The Muon g-2 anomaly: experimental status and prospects

G. Venanzoni
(INFN/PI)

XIIth Meeting on B Physics.Tensions in Flavour measurements: a path toward Physics beyond the Standard Model

22-24 May 2017 *Centro Congressi Università di Napoli Federico II*
Europe/Rome timezone

Outline

- The Muon g-2: summary of the present status
- The Muon g-2 experiment at Fermilab
- The Muong -2 experiment at J-Parc
- New experiment to measure the leading hadronic contributon to g-2 with a muon beam at CERN
- Conclusions

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

$$a_\mu^{E821} = 11659208.9(6.3)\times 10^{-10} \quad (0.54\ \mathrm{ppm})$$

- Tantalizing ~3σ deviation with SM (persistent since >10 years):

$$a_\mu^{SM} = 11659180.2(4.9)\times 10^{-10}\,(DHMZ)$$

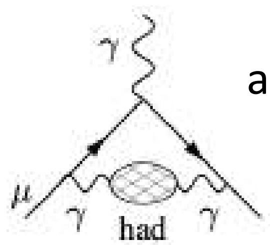
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

$$\boxed{a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8)\times 10^{-10}}$$

- Current discrepancy limited by:
  - Experimental uncertainty→ New experiments at FNAL and J-PARC x4 accuracy
  - Theoretical uncertanty→ limited by hadronic effects

$$a_\mu^{SM} = a_\mu^{QED} + \boxed{a_\mu^{HAD}} + a_\mu^{Weak}$$

Hadronic Vacuum polarization (HLO)



$a_\mu^{HLO} = (692.3\pm4.2)10^{-10}$

$\delta a_\mu/a_\mu \sim 0.6\%$

Three Recent papers relevant for g-2!

Muon g-2

20 years effort!

25 April 2017

High-precision calculation of the 4-loop contribution to the electron g-2 in QED

Stefano Laporta*

Dipartimento di Fisica, Università di Bologna,
Istituto Nazionale Fisica Nucleare, Sezione di Bologna,
Via Irnerio 46, I-40126 Bologna, Italy

Abstract

I have evaluated up to 1100 digits of precision the contribution of the 891 4-loop Feynman diagrams contributing to the electron g-2 in QED. The total 4-loop contribution is

$$a_e = -1.912245764926445574152647167439830054060873390658725345\ldots\left(\frac{\alpha}{\pi}\right)^4 .$$

I have fit a semi-analytical expression to the numerical value. The expression contains harmonic polylogarithms of argument $e^{\frac{i\pi}{3}}$, $e^{\frac{2i\pi}{3}}$, $e^{\frac{i\pi}{2}}$, one-dimensional integrals of products of complete elliptic integrals and six finite parts of master integrals, evaluated up to 4800 digits.

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Experimental Physics

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,f], M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]

[1] INFN Bologna, Viale Carlo Berti-Pichat 6/2, 40127 Bologna, Italy
[2] INFN Pavia, Via Agostino Bassi 6, 27100 Pavia, Italy
[3] INFN Bologna, Via Irnerio 46, 40126 Bologna, Italy
[4] INFN Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy
[5] Dipartimento di Fisica, Università di Pavia, Via A. Bassi 6, 27100 Pavia, Italy
[6] INFN Padova, Via Francesco Marzolo 8, 35131 Padua, Italy
[7] INFN Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[8] Dipartimento di Fisica e Scienze della Terra "M. Melloni", Parco Area delle Scienze 7/A, 43124 Parma, Italy
[9] INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, RM, Italy

Received: 17 October 2016 / Accepted: 17 January 2017 / Published online: 1 March 2017

$\delta a_\mu^{HLO}/a_\mu^{HLO} \rightarrow 0.3\%_{stat}$

The hadronic vacuum polarization contribution to the muon $g-2$ from lattice QCD

M. Della Morte[a], A. Francis[b], V. Gülpers[c], G. Herdoíza[d], G. von Hippel[e], H. Horch[e], B. Jäger[f], H.B. Meyer[e,g], A. Nyffeler[e], H. Wittig[e,g]

[a] CP3-Origins, University of Southern Denmark, Campusvej 55, 5230 Odense M, Denmark
[b] Department of Physics and Astronomy, York University, Toronto, ON, Canada, M3J1P3
[c] School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK
[d] Instituto de Física Teórica UAM/CSIC and Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain
[e] PRISMA Cluster of Excellence and Institut für Kernphysik, Johann Joachim Becher-Weg 45, University of Mainz, D-55099 Mainz, Germany
[f] ETH Zürich, Institute for Theoretical Physics, Wolfgang-Pauli-Str. 27, 8093 Zürich, Switzerland
[g] Helmholtz Institute Mainz, University of Mainz, D-55099 Mainz, Germany

Abstract

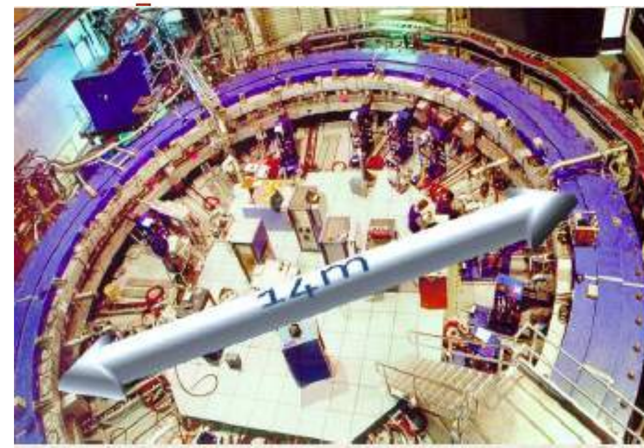
We present a calculation of the hadronic vacuum polarization contribution to the muon anomalous magnetic moment, $a_\mu^{\rm hvp}$, in lattice QCD employing dynamical up and down quarks. We focus on controlling the infrared regime of the vacuum polarization function. To this end we employ several complementary approaches, including Padé fits, time moments and the time-momentum representation. We correct our results for finite-volume effects by combining the Gounaris-Sakurai parameterization of the timelike pion form factor with the Lüscher formalism. On a subset of our ensembles we have derived an upper bound on the magnitude of quark-disconnected diagrams and found that they decrease the estimate for $a_\mu^{\rm hvp}$ by at most 2%. Our final result is $a_\mu^{\rm hvp} = (654 \pm 32\,^{+21}_{-23}) \cdot 10^{-10}$, where the first error is statistical, and the second denotes the combined systematic uncertainty. Based on our findings we discuss the prospects for determining $a_\mu^{\rm hvp}$ with sub-percent precision.

$\delta a_\mu^{HLO}/a_\mu^{HLO} \sim 6\%$

The Muon g-2 experiment at FNAL (E989)

Muon g-2

- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat**. w.r.t. E821. Relocate the BNL storage ring to FNAL.

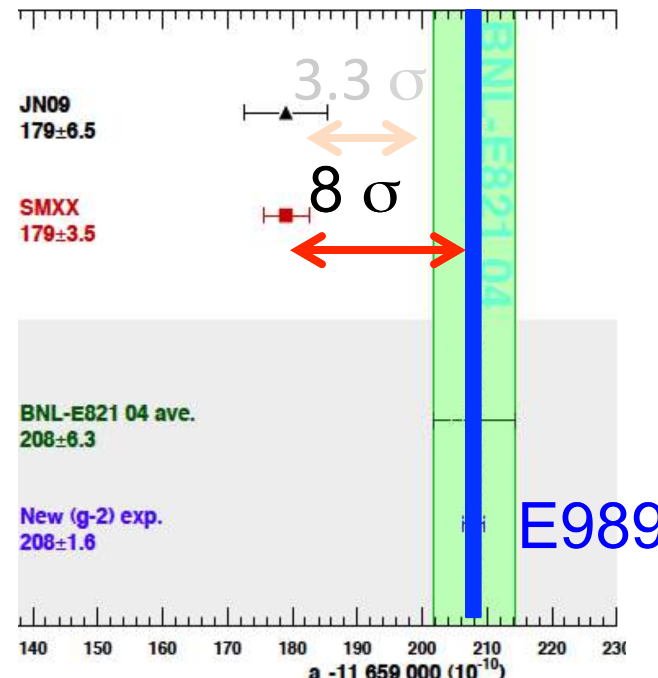


→ δa_μx4 improvement (0.14ppm)

If the central value remains the same ⇒ 5-8σ from SM* (enough to claim discovery of New Physics!)

*Depending on the progress on Theory

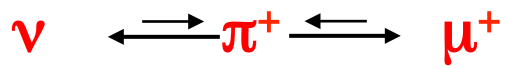
Thomas Blum; Achim Denig; Ivan Logashenko; Eduardo de Rafael; Lee oberts, B.; Thomas Teubner; Graziano Venanzoni (2013). "The Muon (g-2) heory Value: Present and Future". arXiv:1311.2198 [hep-ph].



Complementary proposal at J-PARC in progress

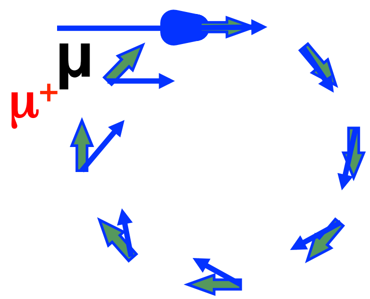
How to measure g-2 in a storage ring

(1) Polarized muons



~97% polarized for forward decays

(2) Precession proportional to (g-2)



$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

a_μ=(g-2)/2

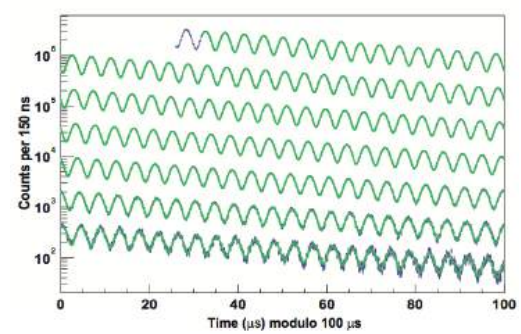
(3) P_μ magic momentum = 3.094 GeV/c

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

E field doesn't affect muon spin when γ = 29.3

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

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



How to measure g-2 in a storage ring

(1) Polarized muons

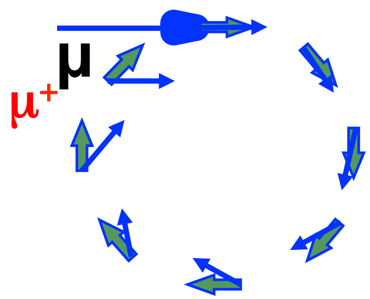
$\nu \longleftarrow \pi^+ \longrightarrow \mu^+$

~97% polarized for forward decays

(2) Precession proportional to (g-2)

$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

a_μ=(g-2)/2



Measure 2 quantities

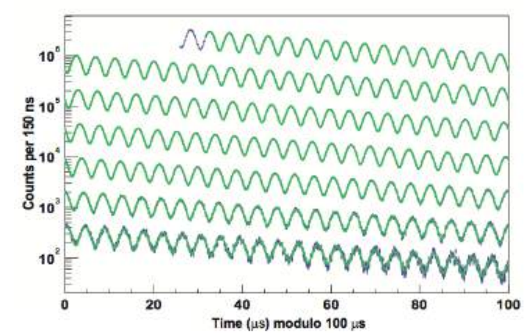
(3) P_μ magic momentum = 3.094 GeV/c

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

E field doesn't affect muon spin when γ = 29.3

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

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



4 key elements for E989 at FNAL

- Consolidated method
- More muons (x20)
- Reduced systematics (ring and detector)
- New crew

- **E821 at Brookhaven**

$$\left.\begin{aligned}\sigma_{\mathrm{stat}} &= \pm 0.46\ \mathrm{ppm}\\ \sigma_{\mathrm{syst}} &= \pm 0.28\ \mathrm{ppm}\end{aligned}\right\}\ \sigma = \pm 0.54\ \mathrm{ppm}$$

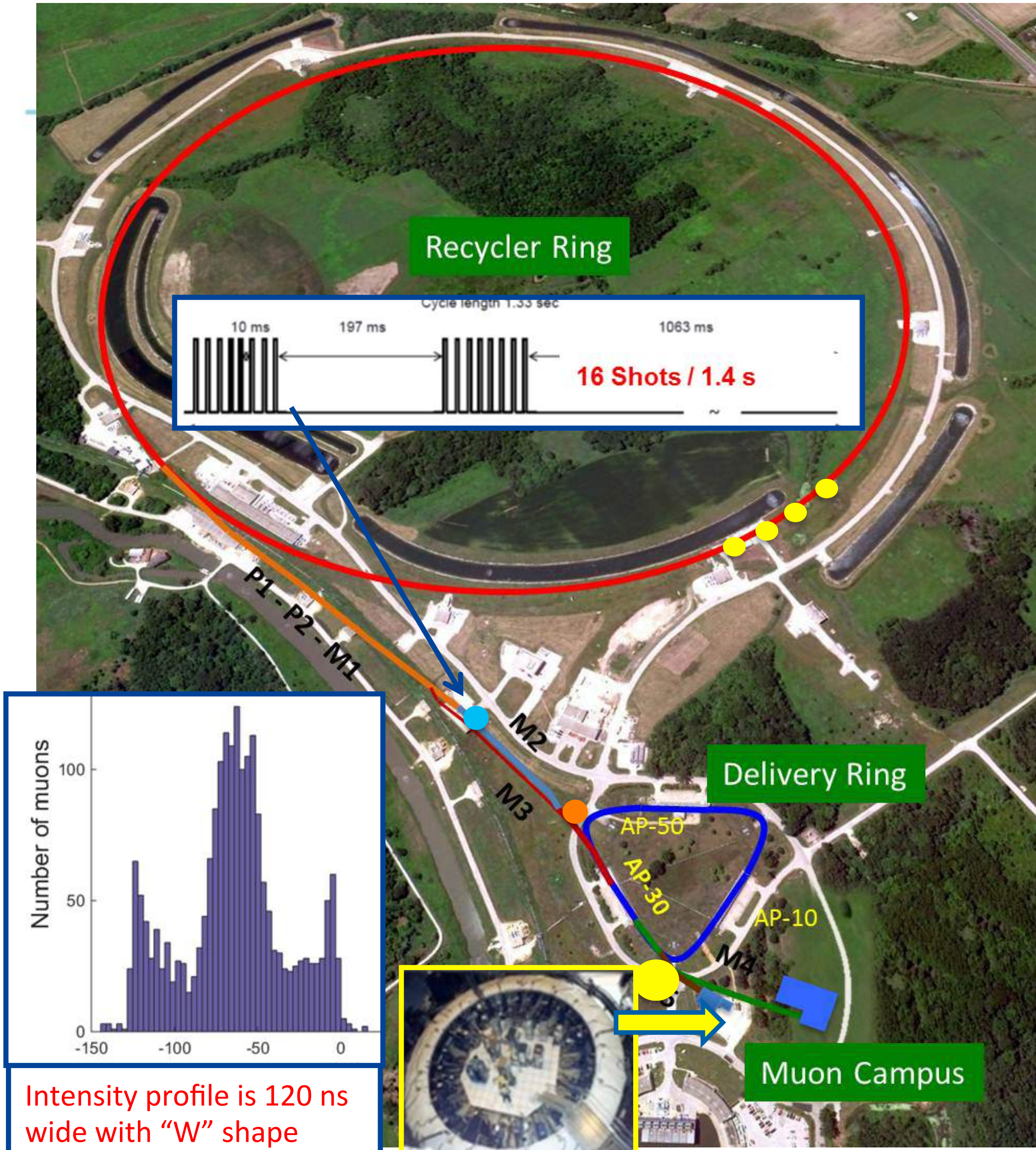
$\hookrightarrow\ 0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

$$\left.\begin{aligned}\sigma_{\mathrm{stat}} &= \pm 0.1\ \mathrm{ppm}\\ \sigma_{\mathrm{syst}} &= \pm 0.1\ \mathrm{ppm}\end{aligned}\right\}\ \sigma = \pm 0.14\ \mathrm{ppm}$$

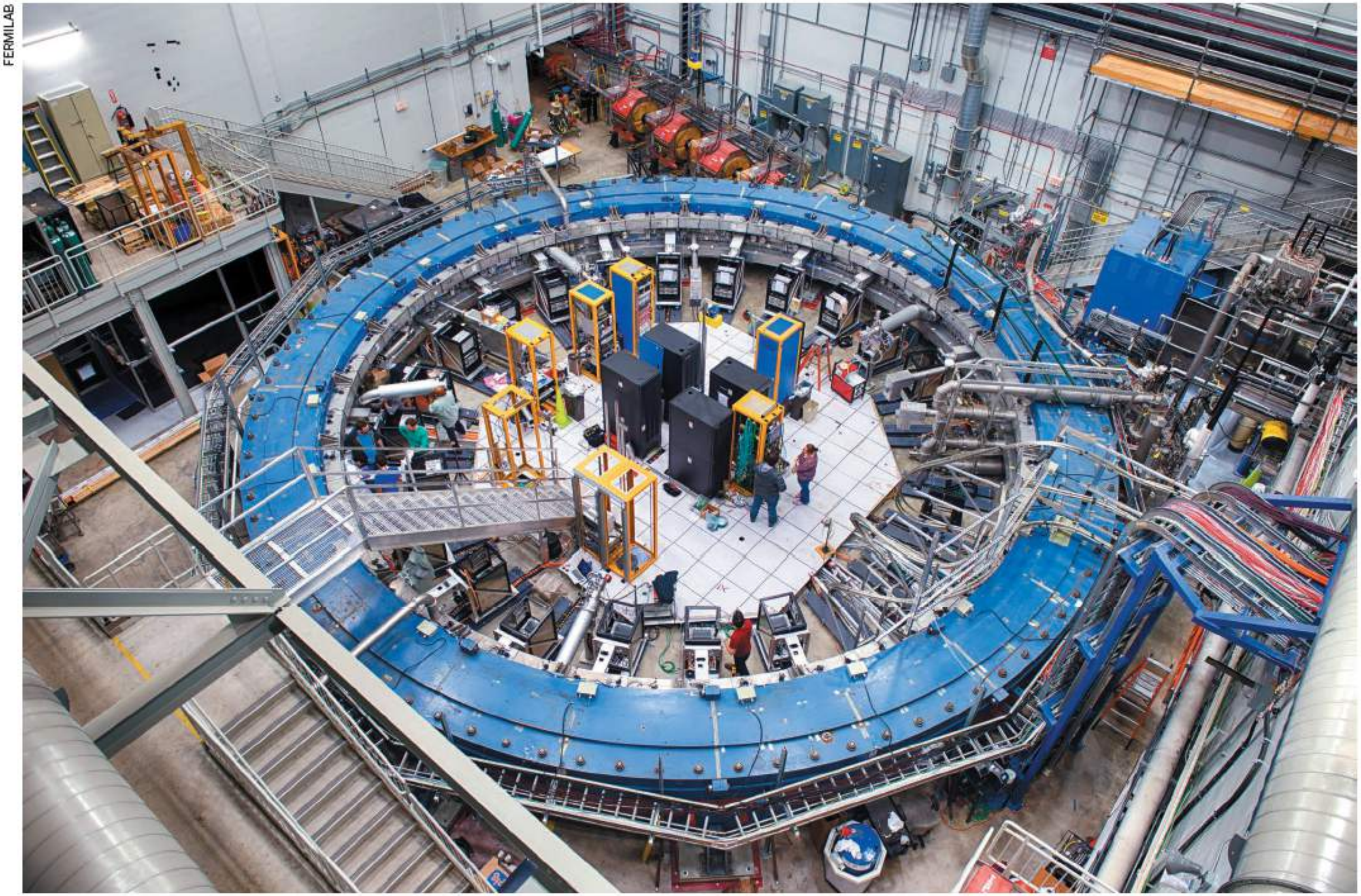
$\hookrightarrow\ 0.07\omega_a \oplus 0.07\omega_p$

Creating the Muon Beam for g-2



- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- p/π/μ beam enters DR; protons kicked out; π decay away
- μ enter storage ring

Nature,11 Aprile 2017



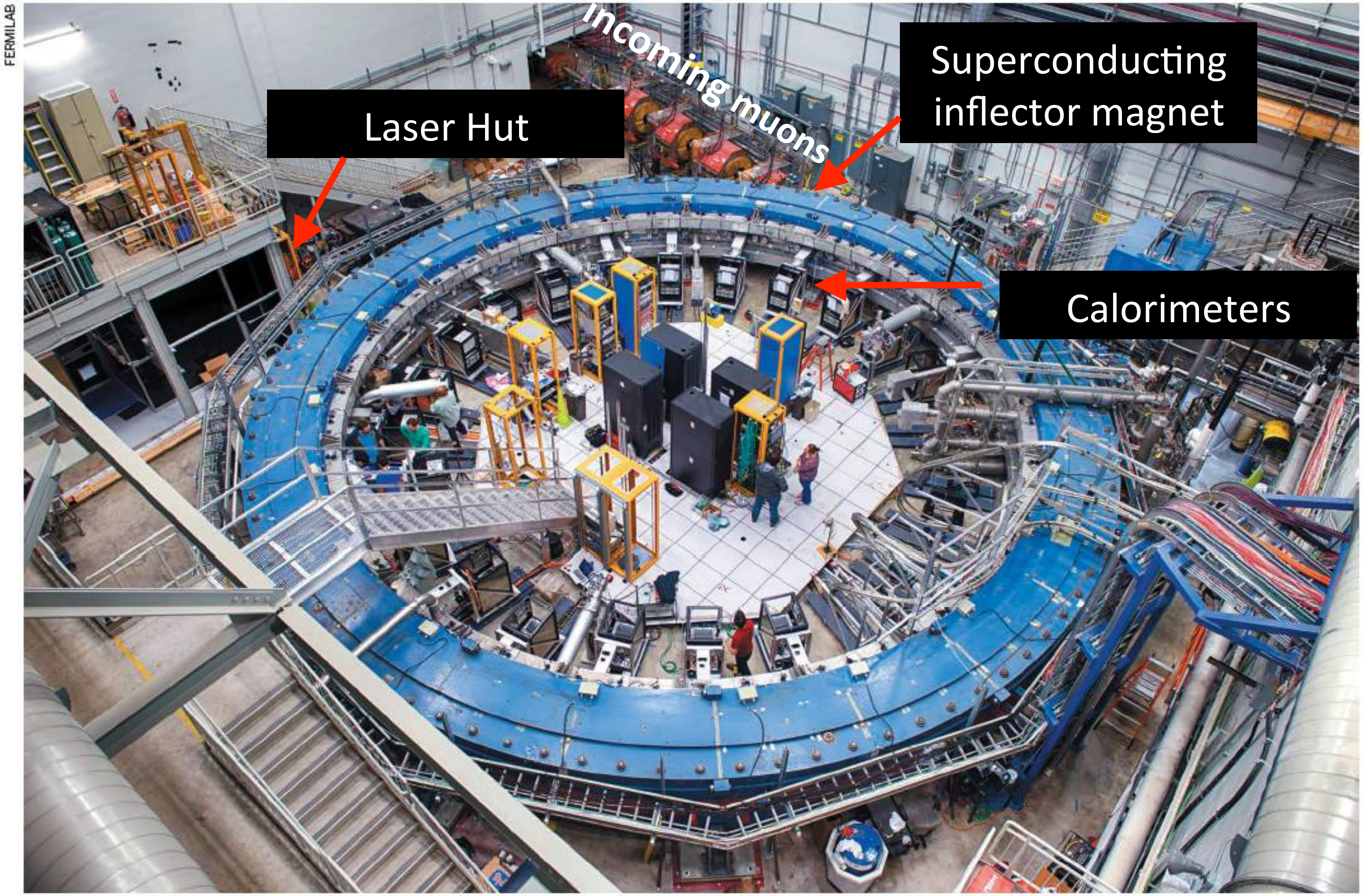
The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

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

PARTICLE PHYSICS

Muons' big moment

Nature,11 Aprile 2017



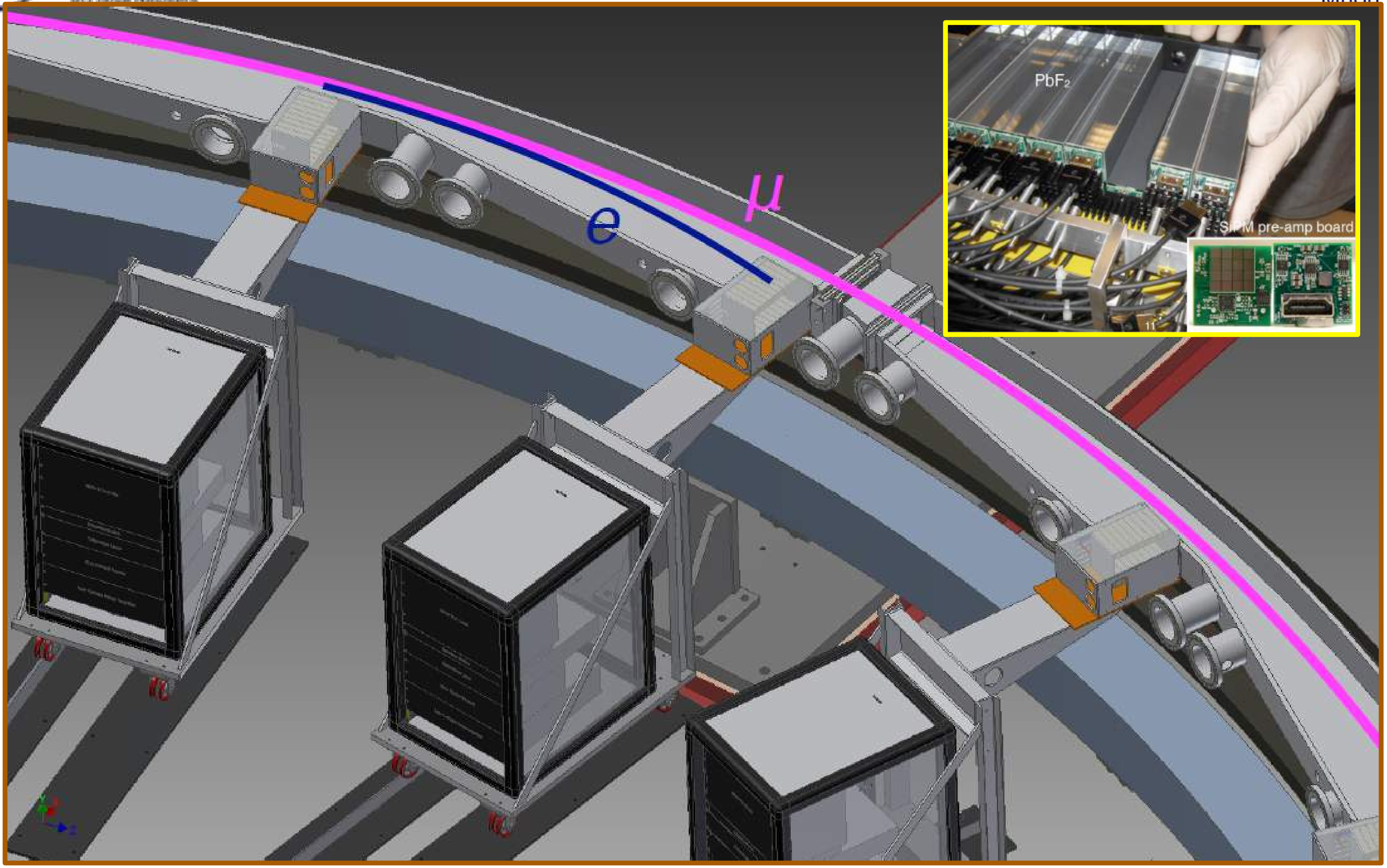
The Muon g−2 experiment will look for deviations from the standard model by measuring how muons wobble in a magnetic field.

PARTICLE PHYSICS

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

Muons' big moment

24 Calos with 54 PbF_2 crystals and fast SiPMs

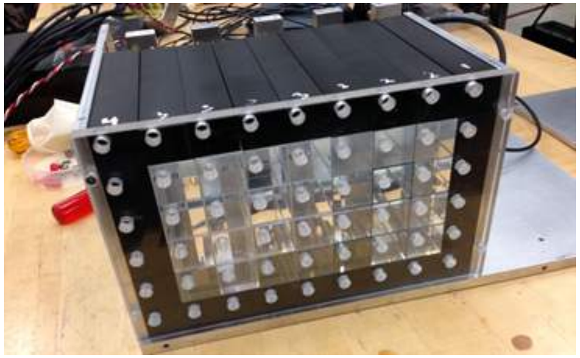


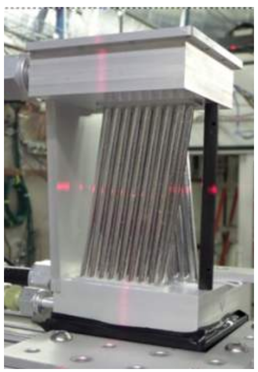
ω_a systematics

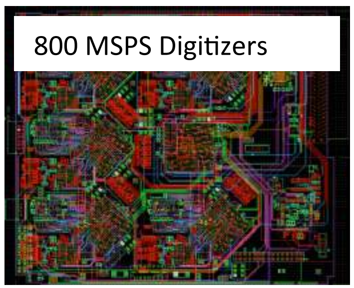
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to 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 and improved hardware

New detector systems

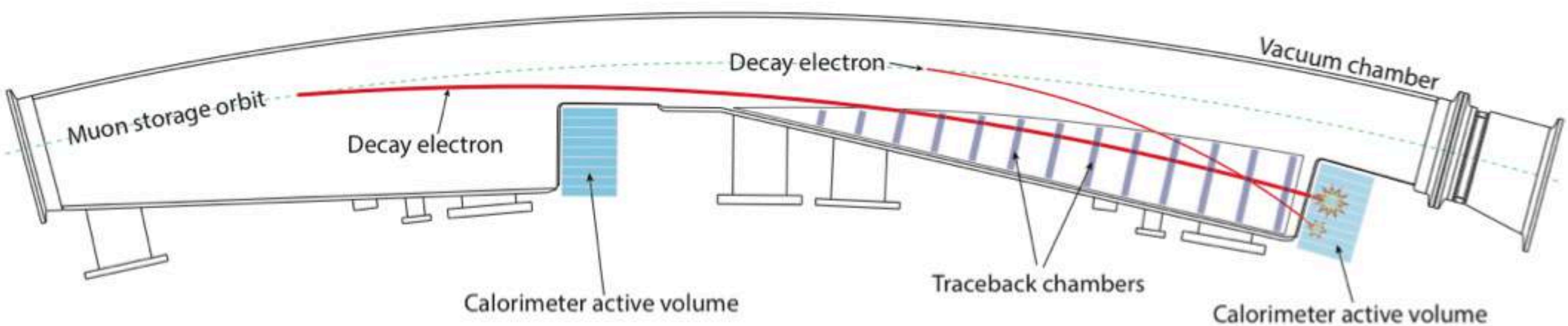




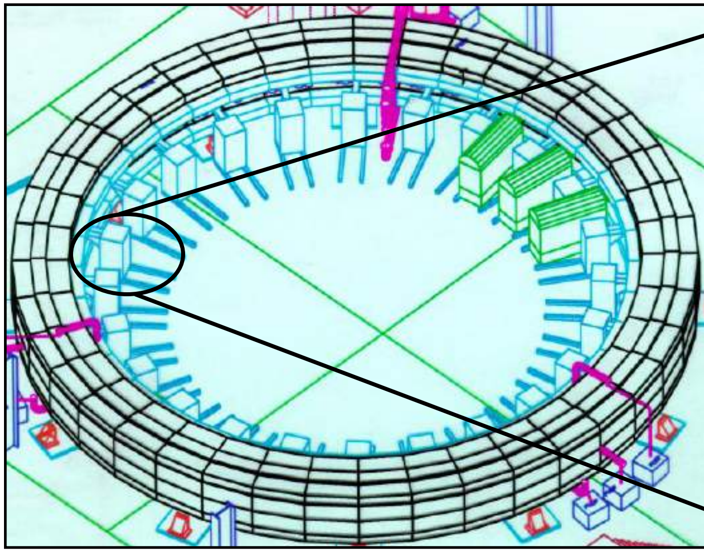


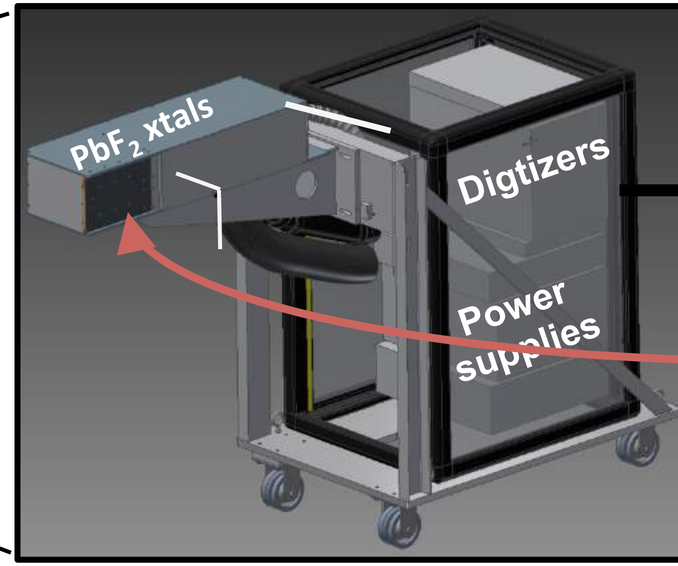
- Calorimeters 24 6x9 PbF_2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Three 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant UK contributions
- New laser calibration system from INFN crucial for untangling gain from other systematics

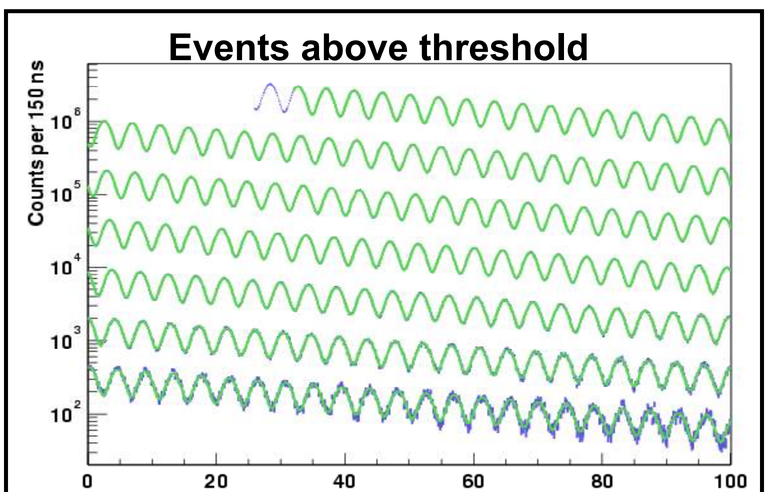
Top view of 1 of 12 vacuum chambers

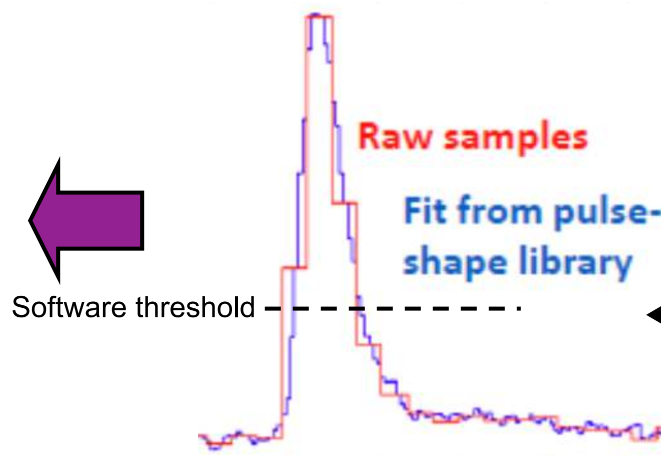


An “event” is an isolated positron above a threshold



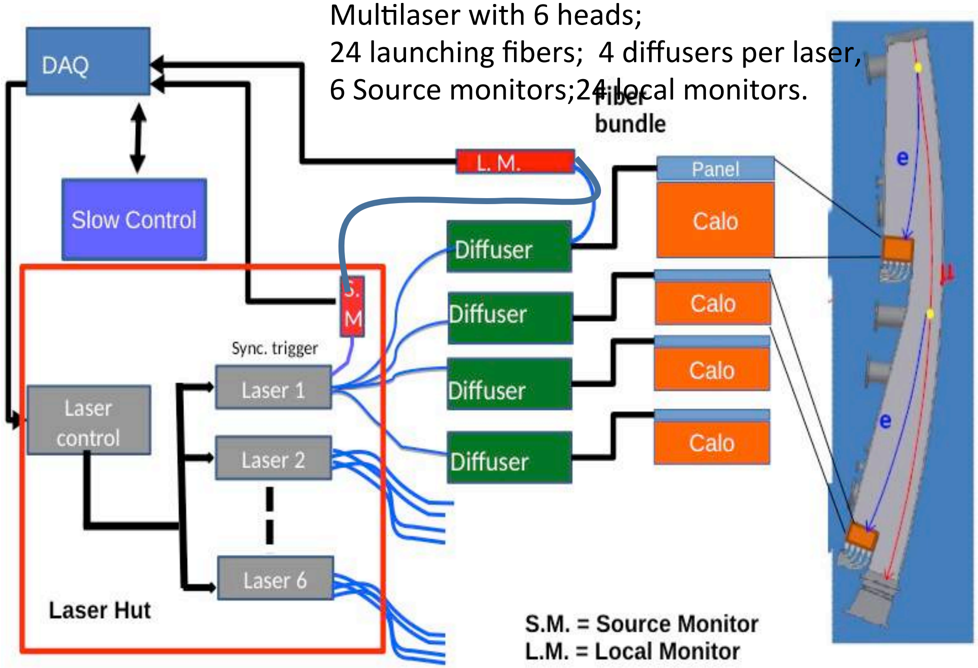


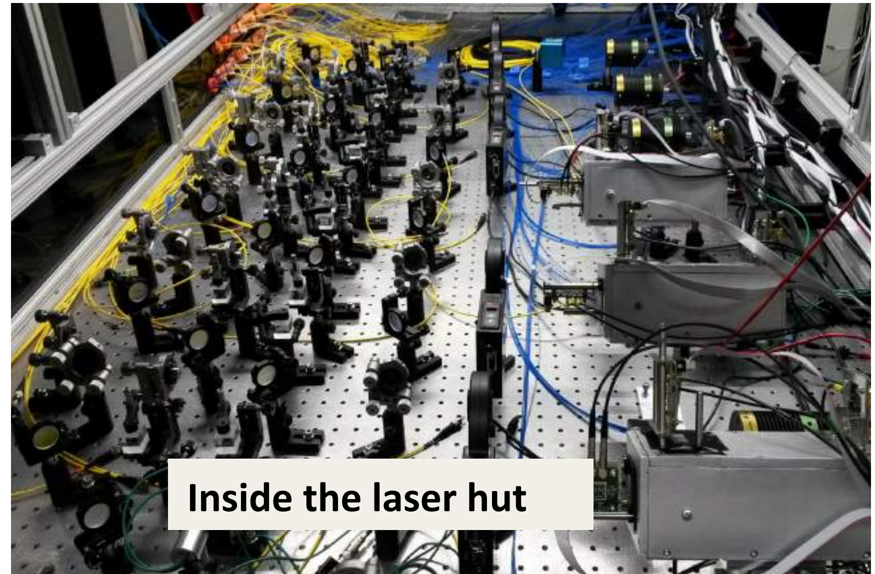


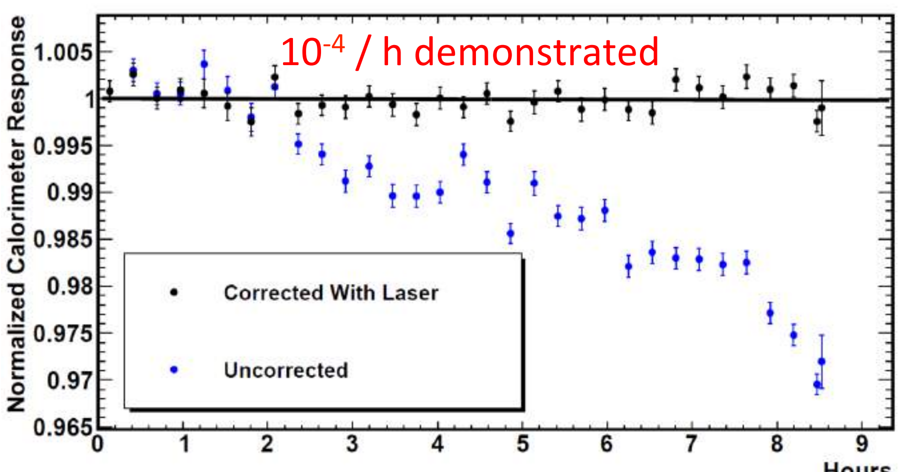


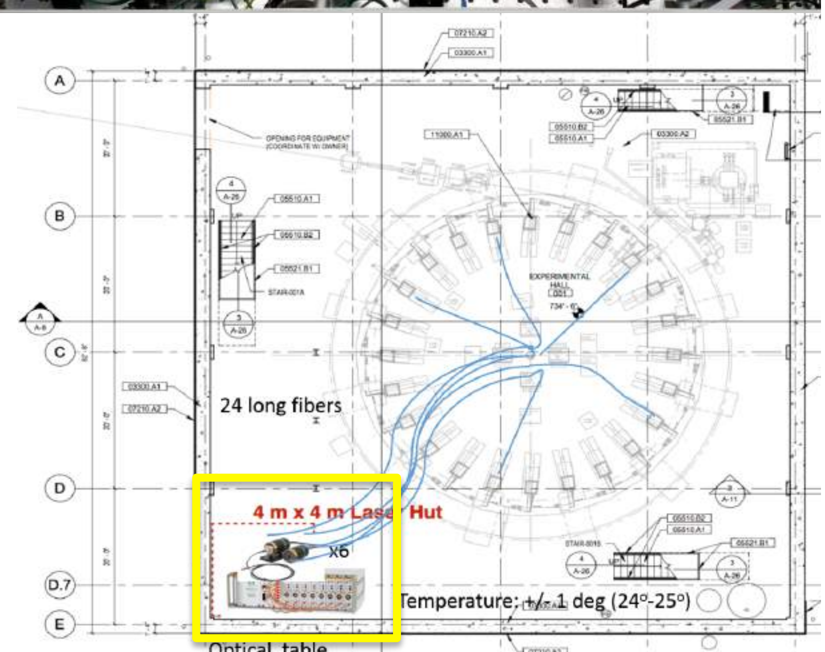
The g-2 laser calibration system

Multilaser with 6 heads;
24 launching fibers; 4 diffusers per laser,
6 Source monitors;24 local monitors.





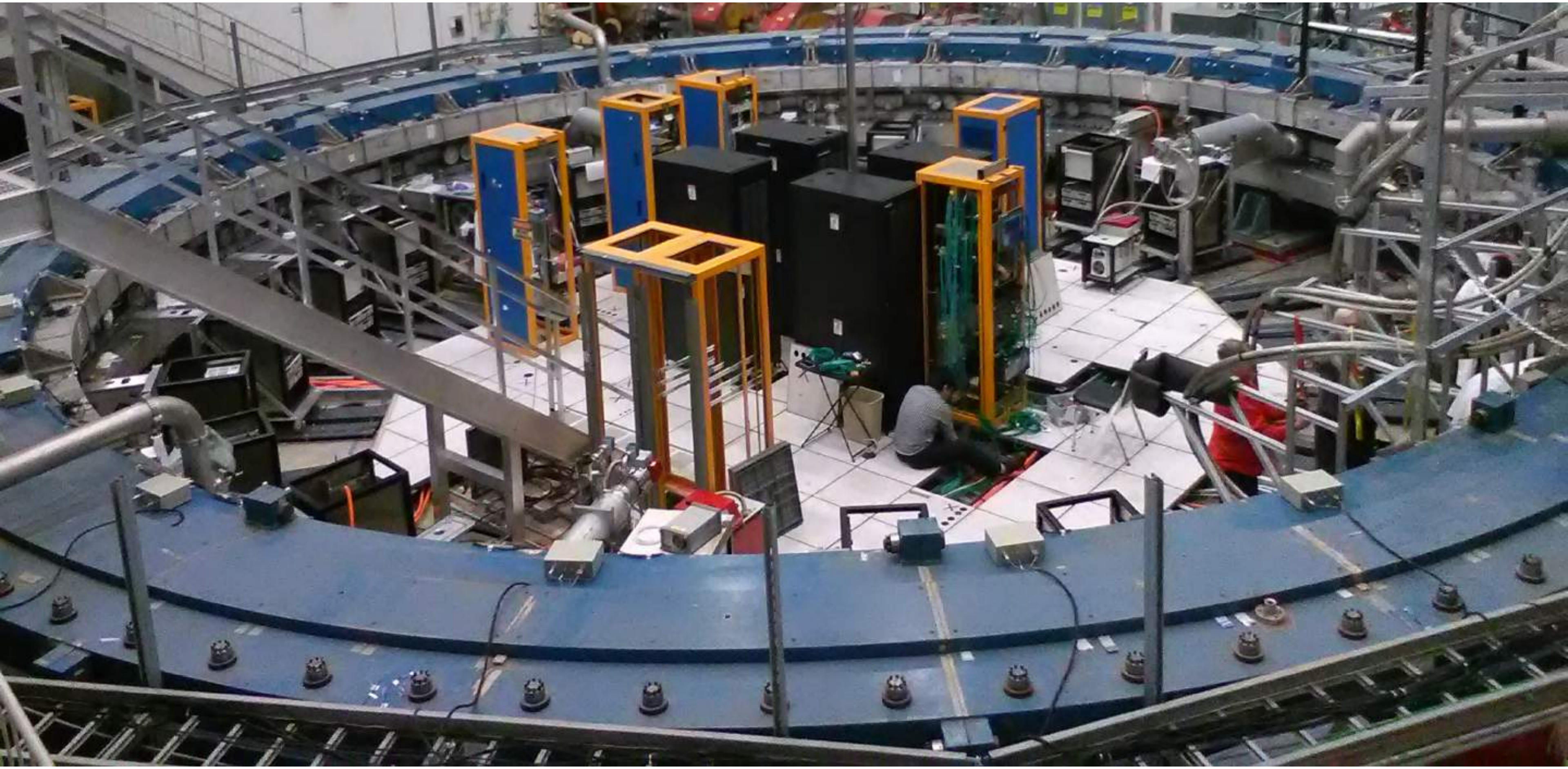




Installation status

24 trolleys in the ring
24 calorimeter in the ring

1 tracker module installed



We have started acquiring laser signals from calorimeters

ω_p systematics

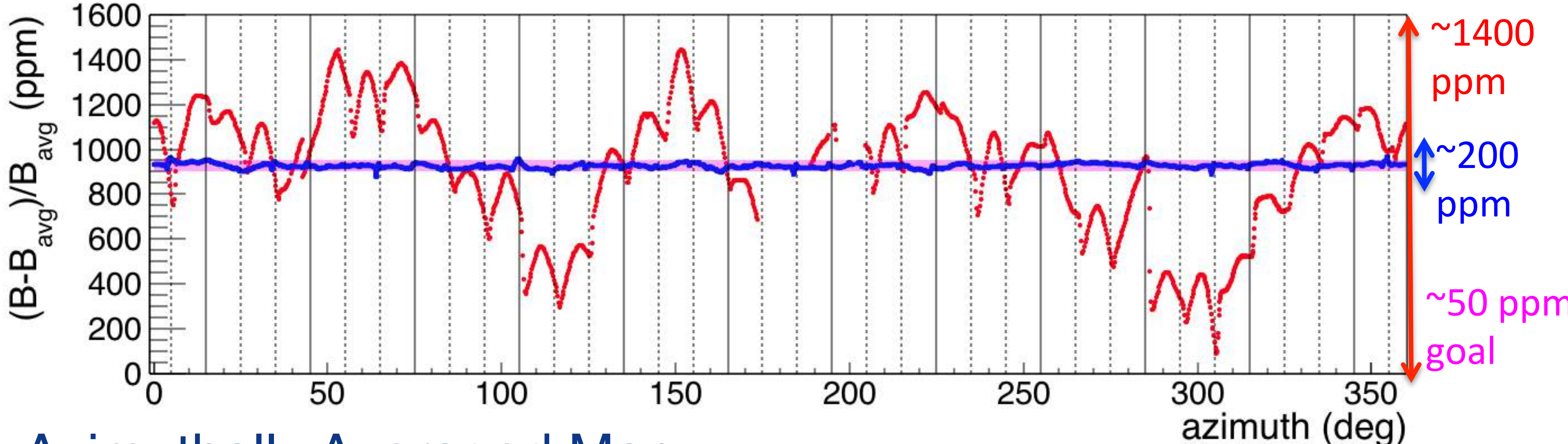
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position 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

- Need to know the average field observed by a muon in the storage ring absolutely to better than 70 ppb, many hardware improvements
- Very challenging…first major step is making the field as uniform as possible
  - Has been our main thrust over the last 9 months

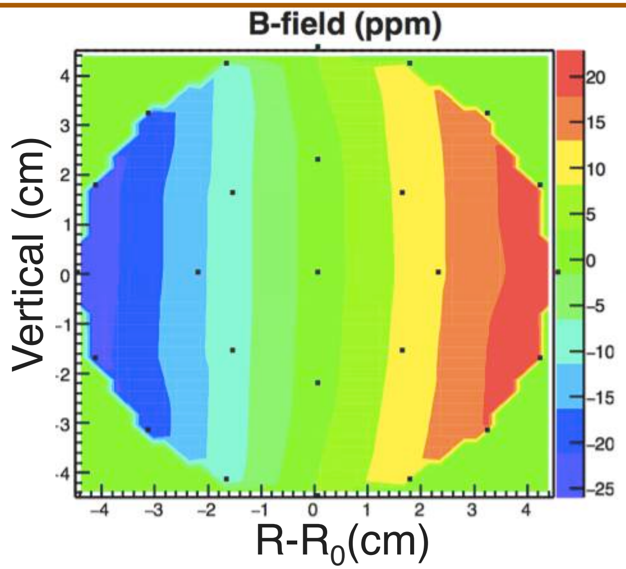
Progress on Field

Oct 2015 → Aug 2016

Goal

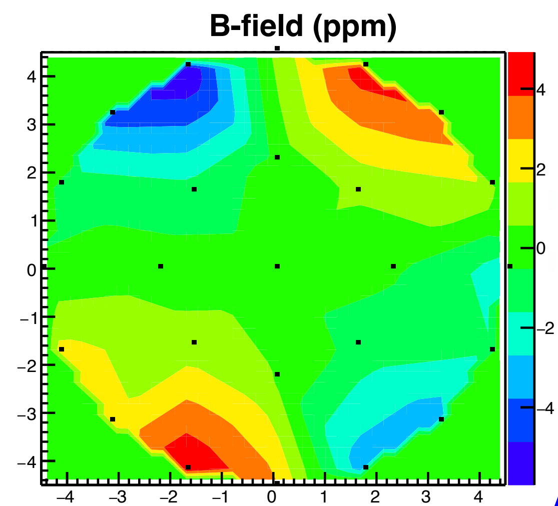


Azimuthally Averaged Map



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

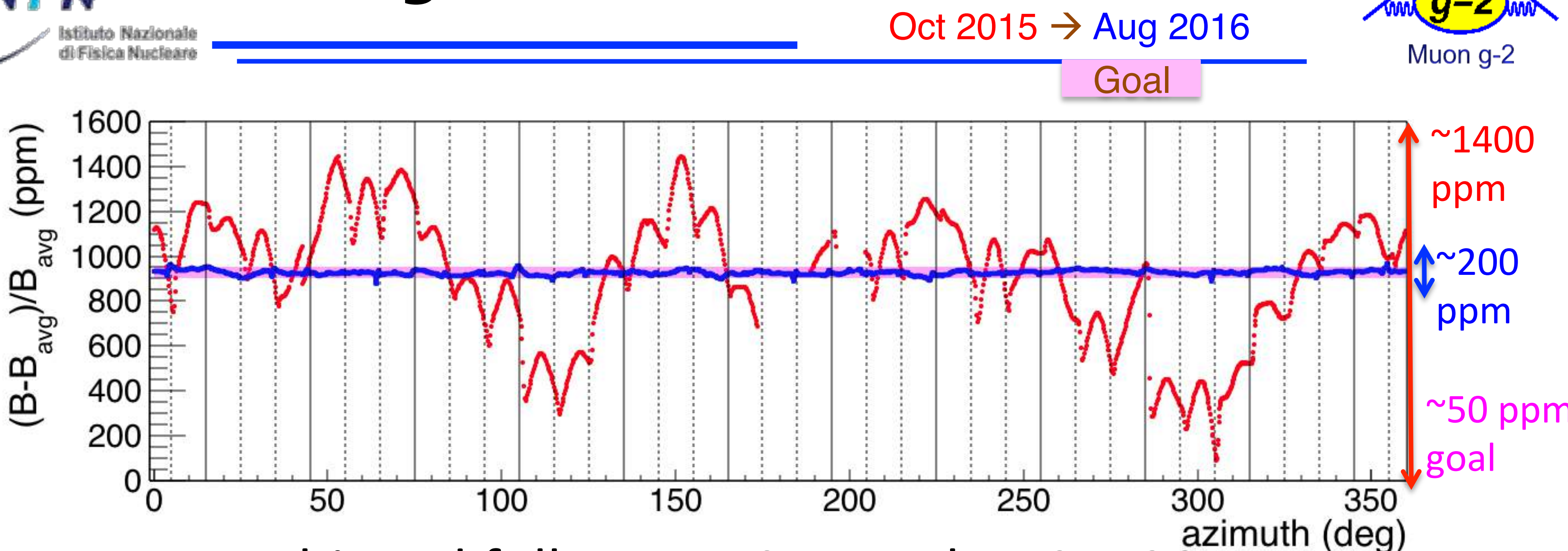
Oct 2015



	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

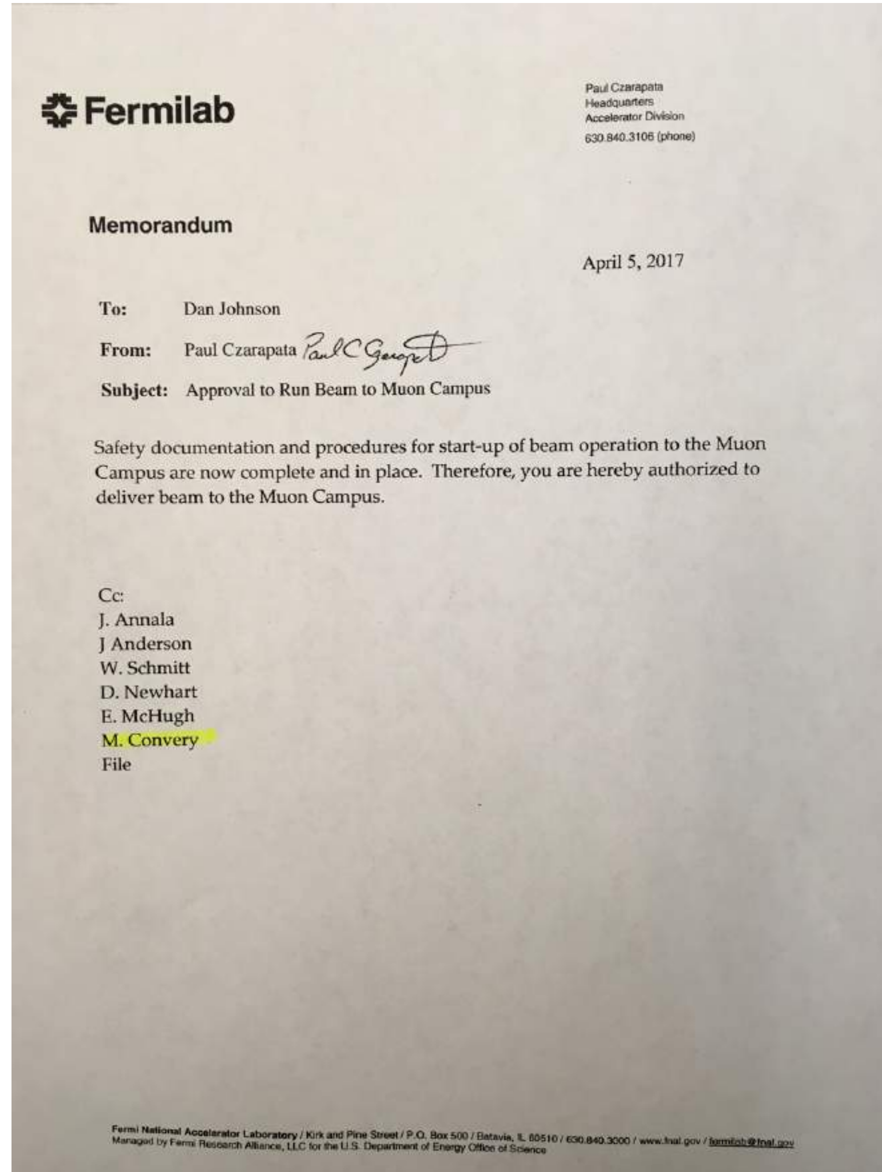
Progress on Field



- Magnet achieved full power September 21, 2015
- Field started out with a peak variation of 1400 ppm
- June 2016 peak to peak variation was reduced to 200 ppm
- The goal of shimming is 50 ppm with a muon weighted systematic uncertainty of 70 ppb
- BNL achieved 100 ppm with an averaged field uniformity of +- 1ppm. They estimated their systematic uncertainty of 140 ppb. We would like to improve of a factor 2!

Milestones (last 6 months)

- 17 novembre2016:
  - the E821 inflector has been cooled and powered to full current
- 24 gennaio2017:
  - the final vacuum chamber installed in the magnet
- March 14-16 2017:
  - Successful beam readiness review
- April 5 2017:
  - Authorization to deliver beam to the Muon Campus



Fermilab

Paul Czarapata
Headquarters
Accelerator Division
630.840.3106 (phone)

Memorandum

April 5, 2017

To: Dan Johnson

From: Paul Czarapata

Subject: Approval to Run Beam to Muon Campus

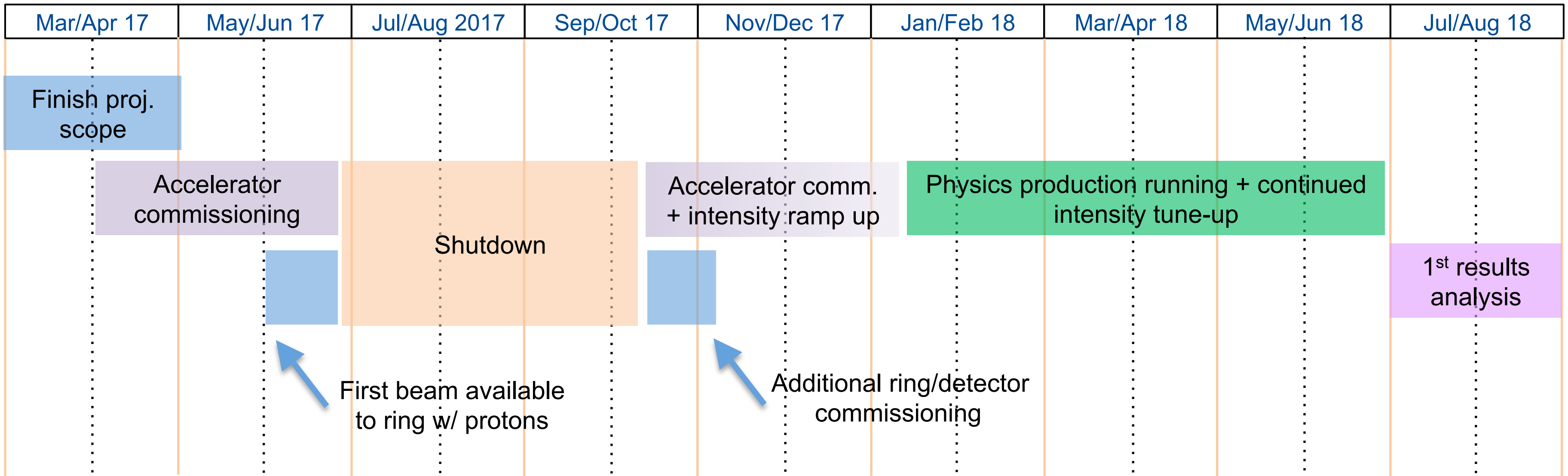
Safety documentation and procedures for start-up of beam operation to the Muon Campus are now complete and in place. Therefore, you are hereby authorized to deliver beam to the Muon Campus.

Cc:
J. Annala
J Anderson
W. Schmitt
D. Newhart
E. McHugh
M. Convery
File

Fermi National Accelerator Laboratory / Kirk and Pine Street / P.O. Box 500 / Batavia, IL 60510 / 630.840.3000 / www.fnal.gov / fermilab@fnal.gov
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Short term schedule

Muon g-2

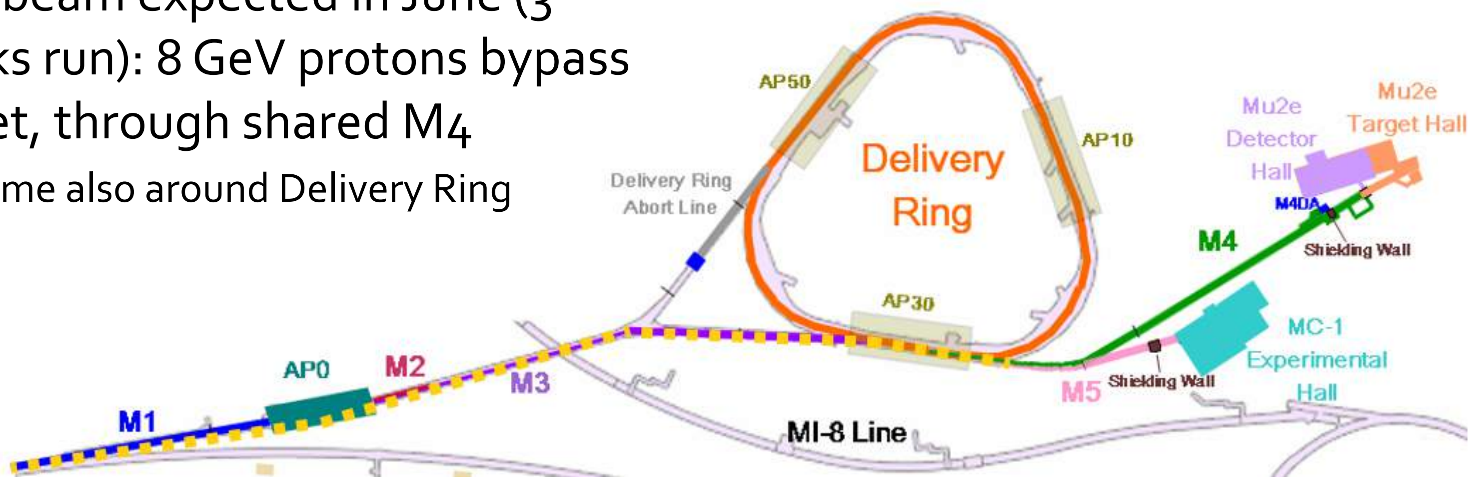


- After many years of design and construction, we are essentially ready for beam
- June: Commissioning
- Fall: Commission Delivery Ring and optimize Muon Storage
- CY2018: Efficient data taking
- Summer 2018: Our goal is a "BNL level" 1st result
- 2 years run for 4x reduction of error (final result expected ~2020)

Short term schedule

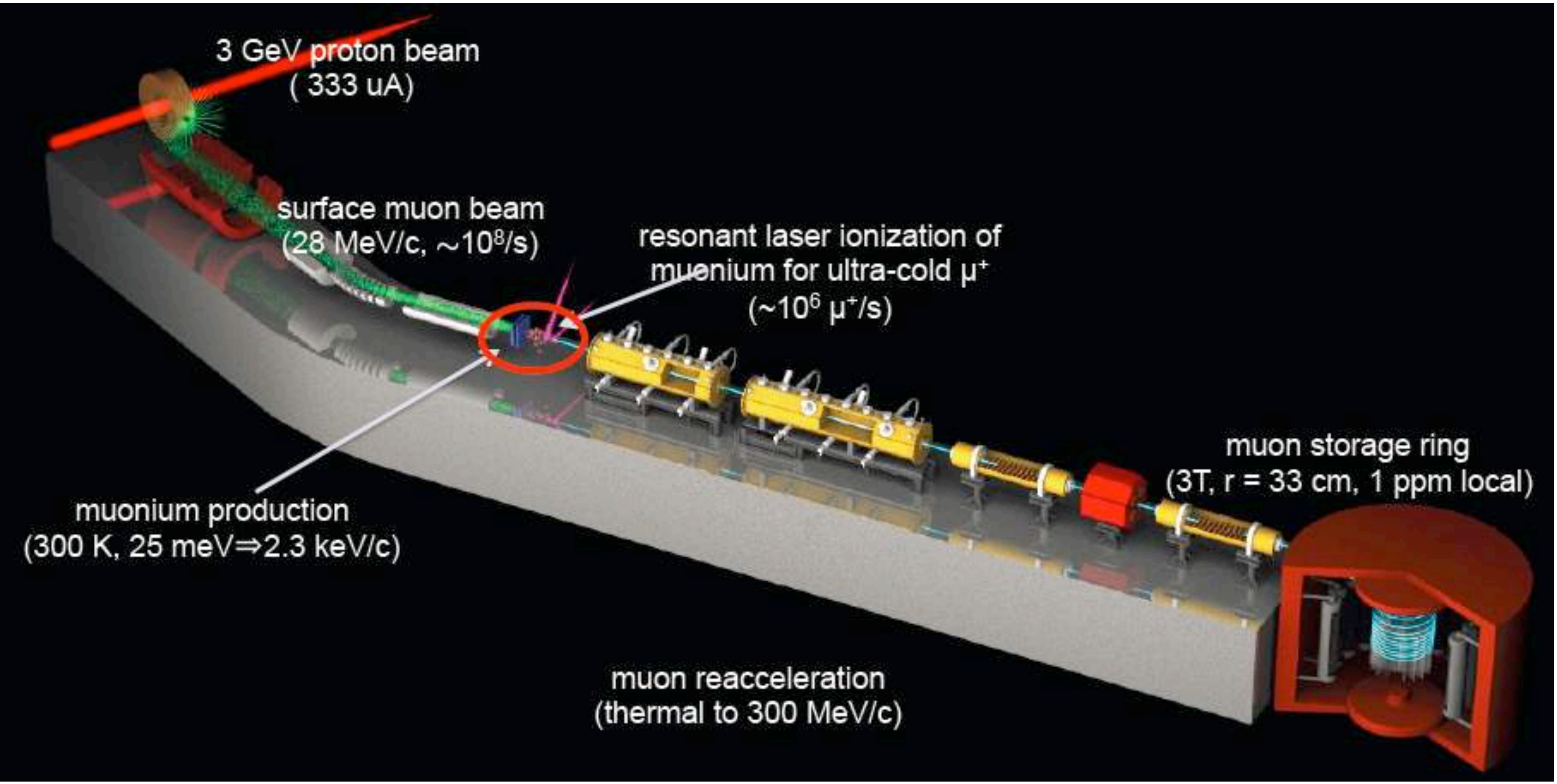
First beam expected in June (3 weeks run): 8 GeV protons bypass target, through shared M4

- If time also around Delivery Ring



- After many years of design and construction, we are essentially ready for beam
- June: Commissioning
- Fall: Commission Delivery Ring and optimize Muon Storage
- CY2018: Efficient data taking
- Summer 2018: Our goal is a “BNL level” 1st result
- 2 years run for 4x reduction of error (final result expected ~2020)

The J-PARC approach



Injection of an ultra-cold, low-energy, muon beam into a small, but highly uniform magnet

What makes them different?

- Eliminate electric focusing removes $\boldsymbol{\beta} \times \boldsymbol{E}$ term

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

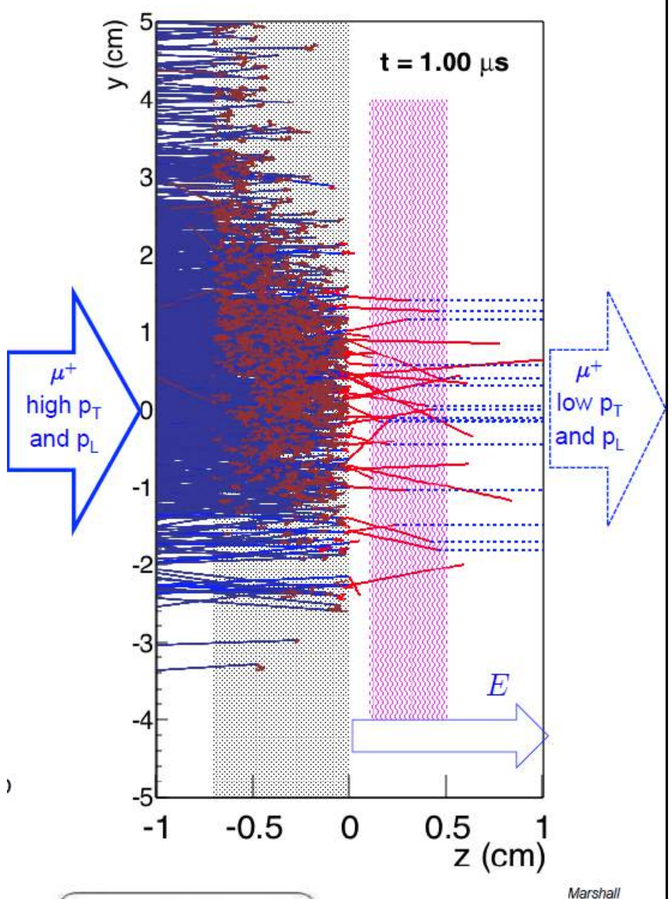
  Do need ~zero P_T to store muons

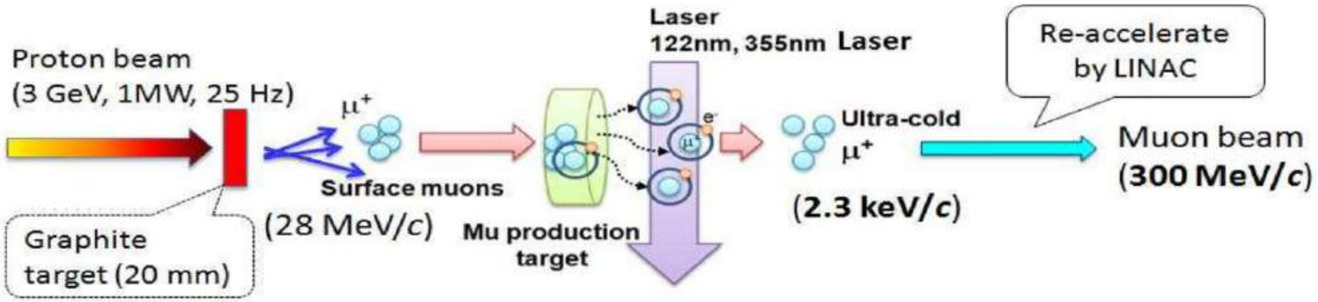
- → Not constrained to run at the "magic momentum"
- Create "ultra-cold" muon source; accelerate, and inject into compact storage ring.
- Consequences are quite interesting …
  - Smaller magnet; intrinsically more uniform

- Aim for BNL level precision as an important check

Ultra-cold Muons

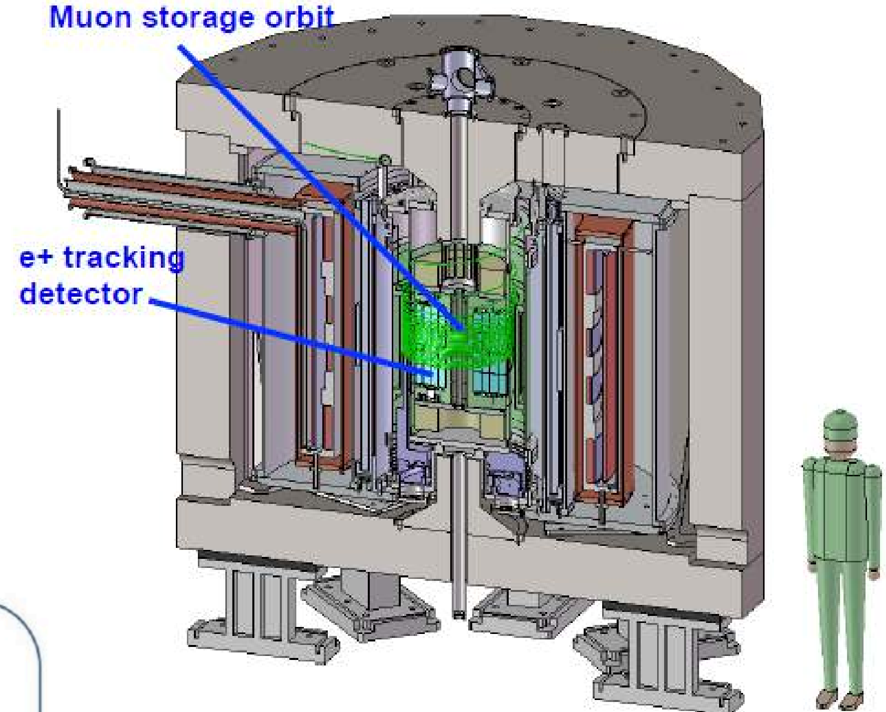
- Surface μ^+
- Stop in Aerogel
- Diffuse Muonium (μ^+e^-) atoms into vacuum
- Ionize
  - 1S → 2P→unbound
  - **Max Polarization 50%**
- Accelerate
  - E field, RFQ, linear structures
  - P = 300 MeV/c



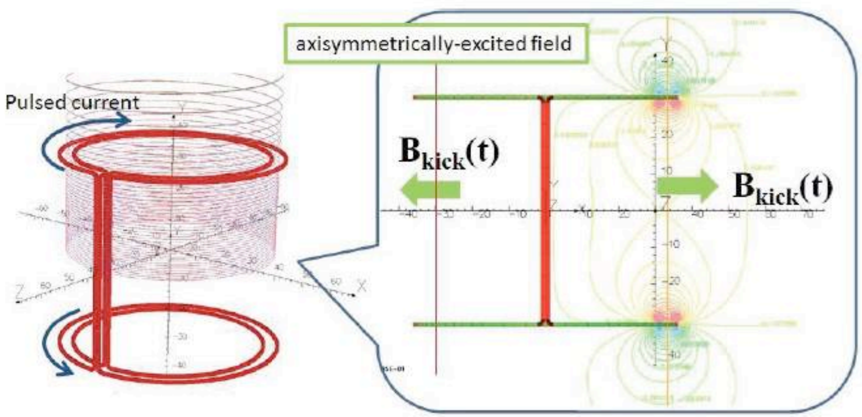


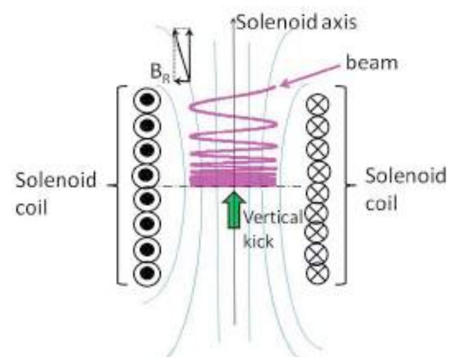
Muon storage magnet

- Superconducting solenoid
  - cylindrical iron poles and yoke
  - vertical B = 3 Tesla, <1ppm locally
  - storage region r = 33.3±1.5 cm, h = ±5 cm
  - tracking detector vanes inside storage region
  - storage maintained by static weak focusing
    - n = 1.5×10^{-4}, $rB_r(z) = -n\, zB_z(r)$ in storage region



a trapped orbit





Detector system of silicon trackers

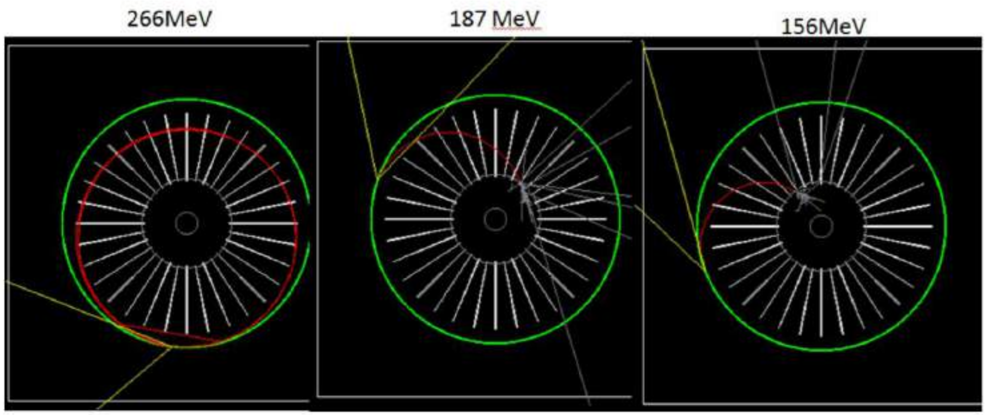
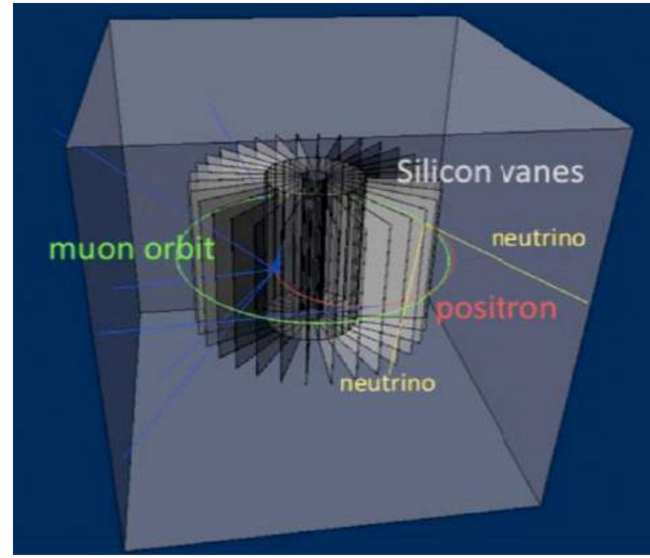
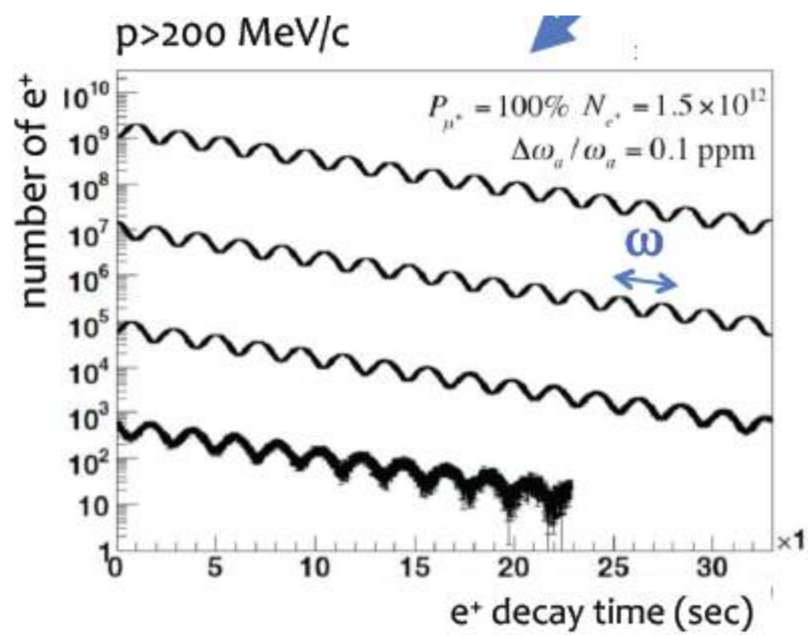


Figure 6: Example positron trajectories in the detector system at three different energies of positrons. The green circle is the muon beam orbit. The red trajectory is the trace of the positron track. The white tracks are photons.





Expected data. Note shorter lifetime at this momentum, and lower asymmetry owing to polarization of source

Comparison

$$\delta\omega_a/\omega_a = \frac{1}{\omega_a \gamma \tau_\mu}\sqrt{\frac{2}{NA^2\langle P\rangle^2}},$$

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

Summary of expected sensitivities

Quantities	Description	Value
T	Running time	2×10^7 s
P	Muon polarization	0.5
$\frac{dN_\mu}{dt}$	Average muon rate in the storage magnet	0.334×10^6/s
N_μ	Total number of muon in the storage magnet	0.668×10^{13}
ϵ_{acc}	Acceptance of the e^+ detector and momentum cut	0.133
ϵ_{trk}	Track reconstruction efficiency	0.9
N_{e+}	Total number of positrons ($N_\mu \epsilon_{acc} \epsilon_{trk}$)	0.80×10^{12}
$\frac{\Delta\omega_a}{\omega_a}$	Uncertainty on anomalous spin precession frequency	0.36 ppm
Δd_μ	Uncertainty on EDM	$1.3 \times 10^{-21} e \cdot \mathrm{cm}$

- Statistical uncertainty estimates
  - $\Delta\omega_a/\omega_a$ = 0.36 ppm (0.163/$PN^{1/2}$)
    - BNL E821 σ_{stat} = 0.46 ppm
  - $\Delta d_\mu = 1.3\times10^{-21}$ $e \cdot$ cm sensitivity
    - BNL E821 $(-0.1\pm0.9)\times10^{-19}$ $e \cdot$ cm
    - $\Delta d_e < 1.05\times10^{-27}$ $e \cdot$ cm

Measurement of a_μ^{HLO} with a 150 GeV μ beam on e^- target at CERN

Muon g-2

Physics Letters B 746 (2015) 325–329

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

A new approach to evaluate the leading hadronic corrections to the muon g-2

C.M. Carloni Calame[a,*], M. Passera[b], L. Trentadue[c,d], G. Venanzoni[e]

[a] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[b] INFN, Sezione di Padova, Padova, Italy
[c] Dipartimento di Fisica e Scienze della Terra "M. Melloni", Università di Parma, Parma, Italy
[d] INFN, Sezione di Milano Bicocca, Milano, Italy
[e] INFN, Laboratori Nazionali di Frascati, Frascati, Italy

Phys. Lett. B 746 (2015) 325

Eur. Phys. J. C (2017) 77:139
DOI 10.1140/epjc/s10052-017-4633-z

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Measuring the leading hadronic contribution to the muon g-2 via μe scattering

G. Abbiendi[1,a], C. M. Carloni Calame[2,b], U. Marconi[3,c], C. Matteuzzi[4,d], G. Montagna[2,5,e], O. Nicrosini[2,f], M. Passera[6,g], F. Piccinini[2,h], R. Tenchini[7,i], L. Trentadue[8,4,j], G. Venanzoni[9,k]

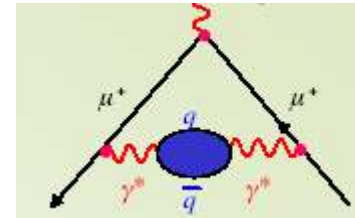
[1] INFN Bologna, Viale Carlo Berti-Pichat 6/2, 40127 Bologna, Italy
[2] INFN Pavia, Via Agostino Bassi 6, 27100 Pavia, Italy
[3] INFN Bologna, Via Irnerio 46, 40126 Bologna, Italy
[4] INFN Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy
[5] Dipartimento di Fisica, Università di Pavia, Via A. Bassi 6, 27100 Pavia, Italy
[6] INFN Padova, Via Francesco Marzolo 8, 35131 Padua, Italy
[7] INFN Pisa, Largo Bruno Pontecorvo 3, 56127 Pisa, Italy
[8] Dipartimento di Fisica e Scienze della Terra "M. Melloni", Parco Area delle Scienze 7/A, 43124 Parma, Italy
[9] INFN, Laboratori Nazionali di Frascati, Via E. Fermi 40, 00044 Frascati, RM, Italy

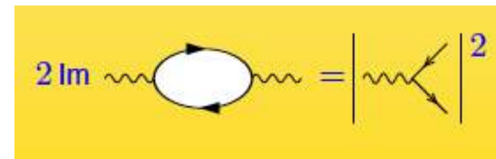
Eur. Phys. J C 77 (2017) 139

a_μ^{HLO} calculation, traditional way: time-like data

$a_\mu=(g-2)/2$ Muon g-2

$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$



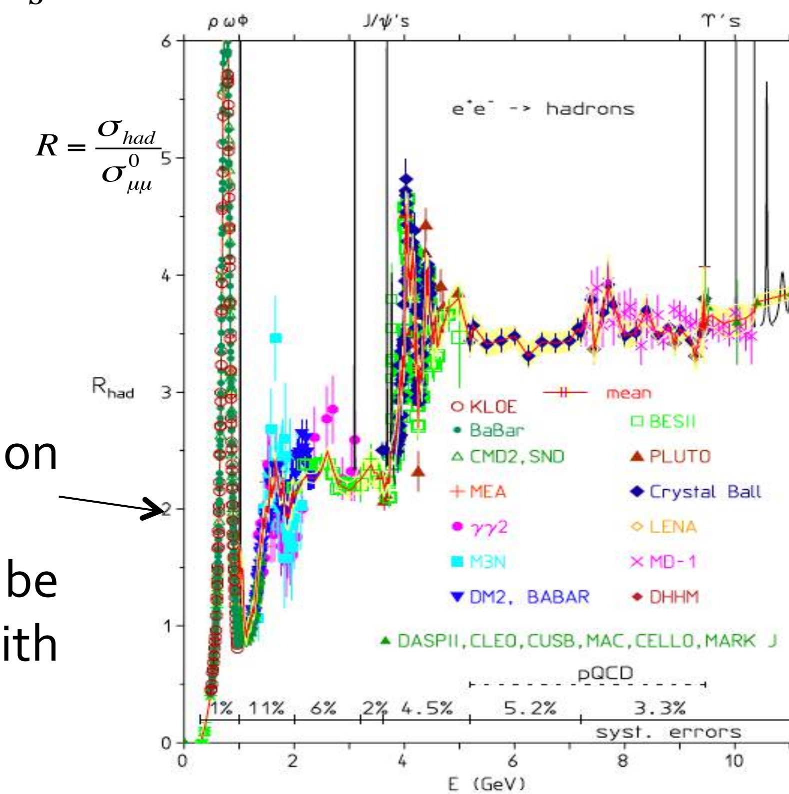


$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)(s/m^2)} \sim \frac{1}{s} \qquad \sigma_{e^+e^-\to hadr}(s) = \frac{4\pi}{s}\mathrm{Im}\,\Pi_{had}(s)$$

Traditional way: based on precise experimental (time-like) data:

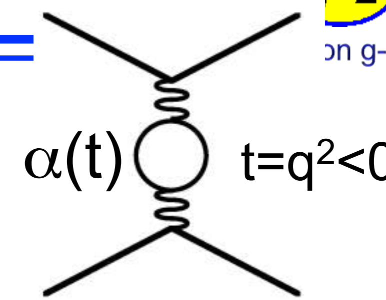
$a_\mu^{HLO} = (692.3\pm4.2)10^{-10}$ (DHMZ)

- Main contribution in the low energy region (highly fluctuating!)
- Current precision at 0.6% → needs to be reduced by a factor ~2 to be competitive with the new g-2 experiments



a_μ^{HLO} from space-like region

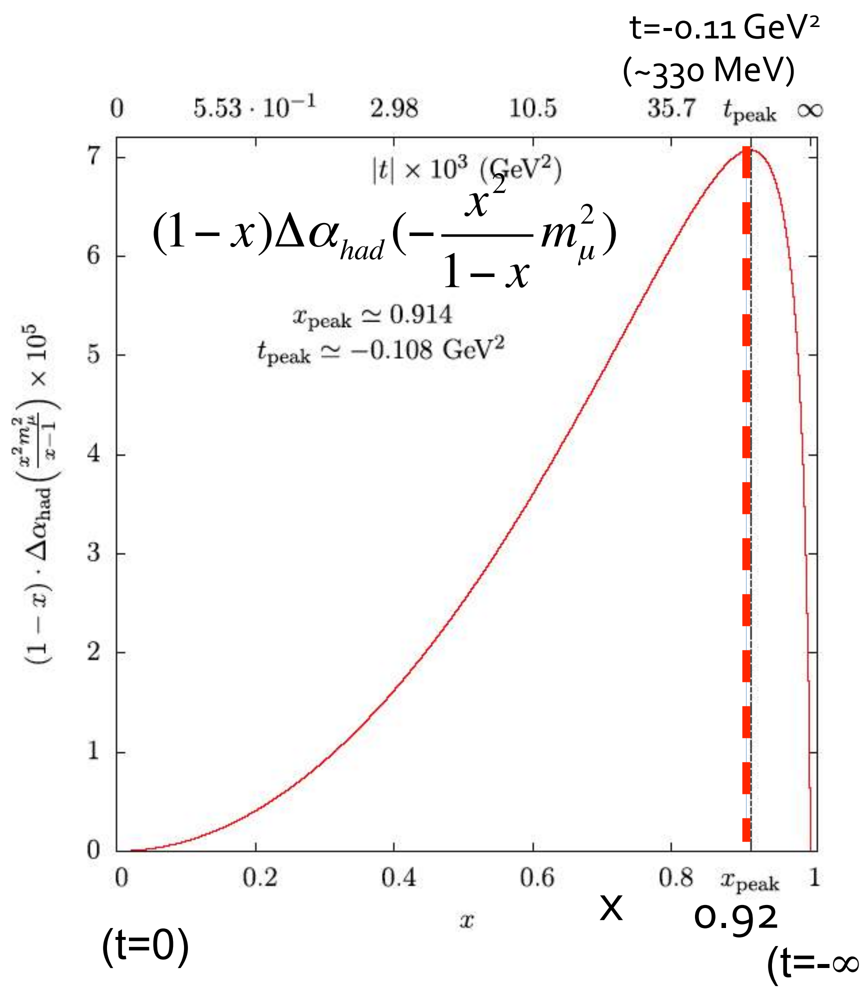
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



$$t = \frac{x^2 m_\mu^2}{x-1} \qquad 0 \le -t < +\infty$$

$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

- a_μ^{HLO} is given by the integral of the curve (smooth behaviour)
- It requires a measurement of the hadronic contribution to the effective electromagnetic coupling in the space-like region $\Delta\alpha_{had}(t)$ ($t=q^2<0$)
- It enhances the contribution from low q^2 region (below 0.11 GeV²)
- Its precision is determined by the uncertainty on $\Delta\alpha_{had}(t)$ in this region

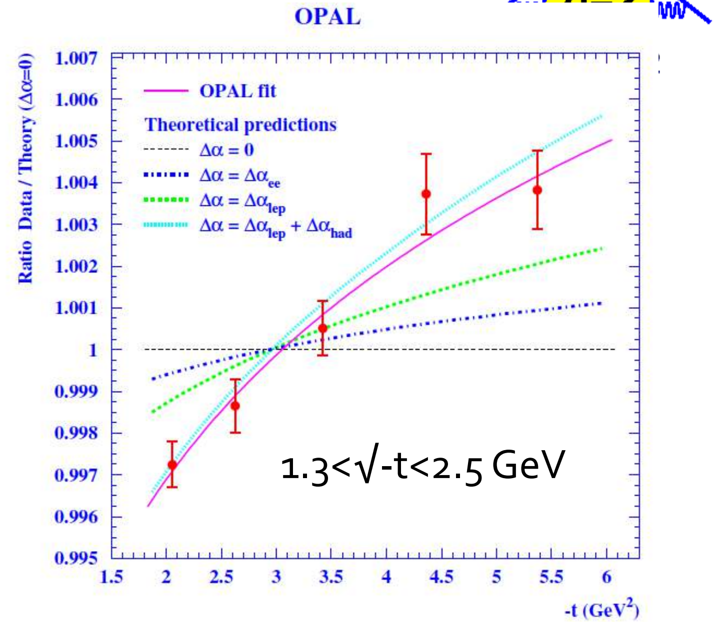


Measurement of $\Delta\alpha_{had}(t)$ spacelike at LEP

- $\Delta\alpha_{had}$ (t) (t<0) has been measured at LEP using small angle Bhabha scattering

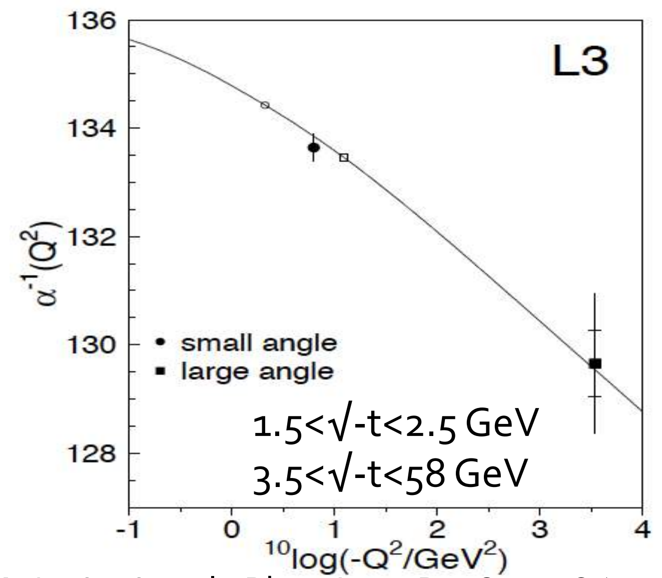
$$f(t) = \frac{N_{\rm data}(t)}{N^0_{\rm MC}(t)} \propto \left(\frac{1}{1-\Delta\alpha(t)}\right)^2 .$$

Accuracy at per mill level was achieved!



G. Abbiendi et al., Eur. Phys. J. C 45, 1–21 (2006)

- For low t values ($\leq$0.11 GeV^2), like in our a different approach is needed!

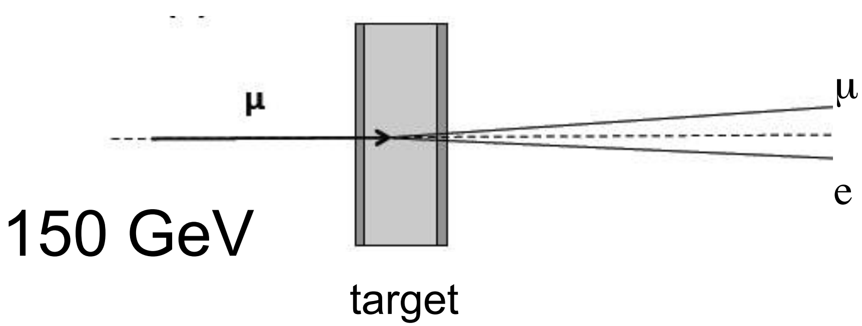


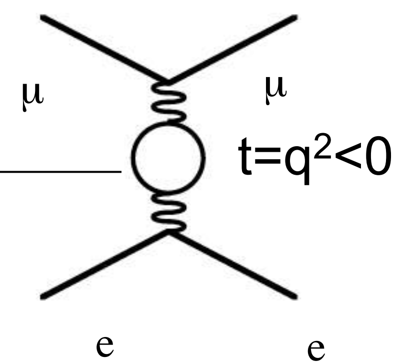
M. Acciarri et al., Phys. Lett. B476 40-48 (2000)

Experimental approach:

High precision measurement of a_μ^{HLO} with a 150 GeV μ beam on Be target at CERN

(through the elastic scattering $\mu e \rightarrow \mu\, e$)





$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

Why measuring $\Delta\alpha_{had}(t)$ with a 150 GeV μ beam on e^- target ?

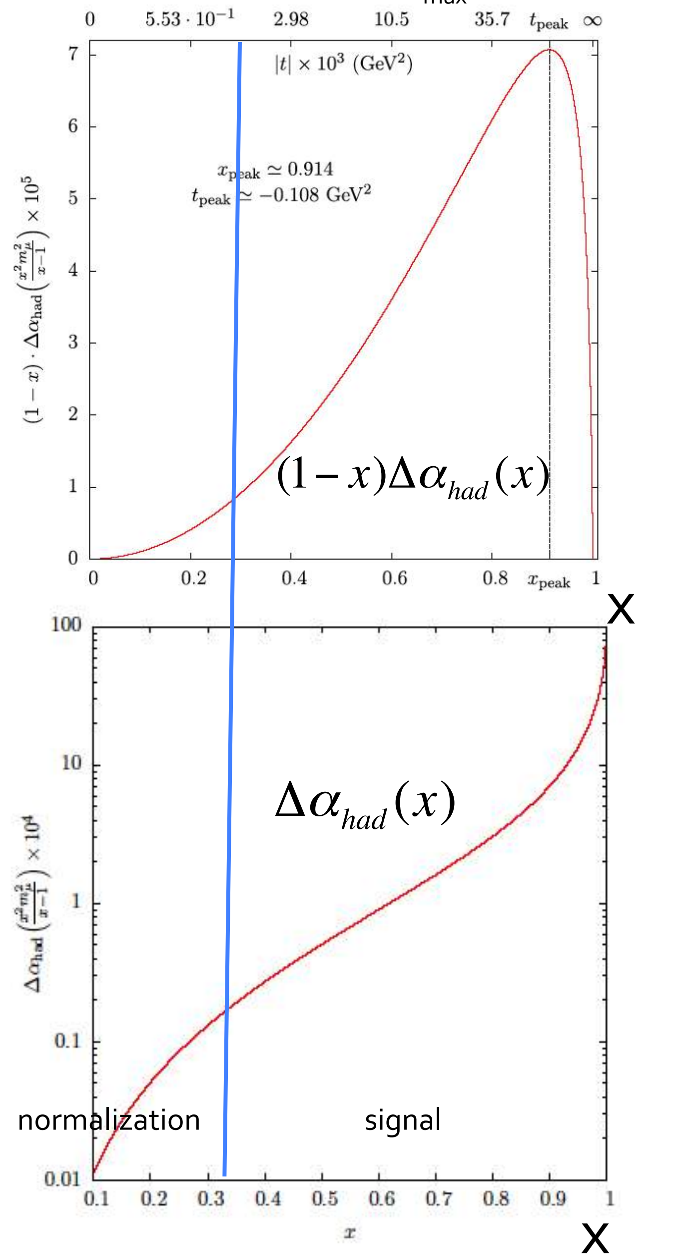
t_{max}=-0.11GeV²

It looks an ideal process!

- $\mu\, e \rightarrow \mu\, e$ is pure t-channel (at LO)
- It gives $0<-t<0.161$ GeV² ($0<x<0.93$) →
- The kinematics is very simple: $t=-2m_eE_e$
- High boosted system gives access to all angles (t) in the cms region

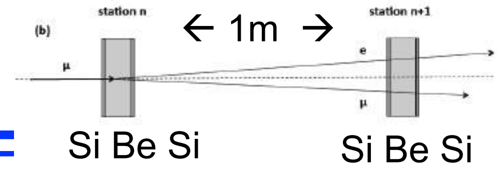
  $\theta_e^{LAB}<32$ mrad ($E_e>1$ GeV)

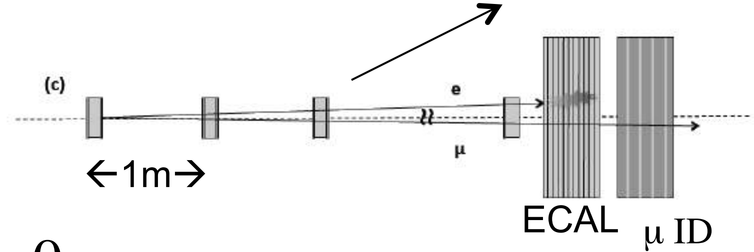
  $\theta_\mu^{LAB}<5$ mrad
- It allows using the same detector for signal and normalization
- Events at $x\sim0.3$ ($t\sim-10^{-3}$ GeV²) can be used as normalization ($\Delta\alpha_{had}(t) <10^{-5}$) →



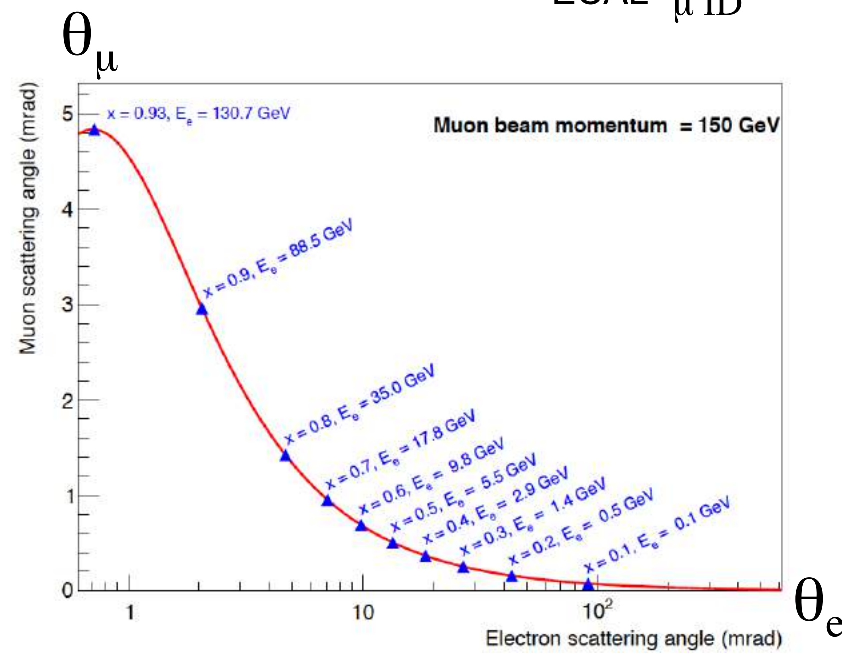
INFN Istituto Nazionale di Fisica Nucleare

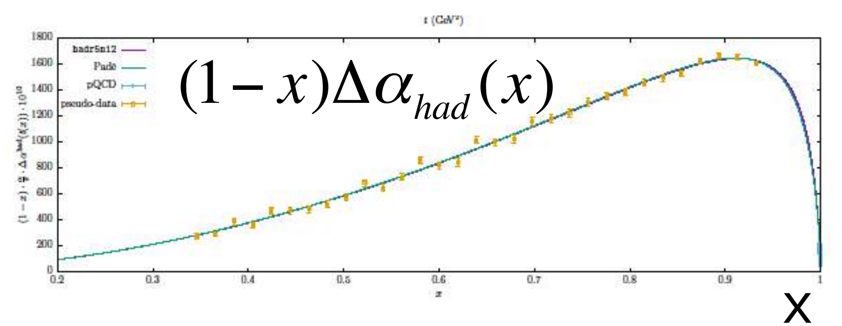
Detector considerations





- Modular apparatus: 20 layers of 3 cm Be (target), each coupled to 1 m distant Si (0.3 mm) planes. It provides a 0.02 mrad resolution on the scattering angle
- The $t=q^2<0$ of the interaction is determined by the electron (or muon) scattering angle (a` la NA7)
- ECAL and μ Detector located downstream to solve PID ambiguity below 5 mrad. Above that, angular measurement gives correct PID
- It provides uniform full acceptance, with the potential to keep the systematic errors at 10^{-5} (main effect is the multiple scattering for normalization which can be studied by data)
- Statistical considerations show that a **0.3%** error can be achieved on a_μ^{HLO} in 2 years of data taking with 2×10^7 μ/s (available at CERN)





μ-e proposal: plans (next 2 years)

- Focus on Multiple Scattering (MSC) effects:
  - How non gaussian tails affects our measurement and can be monitored/ controlled (2D plots and acoplanarity)
- Background subtraction and modeling in GEANT
- Optimization of target/detector and full detail simulation
- Test beam(s) and proto-experiment with a realistic module
- NNLO MC generation of μe process
- Design possible implementation in M2
- Consolidate the collaboration and write a CDR

Proposal part of the Physics Beyond Collider Working Group!

http://pbc.web.cern.ch/

Conclusions

- Exciting period for g-2:
  - ~3.5σ long standing discrepancy between experiment and SM
  - New muon g-2 experiments undergoing at Fermilab (E989) and in J-Parc (E34) with 4x improvement
  - Many theoretical efforts (QED, HLO/HLbL: dispersive approach, Lattice, consolidate/new ideas, etc...)
- E989 at Fermilab:
  - Beam on; magnetic field ready; detector commissioning
  - Data taking expected in late 2017. Goal: **140 ppb (or 16 x 10^{-11}) on a_μ** EDM parasitically
- E34 at J-Parc:
  - Novel method; working out key new issues: source; magnet; detectors, etc. Aiming at 2019 Phase 1 with : **440 ppb goal on a_μ** EDM ~10^{-21} e-cm;
- New proposal for a_μ^{HLO} with a 150 GeV μ beam on e- target aiming at 0.3% statistical error

THE END

J-PARC g–2 goals (Stage 1)

Statistics

- Running time
  - measurement only: 2×10^7 s
- Muon rate from H-line
  - 1MW, SiC target: 3.32×10^8 s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization, $\mathcal{P} = 0.5$
  - 2.25×10^{-3} (stage 2 goal is 0.01)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, and kick
  - 0.92
- Stored muons
  - 3.34×10^5 s^{-1} , total 6.68×10^{12}

Systematics

- $\boxed{\text{Estimations still in progress}}$
  - simulations
  - need experience with prototypes and first stages
  - need running experience to make assessments similar to E989
- ω_p (B measurement)
  - $+$ smaller stored volume, higher local precision that E821
  - $+$ all tracks to storage region
- ω_a (decay time measurement)
  - $+$ all tracking detectors
  - $-$ high rate differences between early and late decay times
    - $+$ polarization flip
- Learning curve could be long and steep
  - we haven't done this experiment before…

Measurement of ω_p to 70 ppb using Pulsed Proton NMR

⇒ Want Larmor frequency of free protons ω_p in storage volume while muons are stored

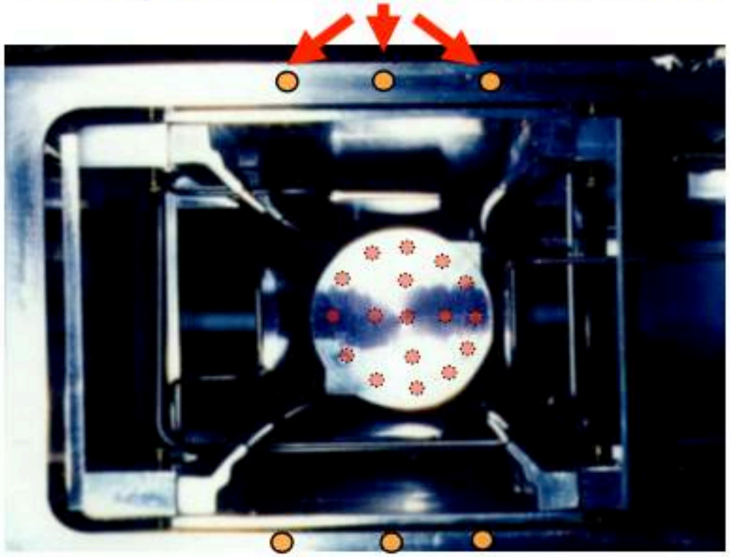
- Can't have NMR probes in storage volume at same time/place as muons!

(1) 387 Fixed probes measure field at same time as muons stored, but outside storage volume

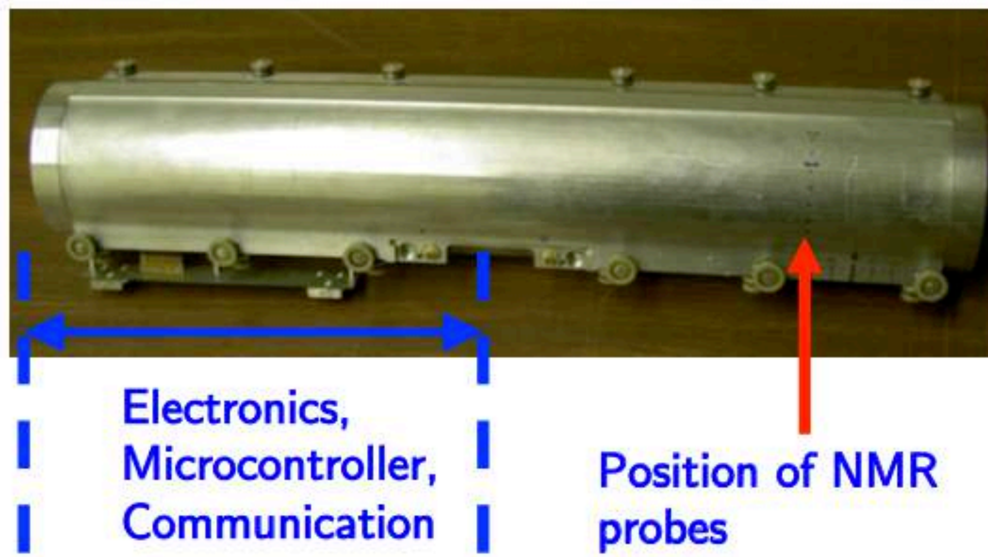
(2) Field inside storage volume measured by NMR trolley, but not when muons stored

- Fixed probes are cross-calibrated when trolley goes by; can infer field inside storage volume when muons stored from fixed probes

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes



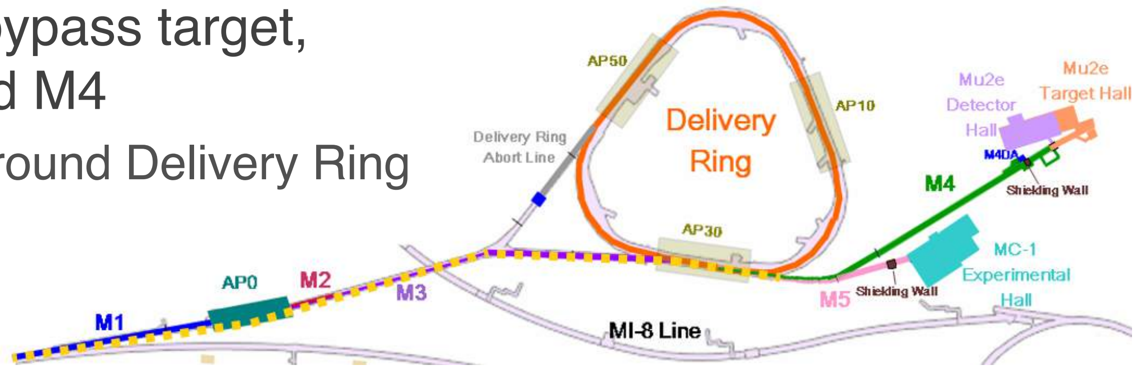
Test run in June 2017

First beam expected in June: 8 GeV protons bypass target, through shared M4

- If time also around Delivery Ring

Test run in June 2017

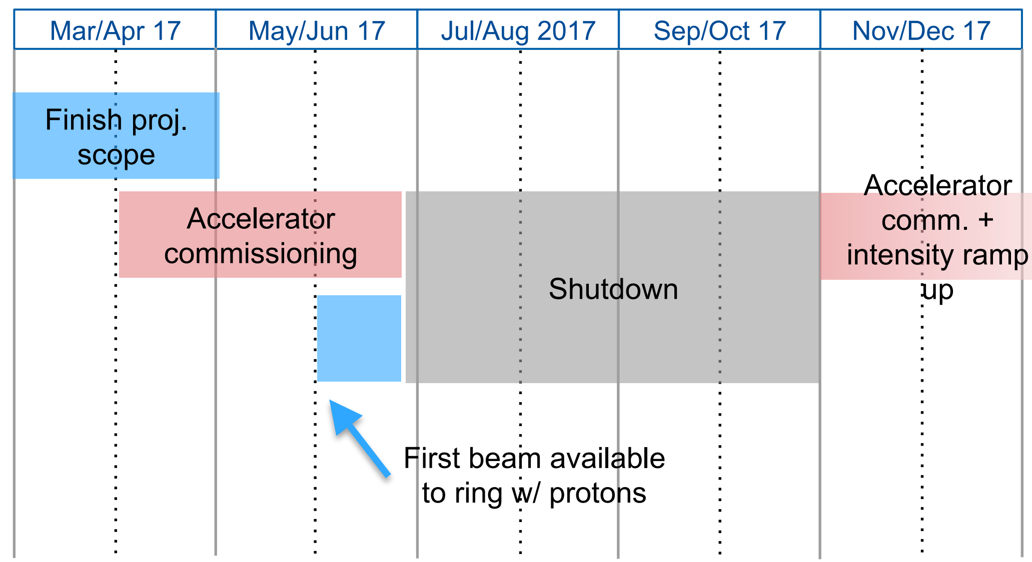
1) First beam expected in June: 8 GeV protons bypass target, through shared M4
   - If time also around Delivery Ring



2) 3 weeks test run (June)

3) Shutdown up to Oct/Nov.

4) Start data taking in Dec.



Fermilab

Conclusioni

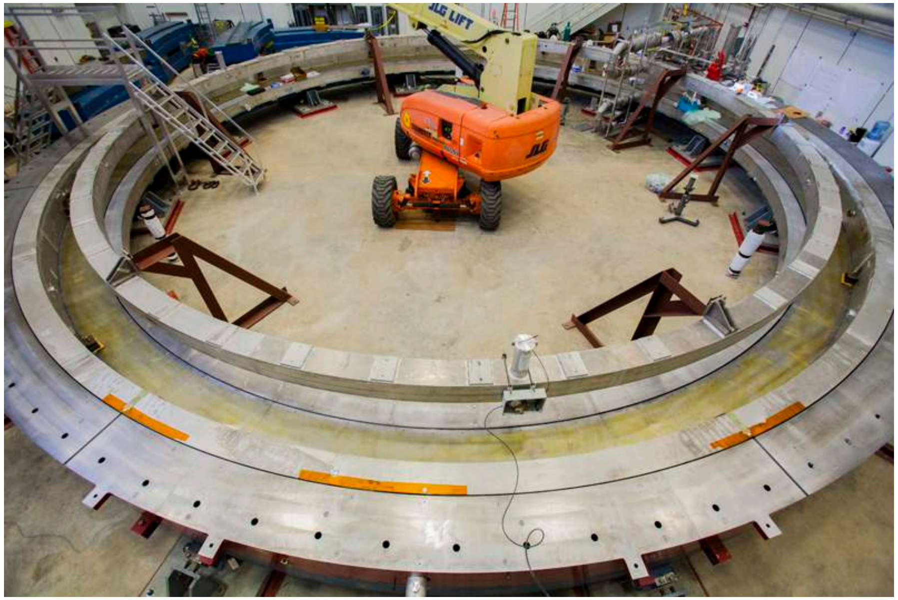
- G-2 sta andando come atteso. Test run per 3 settimane a Giugno poi shutdown e inizio presa dati autunno/inverno
- Attivita' Italiana:
  - Sistema Calibrazione Laser quasi completo e in schedule
  - 1 PC con GPU mancante per processare i nostri dati
  - Necessita' di sblocco SJ per apparati (120kE) e missioni (72 kE) per far fronte agli impegni e al lavoro programmato

Summary

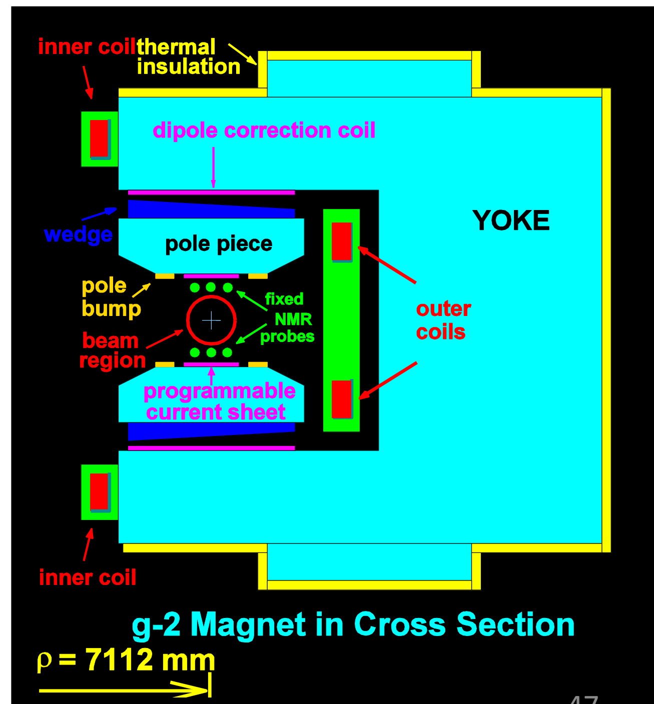
- ***FNAL: status and the plan going forward …***
  - Design complete and implementation well along
  - Beam on; magnetic field ready
  - Detector almost ready; starting commissioning
  - Beam expected in late 2017
  - Goal remains **140 ppb (or 16 x 10^{-11}) on a_μ**
  - EDM parasitically

- ***J-PARC: novel method being developed***
  - Working out key new issues: source; magnet; detectors, etc.
  - Concept has greater reach for EDM owing to detector coverage
  - Aiming at 2019 Phase 1 start with
    - **g-2 to ~400 ppb**,
    - EDM ~10^{-21} e-cm;

Field stability and uniformity improvements



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



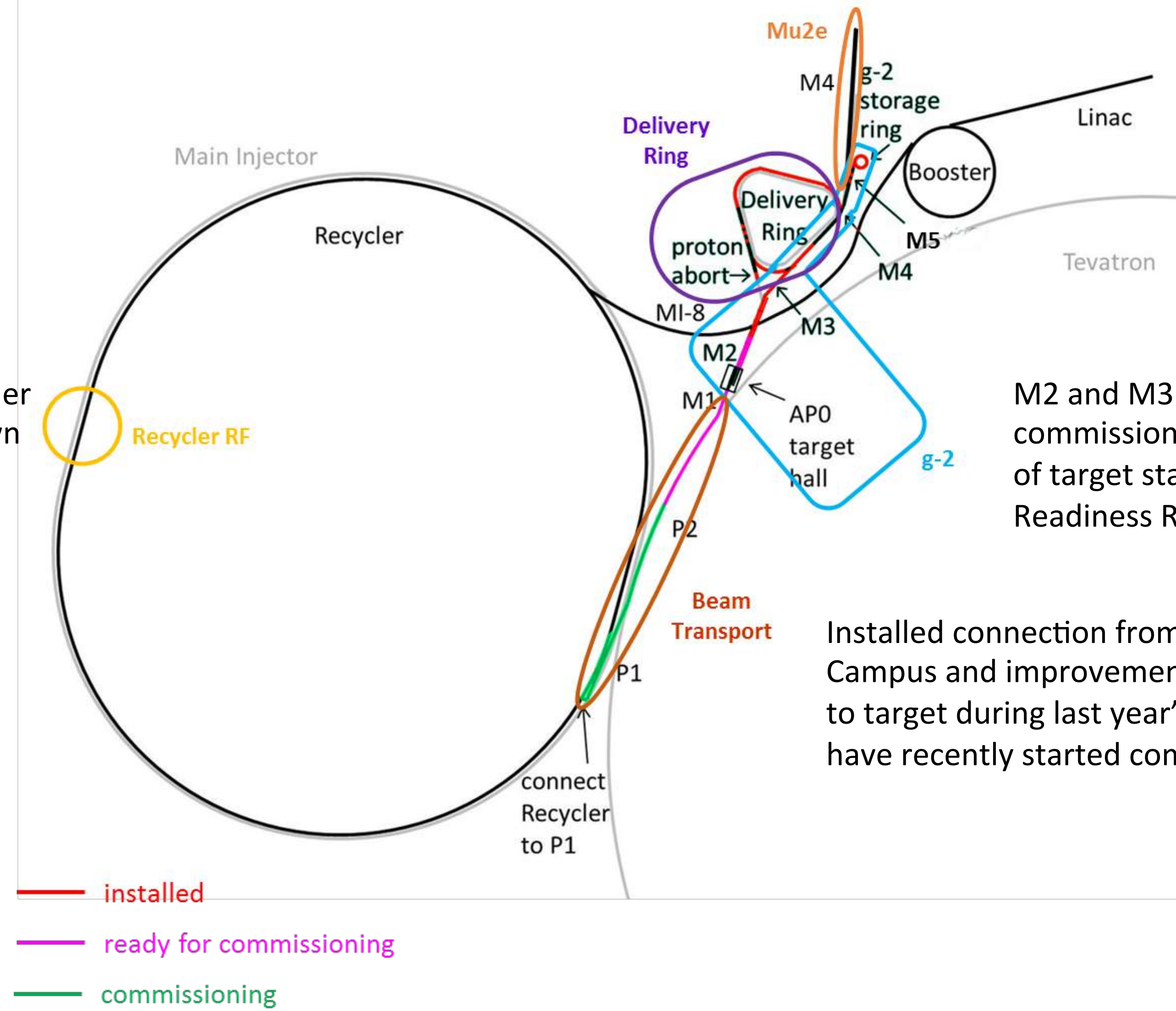
- Construction tolerances
  - 26 ton pieces of yoke steel (30 of them) placed to 125 micron tolerance
  - Pole pieces aligned to 25 micron
- 10 months of interactively shimming B-field with bits of steel and current loops (just ended last month)

Fermilab Muon Campus Vision, circa 2012

- Convert FNAL anti-proton source to produce customized muon beams for experiments like Muon g-2 and Mu2e

Muon Campus today

Muon Campus progress



Delivery Ring and M4/M5 line installation in progress

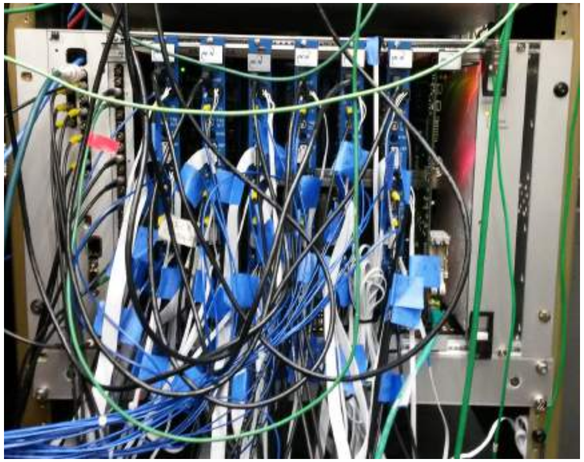
M2 and M3 line installed but can't commission anything downstream of target station until Accelerator Readiness Review

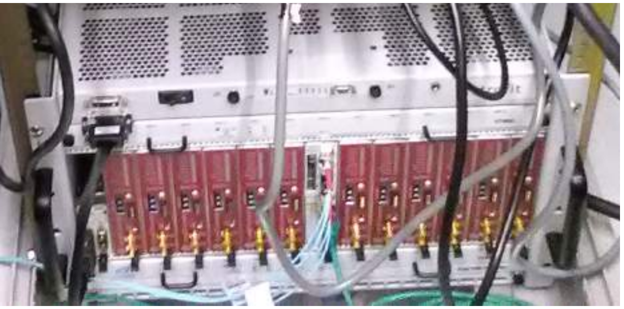
Installing Recycler RF this shutdown

Installed connection from Recycler to Muon Campus and improvements in beamlines up to target during last year's shutdown and have recently started commissioning

Data flow

Laser signals





800MSPS 12 bith WFD

2GPU Servers

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:

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

Fermilab

Schedule overview