Muon g-2 Experiment at Fermilab

State of the Experiment

James Mott, Boston University

for the Muon g-2 Collaboration

Tau2016, Beijing, China

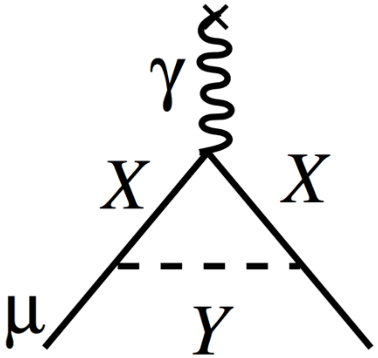
20th September 2016

Muon Magnetic Moment

- The muon has an intrinsic magnetic moment that is coupled to its spin by the gyromagnetic ratio g:

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

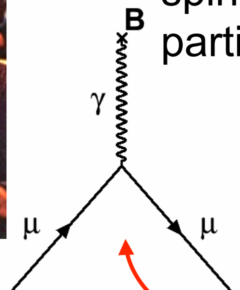
- Interactions between the muon and virtual loops alter this number – X & Y could be SM or new physics:



Standard Model Components of g_μ

Dirac

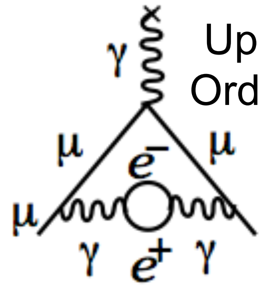
Charged, spin ½ particle



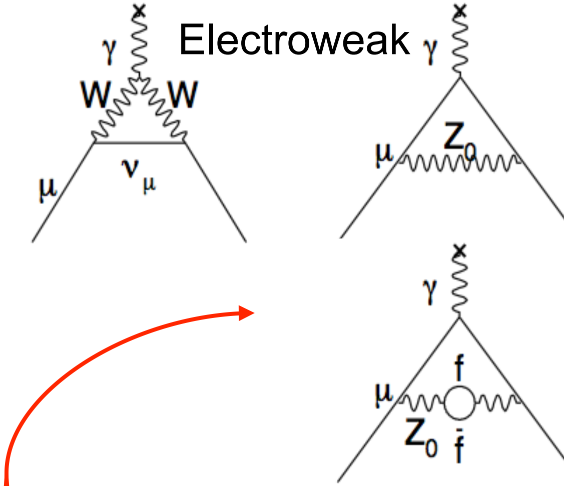
12672 diagrams

Kinoshita

Up to 10th Order QED

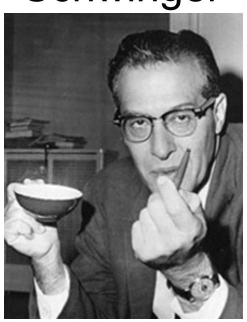


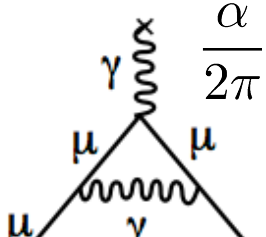
Electroweak



$$g_\mu = 2.002\,331\,841\,78(126)$$

Schwinger

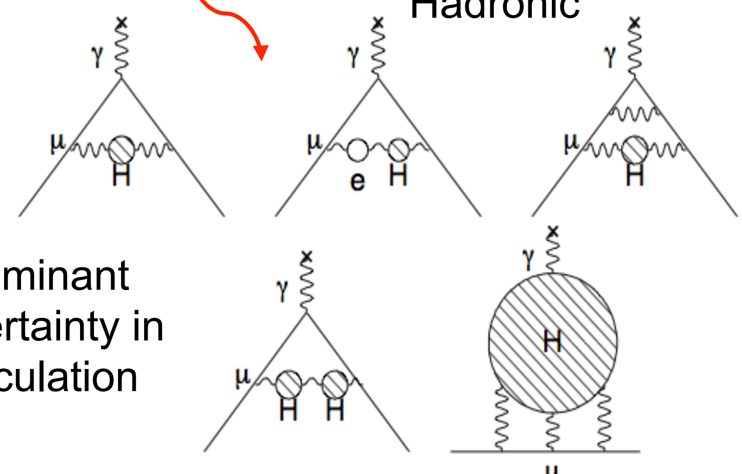




$$\frac{\alpha}{2\pi} = 0.00232$$

1st Order QED

Hadronic

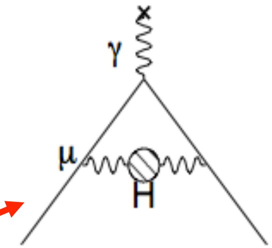


Dominant uncertainty in calculation

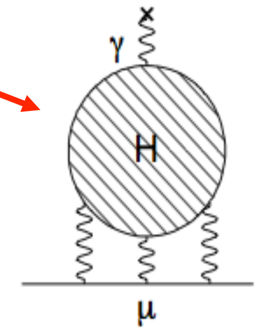
a_μ: Experiment vs Standard Model

- g_μ normally denoted by anomalous piece a_μ: $a_\mu = \frac{g_\mu - 2}{2}$

Contribution	Value (x 10^{-11})
QED (γ + l)	116 584 718.951 ± 0.08
Hadronic VP (lo)*	6 923 ± 42
Hadronic VP (ho)**	-98.4 ± 0.7
Hadronic LBL§	105 ± 26
ElectroWeak	153.6 ± 1.0
Total SM	116 591 802 ± $42_{\text{H-LO}}$ ± $26_{\text{H-LBL}}$ ± 2_{other} (± 49_{tot})



Significant work on-going



E821 Result (Data-taking from 1998 – 2001):

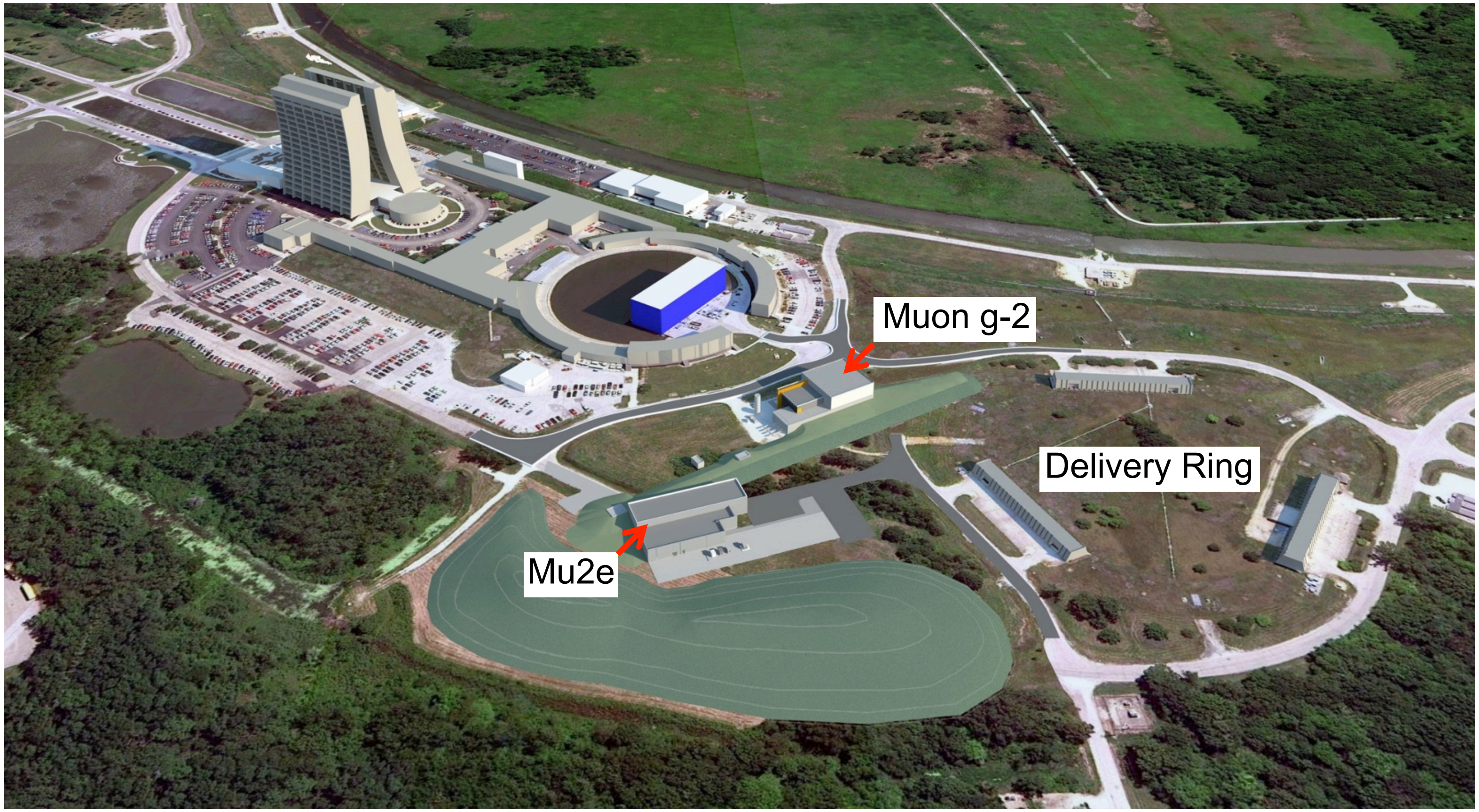
$$a_\mu^{exp} = 116\,592\,089\,(54)_{st}\,(33)_{sy}\,(63)_{tot} \times 10^{-11}$$

Exp - Theory: $\Delta a_\mu^{(\text{today})} = (287 \pm 80) \times 10^{-11}$ (3.6σ)

*Davier et al, Eur. Phys. J. C(2011) 71:1515; **Hagiwara et al, J. Phys. G38, 085003 (2011); §Prades et al, Lepton Moments (2010)

Fermilab Muon Campus Vision, c. 2012

- Convert Tevatron anti-proton source to produce muon beams for experiments such as Muon g-2 and Mu2e



Artist's Impression of Muon Campus

Fermilab Muon Campus Reality, Today

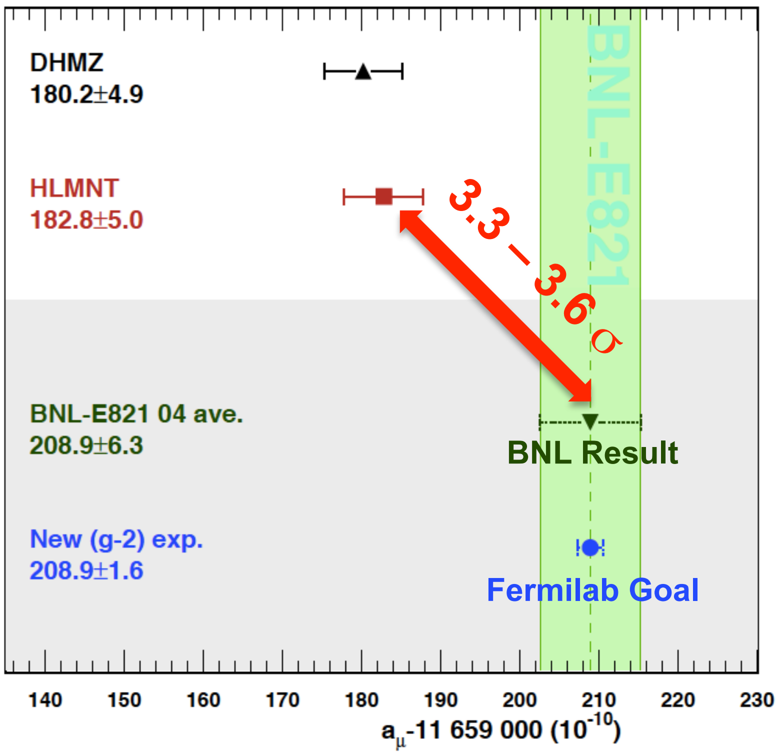
Photograph from Wilson Hall

- Muon g-2 hall complete, storage ring installed & operational
- Mu2e civil construction complete & building outfitting underway
- Conversion of accelerator complex to muon source nearing completion

Muon g-2: Overall Goal

- Reduce experimental error on a_μ by factor 4 & resolve the long-standing E821 g-2 discrepancy

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



Requires 21 x statistics & reduction of key systematics with 4 major steps:

- ✔ – Transport storage ring to Fermilab
- ✔ – New experimental hall for ring
- 75% Done – Modify accelerator to provide a high-purity, intense beam of muons
- 80% Done – Upgrade injection, field, detector, electronics & DAQ systems for higher rates and lower systematics

Muon g-2: Experimental Principle

- Store longitudinally polarised muons in a dipole field
- Measure two quantities to extract a_μ:
  - magnetic field averaged over muon distribution, B
  - anomalous precession frequency, ω_a

$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

Spin precession freq.

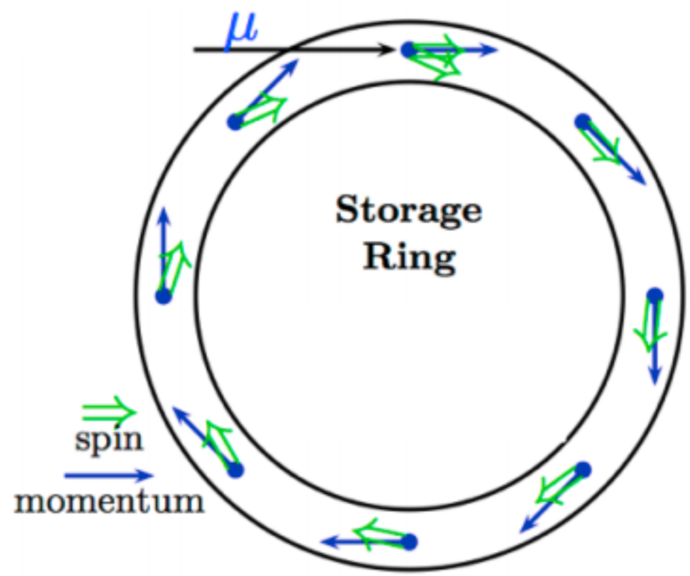
$$\omega_s = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

Larmor precession

Thomas precession

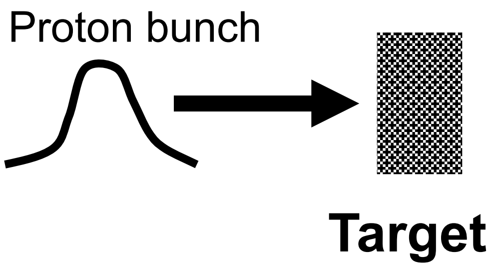
Cyclotron freq.

$$\omega_c = \frac{eB}{\gamma mc}$$



actual precession × 2

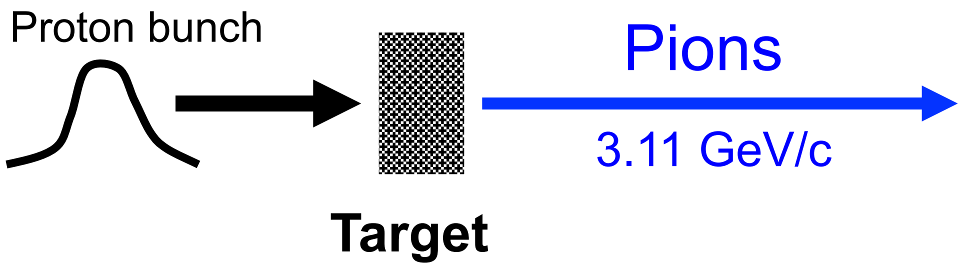
Muon g-2: Muon Production



- 120 ns wide bunch of 8 GeV protons from Booster & Recycler

- Fired at pion production target which is the same as that used for Tevatron Run II anti-proton production (Inconel (Ni-Cr))

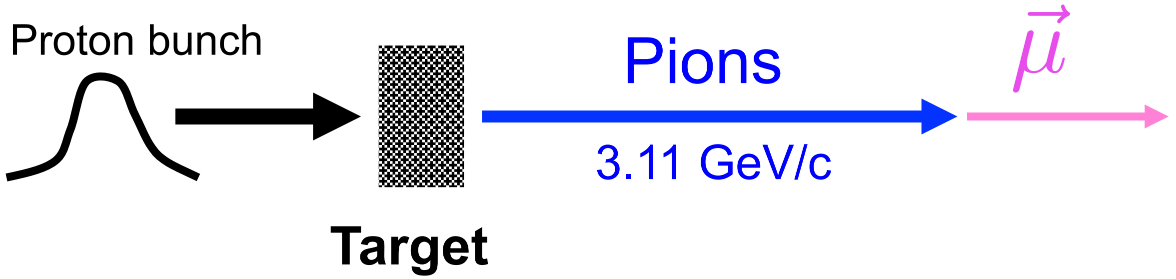
Muon g-2: Muon Production



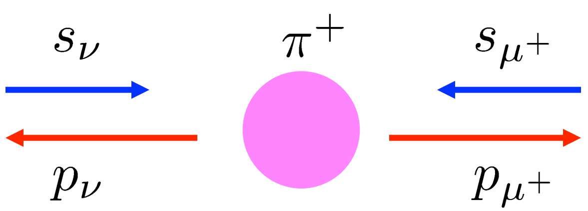
- Outgoing pions focused by a lithium lens and then momentum-selected, centred on 3.11 GeV

- The pions are then collected and sent towards the delivery ring

Muon g-2: Muon Production



- In the delivery ring, pions decay into negative helicity μ^+

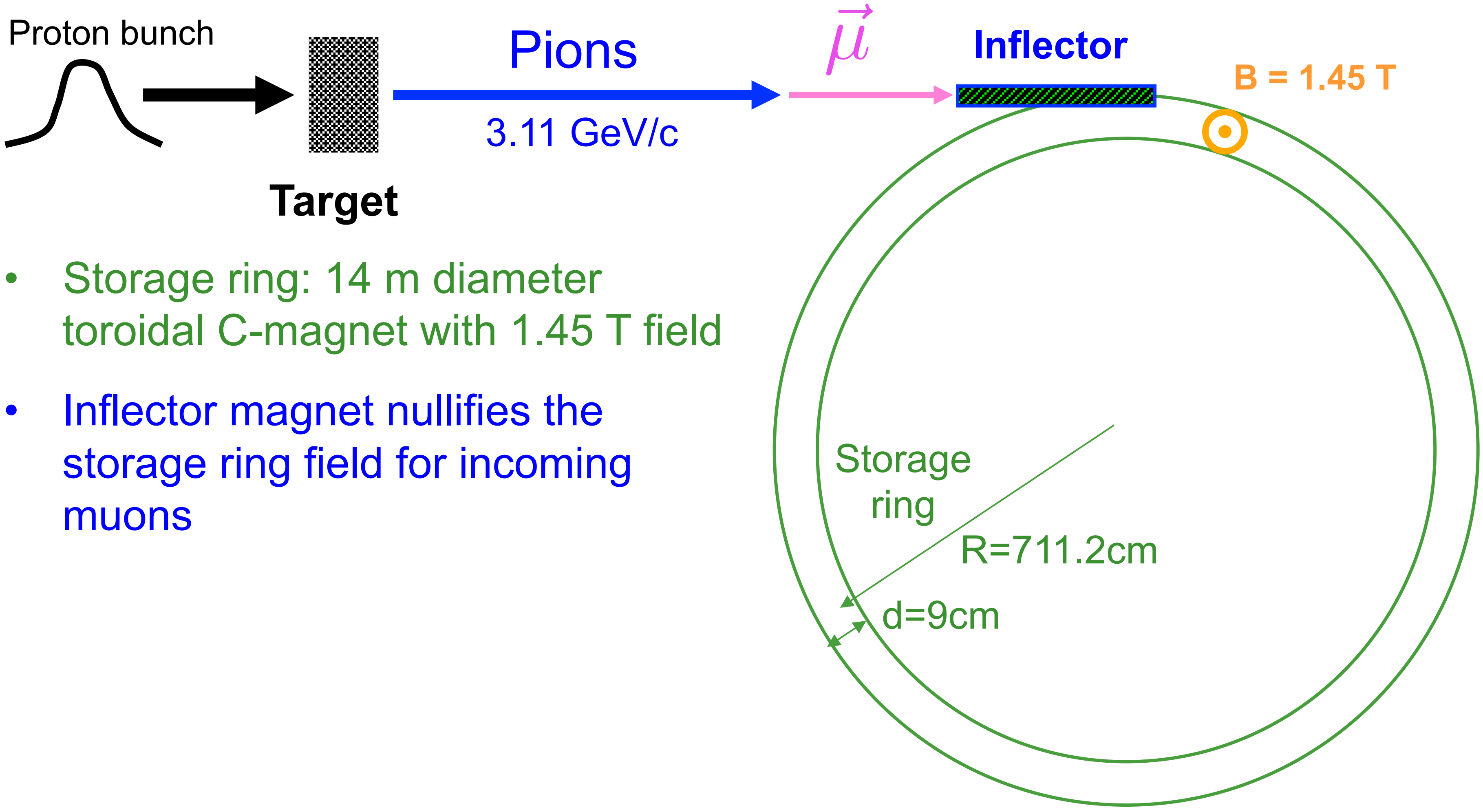


- Create a ~90% polarised beam by selecting highest energy μ^+
- Momentum of selected μ^+ centred on 3.09 GeV (γ = 29.3) to reduce E-field effects:

0 for γ = 29.3

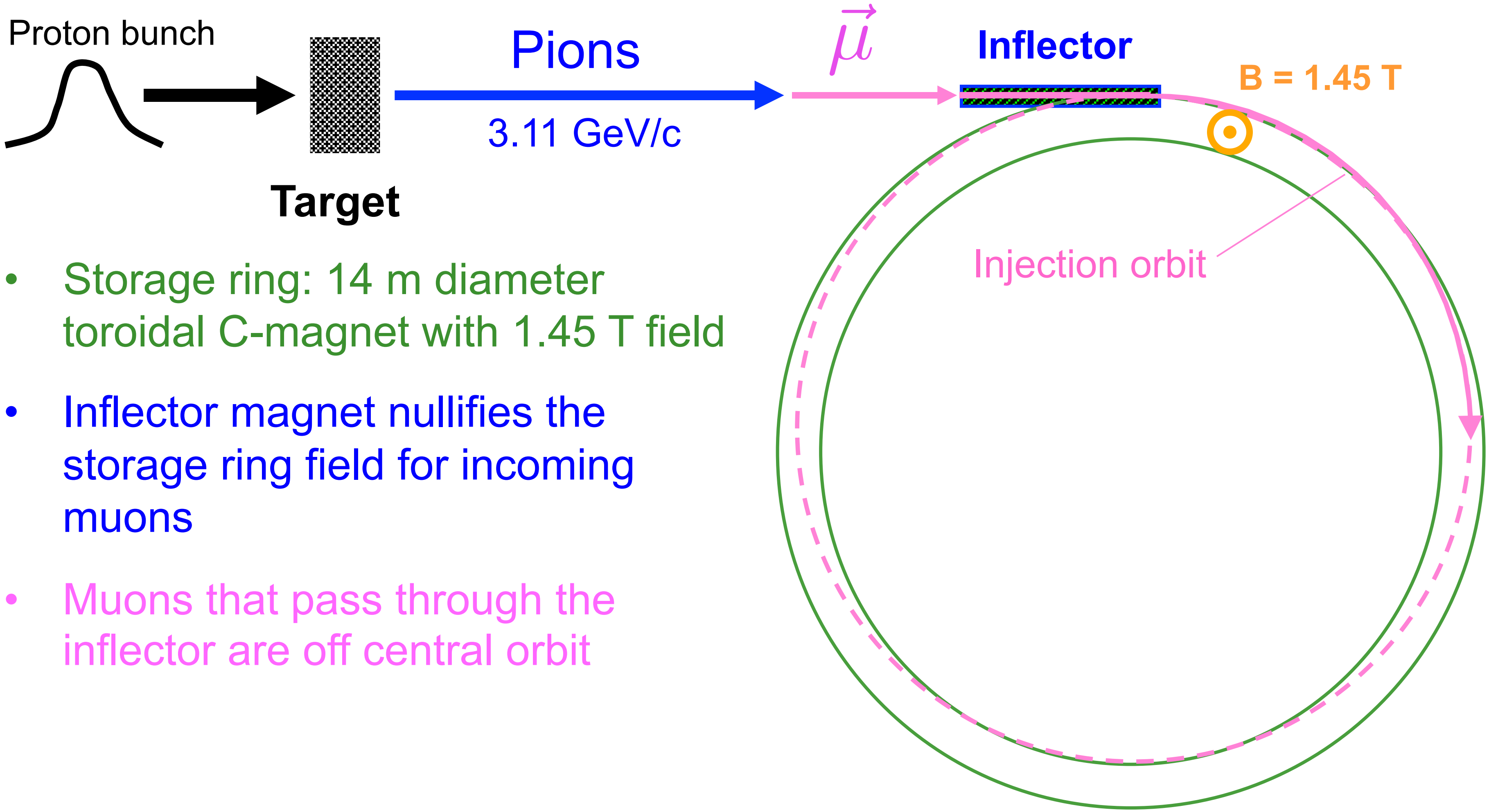
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)} (\vec{\beta} \times \vec{E})\right]$$

Muon g-2: Storing Muons



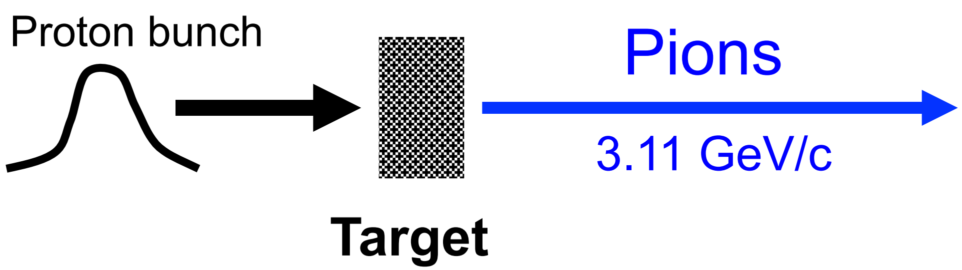
- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons

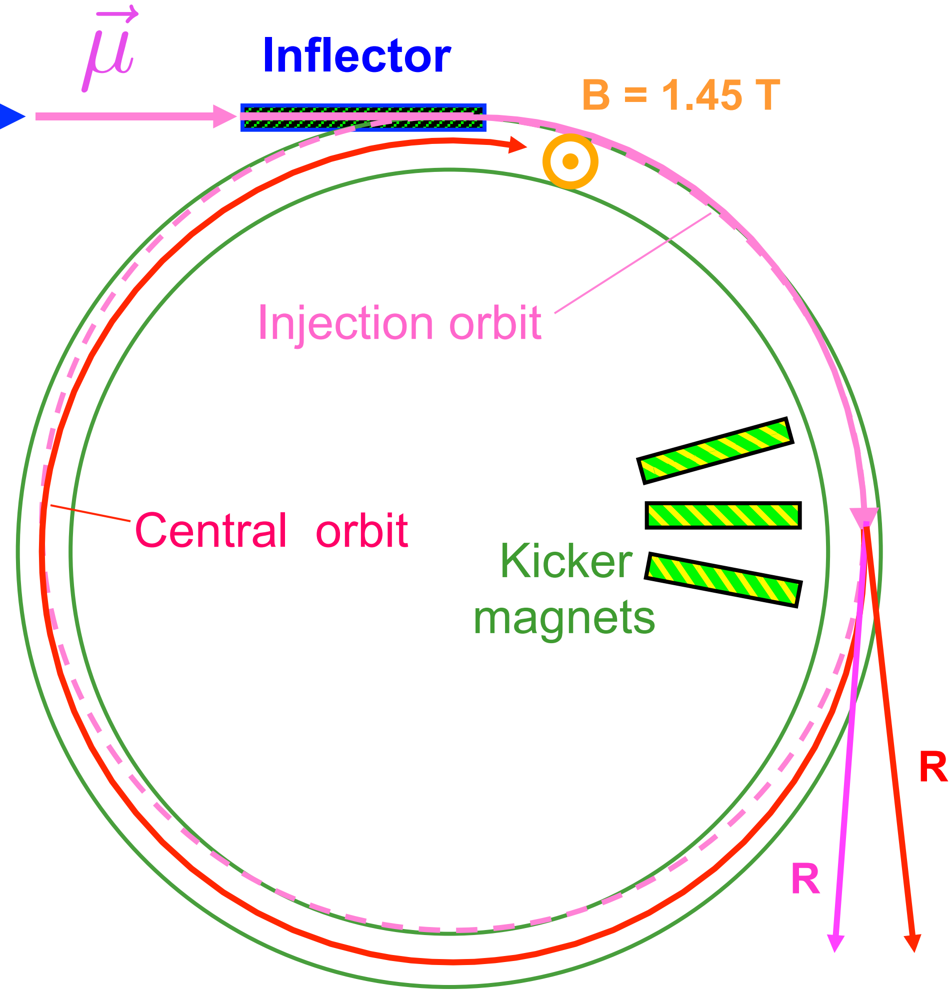
Muon g-2: Storing Muons



- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit

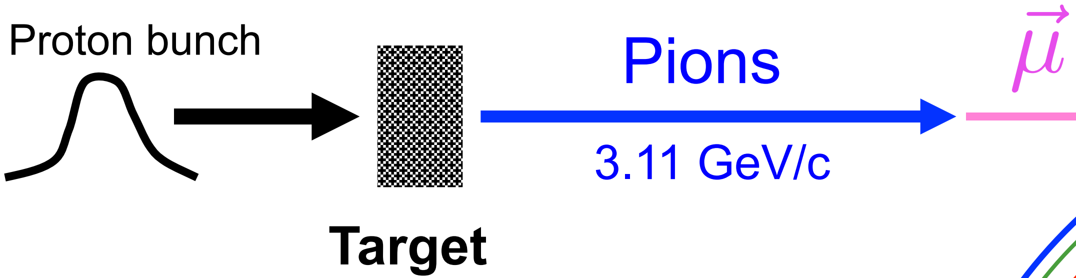
Muon g-2: Storing Muons

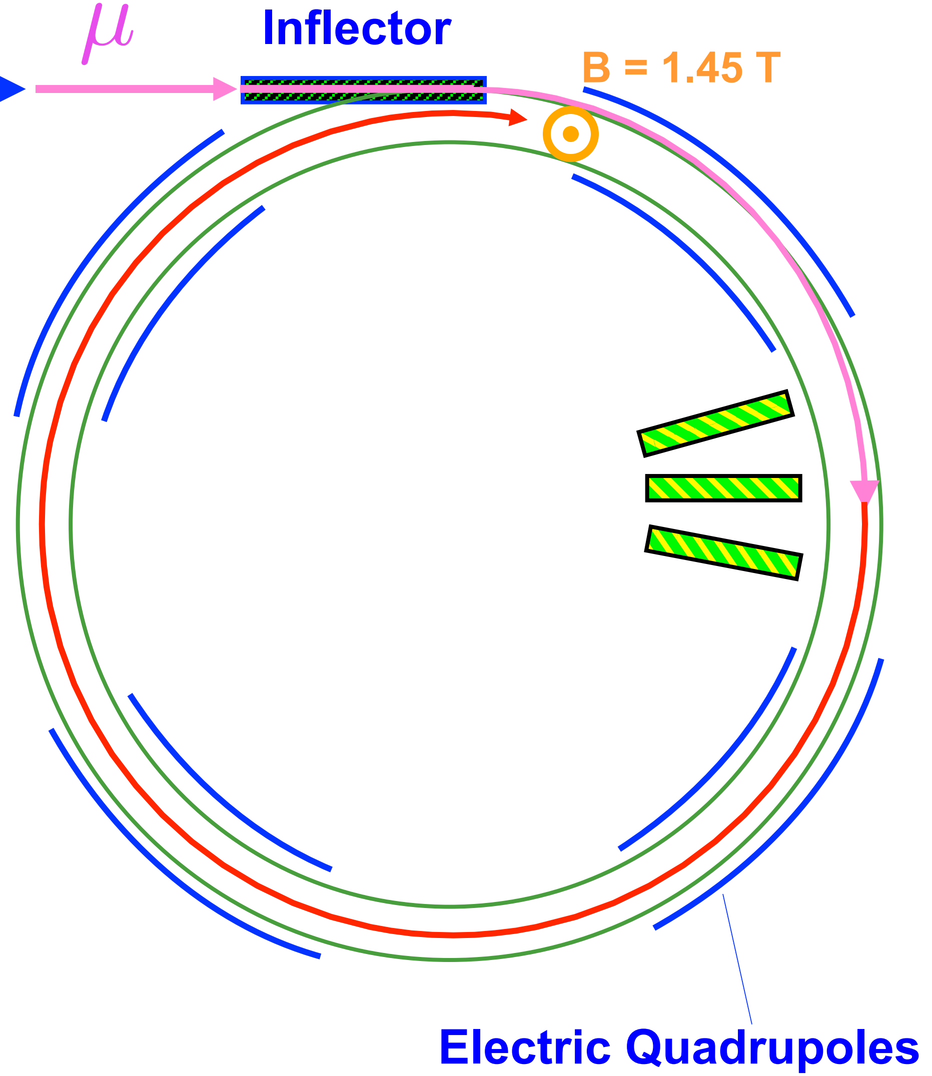




- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Kicker magnets move the orbit to the centre of the storage ring

Muon g-2: Storing Muons

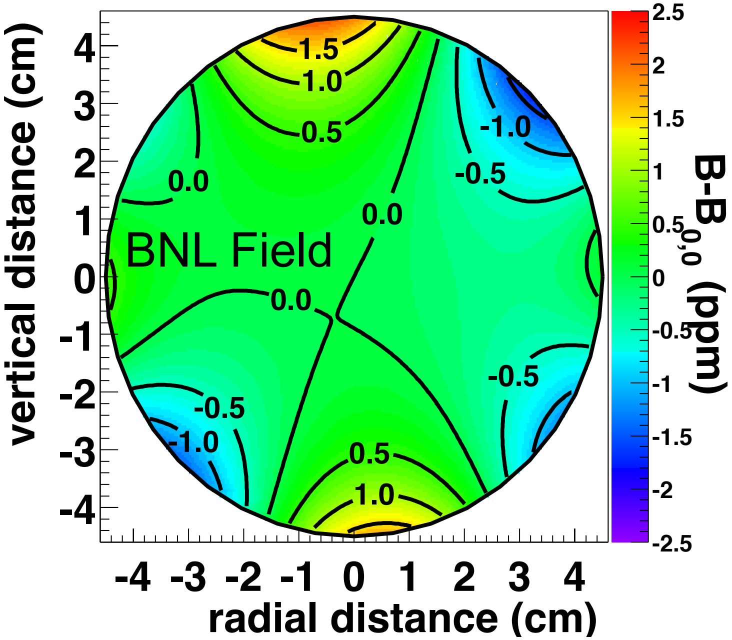


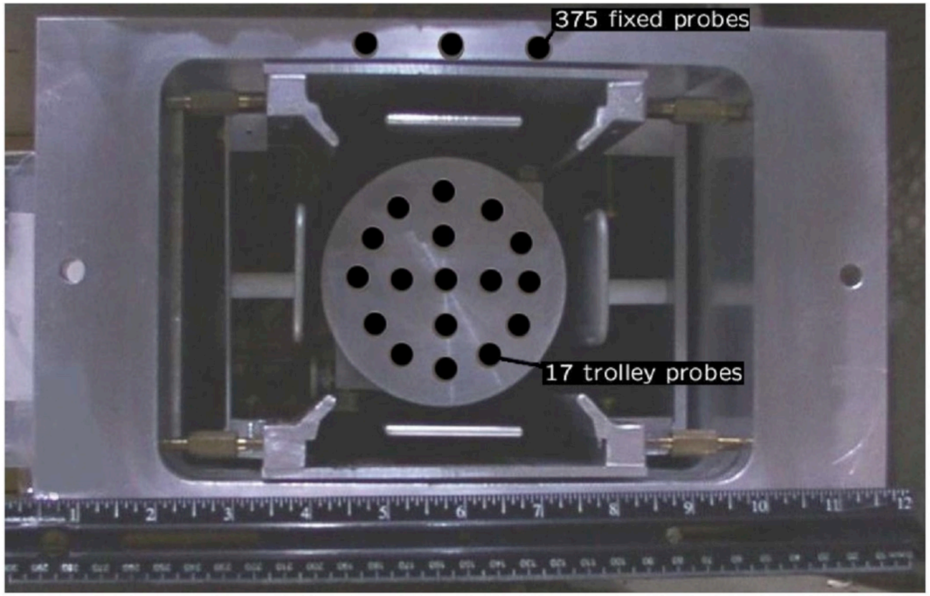


- Storage ring: 14 m diameter toroidal C-magnet with 1.45 T field
- Inflector magnet nullifies the storage ring field for incoming muons
- Muons that pass through the inflector are off central orbit
- Kicker magnets move the orbit to the centre of the storage ring
- Muons focussed vertically with electrostatic quadrupoles

Measuring the Magnetic Field

- Regularly map field inside vacuum chamber with NMR probe trolley
- Monitor field during data-taking with fixed probes and interpolate



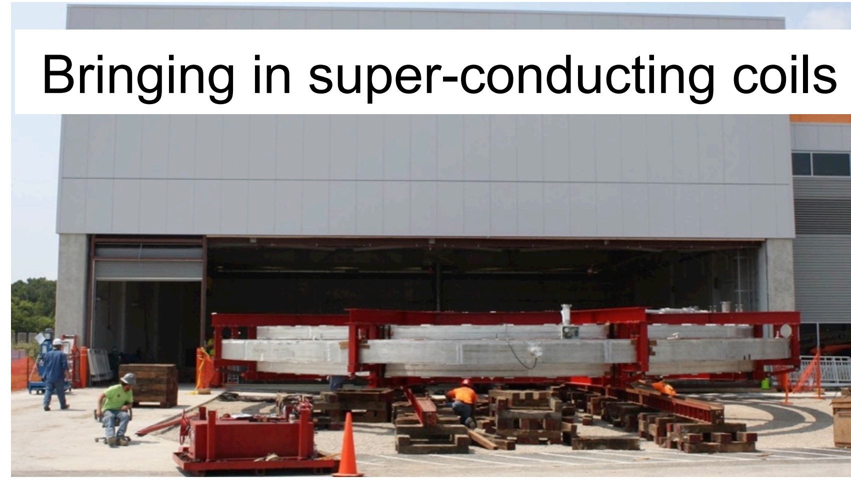


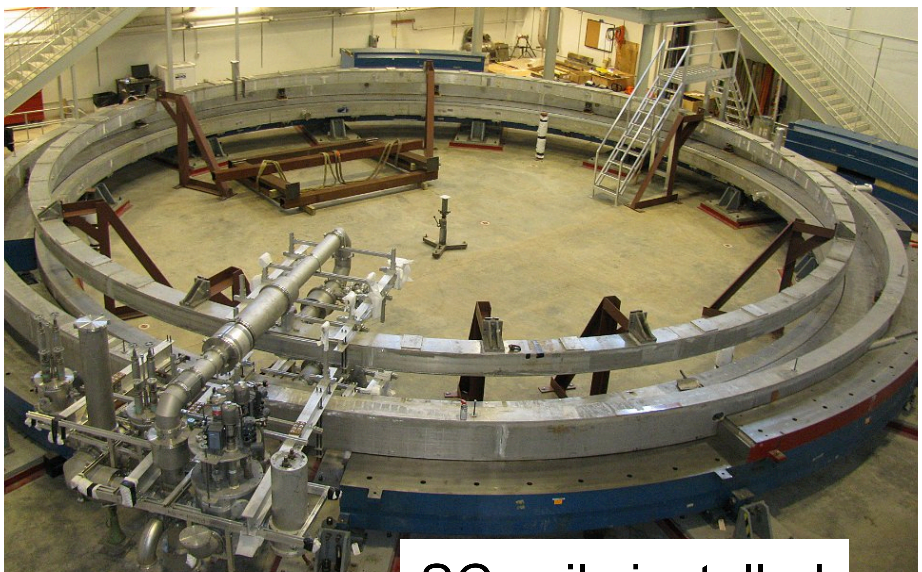
NMR trolley in vacuum chamber

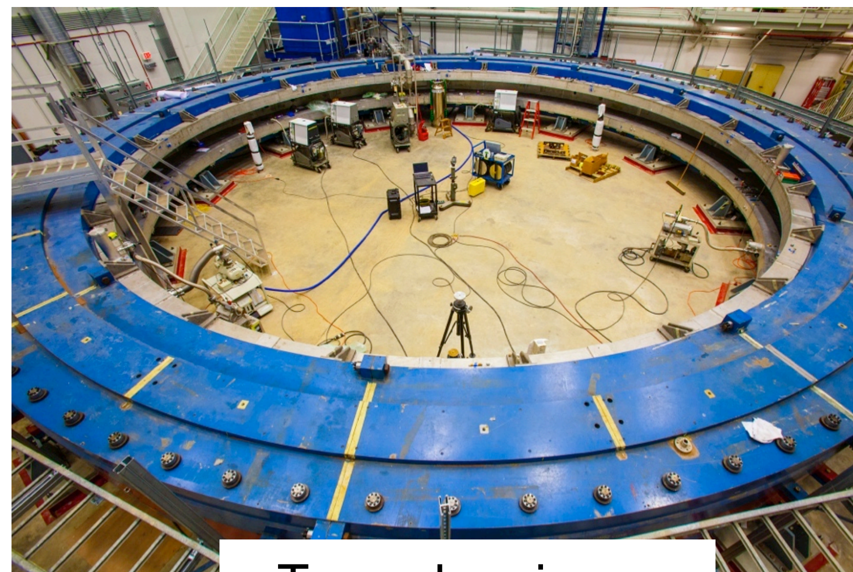
- BNL E821 result averaged around azimuth was good to 1 – 2 ppm
- We're shimming finer to improve this

Magnet Reassembly at Fermilab


Bottom yoke pieces

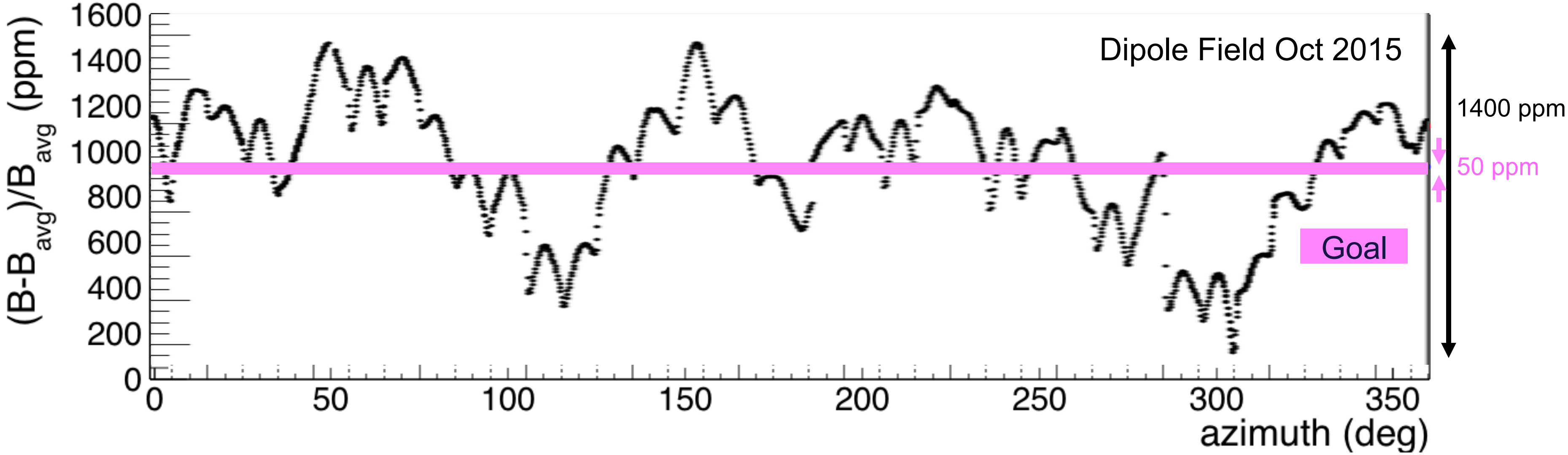

Bringing in super-conducting coils


SC coils installed


Top yoke pieces

First Magnetic Field Measurement

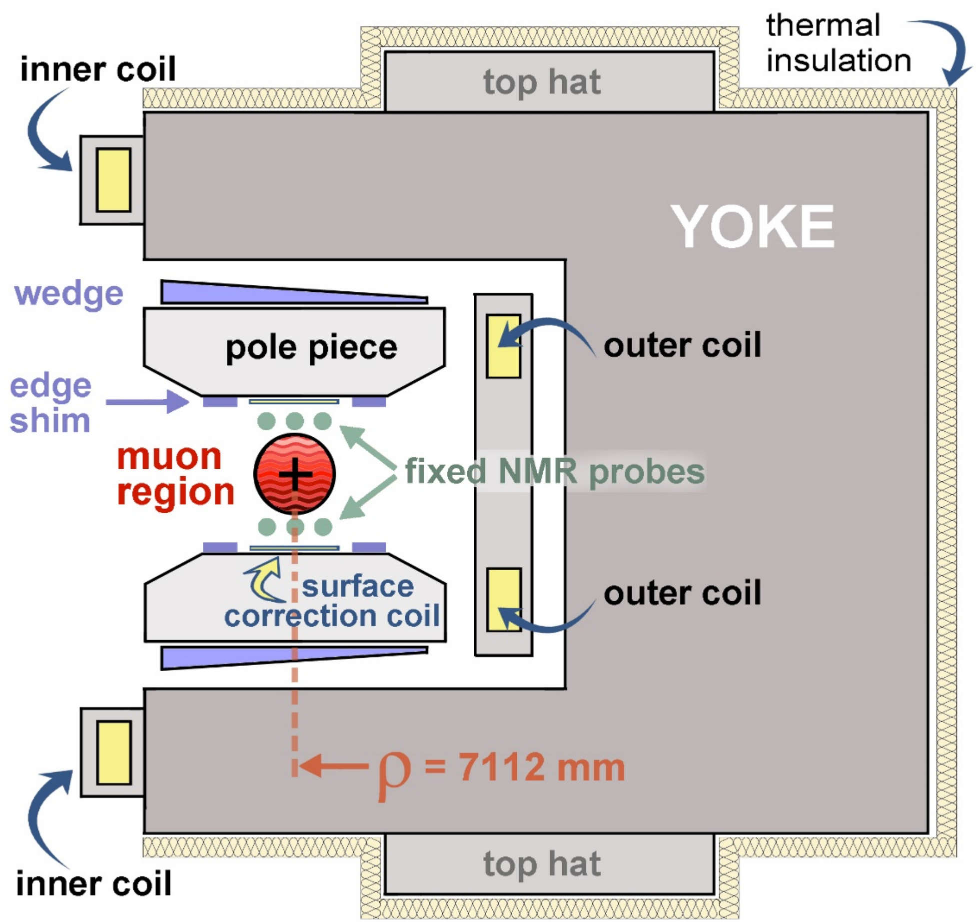
- Magnet achieved full power September 2015 with peak-peak variation of 1400 ppm:



- We care about the field weighted by muon distribution
- For 70 ppb uncertainty, we need a uniform field to relax constraints on measuring the muon distribution
- The goal is 50 ppm after first round of rough shimming

Magnetic Design & Shimming Tools

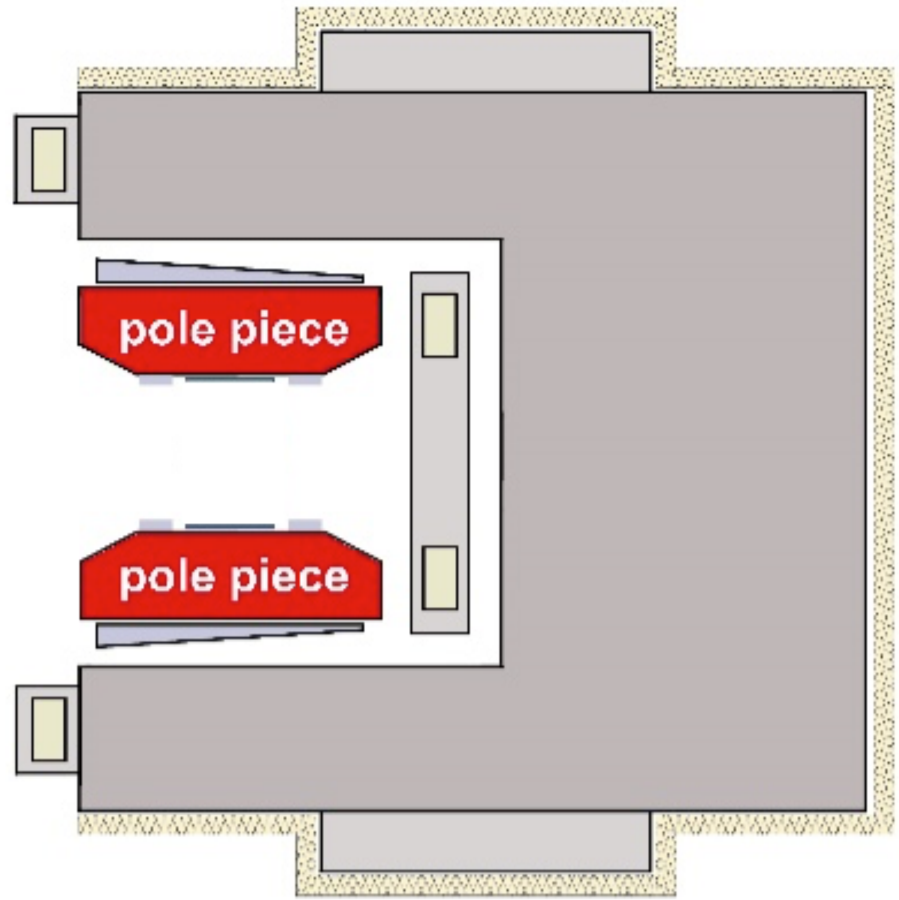
- C-shaped design with 1.45 T dipole field between poles



g-2 Magnet in Cross Section

Magnetic Design & Shimming Tools

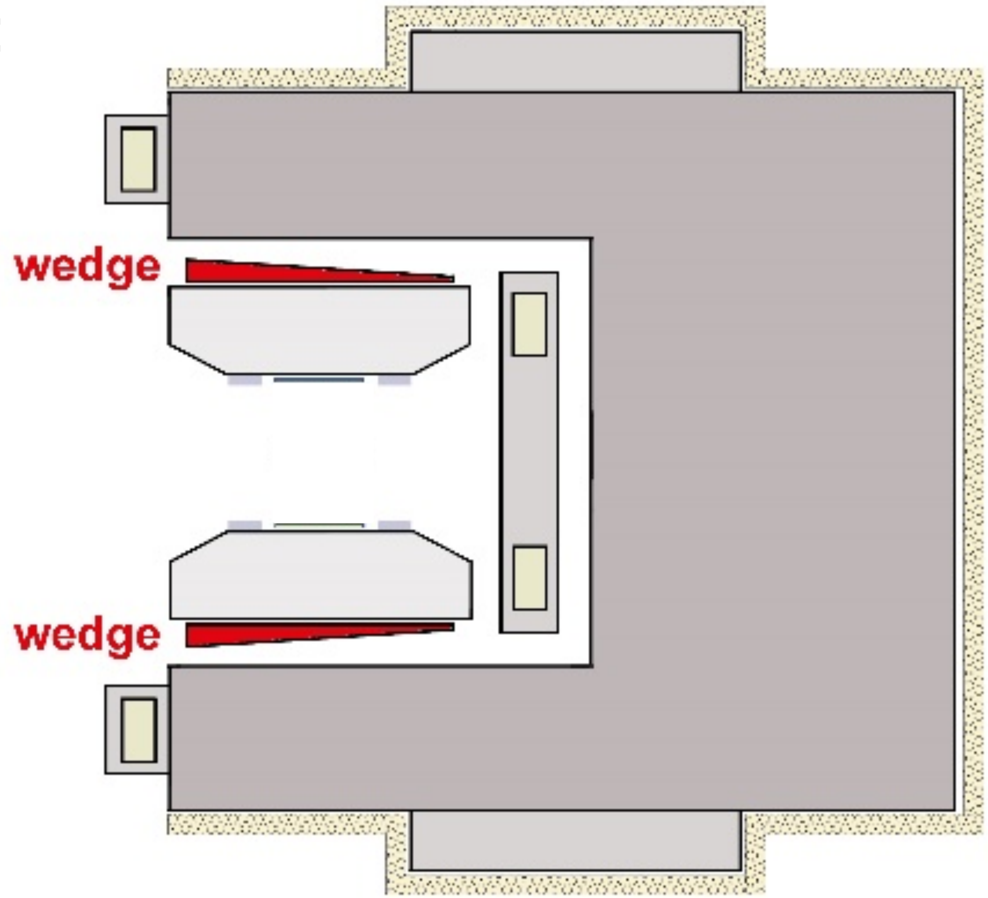
- C-shaped design with 1.45 T dipole field between poles
- Many “knobs” for calibration:
  - 72 Poles
    - Shaping & homogeneity



g-2 Magnet in Cross Section

Magnetic Design & Shimming Tools

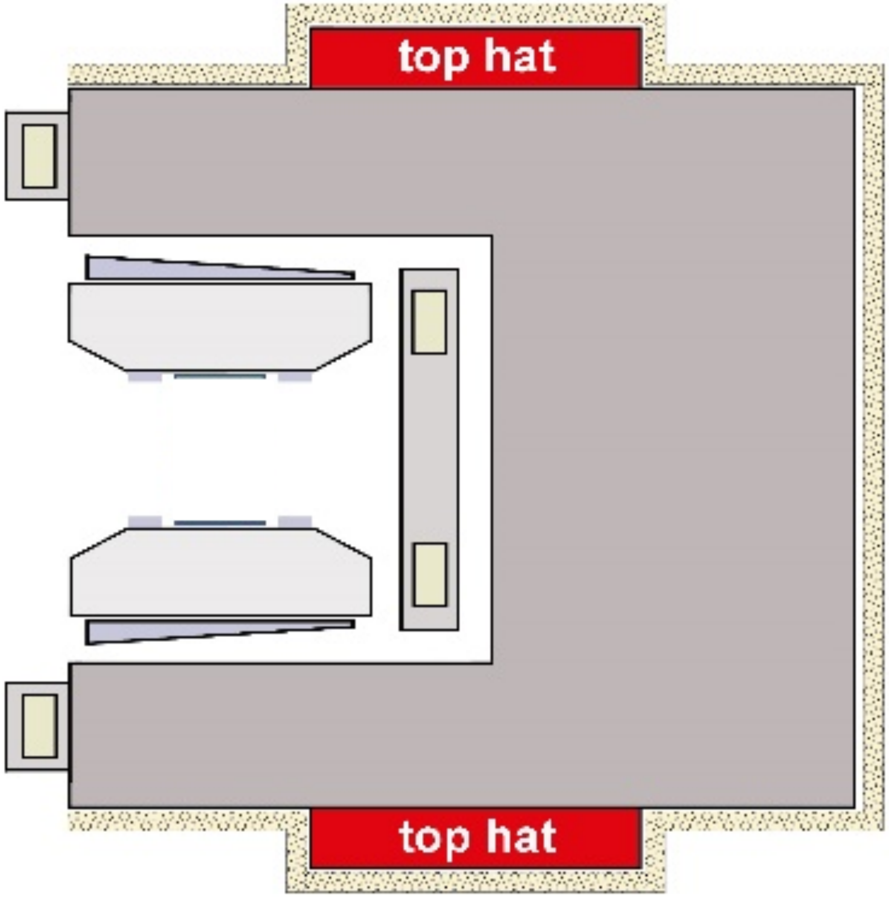
- C-shaped design with 1.45 T dipole field between poles
- Many “knobs” for calibration:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry



g-2 Magnet in Cross Section

Magnetic Design & Shimming Tools

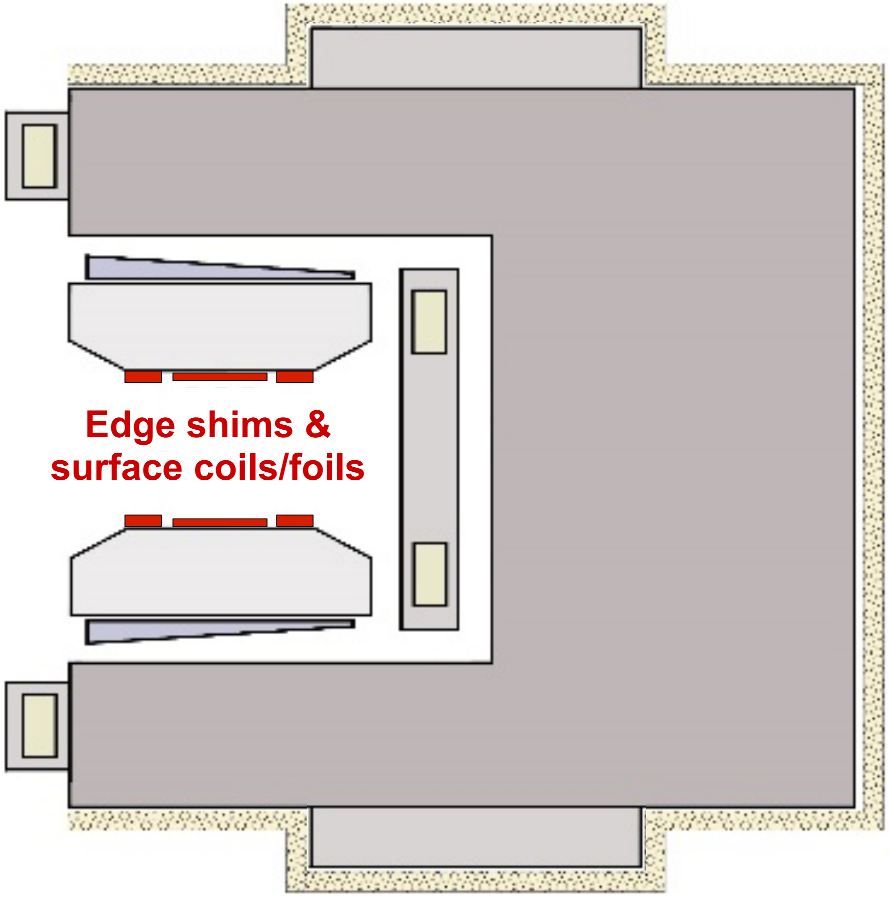
- C-shaped design with 1.45 T dipole field between poles
- Many "knobs" for calibration:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry
  - 48 Iron Top Hats
    - Change effective μ



g-2 Magnet in Cross Section

Magnetic Design & Shimming Tools

- C-shaped design with 1.45 T dipole field between poles
- Many “knobs” for calibration:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry
  - 48 Iron Top Hats
    - Change effective μ
  - 144 Edge Shims
    - Quad/sextapole asymmetry
  - 8000 Surface Iron Foils
    - Local changes of effective μ
  - 100 Active Surface Coils
    - Control current to add ring-wide average field moments

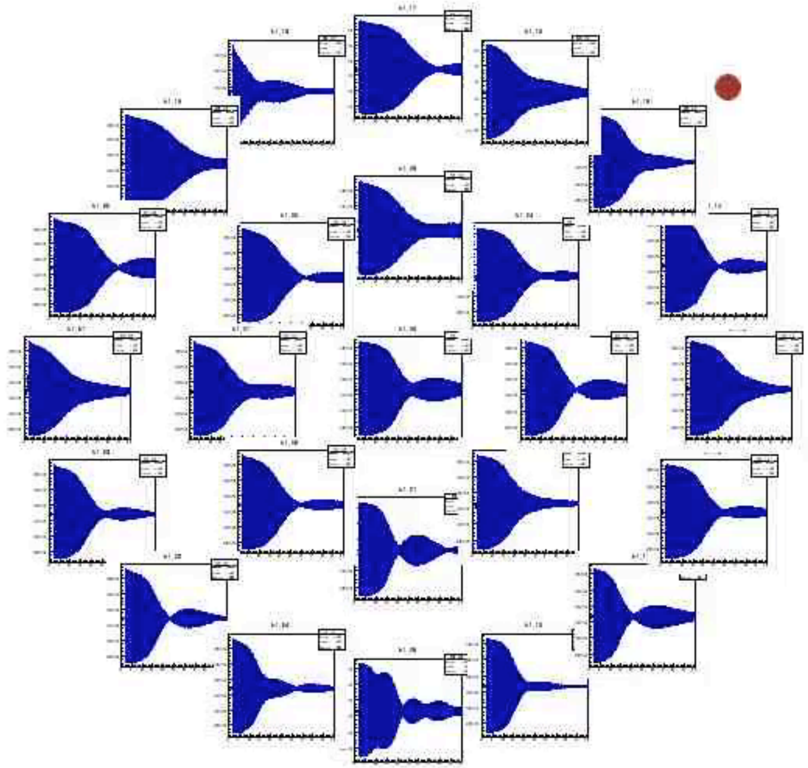


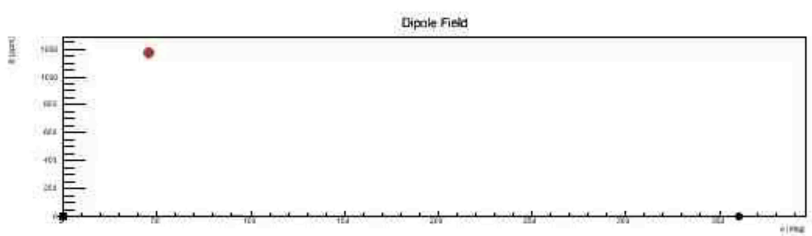
g-2 Magnet in Cross Section

Shimming & Field Measurements

- Field in storage volume is measured using pulsed proton NMR
- Shimming trolley contains array of probes that map whole storage volume
- Extracted frequency gives 10 ppB single shot measurement precision

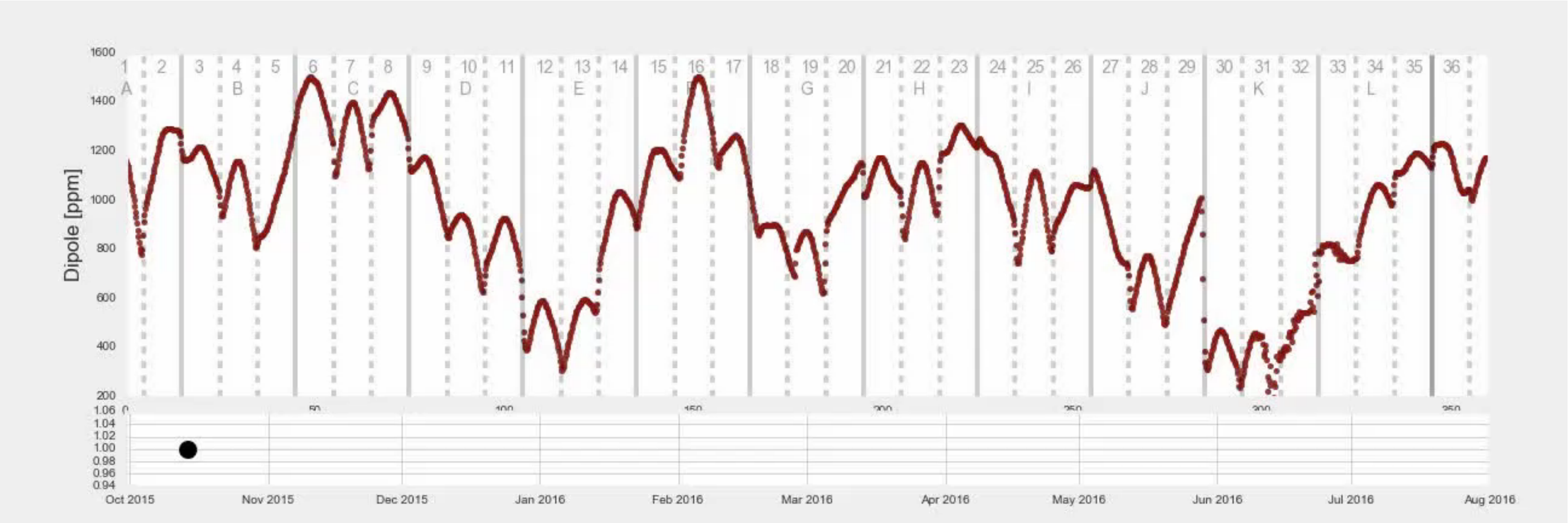
Early stages of shimming:

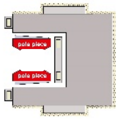




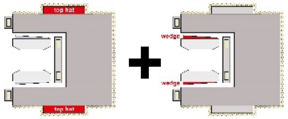
Shimming in Action

- Progress towards a uniform field from Oct '15 to July '16:

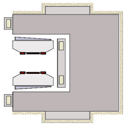




Poles



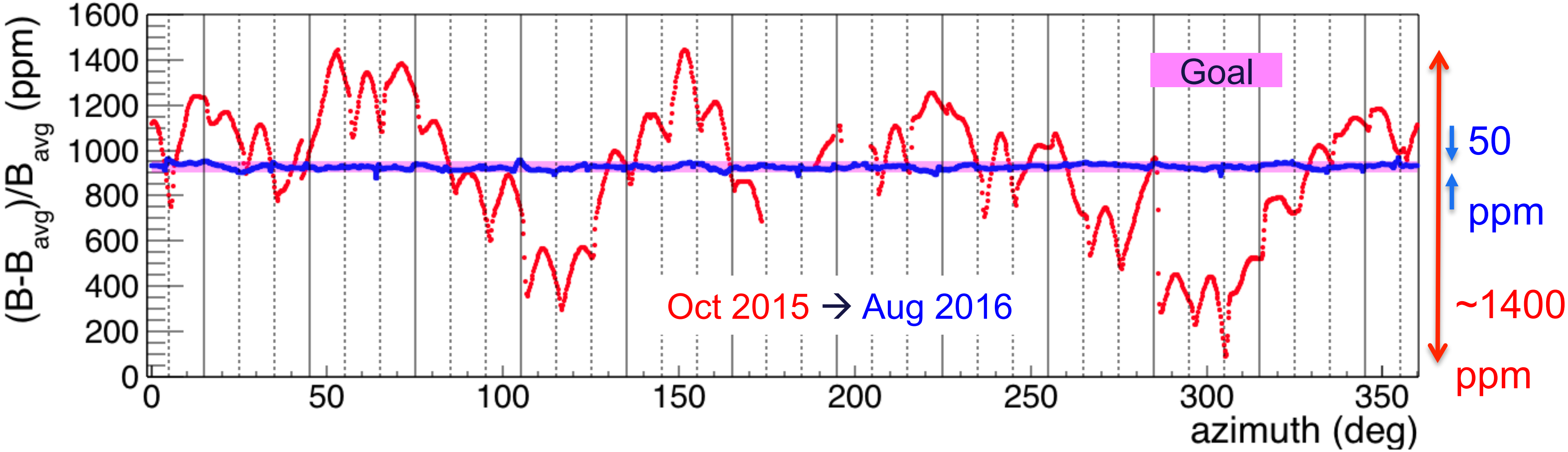
Top hats & wedges



Surface foils

Rough Shimming Result

- August 2016: completed addition of surface foils & achieved 50 ppm goal for rough shimming:



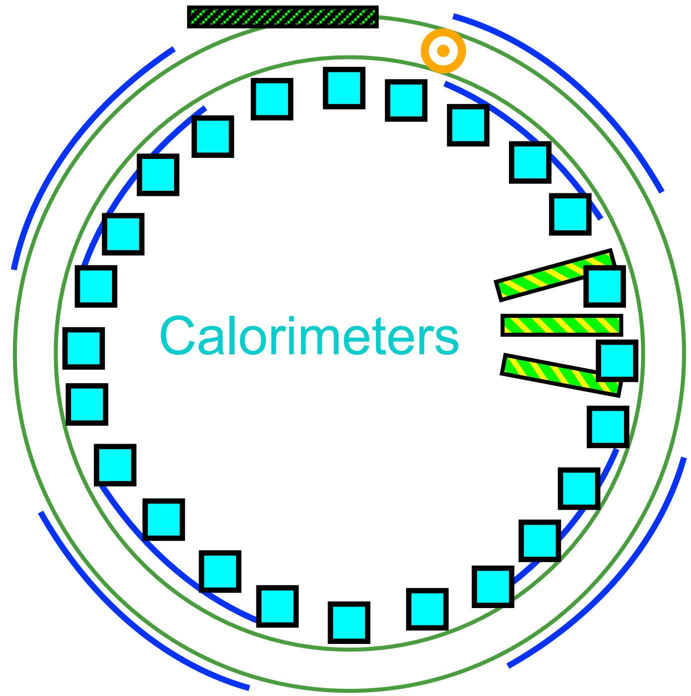
	RMS (ppm)	p-p (ppm)
FNAL (Rough shimmed)	10	75
BNL (Typical scan)	30	230

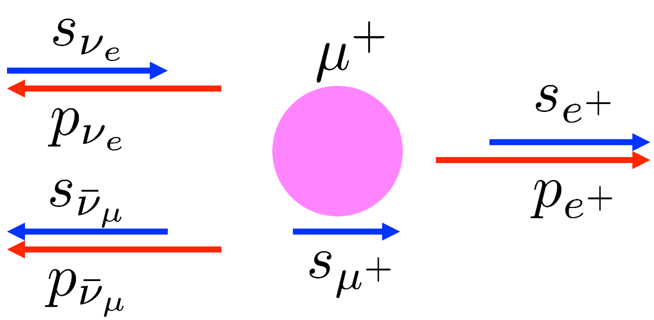
- Now installing vacuum chambers & detector systems

Measuring the precession frequency, ω_a

- We measure ω_a using 24 electromagnetic calorimeters placed around the storage ring

- The highest energy positrons are correlated with the muon spin in our polarised sample





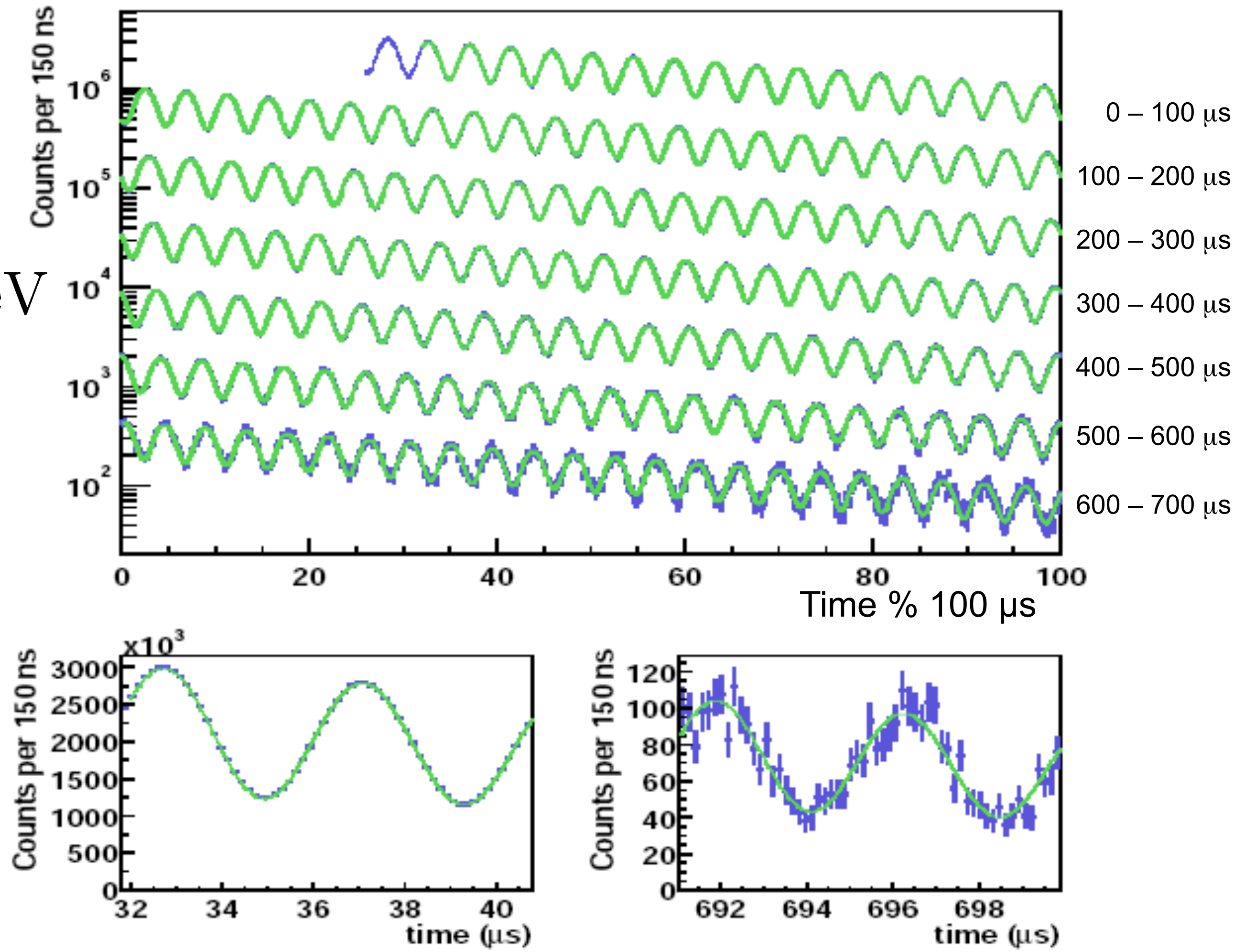
- As the μ^+ spin precesses towards and away from the calorimeters the number of high energy e^+ is modulated by ω_a

Extracting ω_a from the calorimeter data

- Arrival-time spectrum from previous experiment (E821):

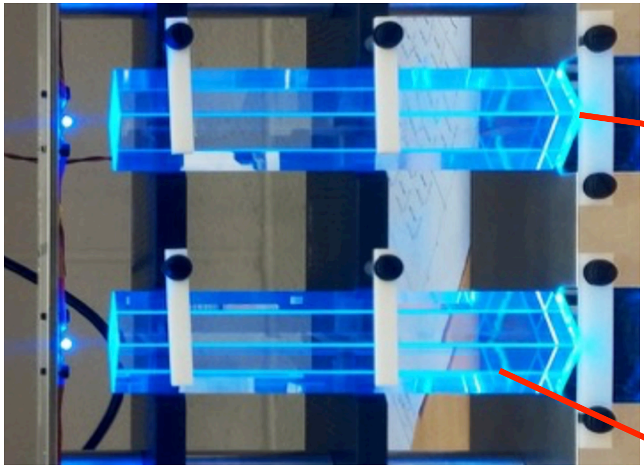
$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

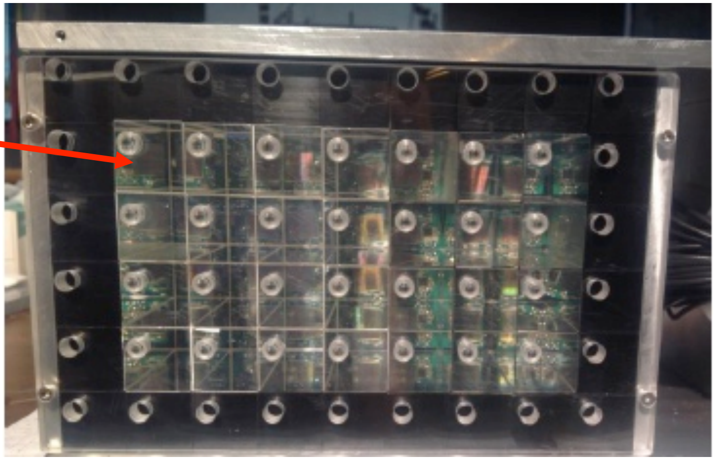
$$E_{e^+} > 1.8\ \mathrm{GeV}$$



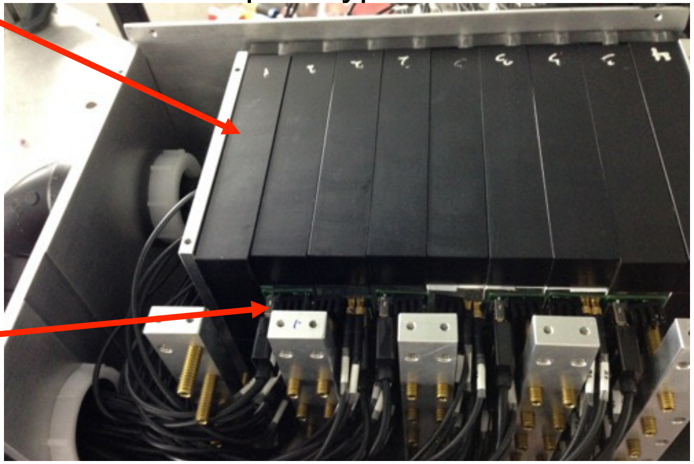
Calorimeter Design

- 24 calorimeters: each is array of 6 x 9 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels)



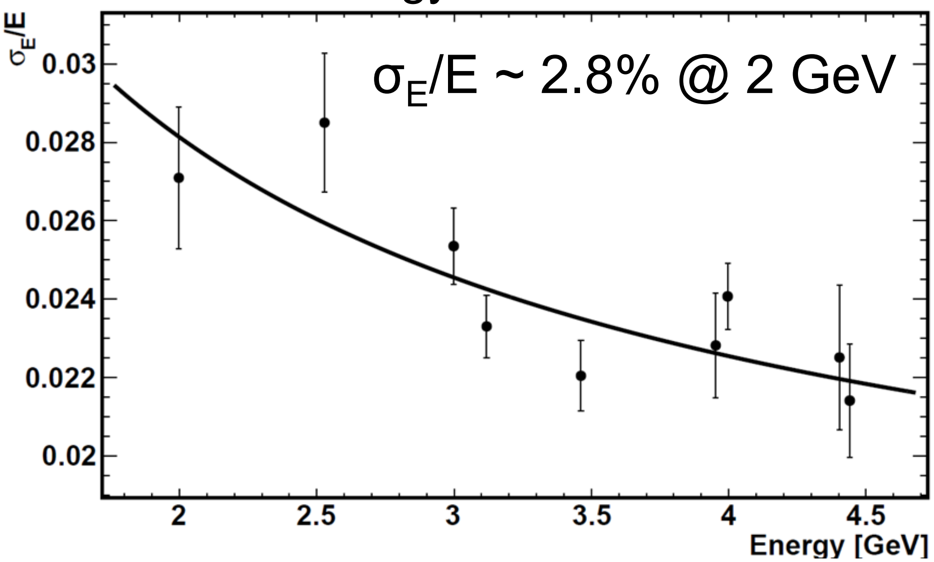


28 channel prototype tested at SLAC

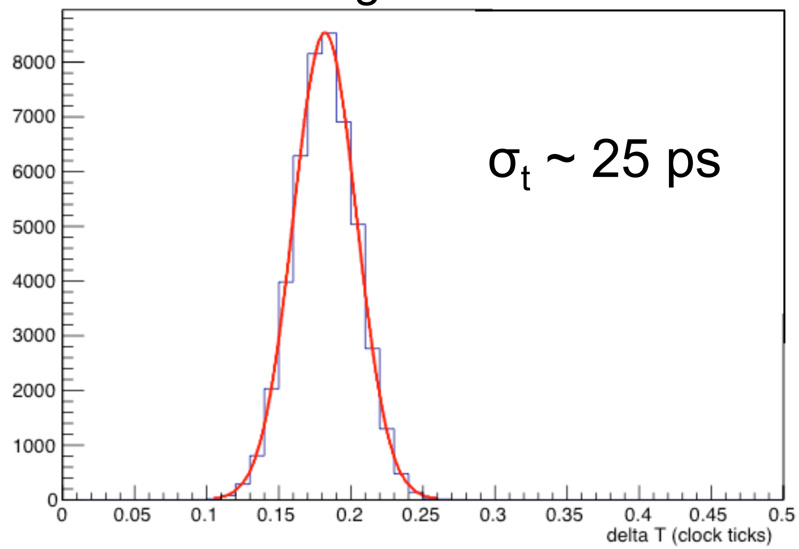


Calorimeter Performance

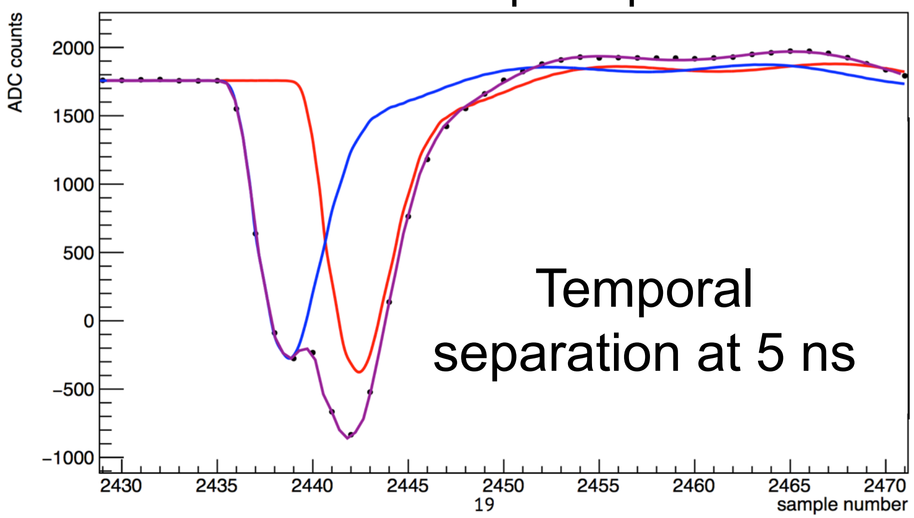
Energy Resolution



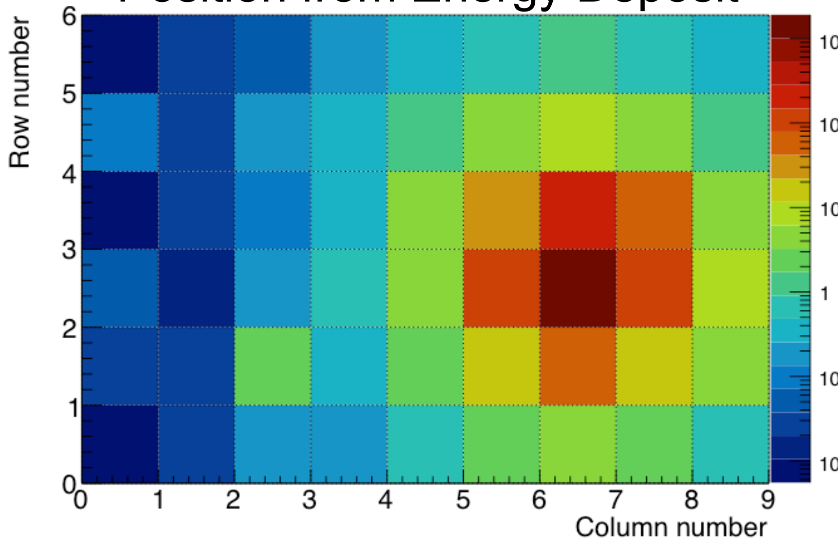
Timing Resolution



Electron pile-up



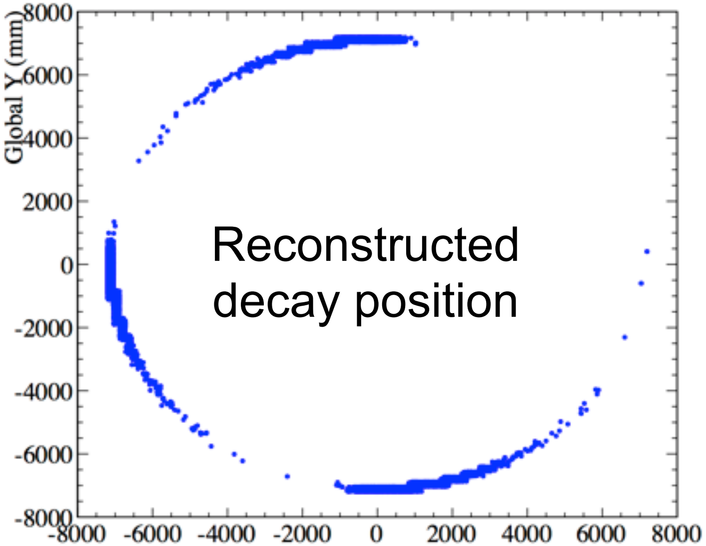
Position from Energy Deposit

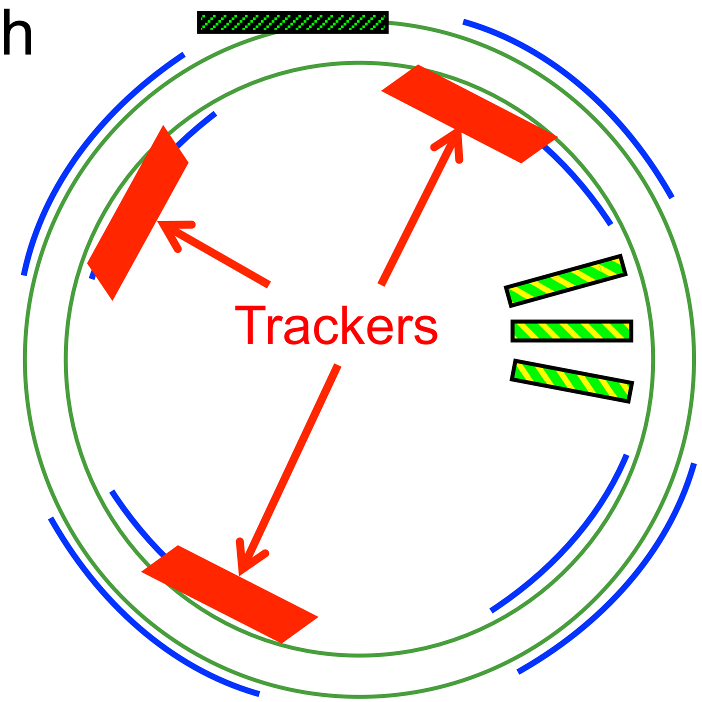


See NIM A 783 (2015), pp 12–21 for details

Measuring the Muon Distribution

- We need to measure the muon distribution to calculate:
  - Average magnetic field $\langle B \rangle_{\mu-\text{dist}}$
  - Pitch correction (vertical betatron motion) $\langle y^2 \rangle$
  - E-field correction (not all muons at magic mom) $\langle x_e^2 \rangle$
- We do this with **three trackers** around the ring
- A non-destructive measurement with a resolution of 1 mm.

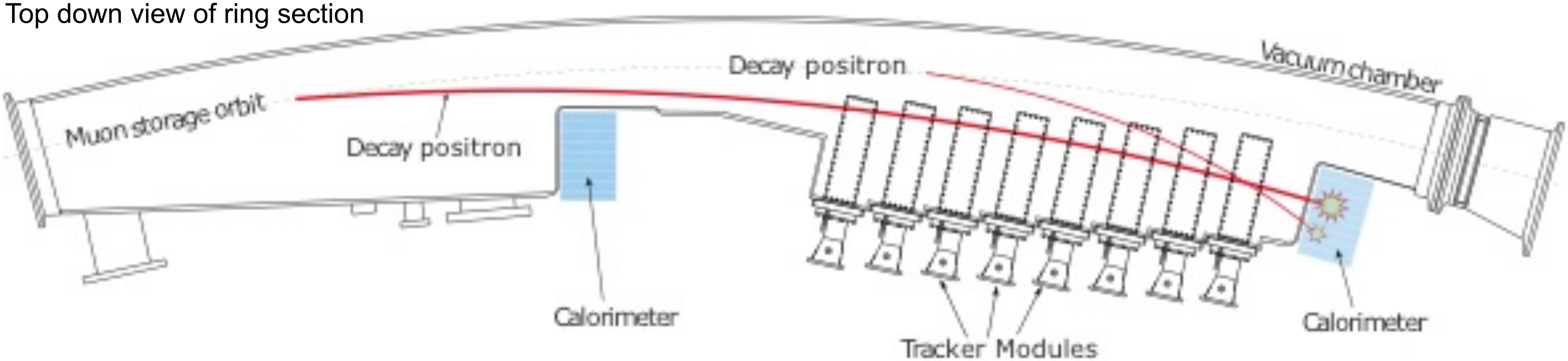




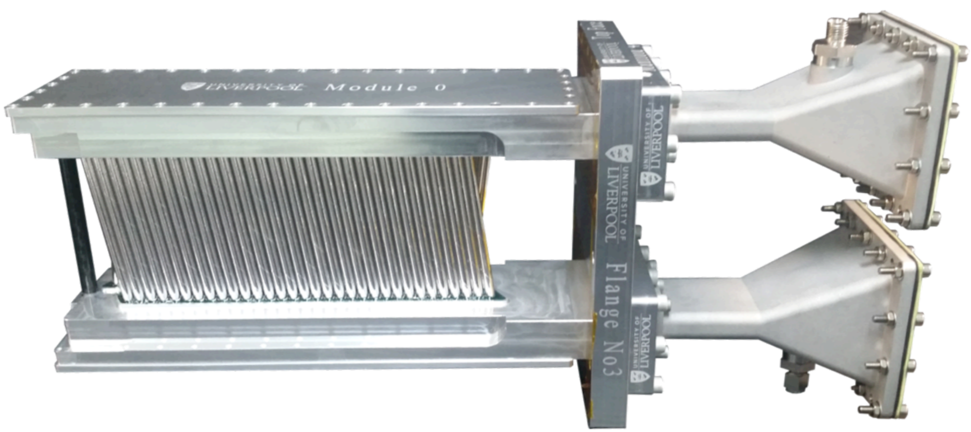
Tracker Design

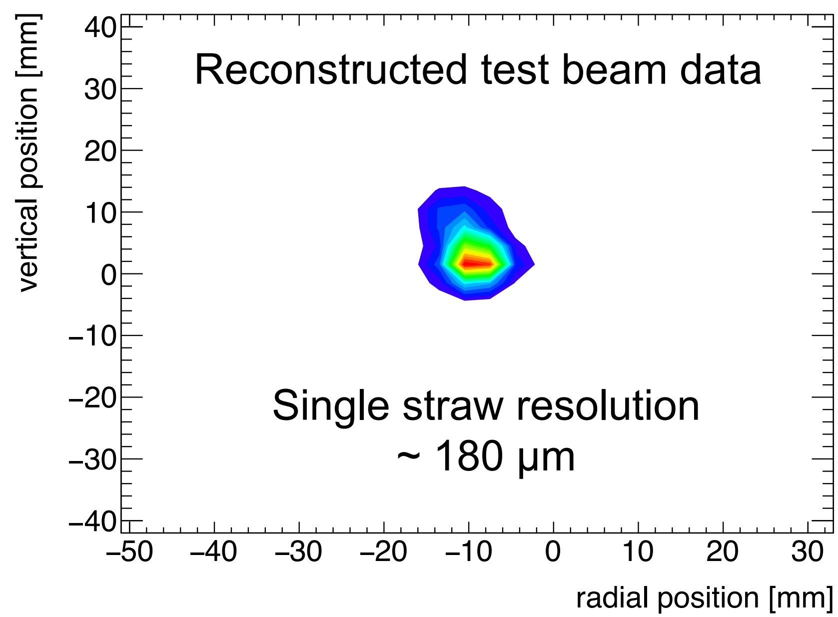
- Each tracker has 8 modules that sit in front of calorimeter

Top down view of ring section

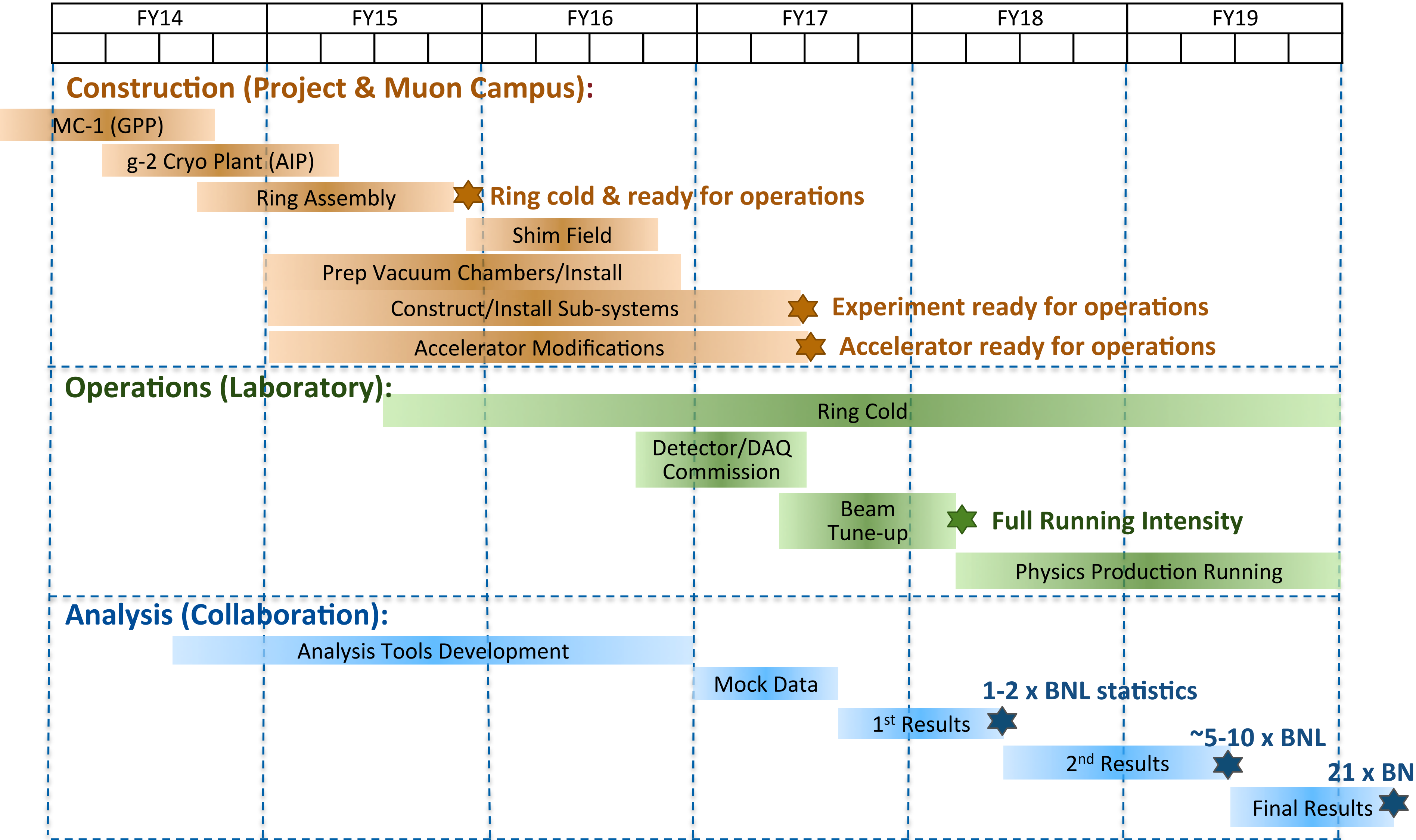


- Each module has 128 straws in four layers





Muon g-2: Current Schedule



Take-home messages

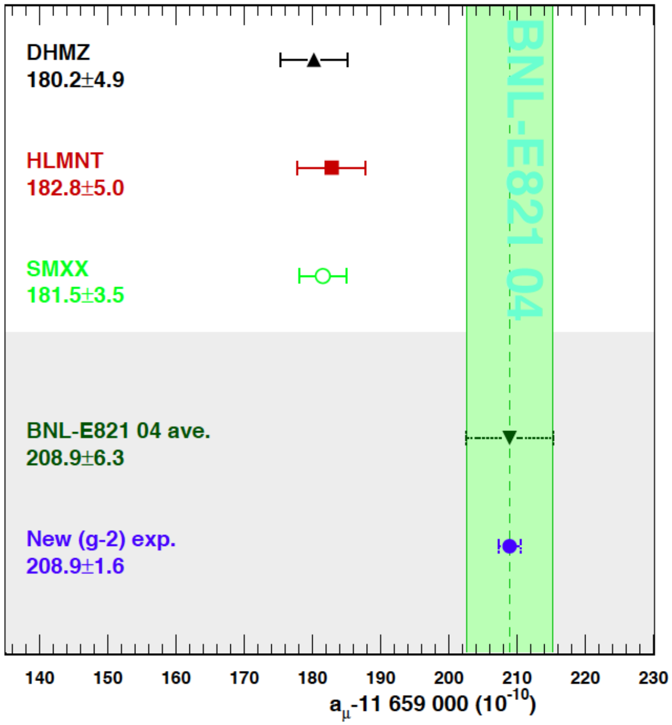
- The Muon g-2 experiment will reduce error by a factor of 4 compared to the previous Muon g-2 (BNL E821)
- The storage ring magnet has been operational for a year and our rough shimming targets have been achieved
- Beamline commissioning begins in April 2017, with real data collection starting Autumn 2017
- We anticipate a result with the same precision as E821 by mid-2018
- We expect to report three results with 100%, 50% and 25% of the E821 uncertainty

Extra Slides

Improvements over E821

Increase statistics: **x 21**

Reduce systematics: **x 2 (ω_p) and x 3 (ω_a)**



Goal: 140 ppb

Expected Improvement

7.5 σ if same central values

Key: More muons per fill & more fills per hour

Key: Finer shimming of magnet and refined monitoring

Key: Modern detectors/electronics/DAQ/calibration

Systematic Errors on ω_a (ppb)

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 simulat	30
Total	180	Quadrature sum	70

Detector Team

Ring Team

Detector Team

Systematic Errors on ω_p (ppb)

	Brookhaven E821			FNAL
Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]
Absolute calibration of standard probe	50	50	50	35
Calibration of trolley probes	200	150	90	30
Trolley measurements of B_0	100	100	50	30
Interpolation with fixed probes	150	100	70	30
Uncertainty from muon distribution	120	30	30	10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	5
Others †	150	100	100	30
Total systematic error on ω_p	400	240	170	70
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 50 ppb/$^\circ$C) and power supply voltage response (400 ppb/V, ΔV=50 mV), and eddy currents from the kicker.

Absolute calibration of the field

Absolute Calibration

- Measured field is not what a free proton sees; need corrections

$$
\begin{aligned}
B_{\text{meas}} &= (1-\delta_t)B \\
&= [1-\sigma(\text{H}_2\text{O},T)-\delta_b-\delta_p-\delta_s]\,B
\end{aligned}
$$

Paramagnetic ion cont.

Diamagnetic shielding

Bulk diamagnetic shape $(\varepsilon - 4\pi/3)\,\chi$

Probe structure

Systematic uncertainties from E821 [NIM **394**, 349 (1997)]

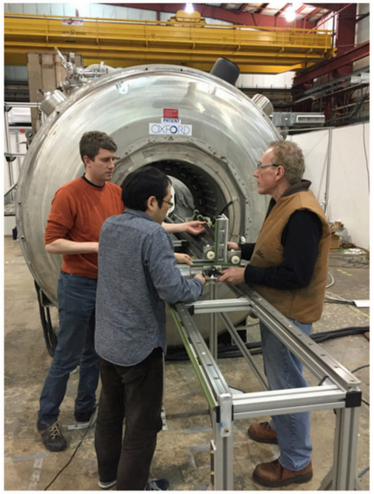
Projections for E989

Source of Error	Uncertainty (ppb)
NMR detection and measurement	15 → 5
Field homogeneity	10
Materials outside the probe	15
Water/sample holder shape	15 → 10
Probe materials	10 →
Diamagnetic shielding (H_2O)	14 → 2.5
Temperature	10 → 5
Total	34 → 28

Diamagnetic shielding measurements: Metrologia **51**, 54 (2014)

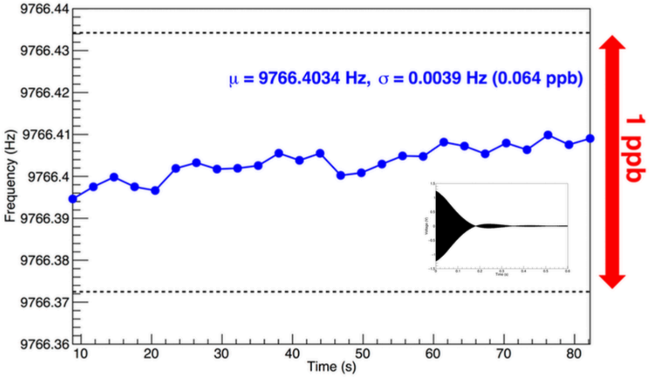
Test Facility at ANL

- MRI solenoid magnet
- High-precision, high-resolution DAQ system



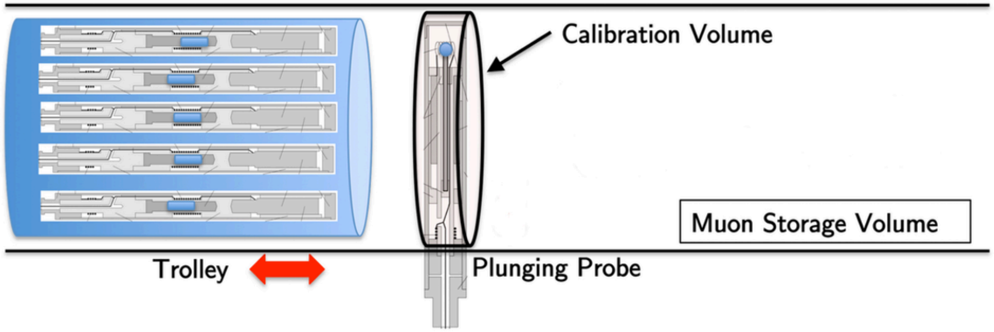
DAQ System Characteristics

- Bandwidth: 61.79 MHz +/- 50 kHz (833 ppm)
- Amplitude: ~ 1 V at t ~ 0
- RMS Noise: ~ 1 mV
- S/N: ~ 1000 at t ~ 0
- Resolution and accuracy: < ~1 ppb

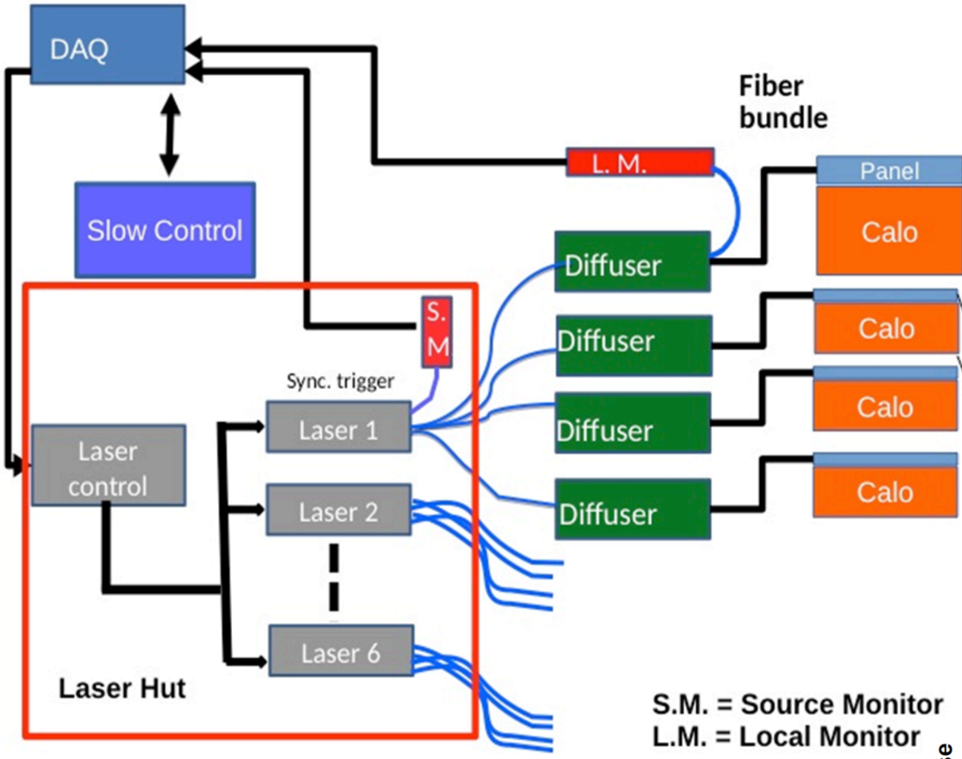


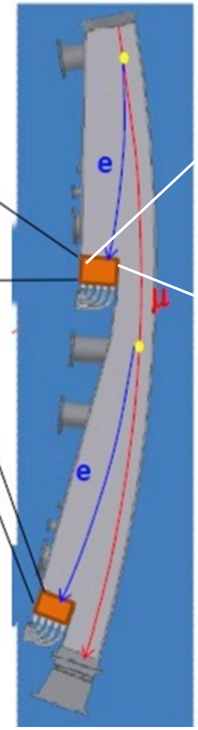
Calibration Procedure (during the experiment):

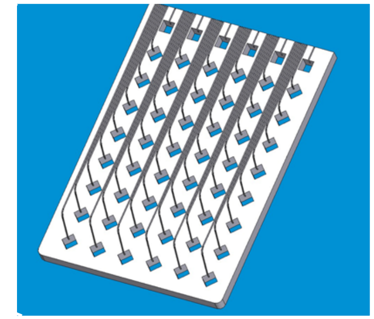
- Move NMR trolley to desired location, take measurements
- Pull NMR trolley far away
- Move plunging probe into position, take measurements (at each trolley probe location)

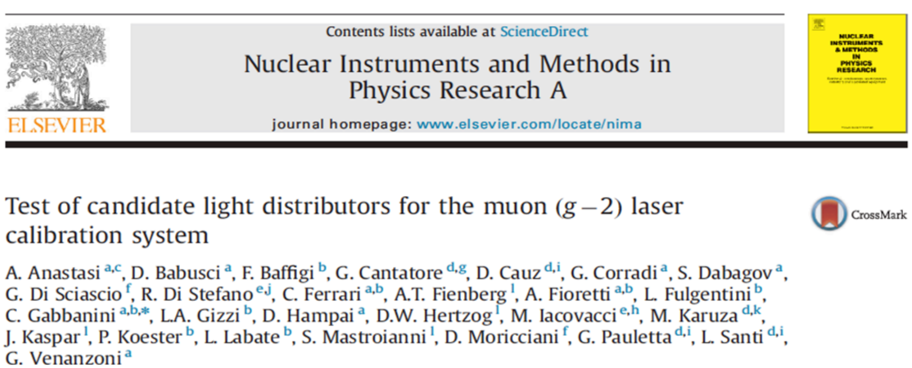


State-of-the-art Laser-based calibration system









Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Test of candidate light distributors for the muon $(g-2)$ laser calibration system

CrossMark

A. Anastasi[a,c], D. Babusci[a], F. Baffigi[b], G. Cantatore[d,g], D. Cauz[d,i], G. Corradi[a], S. Dabagov[a], G. Di Sciascio[f], R. Di Stefano[e,j], C. Ferrari[a,b], A.T. Fienberg[l], A. Fioretti[a,b], L. Fulgentini[b], C. Gabbanini[a,b,*], L.A. Gizzi[b], D. Hampai[a], D.W. Hertzog[l], M. Iacovacci[e,h], M. Karuza[d,k], J. Kaspar[l], P. Koester[b], L. Labate[b], S. Mastroianni[l], D. Moricciani[f], G. Pauletta[d,i], L. Santi[d,i], G. Venanzoni[a]