de Rafael, Roberts '07; PdRV = Prades, de Rafael, Vainshtein '09; N = Nyffeler '09, JN = Jegerlehner, Nyffeler '09; FGW = Fischer, Goecke, Williams '10, '11 (used values from arXiv:1009.5297v2 [hep-ph], 4 Feb 2011)

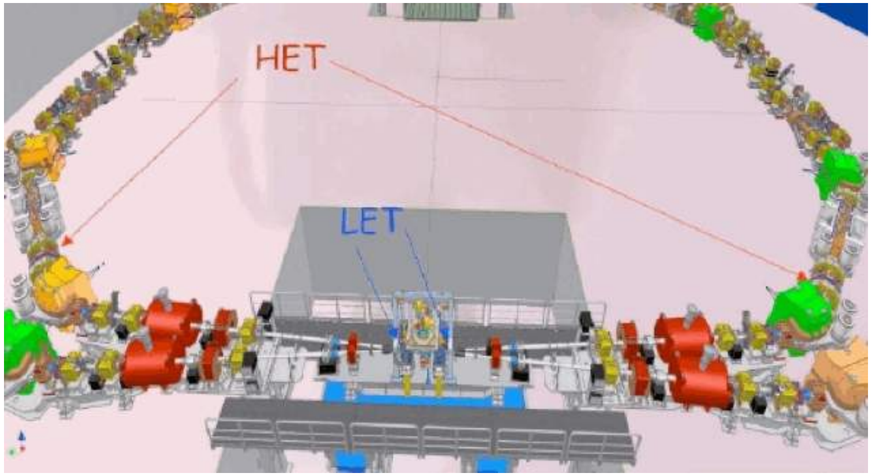
- Terrible name…sounds like the theorists got together and voted
- In reality, at Glasgow workshop they got together and did a careful comparison of what components each had calculated
- They found that within errors all of their calculations were in agreement
- Established the recommended valued of 105 (26) x 10^{-11}

HLBL Outloook

- It is worth noting that the modelers would have to be really wrong to explain the BNL discrepancy with HLBL
  - Contribution would have to be 350% larger
  - Based on their understanding of errors, would have to be off by 10-12σ
- Nevertheless, the question of how well the model errors are understood remains



- Possible improvements
  - Low angle scattering detectors installed at KLOE 2 and BESIII
  - Measurement of $\gamma\gamma^{*} \rightarrow$hadrons relates to ~70% of HLBL
  - $\pi^{0} \rightarrow \gamma\gamma$ life-time (from PrimEx at JLab) help to constrain models
- Real hope for future is that HLBL will come from lattice



Importance of various 'channels'

[Numbers from HLMNT, 'local error infl.', $\cdot 10^{-10}$]

- Errors contributions to a_μ from leading and subleading channels (ordered) up to 2 GeV

Purely from data:

channel	error
$\pi^+\pi^-$	3.09
$\pi^+\pi^-\pi^0\pi^0$	1.26
3π	0.99
$2\pi^+2\pi^-$	0.47
K^+K^-	0.46
$2\pi^+2\pi^-2\pi^0$	0.24
$K^0_S K^0_L$	0.16

'Higher multiplicity' region from 1.4 to 2 GeV with use of isospin relations for some channels: [Use of old inclusive data disfavoured.]

Channel	contr. $\pm$ error
$K\bar{K}2\pi$	3.31 ± 0.58
$\pi^+\pi^-4\pi^0$	0.28 ± 0.28
$\eta\pi^+\pi^-$	0.98 ± 0.24
$K\bar{K}\pi$	2.77 ± 0.15
$2\pi^+2\pi^-\pi^0$	1.20 ± 0.10

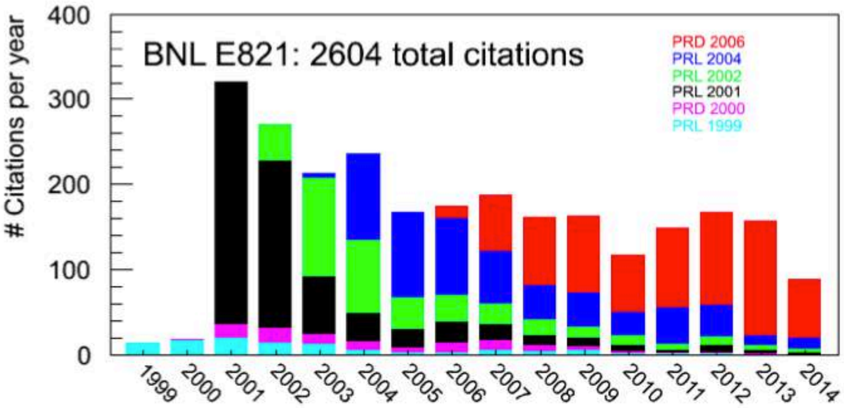
- 'Inclusive' region from 2 to ~ 11 GeV: $\mathbf{41.19 \pm 0.82}$

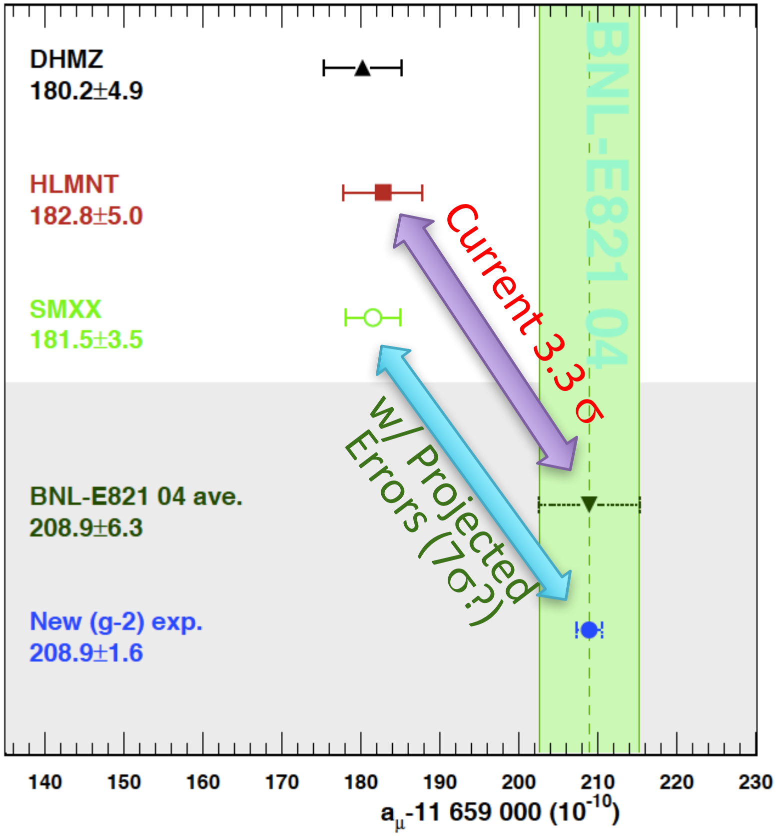
  Can be 'squeezed' by using pQCD (done by DHMZ from 1.8 GeV);

  region from 2 to 2.6 GeV: $\mathbf{15.69 \pm 0.63} \;\rightarrow\; \mathbf{14.49 \pm 0.13}$, only small changes for higher energies.

Mission Need & Scientific Requirements

http://arxiv.org/pdf/1311.2198v1.pdf





- The BNL E821 experiment remains one of the highest cited results in particle physics
  - Applicable to a wide range of theories
  - 3σ discrepancy intriguing

- FNAL E989 experiment granted Mission Need from OHEP on Sep 18, 2012 to develop an experiment that could confirm or refute the BNL result by reducing the experimental error by a factor of 4
  - If current discrepancy persists, significance will be pushed beyond 5σ discovery threshold
  - Anticipated theoretical improvement could lead to >7σ

Strong mix of E821 and new collaborators

- Domestic Universities
  - Boston
  - Cornell
  - Illinois
  - James Madison
  - Massachusetts
  - Mississippi
  - Kentucky
  - Michigan
  - Michigan State
  - Mississippi
  - Northern Illinois University
  - Northwestern
  - Regis
  - Virginia
  - Washington
  - York College
- National Labs
  - Argonne
  - Brookhaven
  - Fermilab
- Consultants
  - Muons, Inc.

Italy
- Frascati
- Roma 2
- Udine
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Japan:
- Osaka

Russia:
- Dubna
- PNPI
- Novosibirsk

England
University College London
Liverpool
Oxford
Rutherford Lab

Korea
KAIST

FTE Committed

Survey of Collaboration for P5

Construction	Runnning	Analysis
2014 - 2016	2017-2019	2019 - 2022
91	80	68

Co-spokespersons: David Hertzog, Lee Roberts
Project Manager: Chris Polly

ω_a Systematic Requirements

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

Overall, ω_a systematics need to be reduced by a factor of 3

- Some errors were data-driven, precision of corrections scales with statistics
- Environmental improvements by changing run conditions, e.g. no hadronic flash
- Many hardware and analysis-driven improvements detailed in parallel sessions

ω_p Systematic Requirements

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

Overall, ω_p systematics need to be reduced by a factor of 2.5

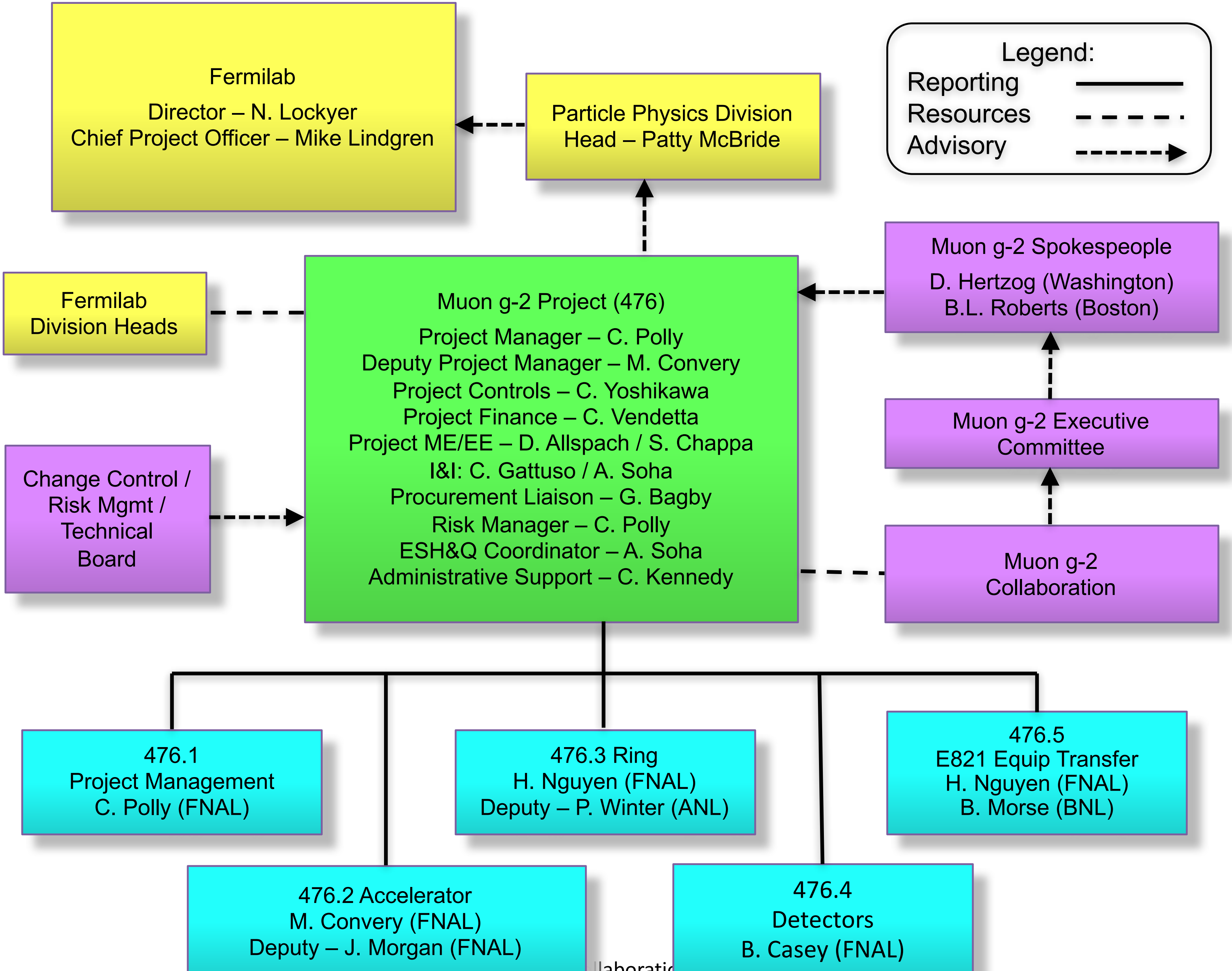
- Better run conditions, e.g. temperature stability of experimental hall, more time to shim magnetic field to high uniformity, smaller stored muon distribution
- Also many hardware and simulation driven improvements detailed in parallel sessions

Domestic Collaborators & Responsibilities

- Argonne
  - Slow controls; Field DAQ; NMR Trolley
- Boston
  - Straw electronics; Fast rotation; Inflector
- Brookhaven
  - Quads, Storage Ring; DAQ, Analysis methods
- Cornell
  - New Kicker; Waveform digitizers; Simulations
- Fermilab
  - Storage Ring, Accelerator, Traceback Straws, Beam Dynamics, Inflector; Simulations
- Illinois
  - Beam dynamics; Clocks and controls
- James Madison
  - Bias distribution
- Massachusetts
  - Magnetic Field
- Kentucky
  - DAQ
- Michigan
  - Magnetic Field
- Michigan State University
  - End-to-end Simulation
- Mississippi
  - Muon beam instrumentation
- Muons, Inc.
  - Beam and target design simulations
- Northern Illinois University
  - Straws and Ring Transport
- Northwestern
  - Tracking; Theory
- Regis
  - Fiber harp monitor; Analysis
- Virginia
  - Bias distribution; Clock distribution; simulations
- Washington
  - Calorimeter, Beam dynamics, Magnetic field
- York College
  - Storage ring simulation

International Collaborators & Responsibilities

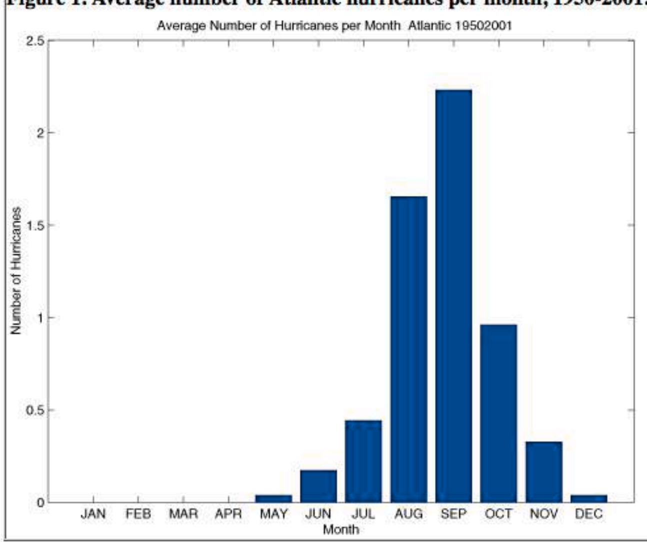
- Italy
  - Frascati,
  - Naples
  - Roma 2,
  - Udine
  - Trieste
    - Calorimeter calibration system, test beam, KLOE
- China:
  - Shanghai
    - Calorimeter crystals and simulations
- The Netherlands:
  - KVI
    - Magnetic field
- Germany:
  - Dresden
    - Theory
- Japan:
  - Osaka
    - SiPM studies
- Russia:
  - Dubna
  - PNPI
  - Novosibirsk
    - TBD
- England
  - University College London
  - Liverpool
  - Oxford
  - Rutherford
    - Straws, Inflector, Theory
- KOREA
  - KAIST

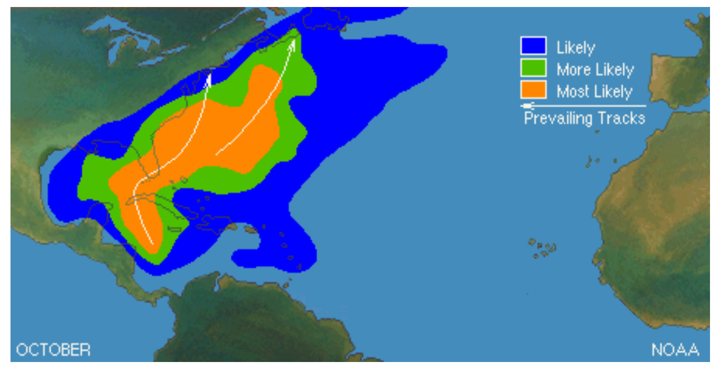

Fermilab
Director – N. Lockyer
Chief Project Officer – Mike Lindgren
Particle Physics Division
Head – Patty McBride
Legend:
Reporting
Resources
Advisory
Fermilab
Division Heads
Muon g-2 Project (476)
Project Manager – C. Polly
Deputy Project Manager – M. Convery
Project Controls – C. Yoshikawa
Project Finance – C. Vendetta
Project ME/EE – D. Allspach / S. Chappa
I&I: C. Gattuso / A. Soha
Procurement Liaison – G. Bagby
Risk Manager – C. Polly
ESH&Q Coordinator – A. Soha
Administrative Support – C. Kennedy
Muon g-2 Spokespeople
D. Hertzog (Washington)
B.L. Roberts (Boston)
Muon g-2 Executive Committee
Change Control / Risk Mgmt / Technical Board
Muon g-2 Collaboration
476.1
Project Management
C. Polly (FNAL)
476.3 Ring
H. Nguyen (FNAL)
Deputy – P. Winter (ANL)
476.5
E821 Equip Transfer
H. Nguyen (FNAL)
B. Morse (BNL)
476.2 Accelerator
M. Convery (FNAL)
Deputy – J. Morgan (FNAL)
476.4
Detectors
B. Casey (FNAL)
llaboratio

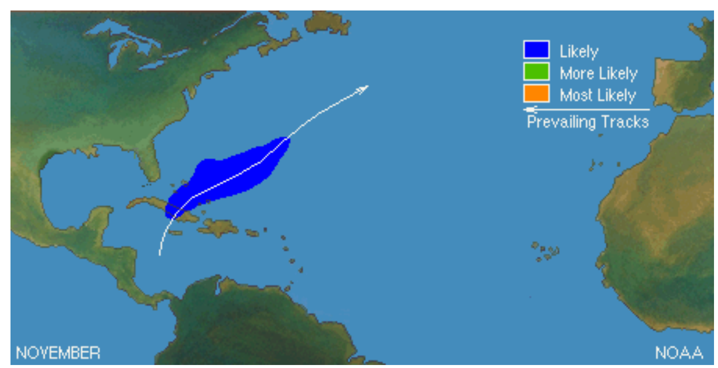
Annual Cycle of Atlantic Hurricanes

The peak of the Atlantic hurricane season happens during the months of August to September, as seen in Figure 1, which shows the average number of hurricanes in the Atlantic per month from 1950-2001. The official hurricane season is defined from June to November, but hurricanes occasionally form in other months.

Figure 1. Average number of Atlantic hurricanes per month, 1950-2001.







About one year later…the building finished