The Muon g-2 experiment at Fermilab

Vladimir Tishchenko

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Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

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Content

- Recap of g-2 lecture W.M. Morse
- Principles of measurements
- Ring reassembly at Fermilab
- Magnetic field shimming
- Upgrades to the experiment
- First result of the Muon g-2 experiment at Fermilab

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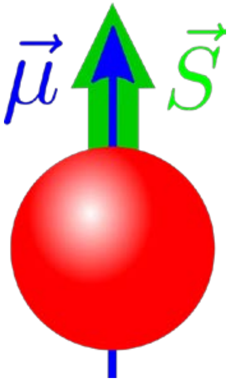
Recap

<u>Muon</u>

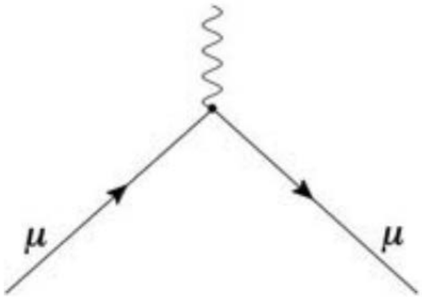


- Elementary particle
- Same electric charge as the electron
- Like the electron, behaves like it is *intrinsically* spinning
- Approximately **200** times heavier than an electron
- Lives about 2μs

The magnetic moment $\vec{\mu}$ of a muon is a vector along the spin $\vec{s}$: $\vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}$

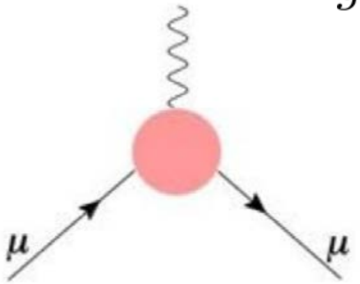
where the proportionality constant (known as g-factor) relates the observed magnetic moment $\vec{\mu}$ of a particle to its spin $\vec{s}$

Dirac theory predicts $g = 2$:



Quantum effects give additional contribution which arise from virtual particles, known and **unknown**:

$$g = 2(1 + a_\mu)$$



$$a_\mu \equiv \frac{g_\mu - 2}{2}$$

$$a_\mu \approx \frac{\alpha}{2\pi} \approx 0.001$$

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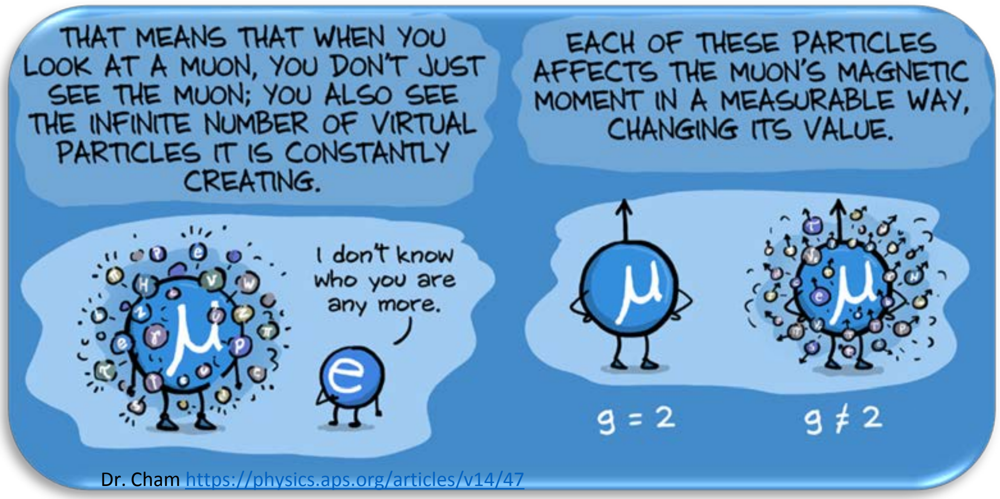
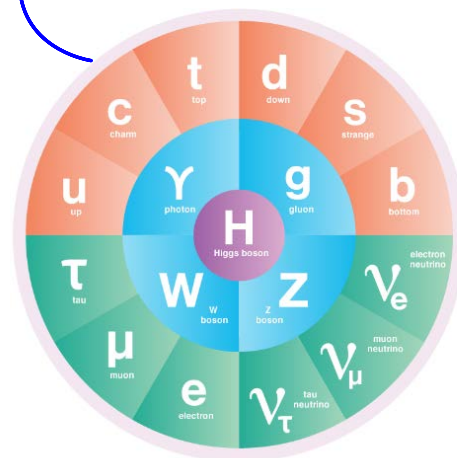
all Standard Model particles contribute to a_μ

$$g_\mu = 2(1 + a_\mu)$$



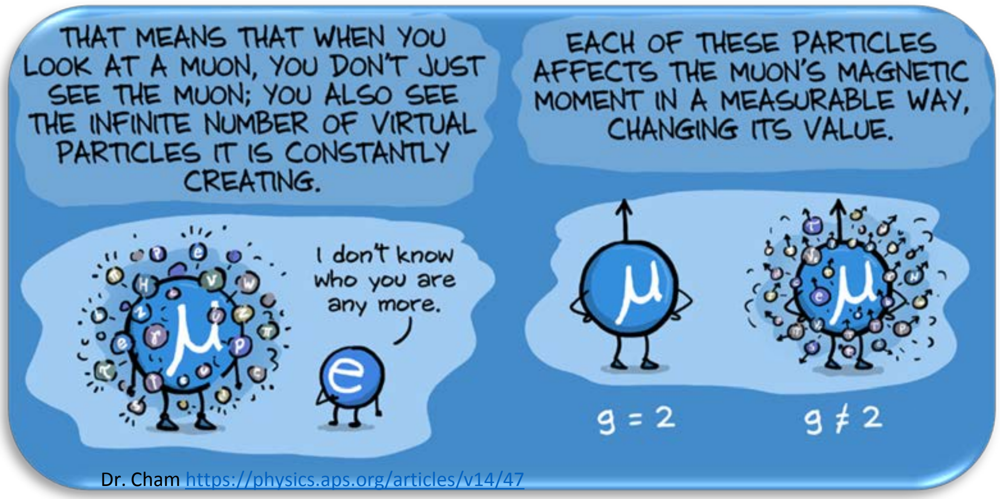
Dr. Cham https://physics.aps.org/articles/v14/47



a_μ can be predicted by Standard Model, very precisely.
It can also be measured, also very precisely.
Comparison between theory and experiment provides critical test of theory.
If measurement disagrees with theory …

all Standard Model particles contribute to a_μ

$$g_\mu = 2(1 + a_\mu)$$



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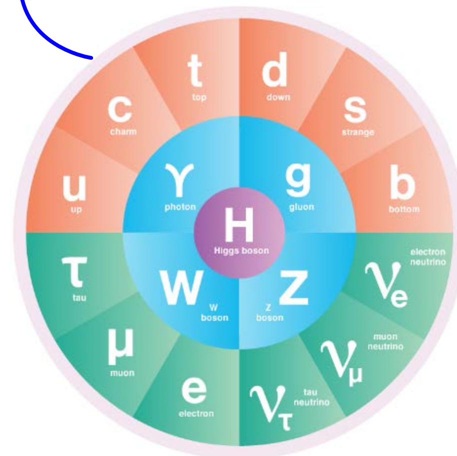
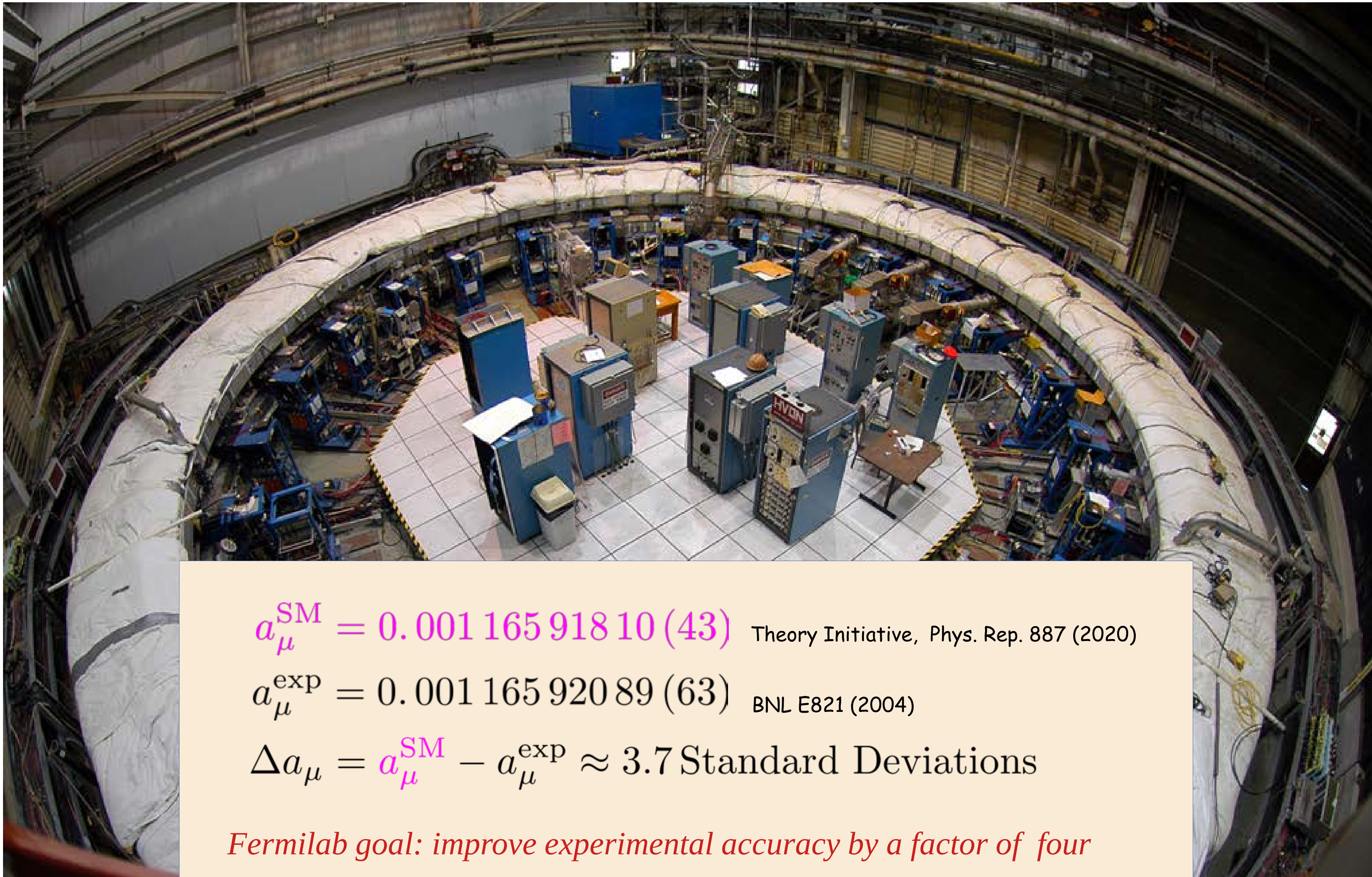


+ NP

a_μ can be predicted by Standard Model, very precisely.
It can also be measured, also very precisely.
Comparison between theory and experiment provides critical test of theory.
If measurement disagrees with theory it may indicate that there exist not yet known particles!

$$\rightarrow \text{muons are } \left(\frac{m_\mu}{m_e}\right)^2 \sim 40,000 \text{ times more sensitive to New Physics than electrons!}$$

Brookhaven Muon g-2 ring, ca. 1995



$$a_\mu^{SM} = 0.001\,165\,918\,10\,(43)$$ Theory Initiative, Phys. Rep. 887 (2020)

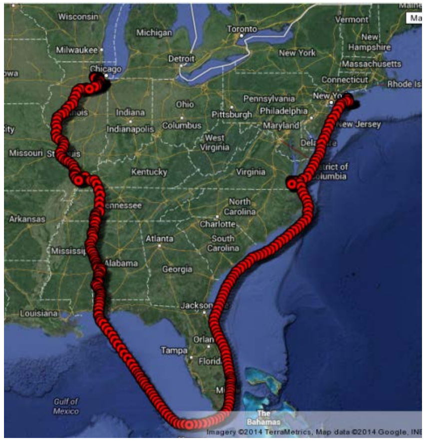
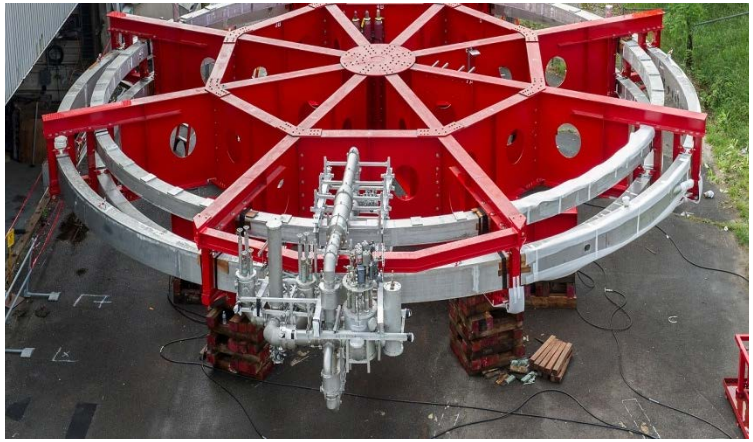
$$a_\mu^{exp} = 0.001\,165\,920\,89\,(63)$$ BNL E821 (2004)

$$\Delta a_\mu = a_\mu^{SM} - a_\mu^{exp} \approx 3.7\,\text{Standard Deviations}$$

Fermilab goal: improve experimental accuracy by a factor of four

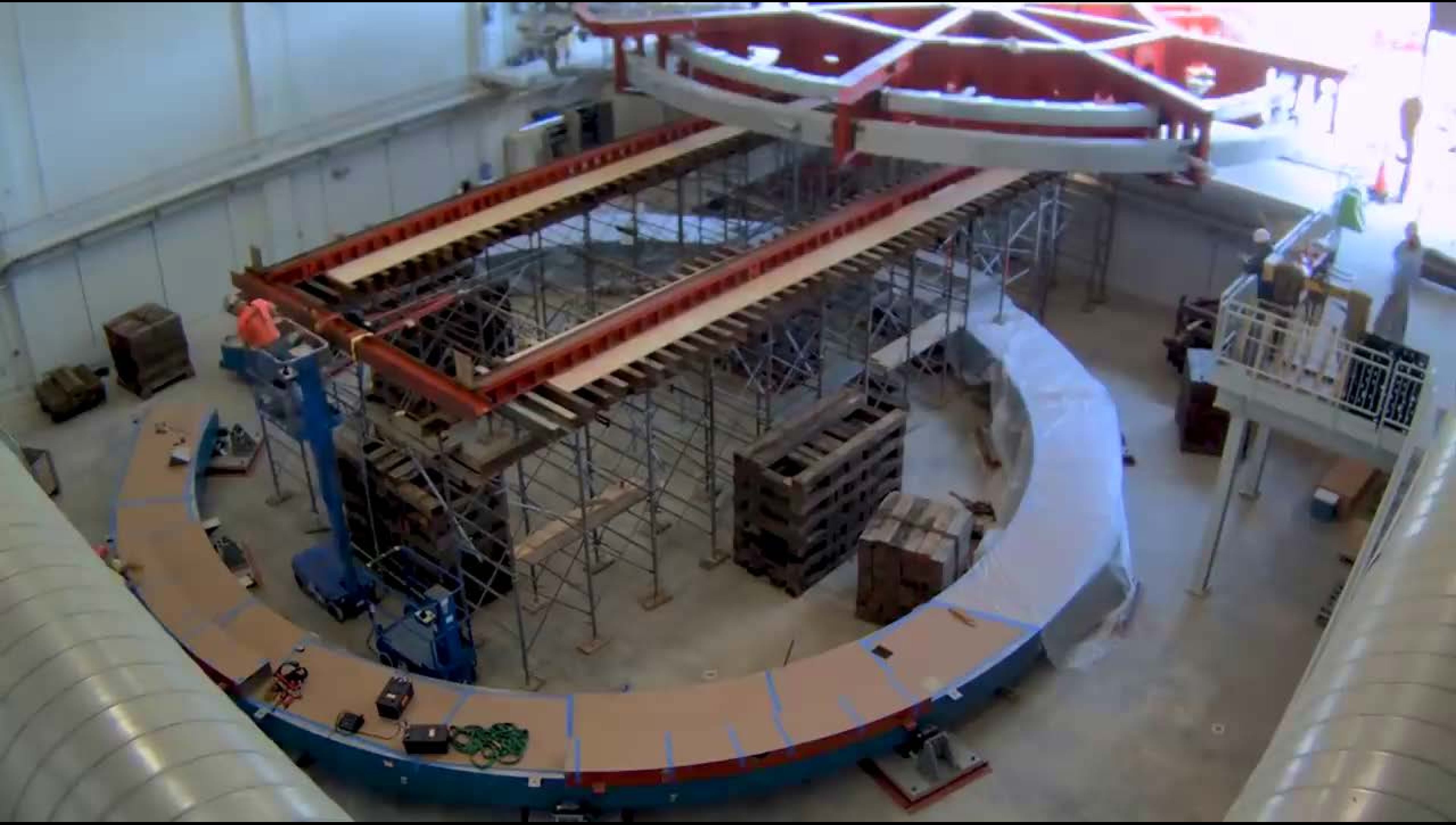
transportation of coils from BNL to Fermilab

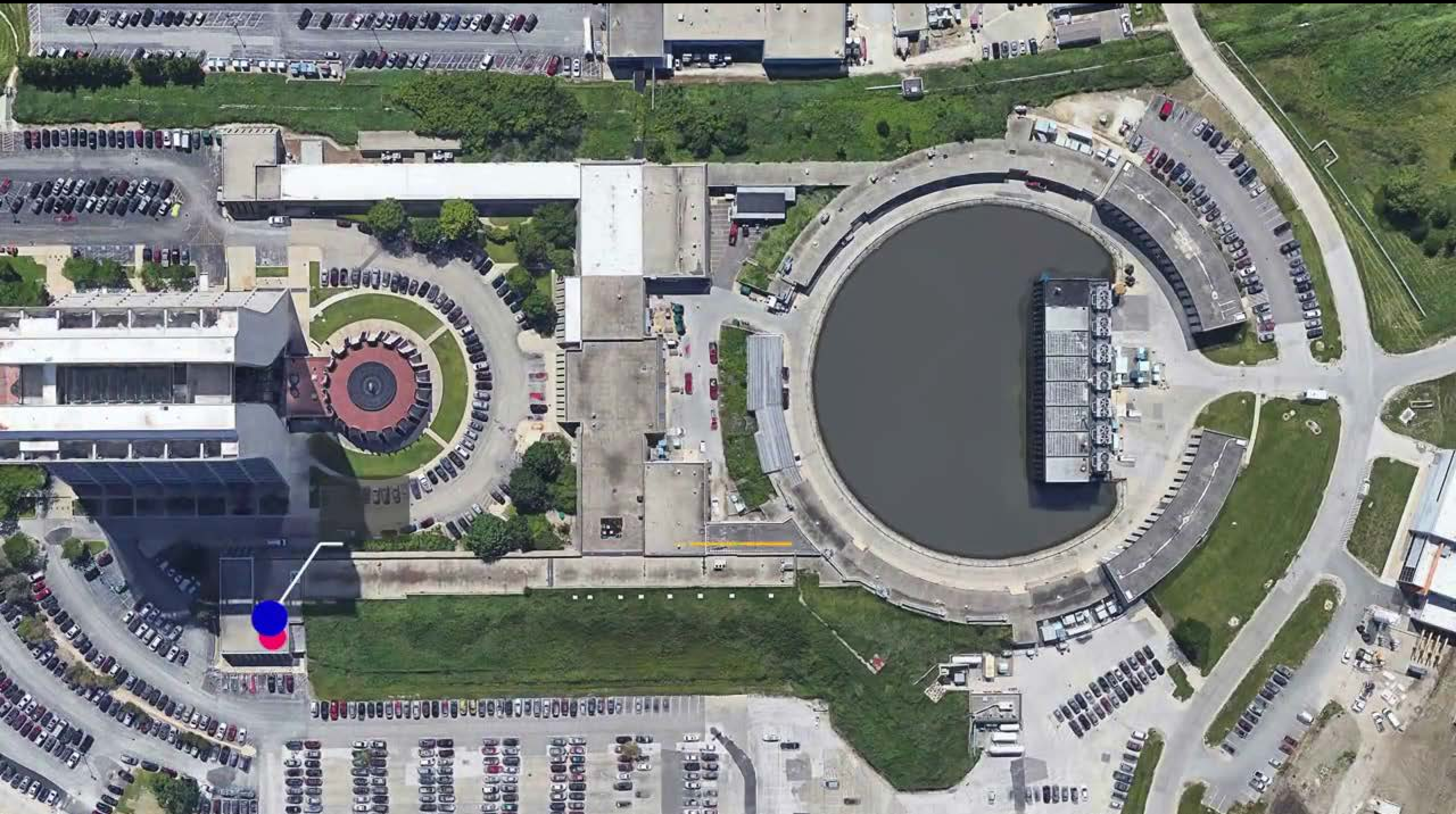
2009 | 2010 | 2011 | 2012 | **2013** | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021

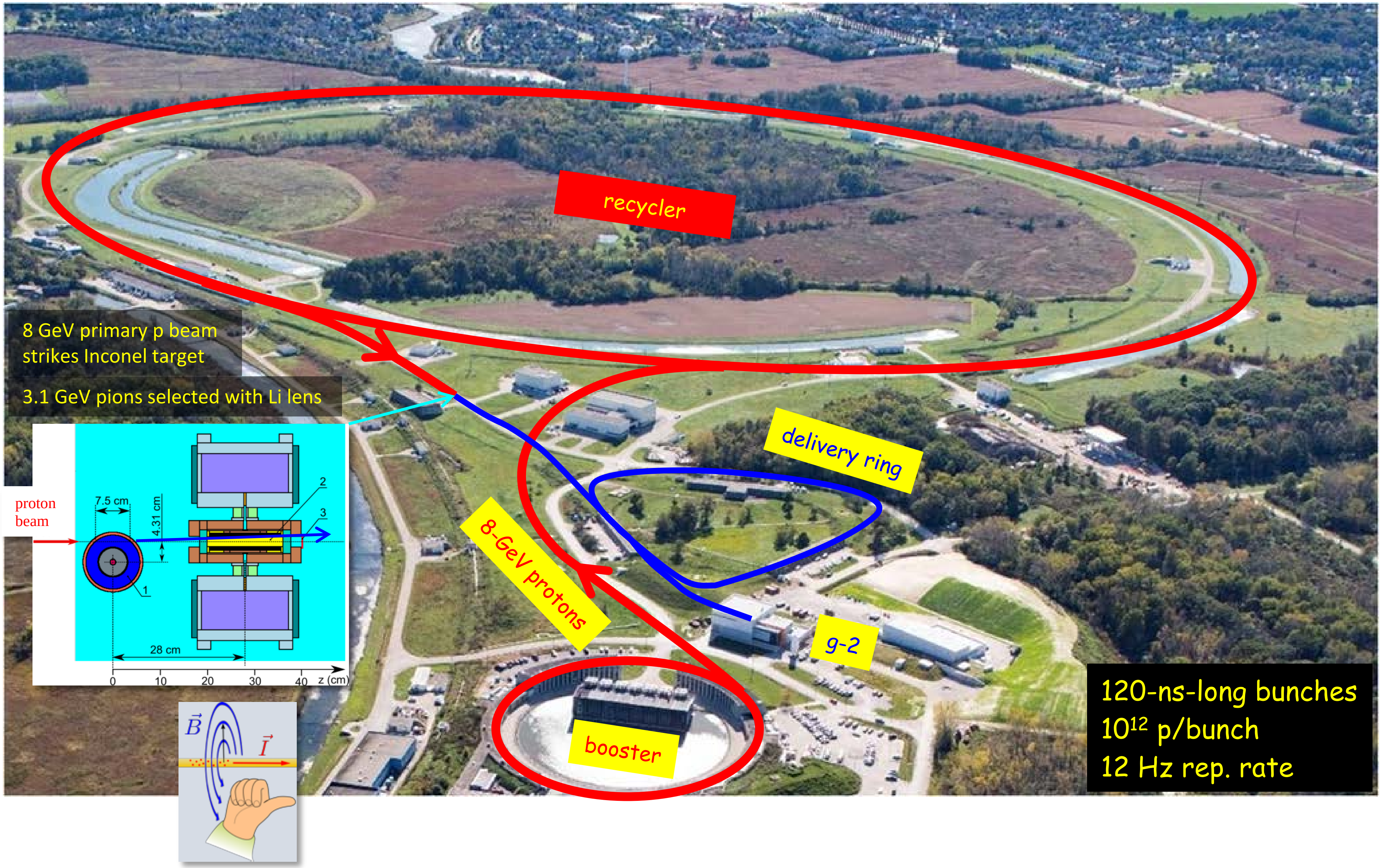


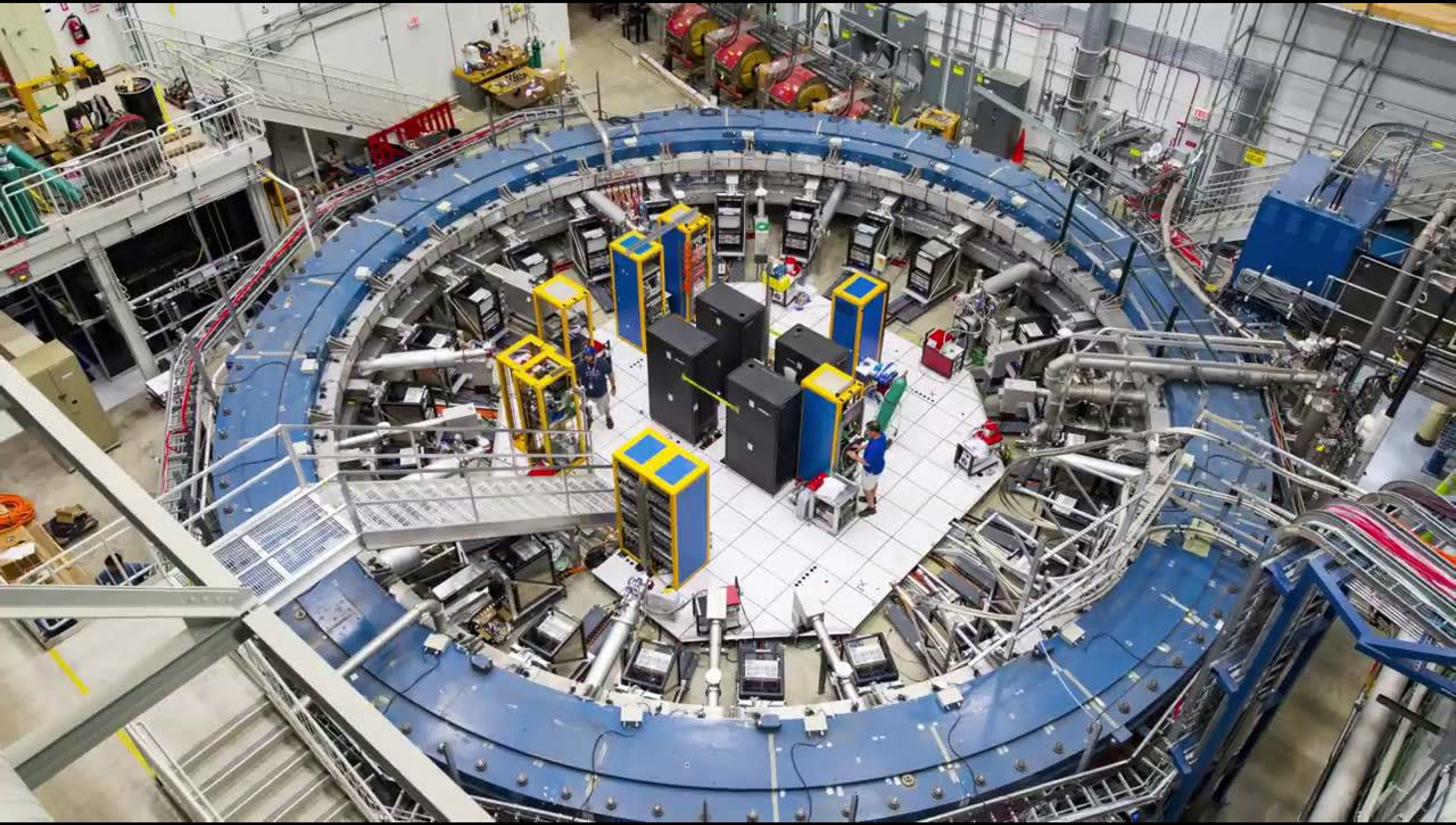

more photos and info: http://muon-g-2.fnal.gov/bigmove





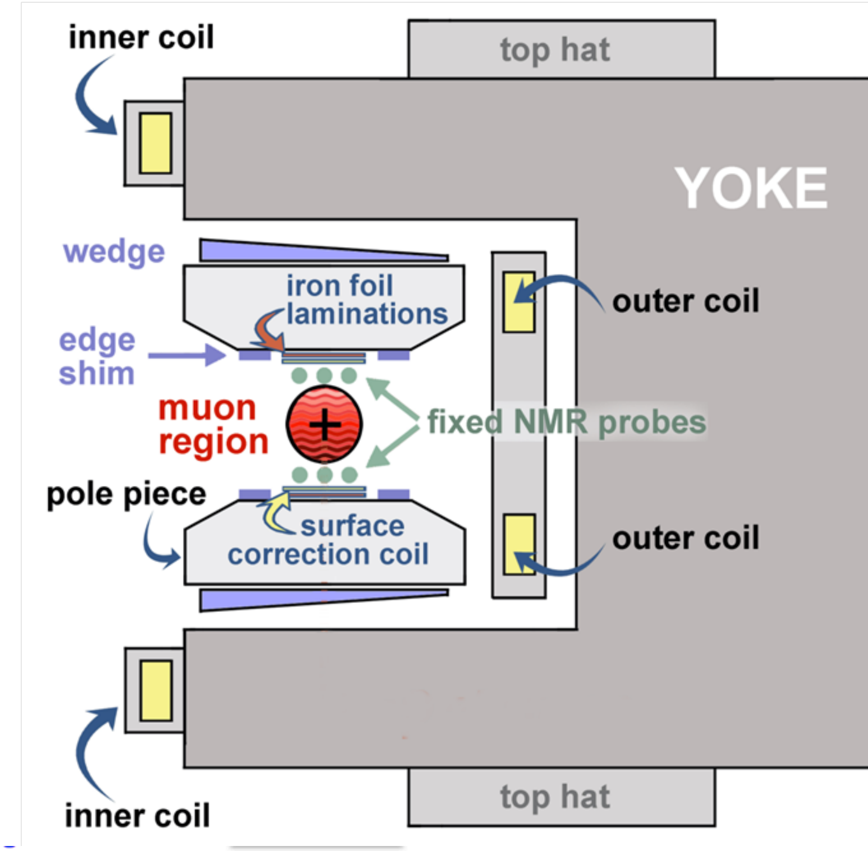
muons in the laboratory





magnet anatomy and *B-field* measurement

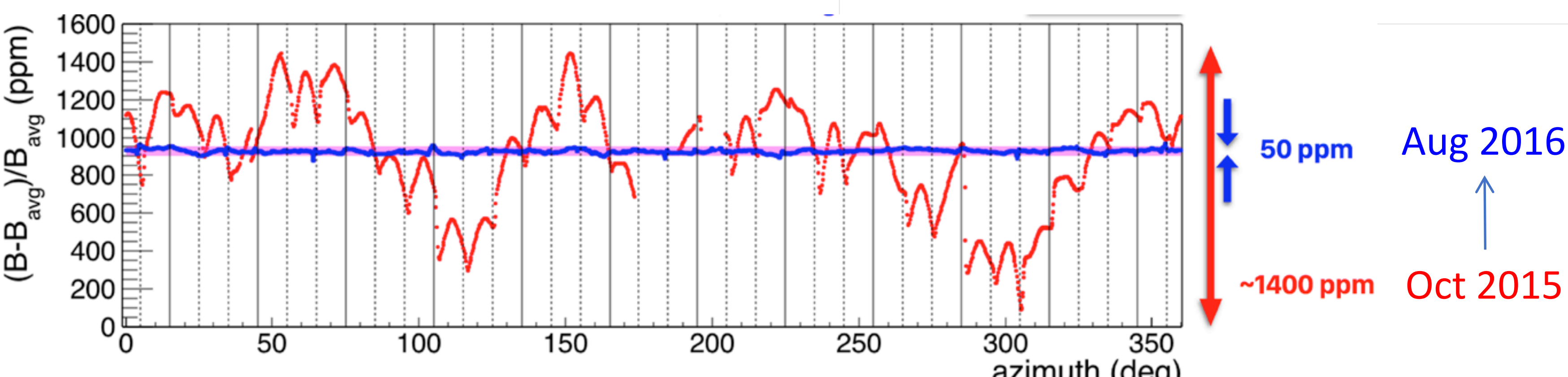
Brilliant magnet design
by Gordon Danby (BNL)



1.45T superferric magnet

Shimmed to 50 ppm uniformity

~3x uniformity improvement



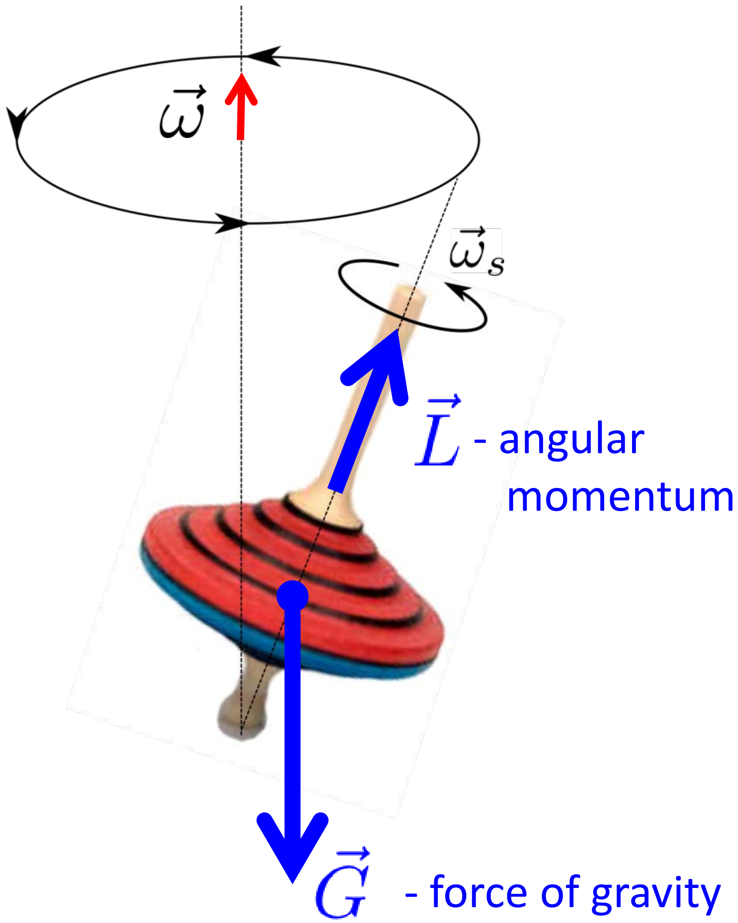
Rough Shimming – lamination shims

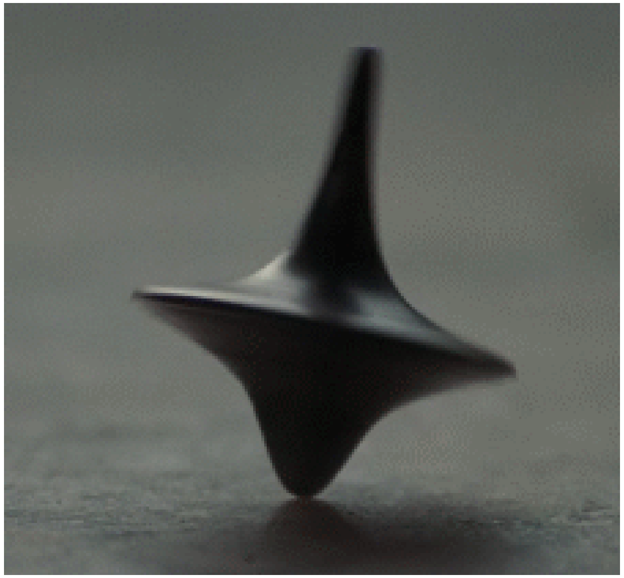
- Lamination shims: small pieces of iron foil
- Predict foil mass required to make local adjustments of the B-field
- 8500 foils installed in total

foils sorted by mass


laminations affixed to the pole surfaces

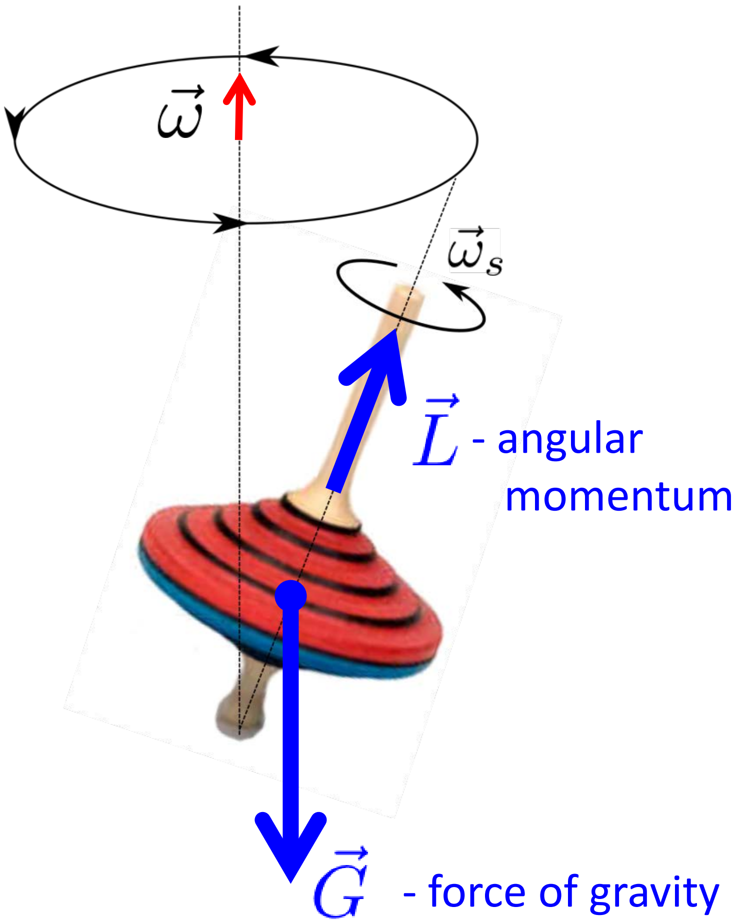
spinning toy top wobbles around gravity force



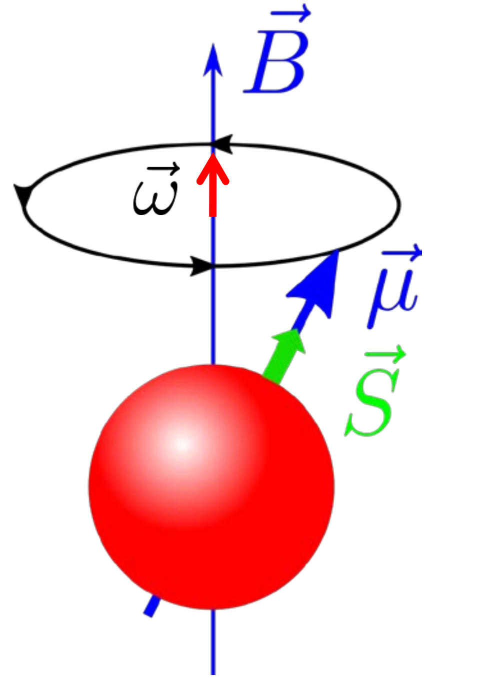


magnetic moment wobbles around magnetic field

toy top / gyroscope



muon

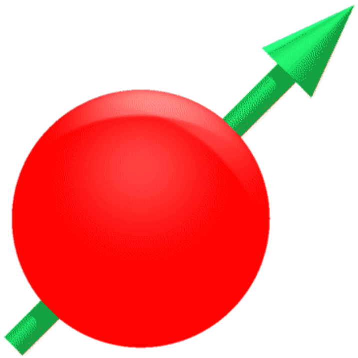


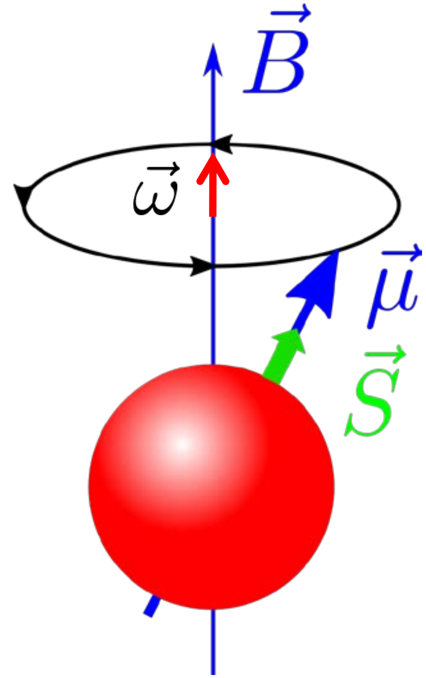
torque: $\vec{\tau} = \vec{\mu} \times \vec{B}$

$$\omega \sim (1 + a_\mu)B$$

Larmor precession

magnetic moment wobbles around magnetic field

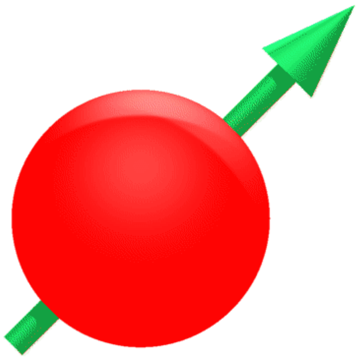




$$\omega \sim (1 + a_\mu) B$$

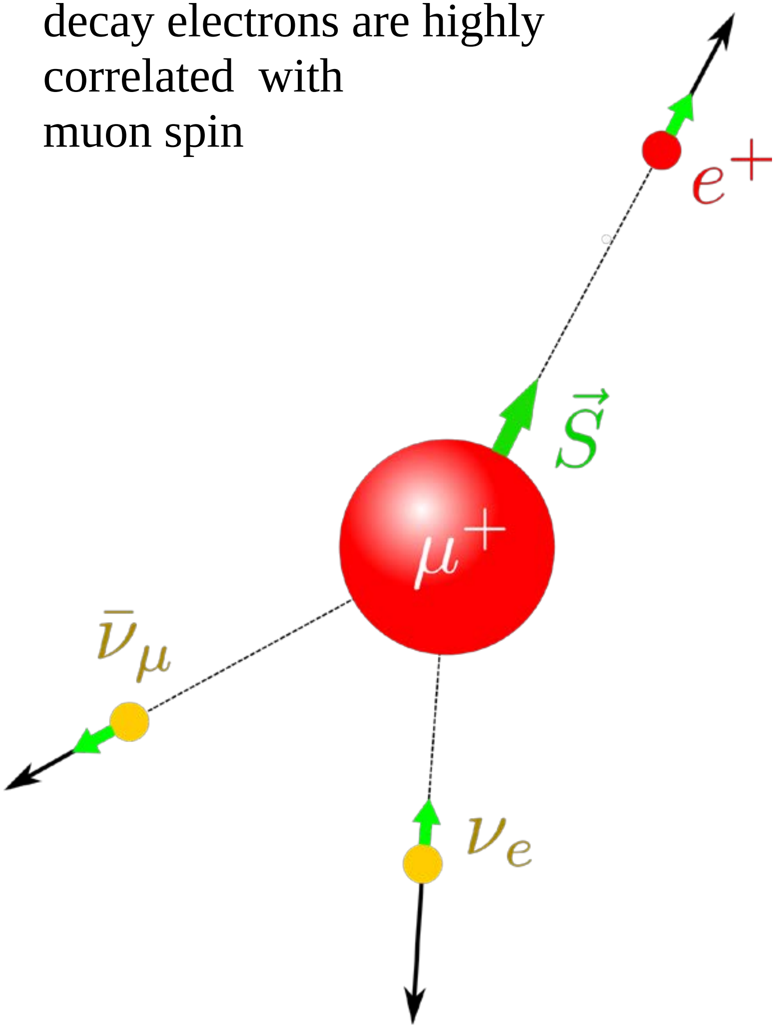
magnetic moment can be deduced by measuring the wobbling frequency in a known magnetic field

muon – self analyzing polarimeter



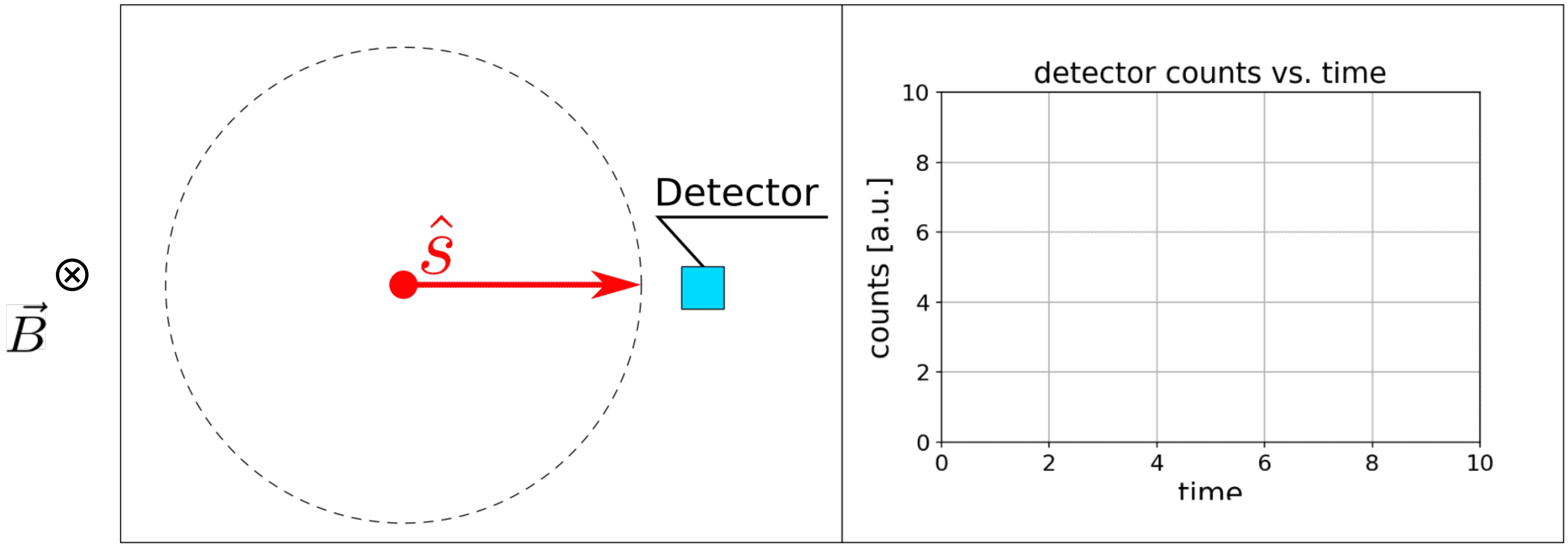
$$\omega \sim (1 + a_\mu)B$$

decay electrons are highly correlated with muon spin



the wobbling of muon spin in a magnetic field can be observed by detecting decay positrons / electrons

measurement of spin precession (wobbling) in a magnetic field



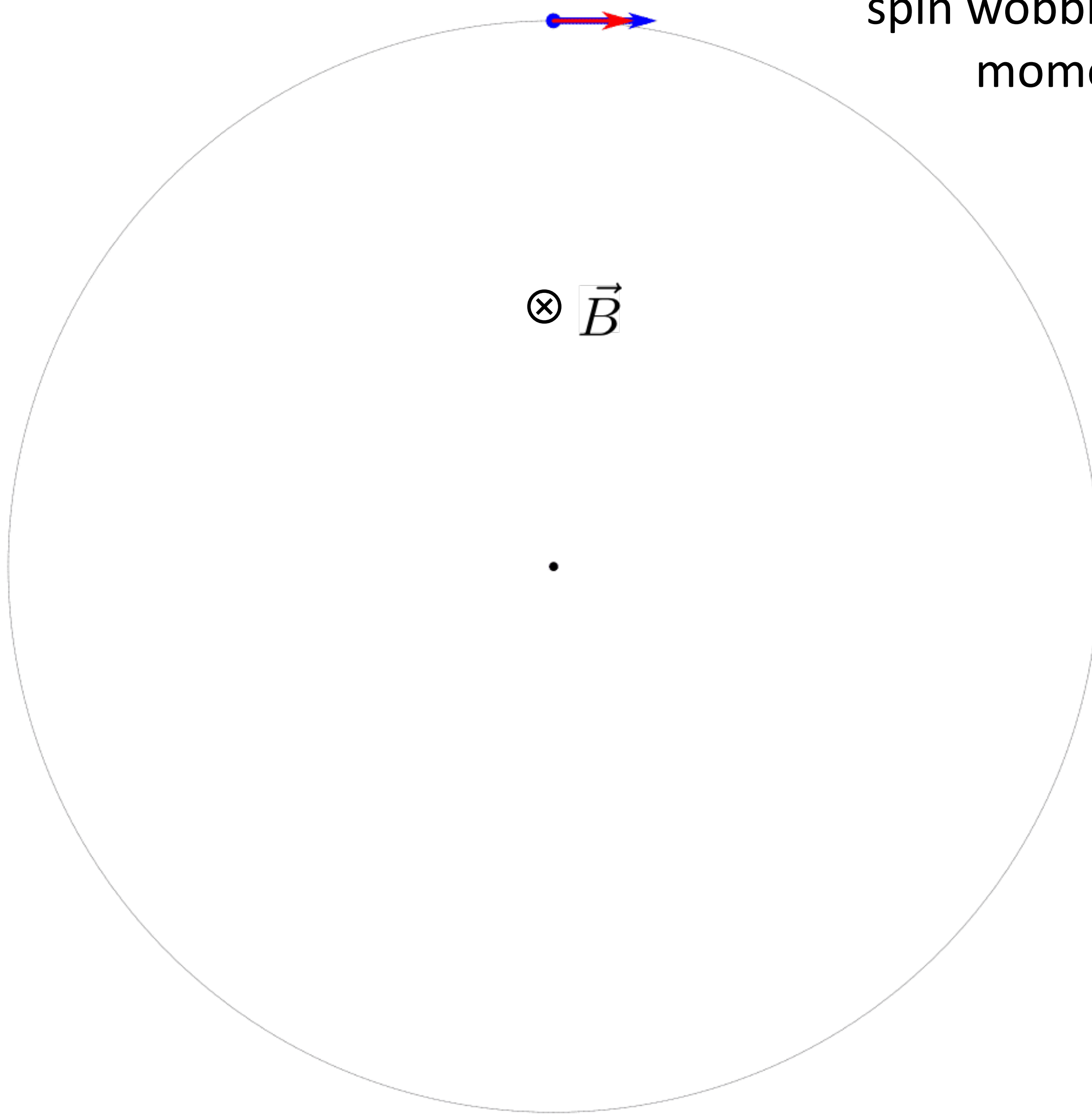
$$\omega_s \sim (1 + a_\mu) B$$

$$\Delta a_\mu \sim \frac{\Delta \omega_s}{a_\mu} \approx 1000 \cdot \Delta \omega_s$$

1% $\qquad$ 0.001%

To measure a_μ to 1% we need to measure the frequency to 0.001%

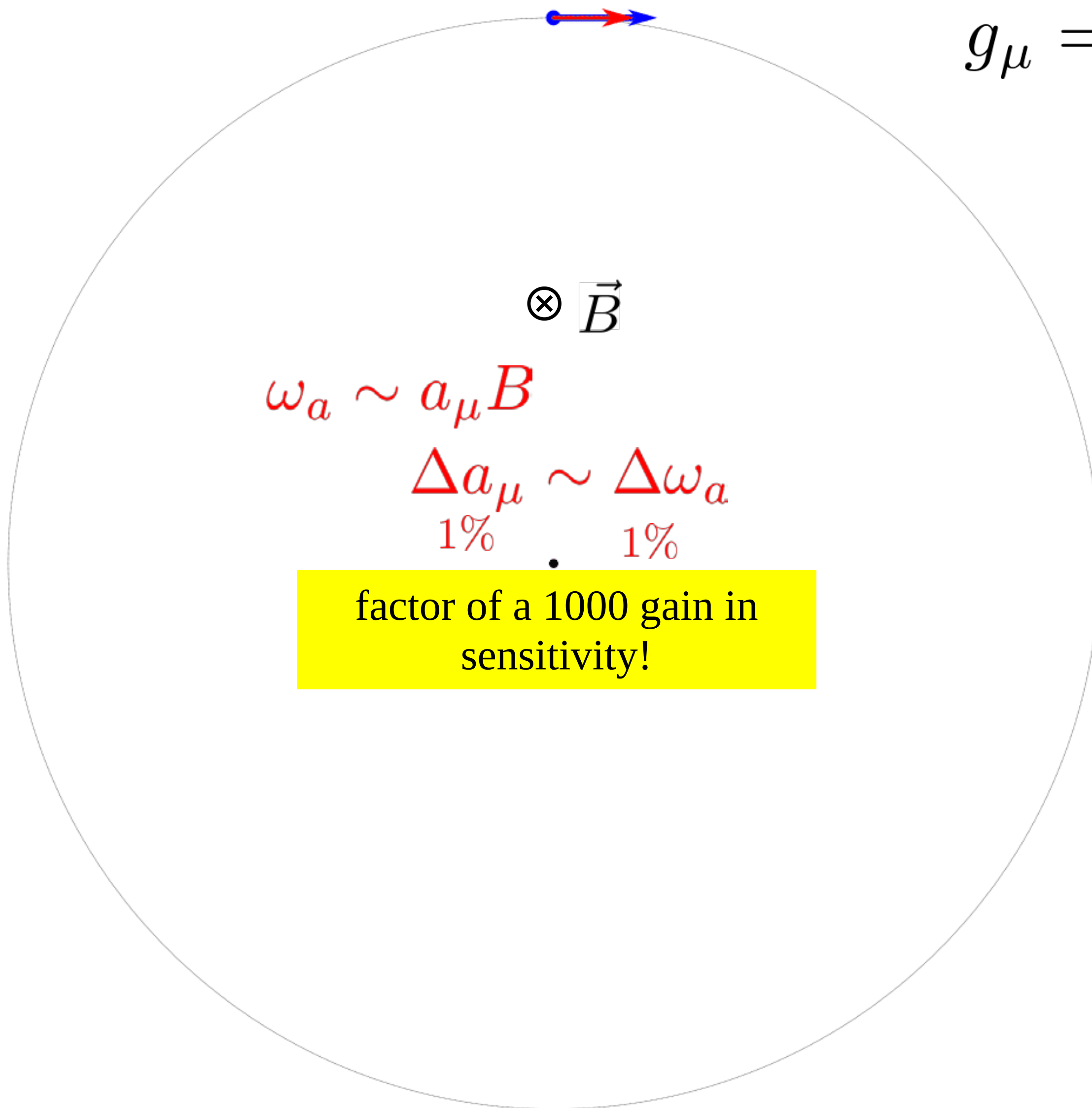
$g_\mu = 2$ $a_\mu = 0$



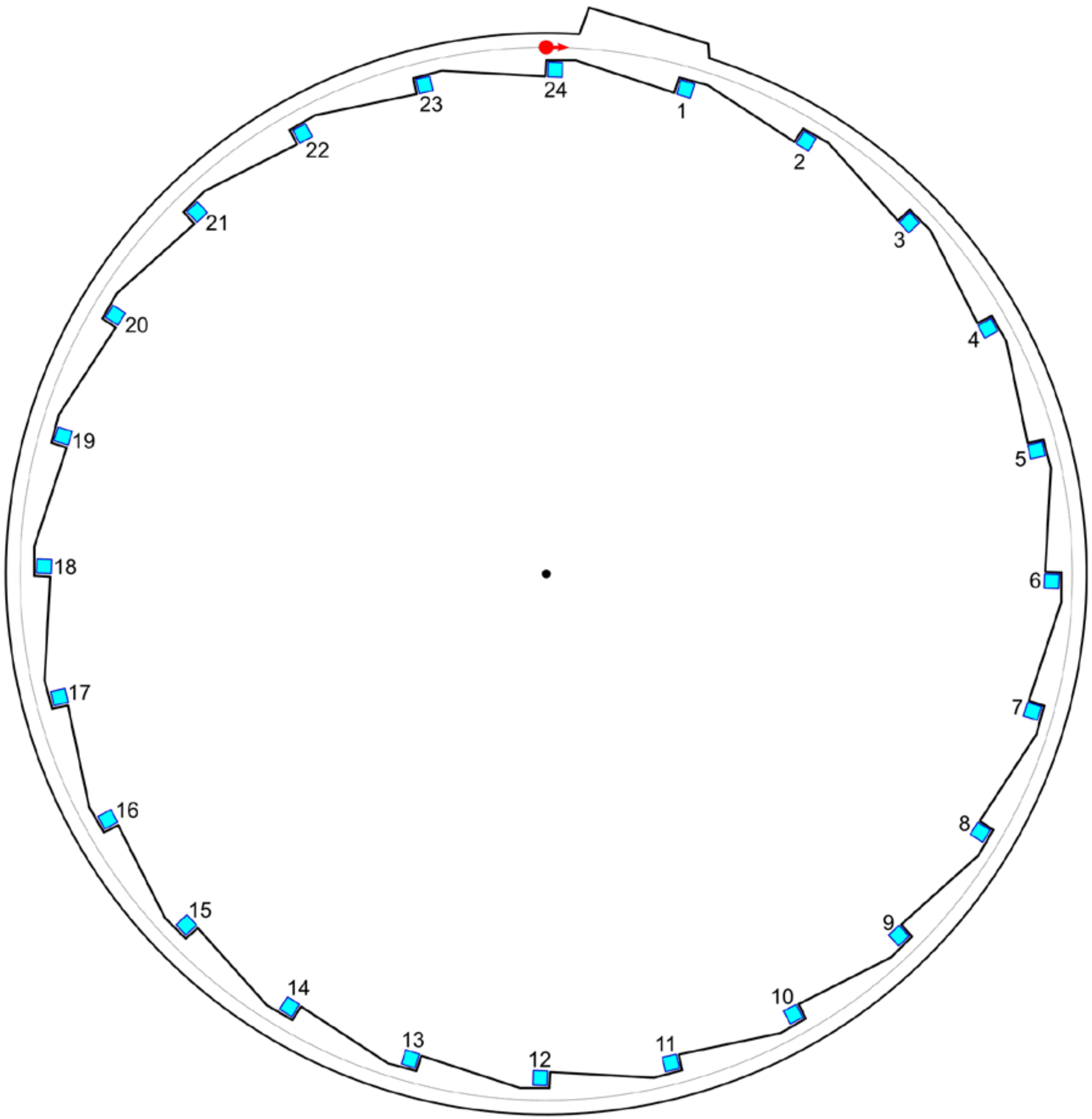
spin wobbles at the rate of momentum (velocity) vector rotation

The spin of a muon orbiting in a magnetic field rotates relative to momentum vector at the frequency of muon magnetic anomaly!

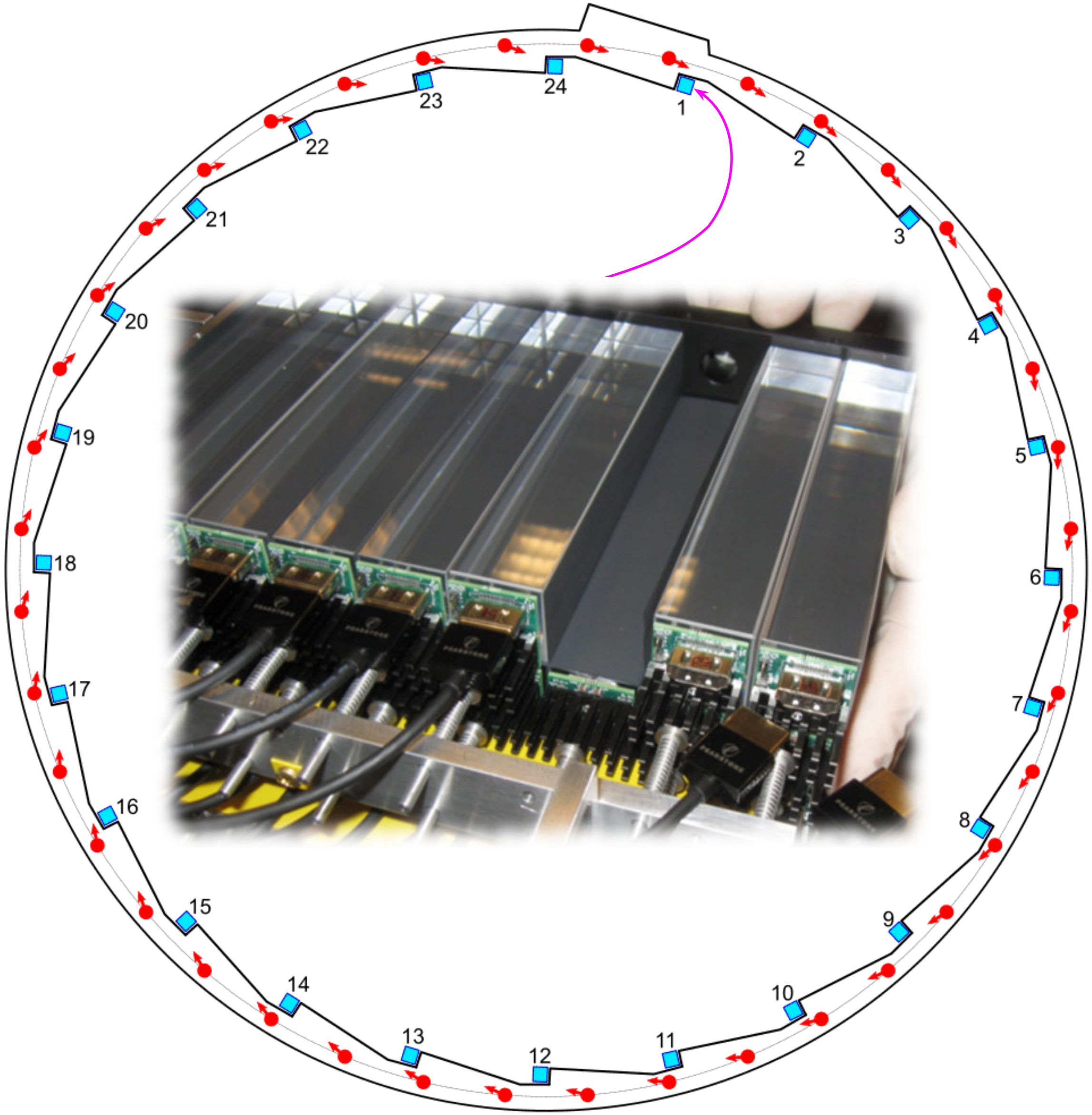
$$g_\mu = 2(1 + a_\mu)$$



in one turn around the ring the spin rotates by 12°

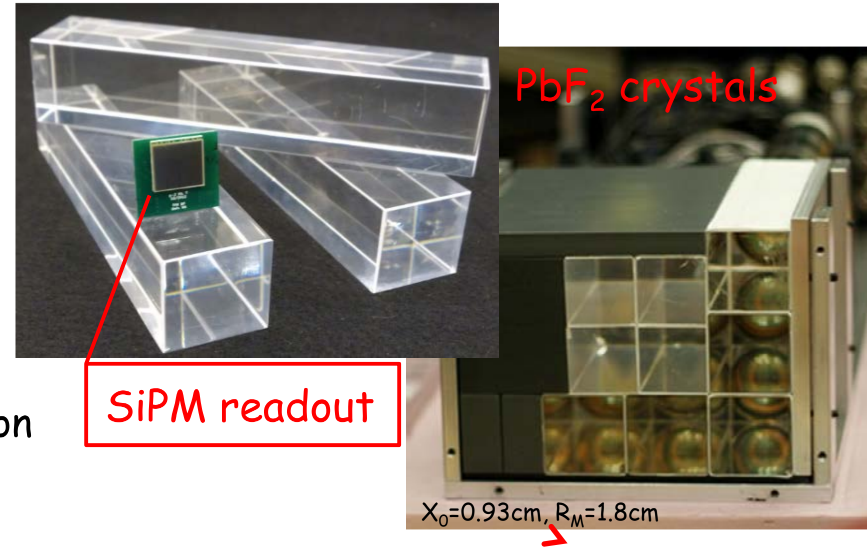


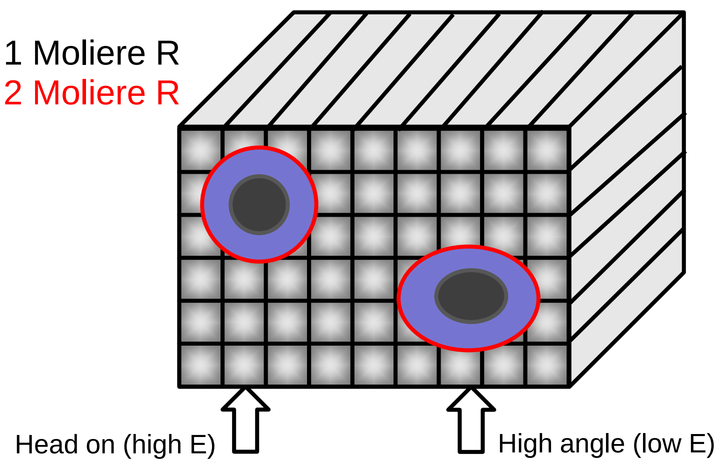
decay positrons are detected by 24 calorimeters

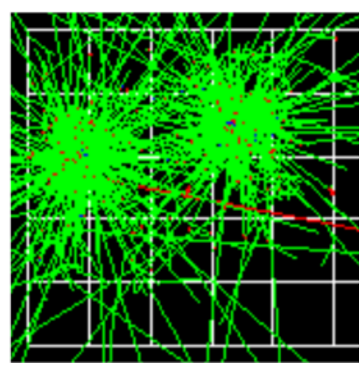


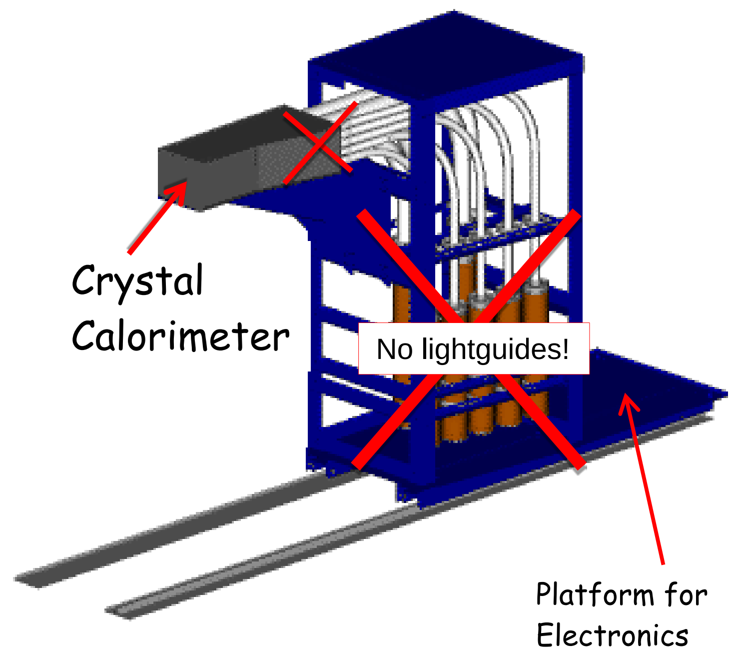
New calorimeters

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

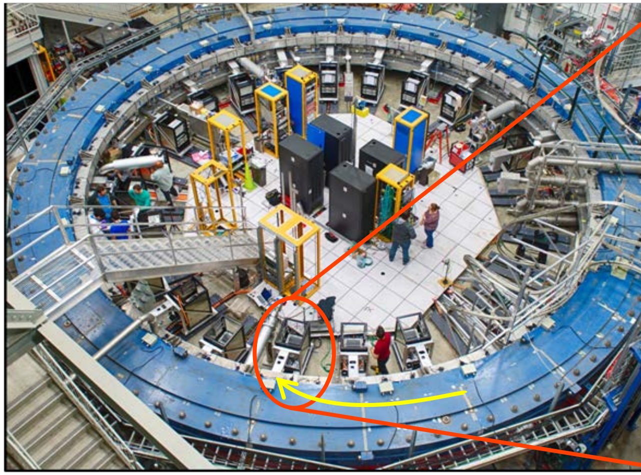


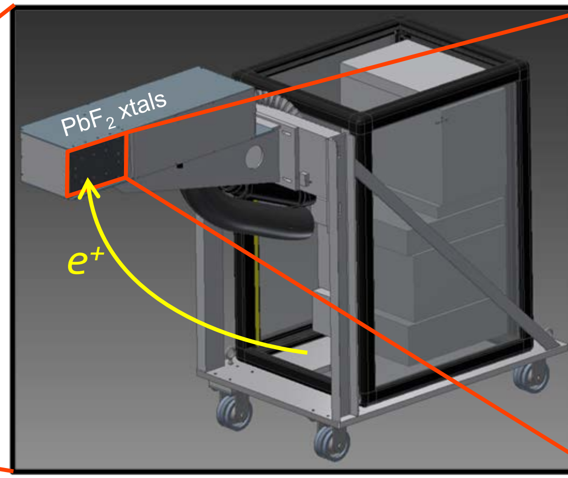




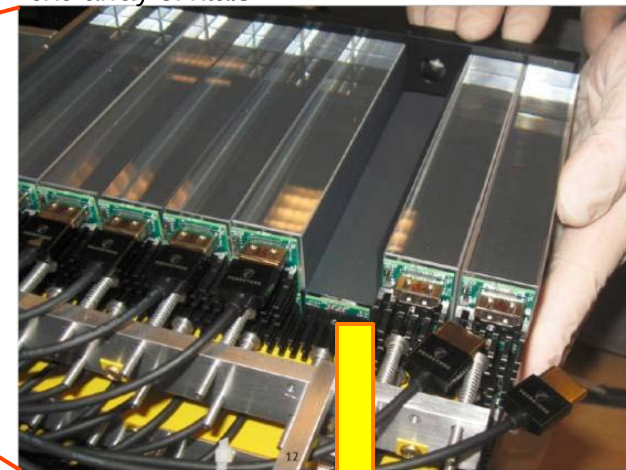


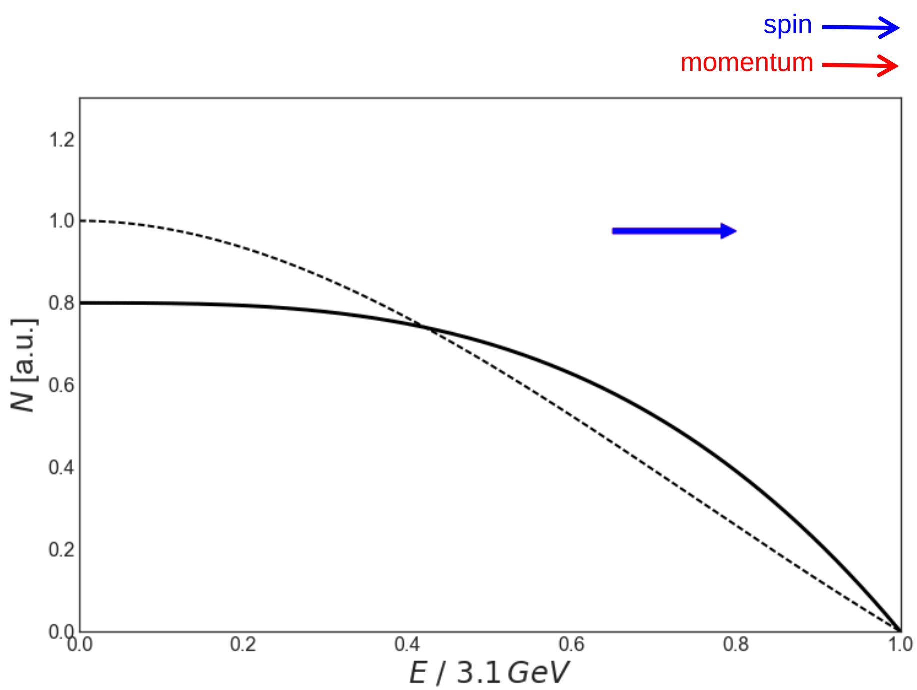
is derived from a time histogram of high-energy e^+ decay events

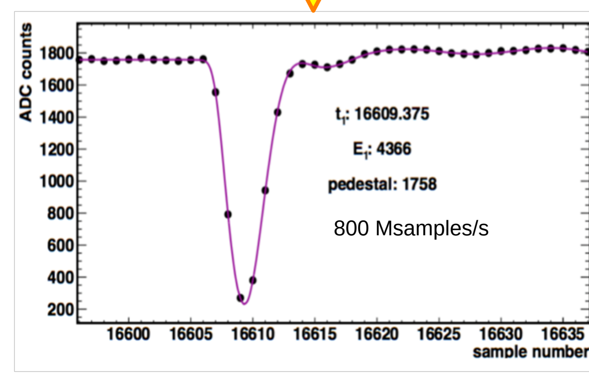




6x9 array of xtals







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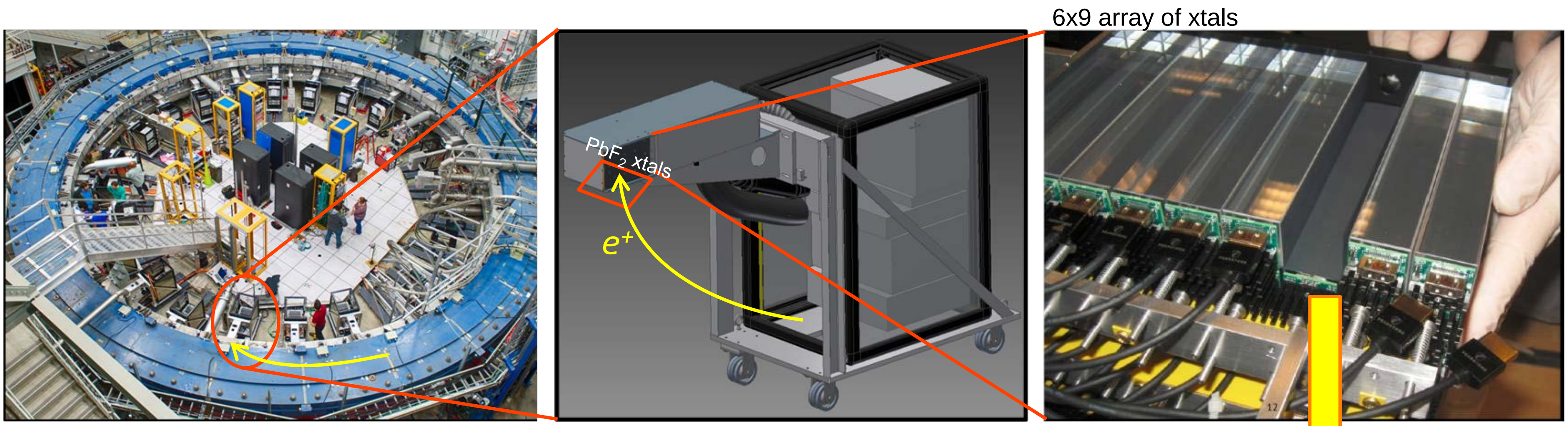
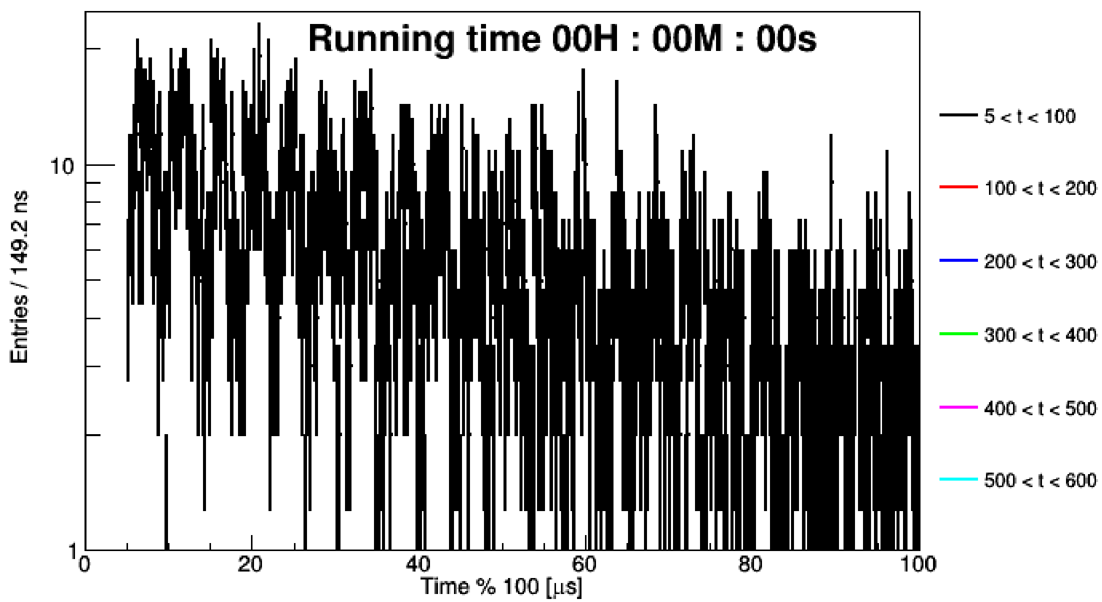
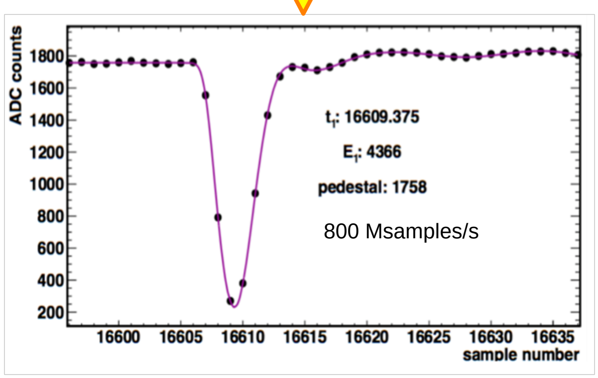
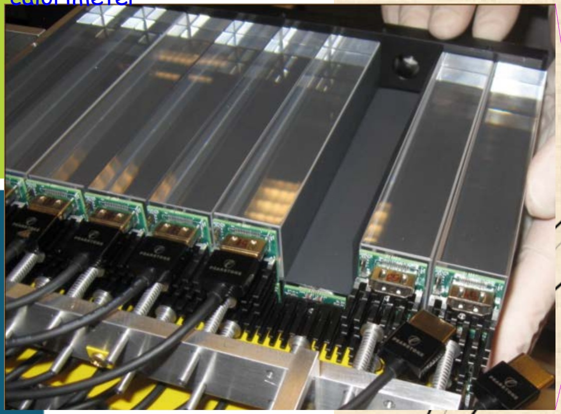
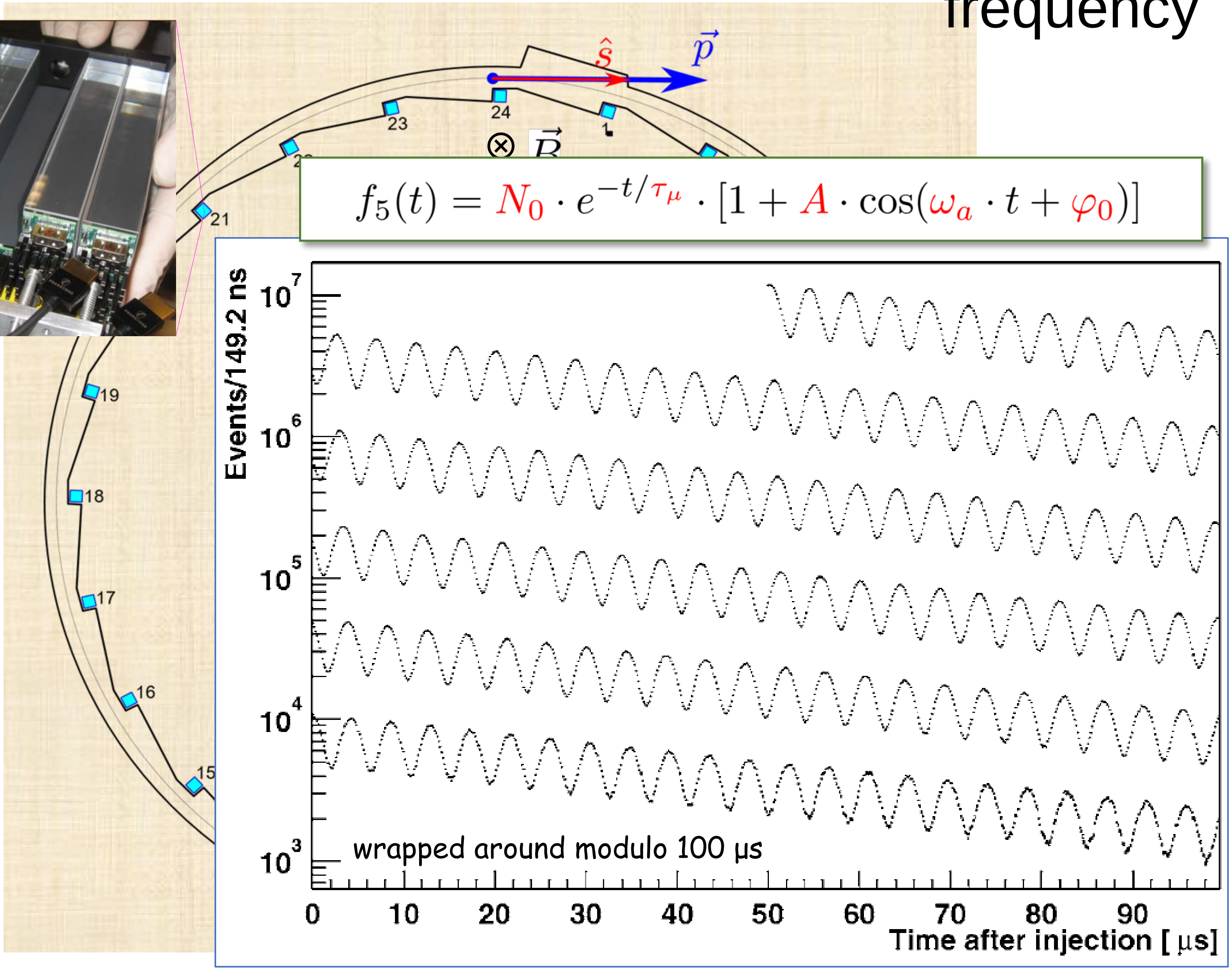






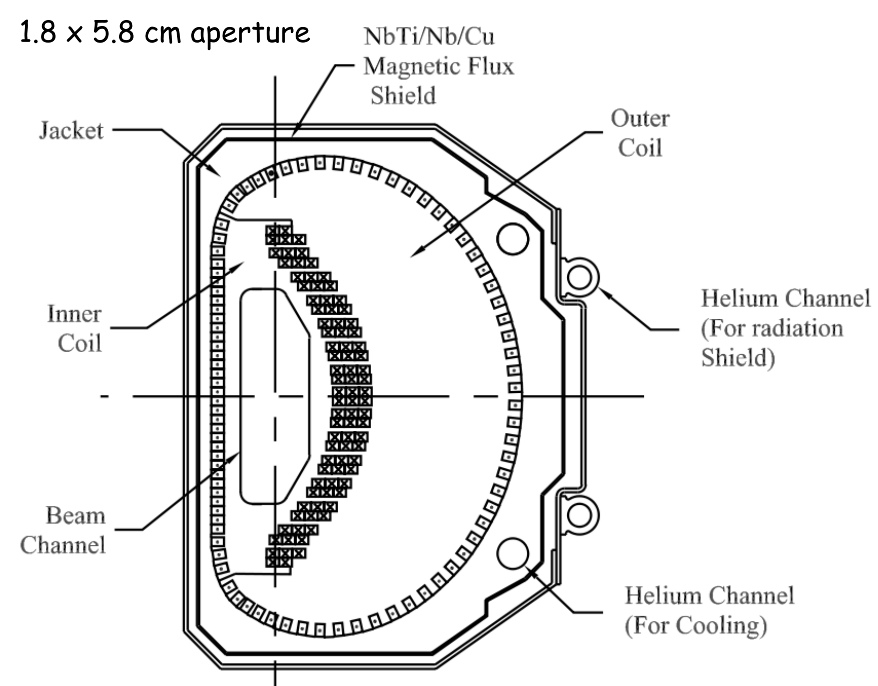
detector counts undulated at anomalous precession frequency



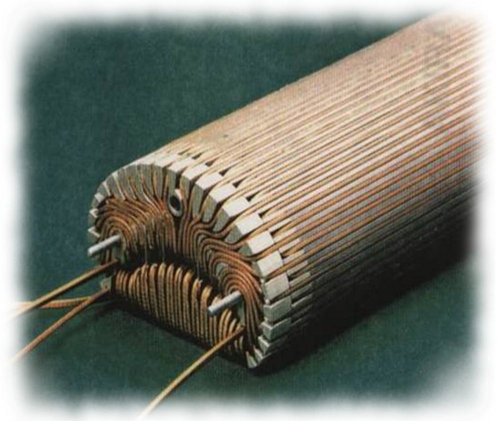


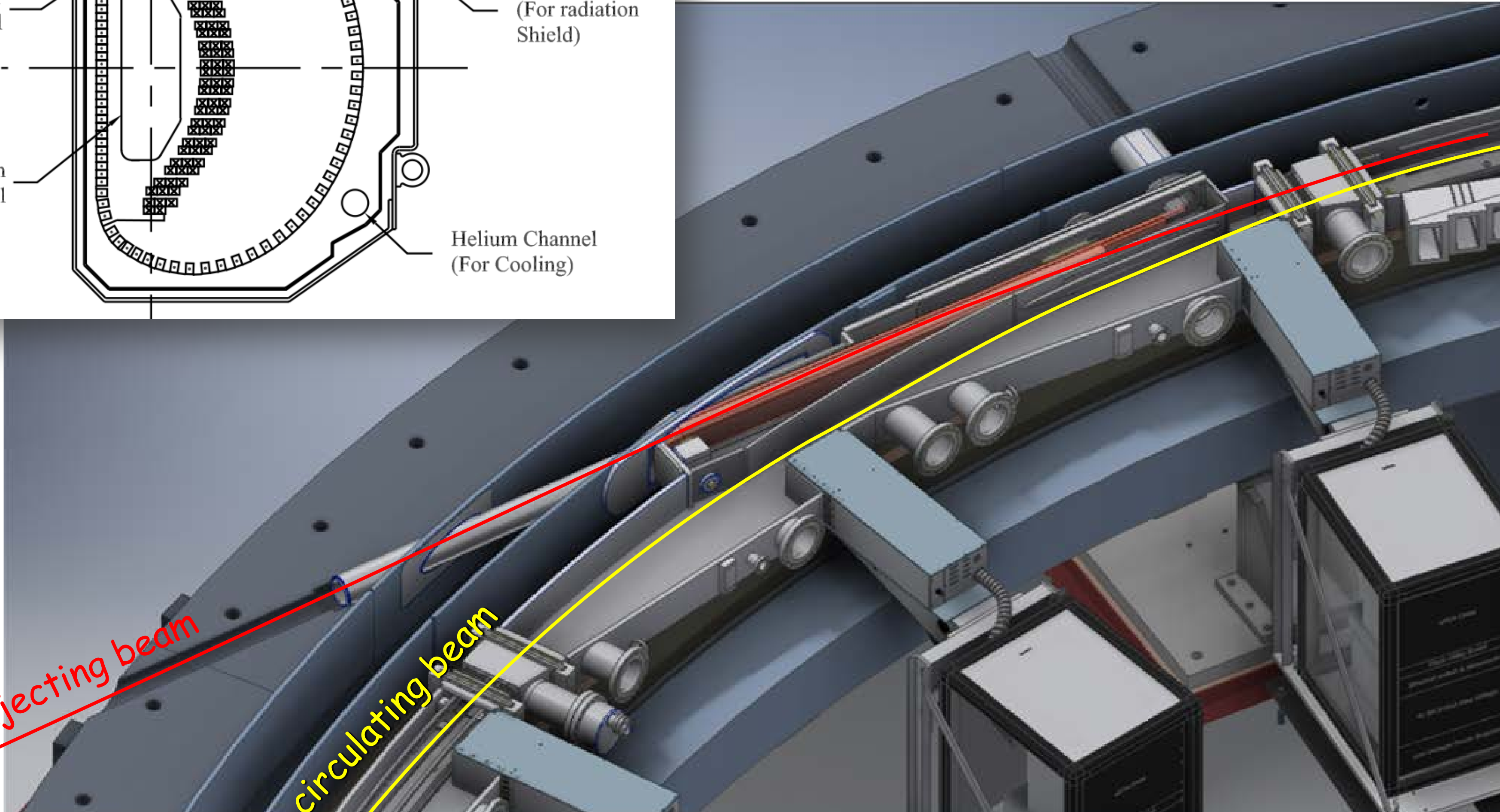
$$f_5(t) = N_0 \cdot e^{-t/\tau_\mu} \cdot [1 + A \cdot \cos(\omega_a \cdot t + \varphi_0)]$$

Superconducting Inflector

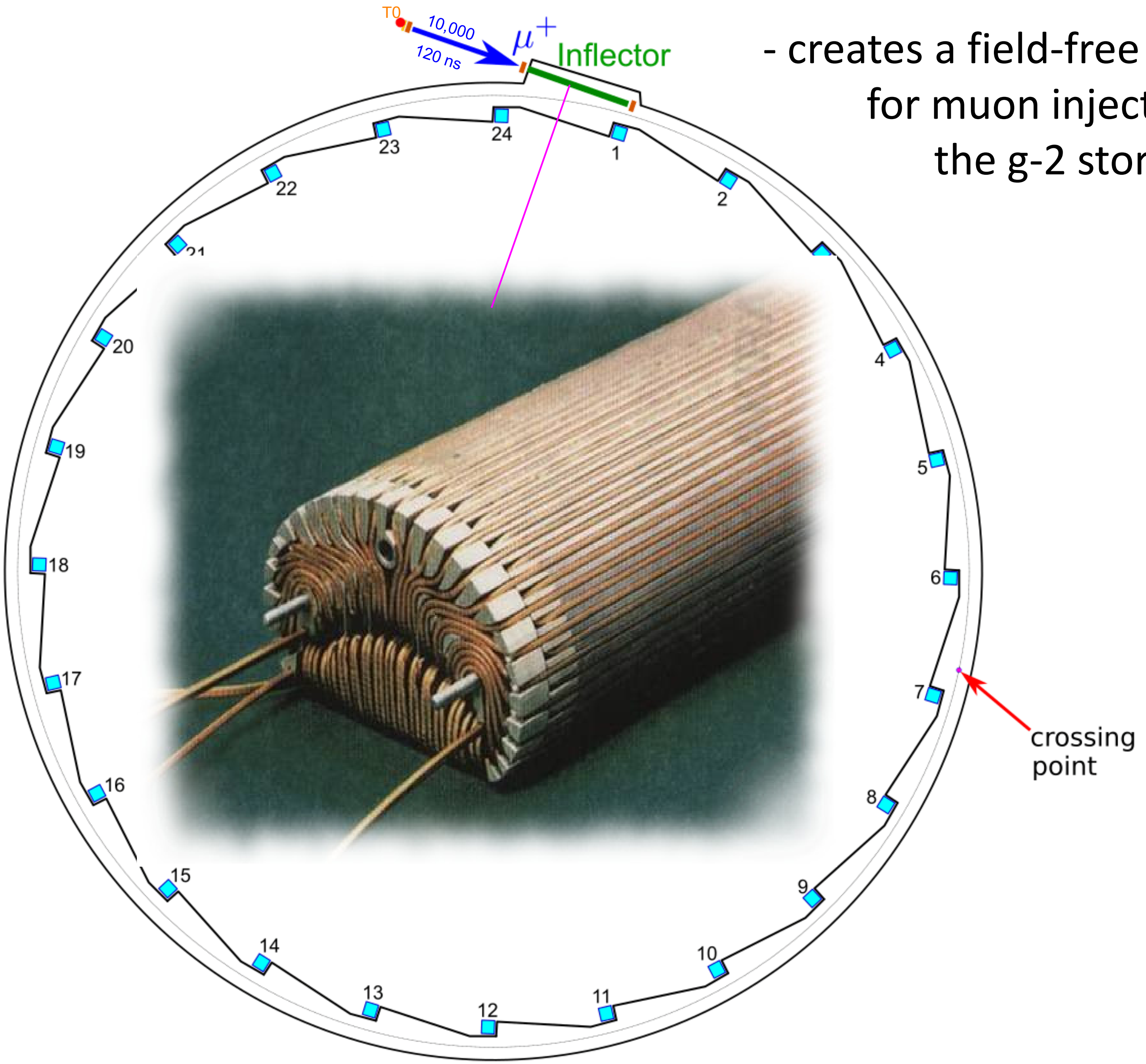


- creates a field-free channel for muon injection into the g-2 storage ring



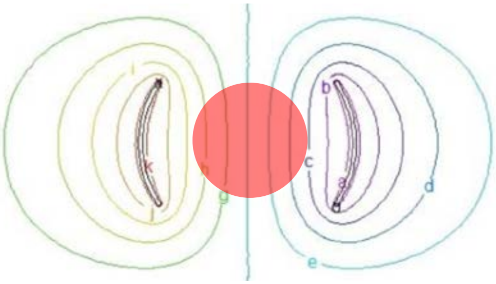


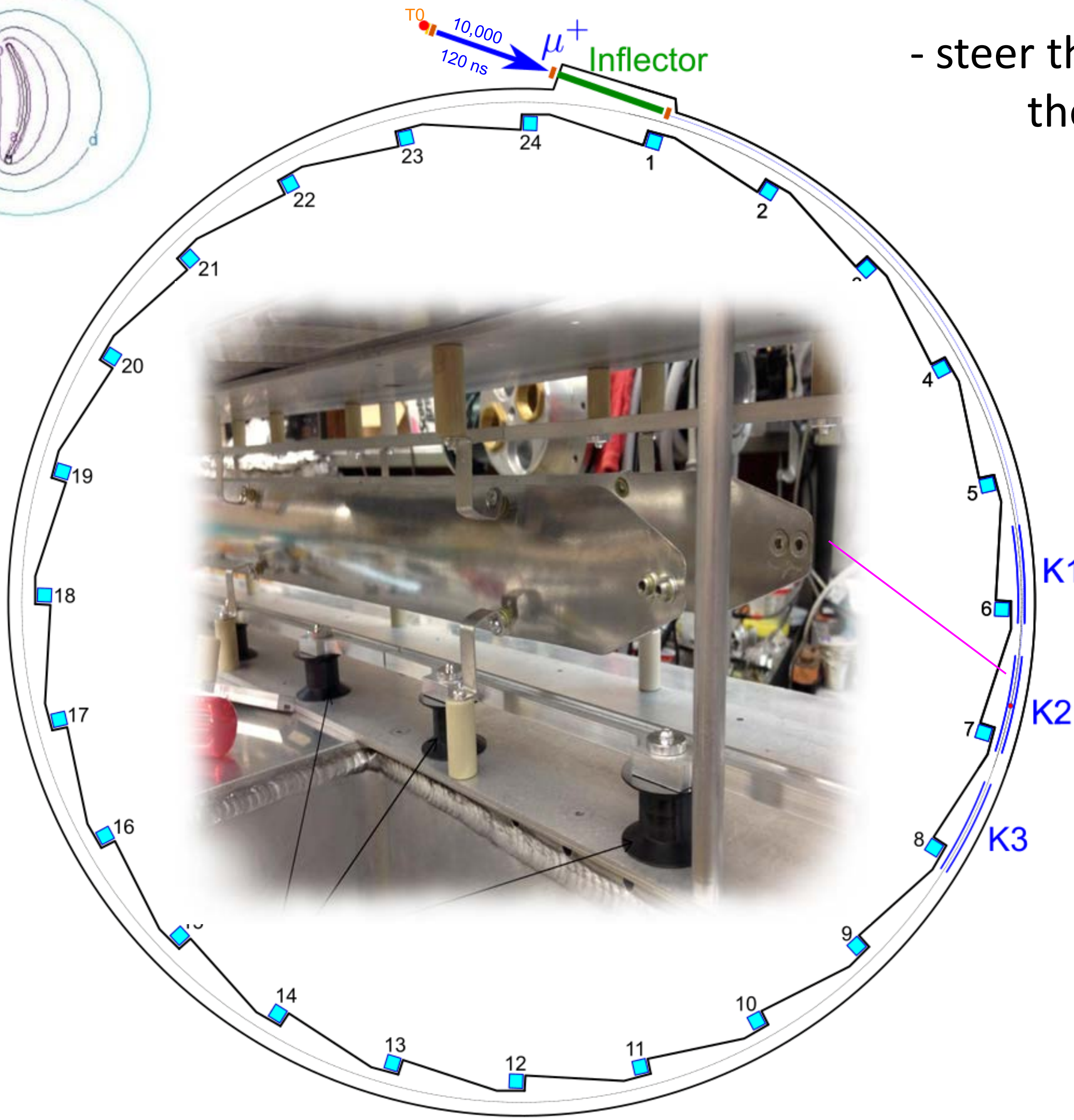
superconducting inflector



- creates a field-free channel for muon injection into the g-2 storage ring

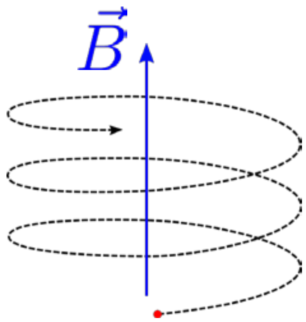
fast non-ferrick kickers

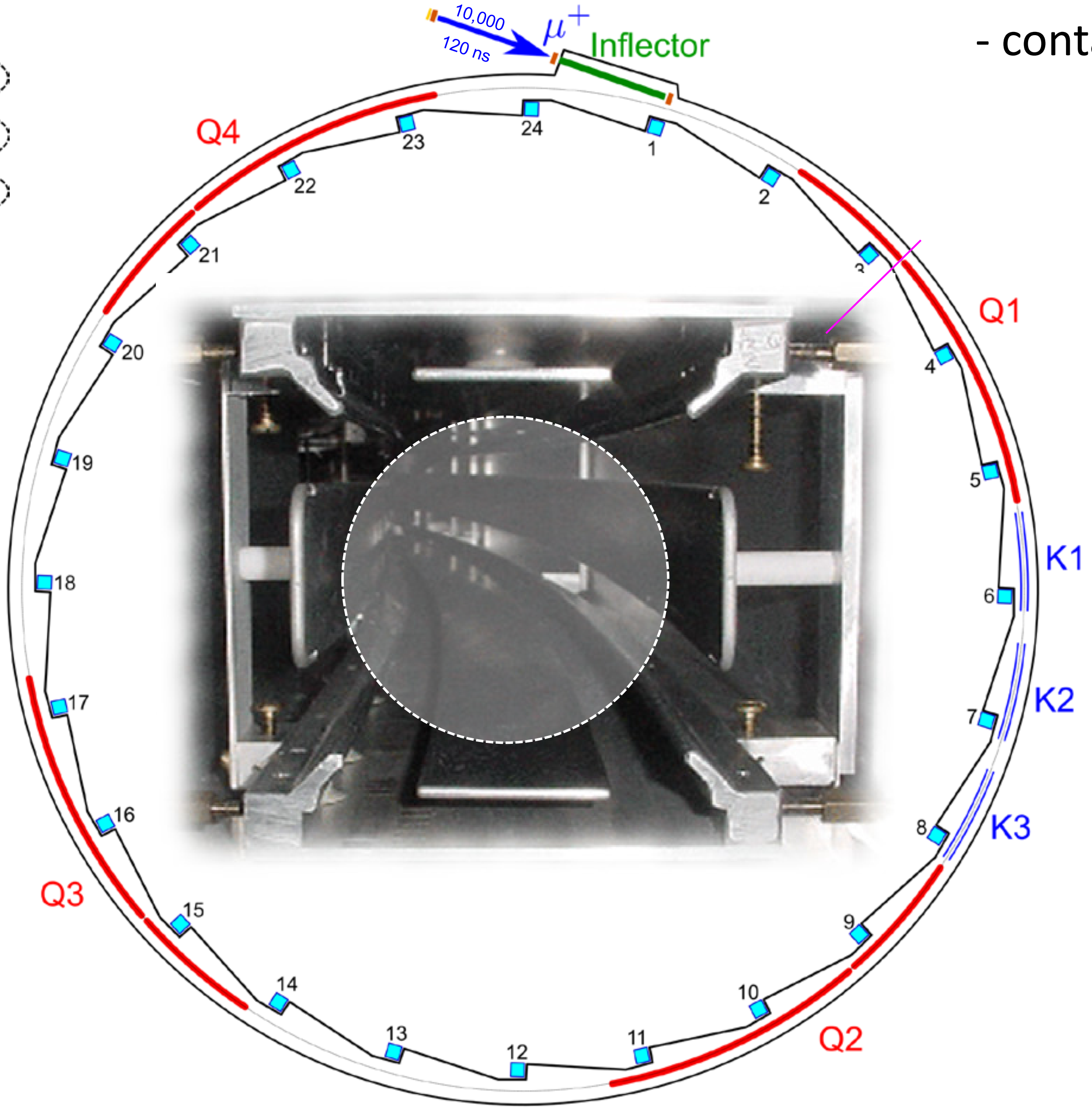




- steer the beam onto the design orbit

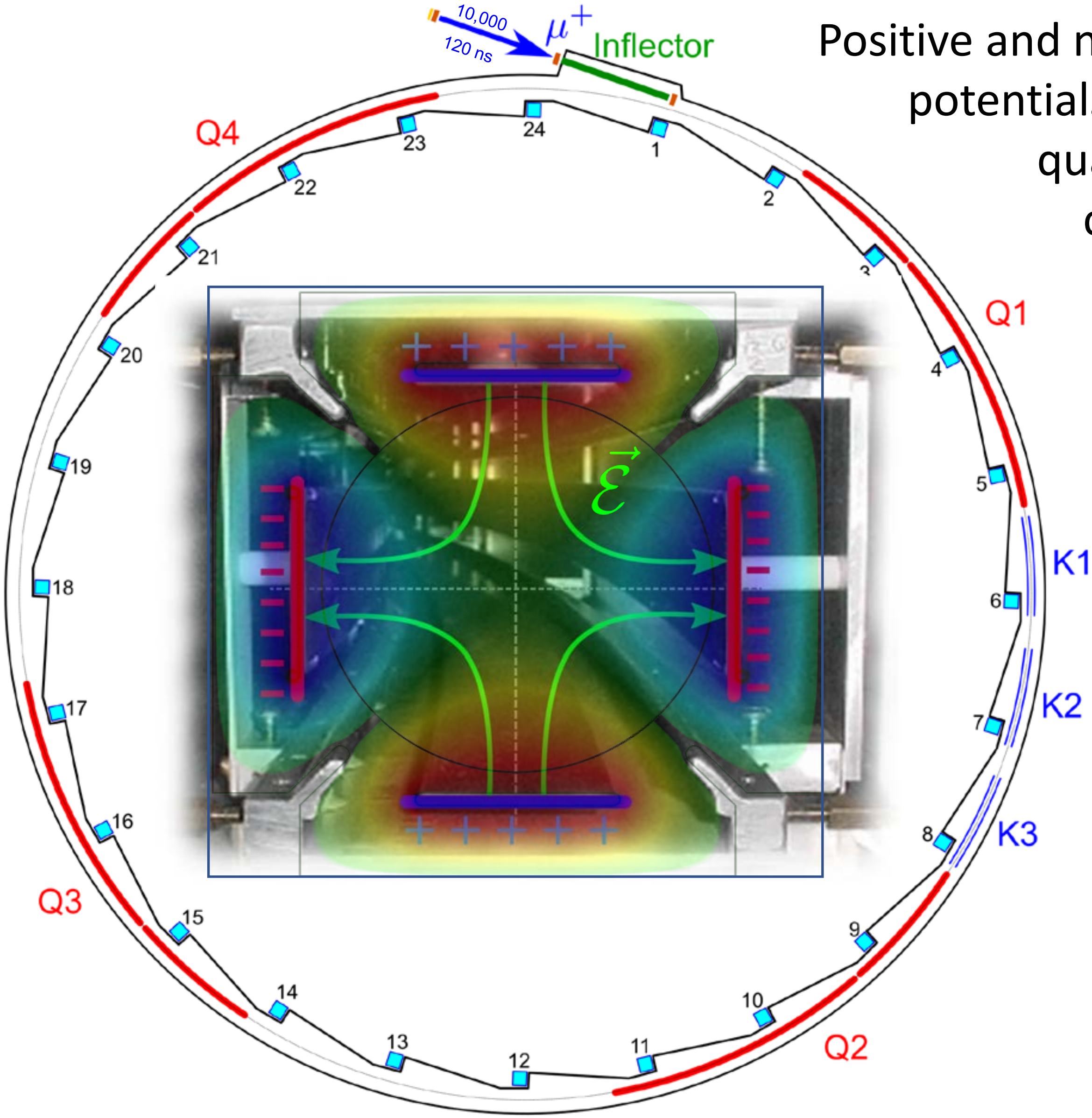
electrostatic quadrupoles





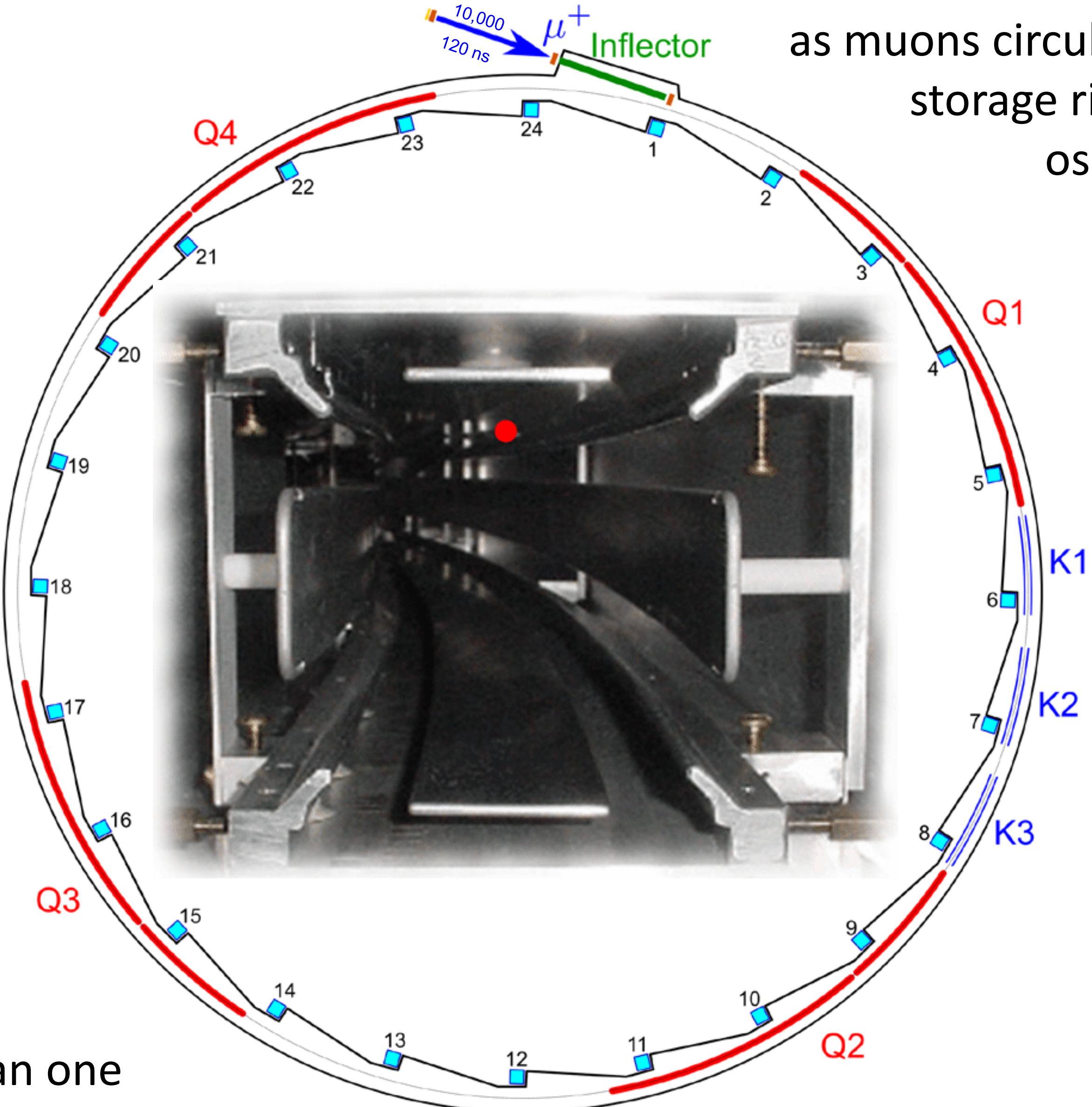
- contain the beam vertically

electrostatic quadrupoles



Positive and negative voltage potentials applied to the quadrupole plates create vertically focusing electrostatic quadrupole field

electrostatic quadrupoles



as muons circulate around the storage ring, they slowly oscillate between the plates

one oscillations takes longer than one revolution around the ring

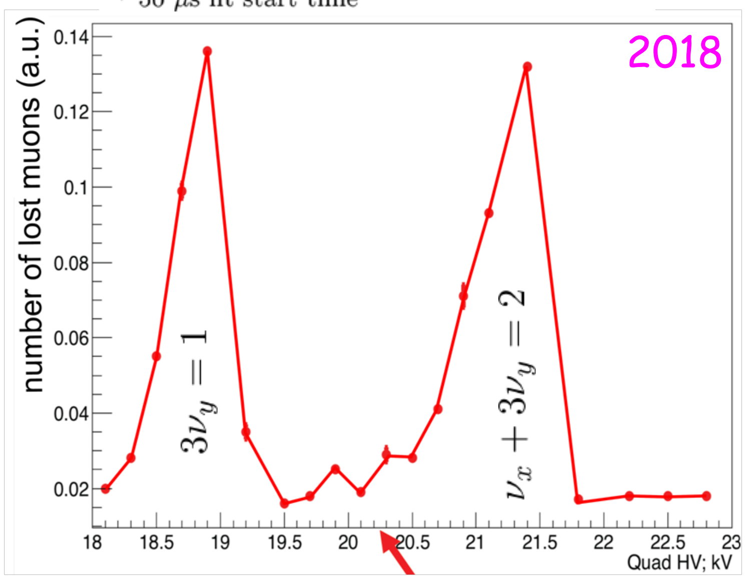
g-2 ring operating point for 2018 run

The ESQ system defines the operating point of muon g-2 storage ring, which must be chosen such that it is away from betatron and spin resonances. The theoretical analysis of resonance conditions was performed by BNL.

In 2018 run, the operation point of g-2 storage ring was chosen to minimize muon losses. The measured muon loss vs. ESQ voltage curve agrees well with theory expectation.

Run-1 data subset	ESQ (kV)	Kicker (HV)	$\delta\omega_a^m$ (stat) ppb
Run-1a	18.3	130	1206
Run-1b	20.4	137	1024
Run-1c	20.4	130	825
Run-1d	18.3	125	676†

† 50 μs fit start time



Sudeshna Ganguly, Muon g-2 internal note #11085

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

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

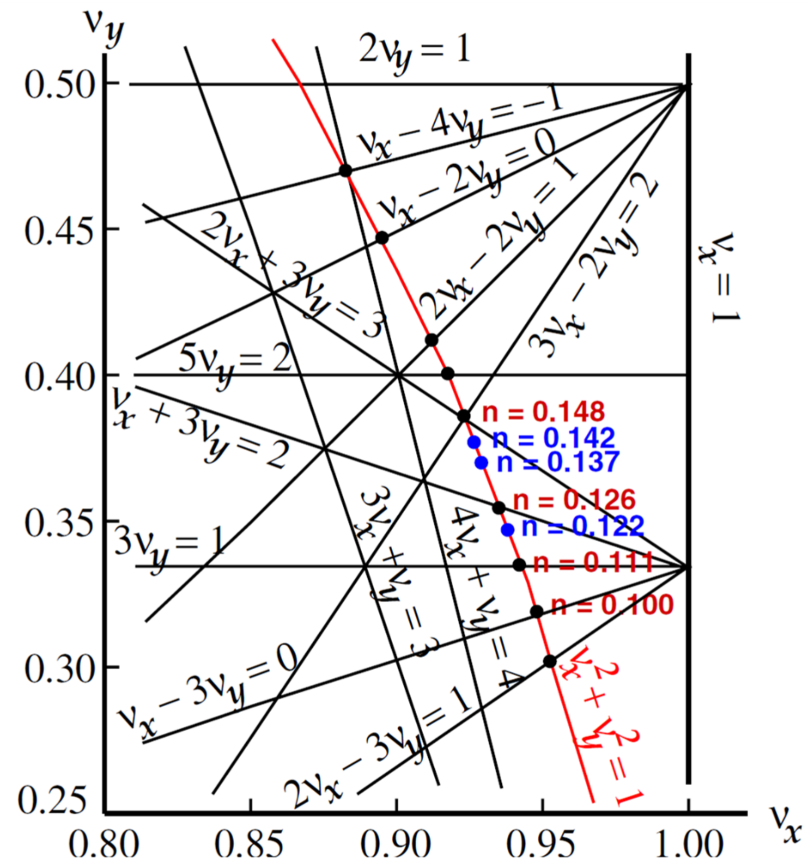
resonance conditions:

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

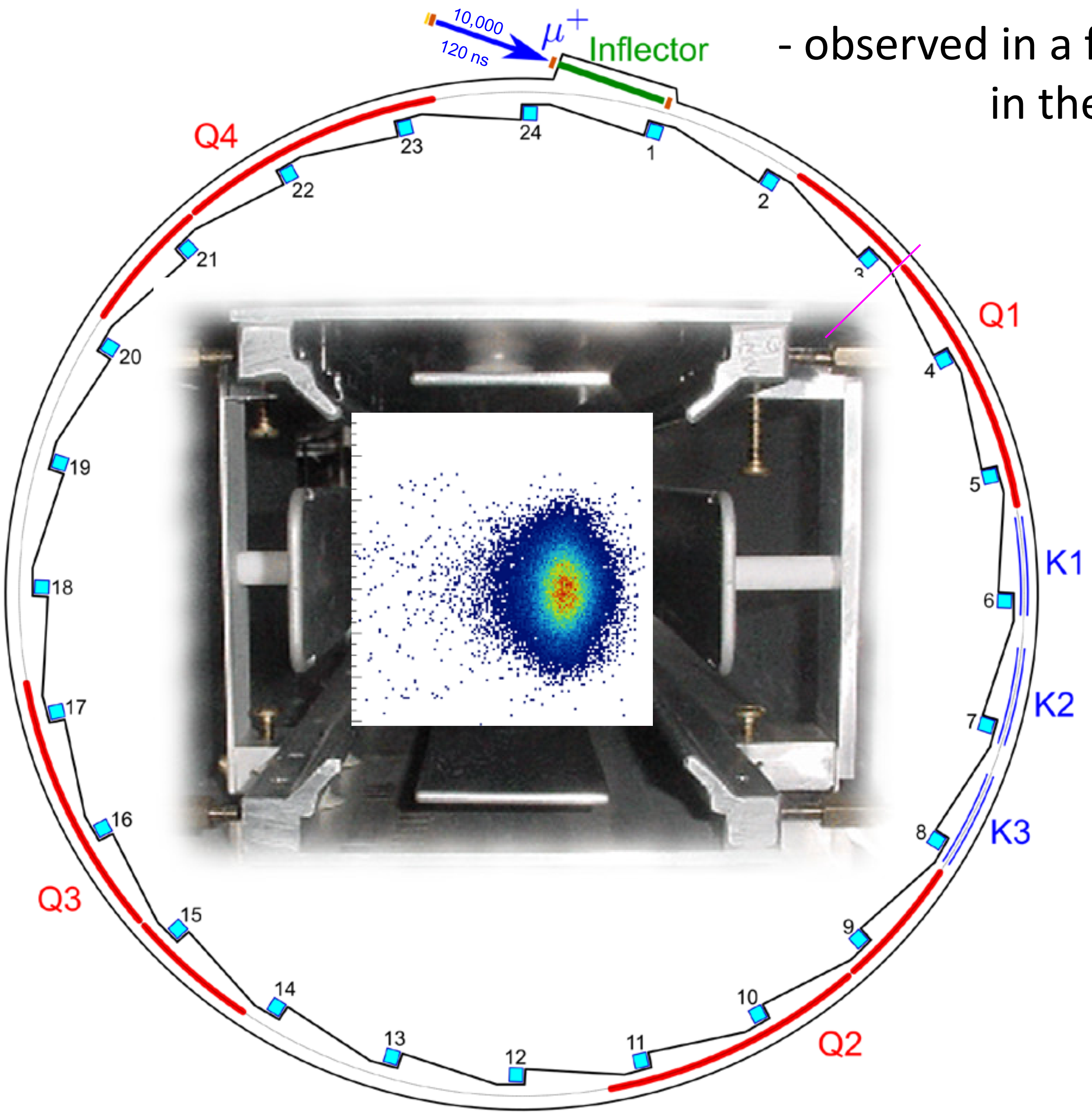
$$L\nu_x + M\nu_y \pm N = a_\mu\gamma \text{ (spin)}$$

where L, M, N are integers.

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

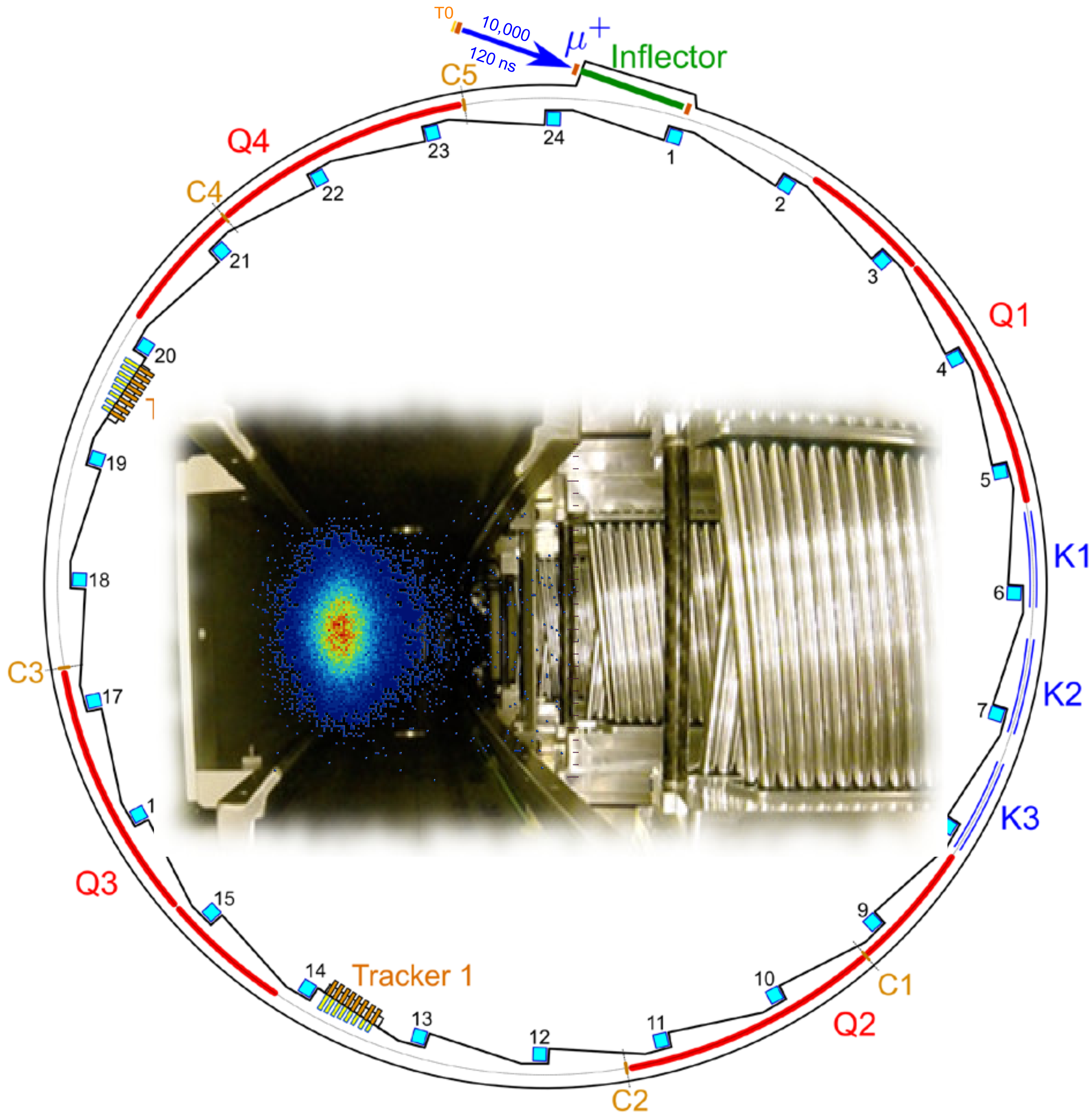


coherent beam oscillations

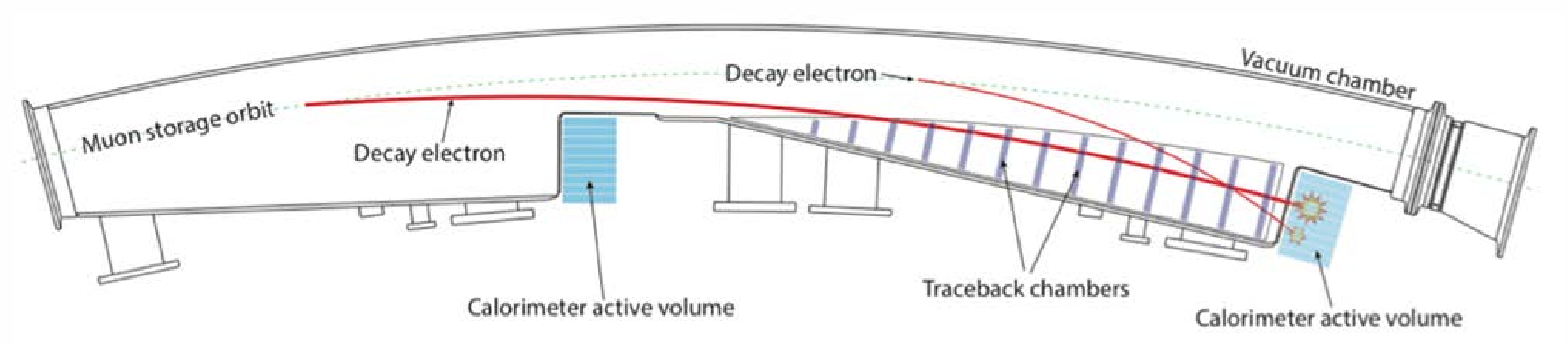


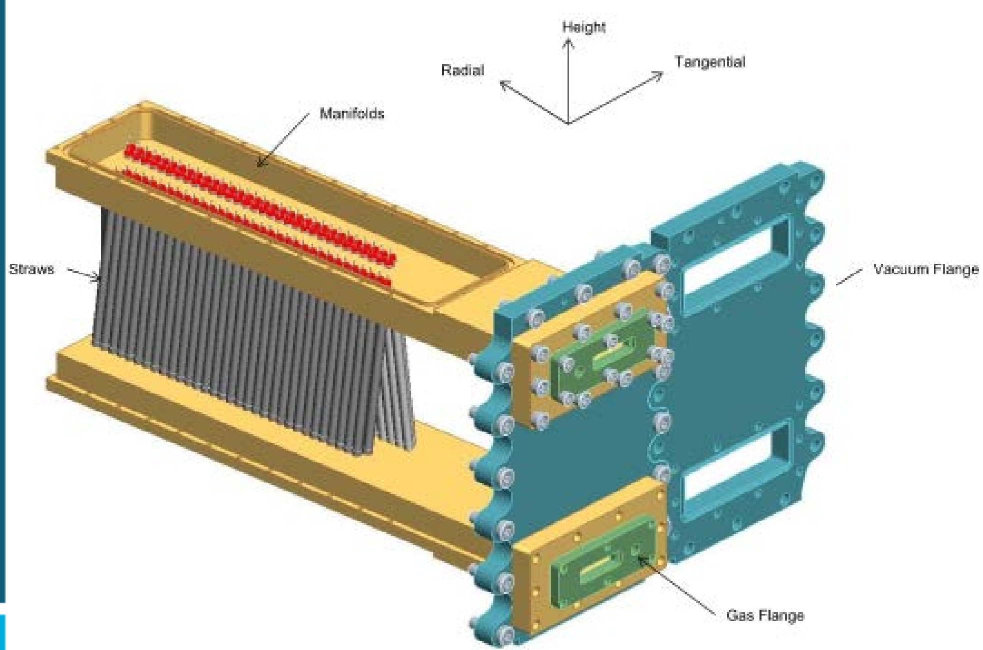
- observed in a fixed location in the storage ring

tracker detectors measure the beam oscillations



FNAL: new in-vacuum Tracker Detectors



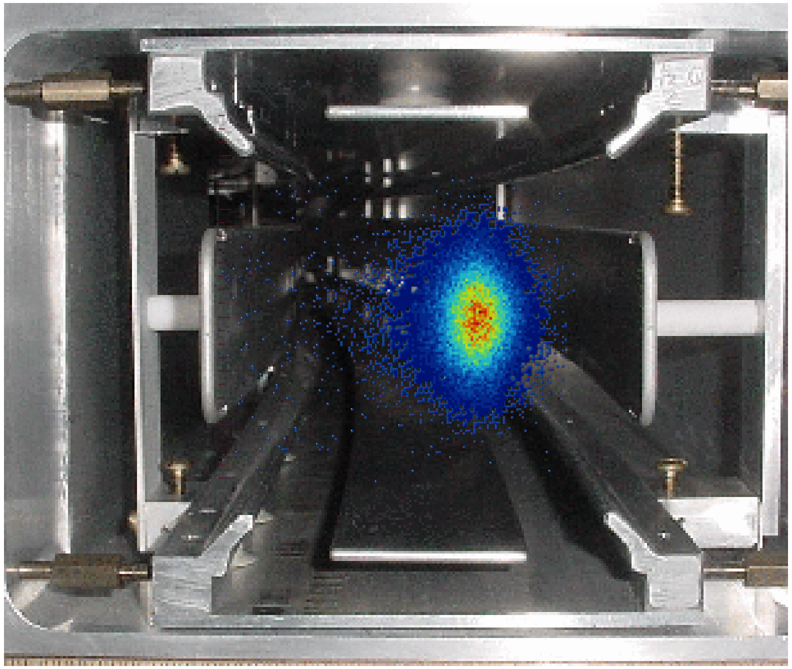


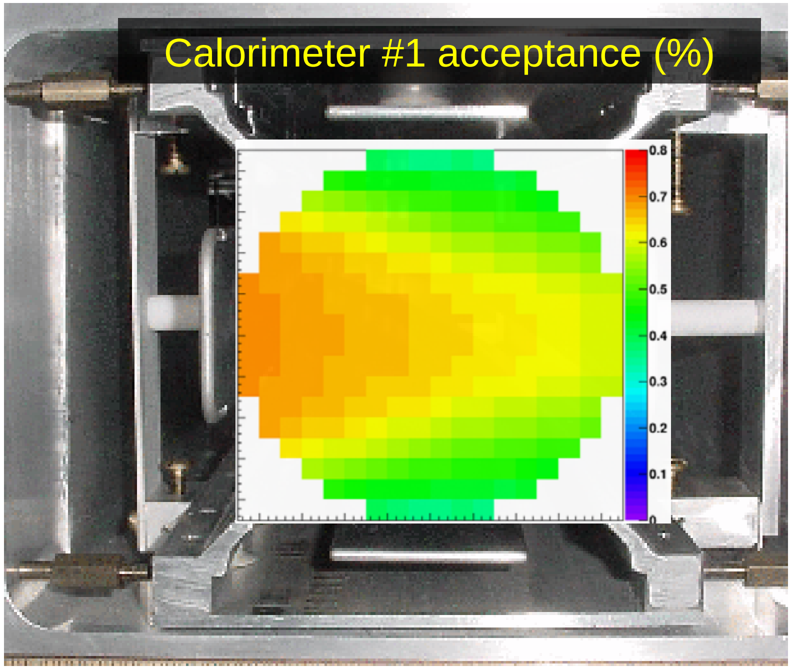
Purpose: measure the muon beam profile at multiple locations around the ring as a function of time throughout the muon fill. Is needed for quantifying systematic uncertainties associated with with ω_a measurements. Will also be used to search for a tilt in the muon precession plane away from the vertical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

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

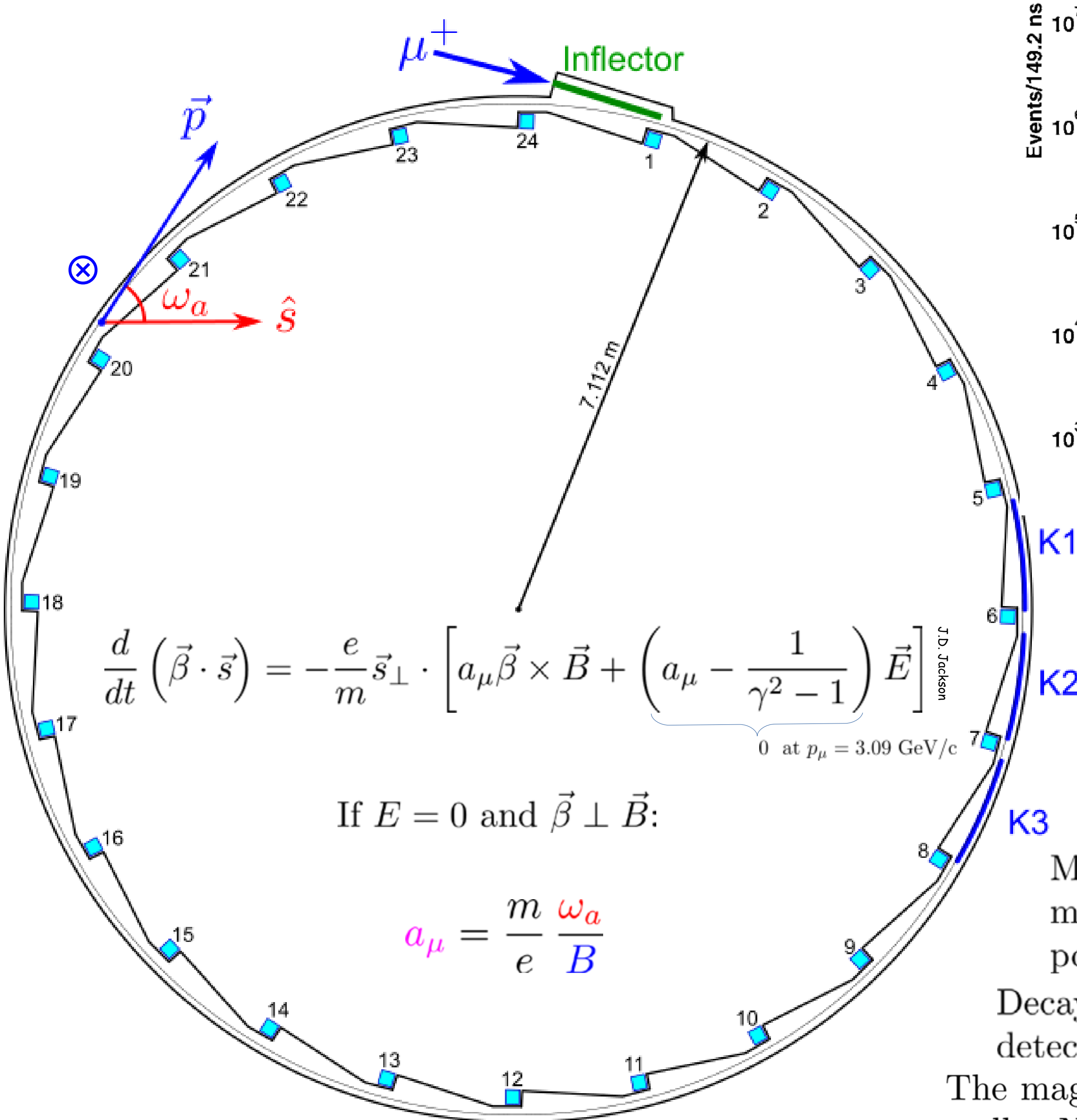
beam oscillations lead to systematic effects

$$f_5(t) = N_0(t) \cdot e^{-t/\tau_\mu} \cdot [1 + A(t) \cdot \cos(\omega_a \cdot t + \varphi_0(t))]$$





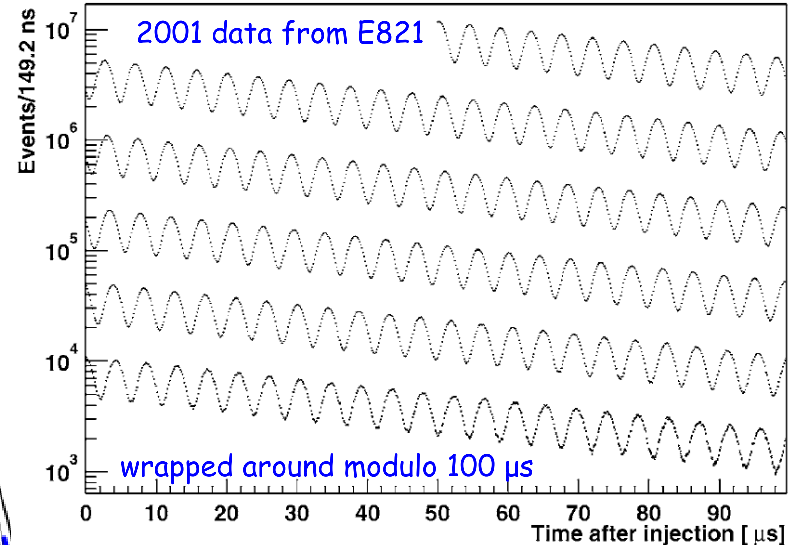
Muon g-2 experiment in a nutshell



$$\frac{d}{dt}\left(\vec{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s}_{\perp}\cdot\left[a_\mu \vec{\beta}\times\vec{B} + \underbrace{\left(a_\mu - \frac{1}{\gamma^2-1}\right)}_{0 \text{ at } p_\mu = 3.09\ \mathrm{GeV/c}}\vec{E}\right]$$

If $E = 0$ and $\vec{\beta}\perp\vec{B}$:

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



a_μ is determined by by measuring the precession rate ω_a of spin $\hat{s}$ relative to momentum $\hat{p}$ in the magnetic field B of a storage ring.

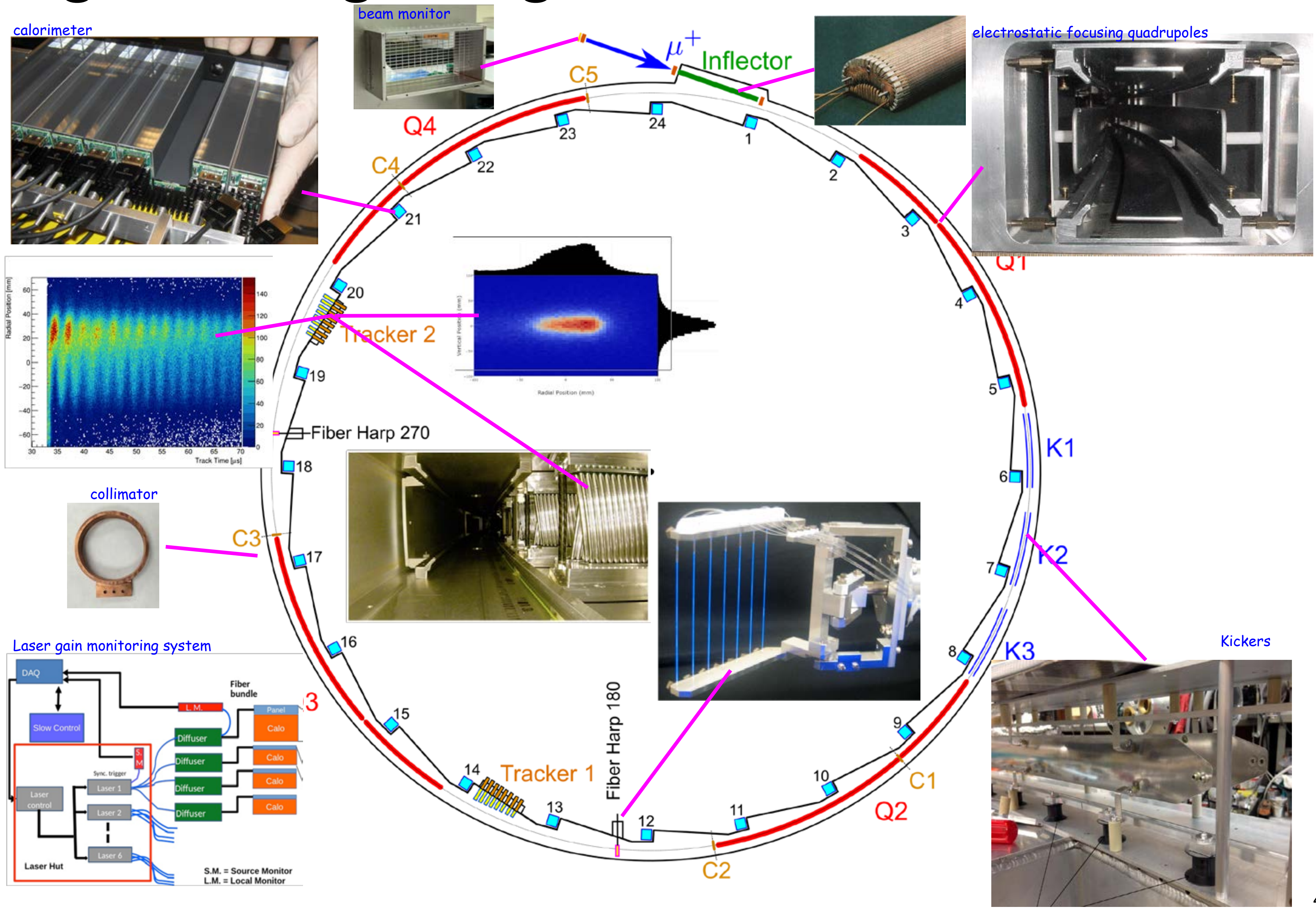
Muon spin precession translates into energy oscillation of decay electrons in the laboratory frame.

Muon spin precession signal is observed as a modulation of the time distribution of decay positrons by applying energy cut.

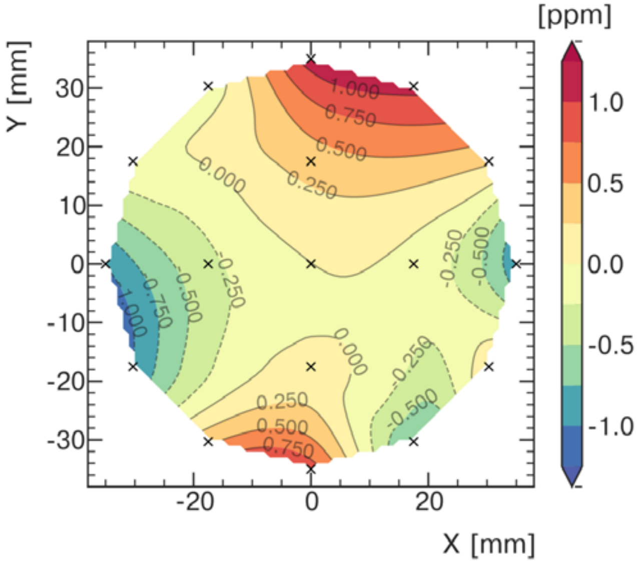
Decay positrons are detected by 24 calorimeter detectors.

The magnetic field is measured by 378 fixed and 17 trolley NMR probes $\rightarrow \omega_p$.

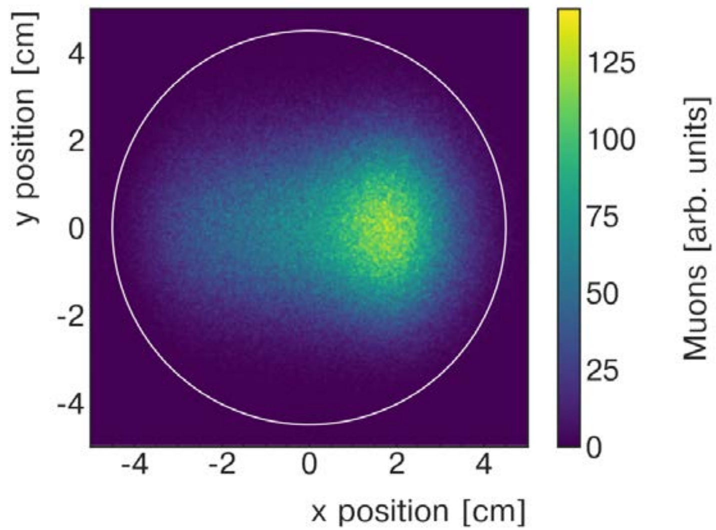
g-2 storage ring instrumentation

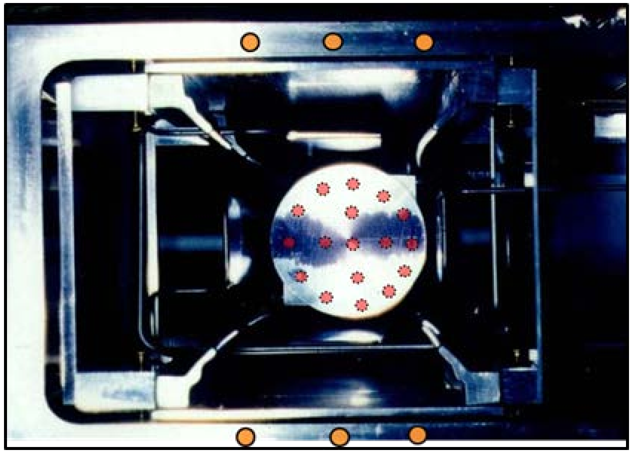


determination



$\otimes$





$$\tilde{\omega}'_p = \frac{\int_0^T \mathrm{d}t \int_0^{2\pi} \mathrm{d}\phi \int_{r_1}^{r_2} \mathrm{d}r \int_{-y_0}^{y_0} \mathrm{d}y \; r\rho^\mu(r,y,\phi,t)\omega'_p(r,y,\phi,t)}{\int_0^T \mathrm{d}t \int_0^{2\pi} \mathrm{d}\phi \int_{r_1}^{r_2} \mathrm{d}r \int_{-y_0}^{y_0} \mathrm{d}y \; r\rho^\mu(r,y,\phi,t)}$$

- Correction for transient fields from pulsed ESQ and Kicker
- Two different analysis methods
- Two independent analysis teams
- Total uncertainty: 114 ppb

a_μ determination from data

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

22 ppb

hyperfine splitting of muonium
CODATA

0.26 ppt

G. Gabrielse

10.5 ppb

$\mu'_p(T_r)$ proton shielded in a spherical water sample at $T_r = 34.7°$ C

$\mu_e(H)$ electron bound in H
Metrologia, 13(4), 1977

0.1 ppb

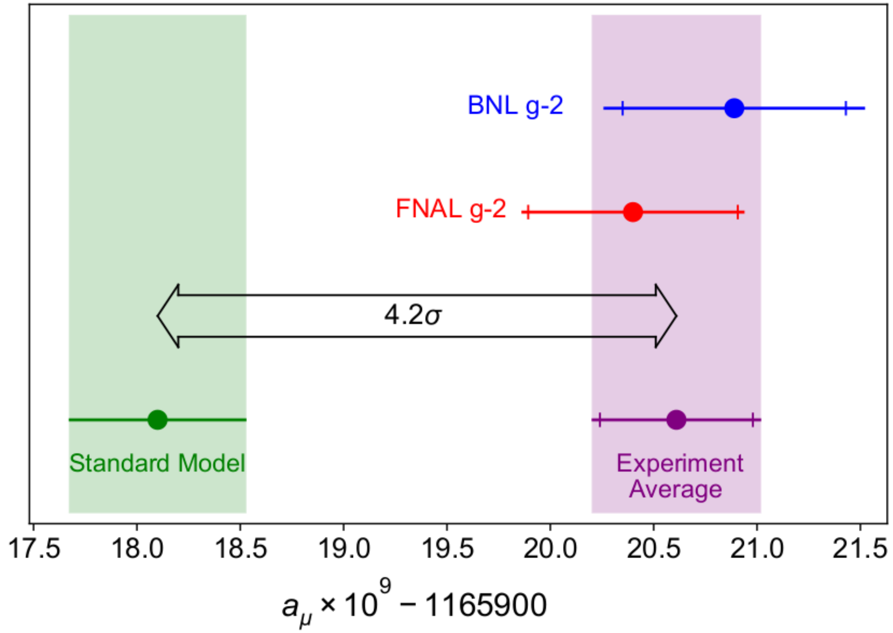
CODATA

systematic uncertainties in Run-1 at Fermilab

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu_p'(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

Fermilab run 1 result (2021)

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm}),$$
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm}).$$



From top to bottom: Experimental values of a_μ from BNL E821, FNAL E989 Run-1, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value for the Standard Model is also shown.

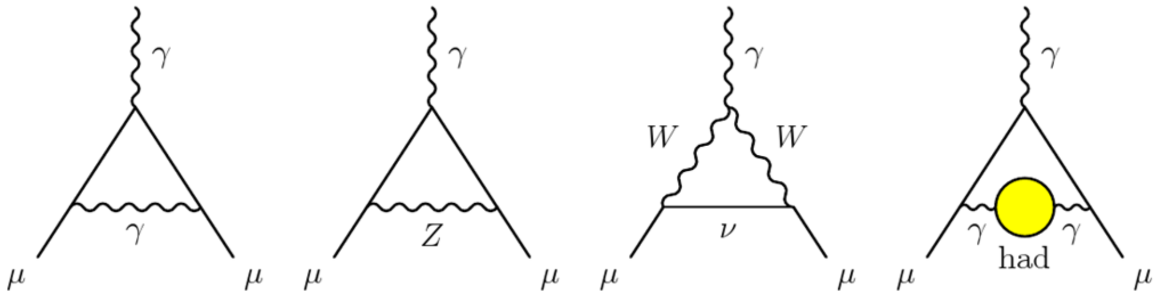
$$a_\mu(\text{FNAL}) - a_\mu(\text{SM}) = (230 \pm 69) \times 10^{-11}\ (3.3\sigma)$$
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}\ (4.2\sigma)$$

All particles contribute to a_μ

$$g_\mu = 2(1 + a_\mu)$$

$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{W}} + a_\mu^{\mathrm{Had}} + a_\mu^{\mathrm{NP}}$$

electromagnetic weak hadronic



+ New Physics

Source	value ($a_\mu \times 10^{-11}$)	error
QED	116 584 718.93	0.10
EW	154	1
HVP	6845	40
HLBL	92	18

sensitivity to new particles: $\sim m^2$

$\rightarrow$ muons are $\left(\frac{m_\mu}{m_e}\right)^2 \sim 40,000$ times more sensitive to New Physics than electrons!

Muon g-2 Theory Initiative

Physics Reports 887 (2020) 1–166

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The anomalous magnetic moment of the muon in the Standard Model

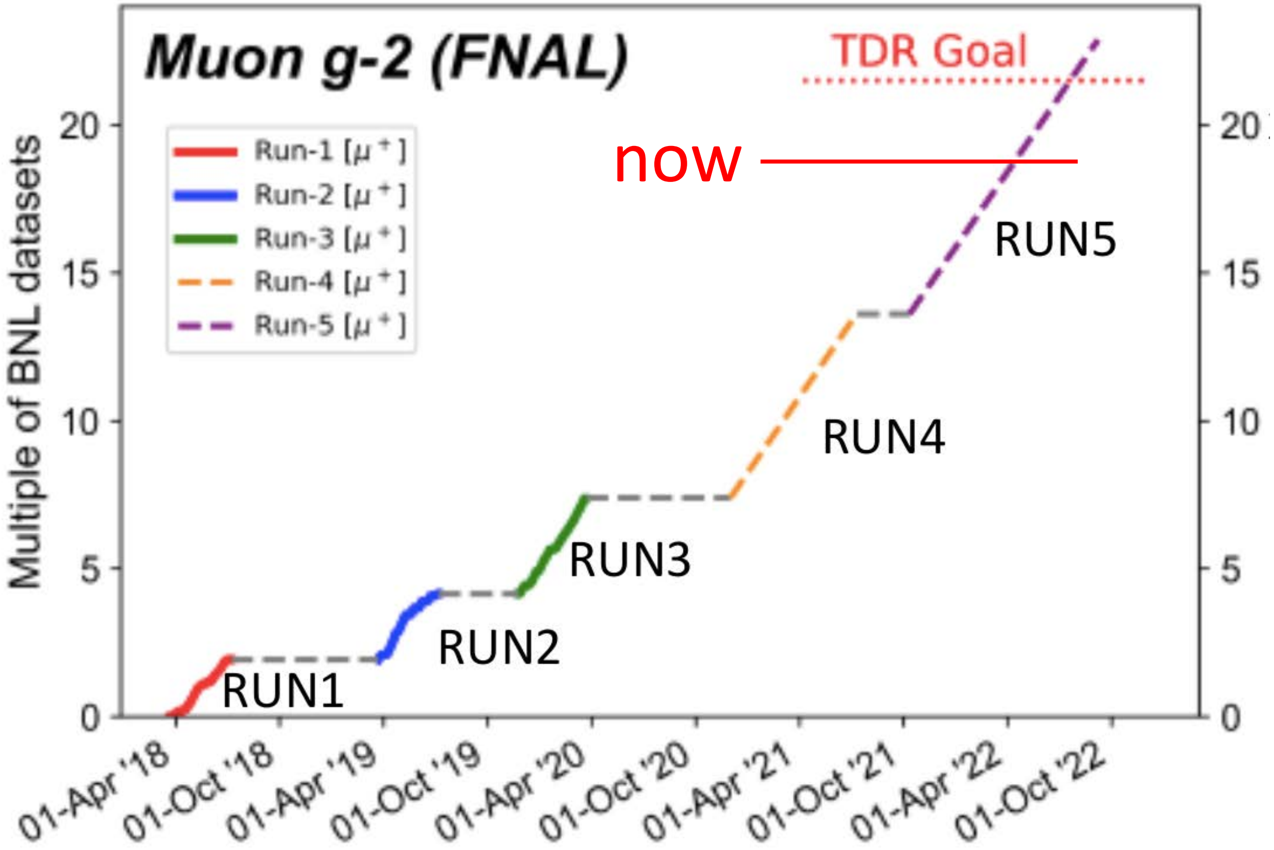
T. Aoyama [1,2,3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7,8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9,12,13], G. Colangelo [14,*], F. Curciarello [15,16], H. Czyż [17], I. Danilkin [12], M. Davier [18,*], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21,22,*], A.X. El-Khadra [23,24,*], A. Gérardin [25], D. Giusti [26,27], M. Golterman [28], Steven Gottlieb [29], V. Gülpers [30], F. Hagelstein [14], M. Hayakawa [31,2], G. Herdoíza [32], D.W. Hertzog [33], A. Hoecker [34], M. Hoferichter [14,35,*], B.-L. Hoid [36], R.J. Hudspith [12,13], F. Ignatov [21], T. Izubuchi [37,8], F. Jegerlehner [38], L. Jin [7,8], A. Keshavarzi [39], T. Kinoshita [40,41], B. Kubis [36], A. Kupich [21], A. Kupść [42,43], L. Laub [14], C. Lehner [26,37,*], L. Lellouch [25], I. Logashenko [21], B. Malaescu [5], K. Maltman [44,45], M.K. Marinković [46,47], P. Masjuan [48,49], A.S. Meyer [37], H.B. Meyer [12,13], T. Mibe [1,*], K. Miura [12,13,3], S.E. Müller [50], M. Nio [2,51], D. Nomura [52,53], A. Nyffeler [12,*], V. Pascalutsa [12], M. Passera [54], E. Perez del Rio [55], S. Peris [48,49], A. Portelli [30], M. Procura [56], C.F. Redmer [12], B.L. Roberts [57,*], P. Sánchez-Puertas [49], S. Serednyakov [21], B. Shwartz [21], S. Simula [27], D. Stöckinger [58], H. Stöckinger-Kim [58], P. Stoffer [59], T. Teubner [60,*], R. Van de Water [24], M. Vanderhaeghen [12,13], G. Venanzoni [61], G. von Hippel [12], H. Wittig [12,13], Z. Zhang [18], M.N. Achasov [21], A. Bashir [62], N. Cardoso [47], B. Chakraborty [63], E.-H. Chao [12], J. Charles [25], A. Crivellin [64,65], O. Deineka [12], A. Denig [12,13], C. DeTar [66], C.A. Dominguez [67], A.E. Dorokhov [68], V.P. Druzhinin [21], G. Eichmann [69,47], M. Fael [70], C.S. Fischer [71], E. Gámiz [72], Z. Gelzer [23], J.R. Green [9], S. Guellati-Khelifa [73], D. Hatton [19], N. Hermansson-Truedsson [14], S. Holz [36], B. Hörz [74], M. Knecht [25], J. Koponen [1], A.S. Kronfeld [24], J. Laiho [75], S. Leupold [42], P.B. Mackenzie [24], W.J. Marciano [37], C. McNeile [76], D. Mohler [12,13], J. Monnard [14], E.T. Neil [77], A.V. Nesterenko [68], K. Ottnad [12], V. Pauk [12], A.E. Radzhabov [78], E. de Rafael [25], K. Raya [79], A. Risch [12], A. Rodríguez-Sánchez [6], P. Roig [80], T. San José [12,13], E.P. Solodov [21], R. Sugar [81], K. Yu. Todyshev [21], A. Vainshtein [82], A. Vaquero Avilés-Casco [66], E. Weil [71], J. Wilhelm [12], R. Williams [71], A.S. Zhevlakov [78]

[1] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*
[2] *Nishina Center, RIKEN, Wako 351-0198, Japan*
[3] *Kobayashi–Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan*
[4] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[5] *LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France*

<u>BNL effort:</u>

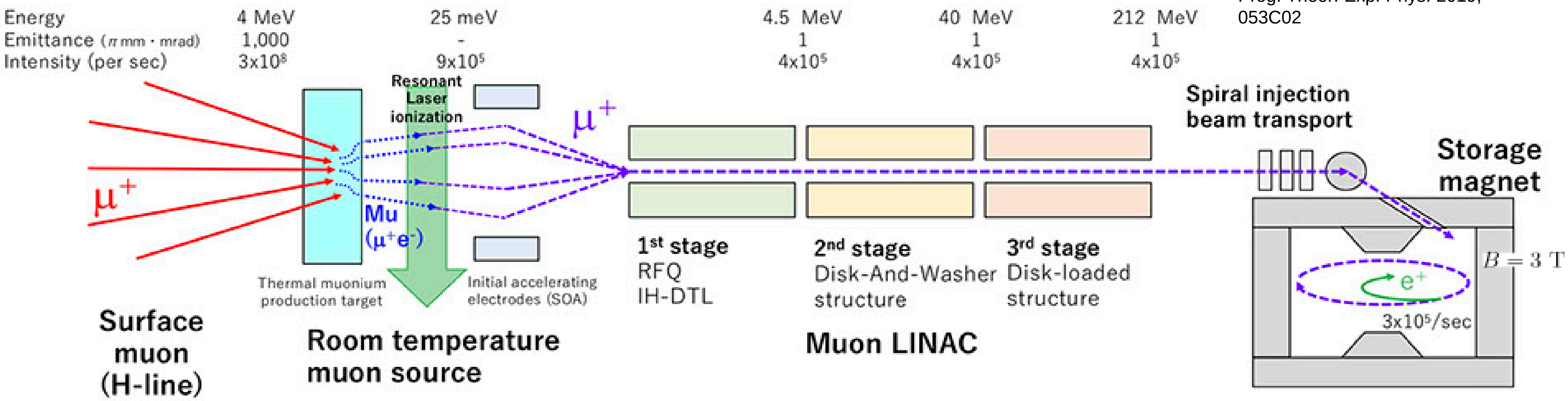
T. Blum
T. Izubuchi
L. Jin
C. Lehner
A.S. Meyer
W.J. Marciano

Moving forward

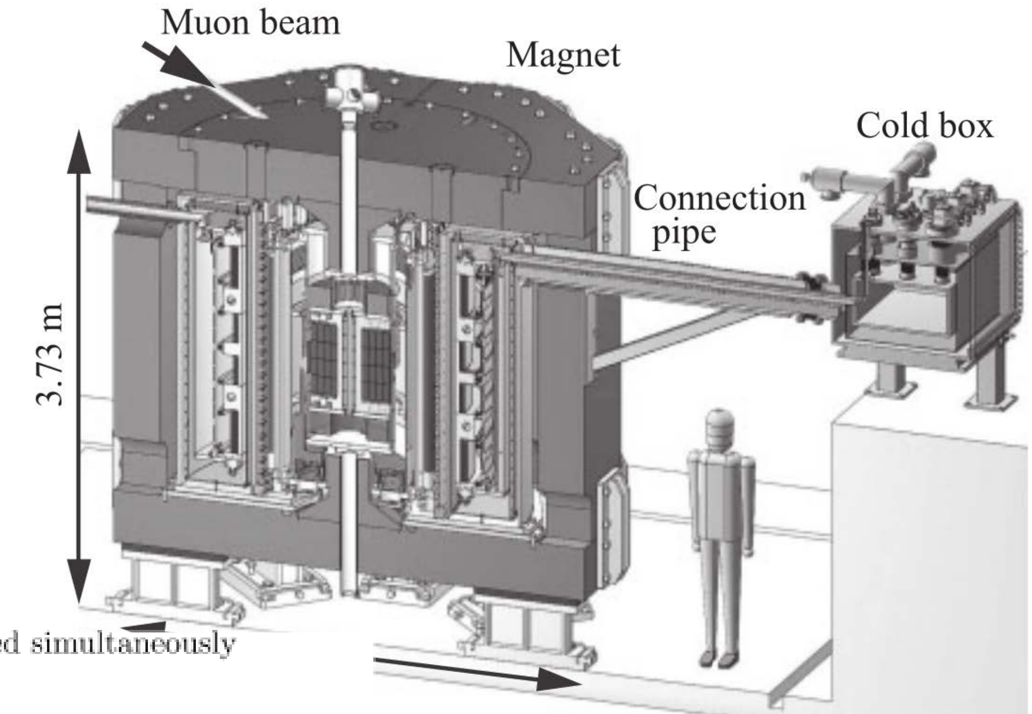


Other efforts in the world – Muon g-2 at JPARC

Prog. Theor. Exp. Phys. 2019, 053C02



- No electrostatic focusing
- Different systematics



- very week magnetic focusing, $n \sim 10^{-4}$
- small emittance beam (0.3π mm·mrad)
- all-magnetic storage ring, no $\vec{\beta} \times \vec{E}$ term

$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}\vec{\beta} \times \vec{B}\right]$$

- $\vec{\omega}_a$ and $\vec{\omega}_\eta$ are orthogonal and can be measured simultaneously
- stat. uncertainty goal: 450 ppb
- stage-2 approval: from IPNS – November, 2018 and IMSS – March, 2019

Summary

- Muons are elementary charged particles, similar to electrons but heavier.
- Muon’s charge in combination with muon’s spin generate magnetic moment – important characteristic of a particle.
- Muon’s magnetic moment can be calculated, very precisely, in the frame of Standard Model of Particle Physics.
- Muon’s magnetic moment can be measured, very precisely, by detecting decay electrons (positrons) in a known magnetic field.
- Muon’s magnetic moment is 40,000 times more sensitive to new particles compared to electrons.
- The Run-1 result of new experiment at Fermilab confirmed BNL measurement
- At present, there is a discrepancy between theory prediction and measurement at the level of ~4.2 standard deviations, which may indicate existence of new particles.