Status of the muon g-2 experiment

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Brookhaven Forum 2017
"In Search of New Paradigms"
Brookhaven National Laboratory
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Outline

- Introduction and motivation
- Principle of the experiment
- Status of the experiment
- Conclusions

anomalous magnetic moment a_μ

$$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m\psi(x)$$

$$\vec{\mu}_\mu = g_\mu \frac{e}{2m_\mu}\vec{S}$$

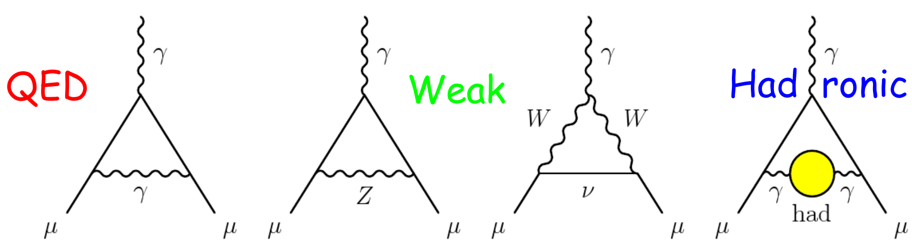
$$g_\mu = 2 \quad \text{for} \quad S = 1/2$$

Quantum loop effects:

$$\mu_\mu = (1 + a_\mu)\frac{e\hbar}{2m_\mu}$$

anomalous magnetic moment $\quad a_\mu \equiv \frac{g_\mu - 2}{2}$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm W} + a_\mu^{\rm Had}$$



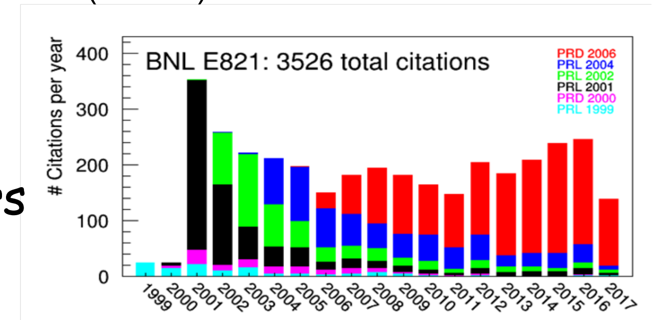
Source	value ($a_\mu \times 10^{-11}$)	error
QED	116 584 718.95	0.08
EW	154	1
HVP	6850.6	42
HLBL	105	26

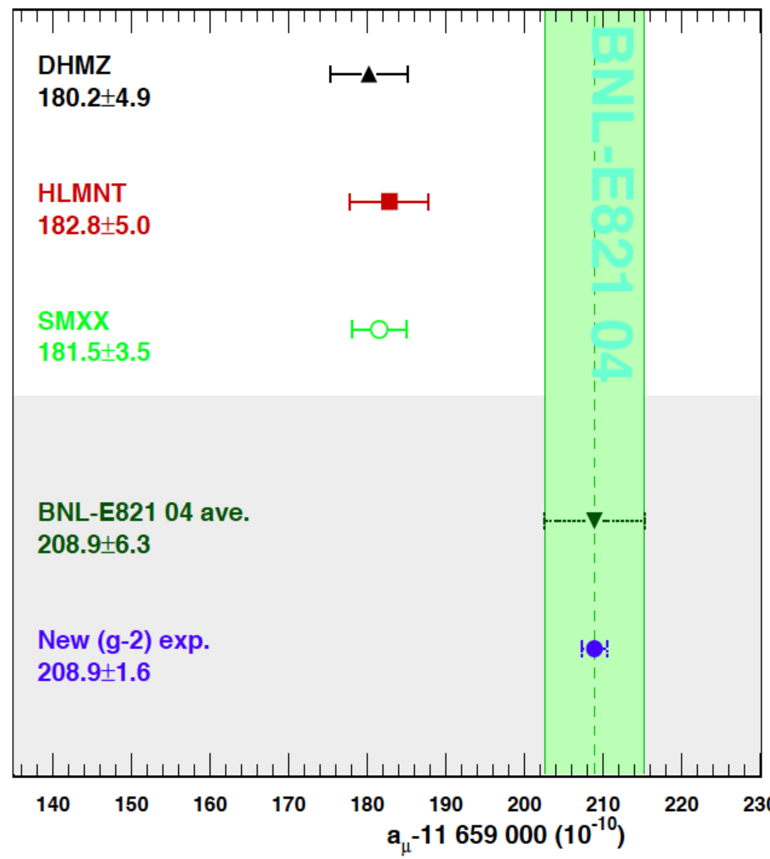
$$a_\mu^{\rm SM} = 116\,591\,803(1)(42)(26) \times 10^{-11}$$

$$a_\mu^{\rm exp} = 116\,592\,023(151) \times 10^{-11}$$ BNL+CERN

$$\Delta a_\mu \approx 3.5\sigma$$

persistent > 10 yrs





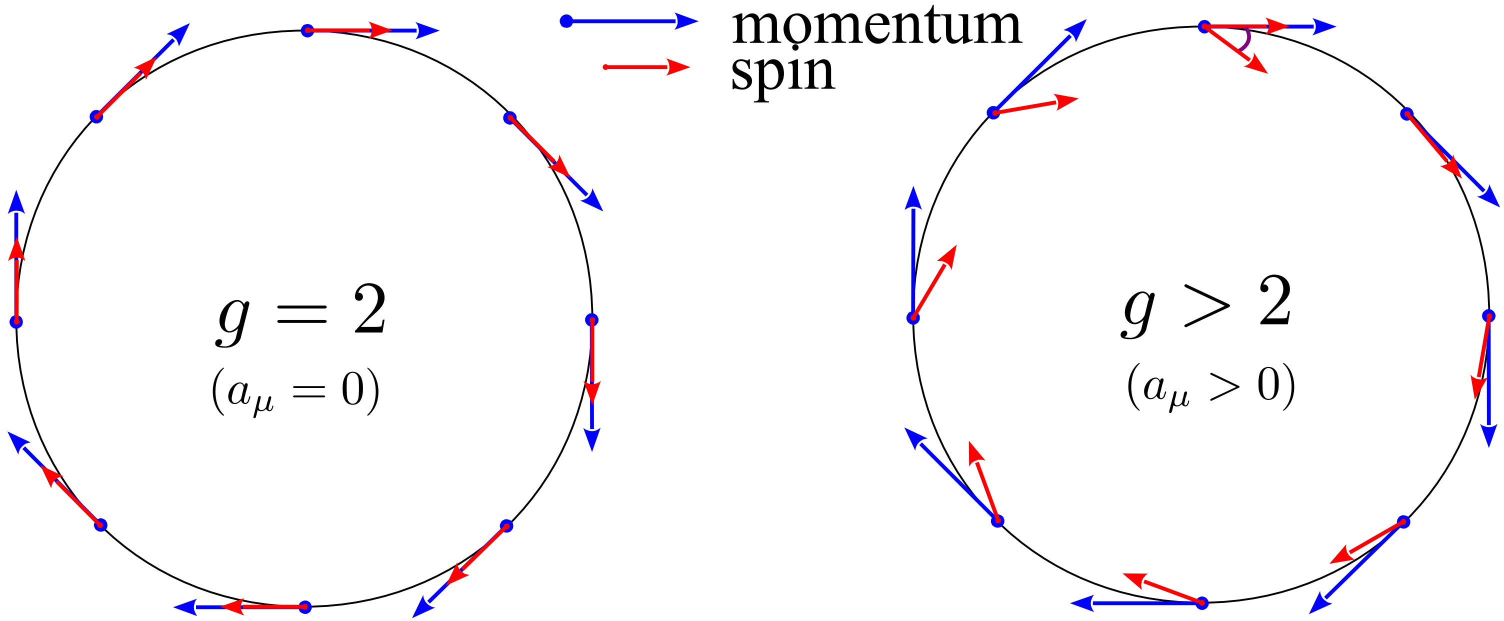
Principles of the experiment

1) Take polarized muons (come naturally from pion decay)

2) Inject muons into a uniform magnetic field

– Momentum precession (cyclotron frequency) $\omega_c = \frac{e}{m\gamma}B$

– Spin precession $\omega_s = \frac{e}{m\gamma}B(1+\gamma a_\mu)$



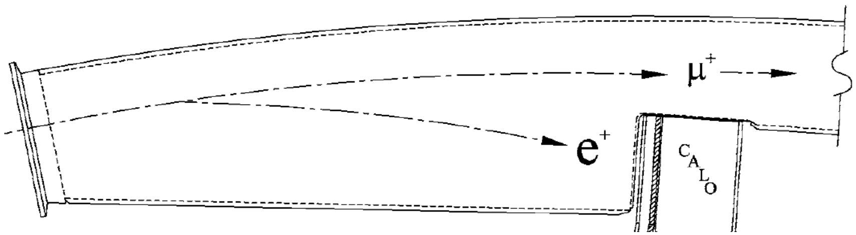
$$\omega_a = \omega_s - \omega_c = \frac{e}{m} a_\mu B$$

BNL g-2 experiment in a nutshell

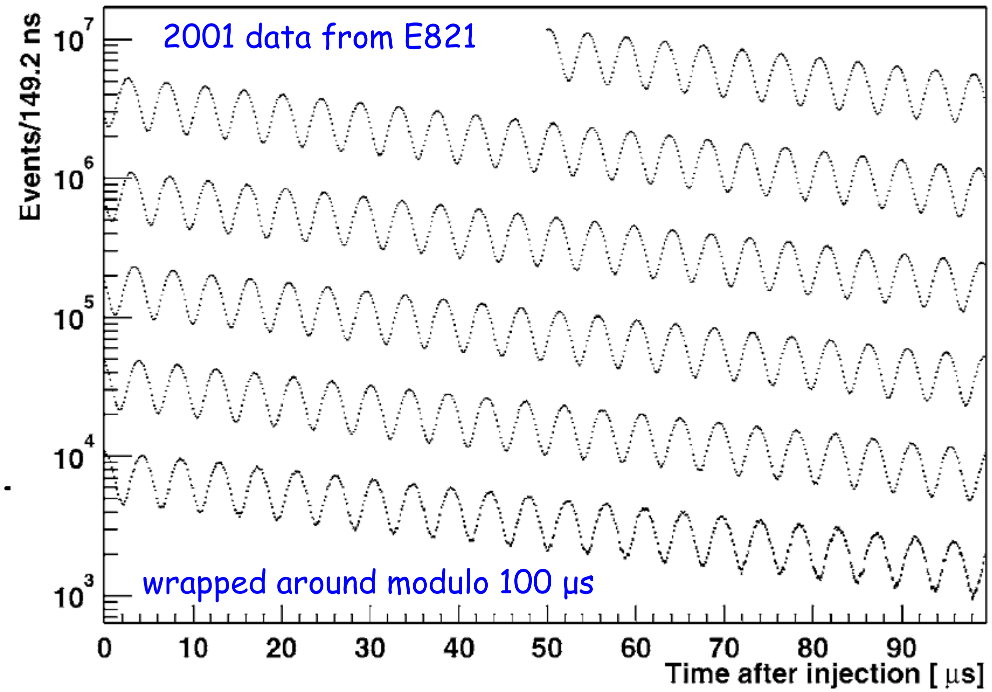
$$a_\mu = \frac{m}{e} \frac{\omega_a}{B}$$

Determining the anomalous magnetic moment requires measuring

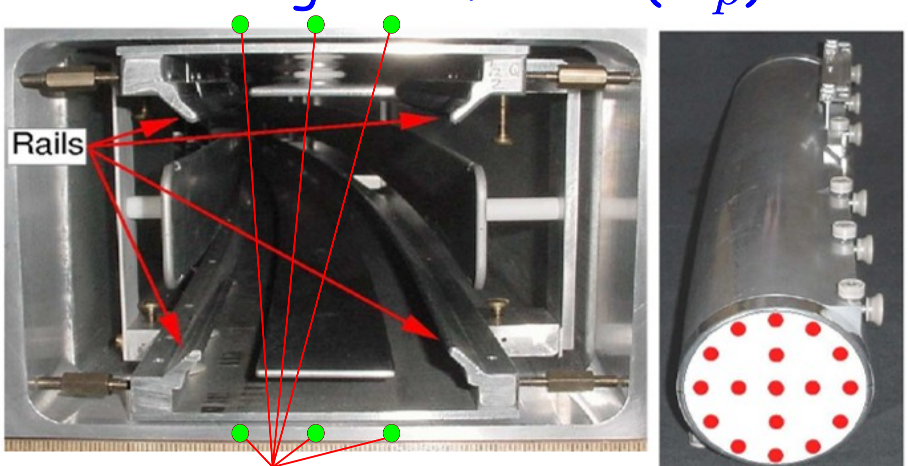
- The spin precession frequency ω_a



muon decay is self-analyzing: higher energy positrons are emitted preferentially in direction of muon spin

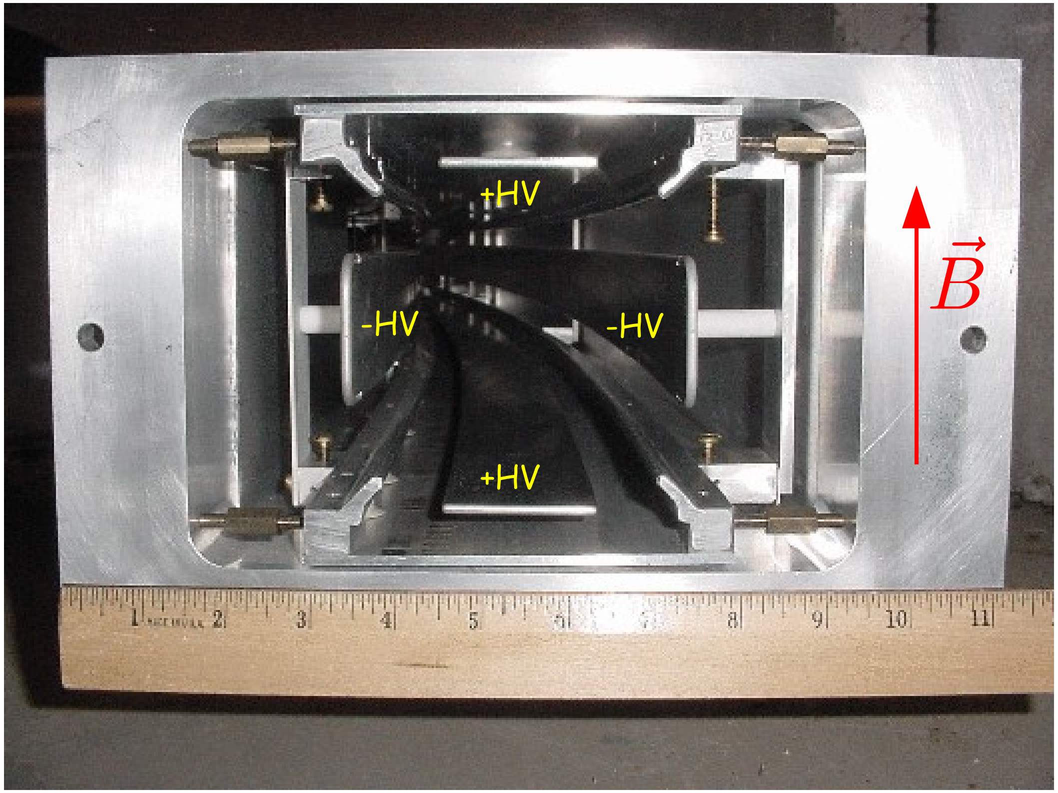


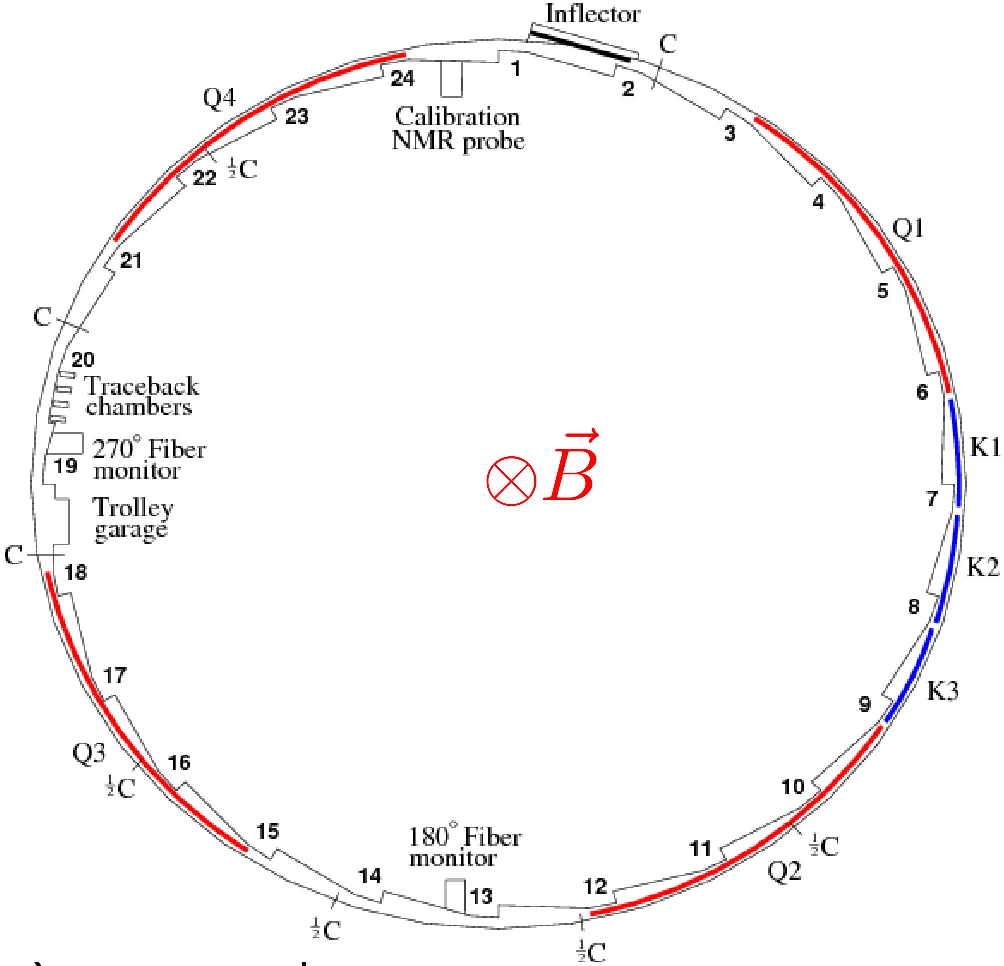
- The magnetic field B (ω_p)



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

Electric quads to contain the beam vertically





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

$$= 0 \quad \text{for } \gamma = 29.3 \quad (p_\mu = 3.09\ \mathrm{GeV/c})$$

E-field contribution vanishes at this "magic" momentum

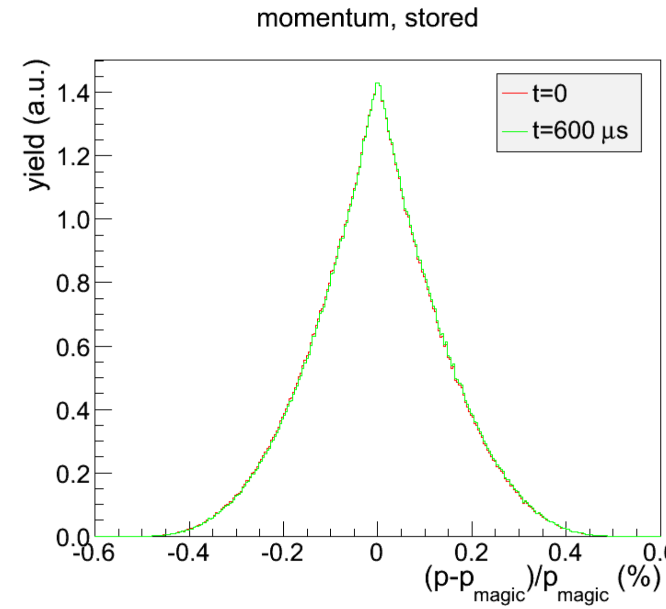
Electric field and pitch correction

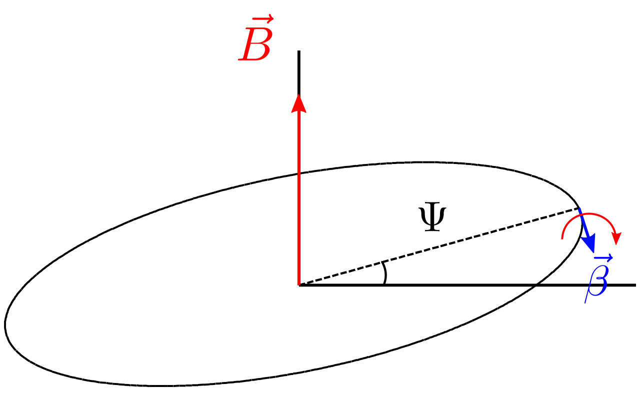
$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

$$\Delta\vec{\omega}_a = -\frac{e}{m}\left(a - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E} = -\frac{e}{m}\left(a - \frac{m^2}{(p_0+\Delta p)^2}\right)\vec{\beta}\times\vec{E}$$

$$\left\langle\frac{\delta\omega_a}{\omega_a}\right\rangle = -2\beta^2 n(1-n)\left\langle\left(\frac{x_e}{R_0}\right)^2\right\rangle$$

E821 C_E = 470 ± 50 ppb





$$\frac{d\vec{s}}{dt} = \vec{s}\times\vec{\Omega}$$

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

$$\Psi(t) = \Psi_m \sin(\omega_y t + \varphi_y)$$

F.J.N. Farley, Phys. Lett. 42 (1972) 66

$$\frac{\Delta\omega_a}{\omega_a} = -\left\langle\frac{1}{4}\Psi_m^2\right\rangle = -n\frac{\langle y^2\rangle}{R_0^2}$$

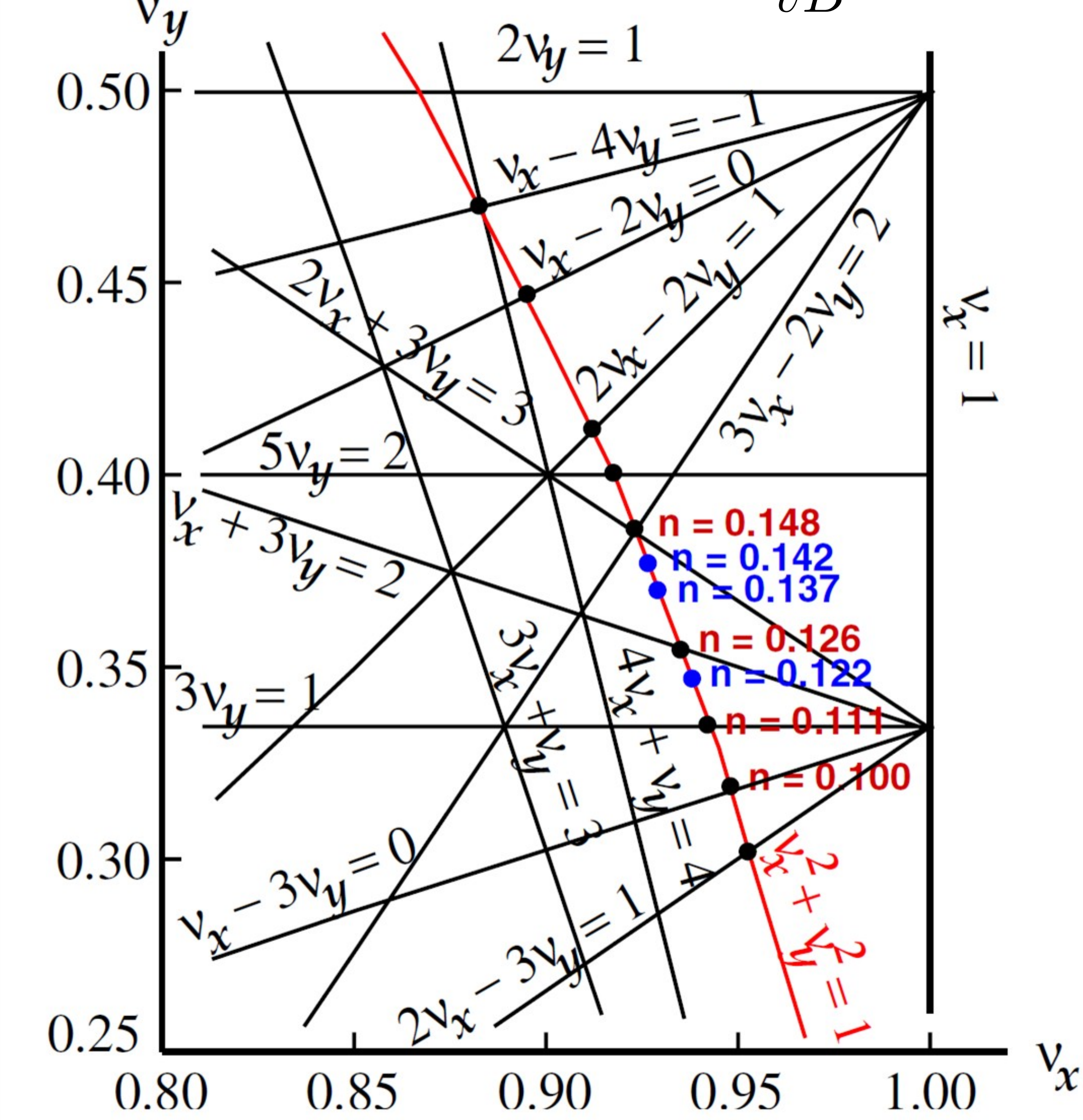
E821 C_p = 270 ± 40 ppb

E989 goal for C_E and C_p combo: 30 ppb

Resonances of g-2 storage ring

$$\nu_x = \omega_x/\omega_c = \sqrt{1-n} \qquad \nu_x^2 + \nu_y^2 = 1$$

$$\nu_y = \omega_y/\omega_c = \sqrt{n} \qquad n \equiv \frac{kR_0}{vB}$$



resonance conditions:

$$L\nu_x \pm M\nu_y \pm N = 0 \text{ (betatron)}$$

$$L\nu_x + M\nu_y \pm N = a_\mu\gamma \text{ (spin)}$$

where L, M, N are integers.

F.J.M. Farley, W.M. Morse, Y.K. Semertzidis
E821 notes # 106, 116, 149

Systematic uncertainties:

- Lost muons
- CBO

uncertainties in E821 and E989 goals

E821: $a_\mu^{\text{exp}} = (11659208.0 \pm 6.3) \times 10^{-10}$ (0.54 ppm)

0.46 ppm statistical

0.28 ppm systematic

$$a_\mu^{\text{exp}} = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

E989 goal: 0.14 ppm

ω_a

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	
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

statistical goal: x20 more muons

uncertainties in E821 and E989 goals

ω_p

D. Kawall, UMass

Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30
Total systematic error on ω_p	170		70

*Improvements in many of these categories will also follow from a more uniformly shimmed main magnetic field.

†Collective smaller effects in E821 from higher multipoles, trolley temperature uncertainty and its power supply voltage response, and eddy currents from the kicker.

Muon g-2 Collaboration (E989)

Domestic Universities

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

- National Labs
  - Argonne
  - Brookhaven
  - Fermilab

Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma
- Triese
- Udine

China:

- Shanghai

Germany:

- Dresden

Russia:

- Dubna
- Novosibirsk

England

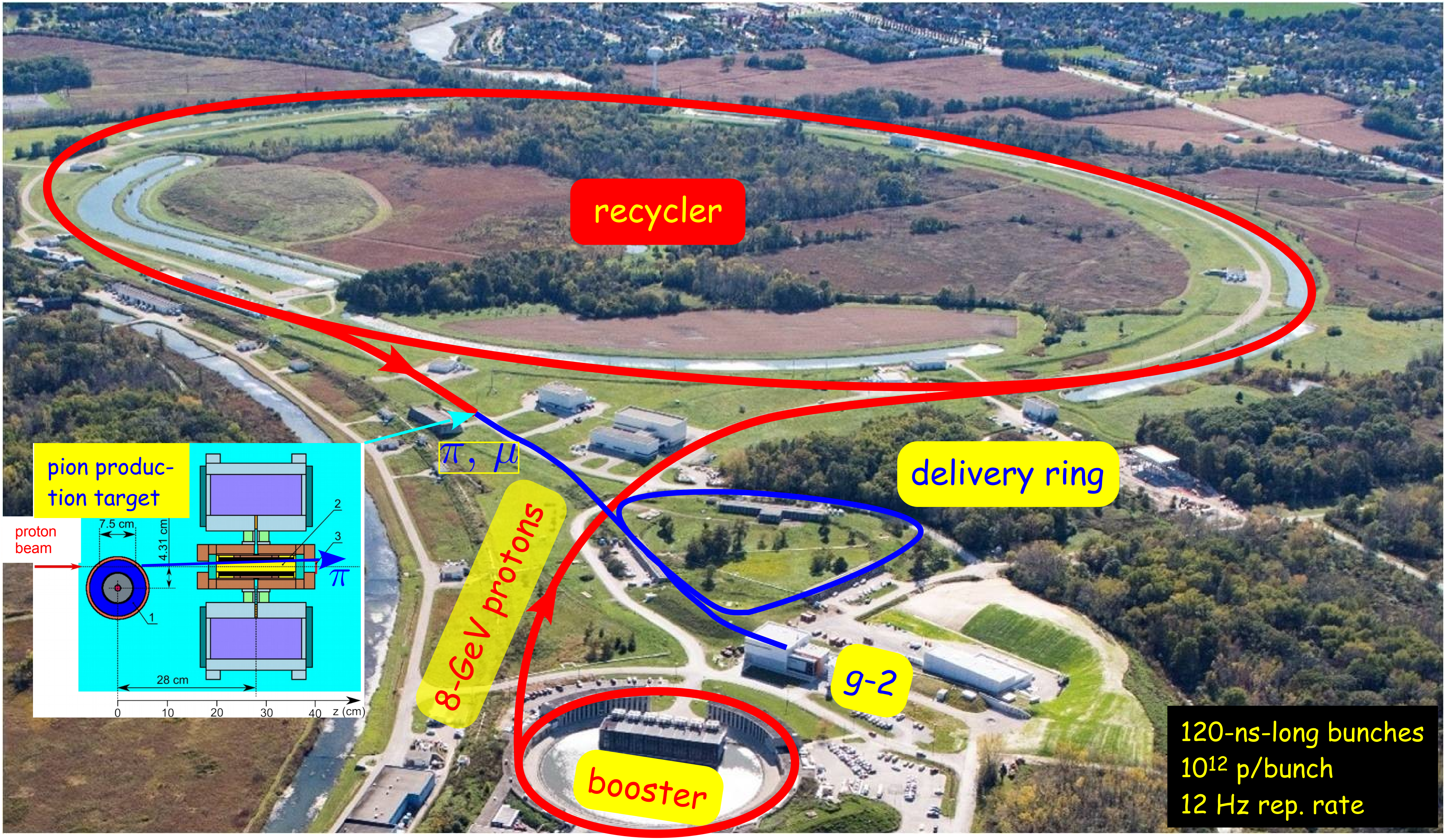
- Lancaster
- Liverpool
- UC London
- Liverpool
-

Korea:

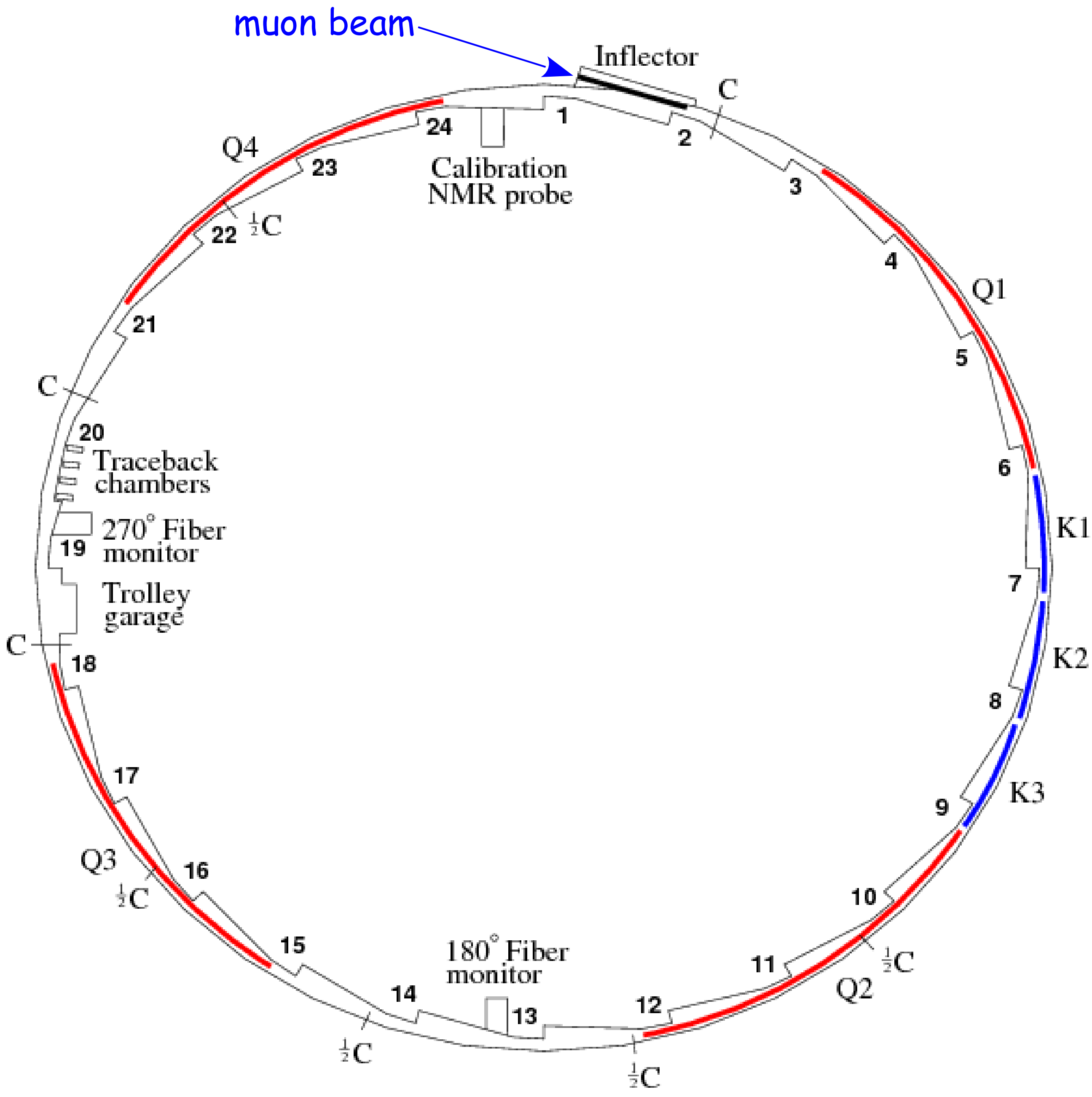
- KAIST

7 countries
36 institutions
- 18 domestic
- 18 international
(192 members)

muons for g-2 (goal: 20x more than at BNL)



… into the g-2 storage ring

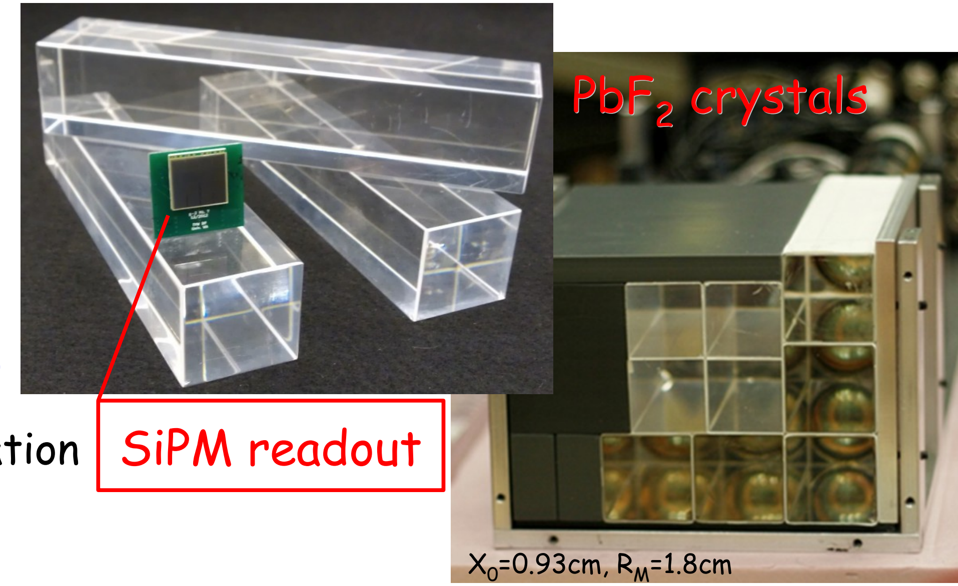


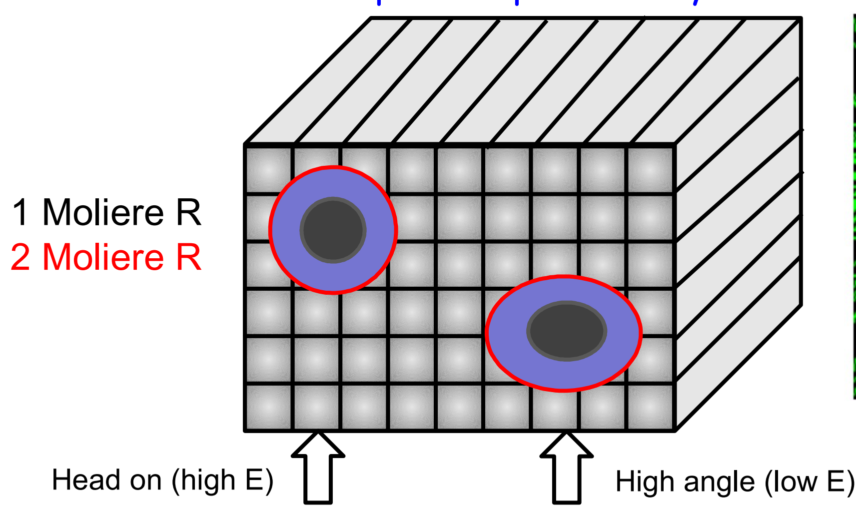
pileup

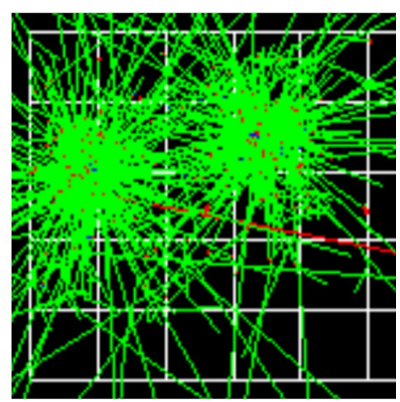
New calorimeters

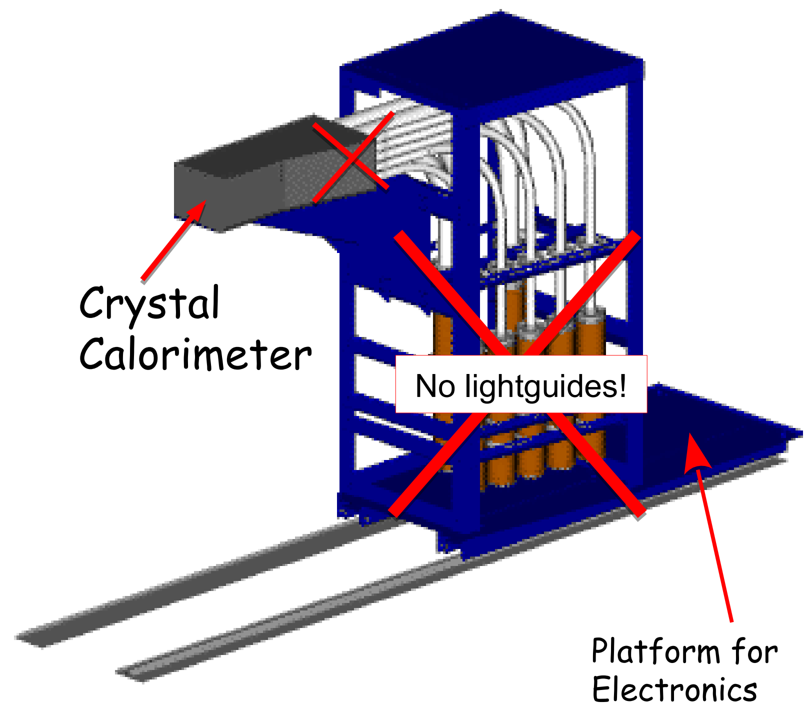
D. Hertzog, UW

- **Compact** based on fixed space
- **Non-magnetic** to avoid field perturbations
- **Resolution** not too critical for dw_a
  - Useful for pileup, gain monitoring, shower partitioning and low thresholds
  - Goal <5% DE/E at 2 GeV (a soft requirement)
- **Gain stability** depends on electronics and calibration system
  - Goal: Short term < 0.1% DG/G in 600 ms
  - Goal: Longer term < 1% DG/G in 24 h
- **Pileup** depends on signal speed and shower separation
  - Subdivide calorimeter
  - Use Cherenkov
  - Goal: 2-pulse separation by space: 2 out of 3
  - Goal: 2-pulse separation by time: Dt > 5 ns



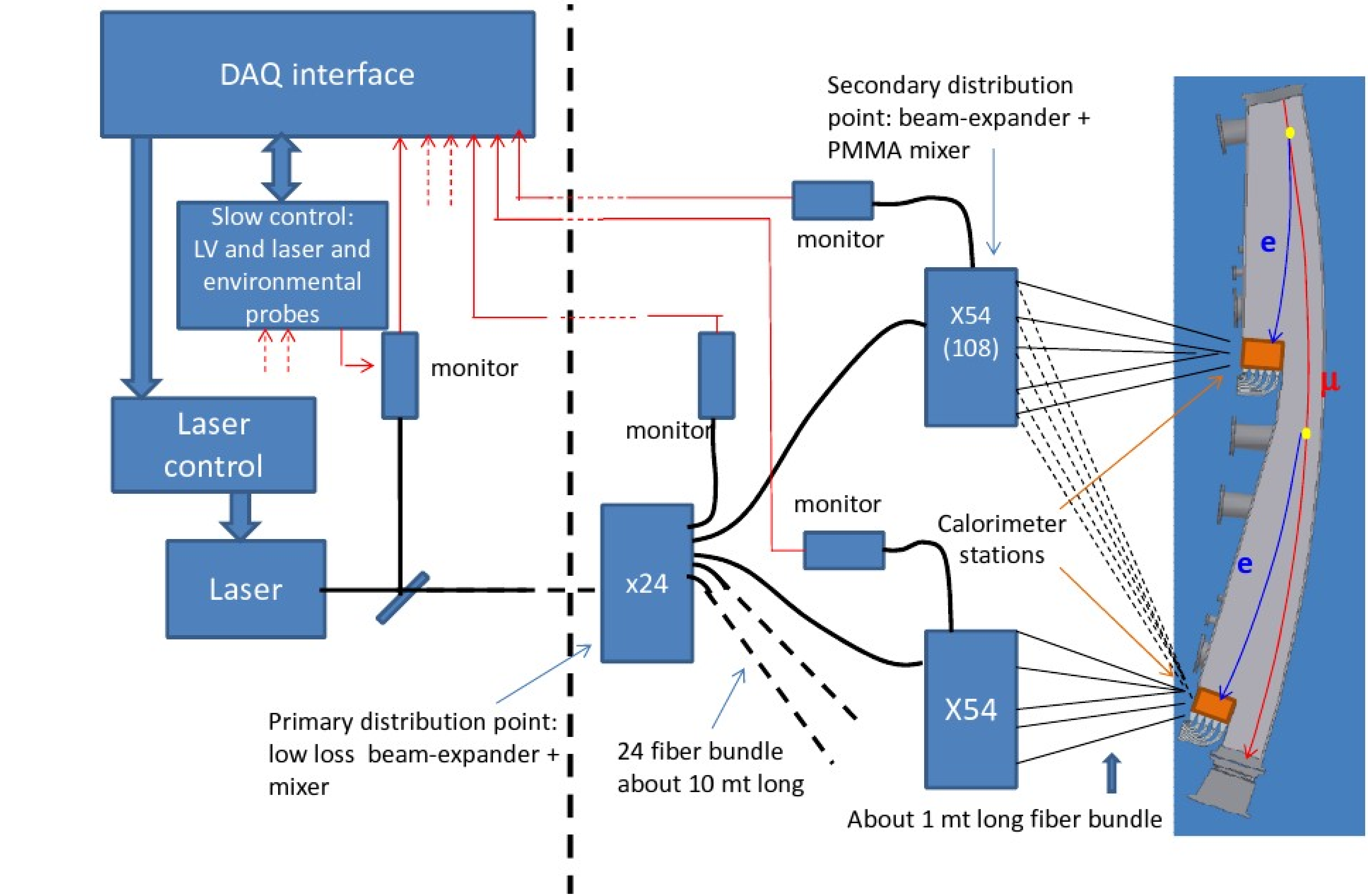






Laser Calibration System

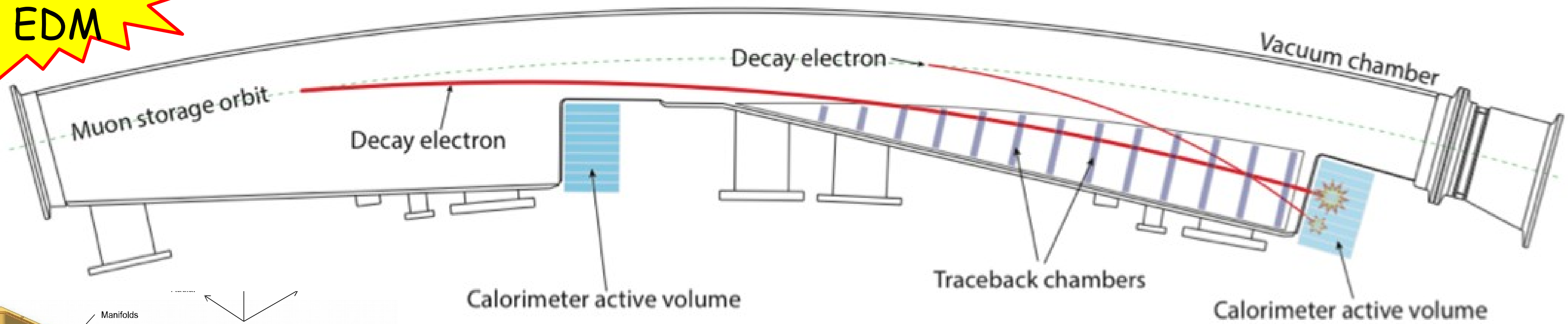
G. Venanzoni, Frascati

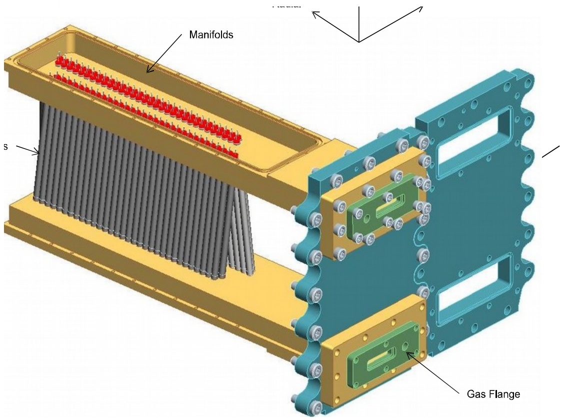


beam, EDM

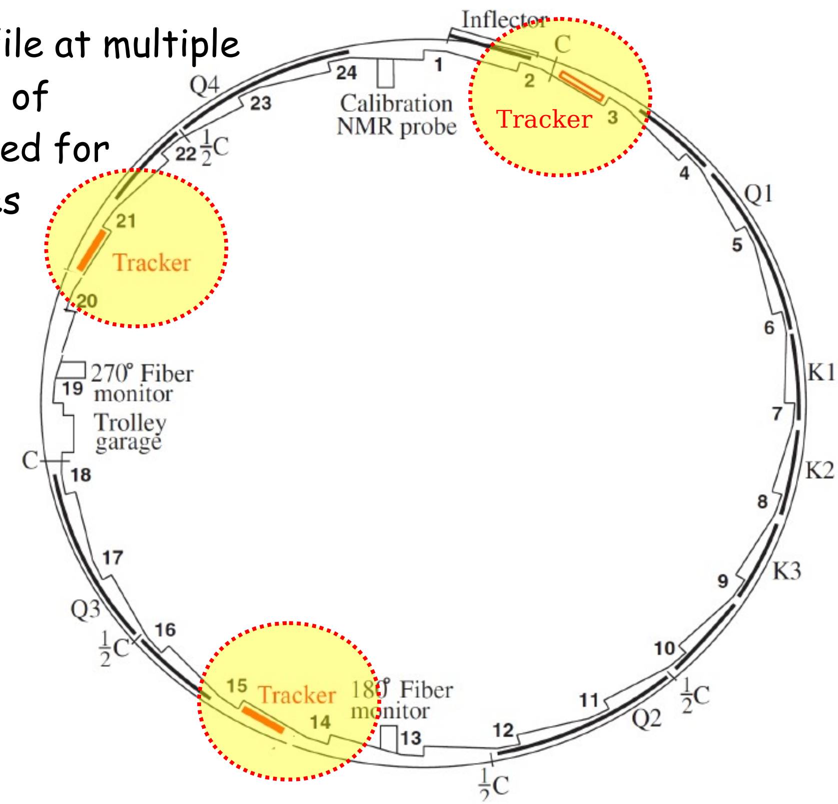
New Tracker

B. Casey, FNAL





Purpose: measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. Is needed for understanding systematic uncertainties associated with ω_a measurements (calorimeter pileup, calorimeter gain, muon loss, differential decay syst. uncertainty, etc). Will also be used to search for a tilt in the muon precession plane away from the vertical orientation (which would be indicative of an EDM of the muon).

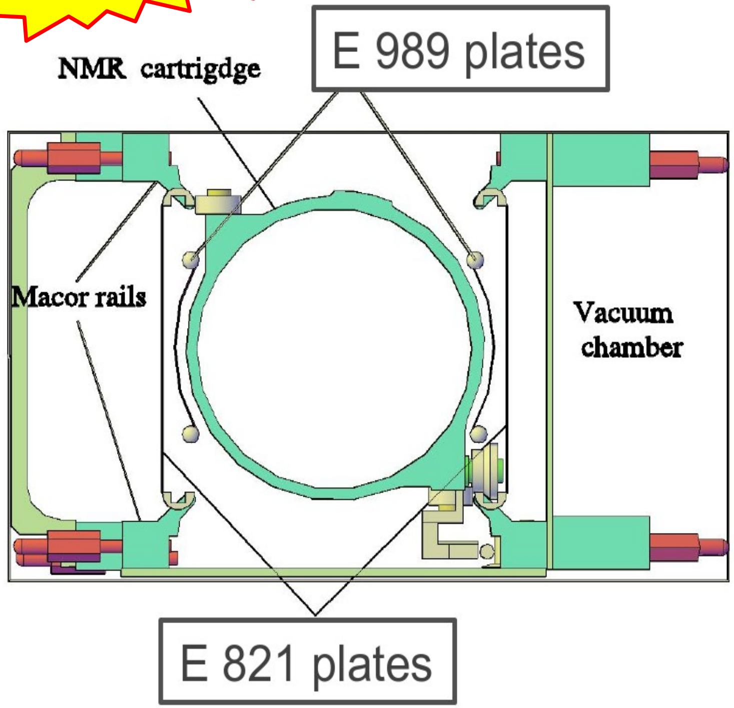


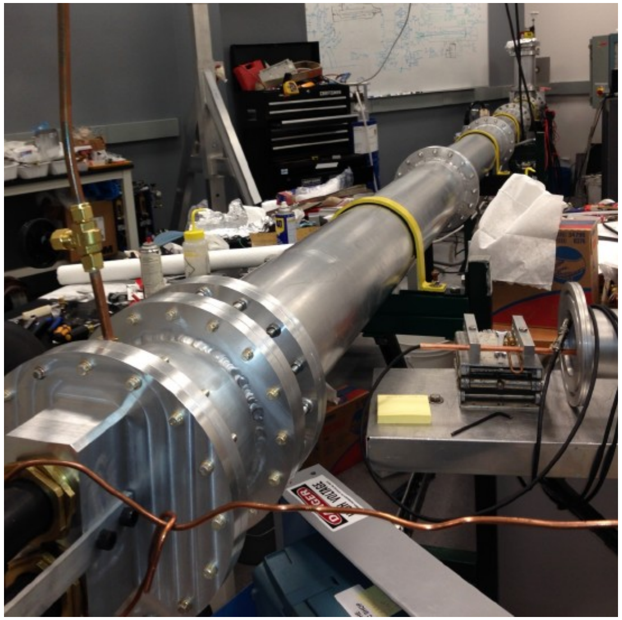
Design: 5-mm-diameter 10-cm-long straw UV doublets at 7.5°.
straw walls: 6 μm Mylar
sense wires: 25 μm gold-plated tungsten at 1500 V
gas: 80:20 Argon:CO_2
readout: ASDQ chips

CBO

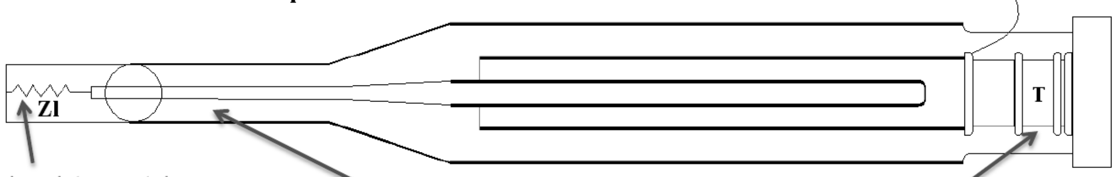
New Kicker

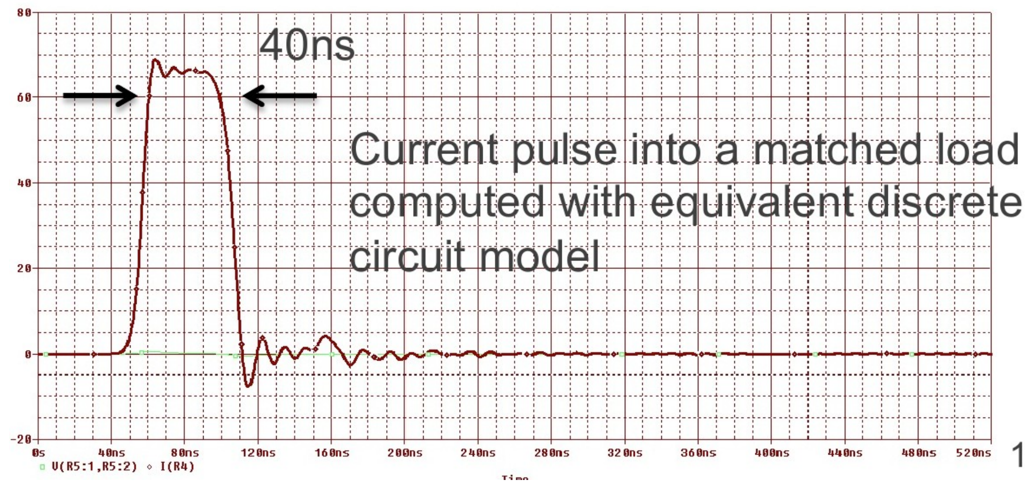
D. Rubin, Cornell





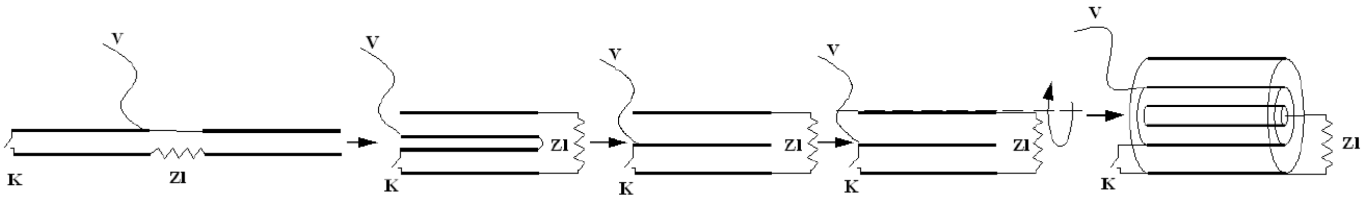
Requirements:
- 3.5 kA
- 120ns width





$$\tau = \frac{2L}{v}$$

width of pulse is proportional to length of blumlein



Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

E989 Proposal

The New (g – 2) Experiment:

A Proposal to Measure the Muon Anomalous

Magnetic Moment to ±0.14 ppm Precision

Request: 4×10^{20} protons on target in 6 of 20 Booster batches during 15 Hz operation

February 9, 2009

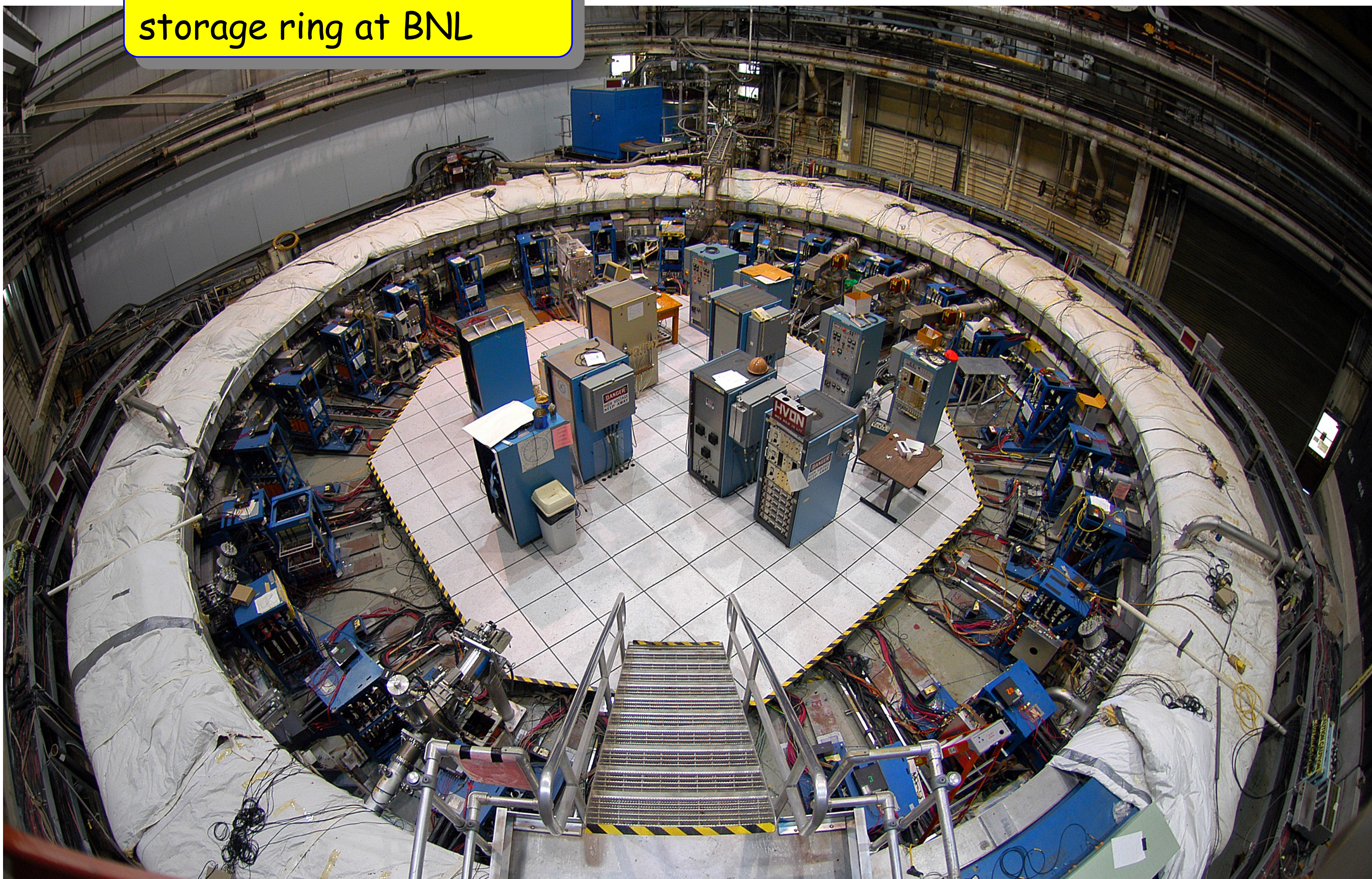
Contactpersons: David W. Hertzog (hertzog@illinois.edu, 217-333-3988)

B. Lee Roberts (roberts@bu.edu, 617-353-2187)

Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

E989 Proposal approved
storage ring at BNL



Experiment timeline

2009 | 2010 | **2011** | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Jan.: Stage 1 approval by FNAL director
May: FY 11 Field Work Proposal granted to develop CDR

Dear Lee and Dave,

Following the recommendation of the PAC and discussions with the Department of Energy on funding projections over the period when we could run the New g-2 Experiment, I grant Stage I approval to g-2. Of course, there is still a lot of work to do to develop a detailed plan for the funding and various further approval processes which will be required to execute the experiment.

We will consider the experiment ready for the Stage II approval when we determine that the available funding is sufficient for the proposal scope of the experiment and there is a detailed MOU between Fermilab and the experiment.

Despite the cautionary words, we are very pleased that your experiment has met a rather high standard, and we very much hope that this approval can lead to establishment of a soundly based plan. If there is any way we can be of assistance in this, please let us know.

Sincerely,

Piermaria Oddone

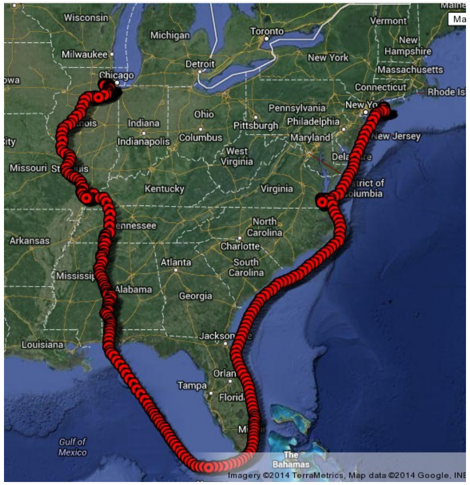
Experiment timeline

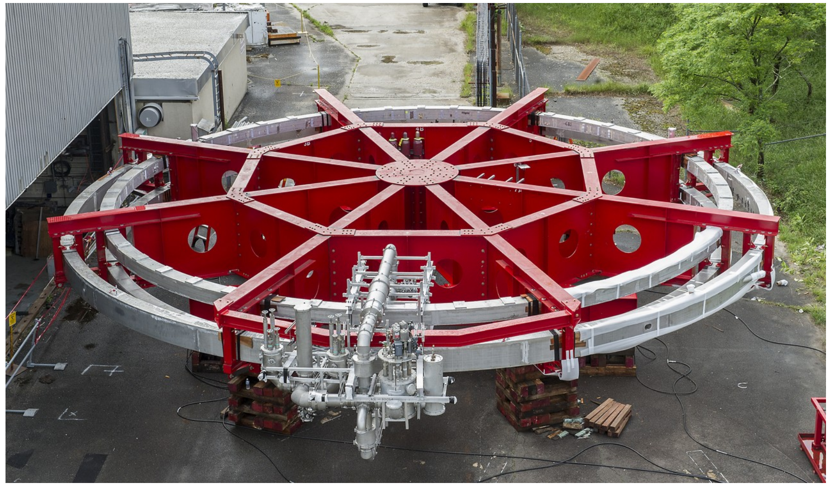
2009 | 2010 | 2011 | **2012** | 2013 | 2014 | 2015 | 2016 | 2017

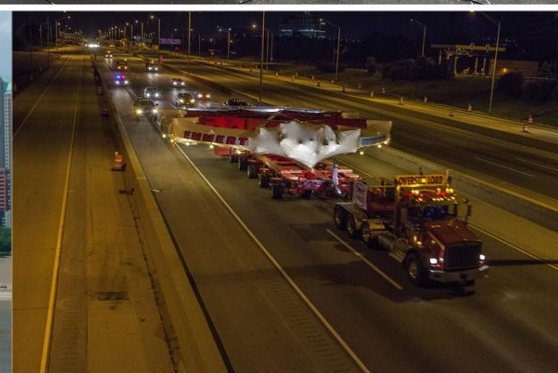
Disassembly of g-2 storage ring started
First yoke piece removed (Sept.)

journey of coils from BNL to Fermilab

2009 › 2010 › 2011 › 2012 › **2013** › 2014 › 2015 › 2016 › 2017







more photos and info: http://muon-g-2.fnal.gov/bigmove

Experiment timeline

2009 | 2010 | 2011 | 2012 | **2013** | 2014 | 2015 | 2016 | 2017

Groundbreaking for MC1

Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | **2014** | 2015 | 2016 | 2017

Beneficial occupancy of MC1

Photo: Brian Drendel, AD

- Hall temperature stability +/- 1°C
- Stable floor (reinforced concrete, 84-cm-thick)

BROOKHAVEN NATIONAL LABORATORY

Experiment timeline

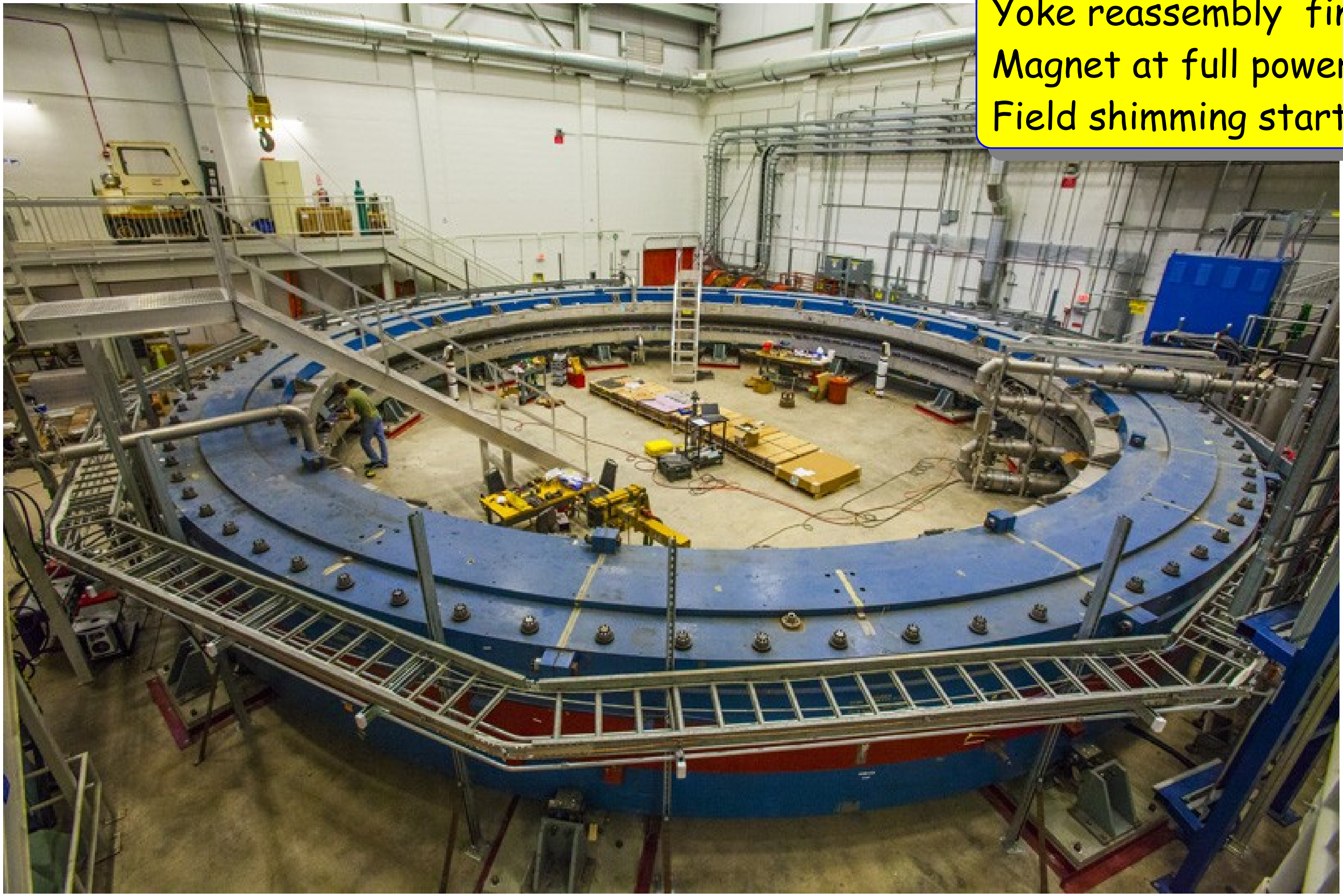
2009 | 2010 | 2011 | 2012 | 2013 | **2014** | 2015 | 2016 | 2017

Ring reassembly started at FNAL

Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | **2015** | 2016 | 2017

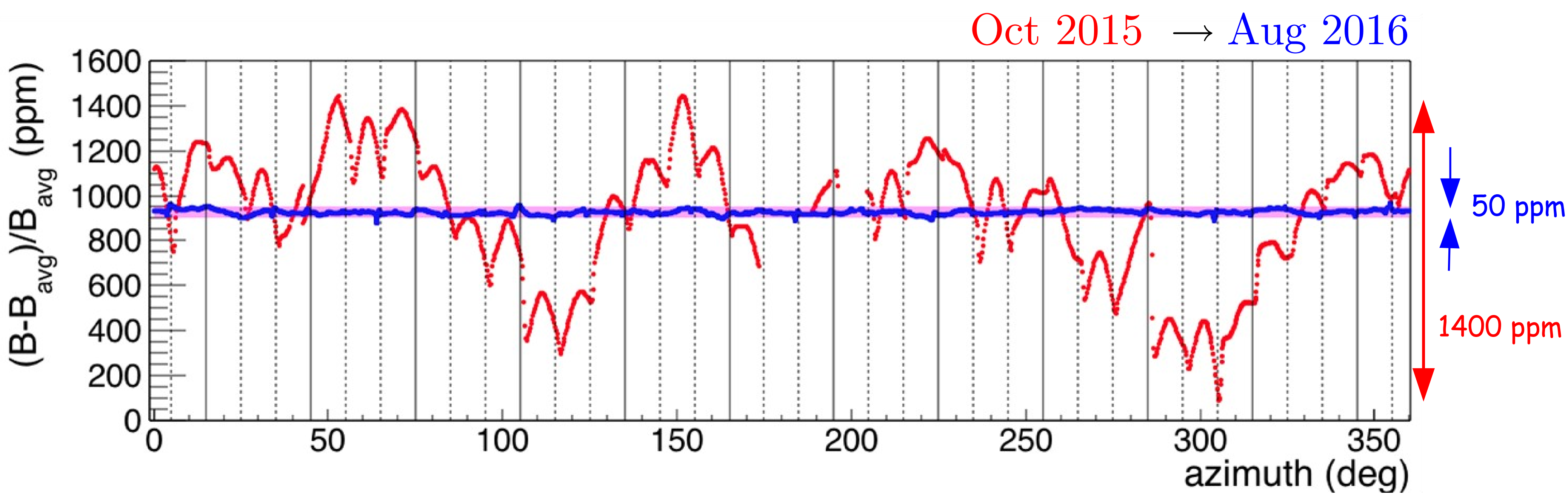
Yoke reassembly finished.
Magnet at full power.
Field shimming started.



Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | **2016** | 2017

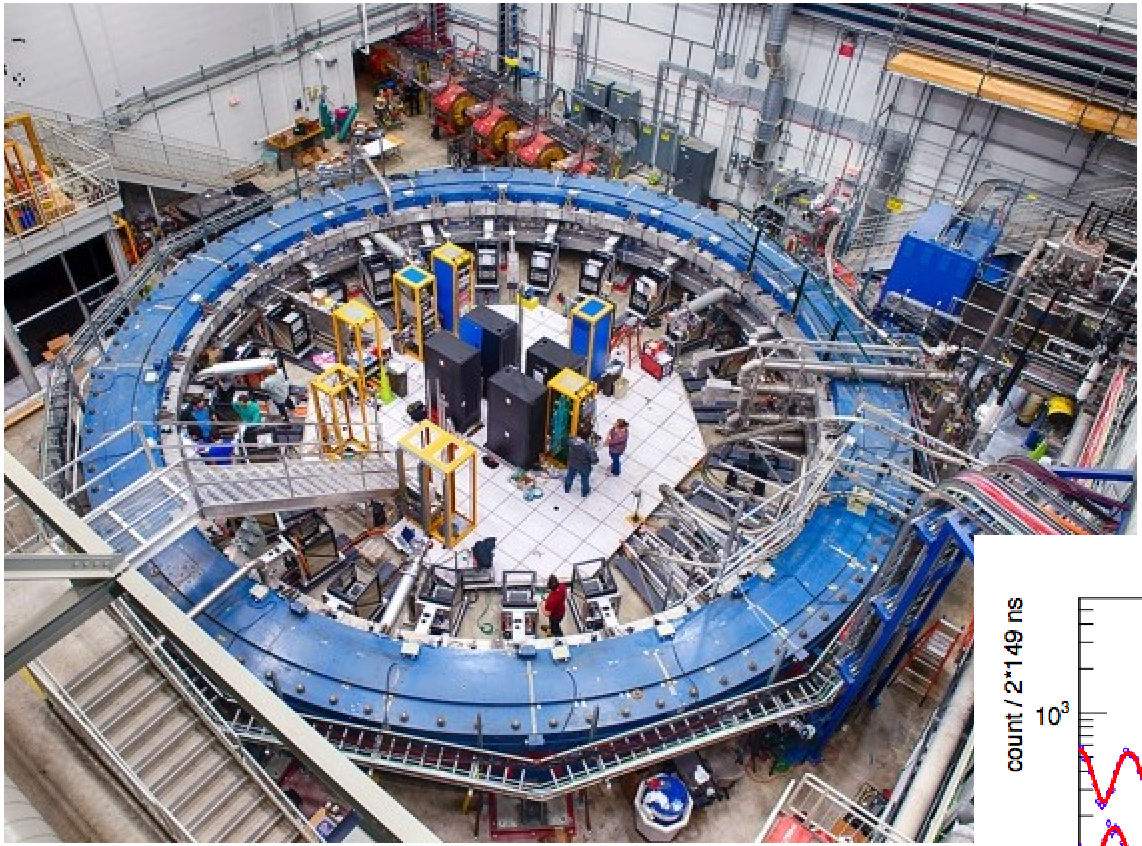
Field shimming finished.
Installation of quadrupoles, kickers, detectors, etc. started.



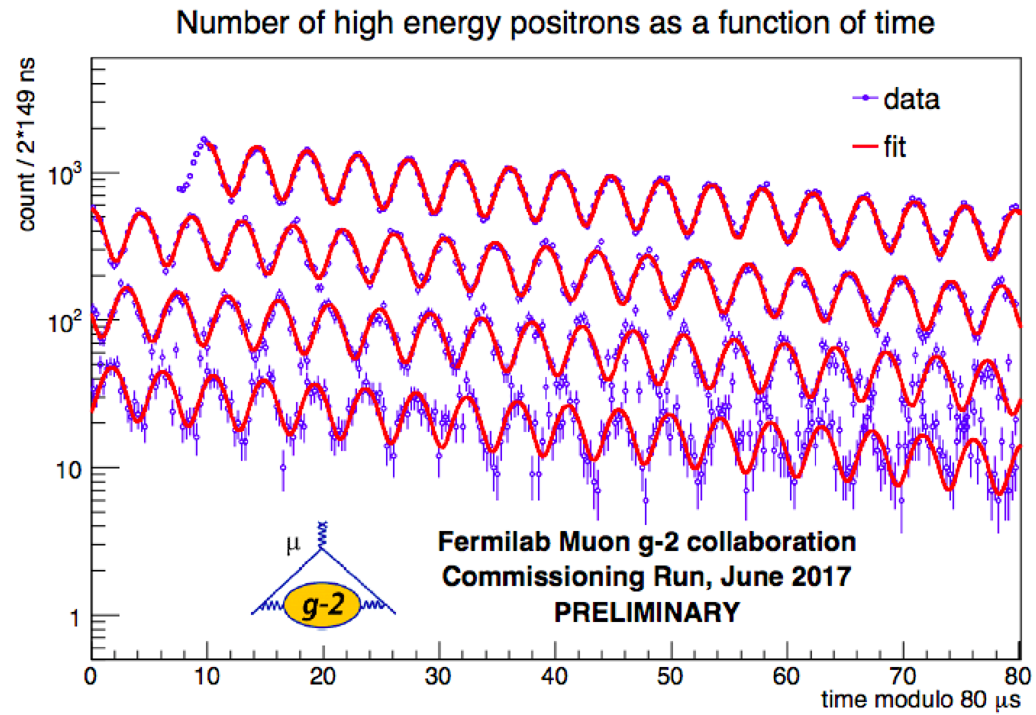
Experiment timeline

2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017

Everything installed
Beam development
first stored muons!



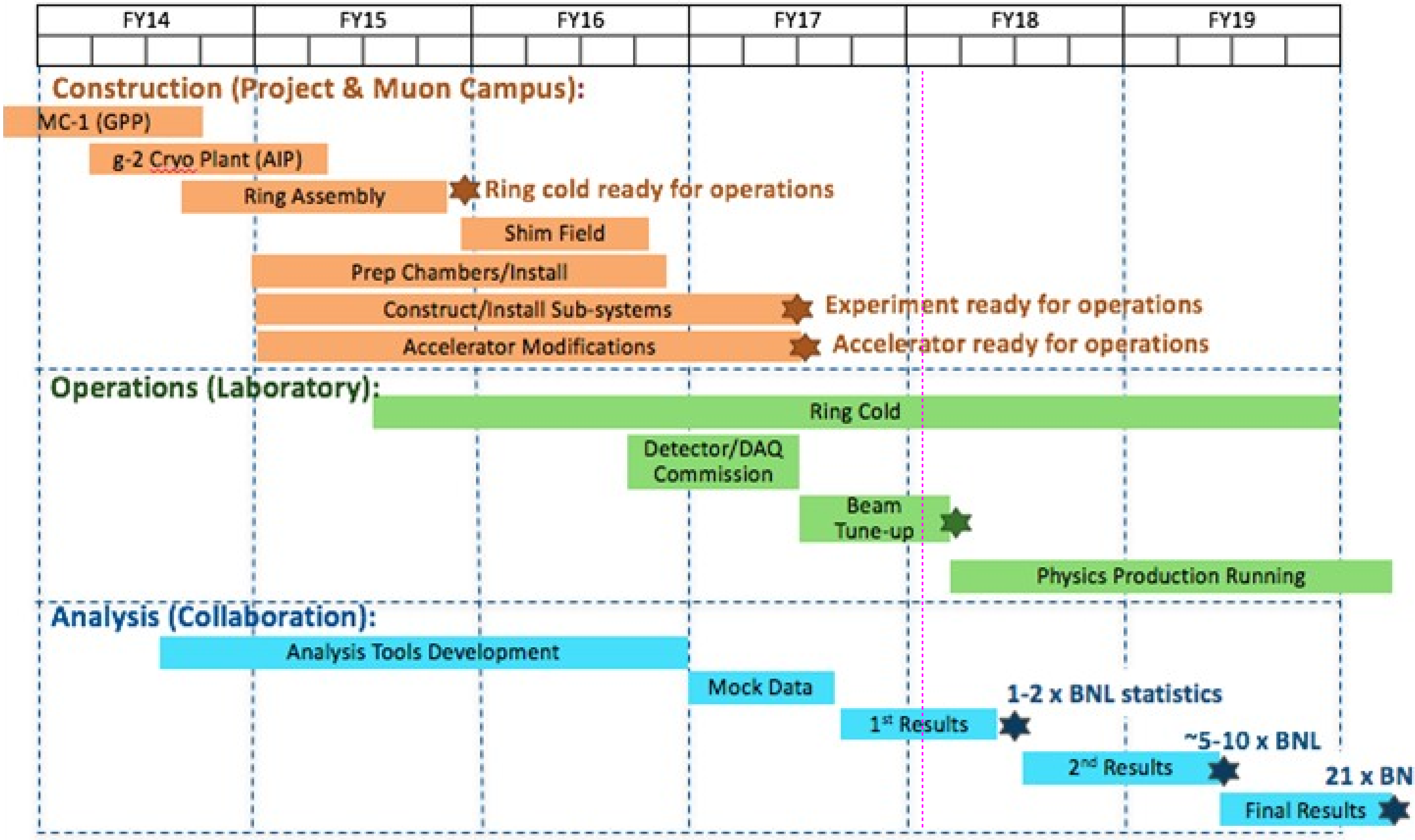
http://www.nature.com/news/muons-big-moment-could-fuel-new-physics-1.21811



Commissioning run summary

- Beam successfully transported through the (new!) beamline and delivered to the experiment.
  x10 lower proton intensity per bunch; 1 Hz (goal: 12 Hz); no DR (100:1 p/μ ratio)
- Stored beam in the g-2 ring within a few days (transmission through the inflector, kicking to the design orbit, etc.)
- Tested as system, for the first time, all components (quads, kickers, etc.).
- Tested interference between different systems (NMR trolley-collimator, kicker-quads, detector operation and noise induced by high-current/high-voltage systems, etc.)
- Tested DAQ and offline data processing using real data.
- Exercised everything we wanted to exercise (high, medium, low priorities)
- Identified places where the performance was subpar
  subpar vacuum -> quads and kickers did not reach nominal operating voltages; kickers/quads interference; unstable power supply of the inflector; minor problems with DAQ and electronics.
- **We are making improvements over the shutdown and getting ready for production data taking!**

Future plans



Summary

- The new experiment at Fermilab E989 to measure the anomaly a_μ of the muon to 4x the precision of the previous BNL experiment (0.54 ppm) is on the way to its physics goal.
- A 5-weeks-long commissioning run completed successfully in July.
- Deficiencies identified during commissioning run are being fixed during shutdown.
- The experiment is expecting beam end of October.

Backup slides