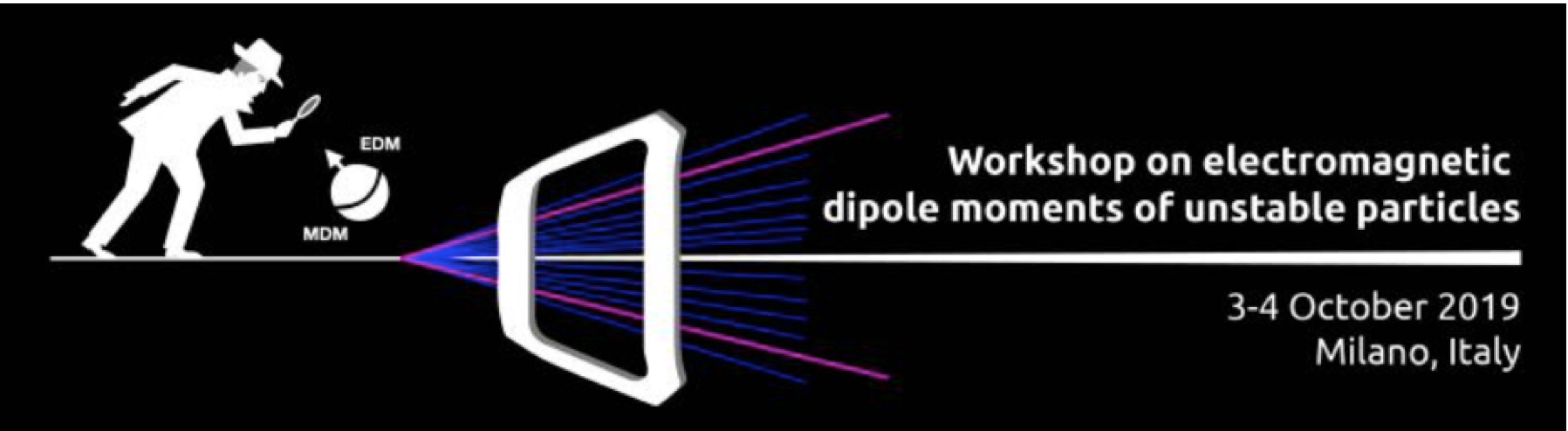
Review on g-2 measurements

Graziano Venanzoni– INFN Pisa



Outline

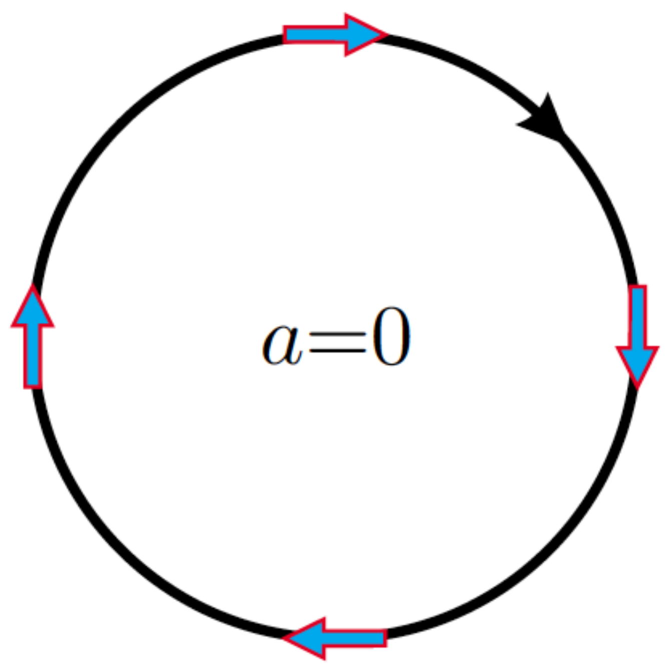
- Reminder on the measurement of electron g-2
- Status of the Muon g-2 experiment at Fermilab
- Status of the Muon g-2 experiment at JPARC
- Conclusions

How to measure the muon anomaly?

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g=2 (a=0) spin remains locked to momentum



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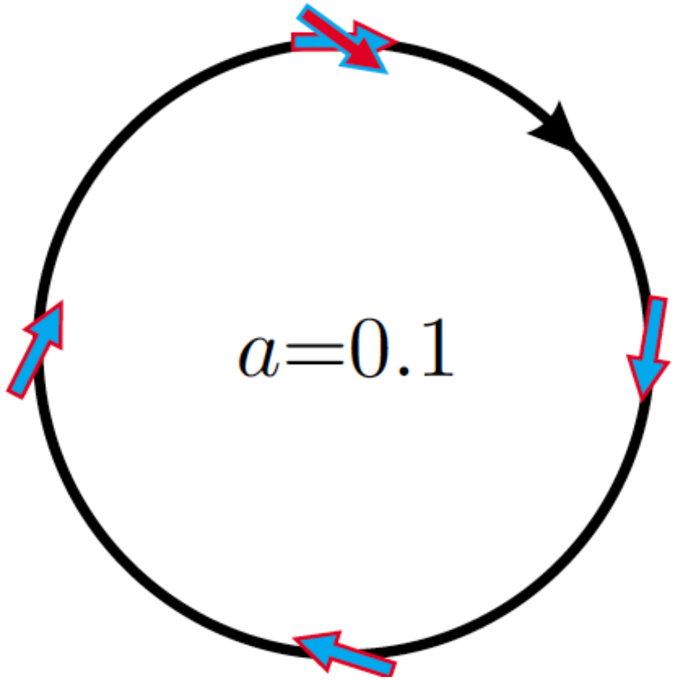
- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin advances respect to the momentum



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$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin go ahead to the momentum

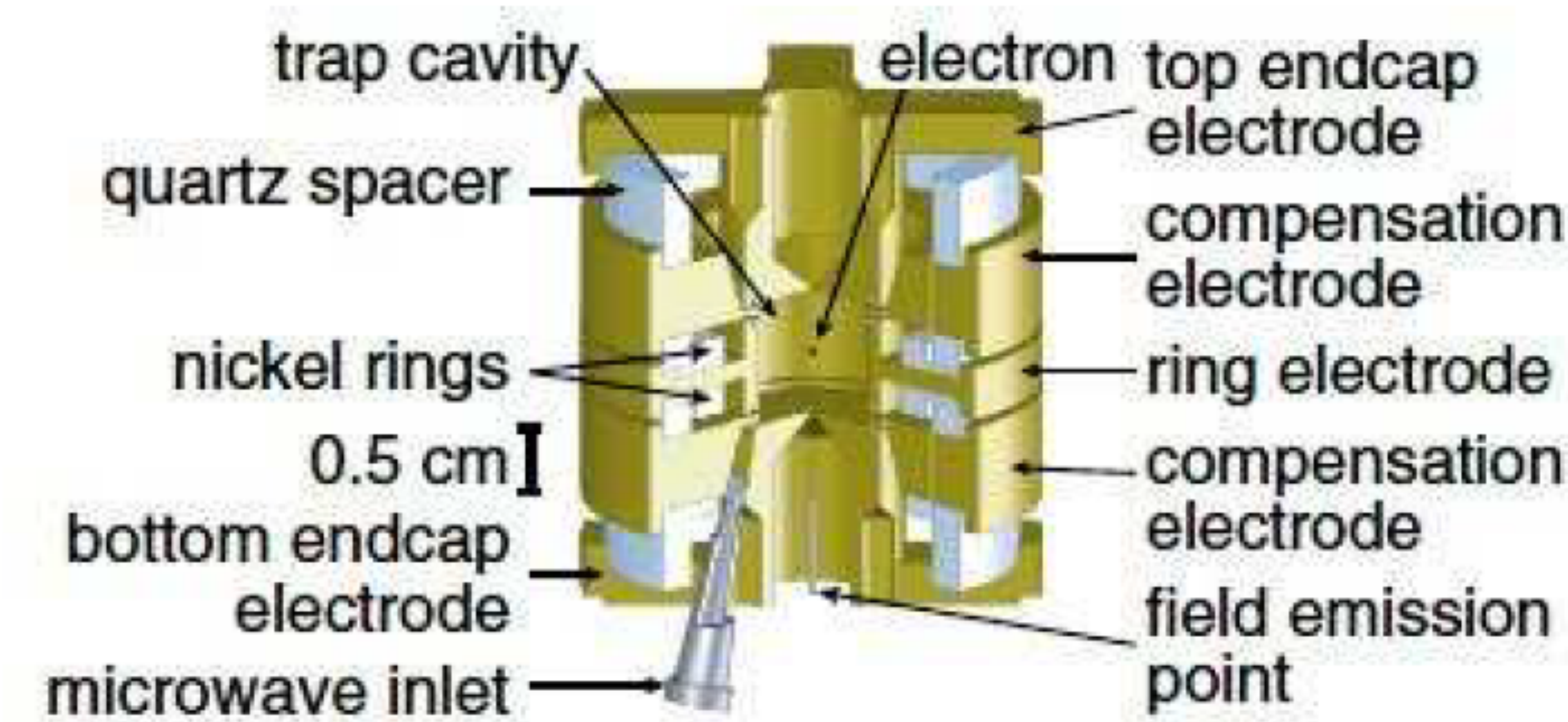
- One measures the anomalous precession frequency $\boldsymbol{\omega_a}$ and the magnetic field **B** obtaining ***a***:

$$a = \frac{(g-2)}{2} = \frac{m\omega_a}{eB}$$

For non-relativistic electrons ω_c=eB/m → $a_e = \omega_a/\omega_c$ (see next slides)

Measurement of a_e

- The e- is confined in a region using magnetic and electric field [Penning trap]. It has been obtained by Gabrielse et al. (2008):



Gabrielse

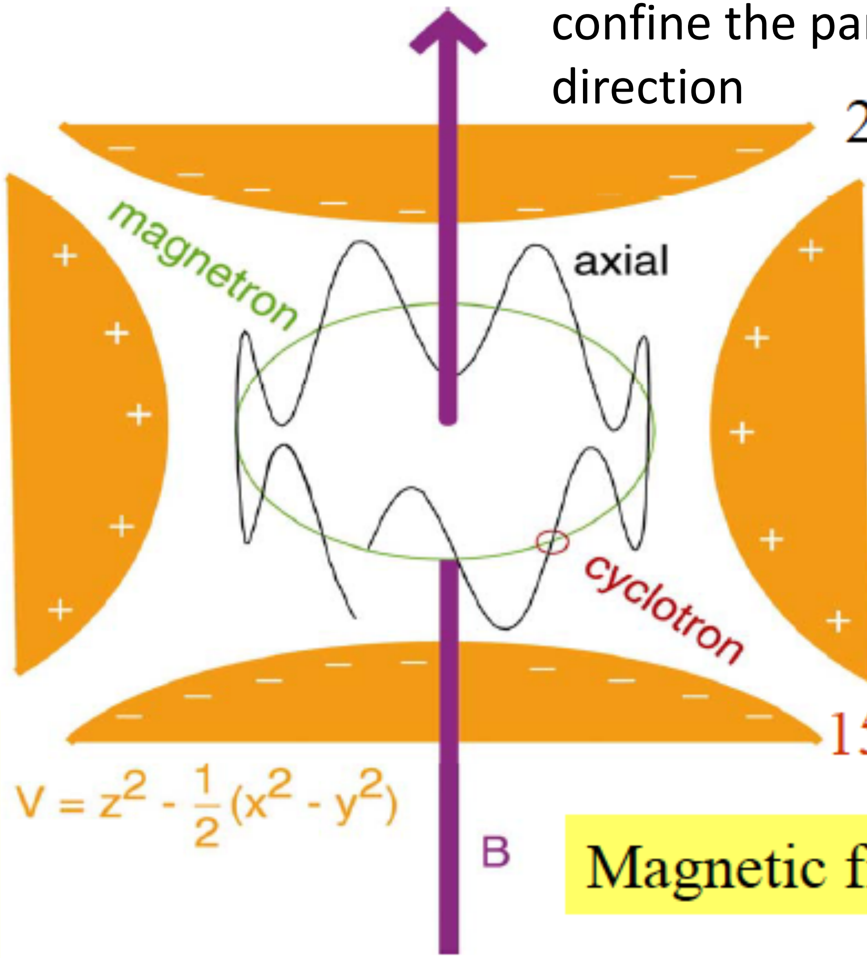
An Electron in a Penning Trap

- very small accelerator
- designer atom

homogeneous axial magnetic field to confine the particles radially and a quadrupole electric field to confine the particles in the axial direction

cool 12 kHz

200 MHz detect



153 GHz

need to measure for g/2

Electrostatic quadrupole potential

Magnetic field

Motion inside a Penning trap

ν_c=164 GHz
ν_z= 62 MHz
ν_m= 12 kHz

r_0= 5mm
B= 6T
U_0= 10V

z~few μm
r_c~10 μm

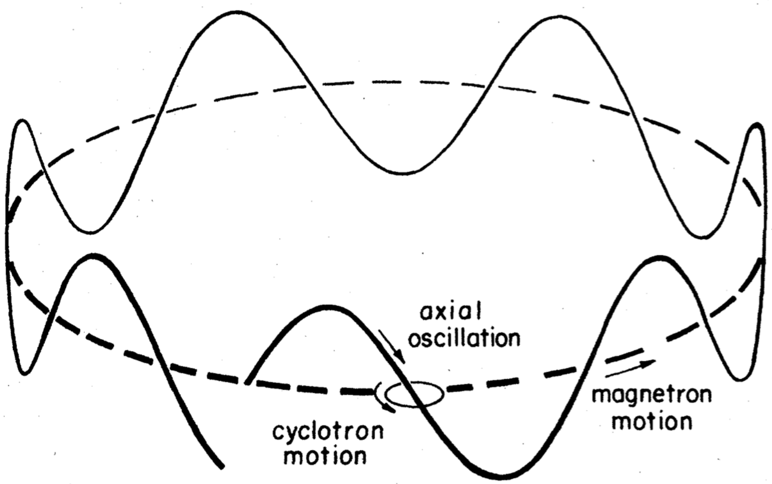


FIG. 3. Orbit of a charged particle in a Penning trap. The dashed line is the large and slow magnetron circle component of the motion. This, added to the axial oscillation, produces the guiding-center motion shown by the solid line. The total motion is given by adding the fast but small cyclotron circular motion about this moving guiding center. (Adapted from Ekstrom and Wineland, 1980.)

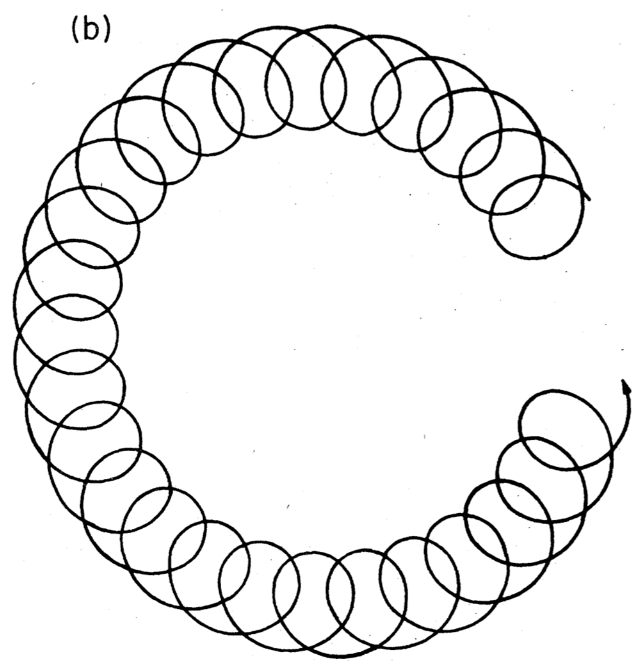


FIG. 7. Projection of the motion of a particle in a Penning trap upon the *xy* plane. The motion is the superposition of (a) circular magnetron and cyclotron motions producing (b) epicycles. The orbits are not to scale.

$$a = (g-2)/2 \approx \omega_a / \omega_c$$

How to measure ω_a?

Quantum structure of the e- levels in the penning trap ("geonium")

$$E_n = \hbar[m\omega_s + (n+\frac{1}{2})\omega_c' + (k+\frac{1}{2})\omega_z - (q+\frac{1}{2})\omega_m]$$

- The energy difference between the level with (n = 0, Sz = + 1/2) and with (n = 1, Sz = -1 / 2) is:

$$\Delta E_n = \hbar[\omega_c' - \omega_s] = \hbar\omega_a$$

- The frequency at which there is a spin-flip and an increase in a unit of n is excited (by Rabi resonant method) and measured.

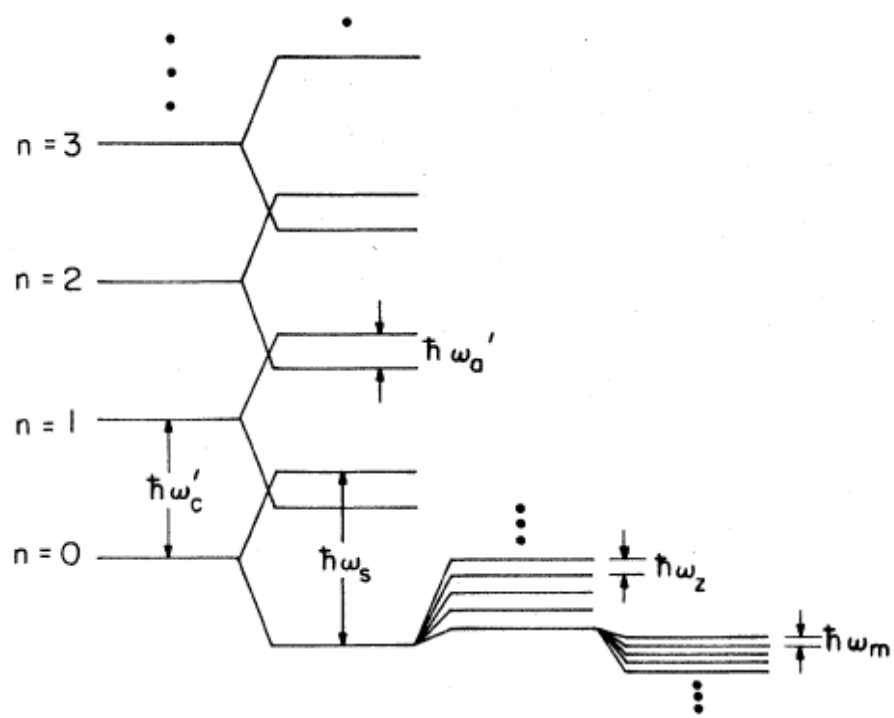


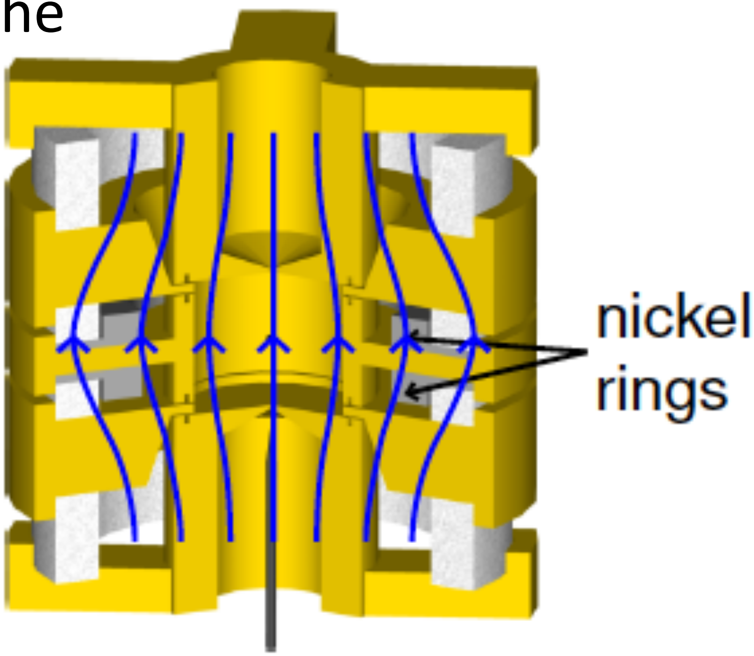
FIG. 8. Splitting of geonium energy levels for an electron (not to scale). The ladder on the far left represents the basic cyclotron energy levels. Progressing to the right, these levels are split first by the spin ($=\frac{1}{2}$), then by the axial binding, and finally by the magnetron motion. The magnetron levels are inverted, since the motion is unbound.

How to measure ω_c?

- ω_c ~ 100 GHz too high to be detected directly
- ω_z = 60 MHz relatively easy to detect
- → Indirect measurement: the axial frequency ω_z is coupled to $\omega_{c.}$ Shift in ω_z indicates a change in ω_c
- Magnetic field of the type $B = B0 + B_2 z^2$

→The axial frequency will depend on the value of the magnetic moment

Microwave radiation is sent in the trap and the shift in ω_z is measured. When the frequency reaches ω_c there is a sharp increase in the shift of ω_z. In this way ω_c is measured with an uncertainty of 500 Hz (3ppb)



$$B_z = B_0 + B_2 z^2$$

Results and Theory

PRL 100, 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

D. Hanneke, S. Fogwell, and G. Gabrielse*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 4 January 2008; published 26 March 2008)

$$a_e(\exp) = 1\,159\,652\,180.73\,(0.28) \times 10^{-12} \quad [0.24\ ppb]$$

PRL 109, 111807 (2012) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2012

Tenth-Order QED Contribution to the Electron $g-2$ and an Improved Value of the Fine Structure Constant

Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]
[1]*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*
[2]*Nishina Center, RIKEN, Wako, Japan 351-0198*
[3]*Department of Physics, Nagoya University, Nagoya, Japan 464-8602*
[4]*Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York, 14853, USA*
(Received 24 May 2012; published 13 September 2012)

$$a_e^{theory} = 1\,159\,652\,181.78\,(77) \times 10^{-12}$$

$$\Delta a_e = (1.05 \pm 0.82) \times 10^{-12}$$

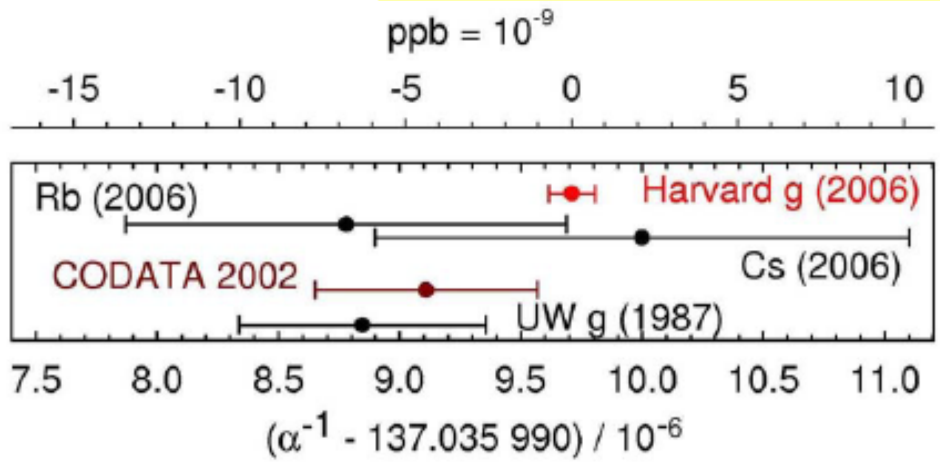
Gabrielse

New Determination of the Fine Structure Constant

$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

- Strength of the electromagnetic interaction
- Important component of our system of fundamental constants
- Increased importance for new mass standard

$$\alpha^{-1} = 137.035\,999\,710$$
$$\pm \quad 0.000\,000\,096 \qquad 7.0\times10^{-10}$$



- First lower uncertainty since 1987
- Ten times more accurate than atom-recoil methods

G. Gabrielse, D. Hanneke, T. Kinoshita, M. Nio, B. Odom, Phys. Rev. Lett. (in press)

Alpha in atom recoil frequency

$$\alpha = \left[2 \frac{R_\infty}{c} \frac{u}{m_e} \frac{M}{u} \frac{h}{M} \right]^{1/2}$$

Rydberg Constant

0.007 ppb P. J. Mohr, *et. al.*, Rev. Mod. Phys. 88, 035009 (2016)

Electron mass in amu

0.03 ppb S. Sturm *et al.*, Nature **506**, 467–470 (2014).

Cs mass in amu

0.06ppb P. J. Mohr, D. B. Newell, B. N. Taylor, Rev. Mod. Phys. 88, 035009 (2016)

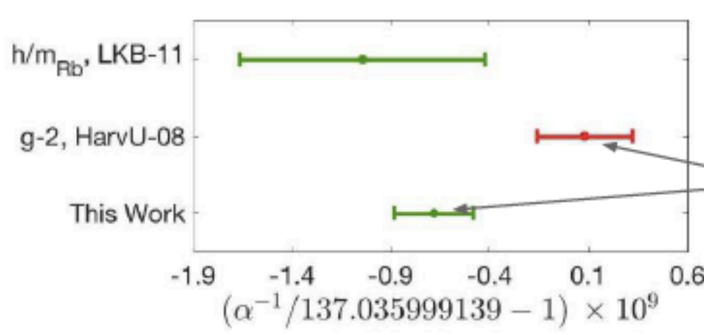
Determined by atom recoil frequency

$$\frac{h}{M} = \frac{4\pi c^2 \omega_r}{\omega^2}$$

$$\alpha^{-1} = 137.035999046(27)$$

σ_{stat}=0.16ppb; σ_{syst}=0.12ppb

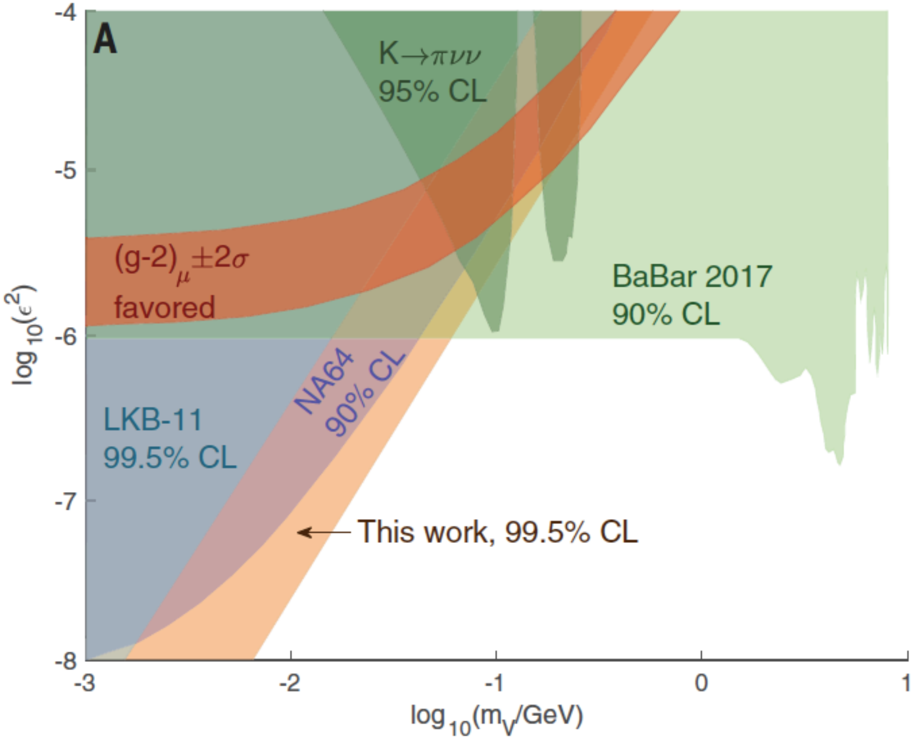
(x3 improvement respect to previous α)



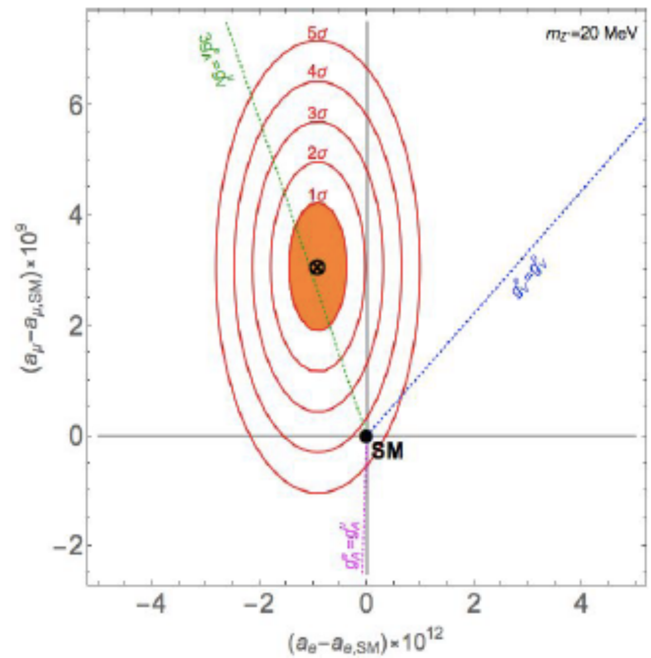
2.5σ tension

Constrains of $(g\text{-}2)_e$ on new physics

Muon g-2



Combine with $g_\mu - 2$



A Tale of Two Anomalies

arXiv:1806.10252

Hooman Davoudiasl *[1] and William J. Marciano †[1]
[1] *Department of Physics, Brookhaven National Laboratory, Upton, NY 11973, USA*

Muon g-2: summary of the present status

- E821 experiment at BNL has generated enormous interest:

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

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

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

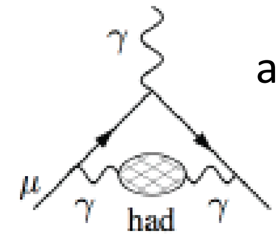
M. Davier, A. Hoecker, B. Malaescu and Z. Zhang, Eur. Phys. J. C71 (2011)

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

- 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)



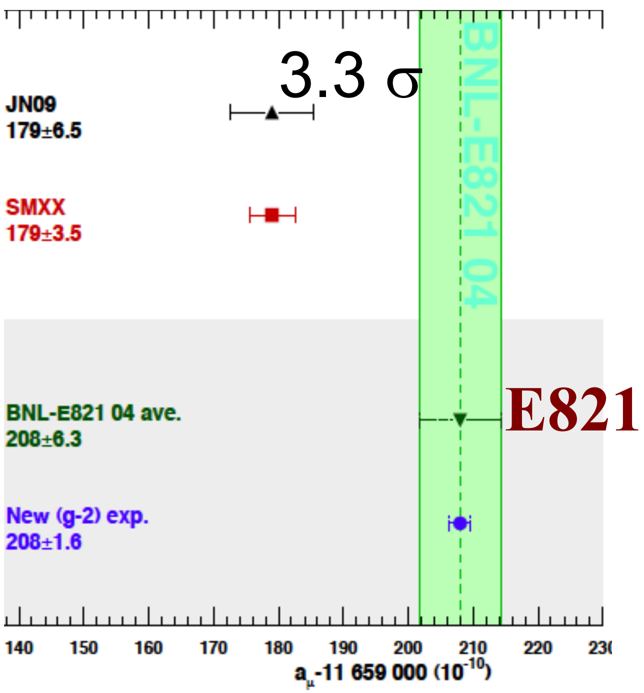
$a_\mu^{HLO} = (692.3 \pm 4.2)10^{-10}$

$\delta a_\mu / a_\mu \sim 0.5\%$

$(g-2)_\mu$: a new experiment at FNAL (E989)

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

$\rightarrow \delta a_\mu$x4 improvement (0.14ppm)



$(g\text{-}2)_\mu$: a new experiment at FNAL (E989)

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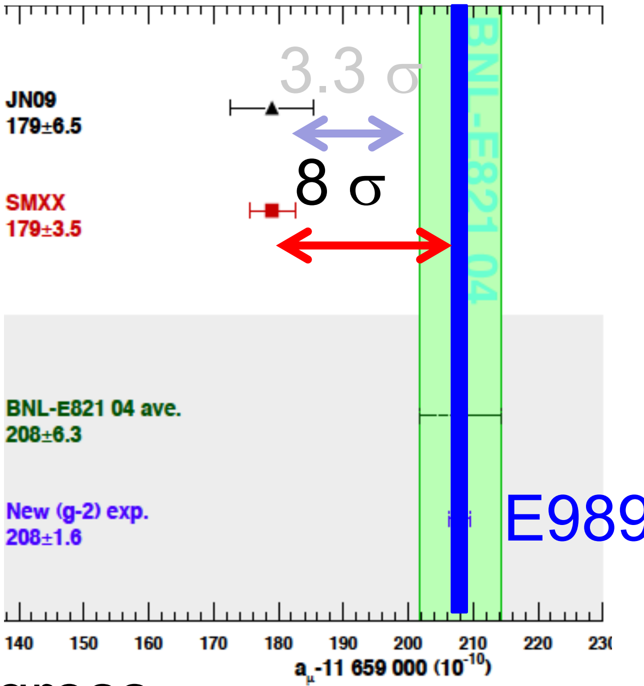
If the central value remains the same $\Rightarrow$ 5-8σ from SM* (enough to claim discovery of New Physics!)



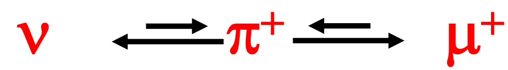
***Depending on the progress on Theory**

→ g-2 Theory Initiative !

Complementary proposal at J-PARC in progress

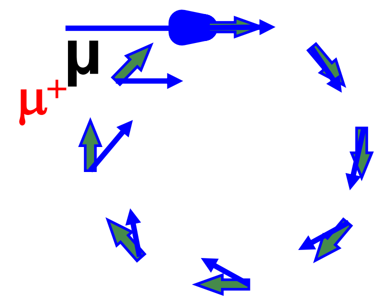
How to measure g-2 in a storage ring

(1) Polarized muons



~97% polarized for forward decays

(2) Precession proportional to (g-2)



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

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

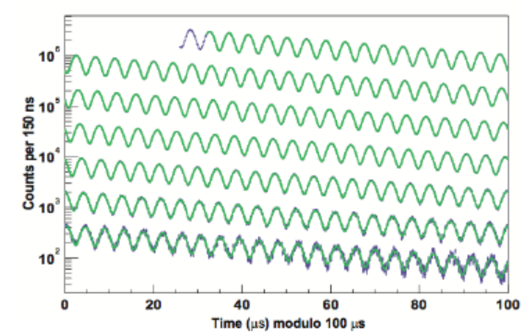
(3) P_μ magic momentum = 3.094 GeV/c

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

E field doesn't affect muon spin when $\gamma = 29.3$

(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

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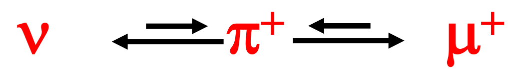

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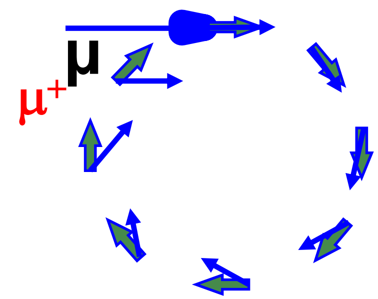
(2) Precession proportional to (g-2)

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

Measure 2 quantities

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



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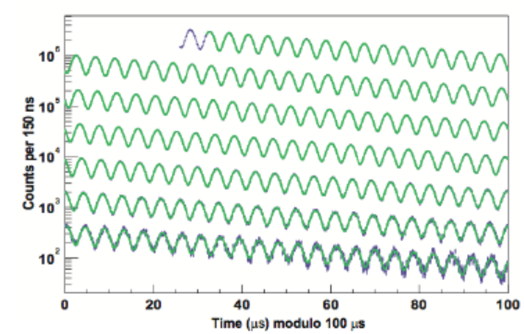


Effect of Beam Dynamics

- The *full equation* is more complex and corrections due to radial (x_e) and vertical (y) beam amplitude and shape are needed

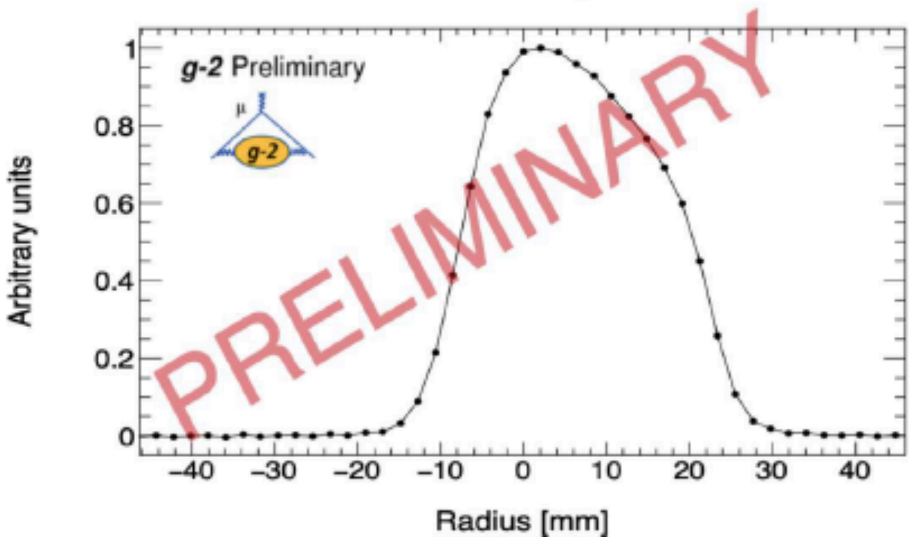
$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}\right]$$

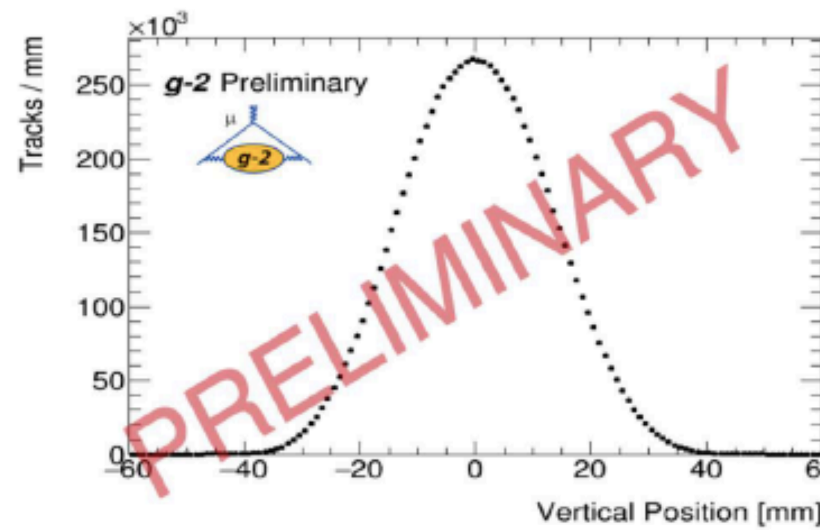
- Running at γ_{magic}=29.3 (p_μ=3.094 GeV/c) this coefficient is null
- Because of beam spread → E-field Correction

- Vertical beam oscillations, field felt by the muons is reduced → Pitch Correction

$$C_E = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

$$C_P = \frac{\Delta\omega_a}{\omega_a} = -\frac{n}{2R_0^2}\langle y^2\rangle$$





Extracting a_μ

FNAL Projected Errors:
140 ppb (total) =
100 (stat)⊕ 100 (syst)

2017 CODATA

-0.001 519 270 380(5) [3 ppb] Hydrogen Maser

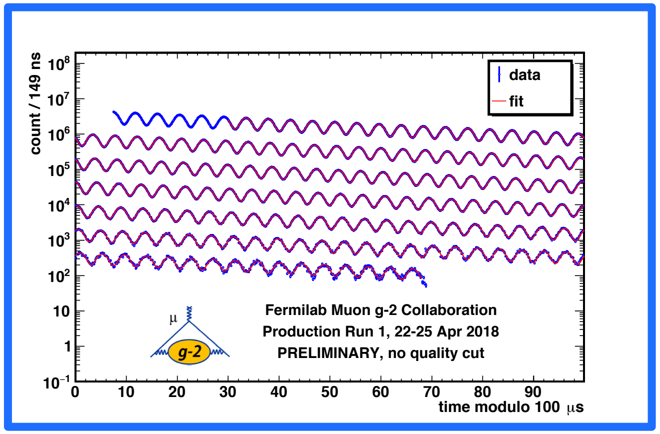
206.768 2826(46) [22 ppb] Muonium Hyperfine

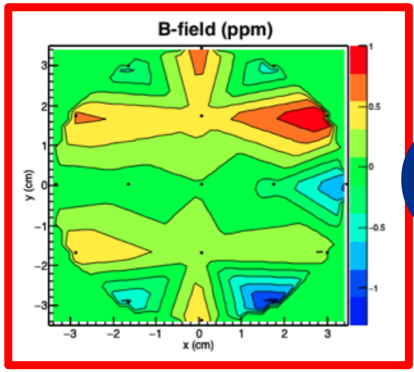
-2.002 319 304 361 82(52) [0.26 ppt] Electron g-2/QED

$$a_\mu = \frac{\omega_a}{\tilde{\omega}_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$$\Downarrow$$

$$\frac{\omega_a}{\omega_p \otimes \rho(r)} \Rightarrow$$





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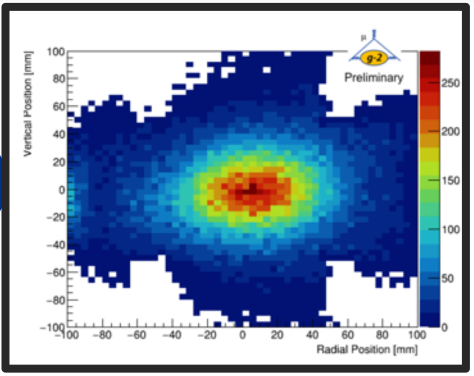
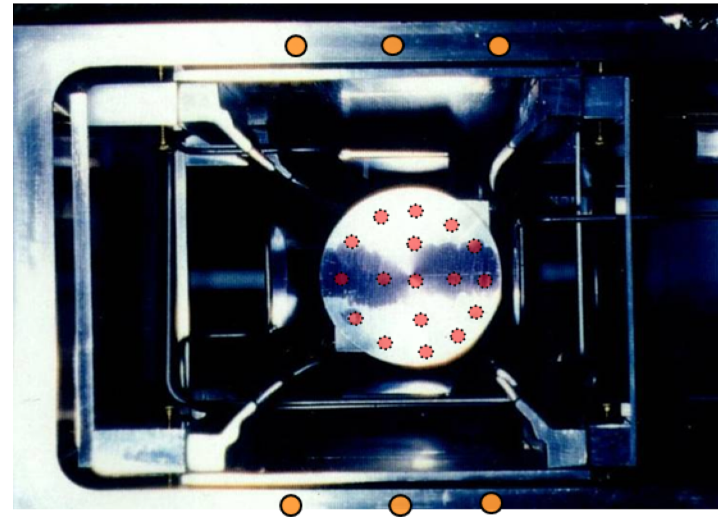
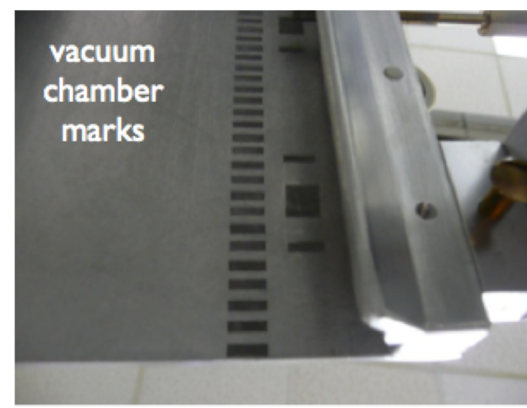
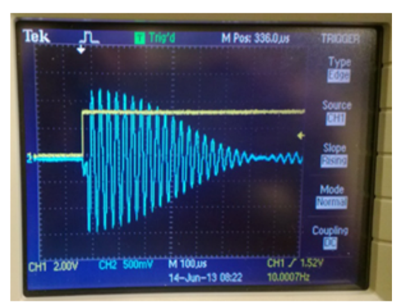


Monitoring the magnetic field

- 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 2-3 days 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







4 key elements for E989 at FNAL

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

- **E821 at Brookhaven**

$$\left.\begin{array}{l}\sigma_{\rm stat} = \pm 0.46 \text{ ppm} \\ \sigma_{\rm syst} = \pm 0.28 \text{ ppm}\end{array}\right\} \sigma = \pm 0.54 \text{ ppm}$$

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

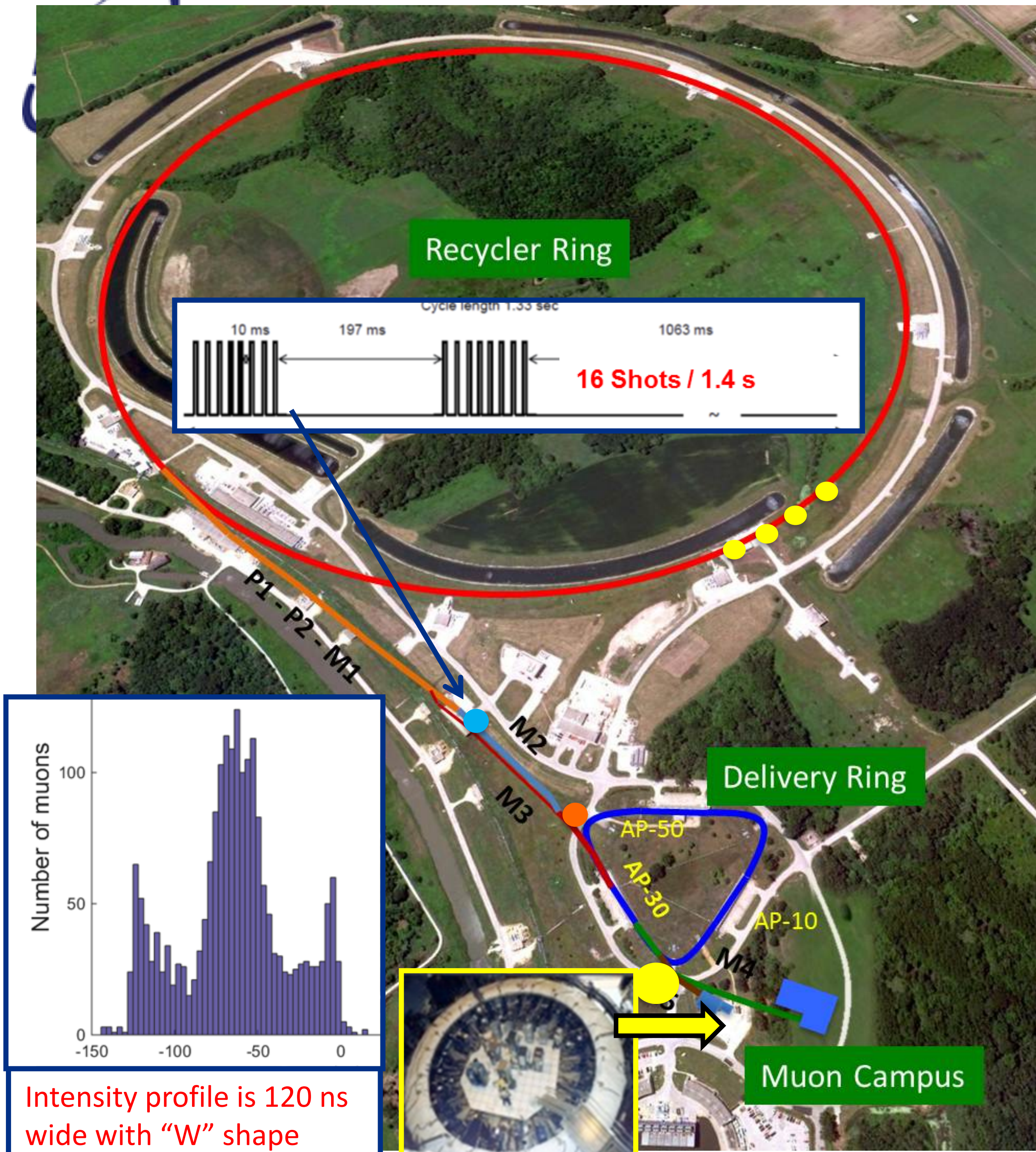
- **E989 at Fermilab**

$$\left.\begin{array}{l}\sigma_{\rm stat} = \pm 0.1 \text{ ppm} \\ \sigma_{\rm syst} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

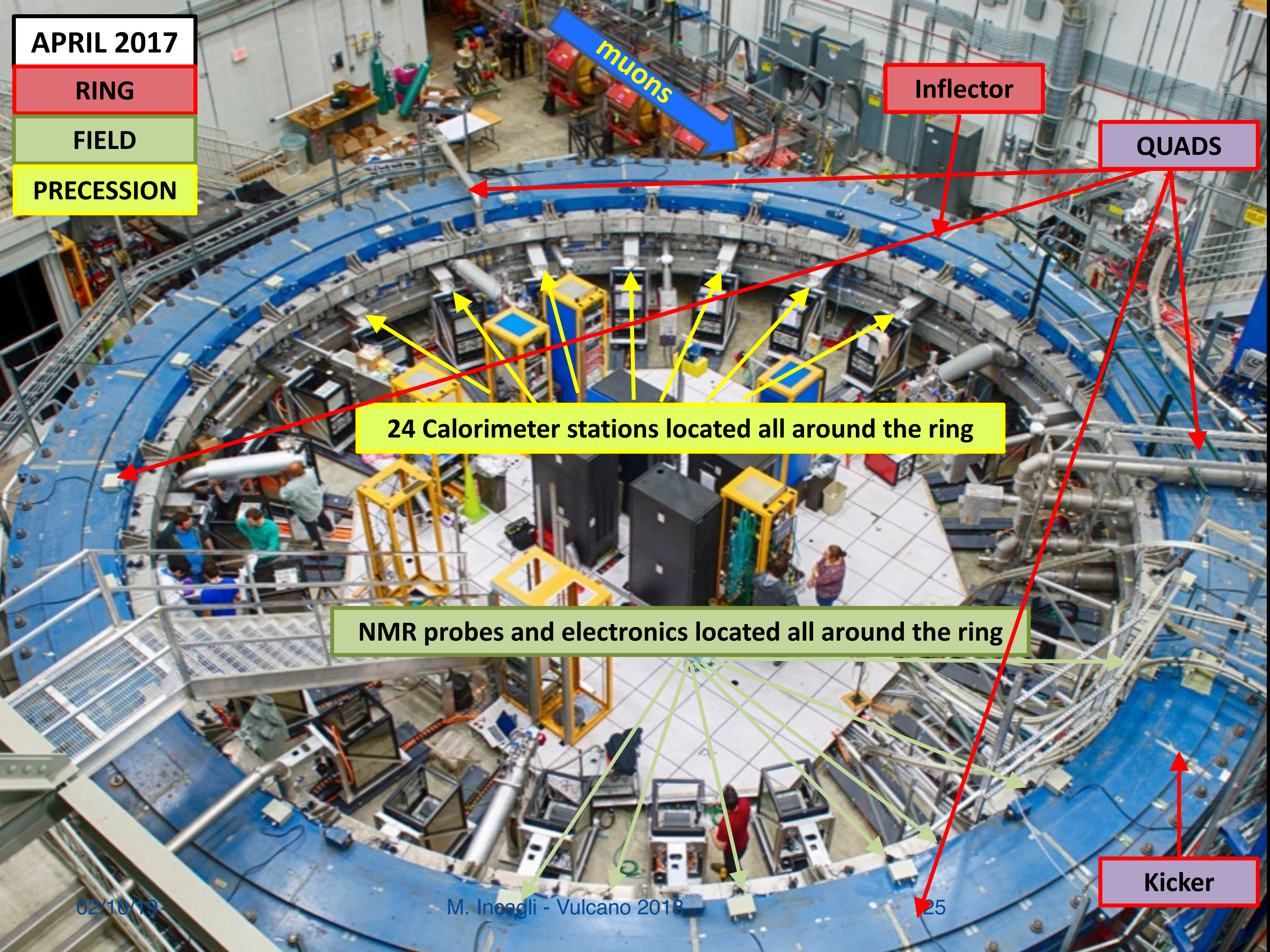
$\hookrightarrow$ $0.07\omega_a \oplus 0.07\omega_p$

Creating the Muon Beam for g-2

- 4×10^{12} 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



Intensity profile is 120 ns wide with "W" shape

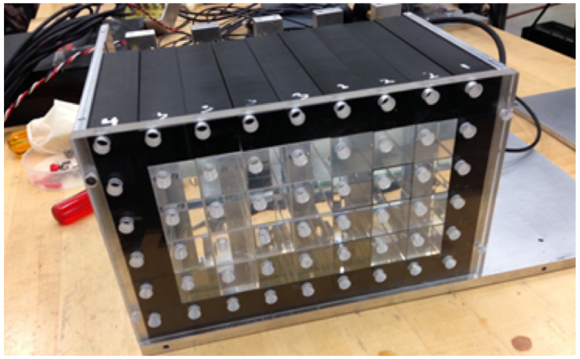

APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

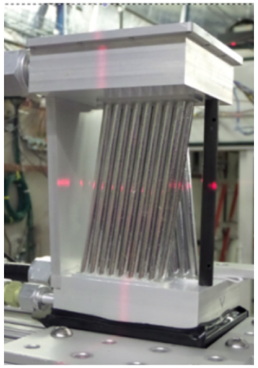
ω_a systematics

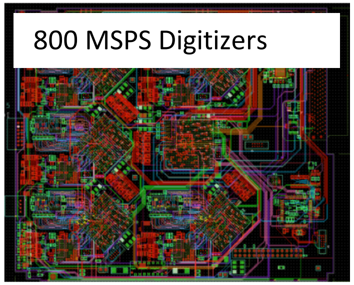
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to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

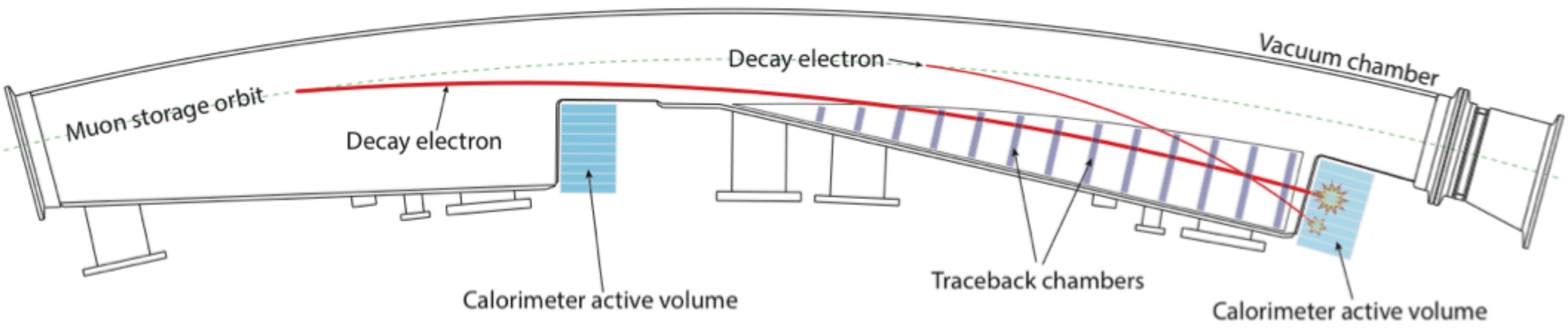






- Calorimeters 24 6x9 PbF_2 crystal arrays with SiPM readout, segmentation to reduce pileup
- New electronics and DAQ, 800MHz WFDs and a greatly reduced threshold
- Two 1500 channel straw trackers to precisely monitor properties of stored muon beam via tracking of Michel decay positrons, significant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

Top view of 1 of 12 vacuum chambers



ω_p systematics

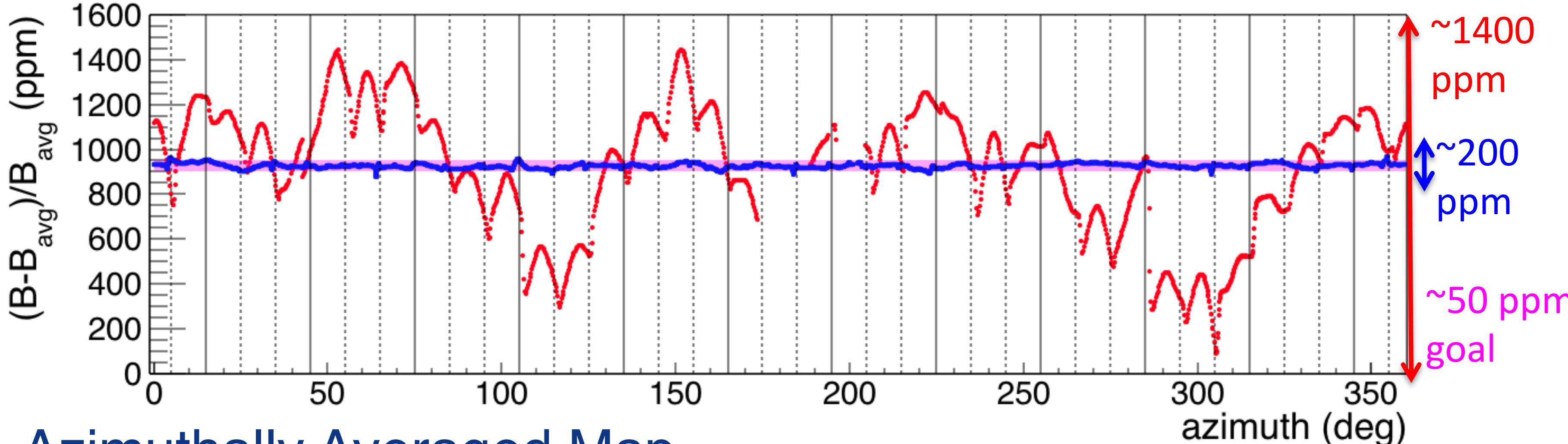
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position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

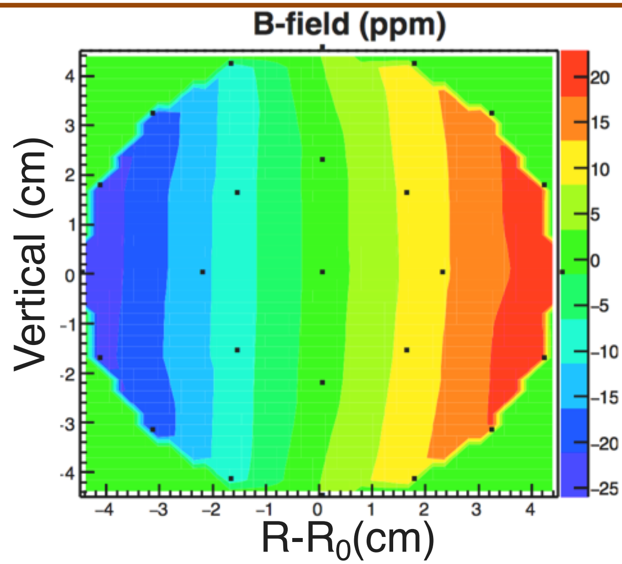
Progress on Field

Oct 2015 → Aug 2016

Goal

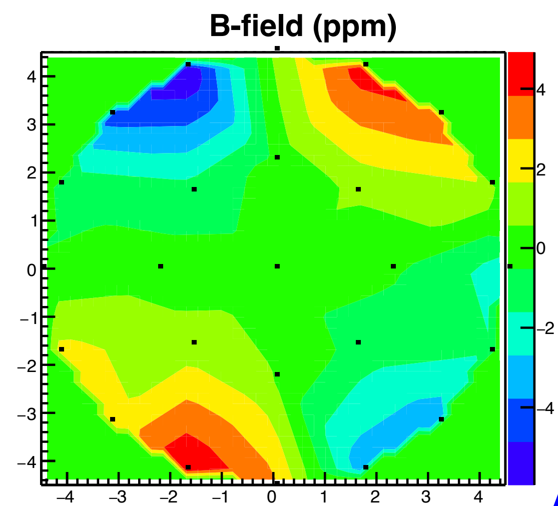


Azimuthally Averaged Map



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

Oct 2015

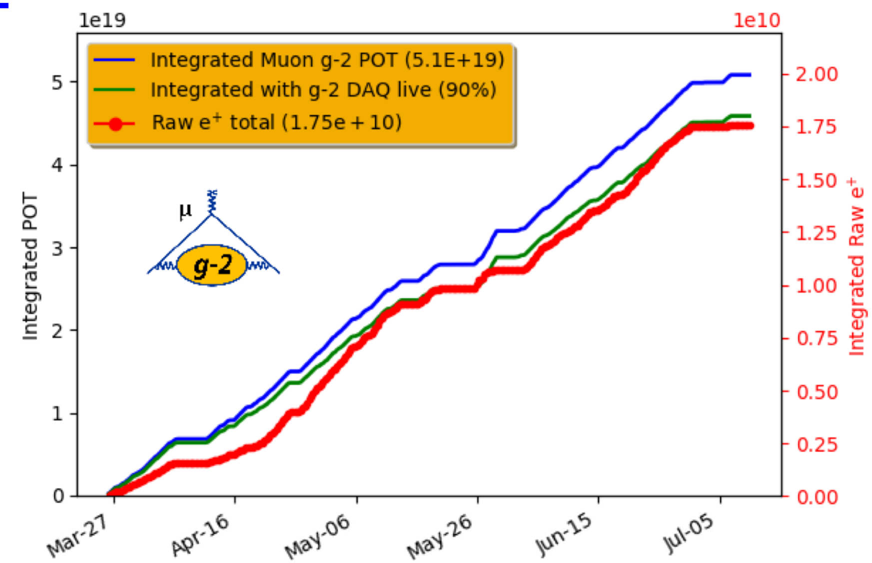


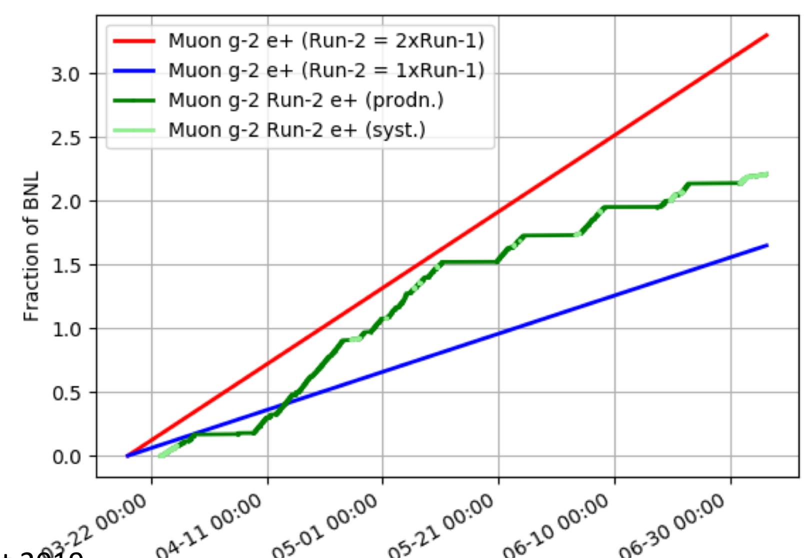
	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

Data accumulated so far

- Run 1 (FY18): Accumulated 1.9 × BNL in raw statistics
  - 1.4 × BNL after DQ cuts and removing systematic runs → 410 ppb stat
  - Anticipate 150-250 ppb systematic error...analysis well underway
  - Conditions not stable, fragmented data sets
- Run 2 (FY19): Accumulated 2.2 × BNL in raw statistics
  - 1.8 × BNL after DQ cuts and removing systematic runs → 350 ppb
  - Reduced systematics (TBD)
  - Ran very stably collecting 1 BNL for about every 25 days of runtime

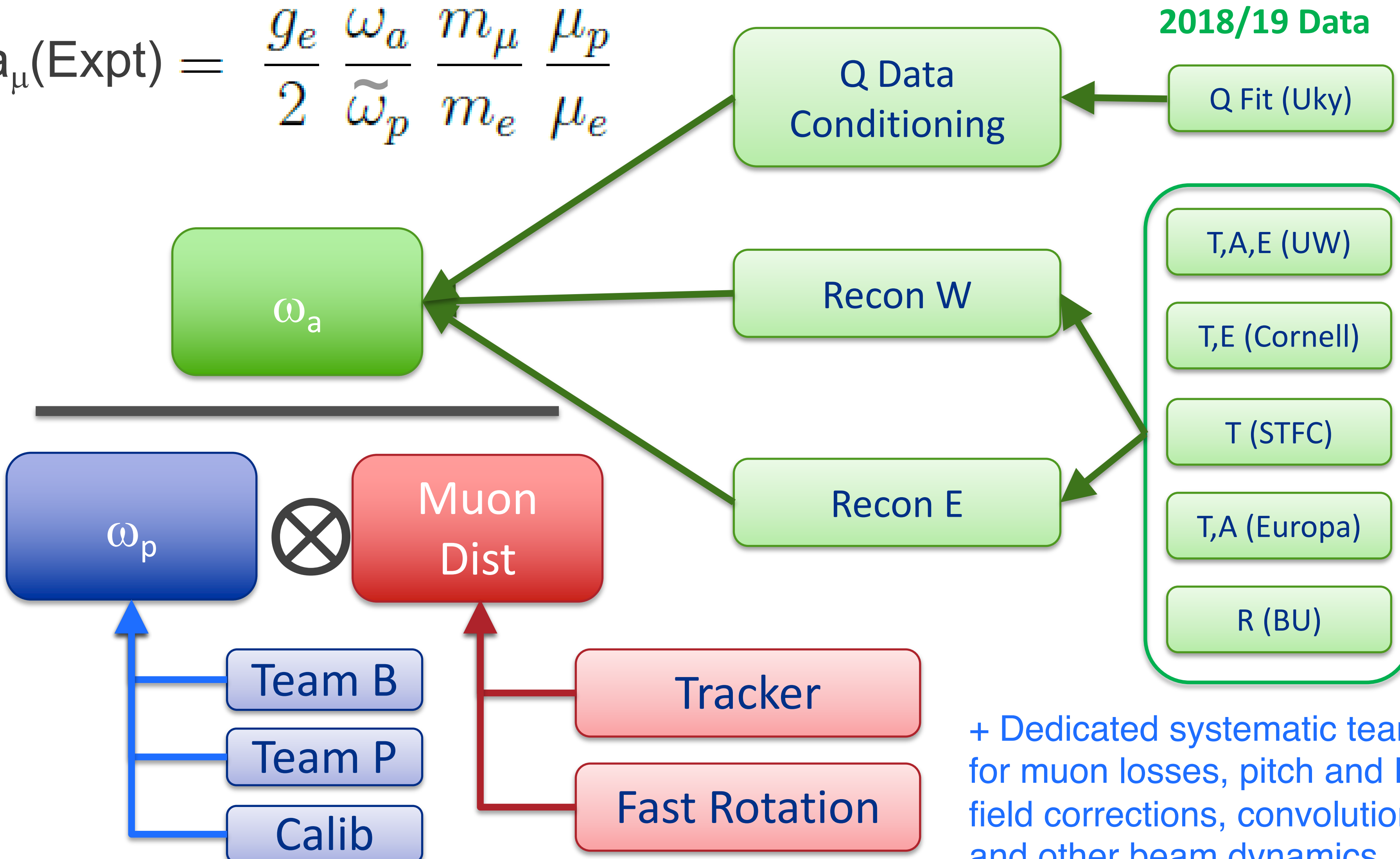




Analysis is in progress on Run1 data!

Overview of analysis structure

$$a_\mu(\mathrm{Expt}) = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$



+ Dedicated systematic teams for muon losses, pitch and E-field corrections, convolution, and other beam dynamics

ω_a Analysis (RUN1)

- In Run1, data have been taken in different Quad and Kicker conditions, while optimizing Storage Ring operations (Run2 data are much more uniform)
- Six datasets identified:

Name	Date acquired	Quad n	Kicker [kV]	Positrons
60 hour	22-25 / 4	0.108	128-132	1.0B
High Kick	26/4 - 2/5	0.120	136-138	1.2B
9 day	4-12 / 5	0.120	128-132	2.4B
Low Kick	17-19 / 5	0.120	123-127	1.2B
Superlow Kick	2-6 / 6	0.108	117-119	0.5B
End Game	6-29 / 6	0.108	122-127	4.0B

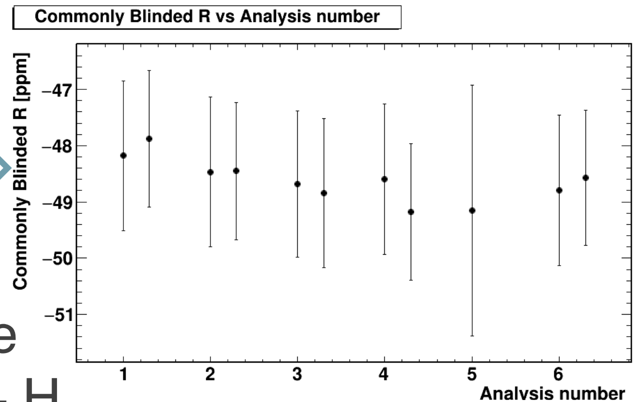
Relative unblinding

10% stat BNL

TOT=10B~1 stat BNL

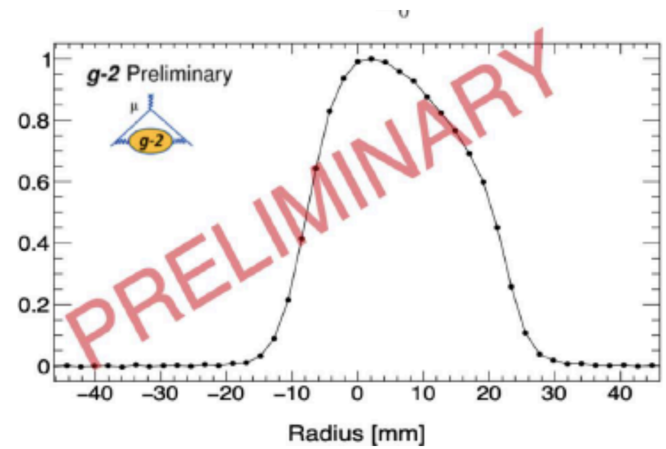
Examples of many positives intermediate results.

- **Relative *un*blinding of 60 H data** set confirmed
  6 precession analyses consistent
  - 3 Reconstruction methods
  - Pileup techniques
  - CBO function accounts for beam motions
  - Gain Corrections
  - Muon loss



6 different precession analyzers

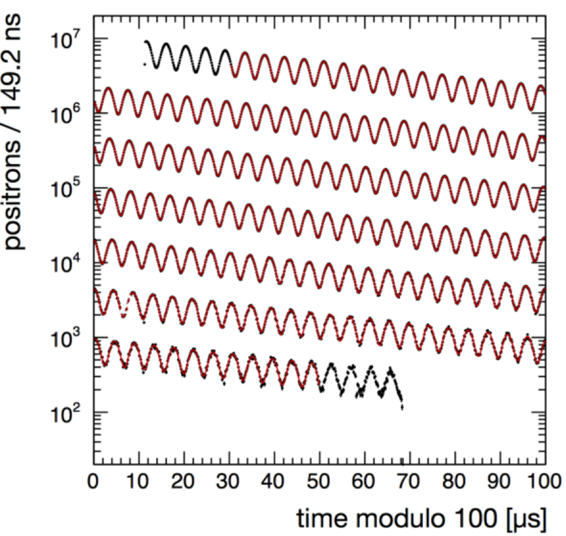
- **Absolute magnetic field calibration** accurate
- **Relative *un*blinding of Field Tracking** of 60+ H sample finds good agreement and led to better understanding of field tracking between Trolley runs
- **Muon momentum distribution** – while not ideally centered – is very well determined by several independent methods.
  - This leads to **accurate and precise E-field corrections**.
  - Significant systematic error checking on this correction has taken place so in very good shape



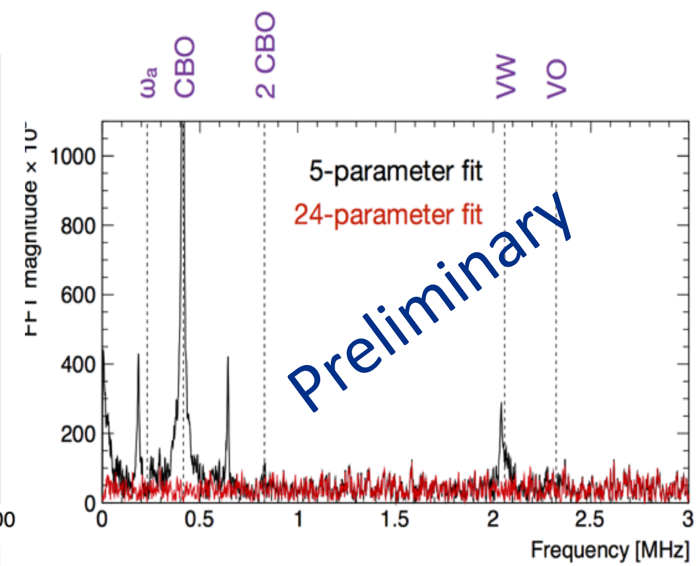
G. Venanzoni, Workshop on EDM of unstable particles, Milan, 3 Oct 2019

An example of just one of the Precession Analyses intermediate reports

$$N(t) = N_0 \cdot \Lambda(t) \cdot N_{1\mathrm{CBO}}(t) \cdot N_{2\mathrm{CBO}}(t) \cdot N_{VW}(t) \cdot N_{VO}(t)$$
$$\cdot\, e^{-t/\tau}\left[1 + A_0 \cdot A_{1\mathrm{CBO}}(t) \cdot \cos(\omega_a(R) \cdot t + \phi_0 + \phi_{1\mathrm{CBO}}(t))\right]$$



"Wiggle" Plot + Fit



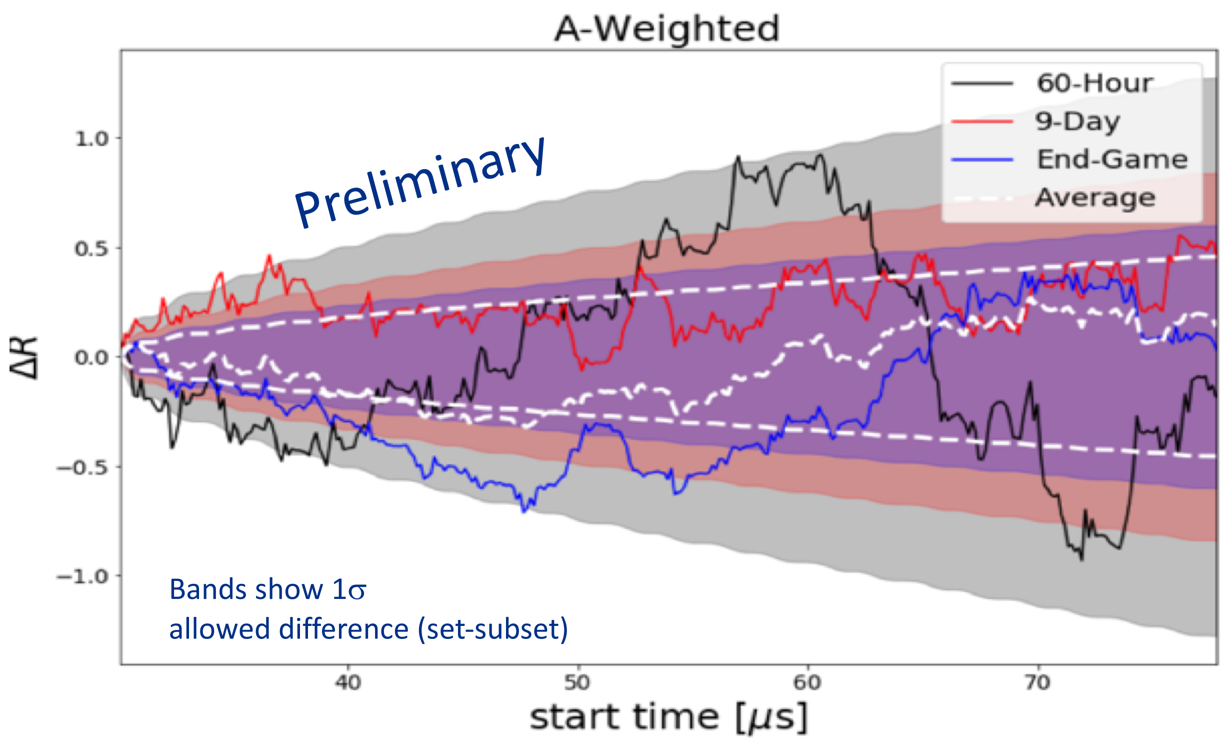
With correct function, the residuals are flat (as they must be) and the χ^2 is good and fit results are stable

non-negligible [≥ 0.1 ppb] systematic source	60 h. σ_R [ppb] T-method	9 d. σ_R [ppb] T-method
pileup amplitude	23.7	2.7
pileup time	1.3	2.8
unseen pileup	≤ 3.2	≤ 1.9
in-fill gain amplitude	9.3	8.9
in-fill gain lifetime	12.5	7.8
short-term double-pulse gain amplitude	~ 15.2	~ 2.5
short-term double-pulse gain lifetime	~ 7.6	~ 6.6
muon-loss statistics	1.1	0.7
muon-loss deuteron correction	≤ 1.1	≤ 0.4
CBO frequency model	4.7	11.0
CBO time shift	0.9	5.5
CBO decoherence-envelope model	32.3	2.1
CBO lifetimes	6.3	12.9
vertical-oscillation lifetime	1.5	2.7
fiber length	≤ 28.0	≤ 1.6
time randomization	12.3	7.6
quadrature sum =	56.1	24.4

Preliminary

An insane amount of checking of any biases is taking place.. This is just showing; net ~25-35x lower than statistical here! (but not all listed)

And, one example of a typical consistency test
The result (in blinded ppm) vs time of fit start for 3 data sets



T-Method
60-Hour: 1.33 ppm
9-Day: 0.88 ppm
EndGame: 0.63 ppm
HighKick: 1.33 ppm

Combined: **0.450 ppm**

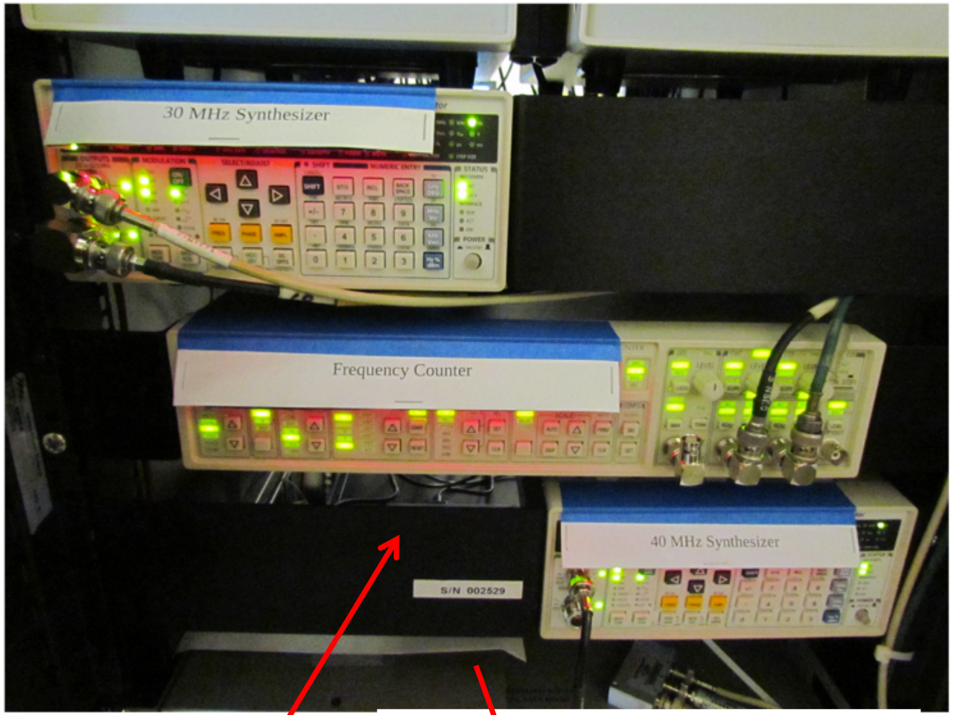
A-Weighted
60-Hour: 1.22 ppm
9-Day: 0.80 ppm
EndGame: 0.57 ppm
HighKick: 1.22 ppm

Combined: **0.410 ppm**

410 ppb is probably the best we can achieve out of the Run-1 Statistical data set (does not include systematics)

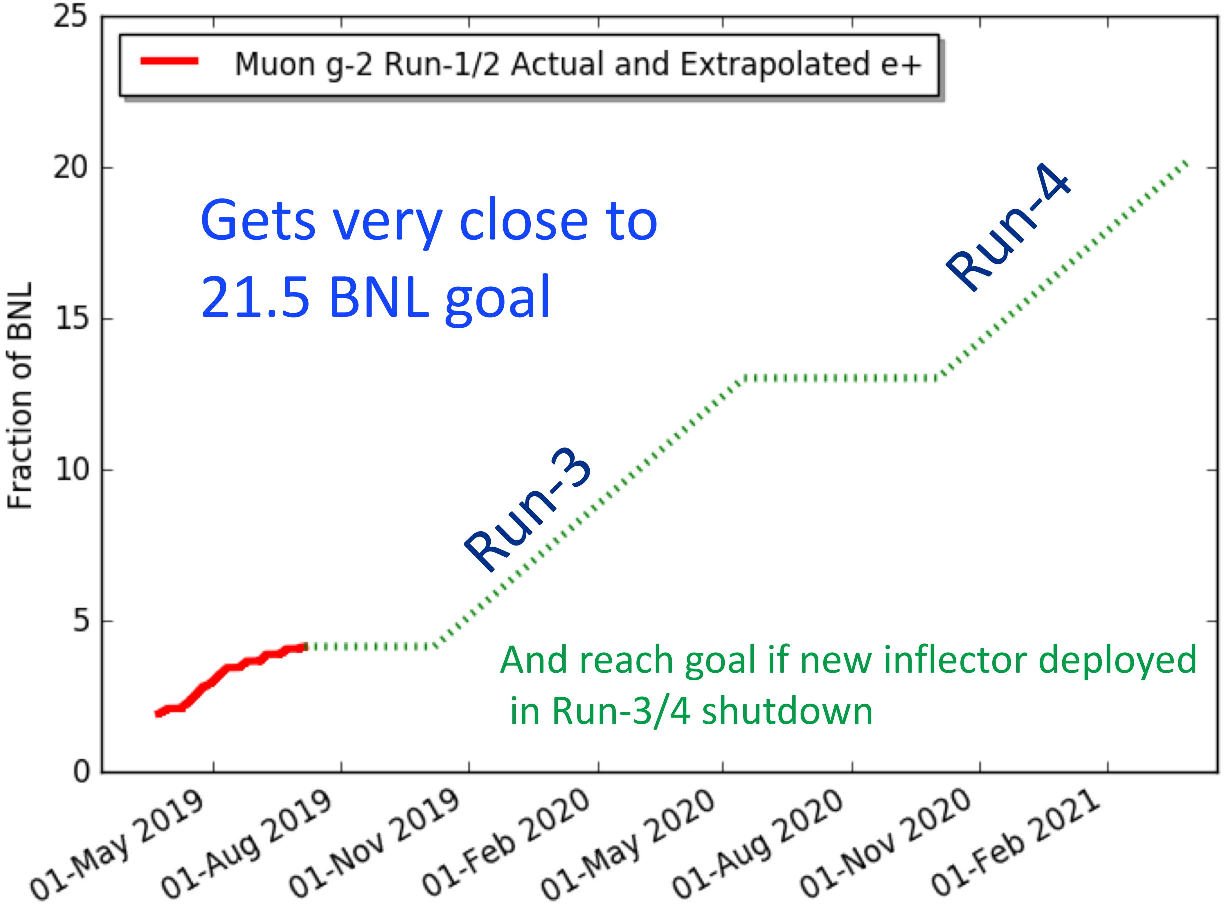
Hardware blinding

- Greg and Joe enthusiastically blinding the clock



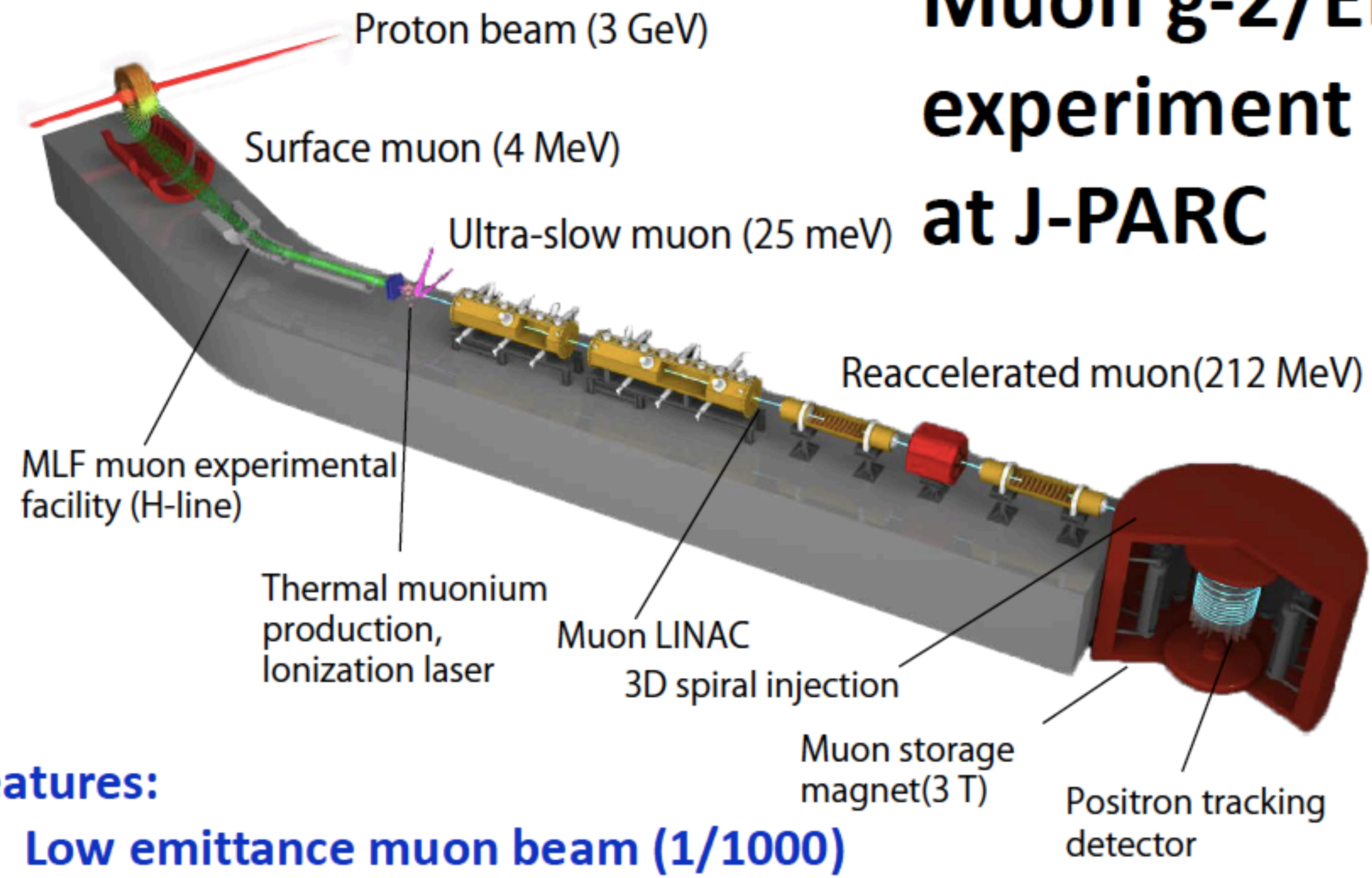
Locked Clock Panel

Future



- Beamtime assumptions
  - Run 3 (FY20) starts Oct 7 and ends May 15
  - Run 4 (FY21) 6 mos g-2, 3 mos Mu2e commissioning
- Running beyond FY21 contingent on how Mu2e schedule evolves and initial g-2 results

Muon g-2/EDM experiment at J-PARC



Features:

- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

What makes them different?

- Eliminate electric focusing removes $\beta \times E$ term

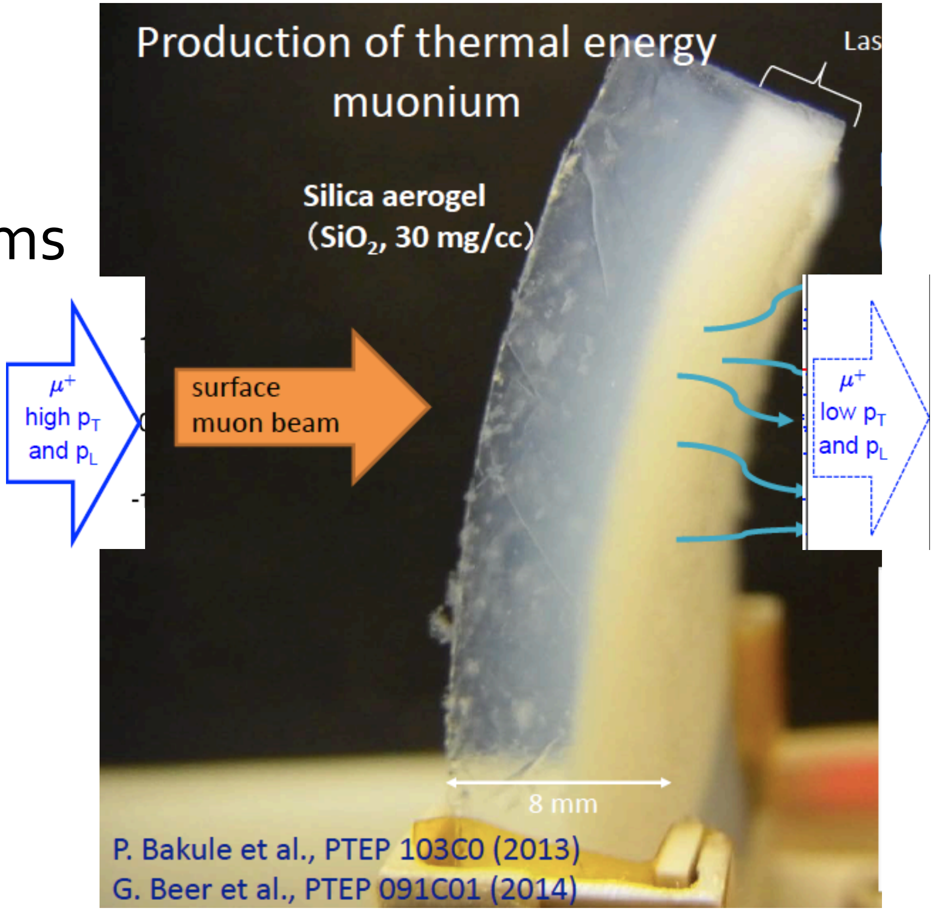
$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

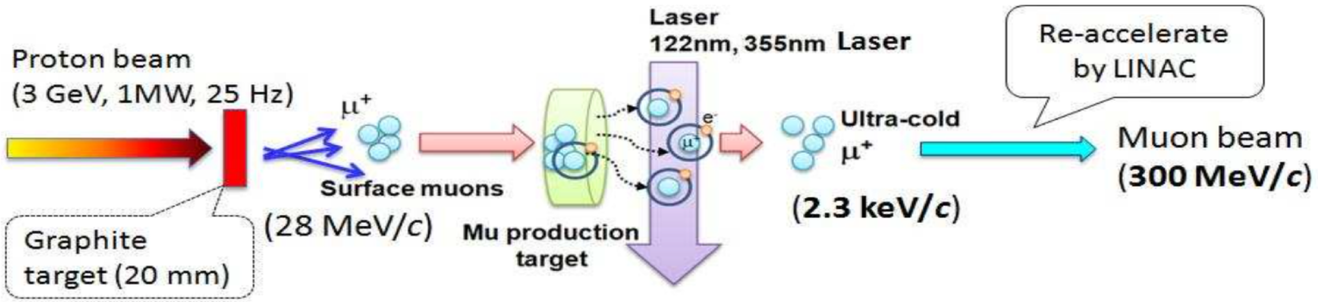
Do need ~zero P_T to store muons

- → 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

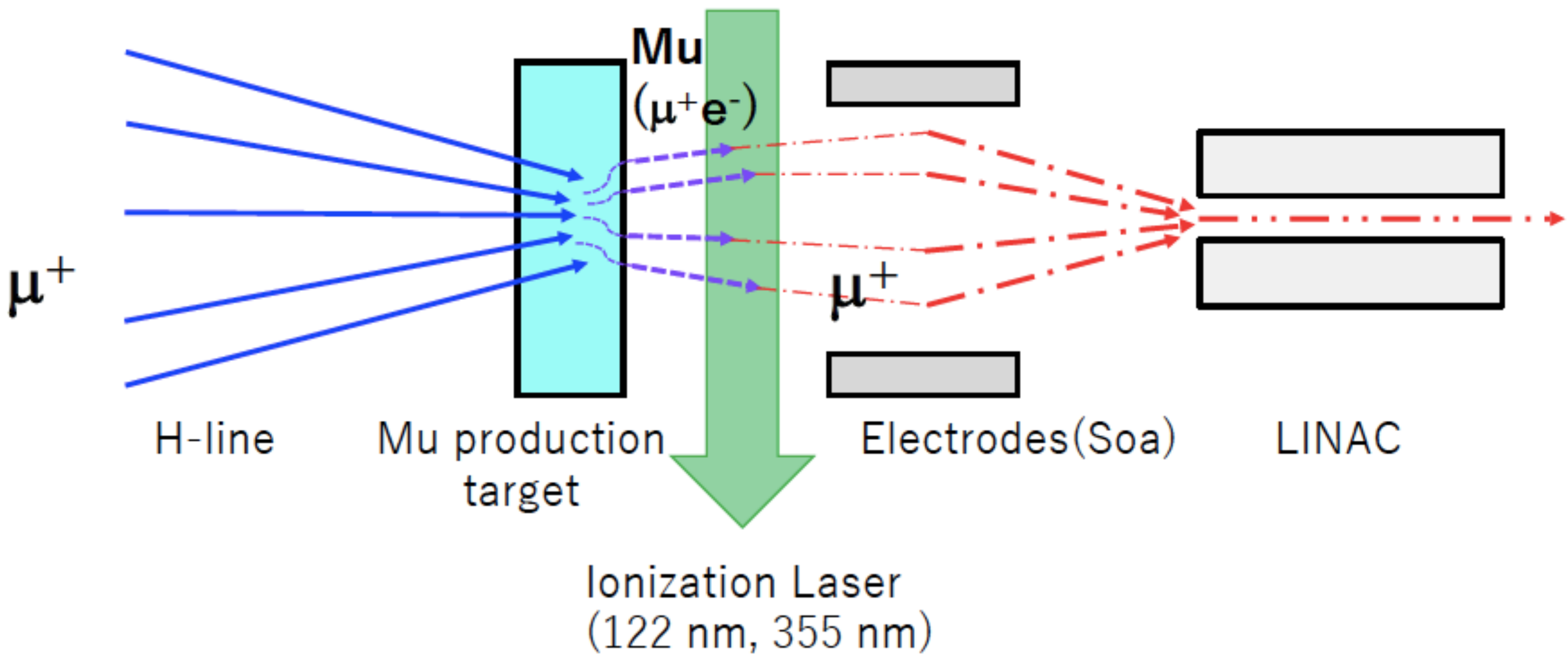




Ultra-cold Muons

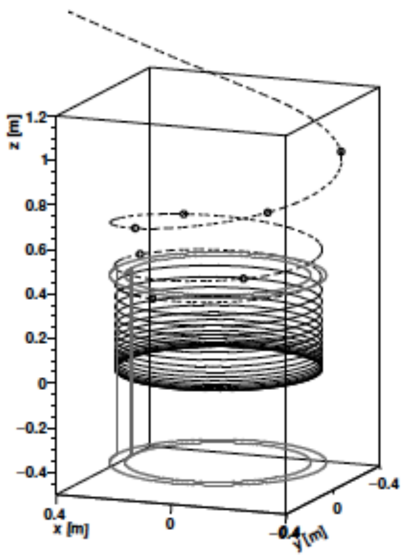
Re-accelerated thermal muon

	surface muon	thermal muon	accelerated muon
E	3.4 MeV	30 meV	212 MeV
p	27 MeV/c	2.3 keV/c	300 MeV/c
Δ p/p	0.05	0.4	$4x10^{-4}$



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



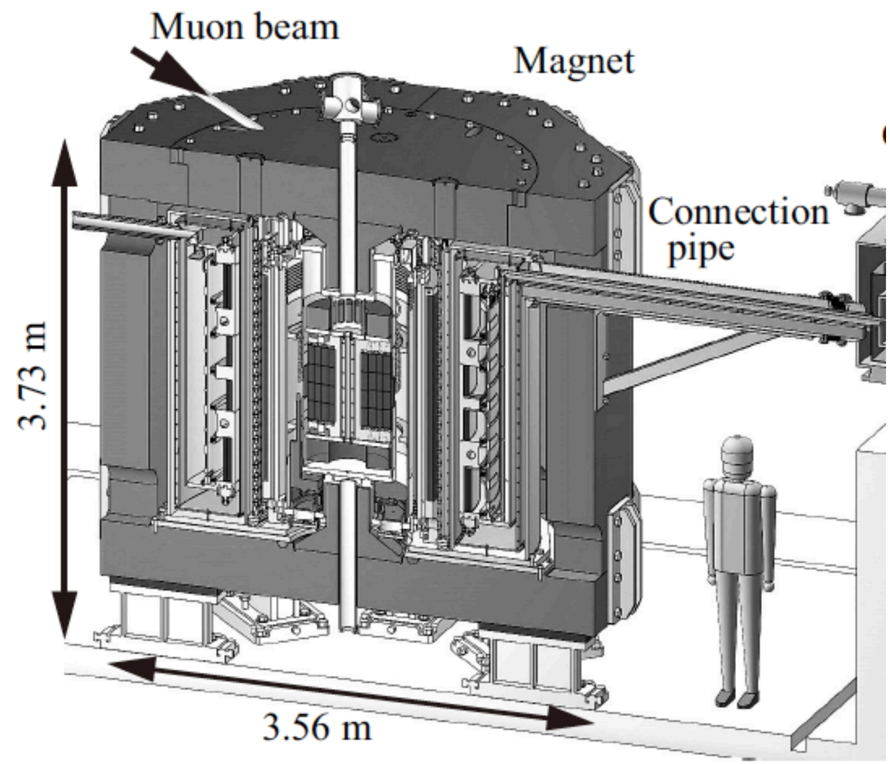
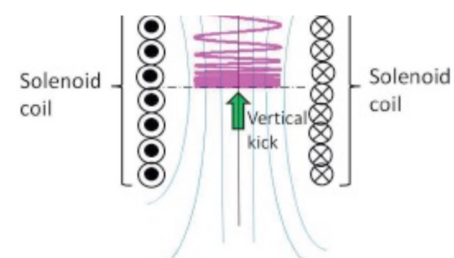
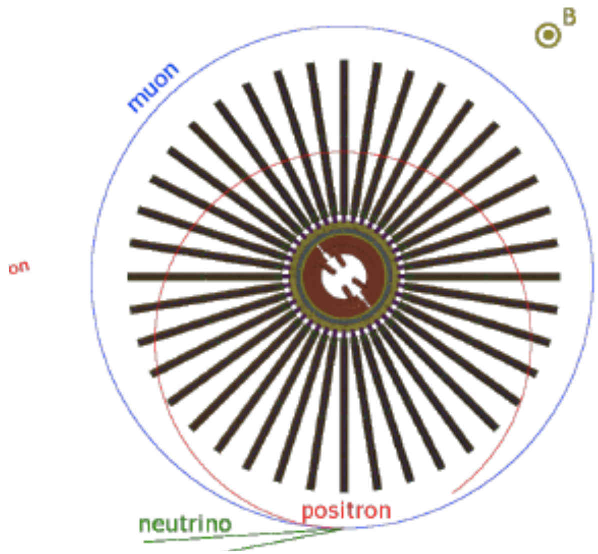
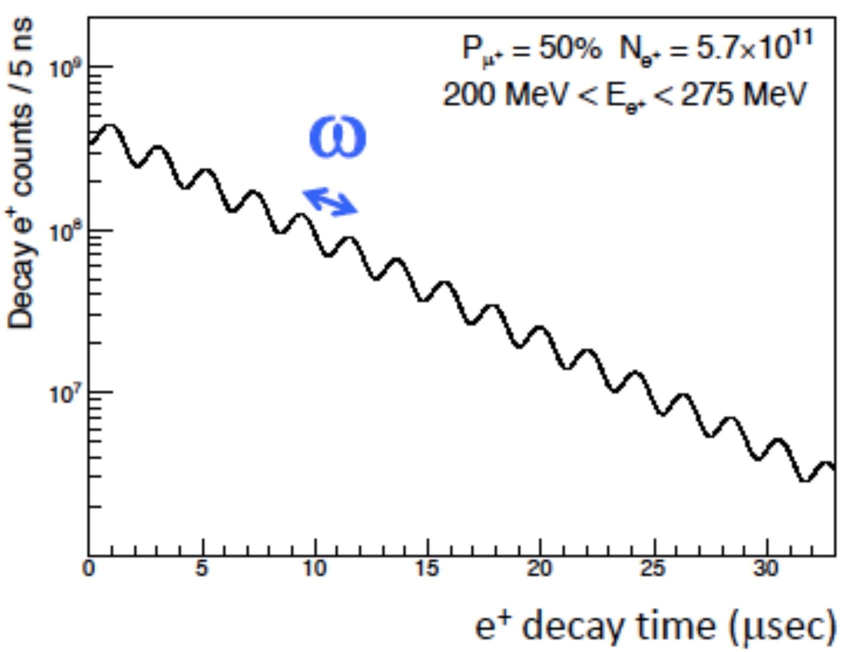


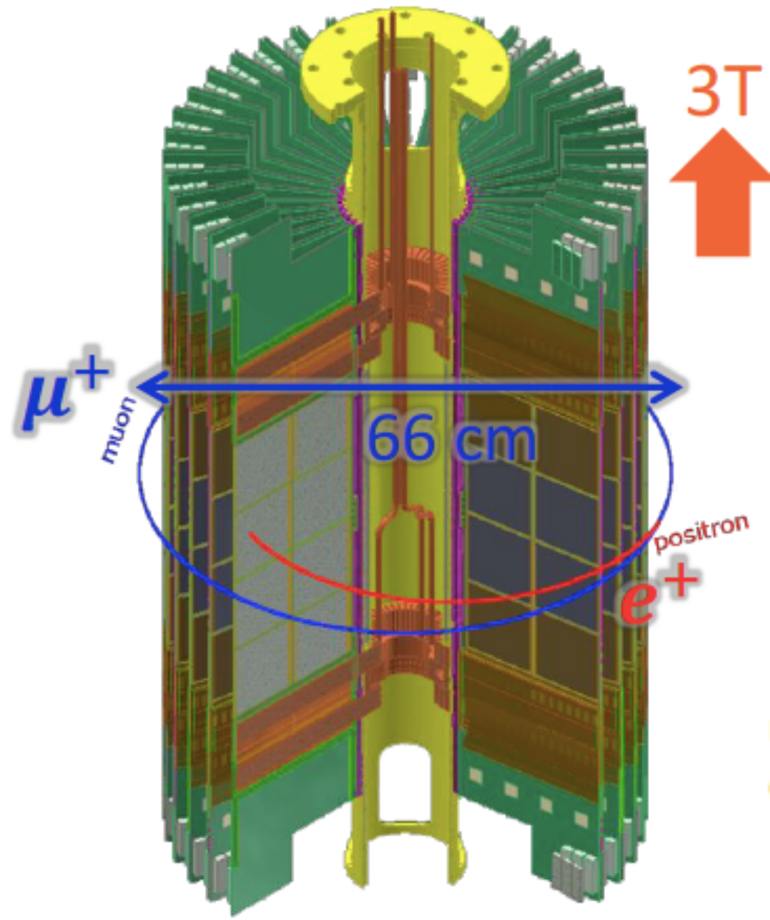
Fig. 8 Overview of the muon storage magnet



Detector system of silicon trackers







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

G.

Comparison of g-2 experiments

Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e \cdot$ cm	–	1.5×10^{-21} $e \cdot$ cm
(syst.)	0.9×10^{-19} $e \cdot$ cm	–	0.36×10^{-21} $e \cdot$ cm
	Completed	Running	In preparation

The first collaboration paper on experimental design

PTEP

Prog. Theor. Exp. Phys. **2019**, 053C02 (22 pages)
DOI: 10.1093/ptep/ptz030

A new approach for measuring the muon anomalous magnetic moment and electric dipole moment

M. Abe[1], S. Bae[2,3], G. Beer[4], G. Bunce[5], H. Choi[2,3], S. Choi[2,3], M. Chung[6], W. da Silva[7], S. Eidelman[8,9,10], M. Finger[11], Y. Fukao[1], T. Fukuyama[12], S. Haciomeroglu[13], K. Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma[18], H. Ikeda[19], M. Ikeno[1], K. Inami[17], K. Ishida[20], T. Itahashi[21], M. Iwasaki[20], Y. Iwashita[22], Y. Iwata[23], R. Kadono[1], S. Kamal[24], T. Kamitani[1], S. Kanda[20], F. Kapusta[7], K. Kawagoe[25], N. Kawamura[1], B. Kim[2,3], Y. Kim[26], T. Kishishita[1], R. Kitamura[14], H. Ko[2,3], T. Kohriki[1], Y. Kondo[14], T. Kume[1], M. J. Lee[13], S. Lee[13], W. Lee[27], G. M. Marshall[28], Y. Matsuda[29], T. Mibe[1,30], Y. Miyake[1], T. Murakami[1], K. Nagamine[1], H. Nakayama[1], S. Nishimura[1], D. Nomura[1], T. Ogitsu[1], S. Ohsawa[1], K. Oide[1], Y. Oishi[1], S. Okada[20], A. Olin[4,28], Z. Omarov[26], M. Otani[1], G. Razuvaev[8,9], A. Rehman[30], N. Saito[1,31], N. F. Saito[20], K. Sasaki[1], O. Sasaki[1], N. Sato[1], Y. Sato[1], Y. K. Semertzidis[26], H. Sendai[1], Y. Shatunov[32], K. Shimomura[1], M. Shoji[1], B. Shwartz[9,32], P. Strasser[1], Y. Sue[17], T. Suehara[25], C. Sung[6], K. Suzuki[17], T. Takatomi[1], M. Tanaka[1], J. Tojo[25], Y. Tsutsumi[25], T. Uchida[1], K. Ueno[1], S. Wada[20], E. Won[27], H. Yamaguchi[1], T. Yamanaka[25], A. Yamamoto[1], T. Yamazaki[1], H. Yasuda[33], M. Yoshida[1], and T. Yoshioka[25,*]

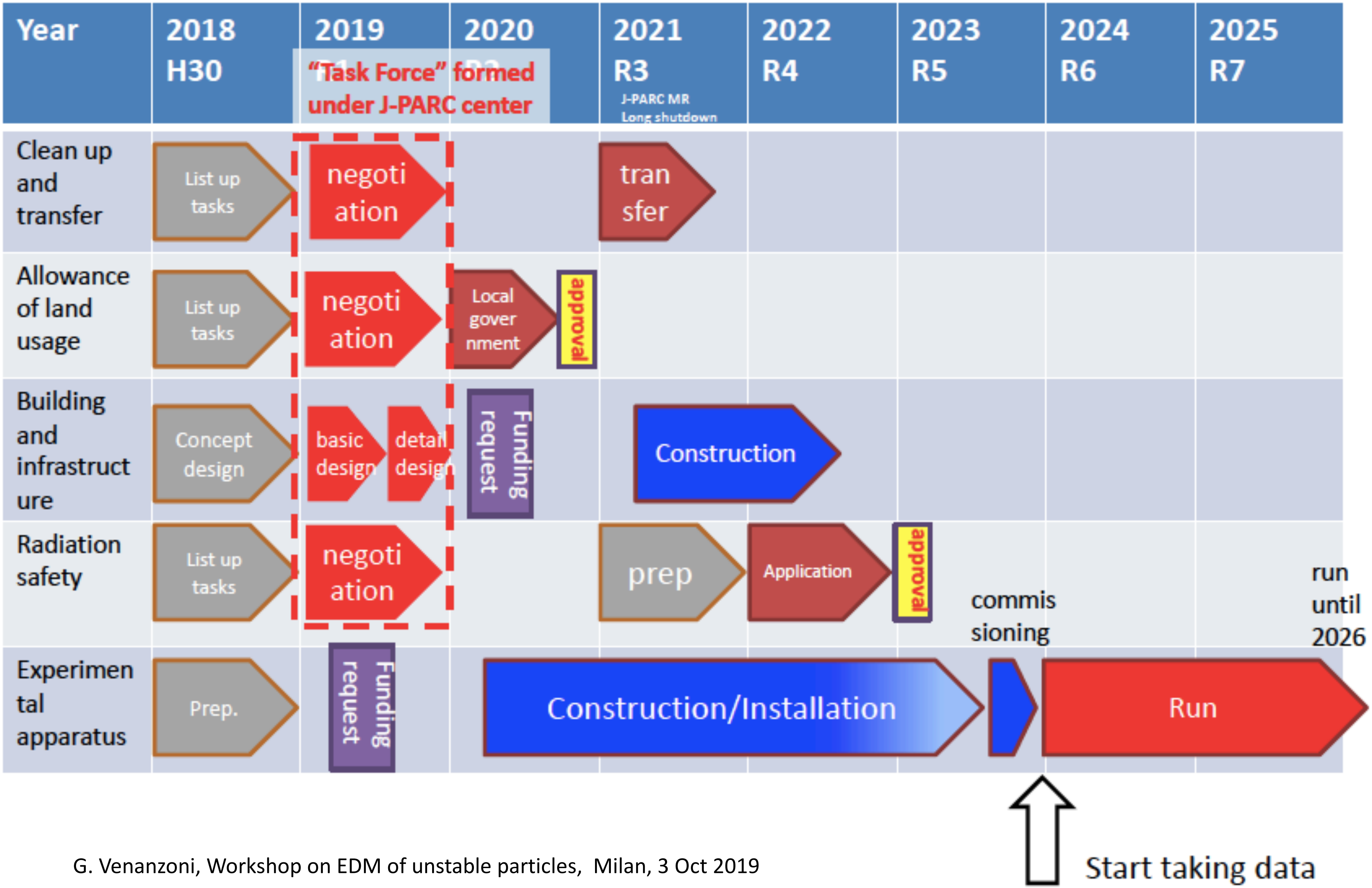
The J-PARC g-2/EDM collaboration

116 members (Canada , China, Czech, France, Japan, Korea, Russia, USA)

History

Date	Events
July, 2009	LOI submitted to PAC8
Jan, 2010	Proposal submitted to PAC9
Jan, 2012	CDR submitted to PAC13, Milestones defined.
July, 2012	Stage-1 status recommended by PAC15 Stage-1 status granted by the IPNS director
May, 2015	TDR submitted to PAC
Oct, 2016	Revised TDR submitted to PAC and FRC
June, 2016	**Selected as a KEK-PIP priority project**
Nov, 2016	Focused review on technical design
Dec, 2017	Responses and Revised TDR submitted to PAC
July, 2018 **Nov, 2018**	Stage-2 status recommended by IPNS-PAC **Stage-2 status granted by the IPNS director**
Jan, 2019 **Mar, 2019**	Stage-2 status recommended by IMSS-PAC **Stage-2 status granted by the IMSS director** **KEK-SAC endorsed the E34 for the near-term priority**

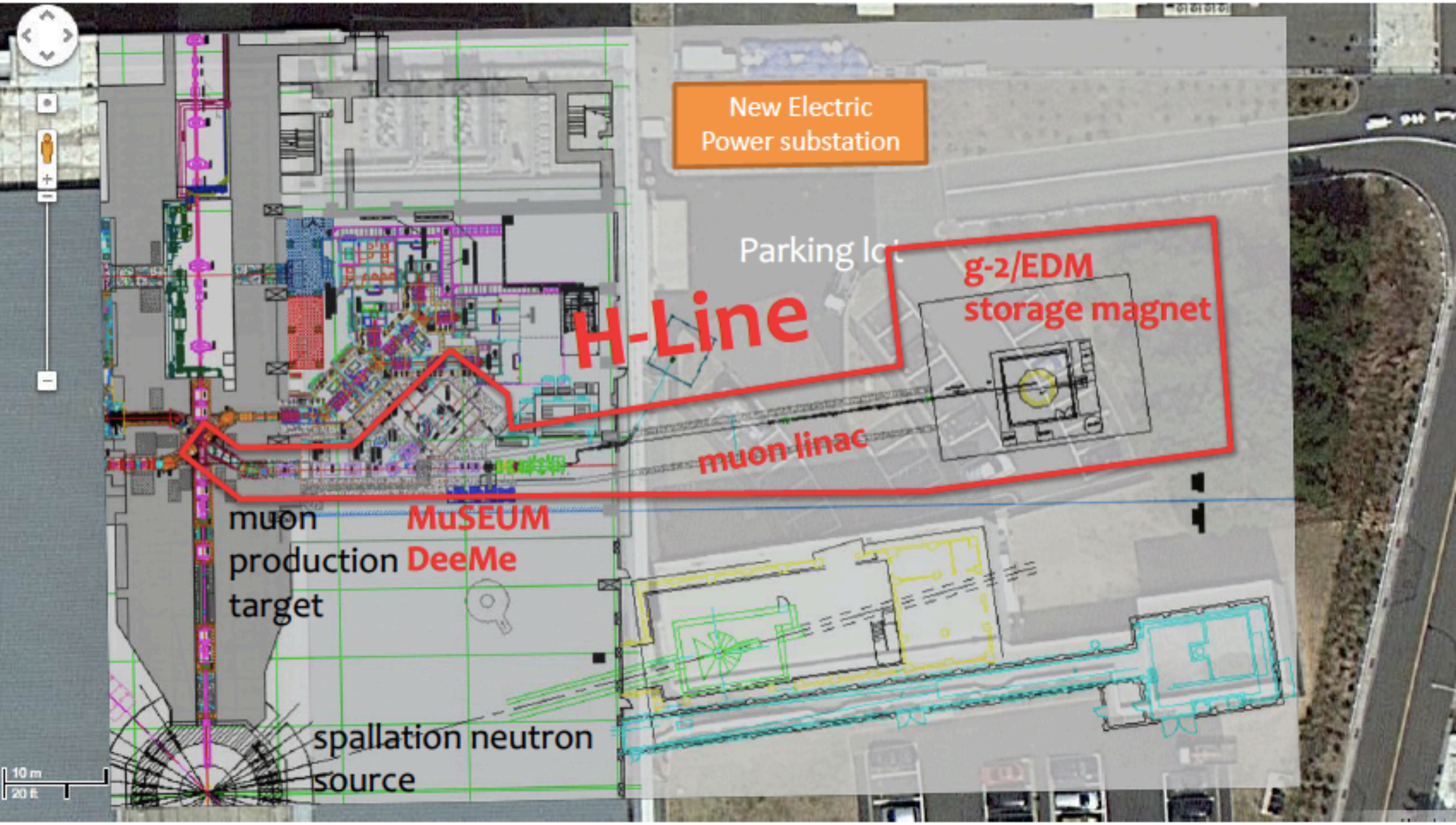
Intended global schedule



G. Venanzoni, Workshop on EDM of unstable particles, Milan, 3 Oct 2019

Proposed experimental site (H-line)

Material and Life science Facility in J-PARC



N. Kawamura et al., PTEP 2018, 113G01 (2018)

Conclusions

- Exciting times for the g-2 of electron and muons: long standing discrepancy of >3 σ for the $(g-2)_\mu$; new exciting discrepancy of >2σ for $(g-2)_e$. New Physics or Statistical fluctuations or some systematic flaw?
- New experiments are expected which should clarify the current situation.
- Muon g-2 experiment at Fermilab (E989) currently taking data. New result with BNL accuracy (O(500 ppb)) expected very soon→ 140 ppb final goal.
- Muon g-2 at J-Parc (E34) aiming at BNL accuracy. Very important cross check especially if E989 will confirm the BNL result
- We look forward to more players (τ, baryons,…) in this game !

Thanks

THE END

Table 5 Summary of statistics and uncertainties

	Estimation
Total number of muons in the storage magnet	5.2×10^{12}
Total number of reconstructed e^+ in the energy window [200, 275 MeV]	5.7×10^{11}
Effective analyzing power	0.42
Statistical uncertainty on ω_a [ppb]	450
Uncertainties on a_μ [ppb]	450 (stat.) $<$ 70 (syst.)
Uncertainties on EDM [10^{-21} e·cm]	1.5 (stat.) 0.36 (syst.)

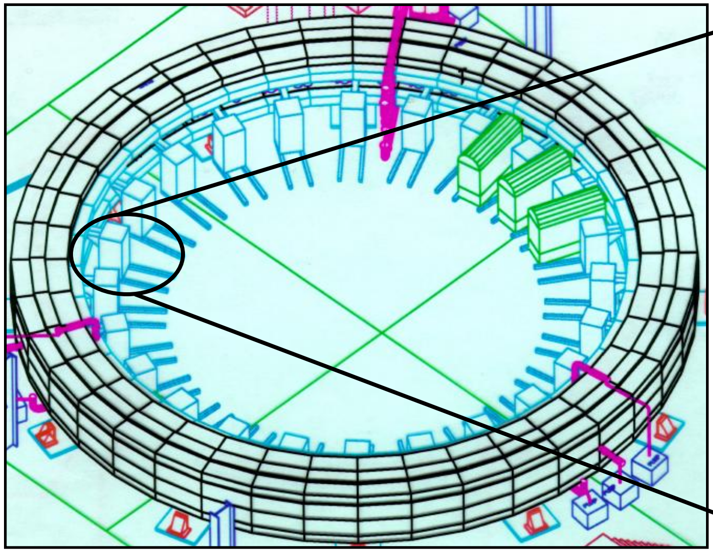
Comparison

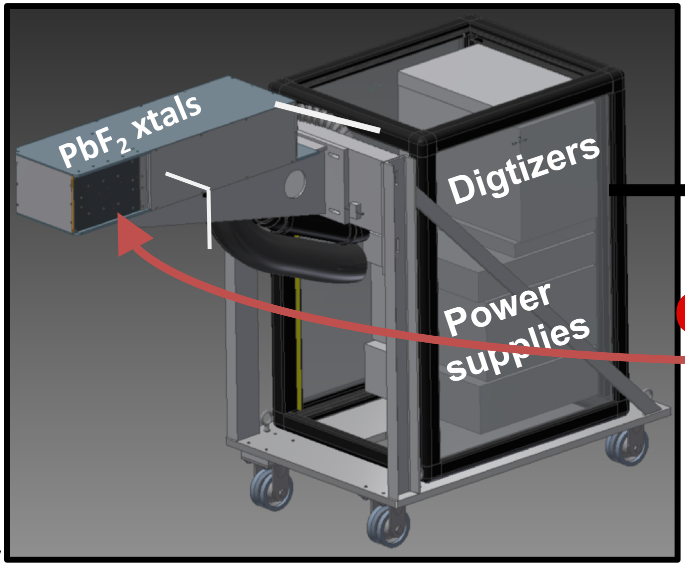
$$\delta\omega_a/\omega_a = \frac{1}{\omega_a \gamma \tau_\mu} \sqrt{\frac{2}{NA^2 \langle P \rangle^2}},$$

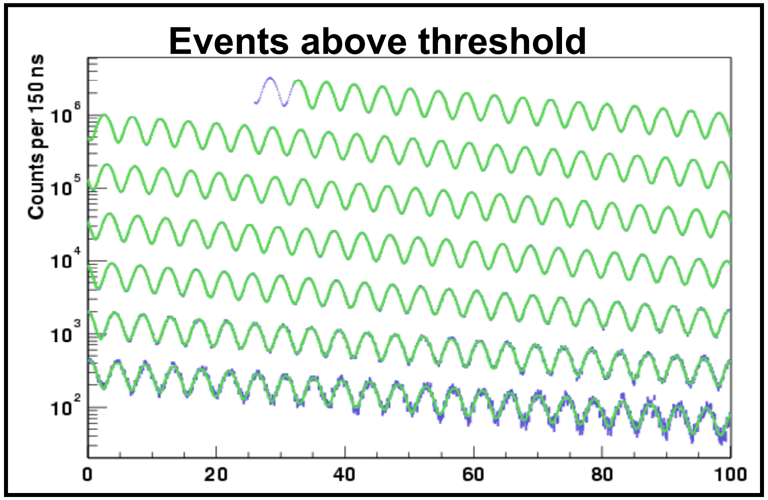
Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

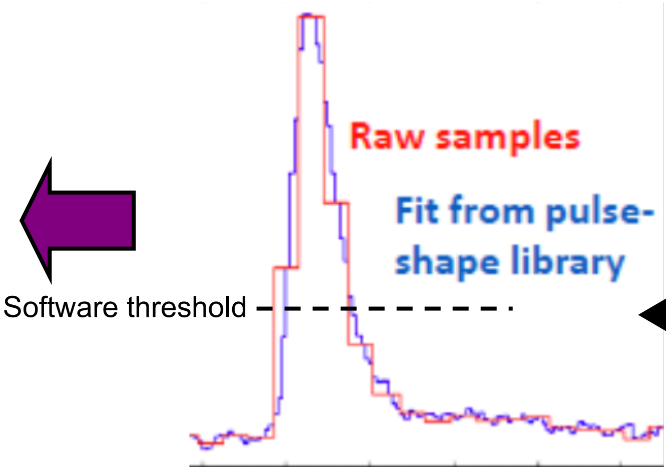
Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events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

An "event" is an isolated positron above a threshold









The ω_a analysis strategy

- 6 independent analysis groups using different *Reconstruction algorythms* and different *Fit methods*
- One method is completely different from all others (Q-method); it has a larger error → used as crosscheck
- 2 Independent Reconstruction algorythms developed (East, West); the Europa team contributes to both algos providing the SiPM gain functions

Team	Reconstruction	Analysis
CU (Cornell)	East	T,E
UW (Washington)	West	T,A
Europa (INFN+UK)	West/Europa	T,A
SJTU (Shangai)	West	T,E
BU (Boston)	West	T,R
Uky (Kentucky)	Q	Q

The 60h dataset: 5-par fit

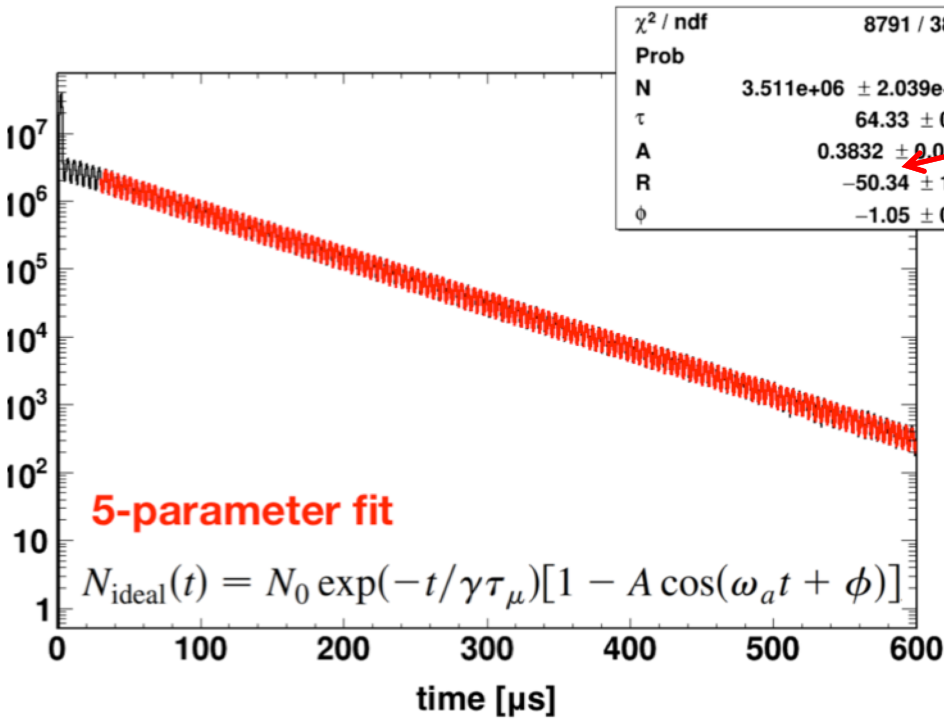
- Simple (ideal) positron oscillation:

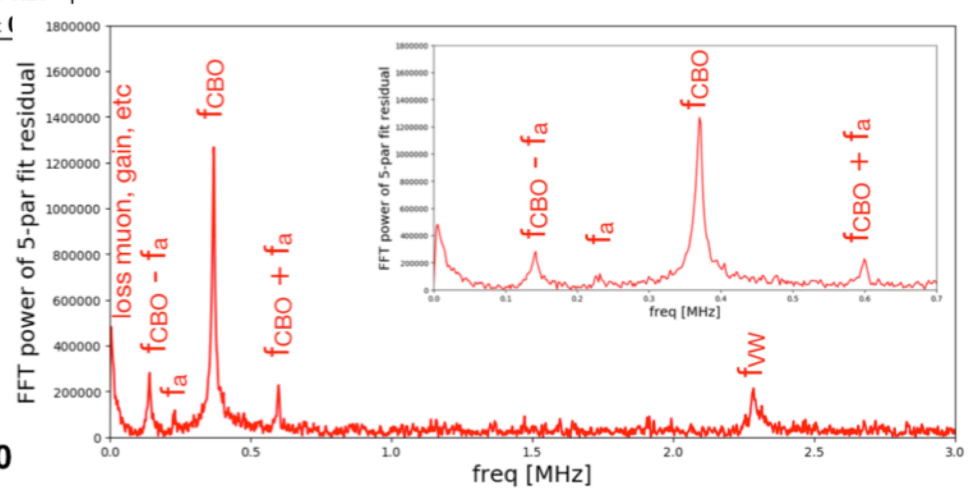
$$N_{\text{ideal}}(t) = N_0 \exp(-t/\gamma\tau_\mu)[1 - A\cos(\omega_a t + \phi)]$$

- This simple fit is clearly not sufficient and typical resonances are observed in the residuals

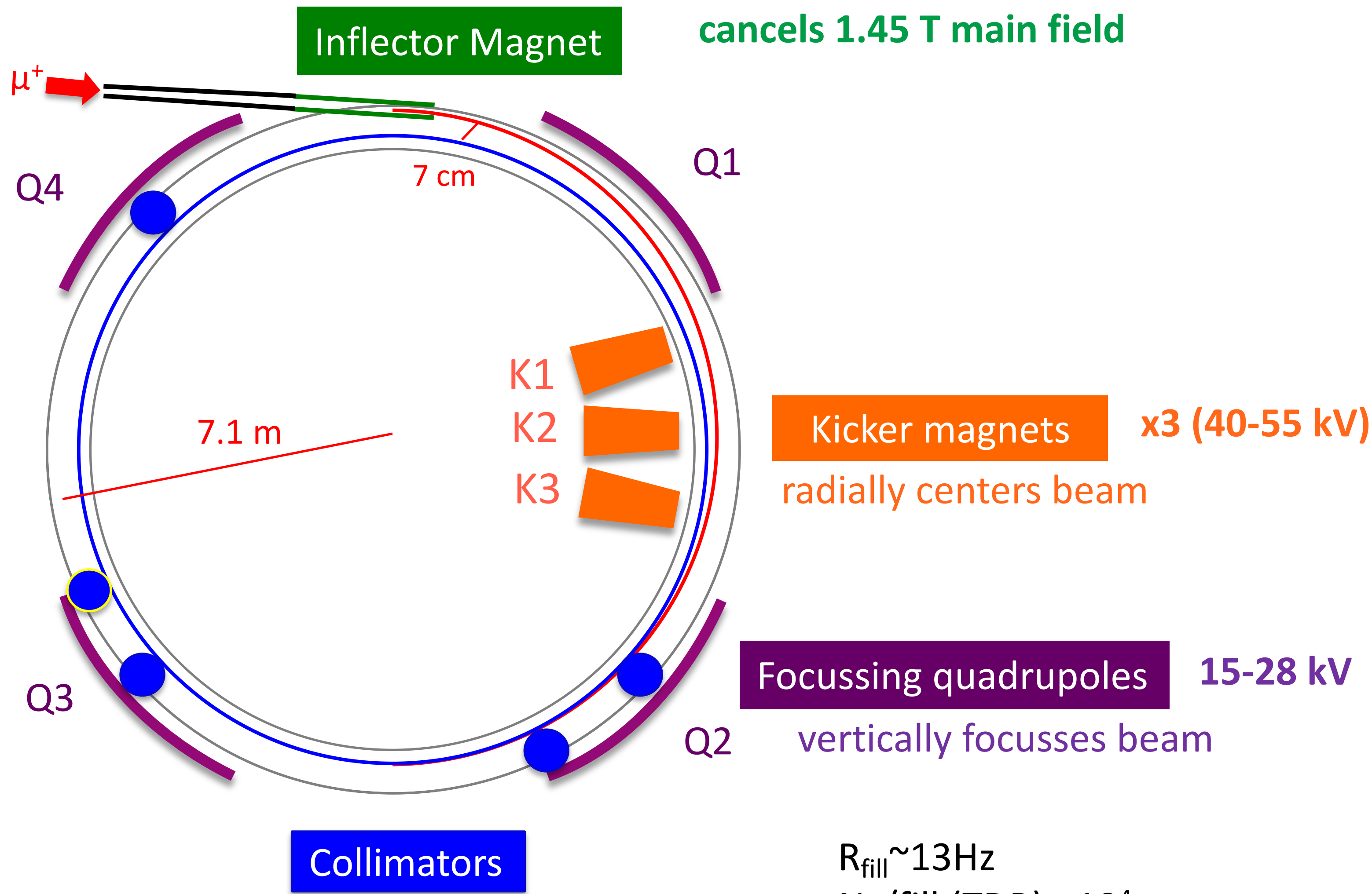
muon lifetime: γ=29.3

NOTE: blinding on ω_a!





Injection / storage



R_{fill}~13Hz

N_{μ}/fill (TDR)~ 10^4

N_{μ}/sec(TDR)~ $1.3x10^5$

$N_{e+\ E>1.8\ GeV}$/fill (TDR)~ 10^3

TDR Numbers

- 1.6 x 10^{11} good decay positrons (E>1.8GeV, t>30μs) for 22 BNL statistics (7x10^9)
- Needs 1.5 x 10^8 fills (=7 months)

→ **3BNL/month; ~10^3 e^+/fill; 10^4 μ/fill**

Item	Factor	Value per fill
Protons on target		10^{12} p
Positive pions captured in FODO, $\delta p/p = \pm 0.5\%$	1.2×10^{-4}	1.2×10^8
Muons captured and transmitted to SR, $\delta p/p = \pm 2\%$	0.67%	8.1×10^5
Transmission efficiency after commissioning	90%	7.3×10^5
Transmission and capture in SR	$(2.5 \pm 0.5)\%$	1.8×10^4
Stored muons after scraping	87%	1.6×10^4
Stored muons after 30 μs	63%	1.0×10^4
Accepted positrons above E = 1.86 GeV	10.7%	1.1×10^3
Fills to acquire 1.6×10^{11} events (100 ppb)		1.5×10^8
Days of good data accumulation	17 h/d	202 d
Beam-on commissioning days		150 d
Dedicated systematic studies days		50 d
Approximate running time		402 ± 80 d
Approximate total proton on target request		$(3.0 \pm 0.6) \times 10^{20}$

Beam structure