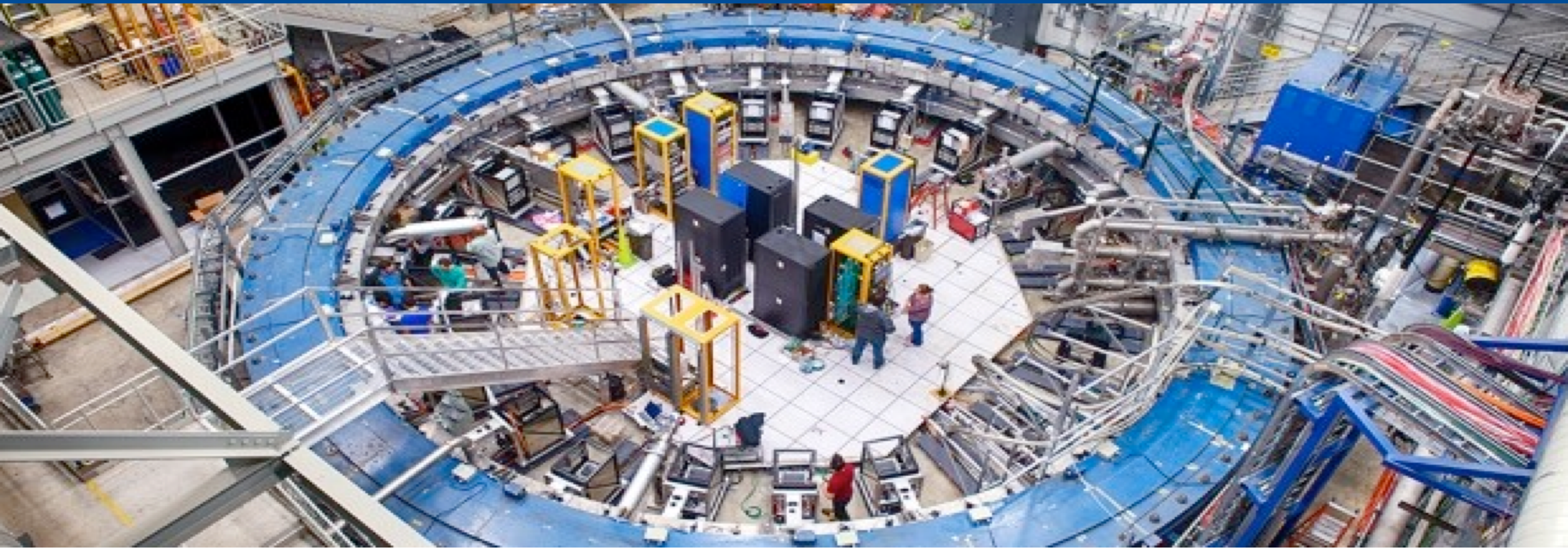


The Muon g-2 experiment(s)

Graziano Venanzoni– INFN Pisa

INTERNATIONAL PHYSICS SCHOOL
MUON DIPOLE MOMENTS AND HADRONIC EFFECTS

NEW DATE
AUG. 29 TO SEPT. 03, 2021
MAINZ, ERBACHER HOF

Simon Eidelman (1948-2021)

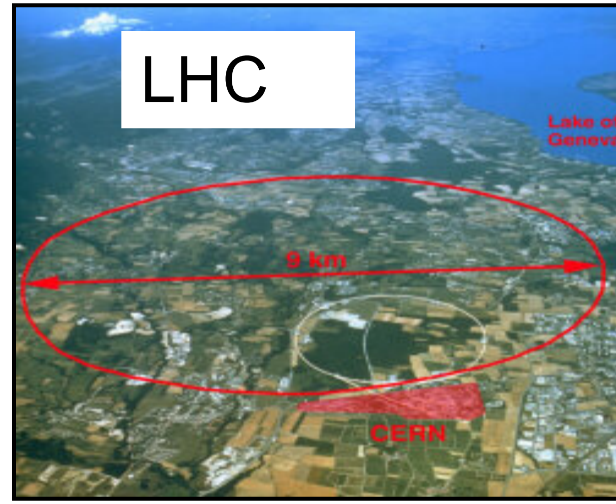
A pioneer of the field, a wonderful colleague, and a friend

Outline

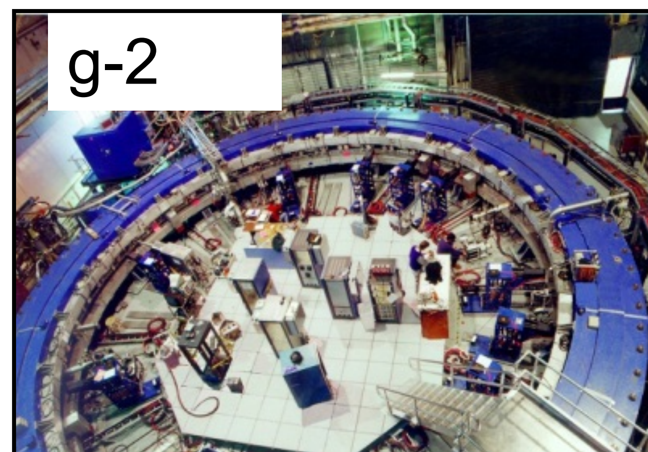
- The g-factor and the muon anomaly a_μ
- A little bit of history (the old Muon g-2 experiments)
- The Muon g-2 at Fermilab (E989)
- The J-PARC Muon g-2 experiment (E34)
- The MUone experiment at CERN

Two ways to look for New Physics

- **High Energy:** increasingly high-energy machines (LHC, ILC / Fcc) are designed and new high-mass "particles" are searched (direct observation). Large detectors and collaborations.



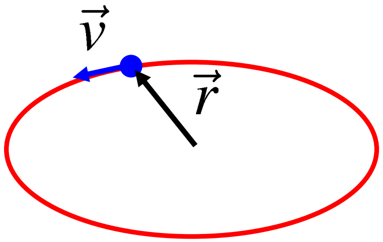
- **High Intensity:** through precision measurements, new low-energy physics effects are sought (deviations from the theory). Small scale apparatuses and collaborations, very high statistics



The giromagnetic ratio g

- A charge particle in a plane orbit has **angular momentum** L and **magnetic moment** μ

$$\mu = \frac{q}{2m}\vec{L}$$



- The ratio μ/(q/2m)L is called giromagnetic ratio g. Classically **g=1**

- For an elementary particle of Spin = 1/2 (e-, μ) the eq. Dirac's predicts **g = 2**

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma} \equiv g\mu_B\vec{S}; \quad \vec{S} = \vec{\sigma}/2, \quad g = 2$$

- The magnetic anomaly is defined as **a = (g-2) / 2.** **g=2 → a=0** according to Dirac

1947: Measurement of g of the electron

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY
Department of Physics, Columbia University, New York, New York

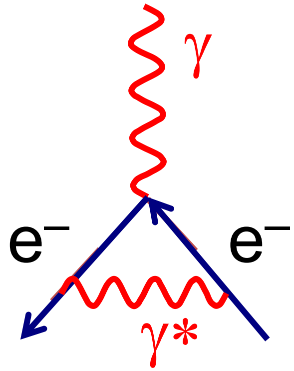
(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L=1$ and $g_S=2(1.00119\pm0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

$$g = 2(1.00119 \pm 0.00005); a = \frac{(g-2)}{2} = 0.00119 \pm 0.00005$$

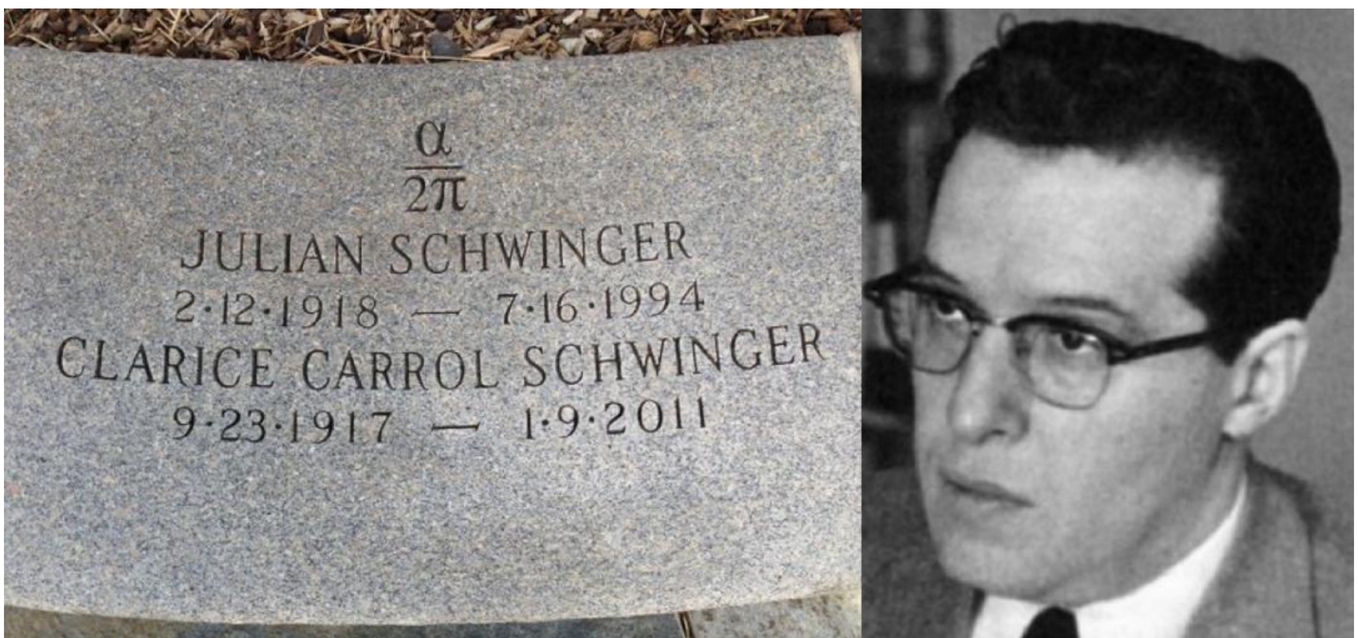
a= 0 according to Dirac

1948: Triumph of quantum field theory (QED)



$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$

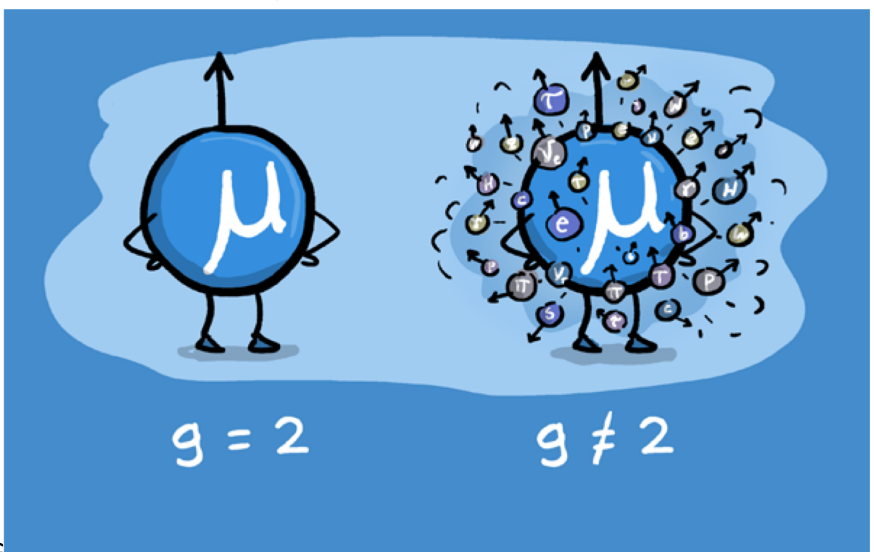
a>0; g>2

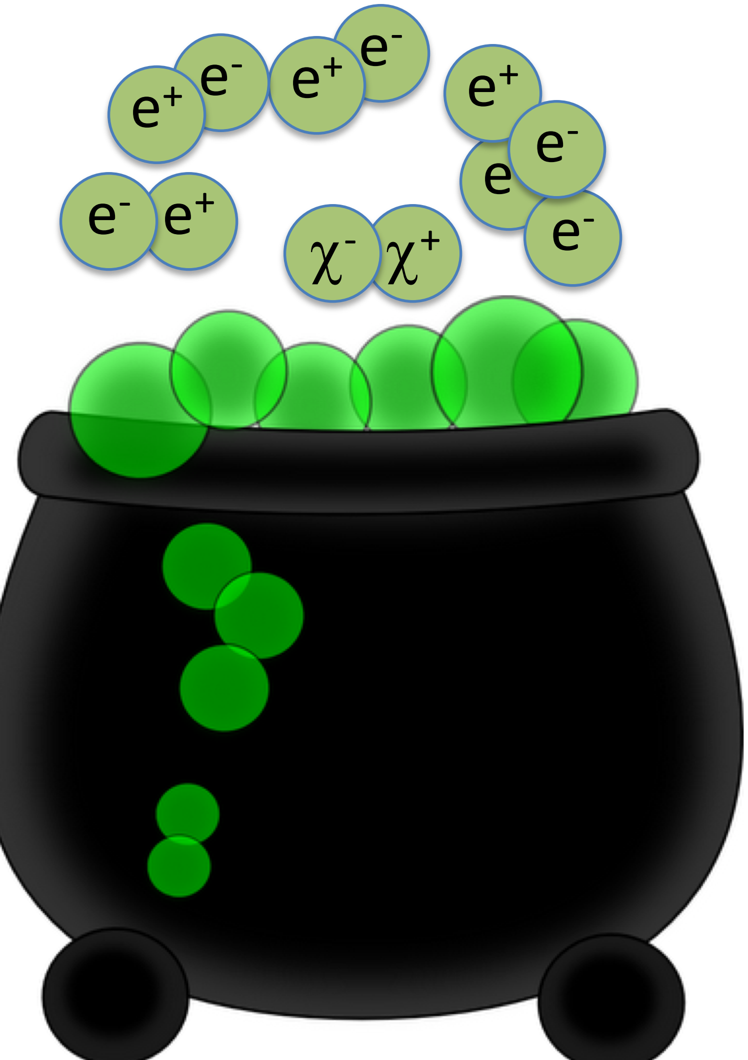


At the end it's all the Quantum Vacuum

- The vacuum is filled with pairs of particles and antiparticles that exist for a very short time and are therefore called **virtual**.

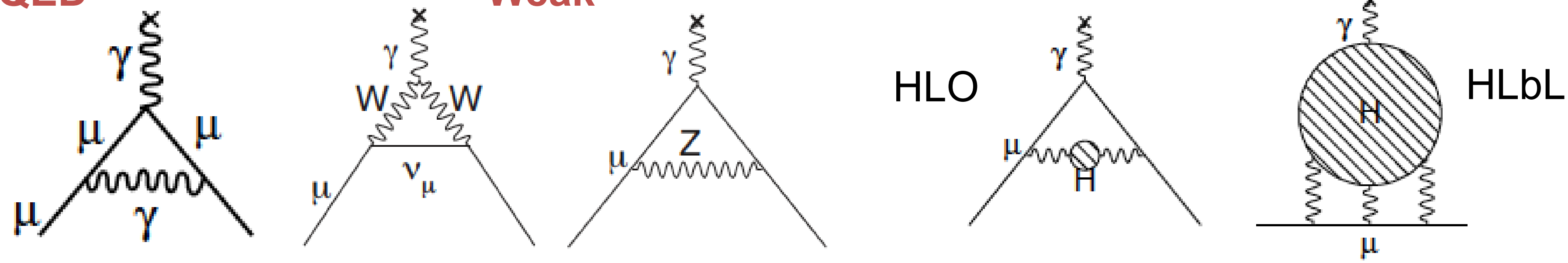
- They produce tangible effects on the physical phenomena we observe → g ≠2





In the SM a_μ can be computed very precisely!

QED **Weak** **Hadronic contribution**



Precisely known

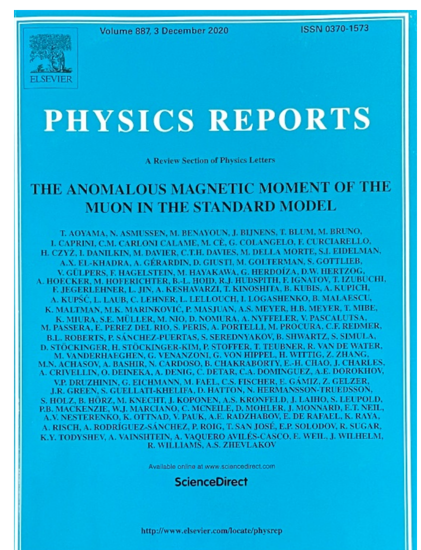
Large uncertainty
(significant work going on)

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

$a_\mu^{QED} \sim \alpha/2\pi \sim O(10^{-3})$ $a_\mu^{Weak} \sim O(10^{-9})$ $a_\mu^{HAD} \sim O(10^{-8})$

$\delta a_\mu^{QED} \sim 1.4\text{x}10^{-12}$ $a_\mu^{Weak} \sim 2\text{x}10^{-11}$ $\delta a_\mu^{HAD} \sim 5\text{x}10^{-10}$

$$a_\mu(\text{SM}) = 116\,591\,810(43) \times 10^{-11} \quad (0.37\,\text{ppm})$$


Volume 887, 3 December 2020 ISSN 0370-1573

ELSEVIER

PHYSICS REPORTS

A Review Section of Physics Letters

THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL

T. AOYAMA, N. ASMUSSEN, M. BENAYOUN, J. BIJNENS, T. BLUM, M. BRUNO, I. CAPRINI, C.M. CARLONI CALAME, M. CÈ, G. COLANGELO, F. CURCIARELLO, H. CZYŻ, I. DANILKIN, M. DAVIER, C.T.H. DAVIES, M. DELLA MORTE, S.I. EIDELMAN, A.X. EL-KHADRA, A. GÉRARDIN, D. GIUSTI, M. GOLTERMAN, S. GOTTLIEB, V. GÜLPERS, F. HAGELSTEIN, M. HAYAKAWA, G. HERDOÍZA, D.W. HERTZOG, A. HOECKER, M. HOFERICHTER, B.-L. HOID, R.J. HUDSPITH, F. IGNATOV, T. IZUBUCHI, F. JEGERLEHNER, L. JIN, A. KESHAVARZI, T. KINOSHITA, B. KUBIS, A. KUPICH, A. KUPŚĆ, L. LAUB, C. LEHNER, L. LELLOUCH, I. LOGASHENKO, B. MALAESCU, K. MALTMAN, M.K. MARINKOVIĆ, P. MASJUAN, A.S. MEYER, H.B. MEYER, T. MIBE, K. MIURA, S.E. MÜLLER, M. NIO, D. NOMURA, A. NYFFELER, V. PASCALUTSA, M. PASSERA, E. PEREZ DEL RIO, S. PERIS, A. PORTELLI, M. PROCURA, C.F. REDMER, B.L. ROBERTS, P. SÁNCHEZ-PUERTAS, S. SEREDNYAKOV, B. SHWARTZ, S. SIMULA, D. STÖCKINGER, H. STÖCKINGER-KIM, P. STOFFER, T. TEUBNER, R. VAN DE WATER, M. VANDERHAEGHEN, G. VENANZONI, G. VON HIPPEL, H. WITTIG, Z. ZHANG, M.N. ACHASOV, A. BASHIR, N. CARDOSO, B. CHAKRABORTY, E.-H. CHAO, J. CHARLES, A. CRIVELLIN, O. DEINEKA, A. DENIG, C. DETAR, C.A. DOMINGUEZ, A.E. DOROKHOV, V.P. DRUZHININ, G. EICHMANN, M. FAEL, C.S. FISCHER, E. GÁMIZ, Z. GELZER, J.R. GREEN, S. GUELLATI-KHELIFA, D. HATTON, N. HERMANSSON-TRUEDSSON, S. HOLZ, B. HÖRZ, M. KNECHT, J. KOPONEN, A.S. KRONFELD, J. LAIHO, S. LEUPOLD, P.B. MACKENZIE, W.J. MARCIANO, C. MCNEILE, D. MOHLER, J. MONNARD, E.T. NEIL, A.V. NESTERENKO, K. OTTNAD, V. PAUK, A.E. RADZHABOV, E. DE RAFAEL, K. RAYA, A. RISCH, A. RODRÍGUEZ-SÁNCHEZ, P. ROIG, T. SAN JOSÉ, E.P. SOLODOV, R. SUGAR, K.Y. TODYSHEV, A. VAINSHTEIN, A. VAQUERO AVILÉS-CASCO, E. WEIL, J. WILHELM, R. WILLIAMS, A.S. ZHEVLAKOV

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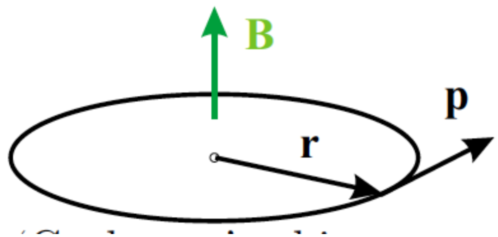
but it can be also measured very precisely…

- A charged particle with spin put in a magnetic field (uniform) rotates in a circular orbit with angular frequency (called cyclotron):

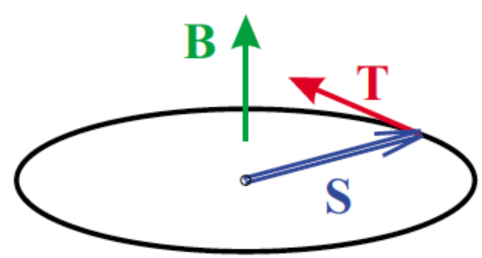
$$\omega_c = \frac{qB}{m}$$



Ciclotron orbit, ω_c

- The presence of the magnetic field acts on the spin by rotating it around the field direction (precession frequency of the spin)

$$\omega_s = g\frac{qB}{2m}$$



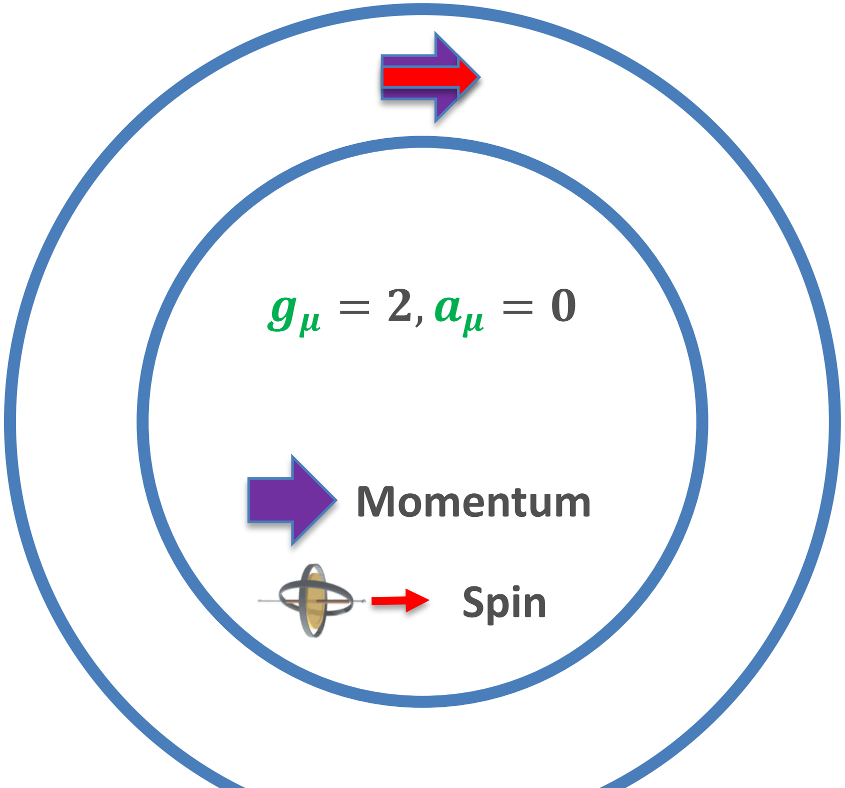
Spin precession, ω_s

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

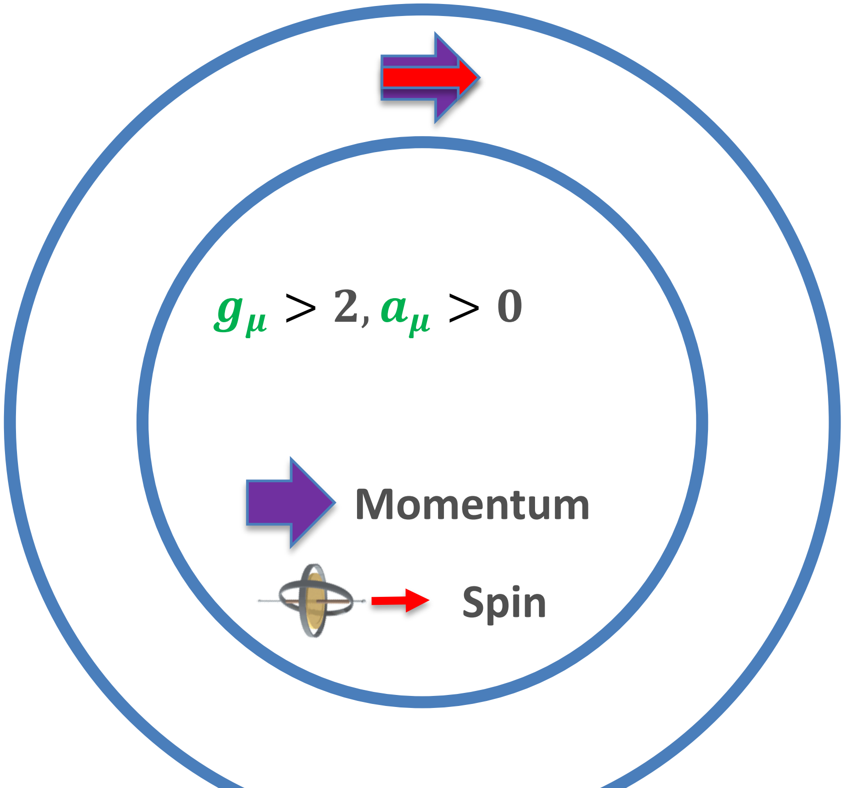


How to measure the muon anomaly?

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

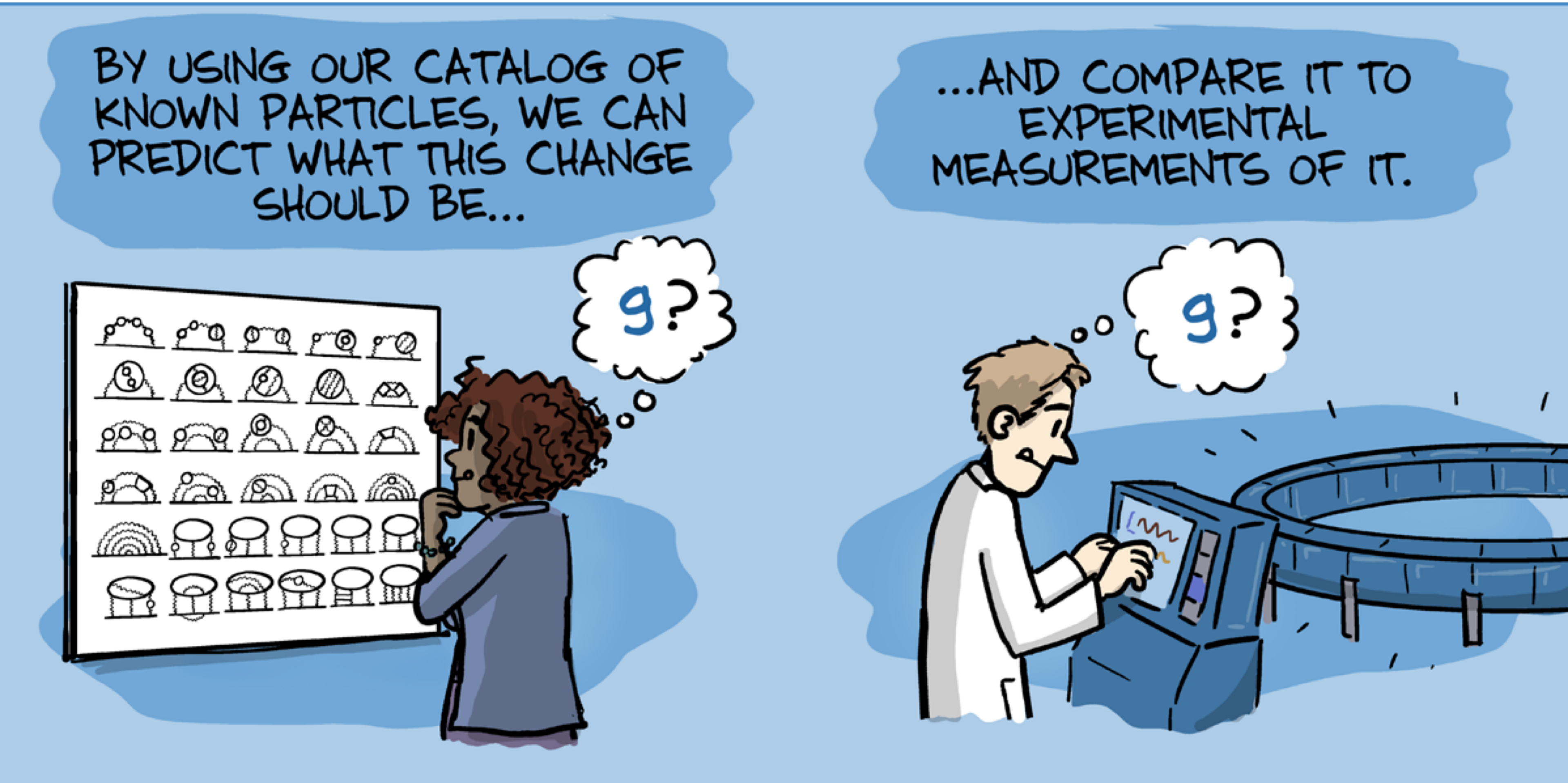
$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

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

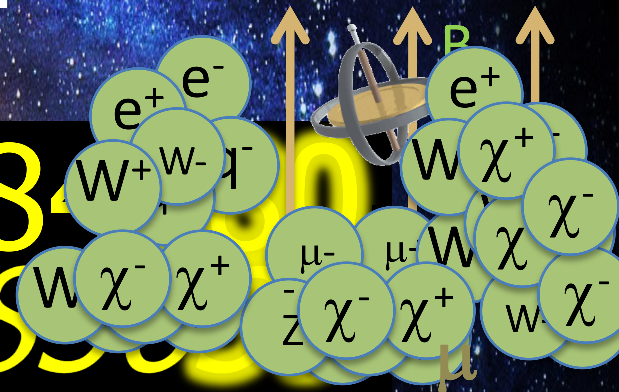


Current experiments
$\delta a_\mu < 1$ppm

If a_μ can be both measured and computed to high accuracy….

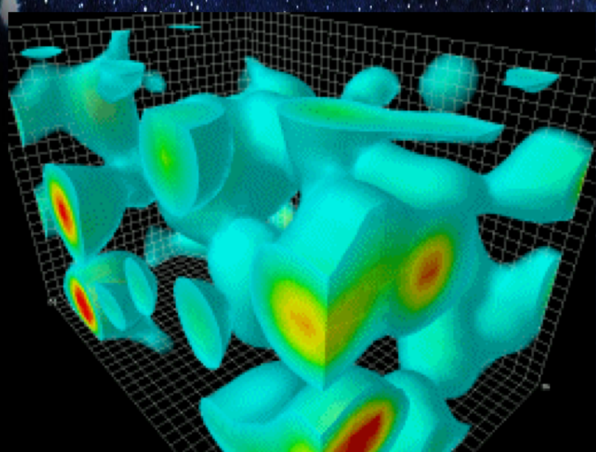


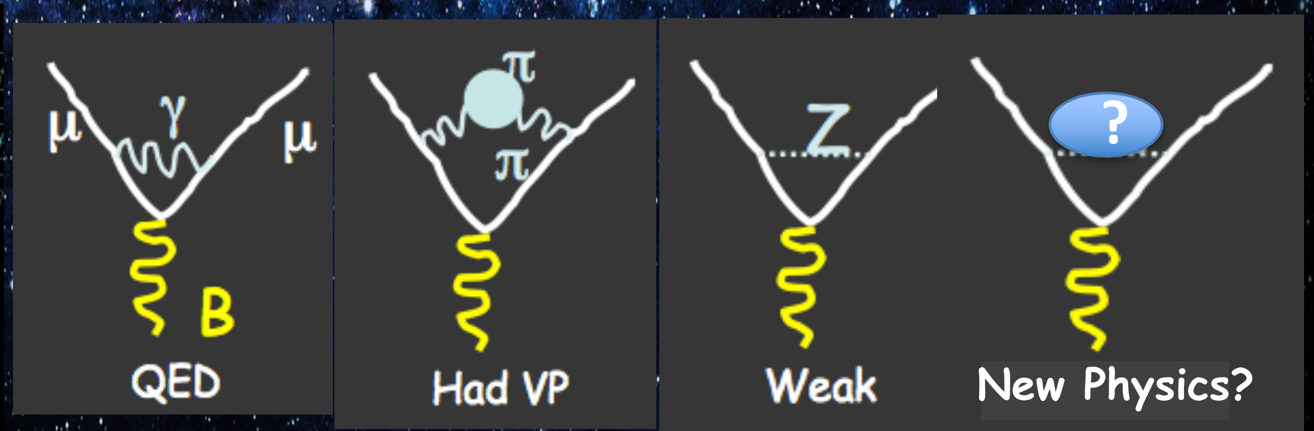
It can reveal the deep structure of the quantum vacuum with its (known and unknown) particle content....



g(expt) 2.0023318

g(theory) *2.0023318*





Let’s start with the history of the muon g-2 experiments

The Muons

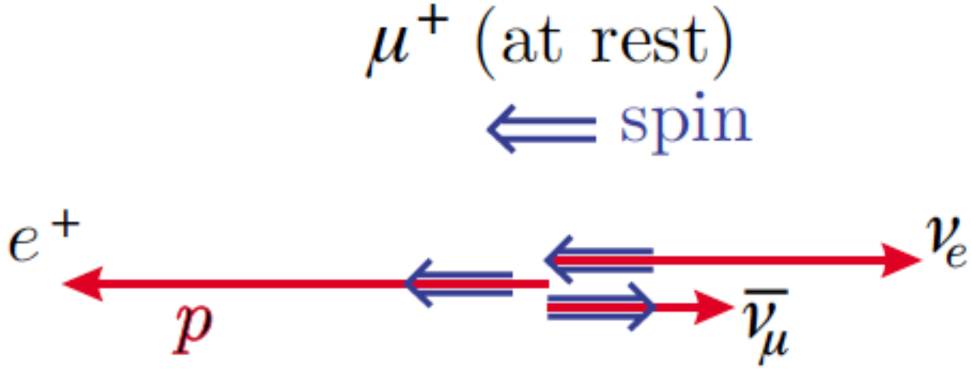
– produced polarized in "forward" direction

$$\pi^- \longrightarrow \mu^- \ \bar{\nu}_\mu$$

– decay with information on where their spin was at the time of decay

$$\mu^- \ \longrightarrow e^- \ \bar{\nu}_e \ \nu_\mu$$

S-p correlation fundamental to all muon anomaly experiments

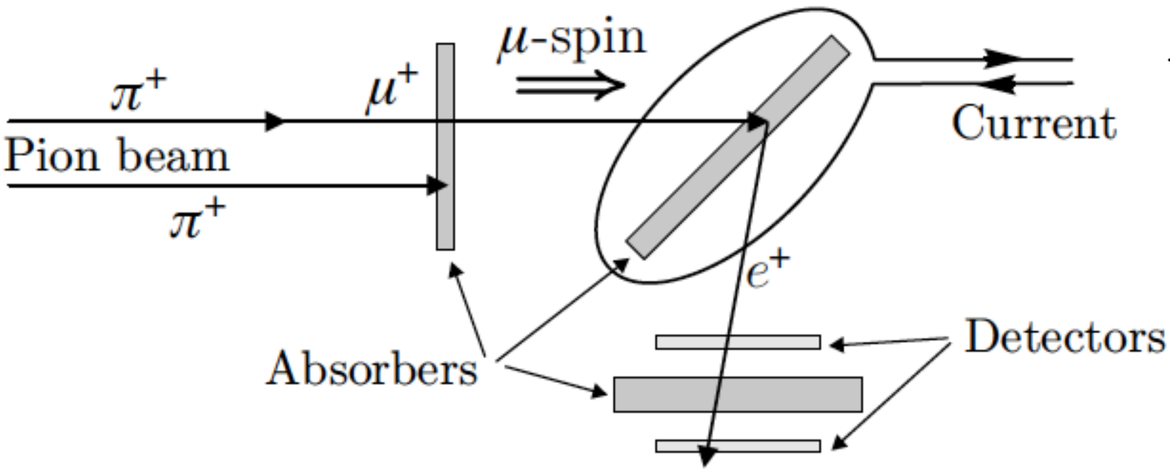


High energy positrons have momentum along the muon spin. The opposite is true for electrons from μ^-.

Detect high energy electrons. The time dependence of the signal tracks muon precession.

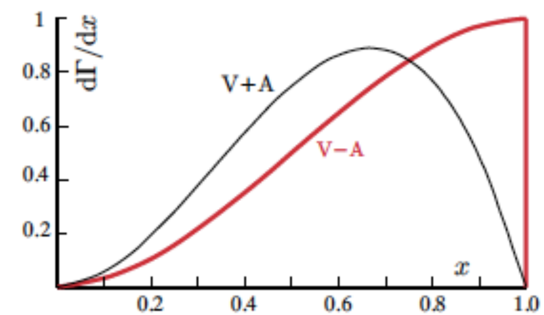
highest energy $e^\pm$ carry μ spin information

Lee and Yang: the parity violation in the production and decay of the muon offer a way to measure the muon magnetic moment



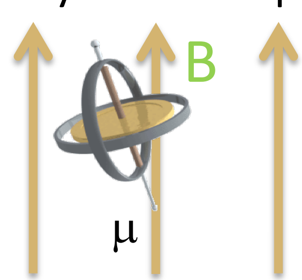
θ=angle between the spin direction of μ and e^- momentum

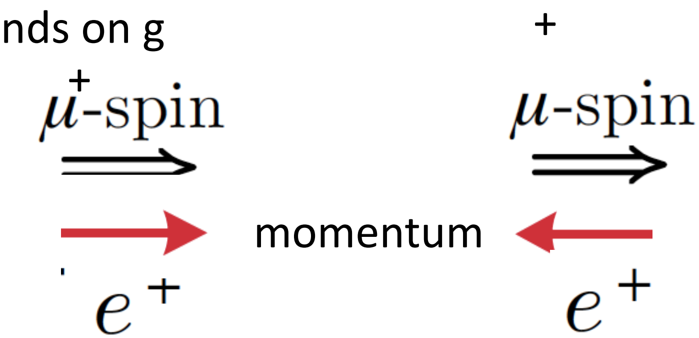
$$\frac{\mathrm{d}\Gamma(\cos\theta)}{\Gamma} = \frac{1}{2}\left(1 - \frac{1}{3}\cos\theta\right)\mathrm{d}\cos\theta.$$



The rate of high energy decay electrons is time modulated by the precession of the magnetic moment with a frequency which depends on g

$$\omega_s = g\frac{eB}{2mc}$$



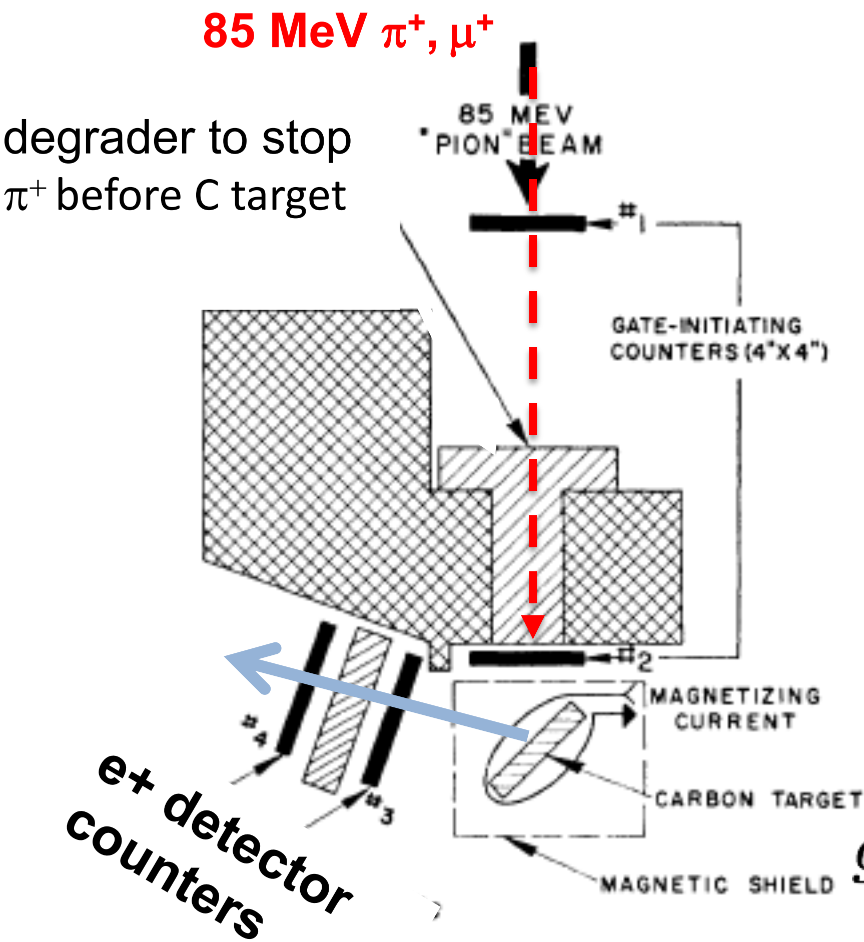


favoured

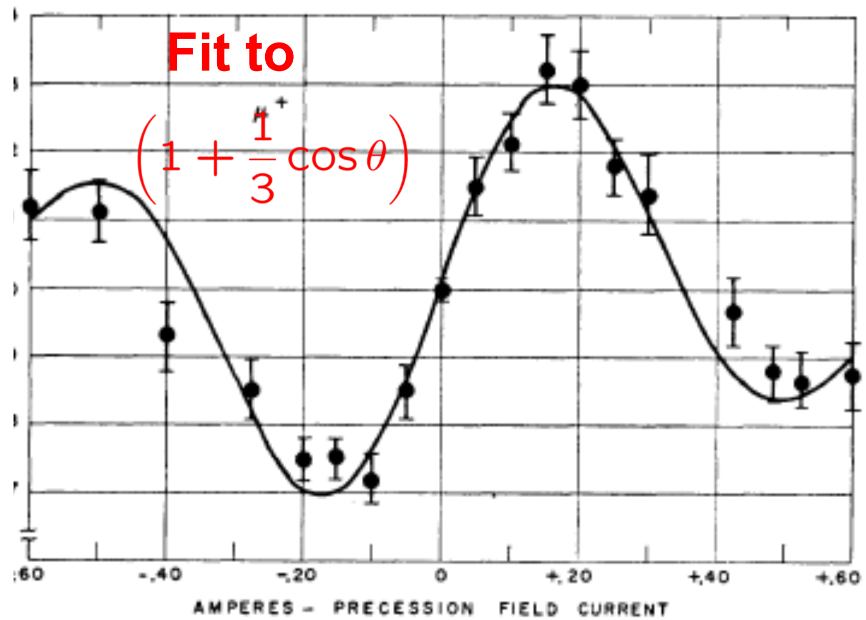
disfavoured

History: the first measurement of g_μ

- 1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)



ect measurement of *g* -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

5% uncertainty

muons behave like electrons

F. Farley, E. Picasso The Muon (g−2) Experiments at CERN
Ann.Rev.Nucl.Part.Sci. 29 (1979) 243-282

The CERN muon g-2 experiments (1960-1979)

Review

The 47 years of muon $g-2$

F.J.M. Farley[a,*], Y.K. Semertzidis[b]

[a]*Yale University, New Haven, CT 06520, USA*
[b]*Brookhaven National Laboratory, Upton, NY 11973, USA*

Received 30 October 2003

F.J.M. Farley, Y.K. Semertzidis / Progress in Particle and Nuclear Physics 52 (2004) 1–83 21

The history of the muon $(g-2)$ experiments

B. Lee Roberts*

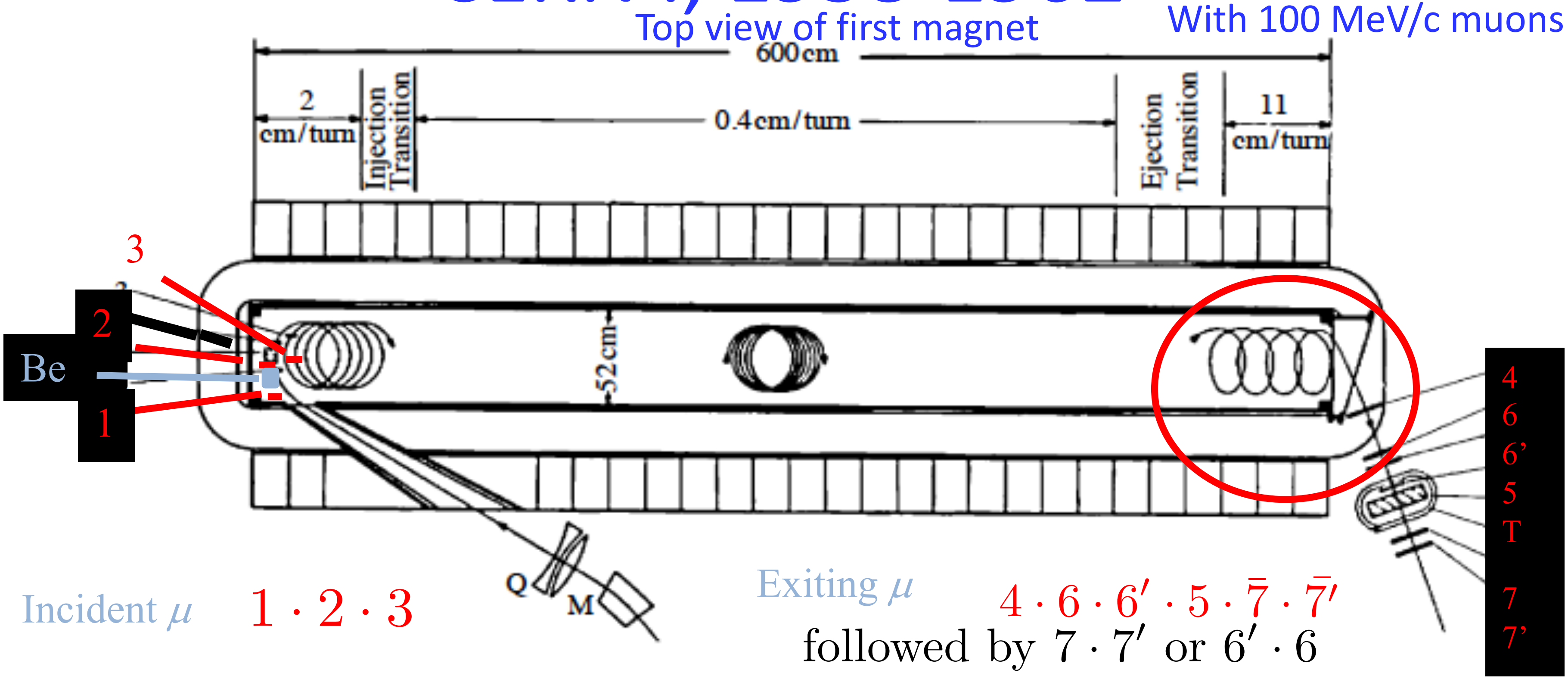
SciPost Phys. Proc. 1, 032 (2019)

Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.

They measure a_μ since the measure the spin relative to the momentum

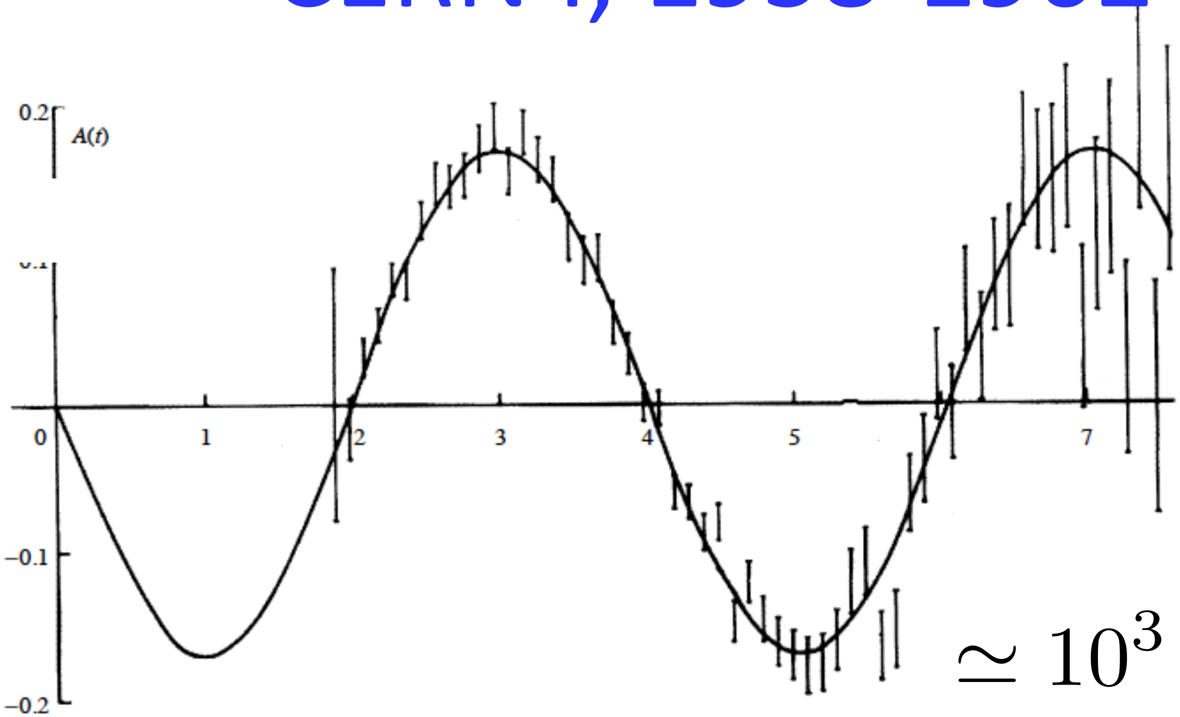
$$\vec{\omega}_a = \omega_S - \omega_C = -\frac{Qe}{m} a_\mu \vec{B}$$

CERN I, 1958-1962



- Inject polarized muon into a long magnet (B ≈ 1.5 T) with a small gradient – particles drift in circular orbits to the other end: 7.5 μs = 1600 turns
- Extract muons with a large gradient into a polarization monitor where they stopped
- Time in the magnetic field was measured by counters
- Measure the time dependent forward-backward decay asymmetry

CERN I, 1958-1962



$$A(t) = A_0 \sin(\omega_a t + \varphi)$$

$$\omega_a = a_\mu (e/mc) \overline{B}$$

$\simeq 10^3 \ \mu^+$ recorded

$$a_\mu = 0.001\,162(5) \ \ (0.43\%)$$ (4300 ppm)

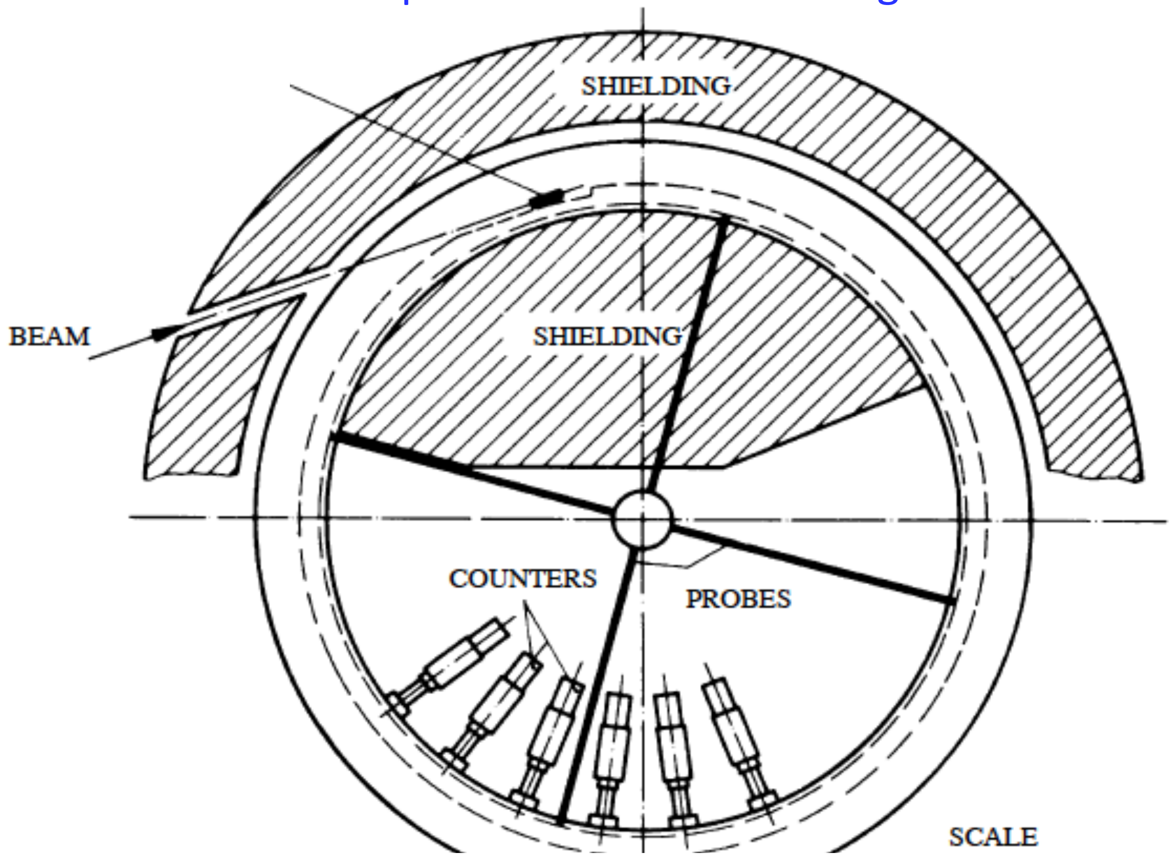
$$C_1 \left(\frac{\alpha}{\pi}\right) + C_2 \left(\frac{\alpha}{\pi}\right)^2$$

- Limitations:
  - not enough data (1 muon/second in analyzer)
  - muon lifetime too short

CERN II, 1962-1968: The First Storage Ring (proton beam)

π production target inside

Top view of the second magnet

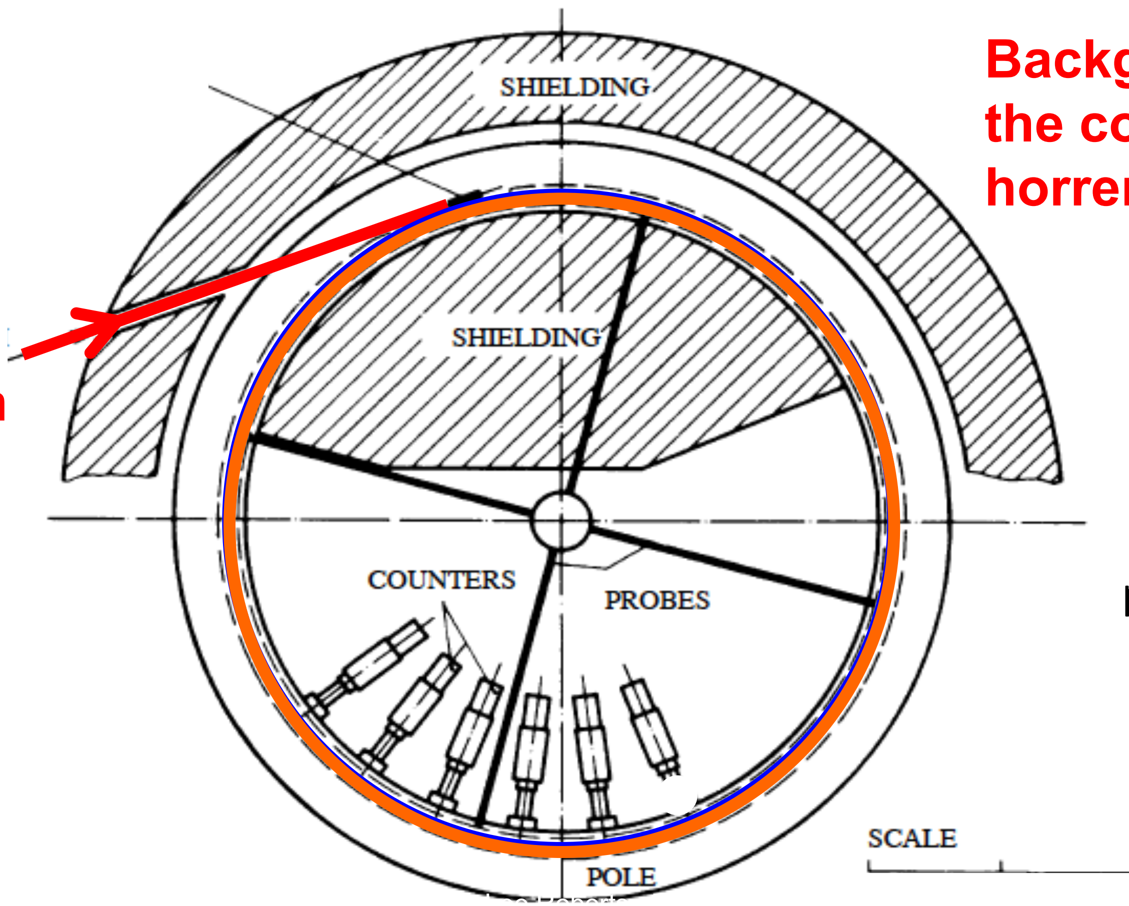


polarization 26%

Fig. 17. The first muon storage ring: diameter 5 m, muon momentum 1.3 GeV/c, time dilation factor 12. The injected pulse of 10.5 GeV protons produces pions at the target, which decay in flight to give muons.

- Go to p_μ = 1.27 GeV/c, γ_μ = 12; $\gamma\tau$ = 27 μs;
- Used a weak-focusing magnetic storage ring; B_z = 1.71 T
- **p + N → π → μ which are stored**

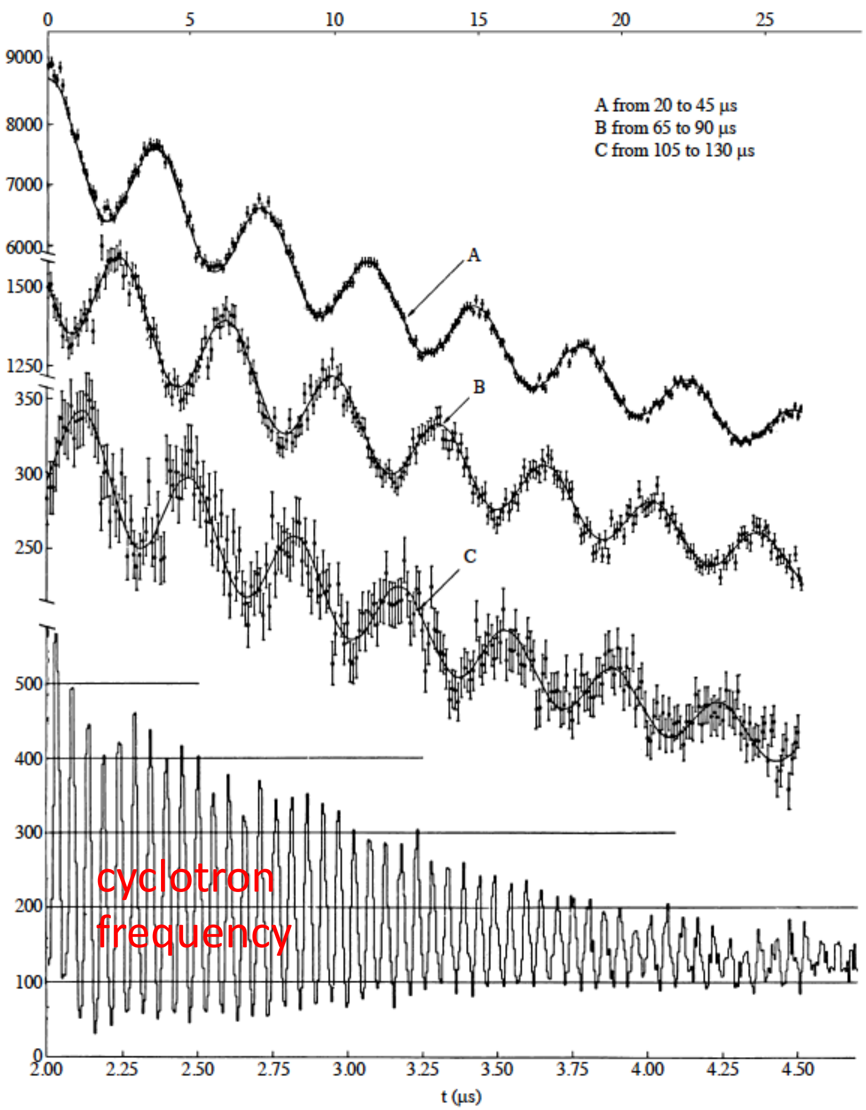
10.5 GeV/c Proton beam



Background flash in the counters was horrendous!

polarization 26%

Arrival time spectrum for E_e > 830 MeV



$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a A \gamma \tau \sqrt{N}}$$

$$C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3$$

$$a_\mu = (116\,616 \pm 31) \times 10^{-8} \quad (266\text{ppm})$$

To get better precision, a number of things needed:

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a A \gamma \tau_\mu \sqrt{N}}$$

- Longer muon lifetime (more wiggles) (higher momentum)
- More muons stored
- To decrease the uncertainty on $\langle B \rangle$, since

$$\omega_a = -a\frac{Qe}{m}\langle B \rangle_{muon-dist}$$

- With gradients in the field, you have to know the muon trajectories very well to determine $\langle B \rangle$
- Find some other way besides magnetic gradients to keep the muons stored.
- What about using an electric quadrupole field to provide vertical focusing?

A miracle happens here

How to keep the muons vertically confined?
2nd CERN used radial variation in *B* field (big systematic)

Use electrostatic quadrupoles - but adds complications

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

A miracle happens here

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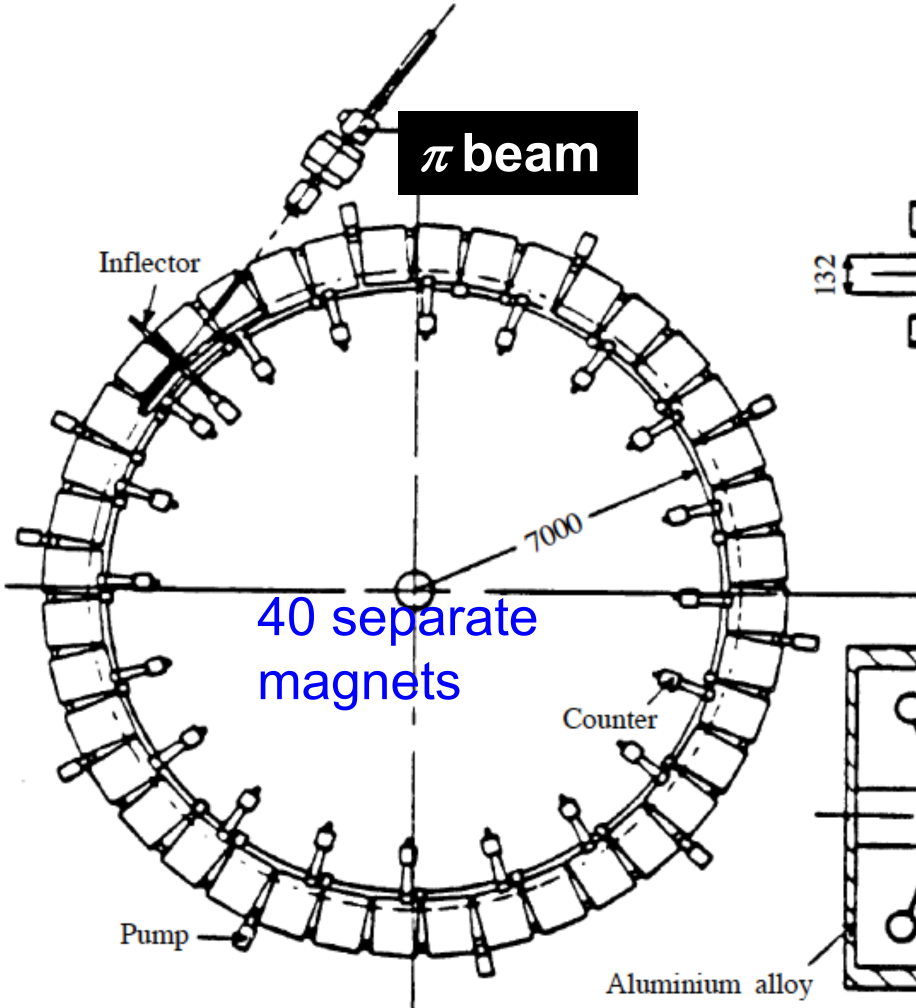
$$\vec{\omega_a} = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)(\vec{\beta} \times \vec{E})\right]$$

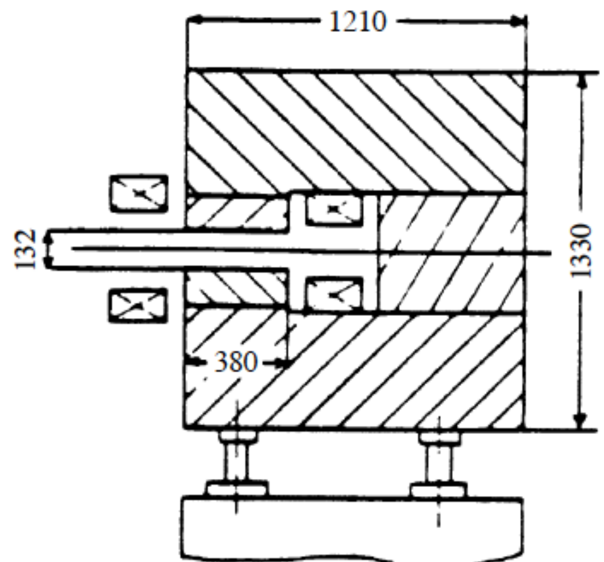
If we choose $\gamma = 29.3 \quad (p_\mu = 3.09 \text{ GeV}/c)$
then coefficient vanishes! The MAGIC momentum!

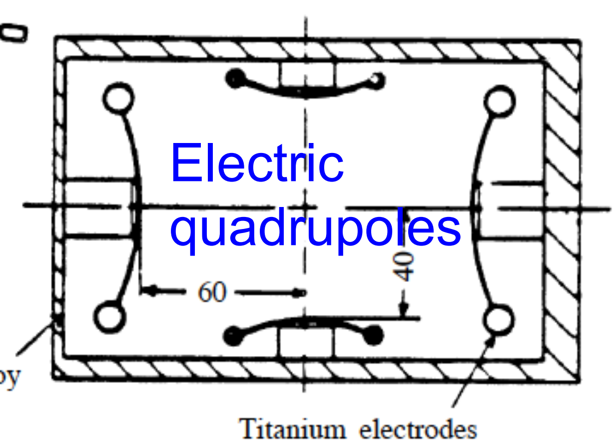
So we can worry less about the electric field (but still will need corrections)
Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

CERN III, 1969-1976

The third magnet, second storage ring. Pion injection, E-field focusing, Magic momentum







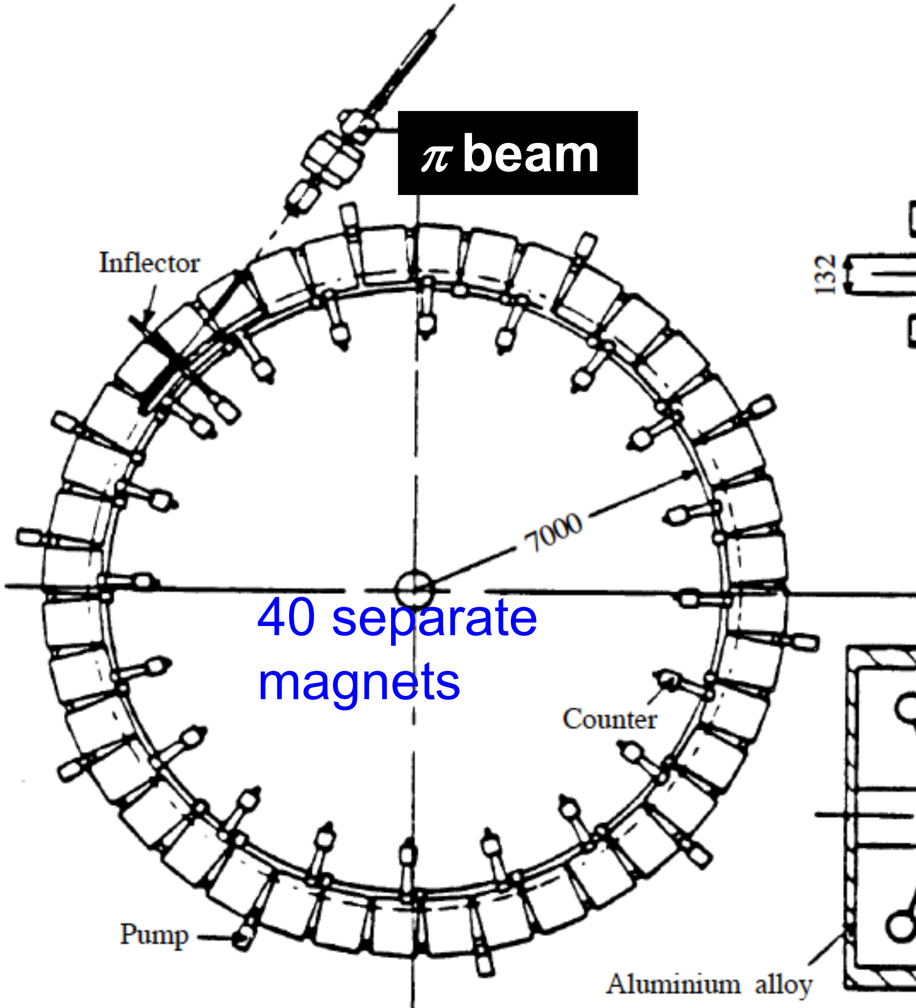
Still have pion flash at injection!

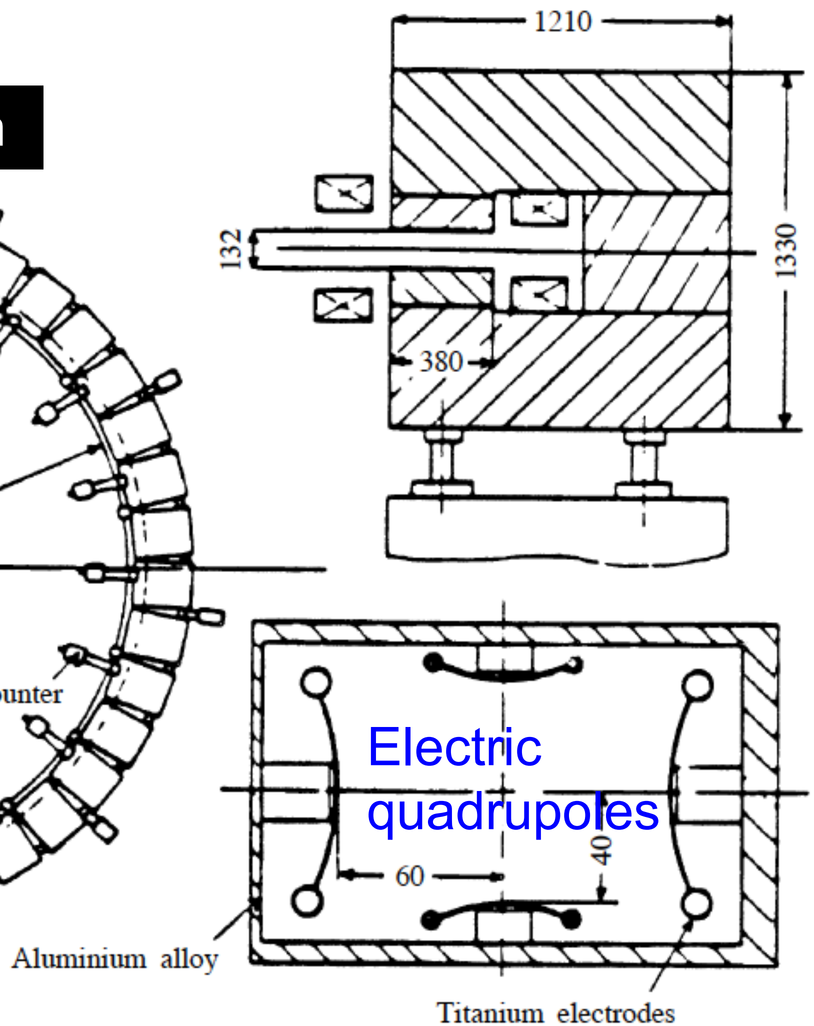
Not as bad as for CERN2

CERN III, 1969-1976

- Inject pions
- Use $\pi \rightarrow \mu$ decay to kick muons onto stable orbits

Muon lifetime dilates to 64 μs

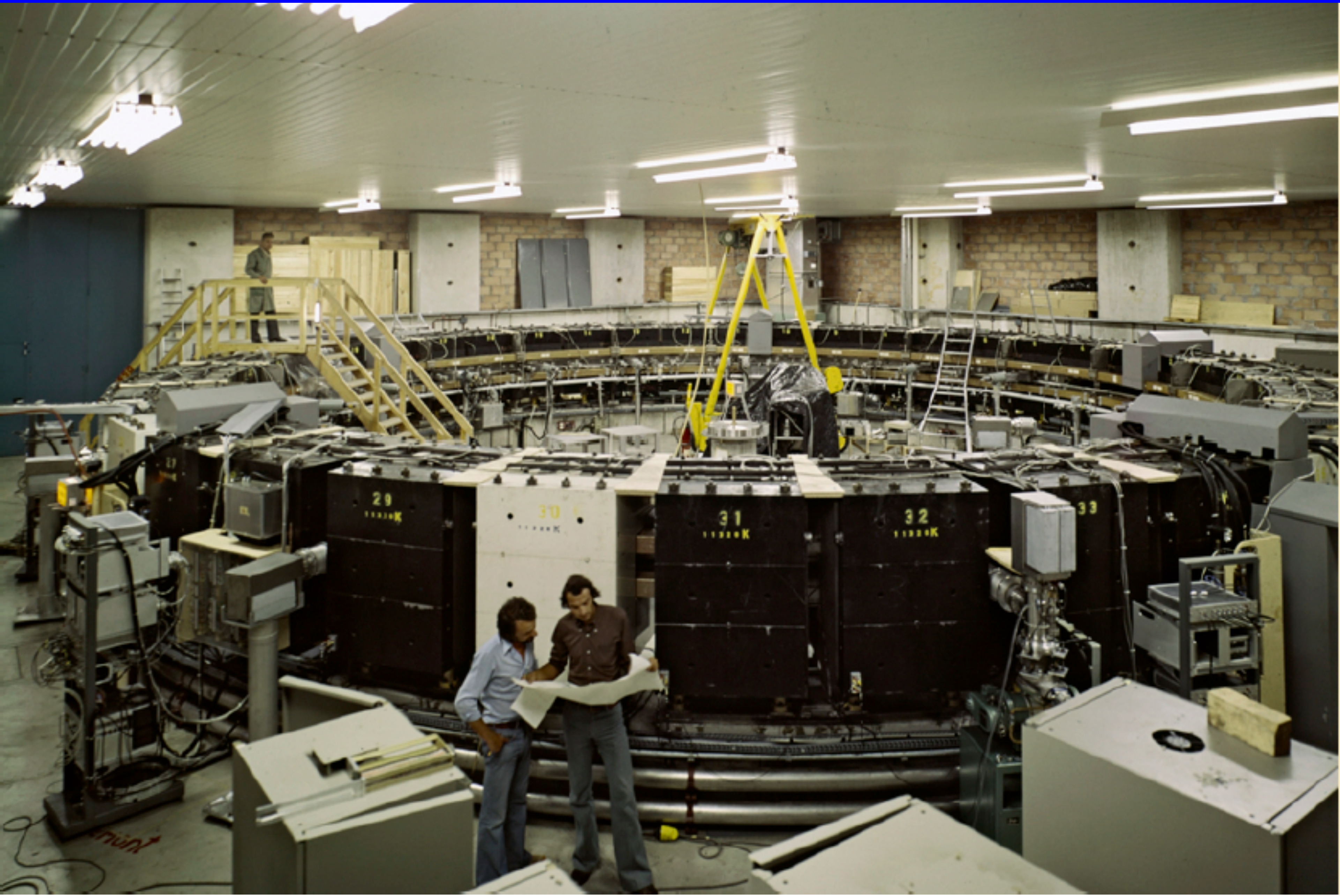




Still have pion flash at injection!

Not as bad as for CERN2

3rd Muon g-2 experiment at Cern



CERN III, 1969-1976. 7.3ppm in *a*.

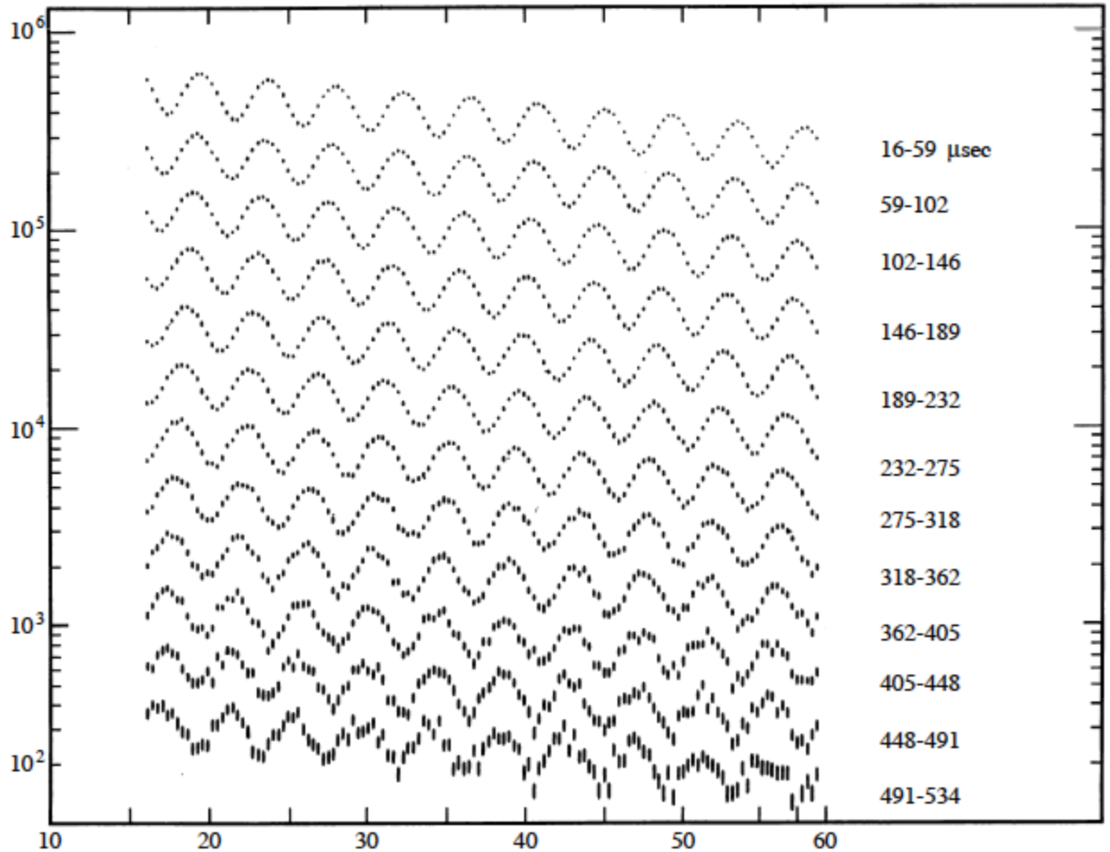


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).

$$a_{\mu^\pm} = (1\,165\,923 \pm 8.5) \times 10^{-9} \quad (7.3 \text{ ppm})$$

$$C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + a_\mu^{Had}$$

Large systematic due to field at magnet edges

Setting the stage for Brookhaven E821

In 1984 QED was calculated to fourth order

Hadronic uncertainties were greatly reduced

Time for new experiment at Brookhaven AGS at sub ppm

Improvements:

Much higher intensity

3 superconducting coils

Circular aperture

Inject muons into ring with inflector and kicker

In-situ B measurements with NMR probes

1984-2001: Measurement of a_μ at BNL

The measurement of the g-2 of the muon has been repeated with x15 better accuracy at Brookhaven National Laboratory (USA)

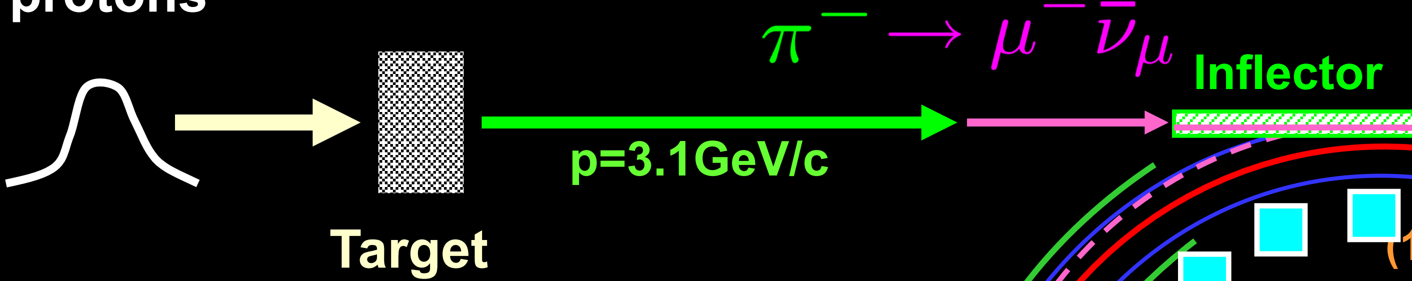
Experimental Technique

25ns bunch of
$\geqslant$ 1 X 10^{12}
protons

$x_c \approx 77$ mm

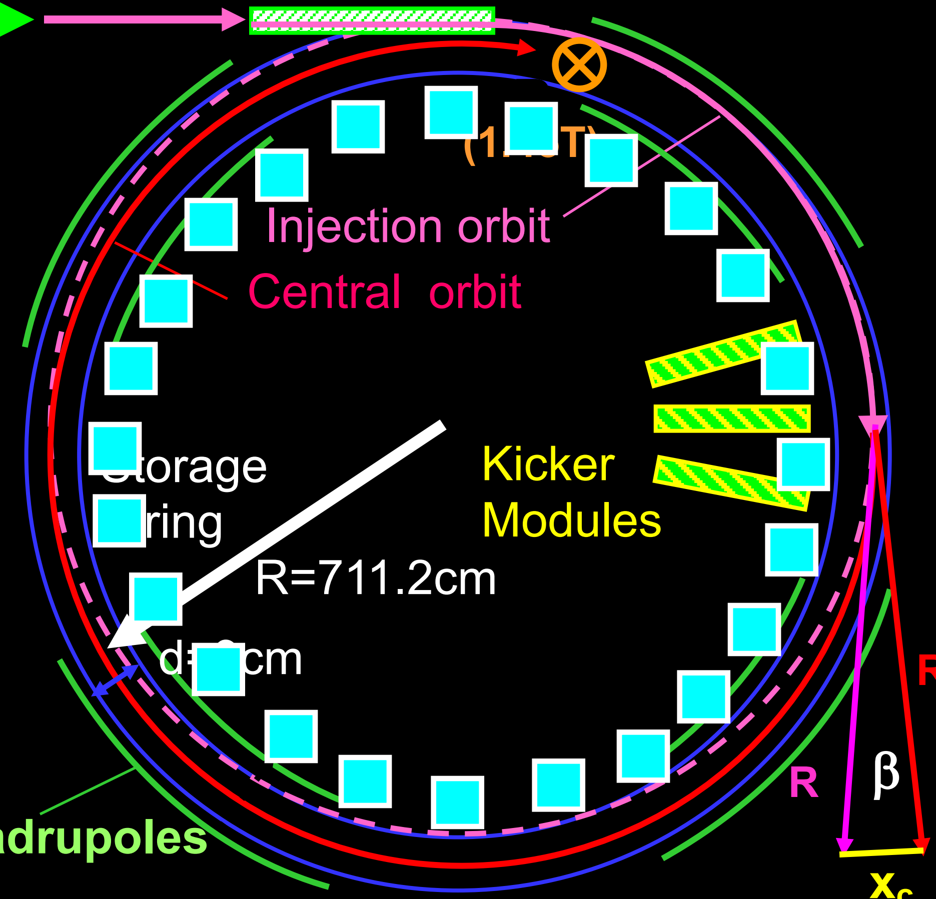
$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

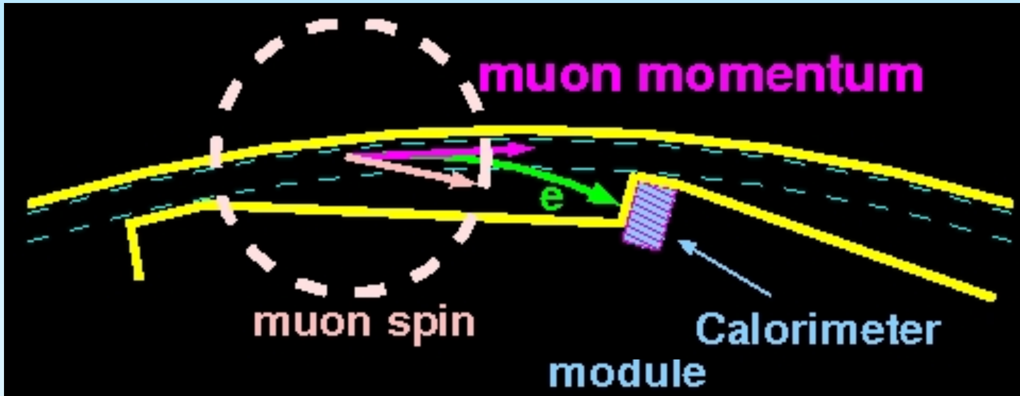


- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

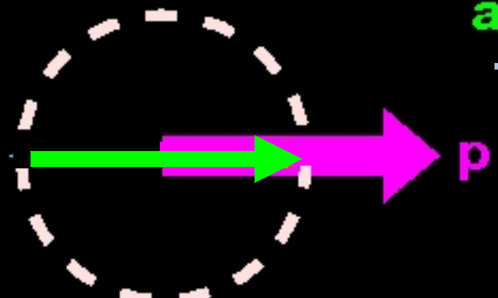
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$



$e^{\pm}$ from $\mu^{\pm} \to e^{\pm} \nu \bar{\nu}$ are detected

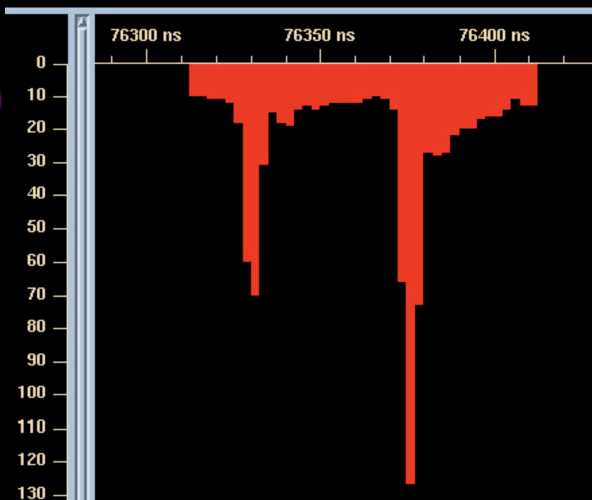


Measures Energy and time

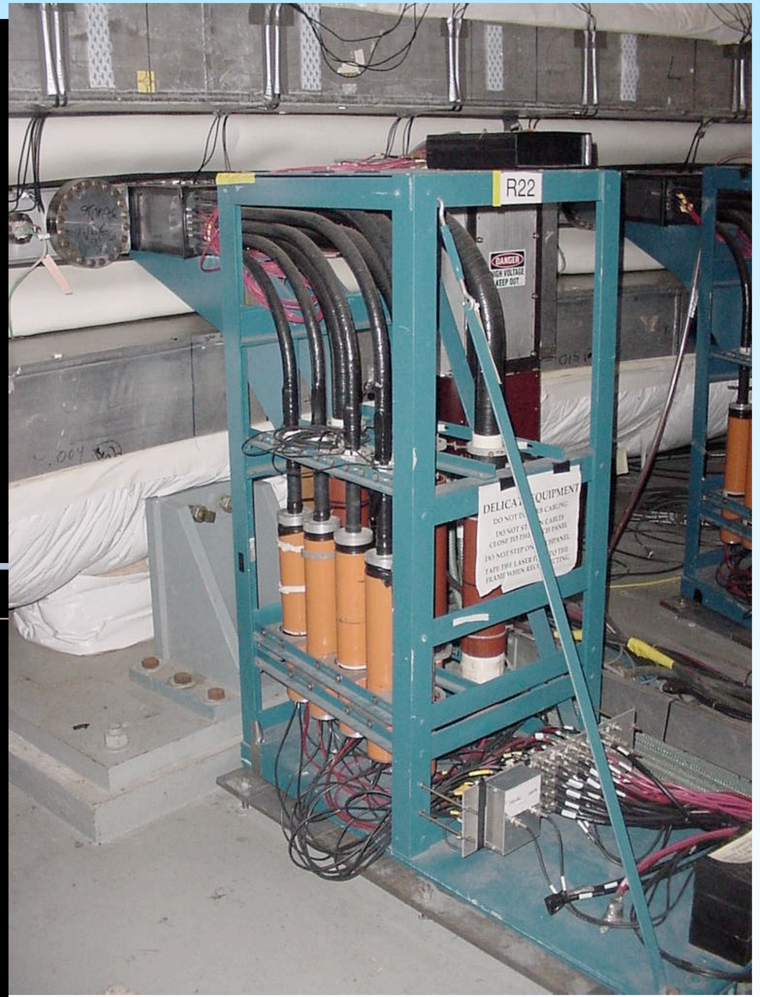


spin forward, more high energy e

spin backward, less high energy e



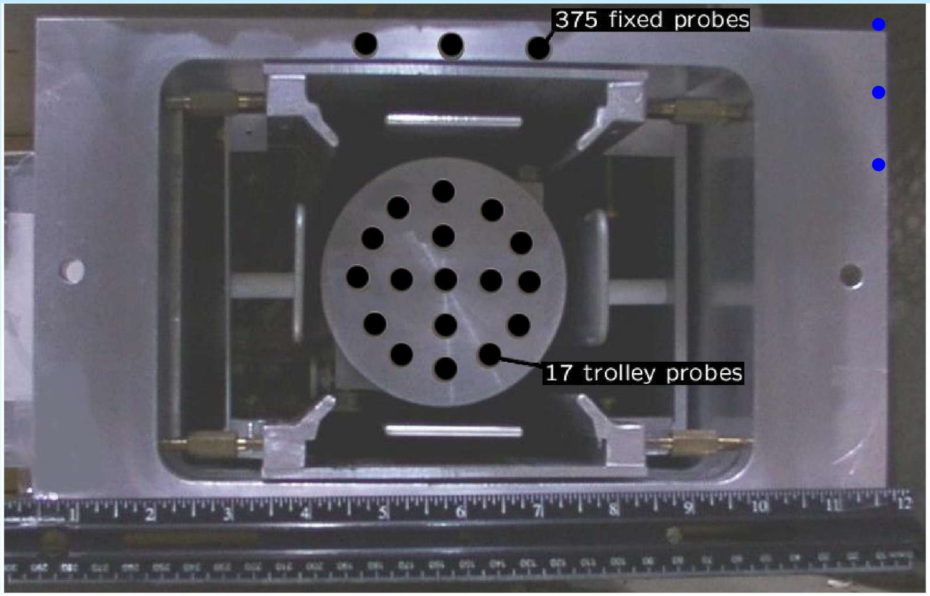
Waveform digitizer gives t, E



Picture of a Lead-Scifi Calorimeter from E821

The magnetic field is measured and controlled using pulsed NMR and the free-induction decay.

ω_p

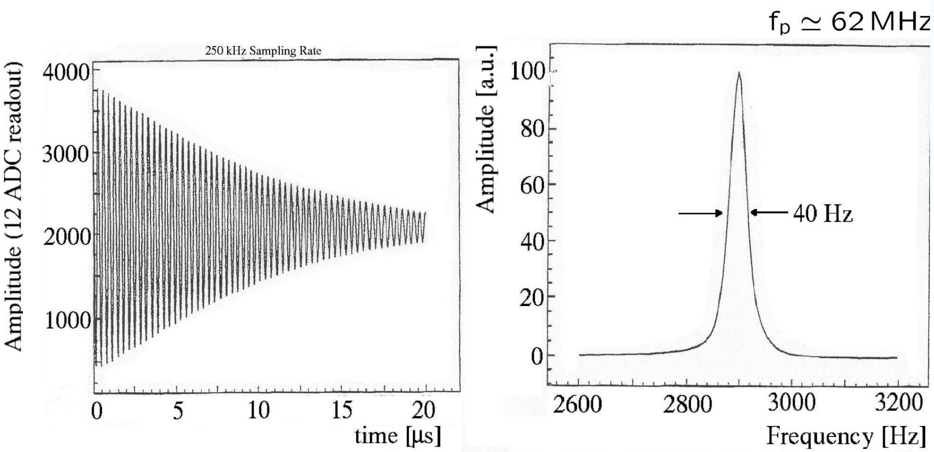


- ω_p= Larmor frequency of the free p
- We measure ω_a and ω_p independently
- Use $\lambda = \mu_\mu / \mu_p$ as the "fundamental constant"

Blind analysis

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

Free induction decay signals:



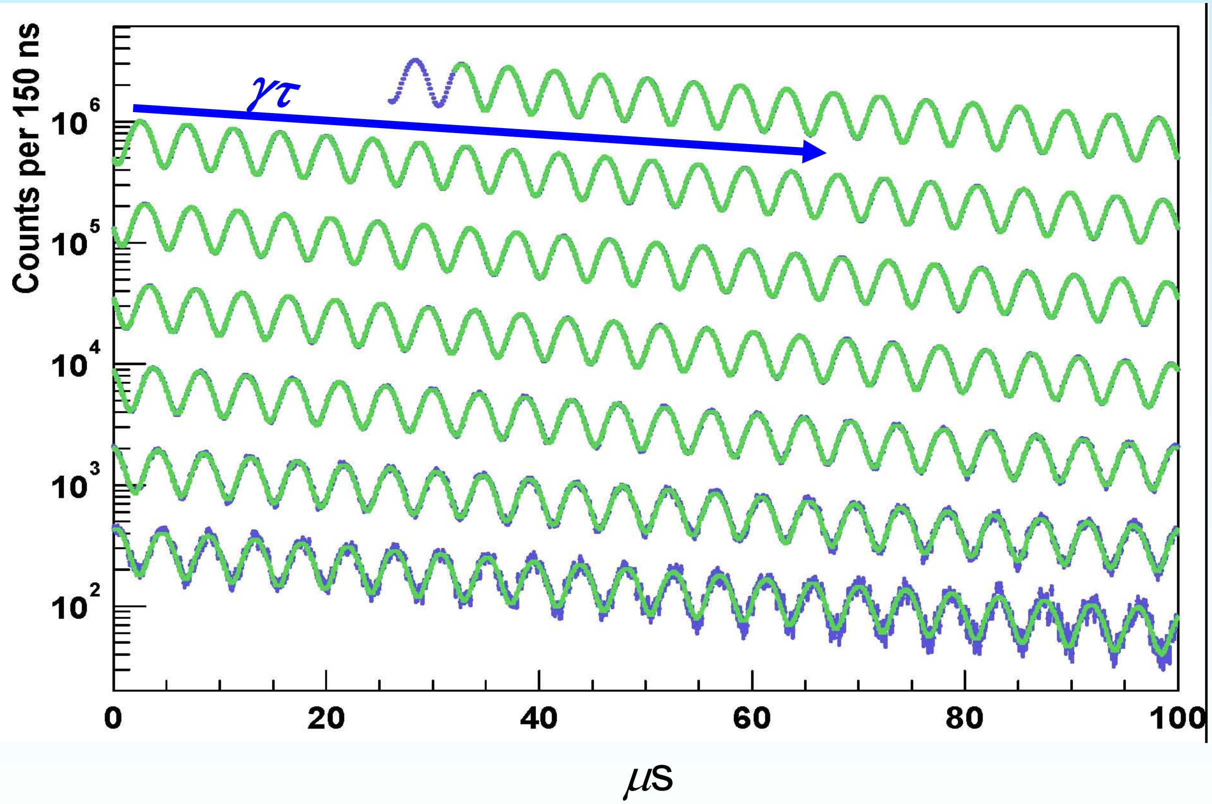
So which was the result for aμ?

The arrival time spectrum of high-energy e^- ω_a

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$

$$3.6 \times 10^9\ e^-$$

$E_e \geq 1.8$ GeV



$\gamma\tau_\mu$ = 64.4 μs;
(g-2): τ_a = 4.37 μs;
Cyclotron: t_C = 149 ns

Fitting this function gives ω_a. Together with the magnetic field one get a_μ:

$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot} \times 10^{-11}$$

(0.5 ppm)

What's the Standard Model prediction?

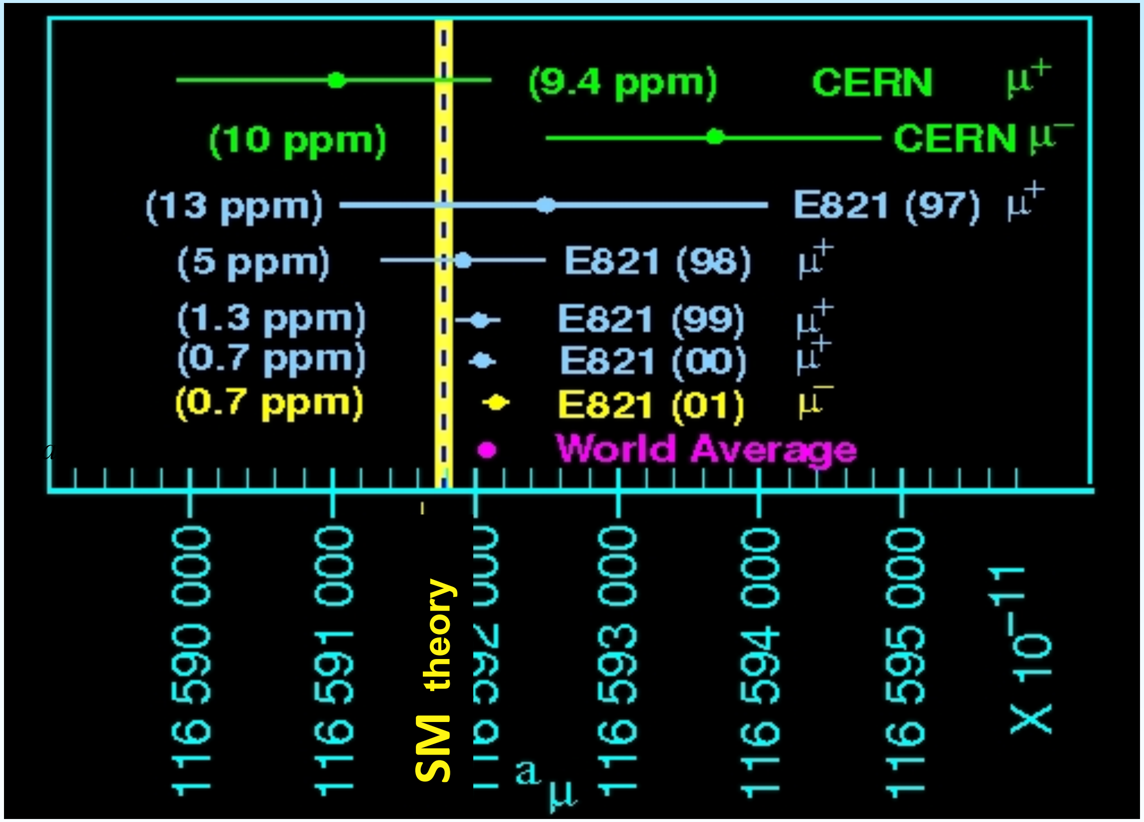
$$a_\mu^{E821} = 116\,592\,089(54)_{stat}(33)_{sys}(63)_{tot}\times 10^{-11}$$

(0.54 ppm!)

A factor 15 improvement in accuracy respect to CERN!

~3.5 “standard deviations” with SM

Error dominated by experimental uncertainty!



$$a_\mu^{SM} = 116\,591\,802 \pm 49 \times 10^{-11}$$ **M. Davier et al. 2011**

$$a_\mu^{E821} - a_\mu^{SM} = (287 \pm 80)\times 10^{-11}\ (3.6\,\sigma)$$

Hint of new physics?

A possible break in the Standard Model?

News Release

For more information, contact:
Karen McNulty Walsh, (631)344-8350, kmcnulty@bnl.gov or
Mona S. Rowe, (631)344-5056, mrowe@bnl.gov

BROOKHAVEN
NATIONAL LABORATORY

01-12
February 8, 2001

Physicists Announce Possible Violation of Standard Model of Particle Physics

UPTON, NY -- Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, in collaboration with researchers from 11 institutions in the U.S., Russia, Japan, and Germany, today announced an experimental result that directly confronts the so-called Standard Model of particle physics. "This work could open up a whole new world of exploration for physicists interested in new theories, such as supersymmetry, which extend the Standard Model," says Boston University physicist Lee Roberts, co-spokesperson for the experiment.

The g-2 muon storage ring at Brookhaven National Lab. Hi-Res

More information

Updates:
December 12, 2001
July 30, 2002

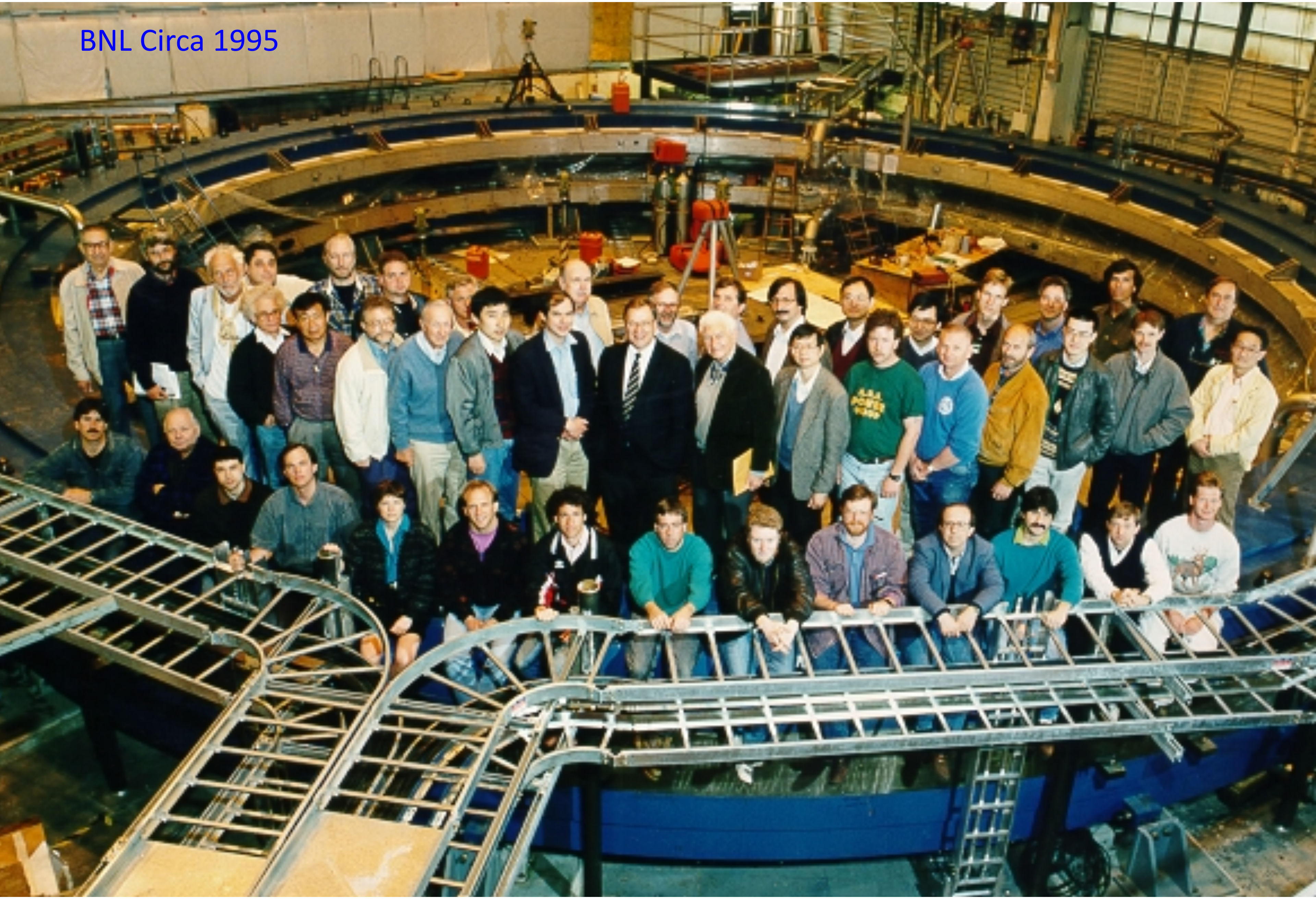
The Physical Review Letters paper.

Full background information

May 2000 and February 2001 stories on g-2 from the Brookhaven Bulletin

Additional pictures

What is a Muon?
Essentially, a "heavy" electron. The muon, electron, and tau particles are generically referred to as charged leptons, and they have the


BNL Circa 1995

The Muon g-2 experiment at FNAL (2009 – present)

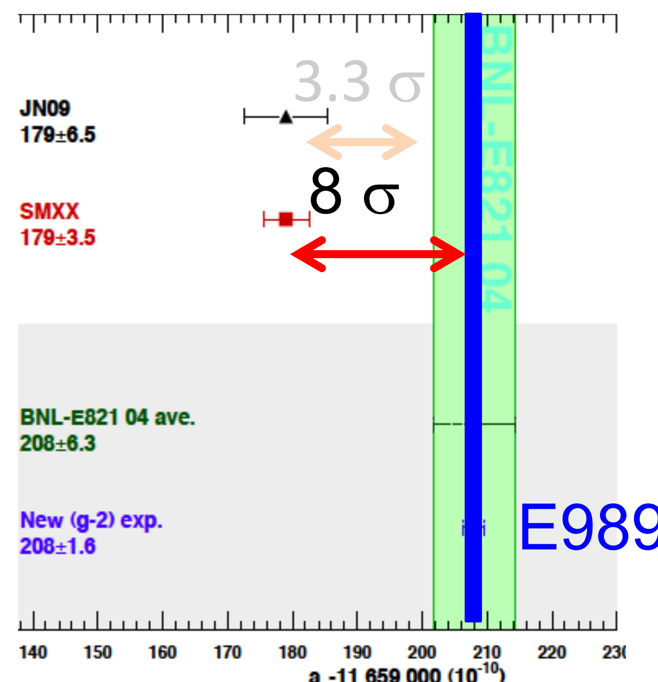
- New experiment at FNAL (E989) at magic momentum, consolidated method. **20 x stat.** w.r.t. E821. **Relocate** the BNL storage ring to FNAL.

→ δa_μx4 improvement (0.14ppm)

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

*Depending on the progress on Theory

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



Complementary proposal at J-PARC in progress

4 key elements for E989 at FNAL

- Consolidated method (same ring of the BNL experiment)
- More muons (x20)
- improved beam and detector → Reduced systematics
- New crew → new ideas

- **E821 at Brookhaven**

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

↳ $0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

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

$0.07\omega_a \oplus 0.07\omega_p$

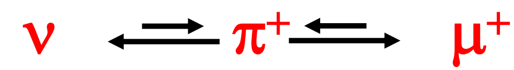
Towards 140ppb

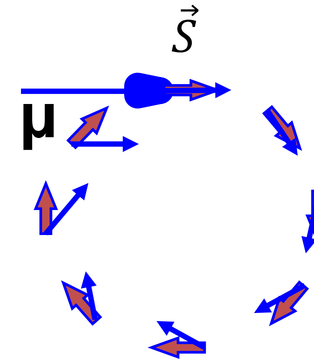
δa_μ	BNL (ppb)	FNAL goal (ppb)	
ω_a statistic	480	100	**20 × BNL statistics**: more muons/sec, higher quality beam, less beam background
ω_a systematic	180	70	**new instrumentation for ω_a measurement**: segmented and fast EM calorimeters with laser calibration system
$\overline{\omega}_p$ systematics	170	70	**improved ω_p measurement:** new precise NMR probes and tracker system for beam distribution
Total	**540**	**140**	

Key ingredients

1) Polarized muons

~97% polarized for forward decay





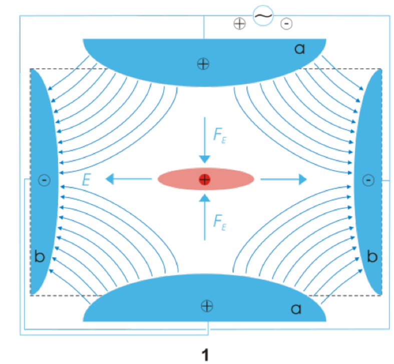
2) Precession proportional to (*g*-2)

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

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

Measure 2 quantities

3) P_μ magic momentum = 3.09 GeV/c

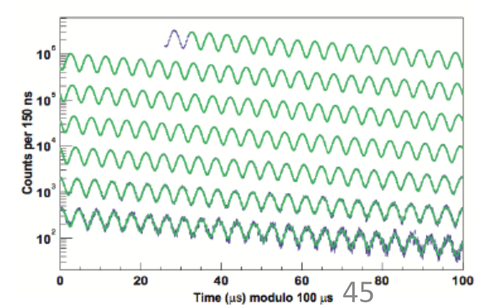


$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}\right]$$

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

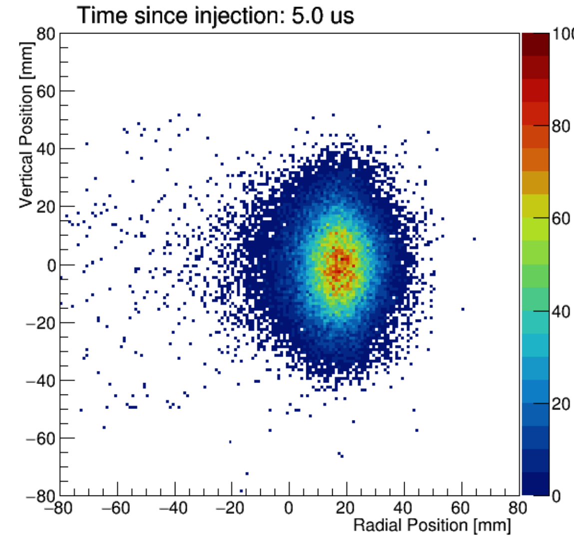
4) Decay e^+ emitted preferably in spin direction of the muon

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



However there are beam dynamics effects

- The muon beam oscillates and breathes as a whole
- The full equation is more complex and corrections due to radial (x) and vertical (y) beam motion are needed



$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c =$$

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

- Running at γ_{magic}=29.3 (p=3.094 GeV/c) this coefficient is null
- Because of momentum spread (<0.2%)→ **E-field Correction**

- Vertical beam oscillation → **Pitch correction**

Extracting a_μ(simplified)

By expressing B in terms of the precession frequency ω_p' of a proton shielded in a spherical water sample:

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

External (precise) data

$$B = \frac{\hbar \omega_p'}{2\mu_p'}$$

$$e = \frac{4 m_e \mu_e}{\hbar g_e}.$$

$$R' = \frac{\omega_a}{\tilde{\omega}_p'}$$

ratio of muon to proton precession in the same magnetic dipole field

$\tilde{\omega}_p'$ =Proton Larmor precession frequency **weighted for the muon distribution**

Muon g-2 collaboration

USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

USA National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

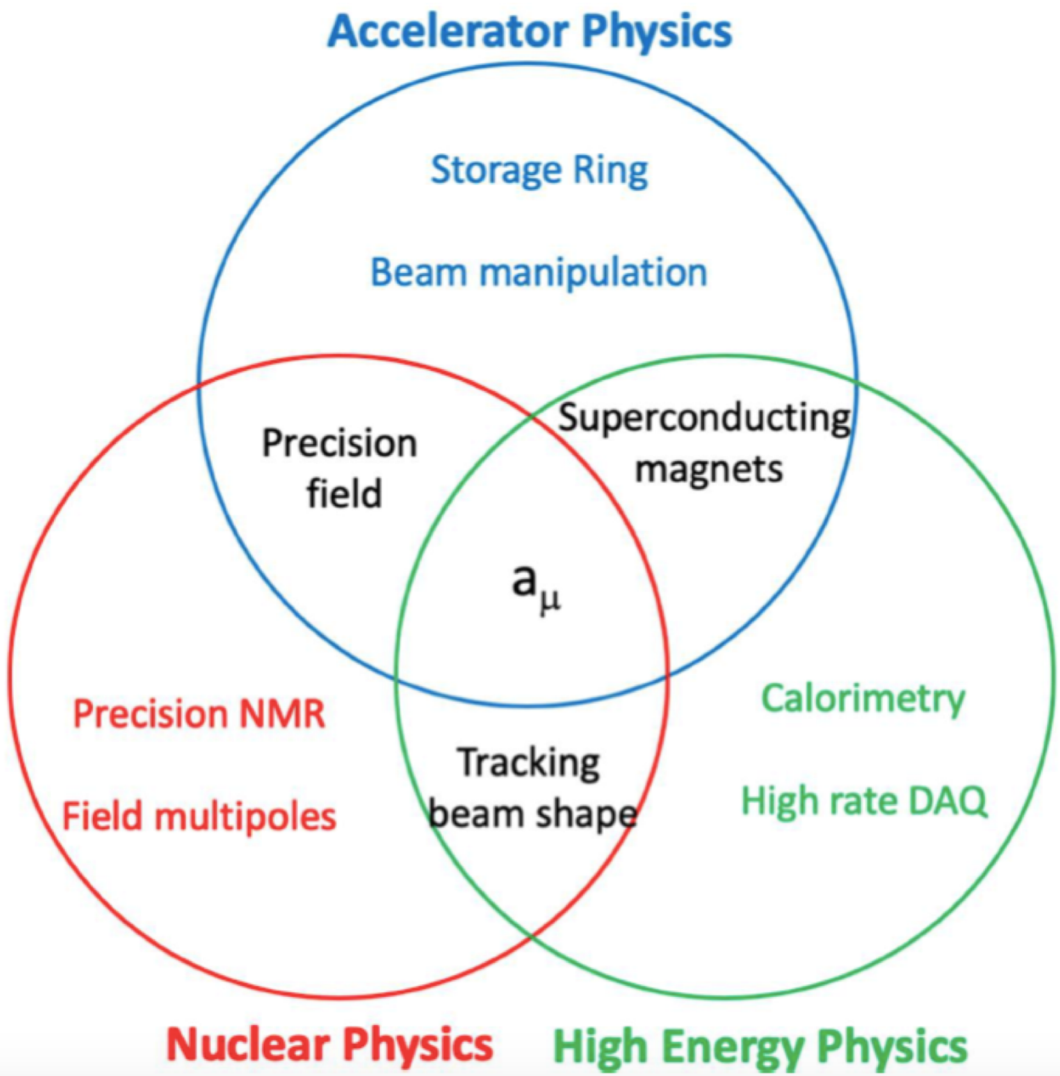
Korea
- CAPP/IBS
- KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

>200 collaborators
35 Institutions
7 countries

Three different communities to measure a_μ



June 2013: The ring leaves from BNL

2013: The Big Move

2013: The Big Move

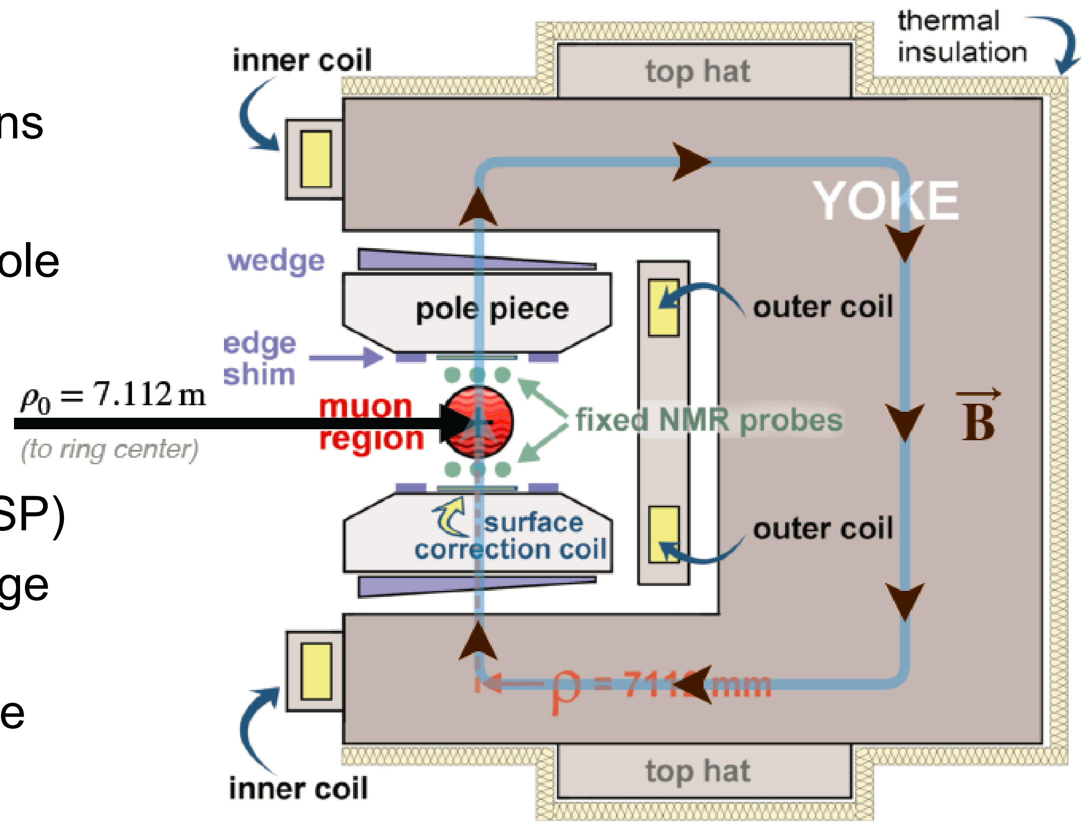
26 July 2013:…the ring arrives to FNAL

FERMILAB

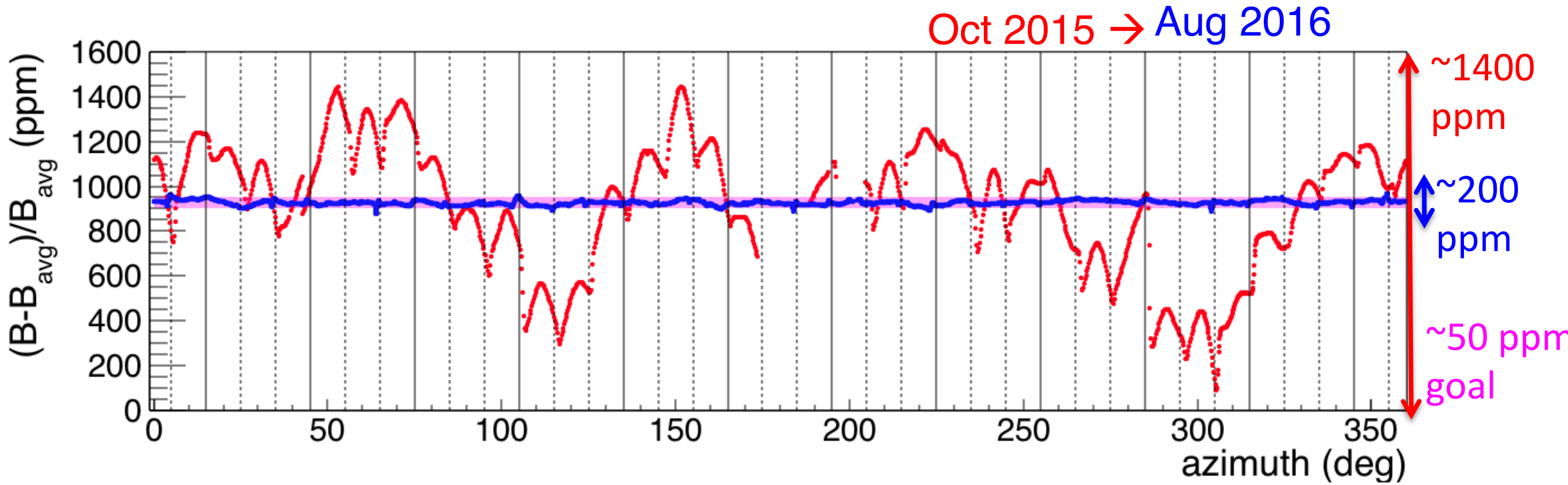
[redacted]

Shimming tools for the Magnetic Field

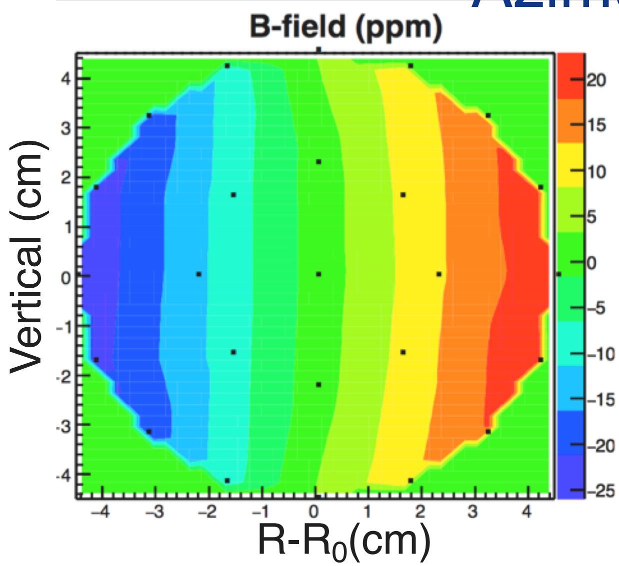
- **B Field** 1.45T
- **12 Yokes**: C shaped flux returns
- **72 Poles**: shape field
- **864 Wedges:** angle - quadrupole (QP))
- **24 Iron Top Hats**: change effective mu
- **Edge Shims**: QP, sextupole (SP)
- **8000 Surface iron foils**: change effective mu locally
- **Surface coils**: will add average field moments (360 deg)



B Field shimmed at 3x finer uniformity than BNL

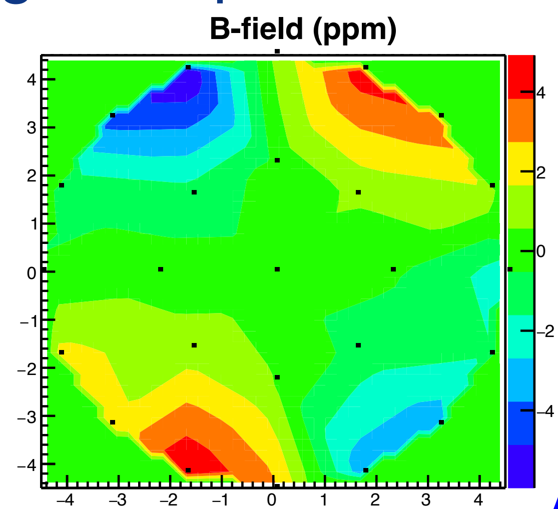


Azimuthally Averaged Map



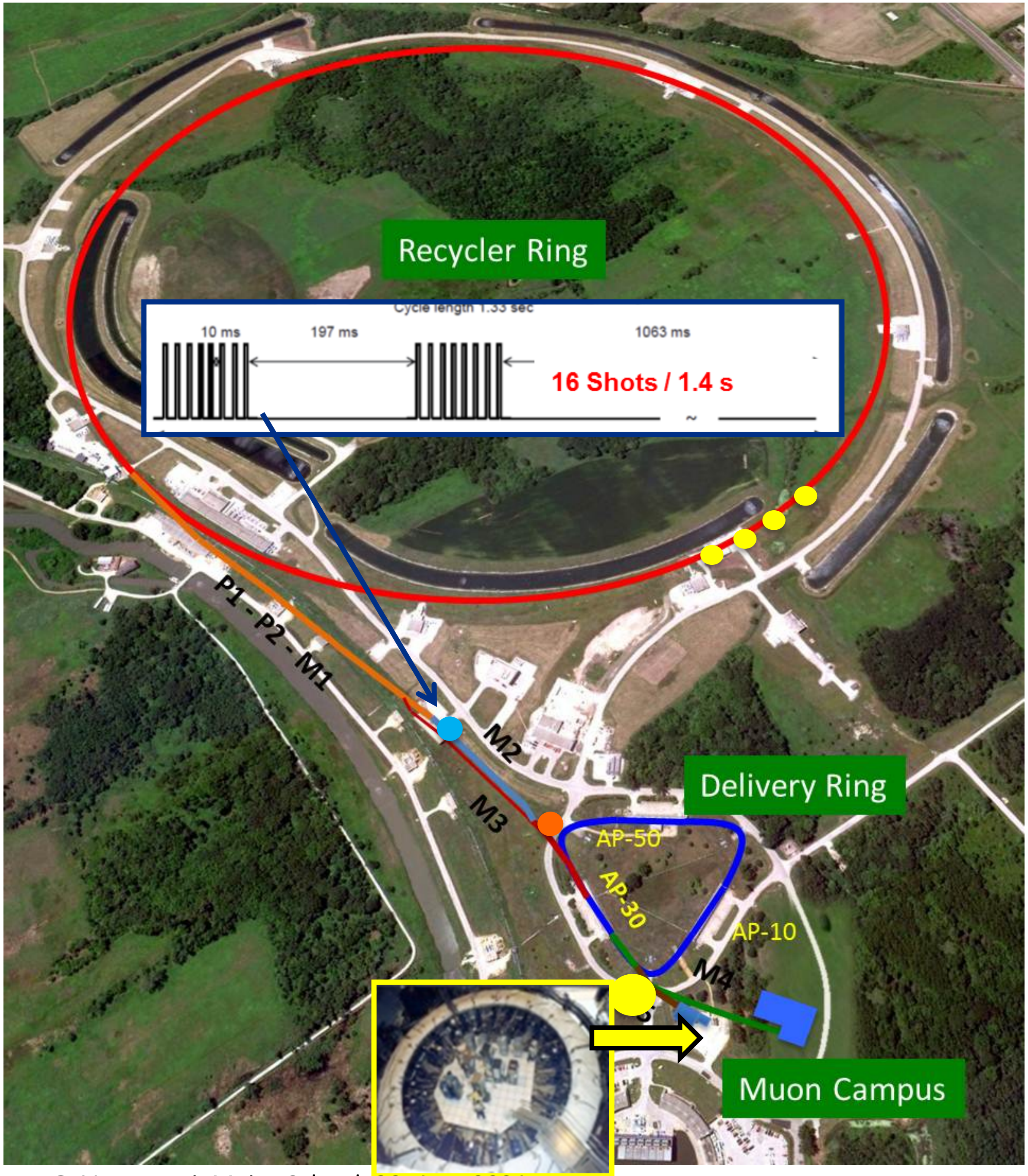
	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07

Oct 2015



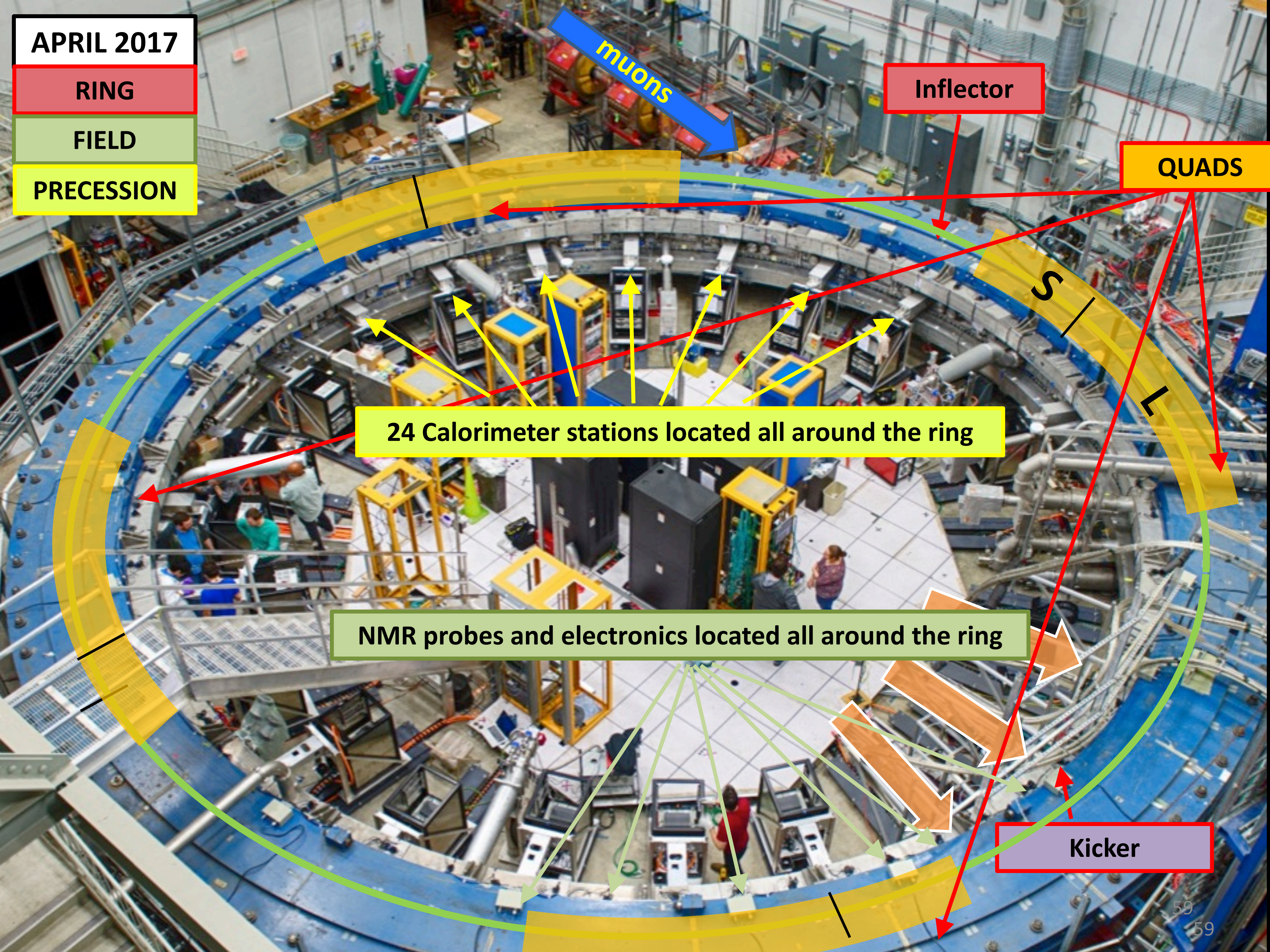
	Norm	Skew
Quad	-0.02	-0.57
Sext	-0.70	3.84
Octu	-0.76	0.56
Decu	0.44	-1.61

Aug 2016

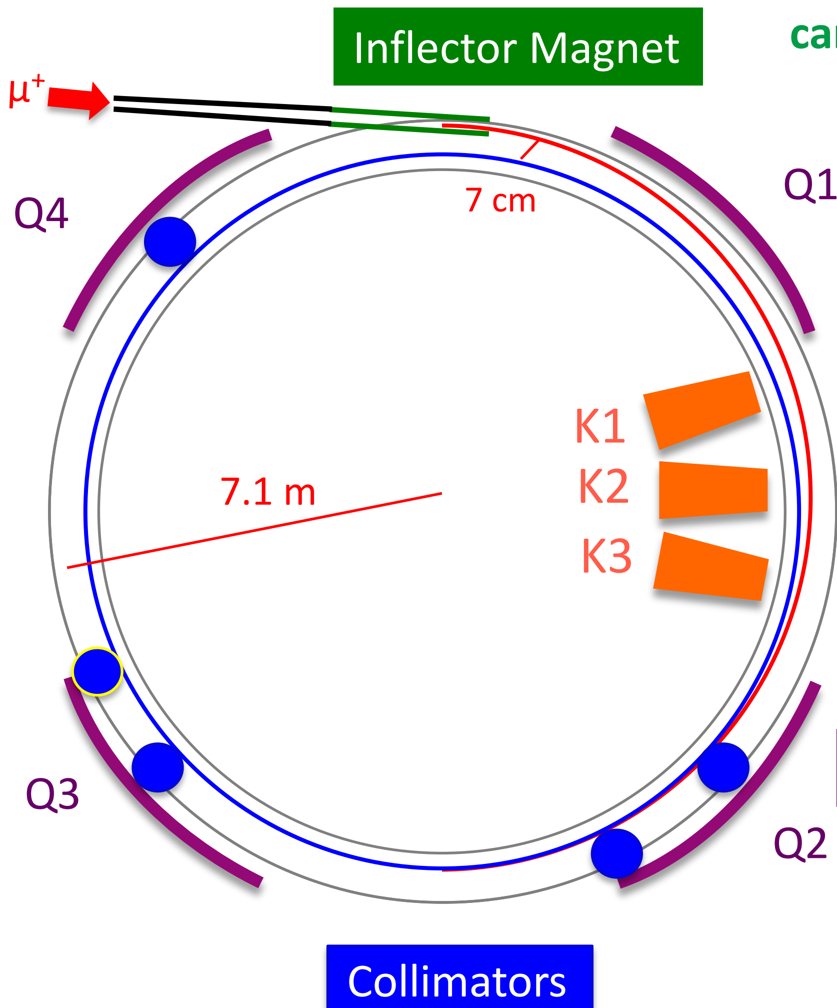


Creating the Muon Beam for g-2

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


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

Injection / storage



cancels 1.45 T main field

Kicker magnets **x3 (40-55 kV)**

radially centers beam

Focussing quadrupoles **15-28 kV**

vertically focusses beam

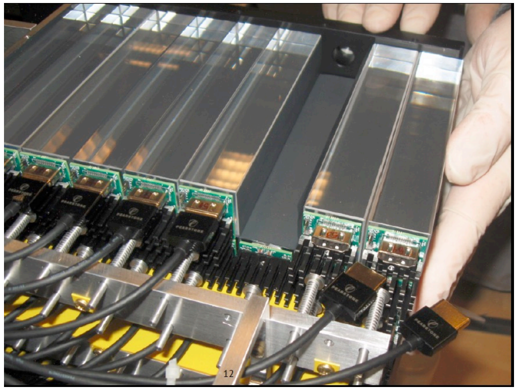
R_{fill}~13Hz

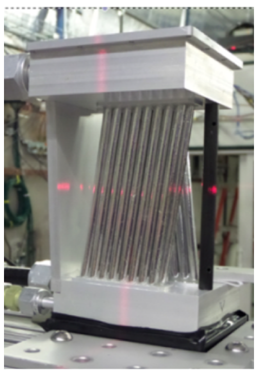
N_{μ}/fill (TDR)~ 10^4

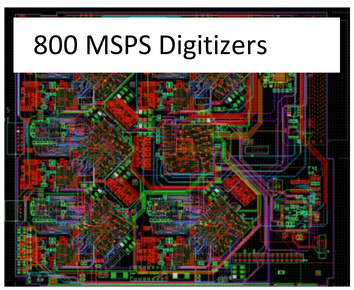
N_{μ}/sec(TDR)~ 1.3×10^5

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

Detector systems

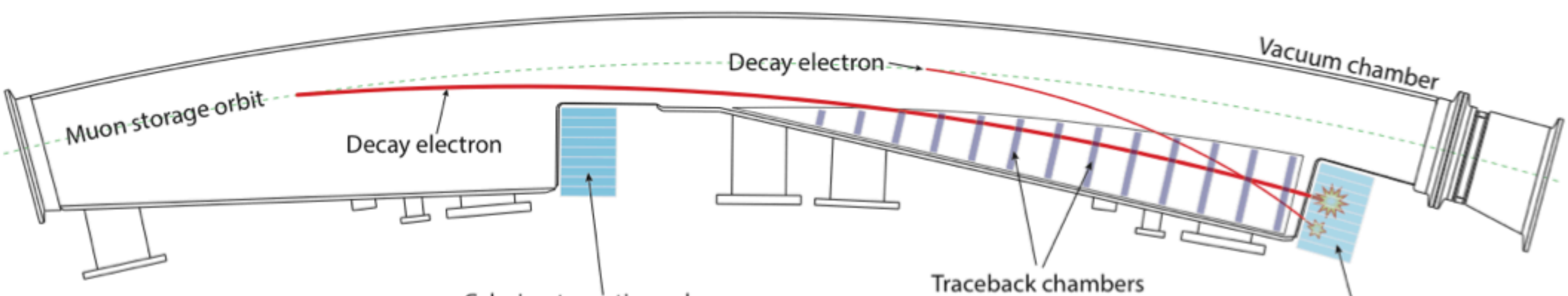




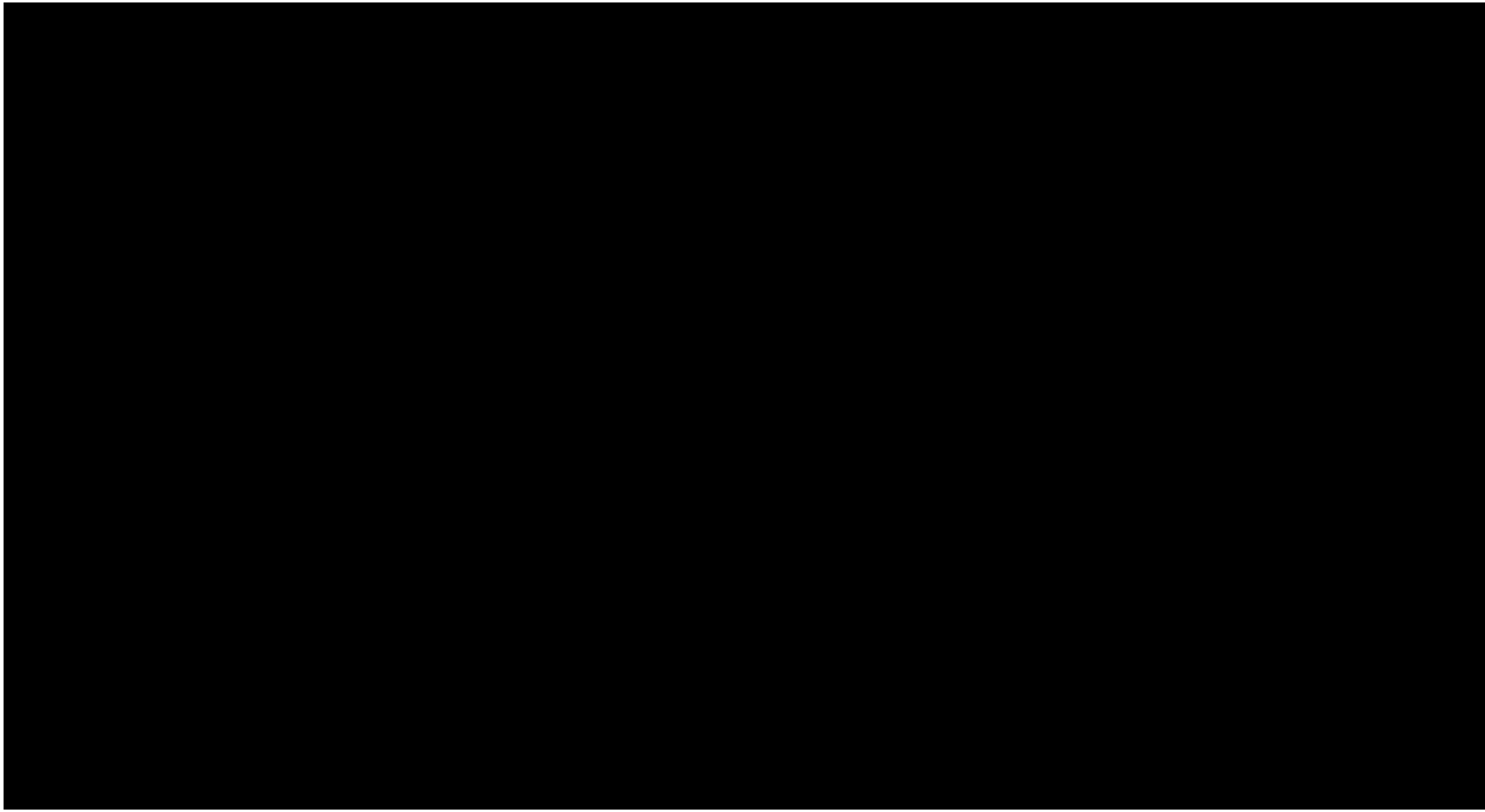


- Calorimeters: fast PbF_2 crystal arrays with SiPM readout → greatly reduce pileup
- State of the art laser calibration system
- WFD electronics → greatly reduced energy threshold
- Two straw tube trackers to precisely monitor properties of stored muons

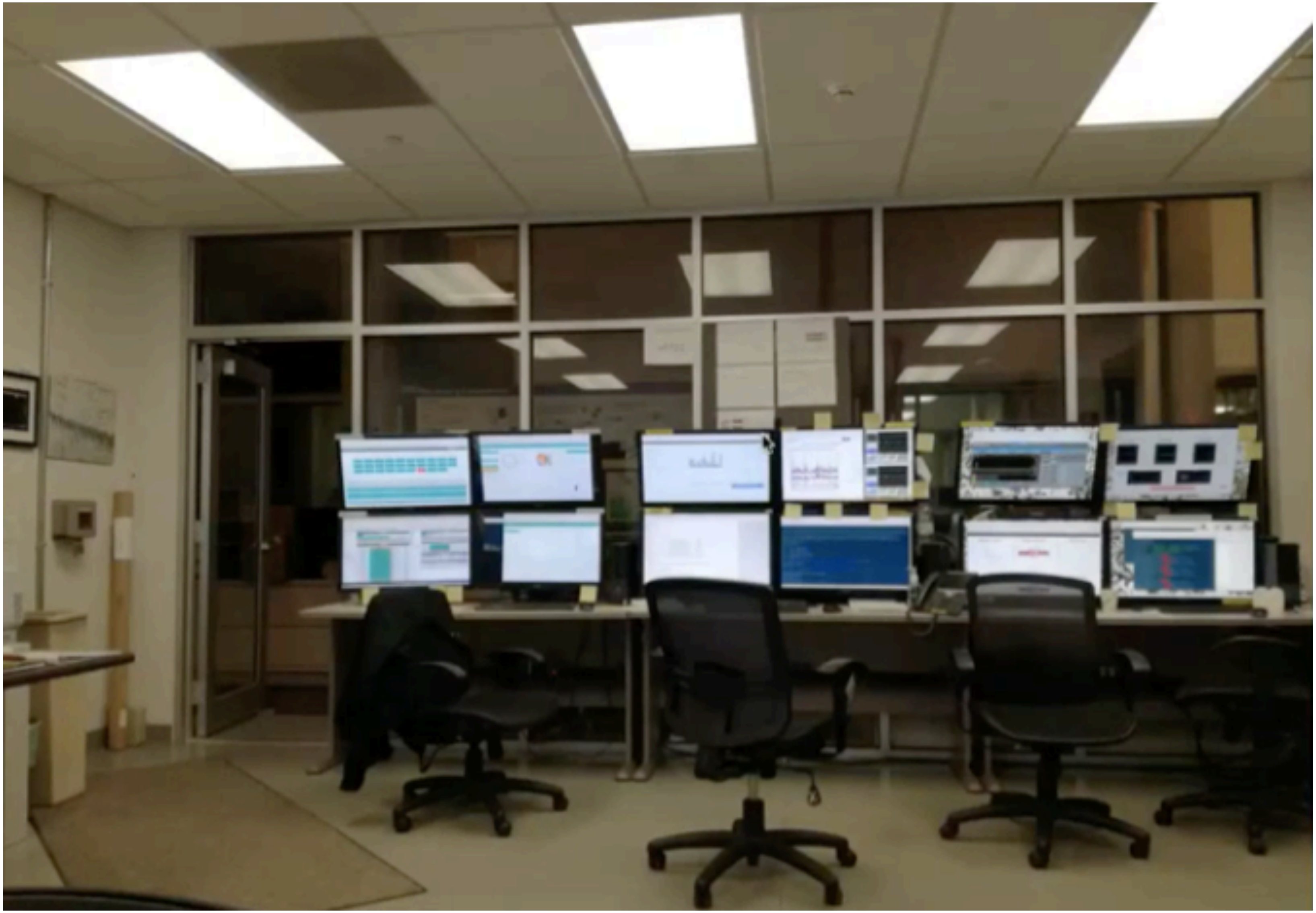
Top view of 1 of 12 vacuum chambers



From a muon's eyes



The control room



A blinded analysis

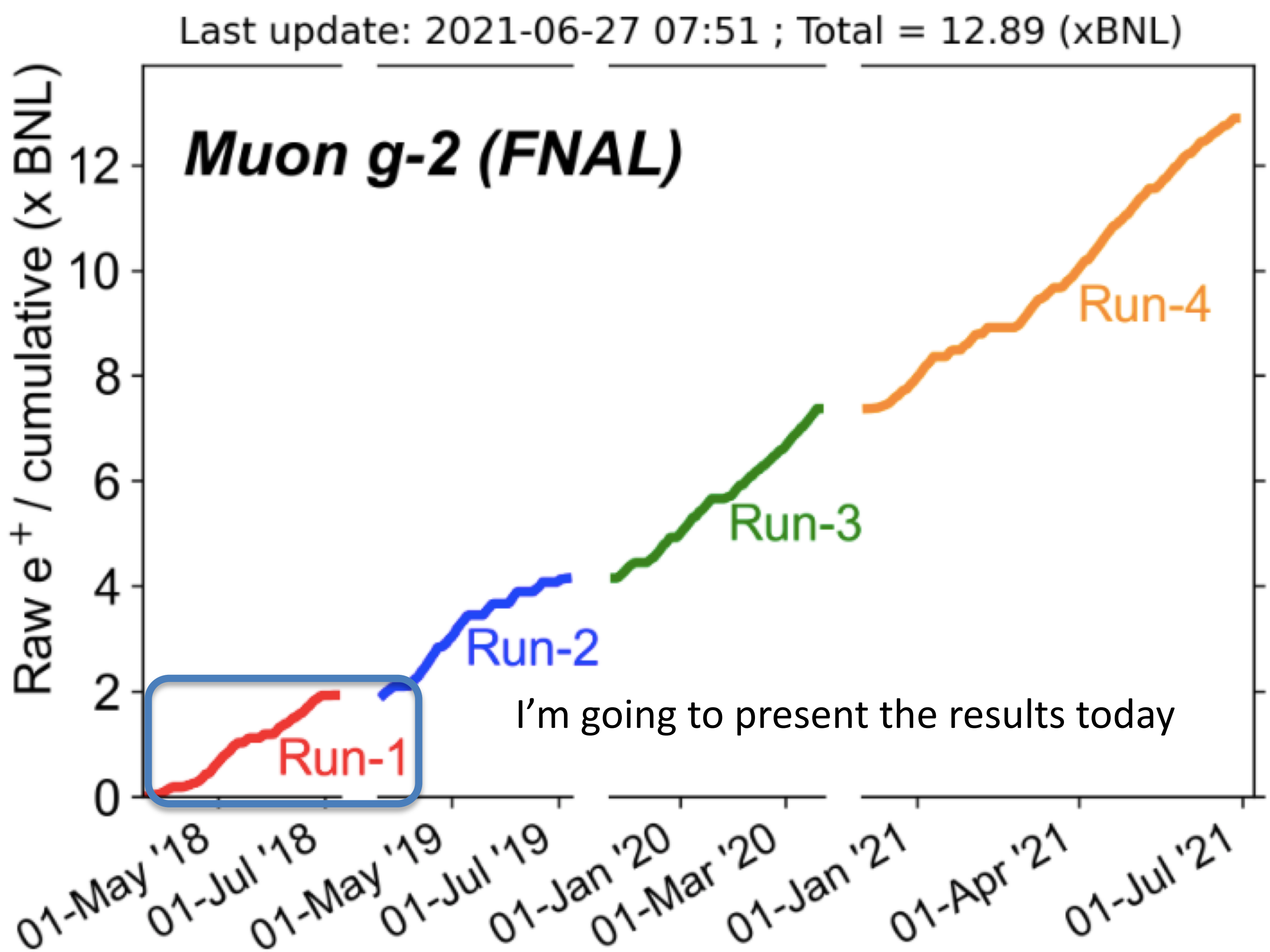
- The analysis is twofold blinded:
  - Clock frequency blinding (HW)
  - Unknow offset in the analysis of ω_a (Software)
- The HW blinding factor is known only to two people outside the collaboration and revealed at the completion of the analysis

blinding the clock in 2018

Locked Clock Panel

E989 collected data

We have collected ~13 x BNL over the last 4 years:



Total statistics RUN1 =8.2B e^+ ~1.2x BNL one

RUN1: analysis structure

- Multiple analysis groups with different methodologies:
  - Six groups analyse ω_a with 2 different energy and time reconstructions and 4 different analysis methods
  - Two groups for the analysis of ω_p + one group for calibration
  - Different groups for beam dynamics corrections

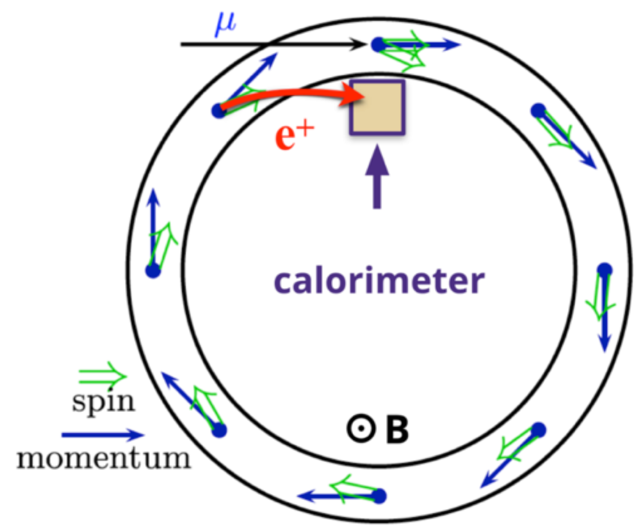
ω_a Measurement

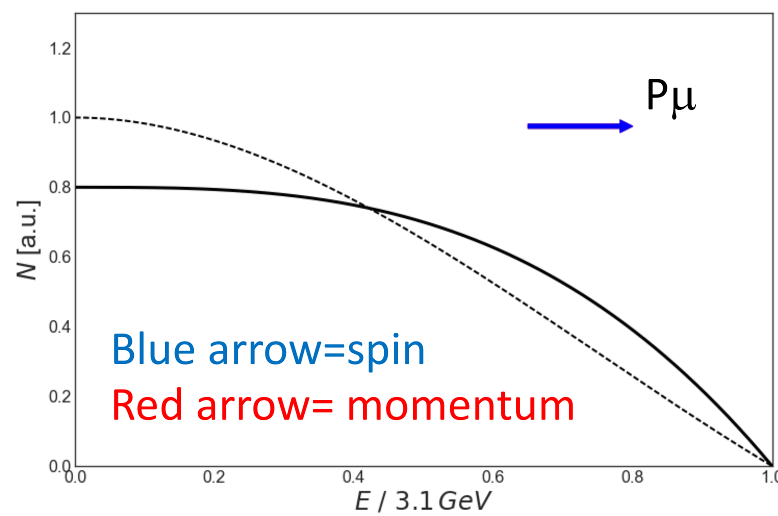
- The number of positrons is modulated by the anomalous precession frequency

$$N_0 e^{-t/\tau}[1 - A\, cos(\omega_a t + \phi)]$$

- 4 different analysis methods:
  - T: simple energy threshold >1.7 GeV
  - A: asymmetry weighted with threshold >1.1 GeV
  - R: ratio method
  - Q: No clustering: total energy above minimal threshold

- A-method used to provide ω_a





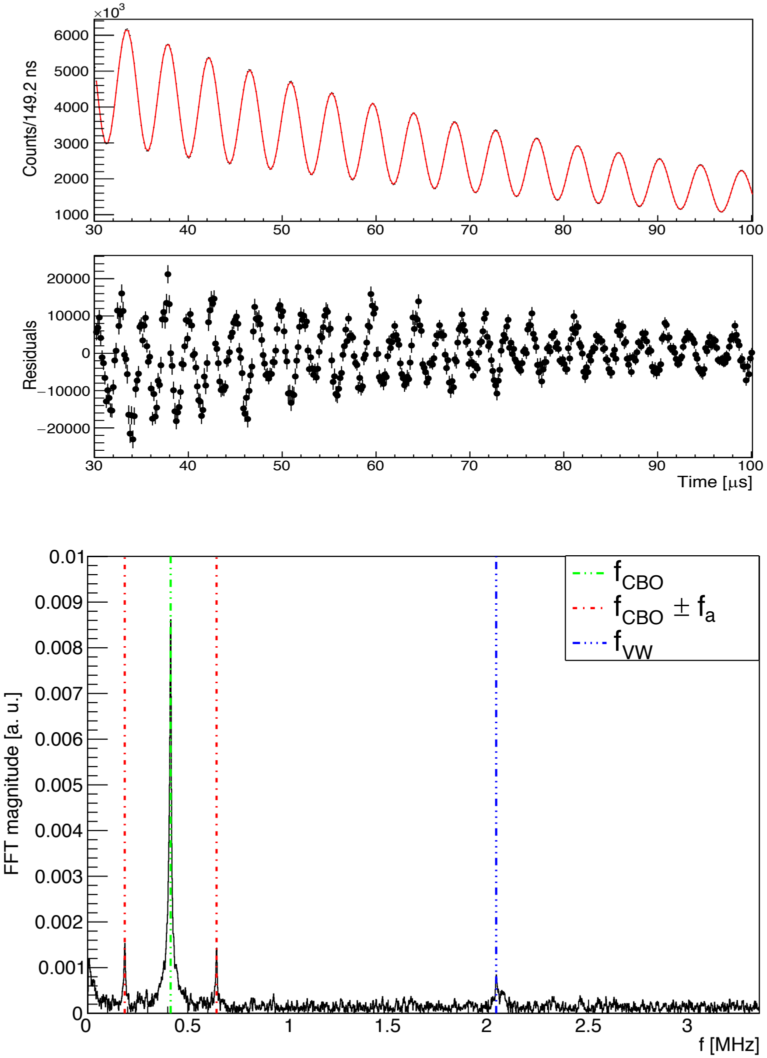
E and t are the measured observables.

The ω_a fit

- The wiggle plot is fitted with a decay exponential modulated by the precession frequency:

$$f_5(t) = N_0 e^{-t/\tau}[1 - A\, cos(\omega_a t + \phi)]$$

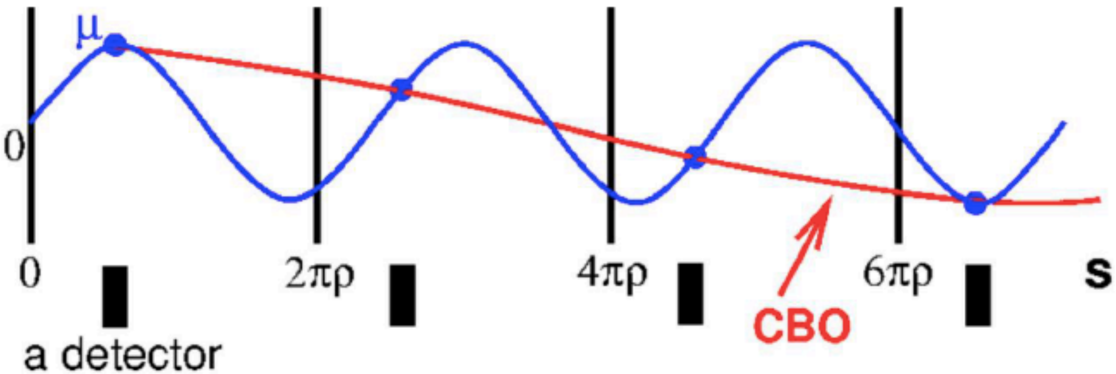
- The 5 parameters function presents peaks in the Fast Fourier Transform (FFT) of the residuals due to beam dynamics effects
- Increasing the number of corrections in order to remove peaks

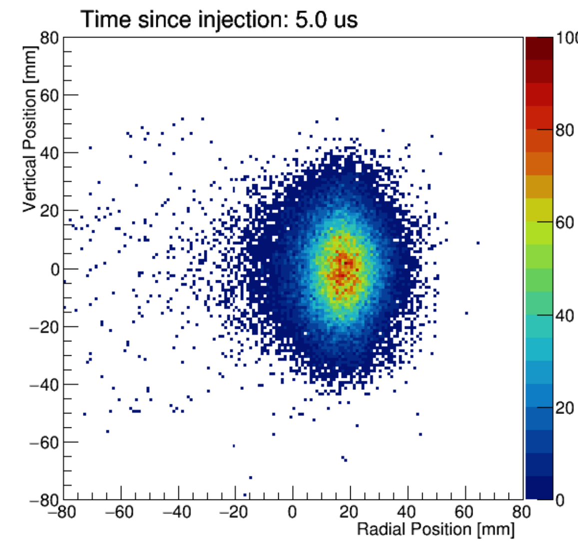


Structure in residual: Beam oscillation

- Coherent Betatron Oscillations (CBO) sampled by each detector at one point around the ring

$$\lambda_{\mathrm{CBO}} \simeq \text{ 14 turns}$$





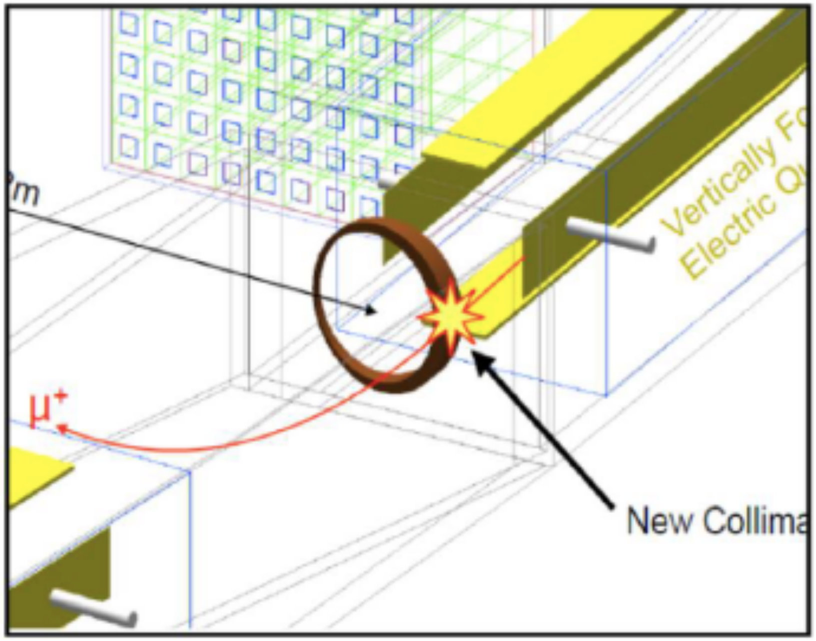
- Beating effects and additional radial and vertical frequencies

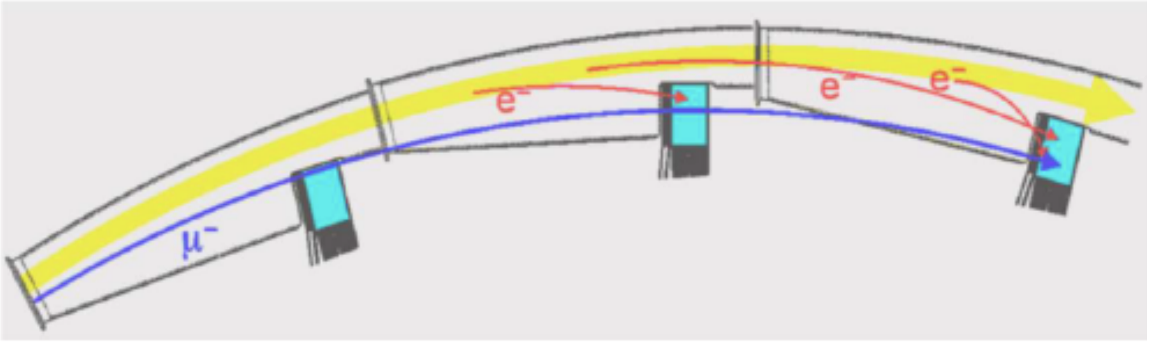
Lost Muons

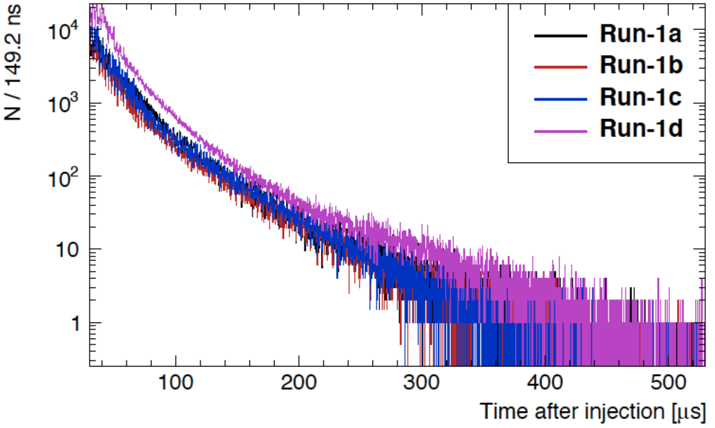
- Muon losses distort the exponential decay of the number of stored muons
- Muon Loss term :

$$J(t) = 1 - K_{LM} \int_0^t e^{\frac{t'}{\tau}} L(t')dt'$$

- $L(t)$ measured from the detection of Minimum Ionizing Particles in the calorimeters







The fit equation

$$N_0\, e^{-\frac{t}{\gamma\tau}}\,(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)$$

$$A_{\rm BO}(t) = 1 + A_A \cos(\omega_{\rm CBO}(t) + \phi_A)e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$\phi_{\rm BO}(t) = 1 + A_\phi \cos(\omega_{\rm CBO}(t) + \phi_\phi)e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$N_{\rm CBO}(t) = 1 + A_{\rm CBO}\cos(\omega_{\rm CBO}(t) + \phi_{\rm CBO})e^{-\frac{t}{\tau_{\rm CBO}}}$$

$$N_{\rm 2CBO}(t) = 1 + A_{\rm 2CBO}\cos(2\omega_{\rm CBO}(t) + \phi_{\rm 2CBO})e^{-\frac{t}{2\tau_{\rm CBO}}}$$

$$N_{\rm VW}(t) = 1 + A_{\rm VW}\cos(\omega_{\rm VW}(t)t + \phi_{\rm VW})e^{-\frac{t}{\tau_{\rm VW}}}$$

$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y)e^{-\frac{t}{\tau_y}}$$

Red = free parameters

Blue= fixed parameters

$$J(t) = 1 - k_{LM}\int_{t_0}^{t} \Lambda(t)dt$$

Muon Loss term

$$\omega_{\rm CBO}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F\omega_{{\rm CBO}(t)}\sqrt{2\omega_c/F\omega_{\rm CBO}(t) - 1}$$

$$\omega_{\rm VW}(t) = \omega_c - 2\omega_y(t)$$

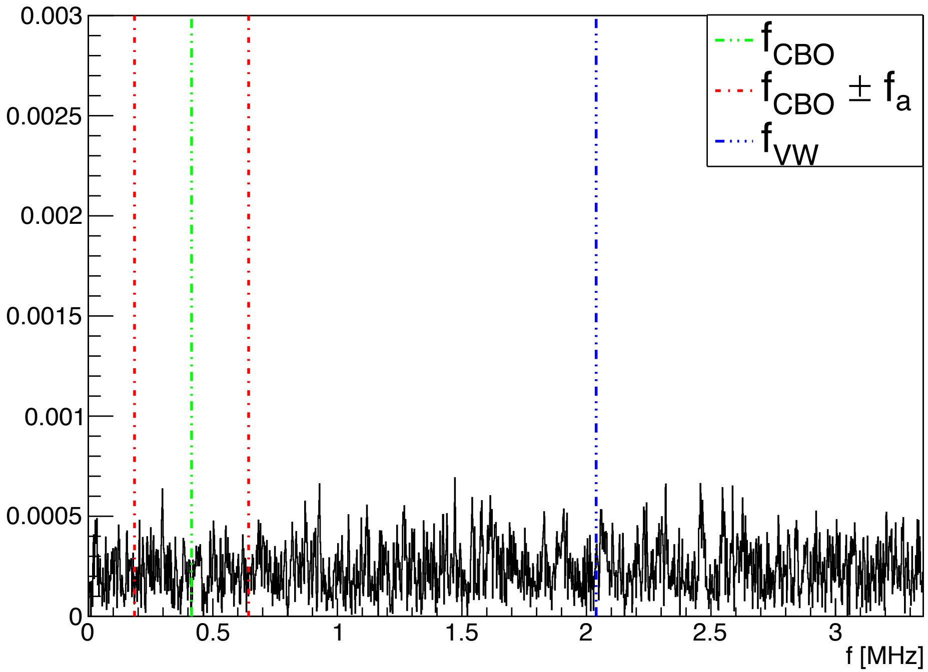
ω_y, ω_{vw} vertical oscillations

ω_{CBO}, ω_{2CBO}, radial oscillation

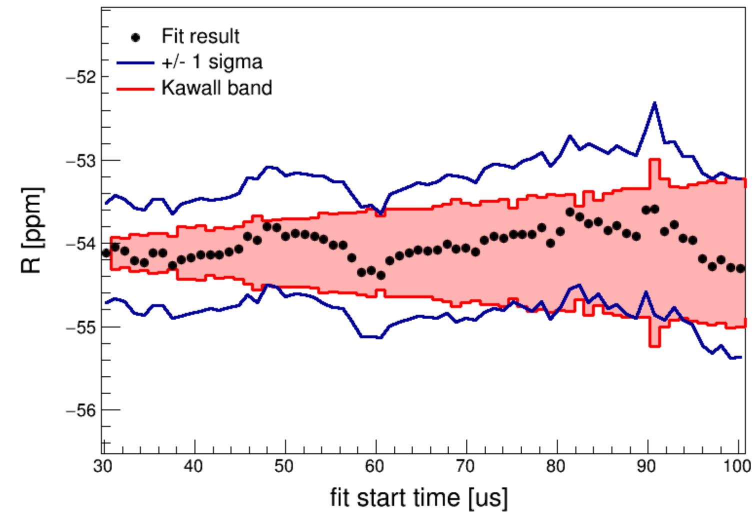
Final Fit

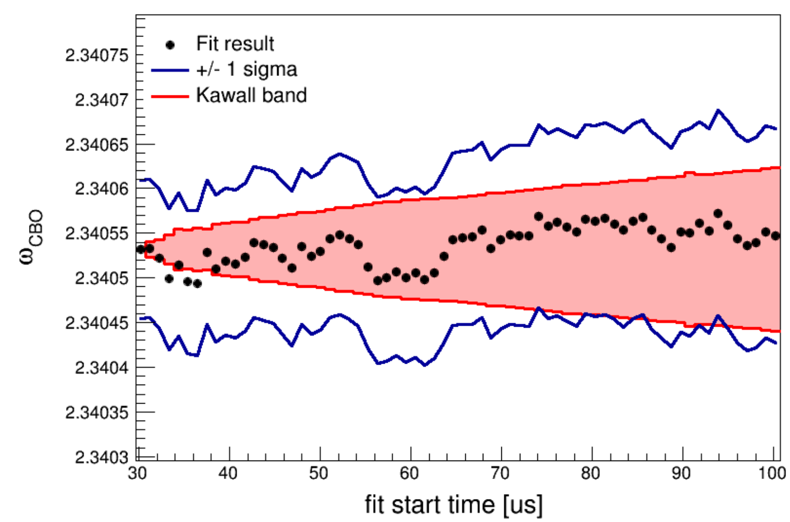
$R_{(blinded)} = (1 + \omega_{blind} / \omega_{ref})$ [ppm]

Fourier transform of residuals



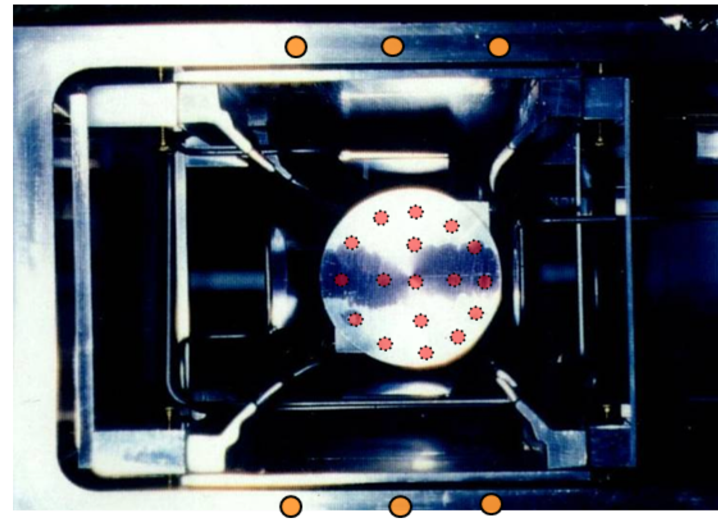
No unaccounted frequencies

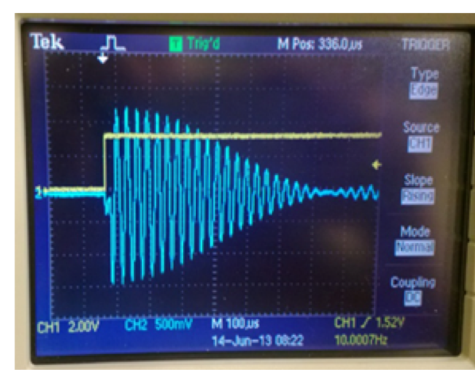




Measuring the magnetic field

- 378 Fixed probes monitor field 24/7
- 17-probe NMR trolley maps the magnetic field over the muon storage region
  - Trolley runs every 2-3 days
- Free induction decay signal of the probes digitized and analyzed to extract a precession frequency





Measuring the magnetic field

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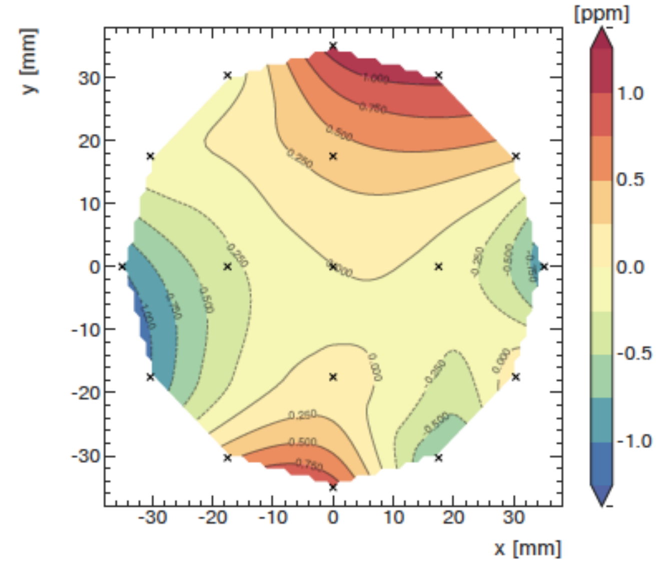
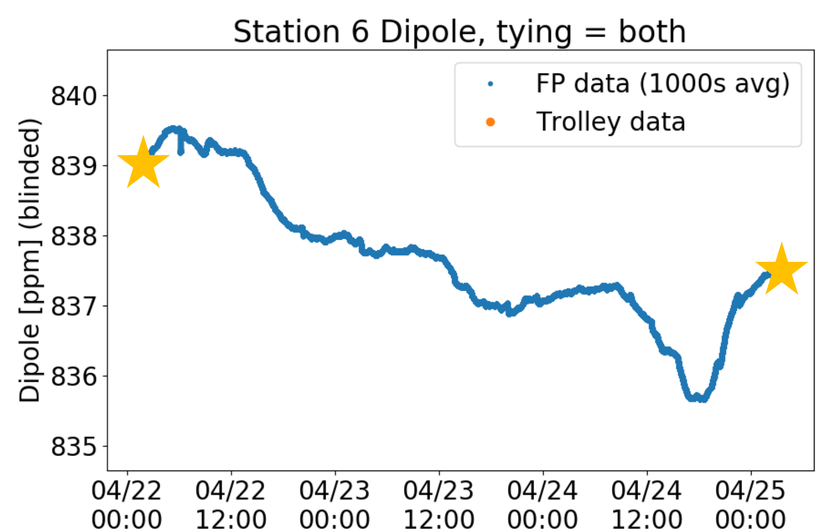
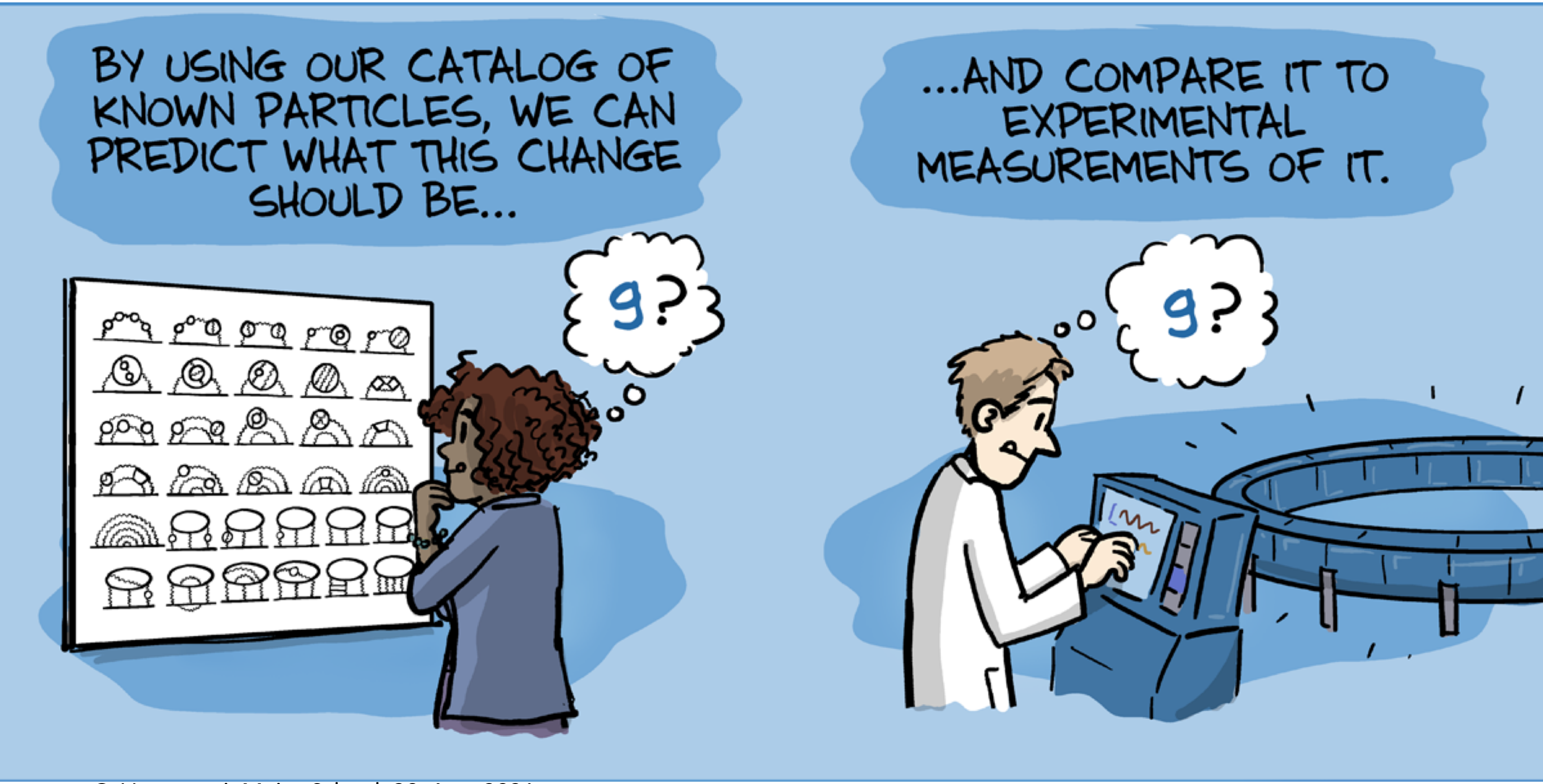


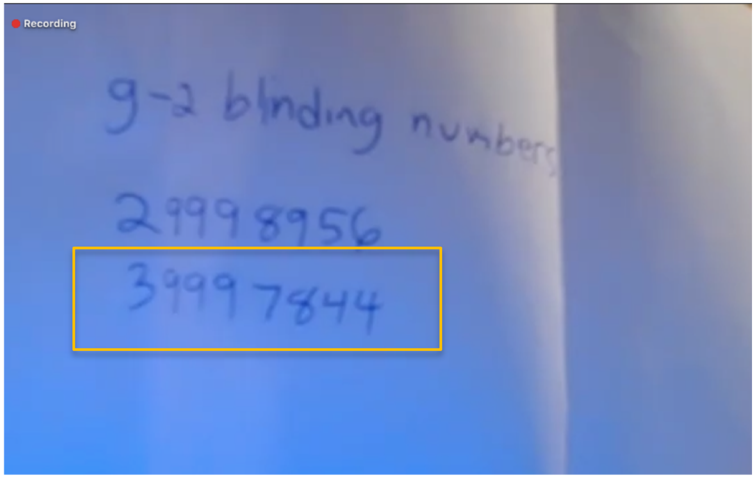


Experiment theory comparison



a_μ: Unblinding

The collaboration met on 25 February for the unblinding:
The sealed envelopes were opened
The number was included in two independent programs
And the result was …



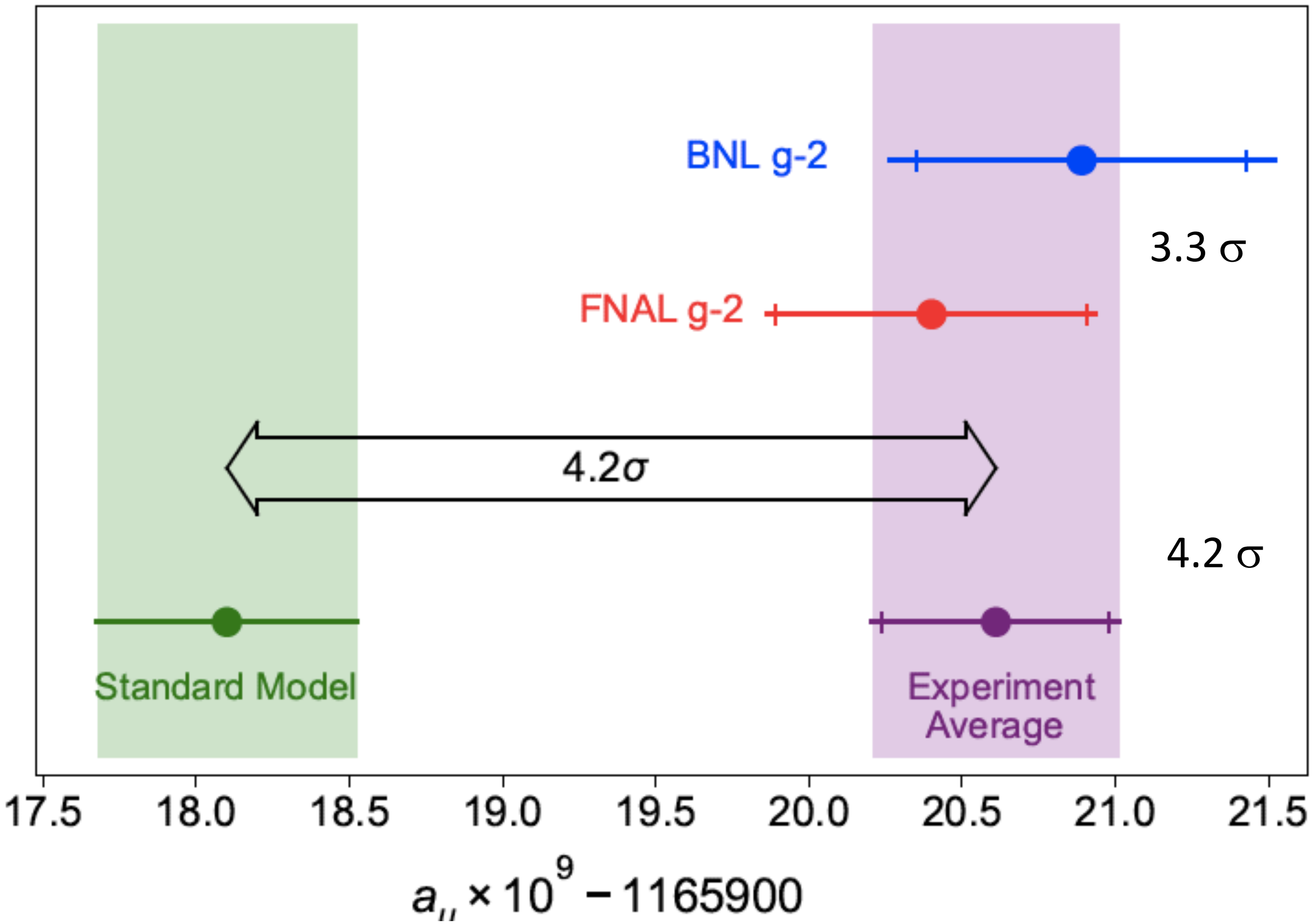
Secret offset

a_μ: Unblinding meeting

Result

1:40000 chance that the SM is correct!

3.7 σ



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

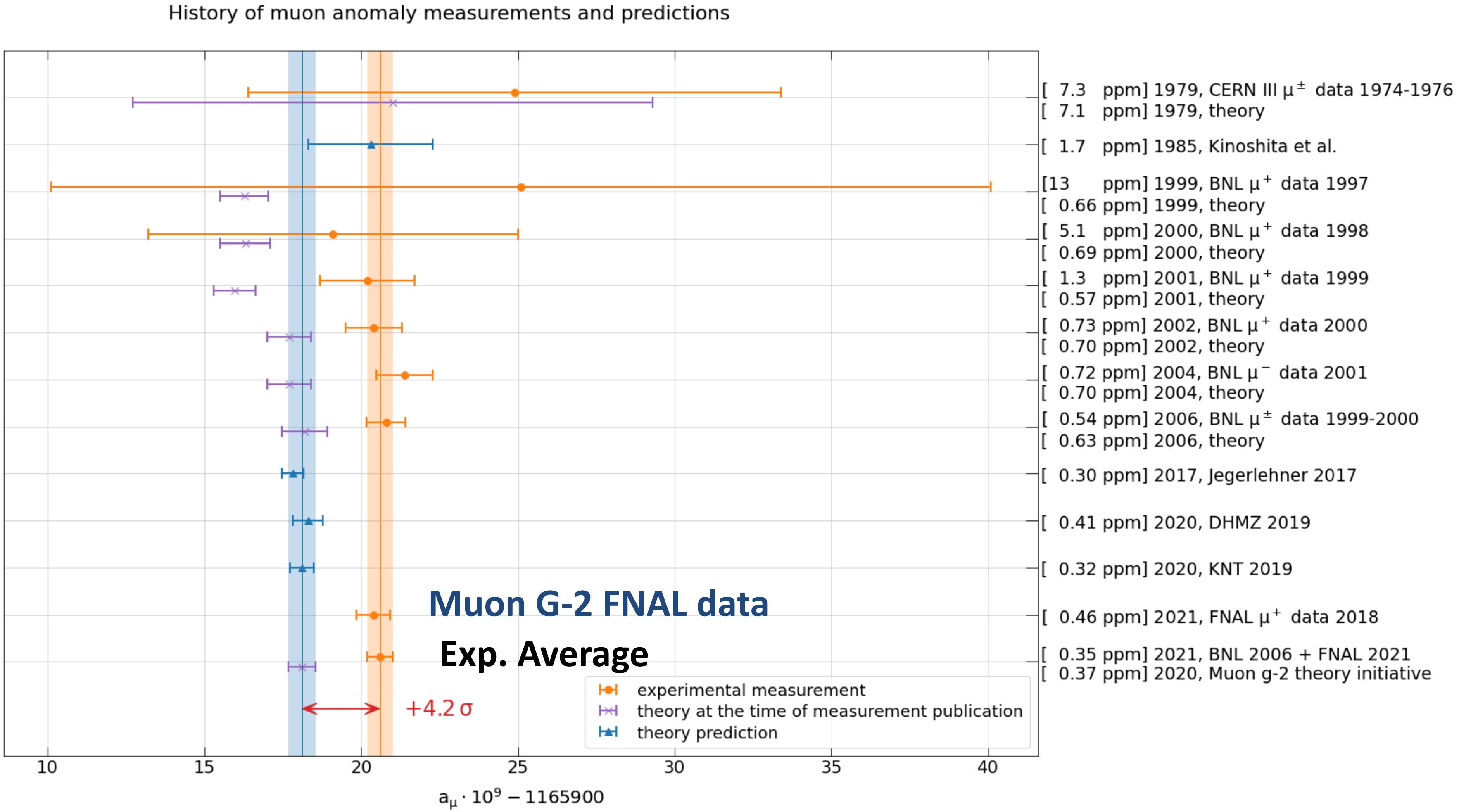
a_μ: Unblinding

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

434 ppb stat $\oplus$ 157 ppb syst error

$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

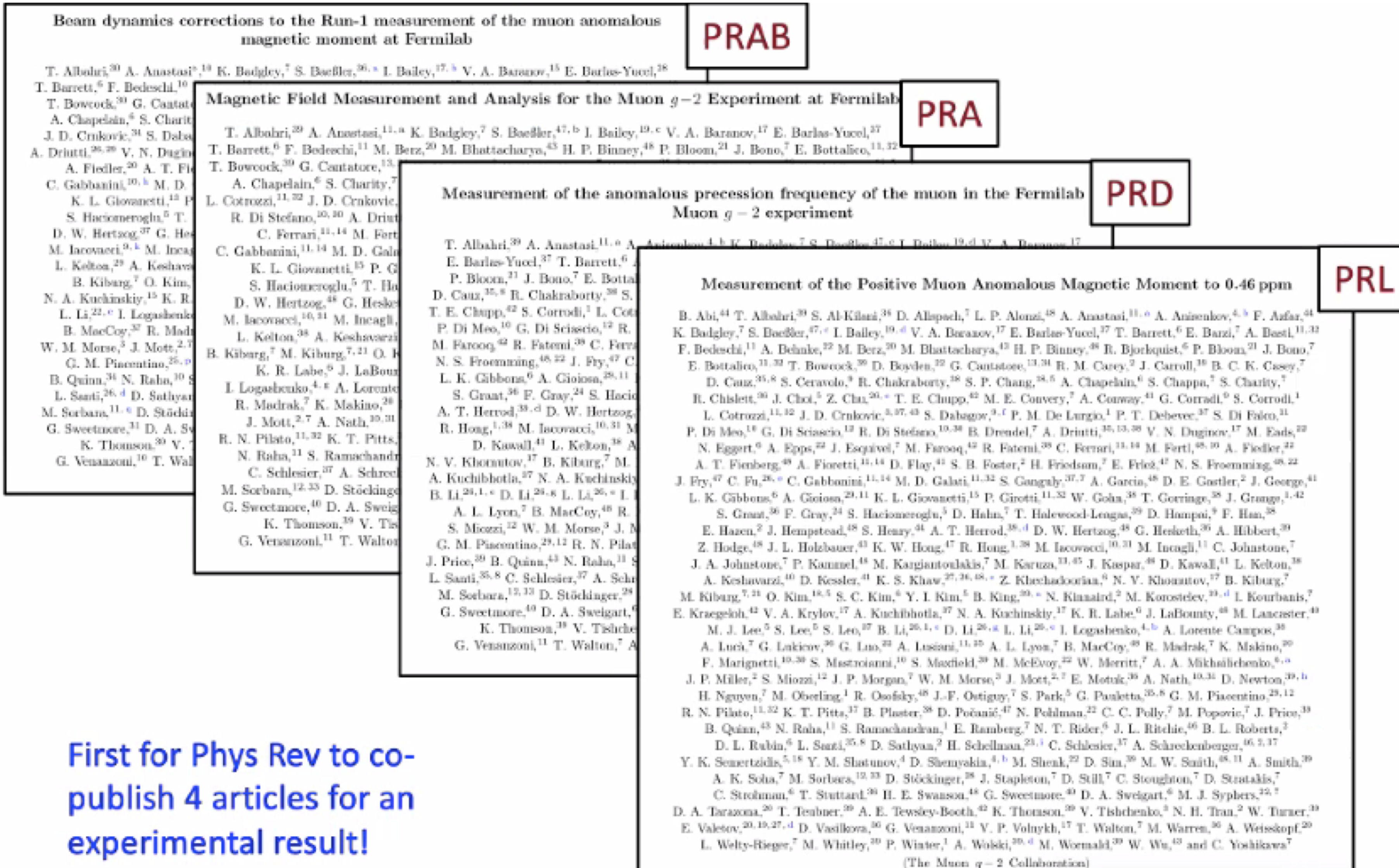
Updated g-2 history (April 8 2021)



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

G. Venanzoni, BINP Seminar Novosibirsk, 9 April 2021

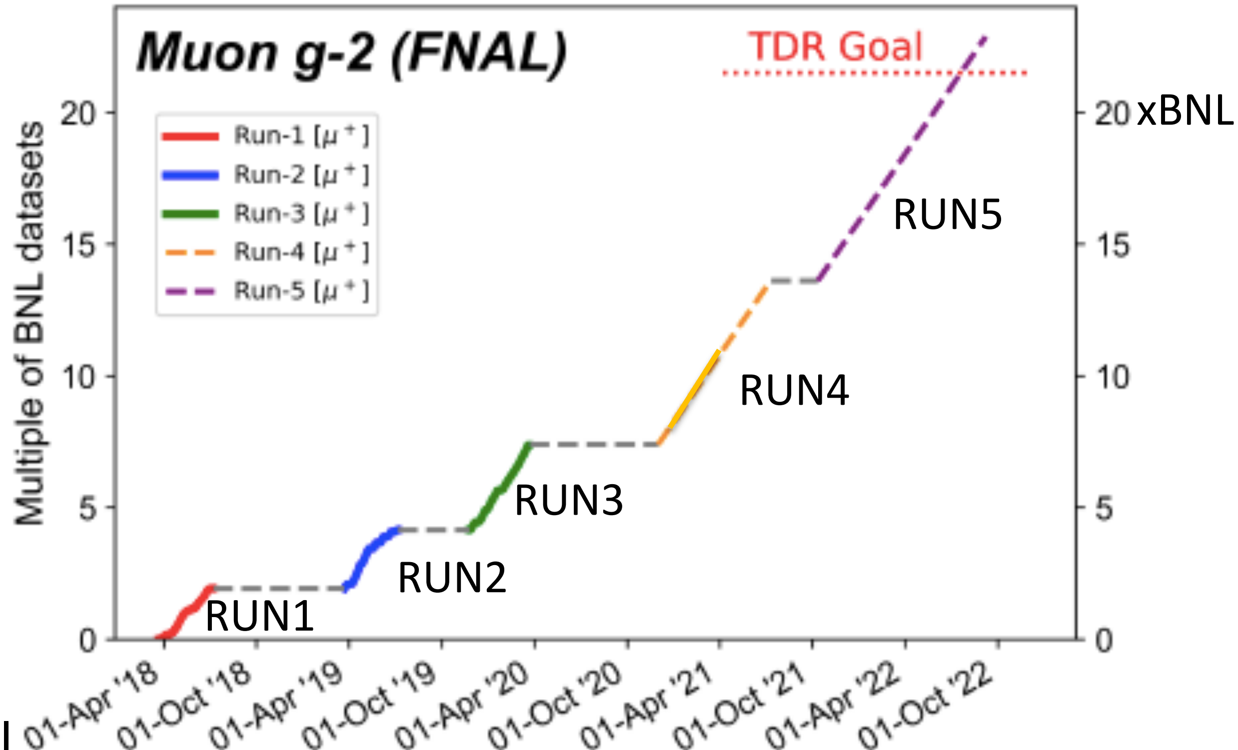
4 articles published in PR journals



First for Phys Rev to co-publish 4 articles for an experimental result!

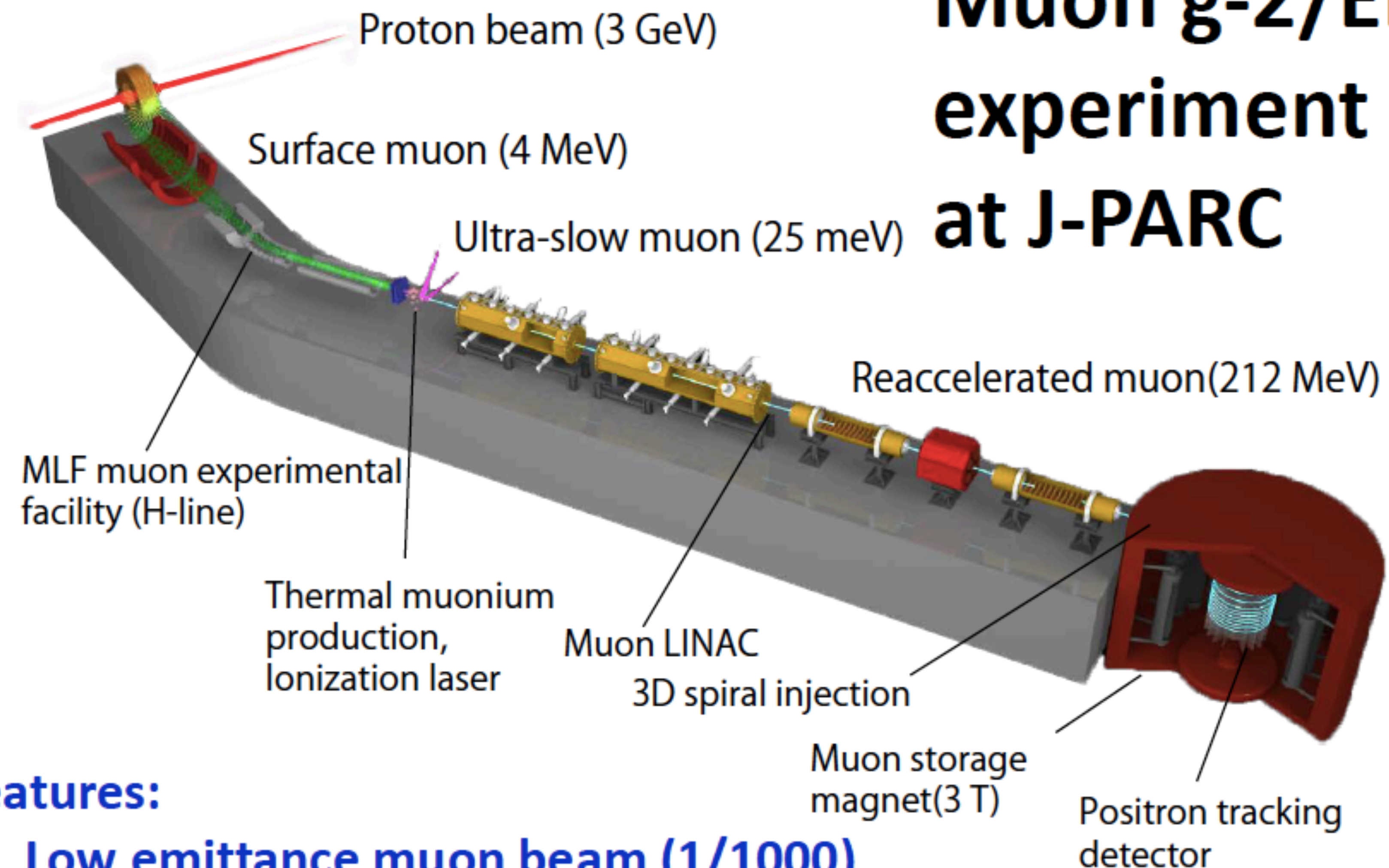
What awaits us

- RUN1 is only 6% of the final dataset
- Analysis of RUN2/3 (expect an improvement of a factor ~2 in precision)
- RUN4 (November June 2021) brought the statistics to ~13 BNL
- RUN5 in 2021-2022 should allow to achieve the x20 BNL project goal
- RUN6 in 2022-2023 most likely with μ-



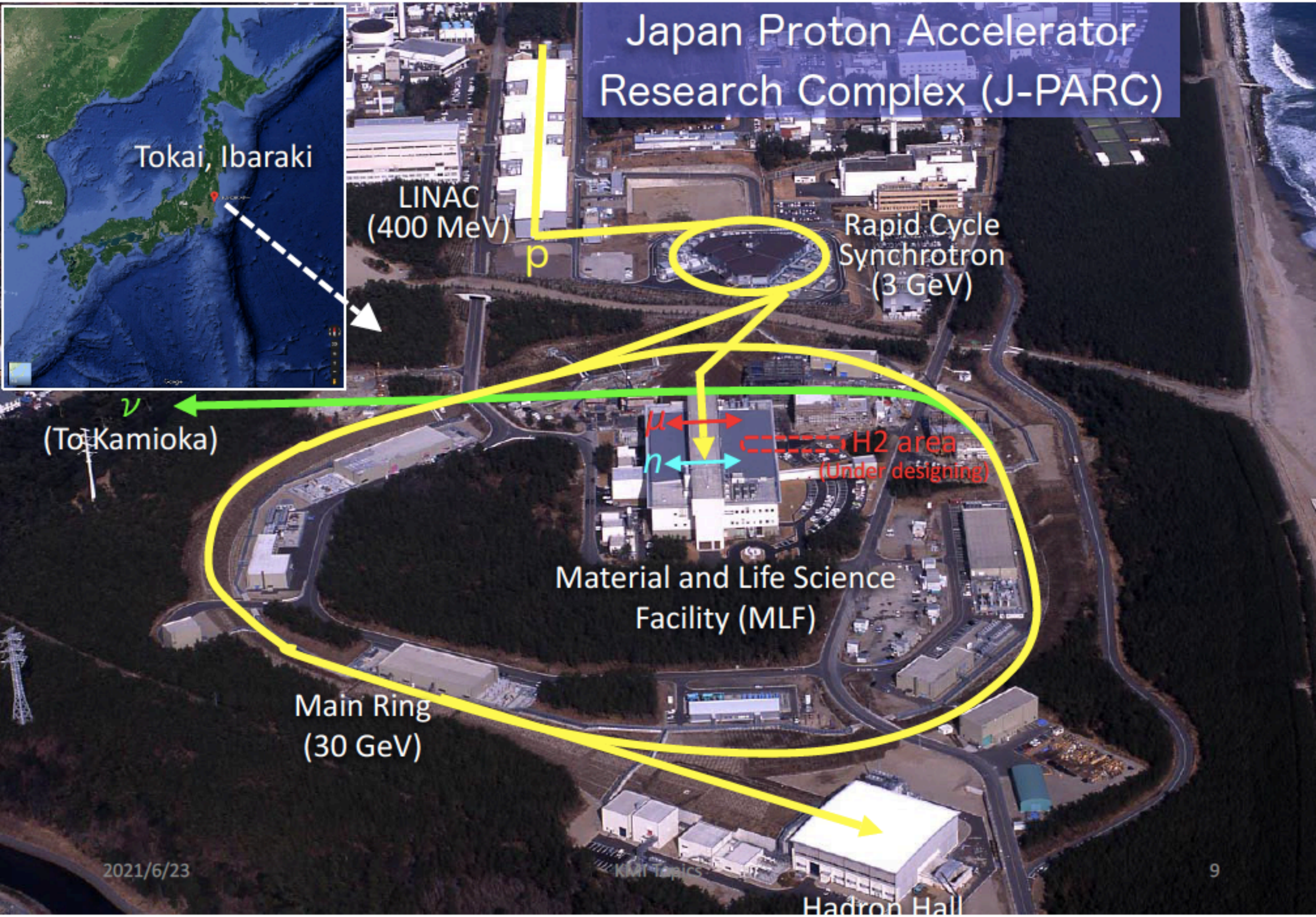
The Muon g-2 Collaboration (Elba 2019)

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**


Japan Proton Accelerator
Research Complex (J-PARC)
Tokai, Ibaraki
LINAC
(400 MeV)
p
Rapid Cycle
Synchrotron
(3 GeV)
ν
(To Kamioka)
μ
n
H2 area
(Under designing)
Material and Life Science
Facility (MLF)
Main Ring
(30 GeV)
Hadron Hall
2021/6/23
9

What makes them different?

- Eliminate electric focusing removes β x $\boldsymbol{E}$ term

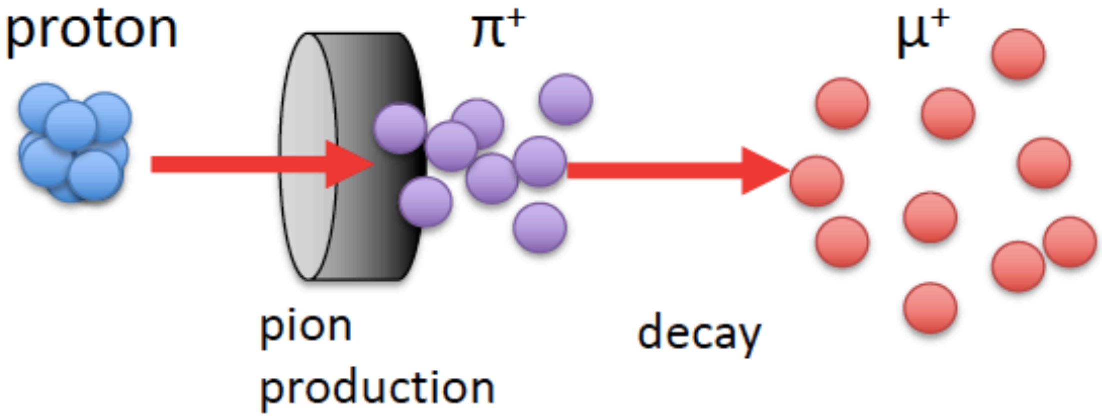
$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

  Do need ~zero P_T to store muons

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

- Aim for BNL level precision as an important check

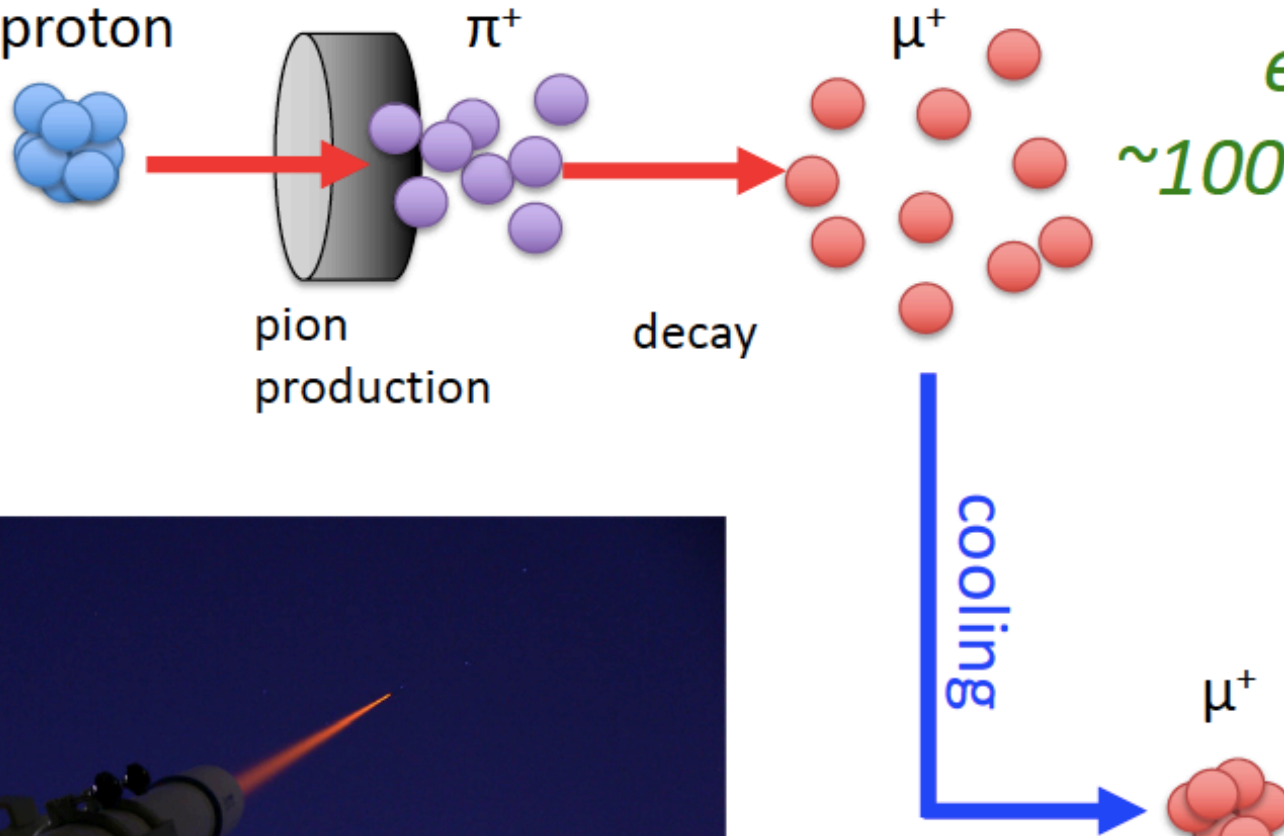
Conventional muon beam (BNL, Fermilab)



emittance
~1000π mm ▪mrad

Strong focusing
Muon loss
BG π contamination

Muon beam at J-PARC



emittance

~1000π mm ･mrad

Strong focusing
Muon loss
BG π contamination

emittance

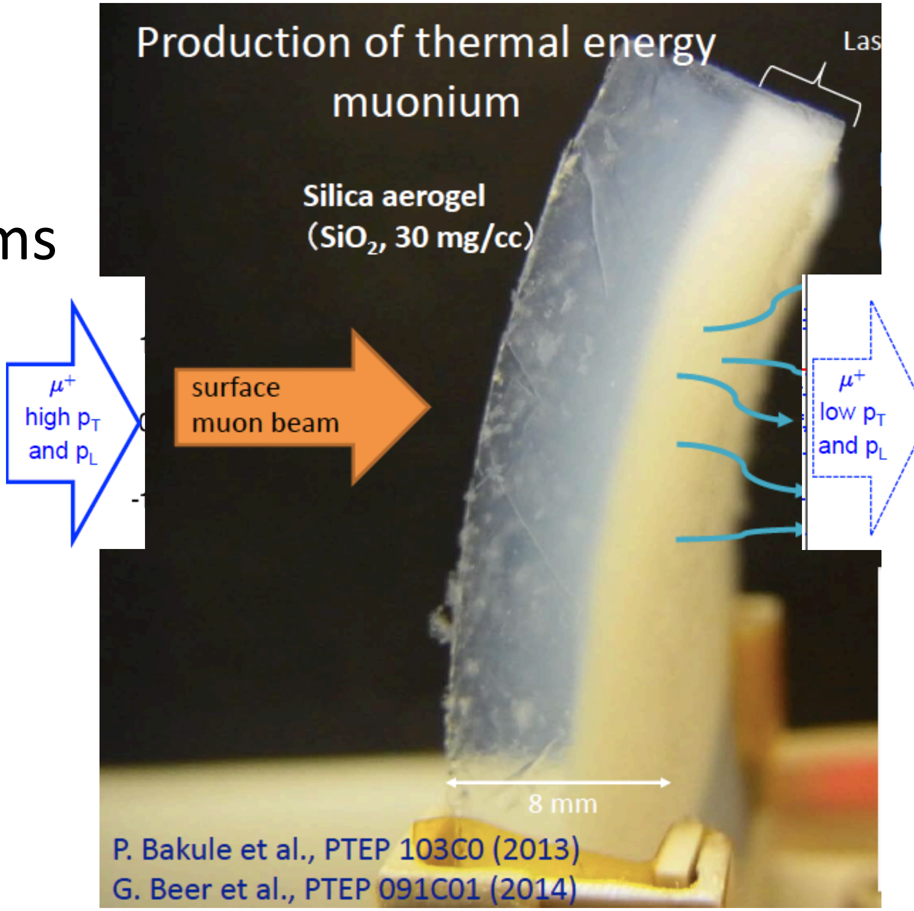
1π mm ･mrad

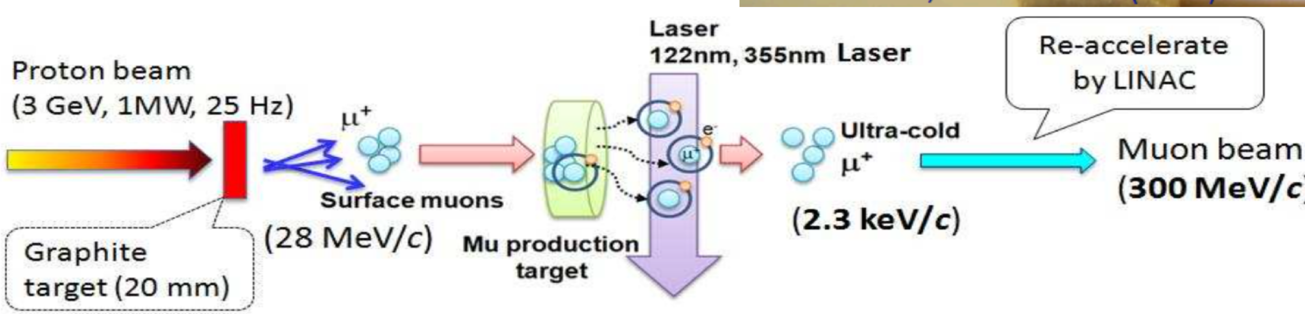
Reaccelerated thermal muon

Free from any of these

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

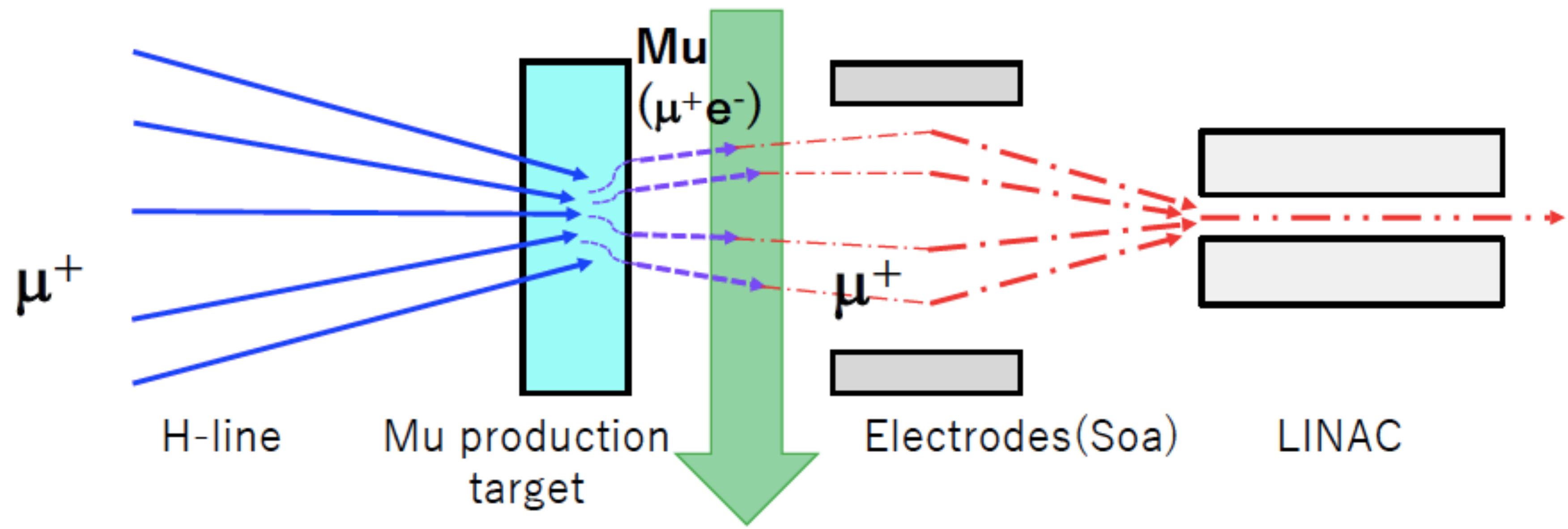




Ultra-cold Muons

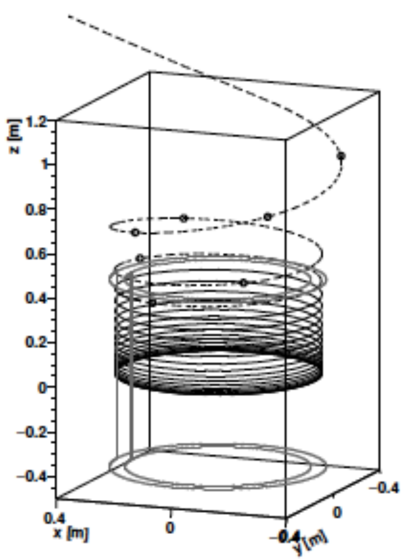
Re-accelerated thermal muon

	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	4×10^{-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



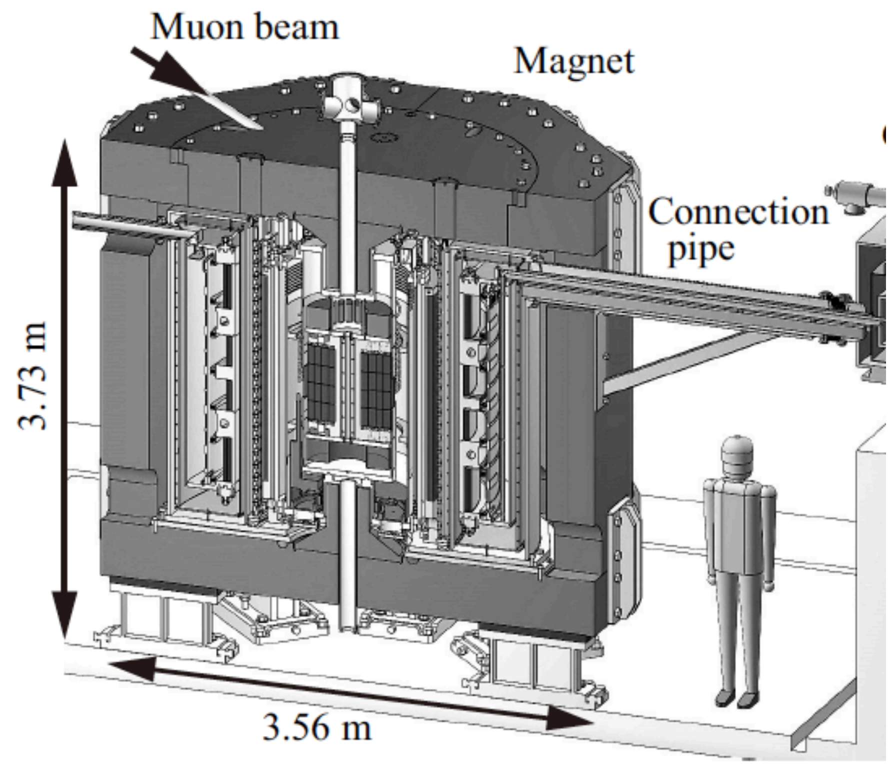
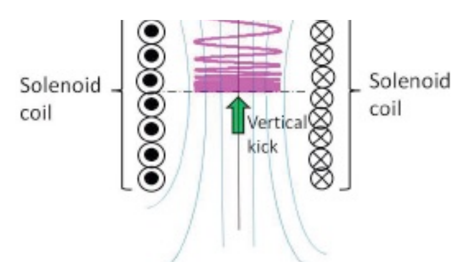
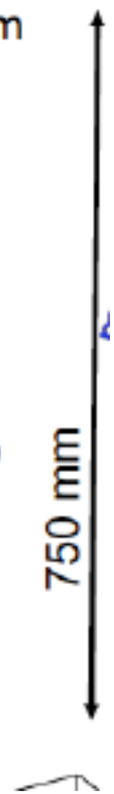


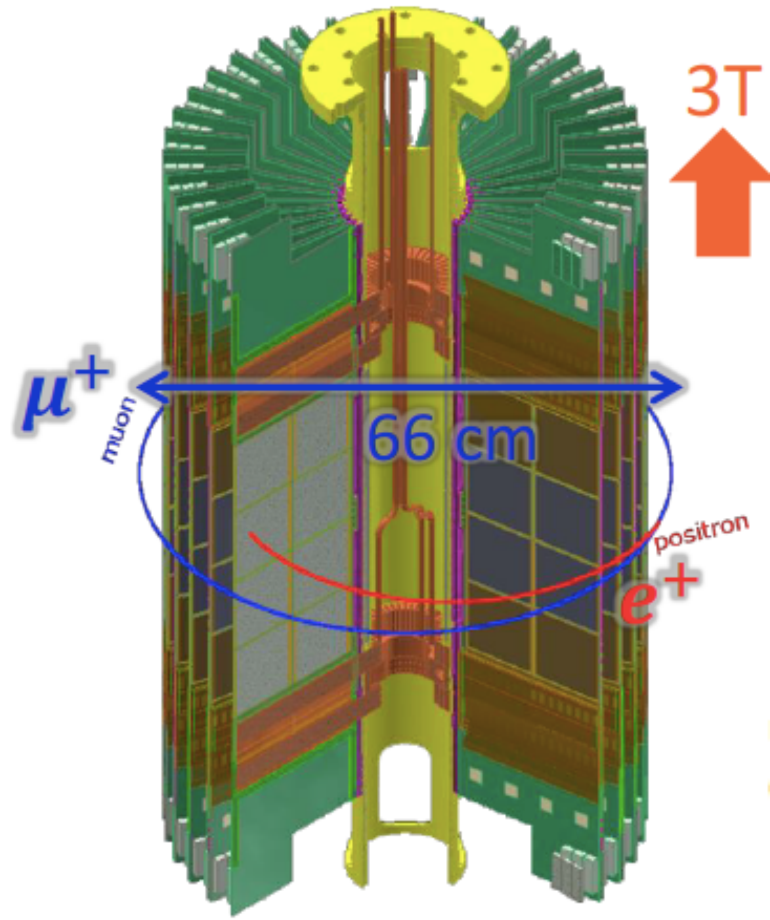
Fig. 8 Overview of the muon storage magnet



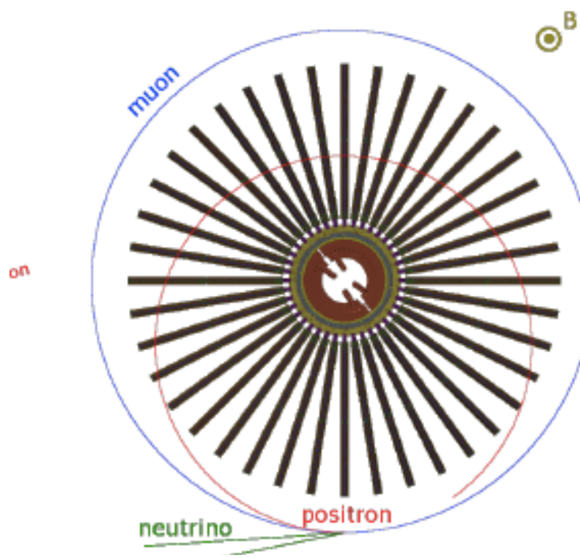
Detector system of silicon trackers

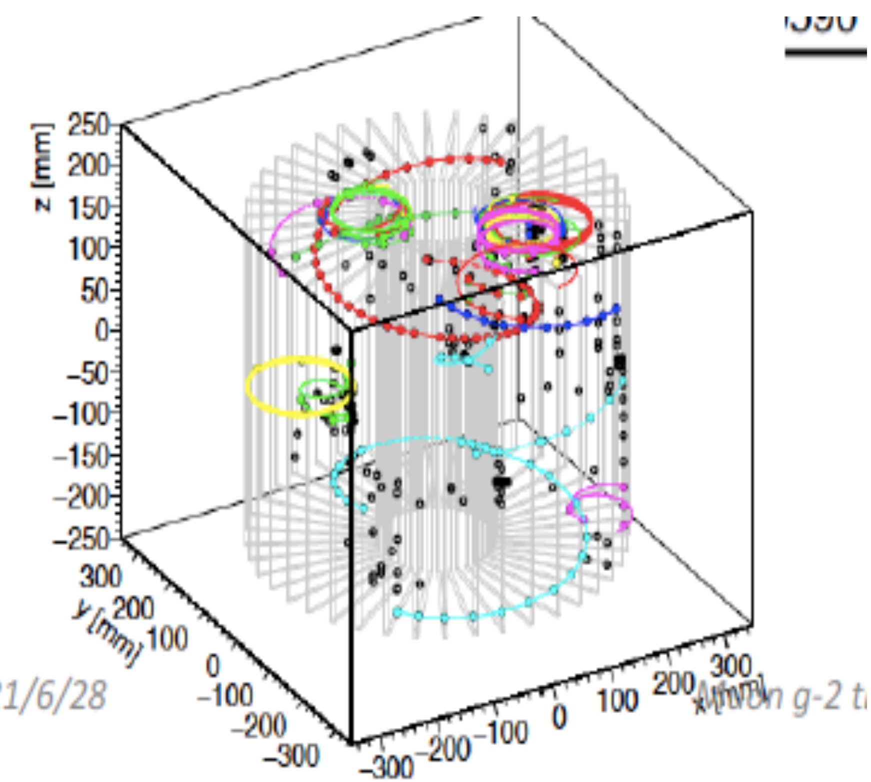
- Requirements
  - Detection of e+ (100<E<300 MeV)
  - Reconstruction of momentum vector
  - Stability over rate changes (1.4 MHz → 14 kHz)
- Specifications
  - Sensor: p-on-n single-sided strip
  - Number of vanes: 40
  - Number of sensors : 640
  - Number of strips : 655,360
  - Area of sensors : 6.24 m^2

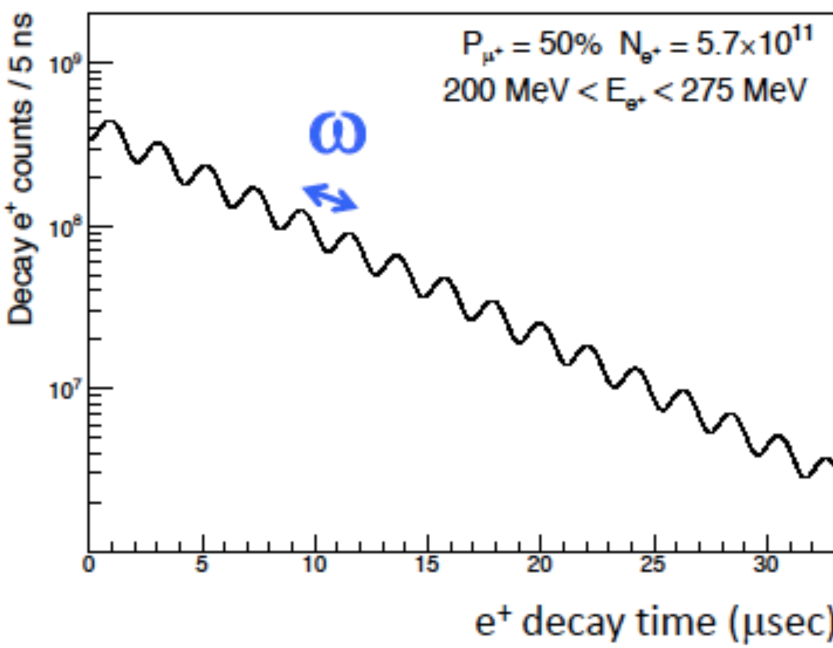




Detector system of silicon trackers







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

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.)	$0.2 \times 10^{-19}\ e \cdot$ cm	–	$1.5 \times 10^{-21}\ e \cdot$ cm
(syst.)	$0.9 \times 10^{-19}\ e \cdot$ cm	–	$0.36 \times 10^{-21}\ e \cdot$ 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

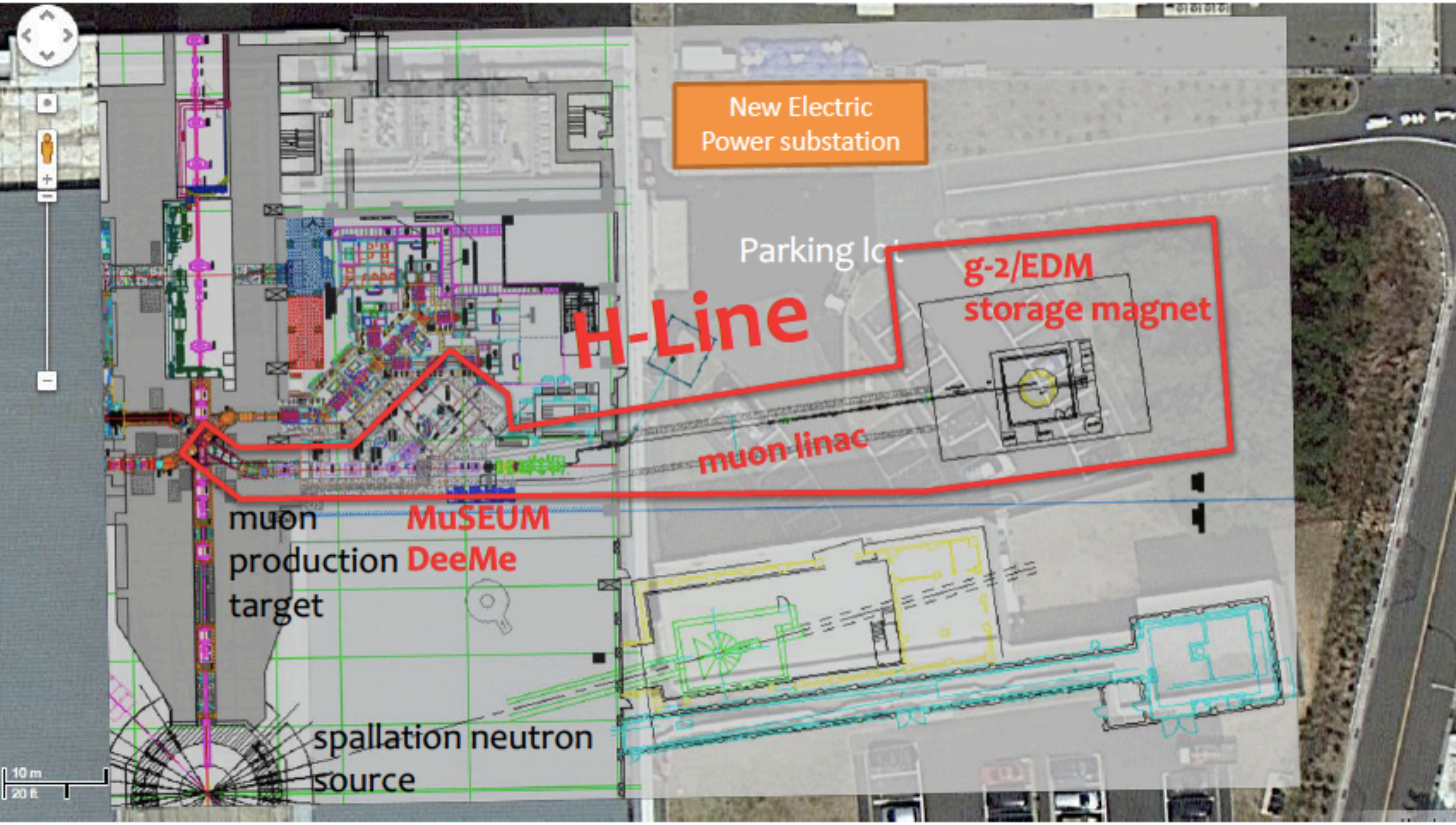
M. Abe[1], S. Bae[2,3], G. Beer[4], G. Bunce[5], H. Choi[2,3], S. Choi[2,3], M. Chung[6], W. da Silva[7], S. Eidelman[8,9,10], M. Finger[11], Y. Fukao[1], T. Fukuyama[12], S. Haciomeroglu[13], K. Hasegawa[14], K. Hayasaka[15], N. Hayashizaki[16], H. Hisamatsu[1], T. Iijima[17], H. Iinuma[18], H. Ikeda[19], 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)

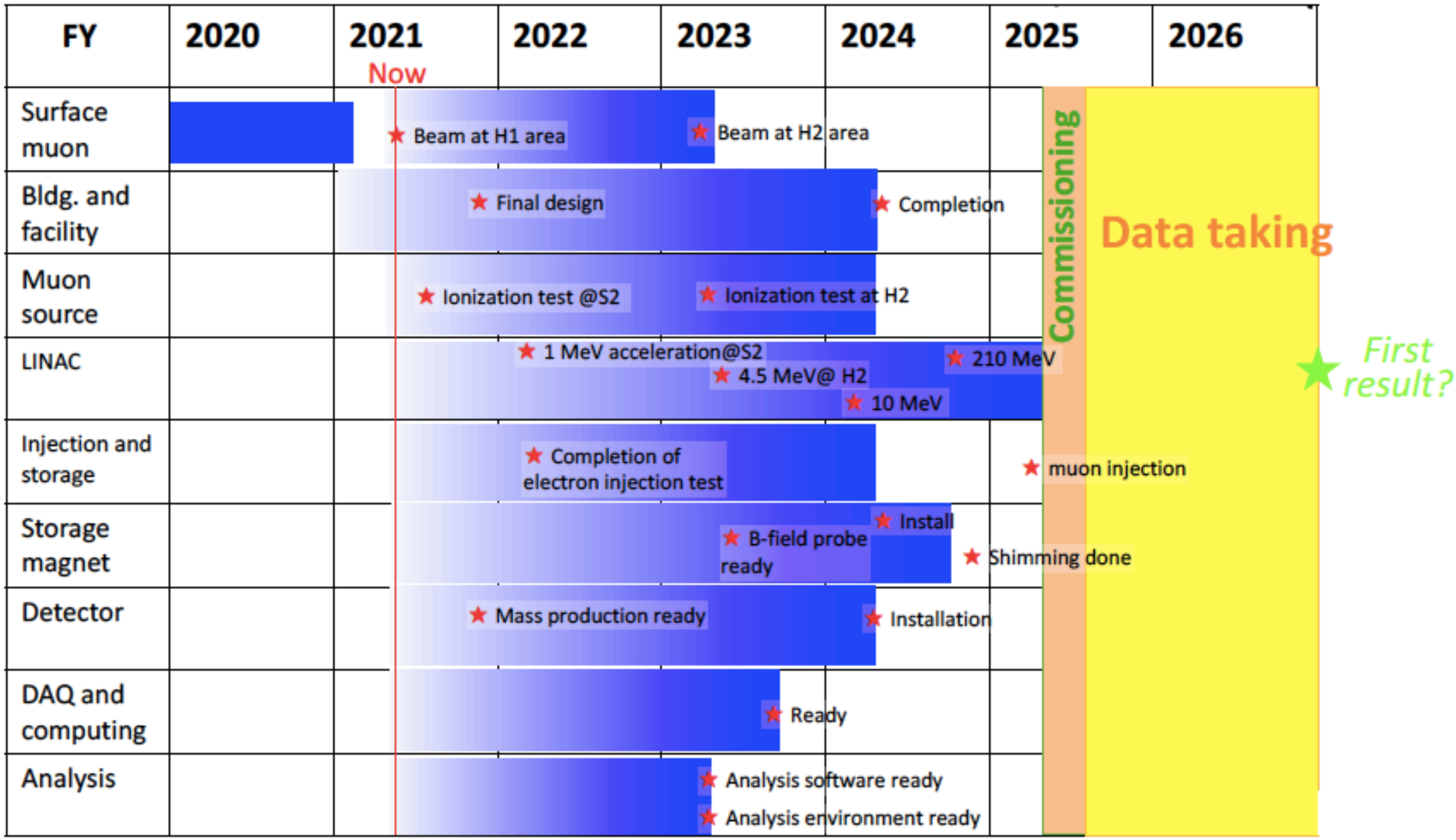
Proposed experimental site (H-line)

Material and Life science Facility in J-PARC



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

Intended schedule and milestones



- The experiment was endorsed as the near-term priority by KEK Science Advisory Committee (SAC) (2019.3).
- KEK prepares for the funding request to MEXT (2020.6-).

Summary

- J-PARC E34 intends to measure the muon g-2 and EDM with a new experimental approach.
  - Very different experimental approach from that of the BNL/FNAL experiments.
    - ✓ Small-emittance muon beam with no strong focusing,
    - ✓ MRI-type storage ring with a good injection efficiency and high uniformity of local B-field,
    - ✓ Full-tracking detector with large acceptance.
- The experiment is getting ready for realization.
  - The development and construction is in progress to start data taking in FY2025.
    - ✓ R&Ds of the experimental apparatus keep progressing well,
    - ✓ Funding requests are being made to MEXT,
    - ✓ Intending to reach the BNL precision in ~2-year running.

Status of MUonE experimental proposal

Phys. Lett. B 746 (2015) 325

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

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

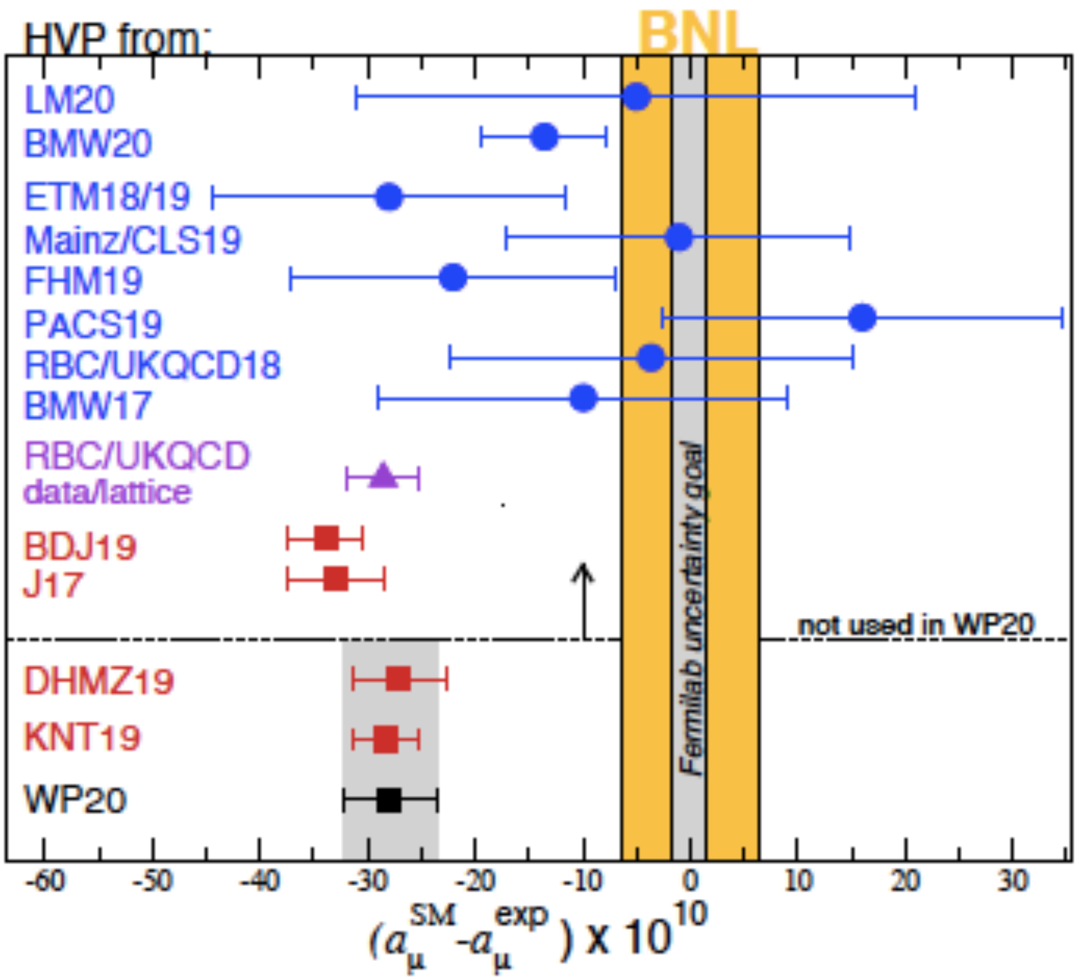
[a] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[b] *INFN, Sezione di Padova, Padova, Italy*
[c] *Dipartimento di Fisica e Scienze della Terra "M. Melloni" Università di Parma, Parma, Italy and INFN, Sezione di Milano Bicocca, Milano, Italy*
[d] *INFN, Laboratori Nazionali di Frascati,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

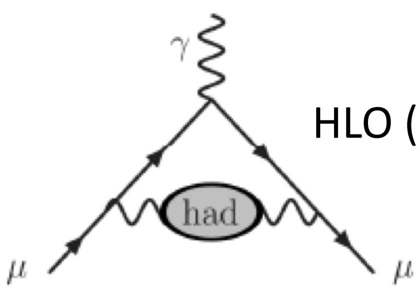
Eur. Phys. J. C (2017) 77: 139.

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

G. Abbiendi[1], C. M. Carloni Calame[2], U. Marconi[1], C. Matteuzzi[3], G. Montagna[4,2], O. Nicrosini[2], M. Passera[5], F. Piccinini[2], R. Tenchini[6], L. Trentadue[7,3], and G. Venanzoni[8]
[1] *INFN, Sezione di Bologna, Bologna, Italy*
[2] *INFN, Sezione di Pavia, Pavia, Italy*
[3] *INFN, Sezione di Milano Bicocca, Milano, Italy*
[4] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[5] *INFN, Sezione di Padova, Padova, Italy*
[6] *INFN, Sezione di Pisa, Pisa, Italy*
[7] *Dipartimento di Fisica e Scienze della Terra "M. Melloni", Università di Parma, Parma, Italy*
[8] *INFN, Laboratori Nazionali di Frascati, Frascati, Italy*

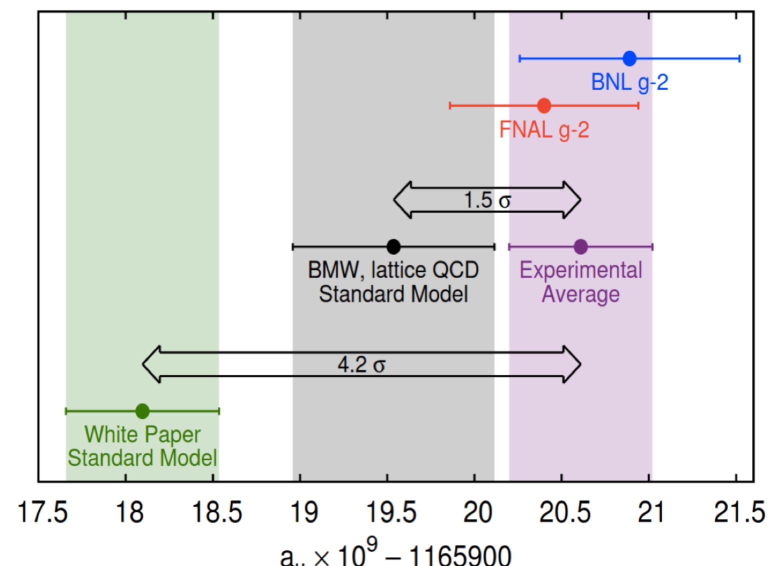
Muon g-2: present status





HLO (HVP)

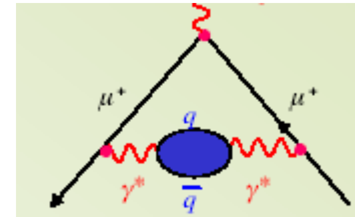
- HVP is the main limitation to the improvement in precision to the SM evaluation a_μ
- Recent evaluation(s) of HVP from lattice (BMW20) in tension with the e^+e^- evaluation (WP20)

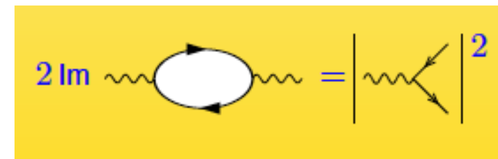


a_μ^{HLO} calculation, traditional way: time-like data

[C. Bouchiat, L. Michel,'61; N. Cabibbo, R. Gatto 61; L. Durand '62-'63; M. Gourdin, E. De Rafael, '69; S. Eidelman F. Jegerlehner 95, Davier et al '97, Hagiwara et al 2003,…]

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





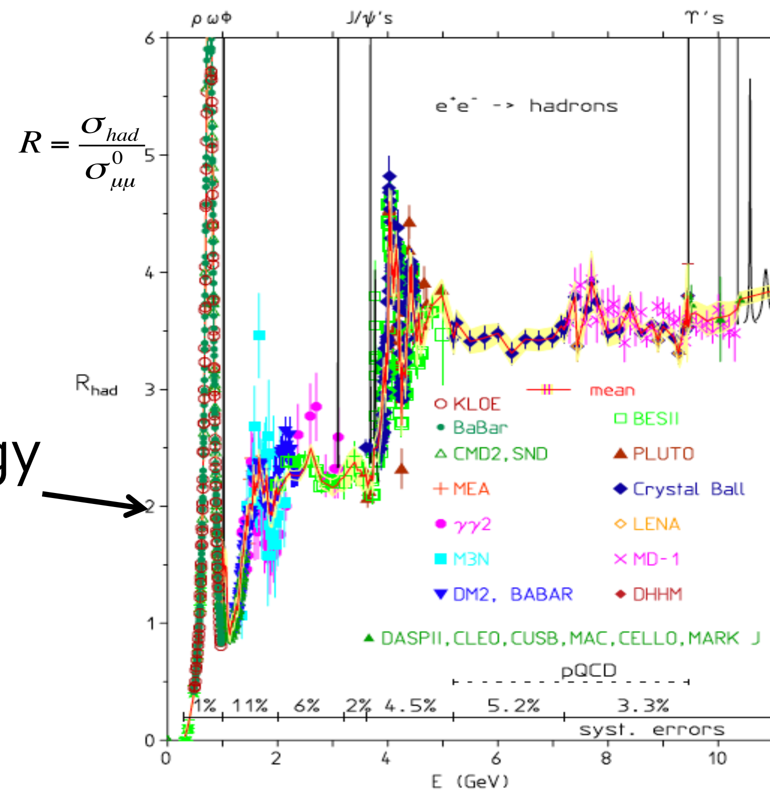
$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty}\sigma_{e^+e^-\to hadr}(s)K(s)\,ds$$

$$K(s)=\int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)(s/m^2)}\sim\frac{1}{s}$$

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

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

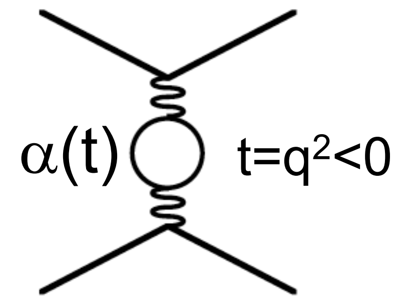
- Main contribution in the low energy region (highly fluctuating!)
- Current precision at 0.6%



a_μ^{HLO} from space-like region

[C.M. C. Calame et al, Phys. Lett. B 746 (2015) 325]

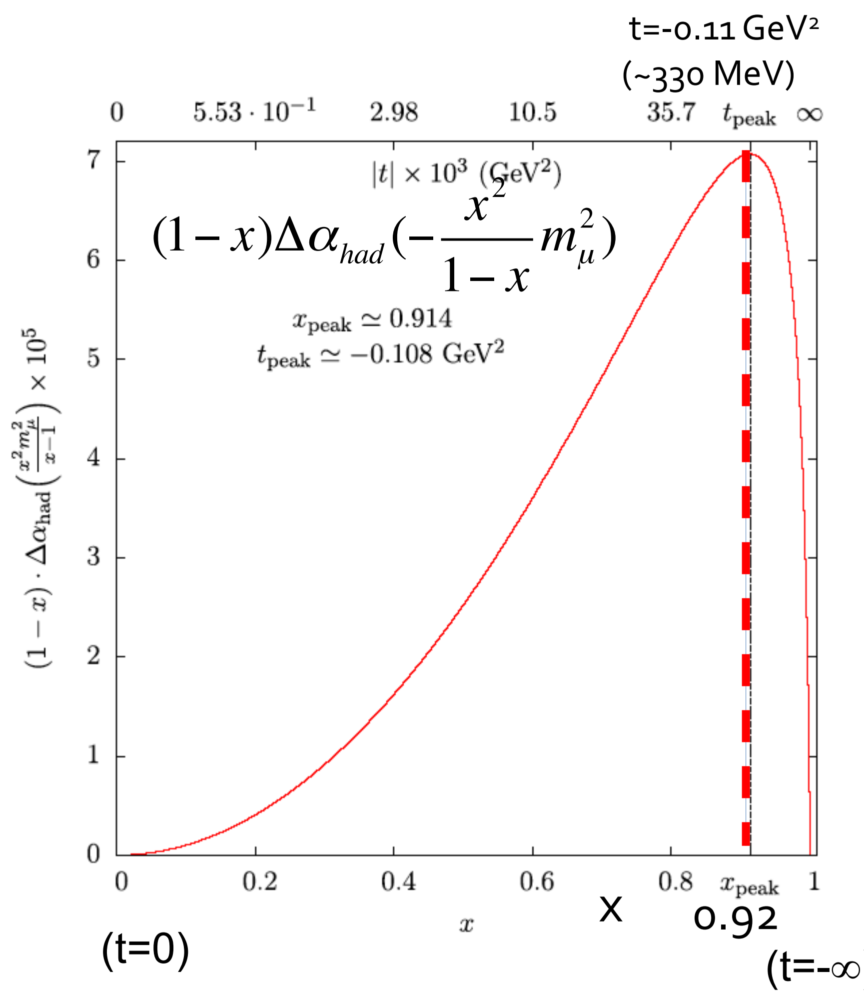
$$a_\mu^{HLO} = -\frac{\alpha}{\pi}\int_0^1 (1-x)\Delta\alpha_{had}\left(-\frac{x^2}{1-x}m_\mu^2\right)dx$$



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

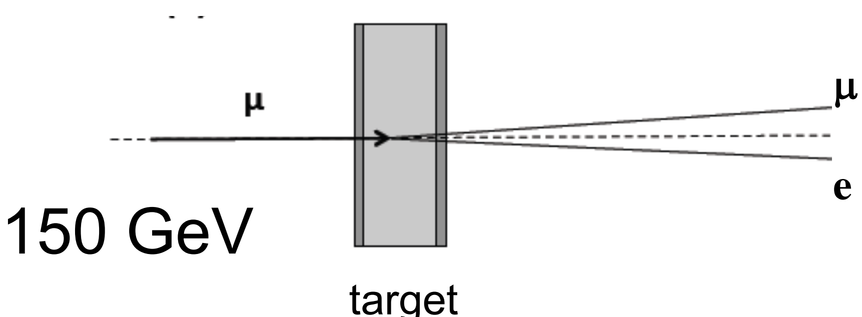
$$x = \frac{t}{2m_\mu^2}\left(1-\sqrt{1-\frac{4m_\mu^2}{t}}\right); \qquad 0 \le x < 1;$$

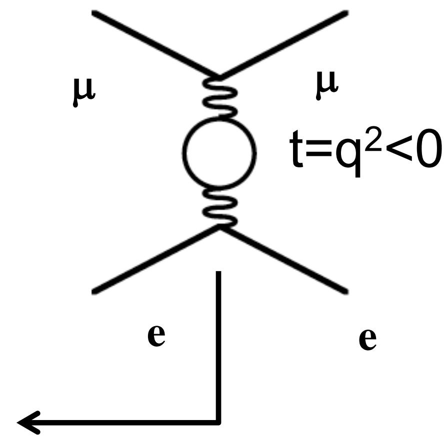
- a_μ^{HLO} is given by the integral of the curve (smooth behaviour)
- It requires a measurement of the hadronic contribution to the effective electromagnetic coupling in the space-like region $\Delta\alpha_{had}(t)$ ($t=q^2<0$)



Experimental approach:

Extract $\Delta\alpha_{had}(t)$ from process $\mu e \rightarrow \mu e$ using 150 GeV μ on beryllium target. The measurement doesn't rely on the precise knowledge of the luminosity but on the shape of the distribution (relative measurement)

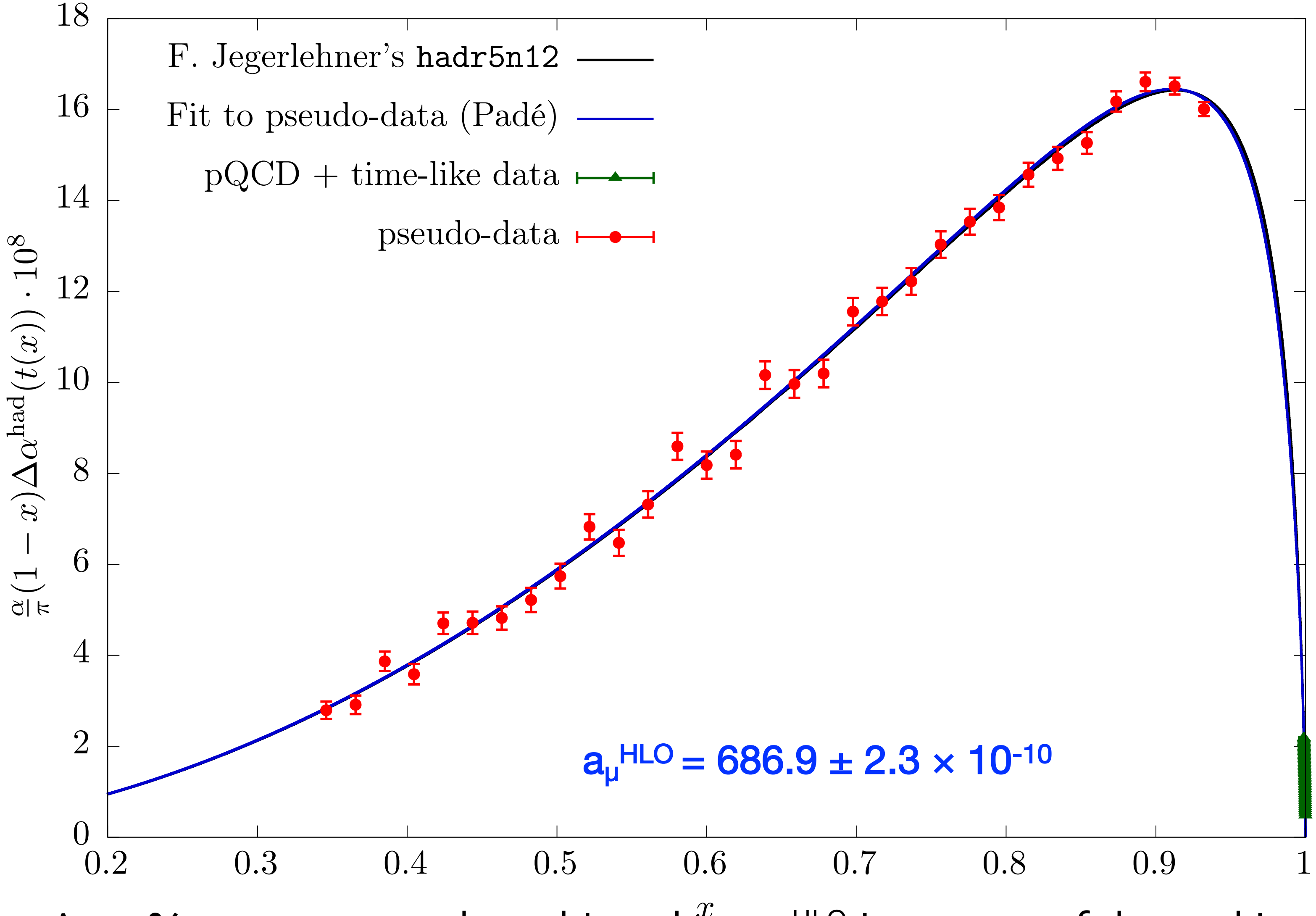




$$\left|\frac{\alpha(t)}{\alpha_0}\right|^2 = \left|\frac{1}{1-\Delta\alpha(t)}\right|^2$$

Statistical reach of MUonE on a_μ^{HLO}

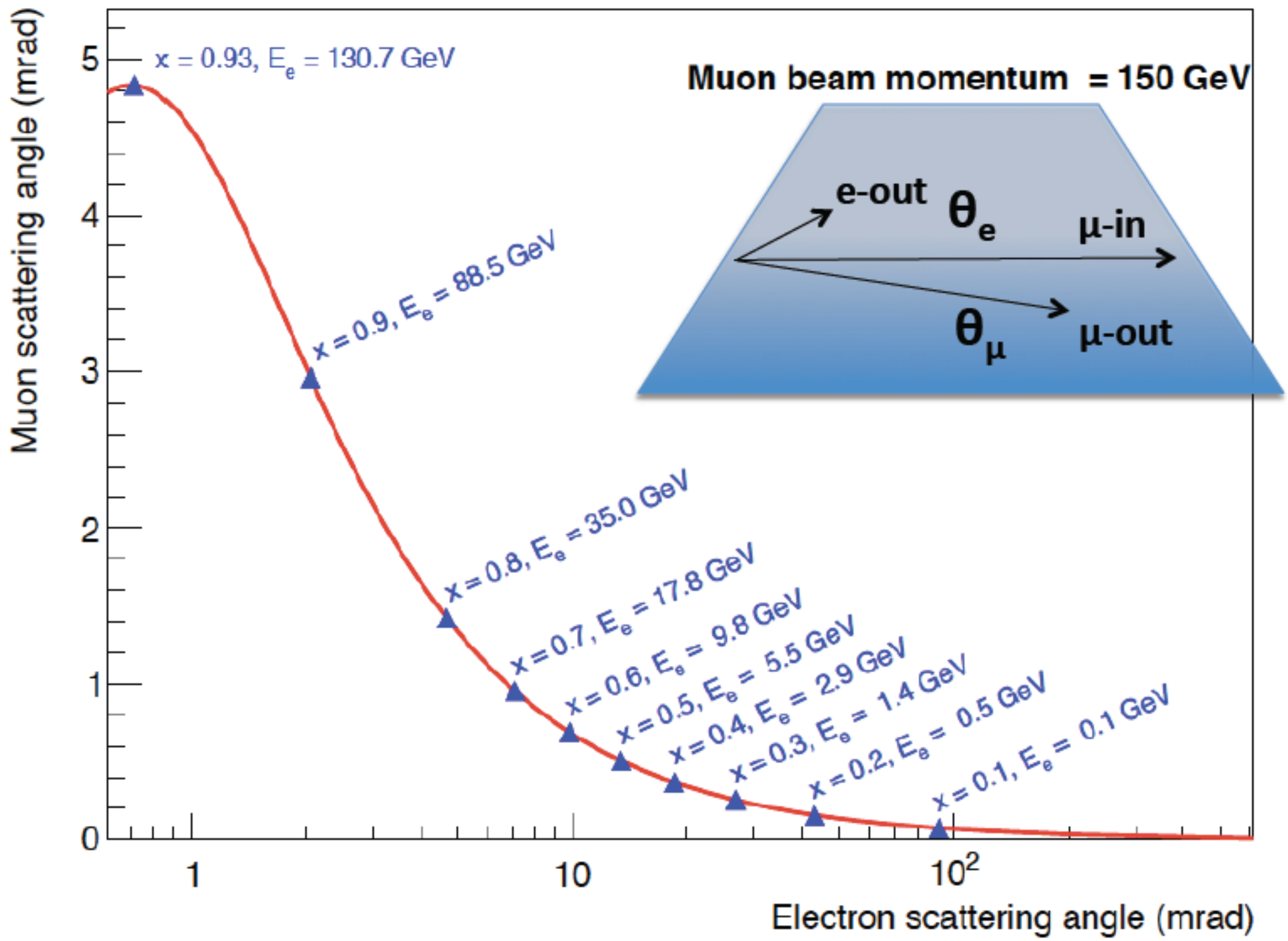
(2 years of data taking at 1.3 x10^7 μ/s)



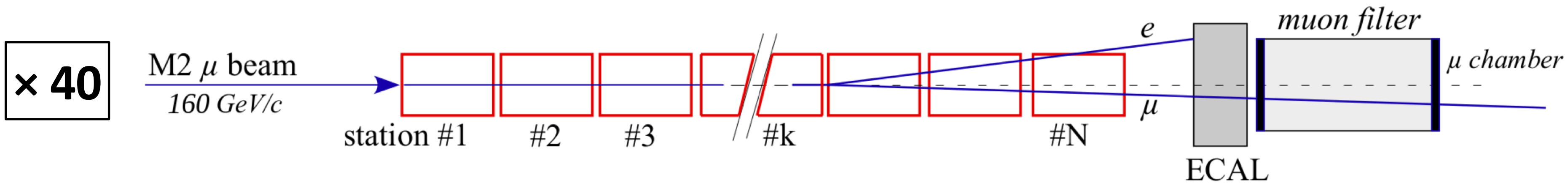
A **0.3%** stat error can be achieved on a_μ^{HLO} in 2 years of data taking with ~10^7 μ/s (4×10^{14} μ total)

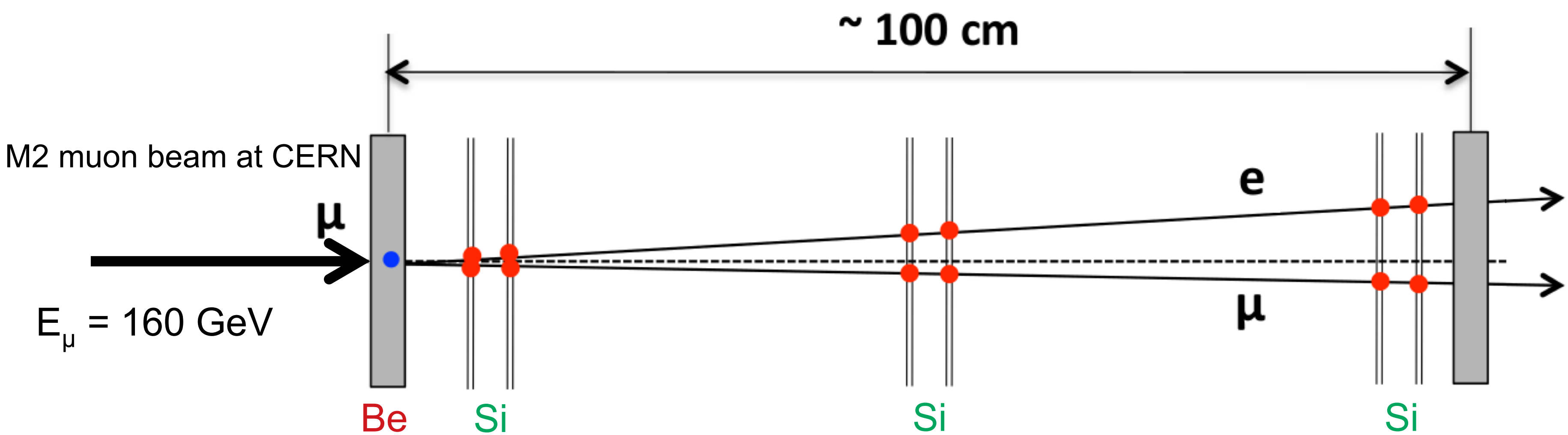
Elastic scattering in the (θ_e , θ_μ) plane

Coplanarity of the momentum vectors and angular kinematical constraint



The experimental apparatus

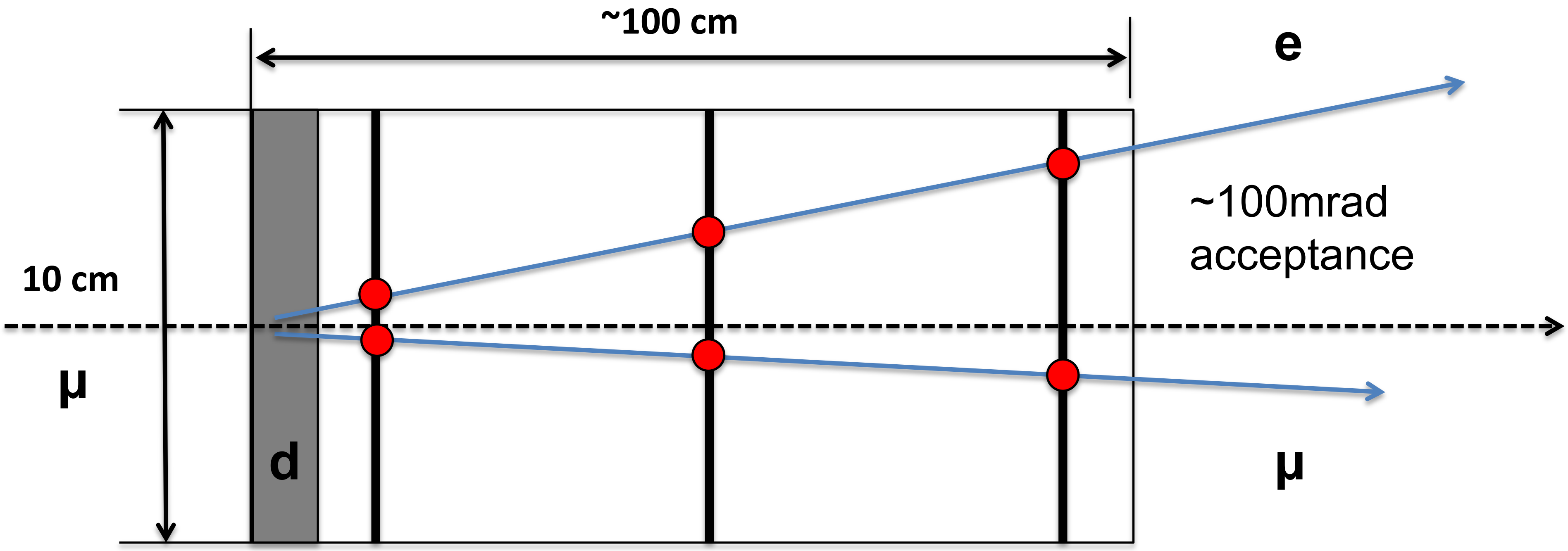




Beryllium target 1.5 cm thickness

Tracking system: 3 pairs of silicon strip detectors

Single Unit



~1.5 cm
Be Target

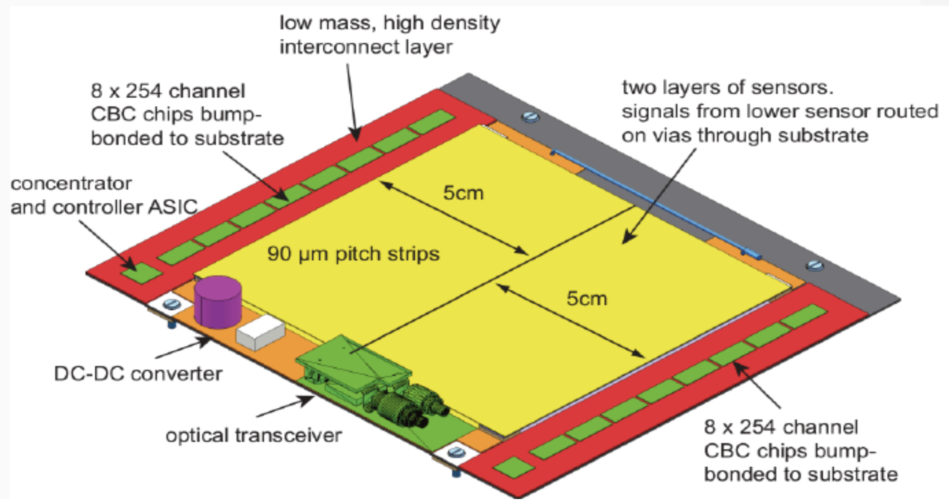
State-of-art Silicon detectors

hit resolution ~20 μm

Expected angular resolution ~ 20 μm / 1m = 20 μrad
At the end ECAL and Muon Filter for PID

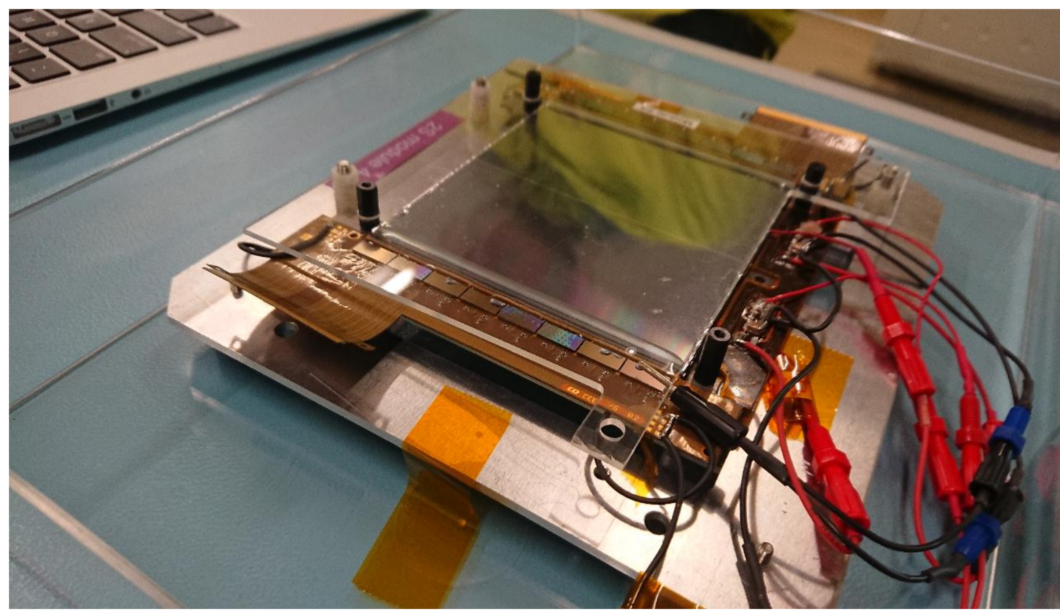
Tracking system

Requirements:
- Good resolution (~ 20 µm)
- High uniformity ($\varepsilon \gtrsim$ 99.99%)
- Capable to sustain high rate (50 MHz)
- Available technology (pilot run 2021)



Achievement: CMS 2S Module
- Thickness : 2 × 320 µm
- Pitch: 90 µm → σ_x = 26 µm
- Angular resolution: σ_θ ~ 30 µrad
- Readout rate: 40 MHz
- Area: 10 cm × 10 cm

- Efficiency= 99.988 ± 0.008



Systematics

1. Multiple scattering
2. Tracking (alignment & misreconstruction)
3. PID
4. Knowledge of muon momentum distribution
5. Background
6. Theoretical uncertainty on the mu-e cross section (see later)
7. ...

All the systematic effects must be known to ensure an error on the cross section < 10ppm

Last years progress

1. Multiple scattering studies (TB 2017)
2. Test beam at μ beamline (M2) at CERN in 2018
3. Baseline choice of Si detectors (CMS)
4. MC NLO studies
5. LoI at SPSC
6. Test RUN approved for 2021 (→2022)
7. Theory progress towards NNLO MC

-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

Location at CERN M2

- **Between BSM and COMPASS**

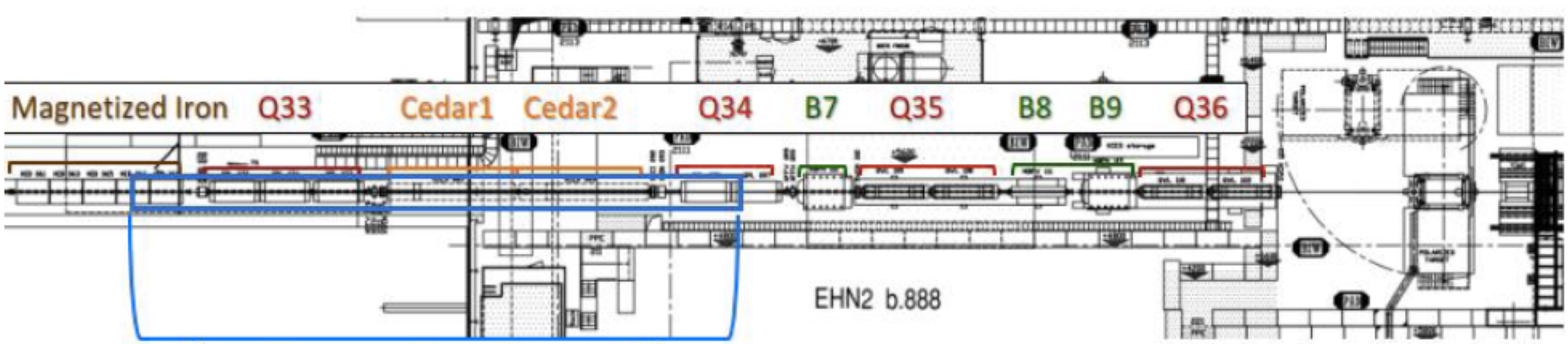
1/ μ-e setup upstream of present COMPASS experiment, i.e. within M2 beam-line

- More upstream of Entrance Area of EHN2 (Proposed by Johannes B. & Dipanwita B.)

- Pro: Could allow running μ-e/μ-p_{Radius} in parallel.

- Questions: will require displacements (also removal) of some M2 components.

- Beam(s) compatibility for μ-e & μ-p_{Radius} : Optic's wise looks OK (see Add. Sl.14 from D.B.)



μ-e Upstream (under-study) ~ 30 m

⇦

Σ length required (updated): 35 m targets + trackers + 0.8 m Ecals + 3 m (μ-Filter) ~ 39 m

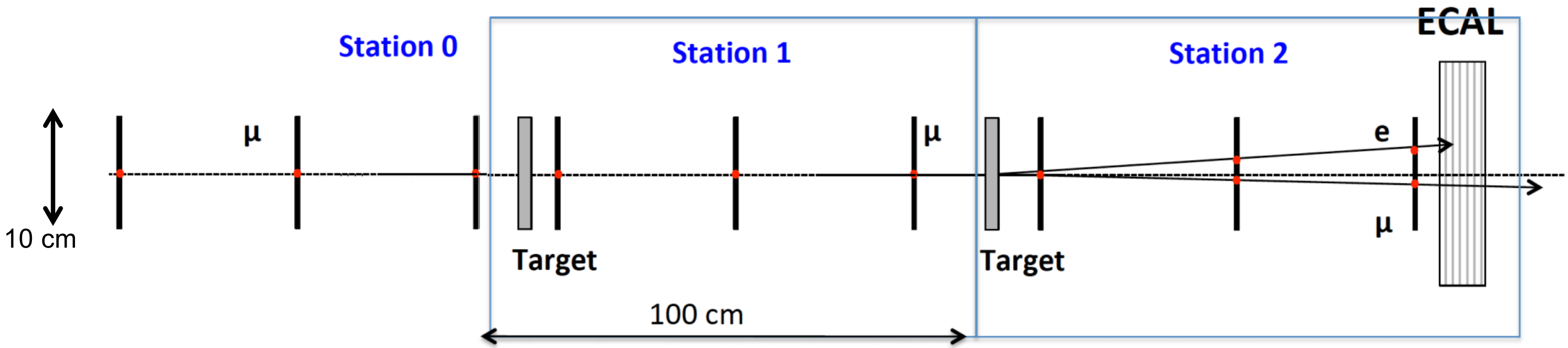
10

Space available : 40 m upstream COMPASS

Location at CERN M2

Test Run 2021 setup

A Test Run with a reduced detector has been approved by SPSC, to validate our proposal.

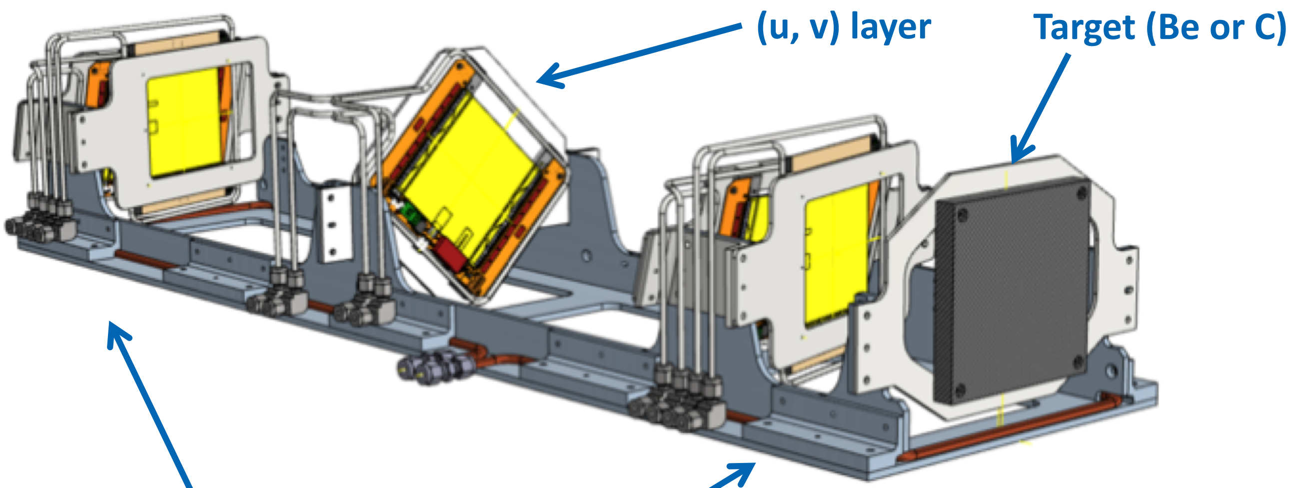


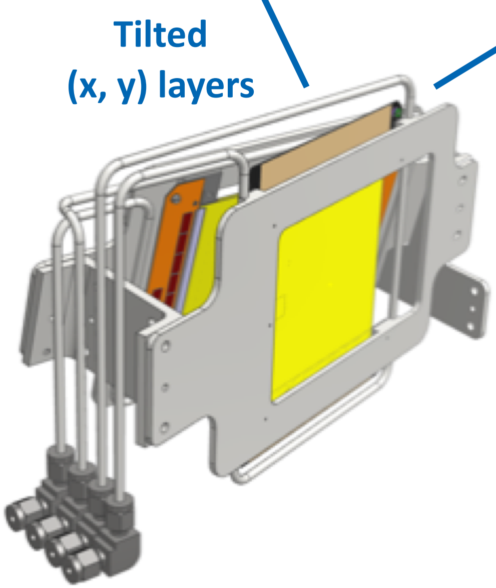
- Pretracker +
- 2 MUonE stations +
- ECAL

Main goals:

- Confirm the system engineering.
- Monitor mechanical and thermal stability.
- Check the DAQ system.
- Extract $\Delta\alpha_{lep}(t)$.

Tracking station





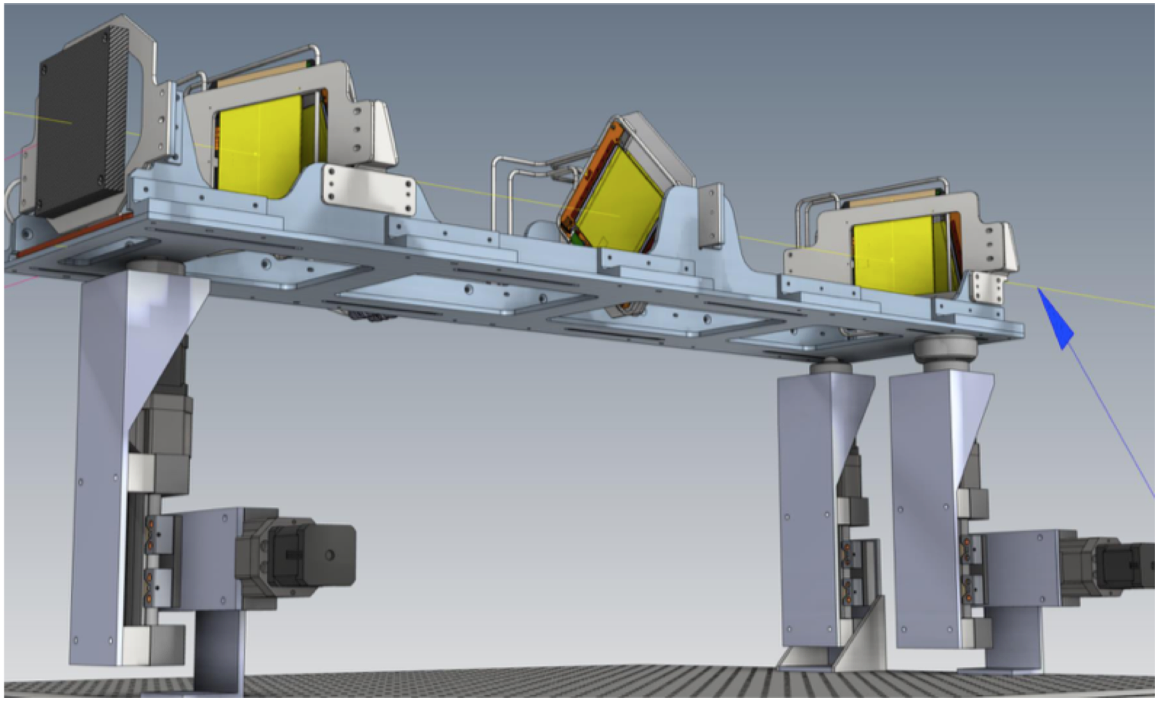
Relative position within a station must be stable at 10 μm.

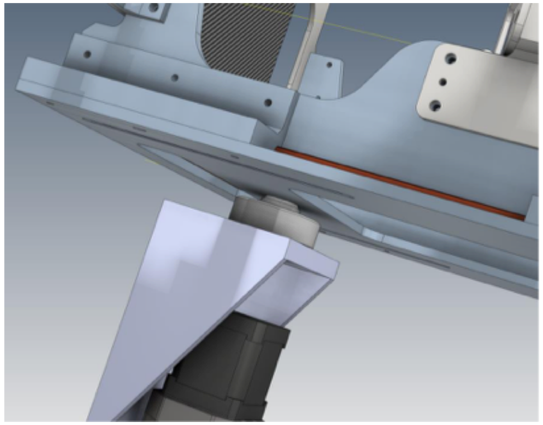
↓

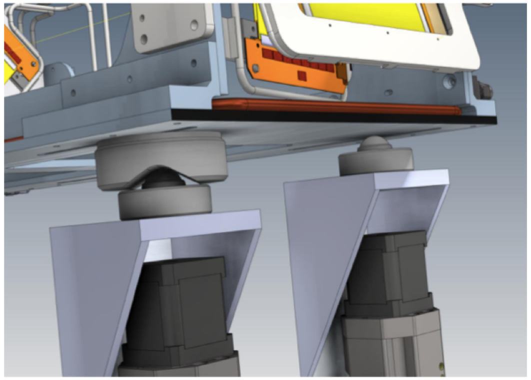
Low CTE mechanical structure: INVAR (alloy of 65%Fe, 35%Ni).

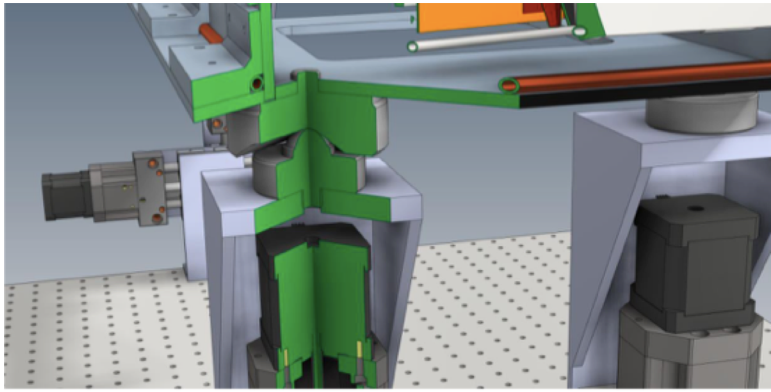
- (x, y) layers tilted by 233 mrad, to improve single hit resolution.
  - Simulation studies show a resolution of ~10 μm.
- (u, v) layers to solve reconstruction ambiguities.

Tracking station









Theory

- QED NLO MC generator with full mass dependence has been developed and is currently under use (Pavia group)
- MC with approximate NNLO: MESMER (Pavia) and MCMule (PSI)
- **Huge theoretical activity (***"Theory for muon-electron scattering @ 10ppm",* P.Banerjee et al, Eur.Phys.J.C80(2020)591**):**
- P. Mastrolia, M. Passera, A. Primo, U. Schubert, JHEP 1711 (2017) 198
  S. Di Vita, S. Laporta, P. Mastrolia, A. Primo, U. Schubert, JHEP 1809 (2018) 016
  M. Alacevich et al, JHEP 02 (2019) 155
  M. Fael, JHEP 1902 (2019) 027
  M. Fael, M. Passera, PRL 122 (2019) 192001
  A. Masiero, P. Paradisi, M. Passera, PRD 102 (2020) 075013
  P. Banerjee et al, EPJC 80 (2020) 591C
  M. Carloni Calame, et al, JHEP 11 (2020) 028
  P. Banerjee, T. Engel, A. Signer, Y. Ulrich, SciPost Phys 9 (2020) 02
  R. Bonciani et al, arXiv:2106.13179

An unprecedented precision challenge for theory: a full NNLO MC generator for μ-e scattering (10^{-5} accuracy)
→ **International** efforts!

being formed, still growing up

The MUonE Collaboration

CERN
Exp

INFN +Univ. (Bologna, Milano-Bicocca, Padova, Pavia, Perugia, Pisa, Trieste)
Exp-Th

Imperial College (London), Liverpool U. ***Exp-Th***

Krakow IFJ Pan
Exp

Northwestern U., Virginia U.
Exp

Budker Inst. (Novosibirsk)
Exp

Demokritos INPP (Athens) ***Exp***

Shanghai Jiao Tong U.
Exp

PSI (Villigen), ETH and U.Zürich
Th

+ other involved theorists from: U.Valencia (E), KIT/Karlsruhe (D), New York City Tech (USA)

Conclusion

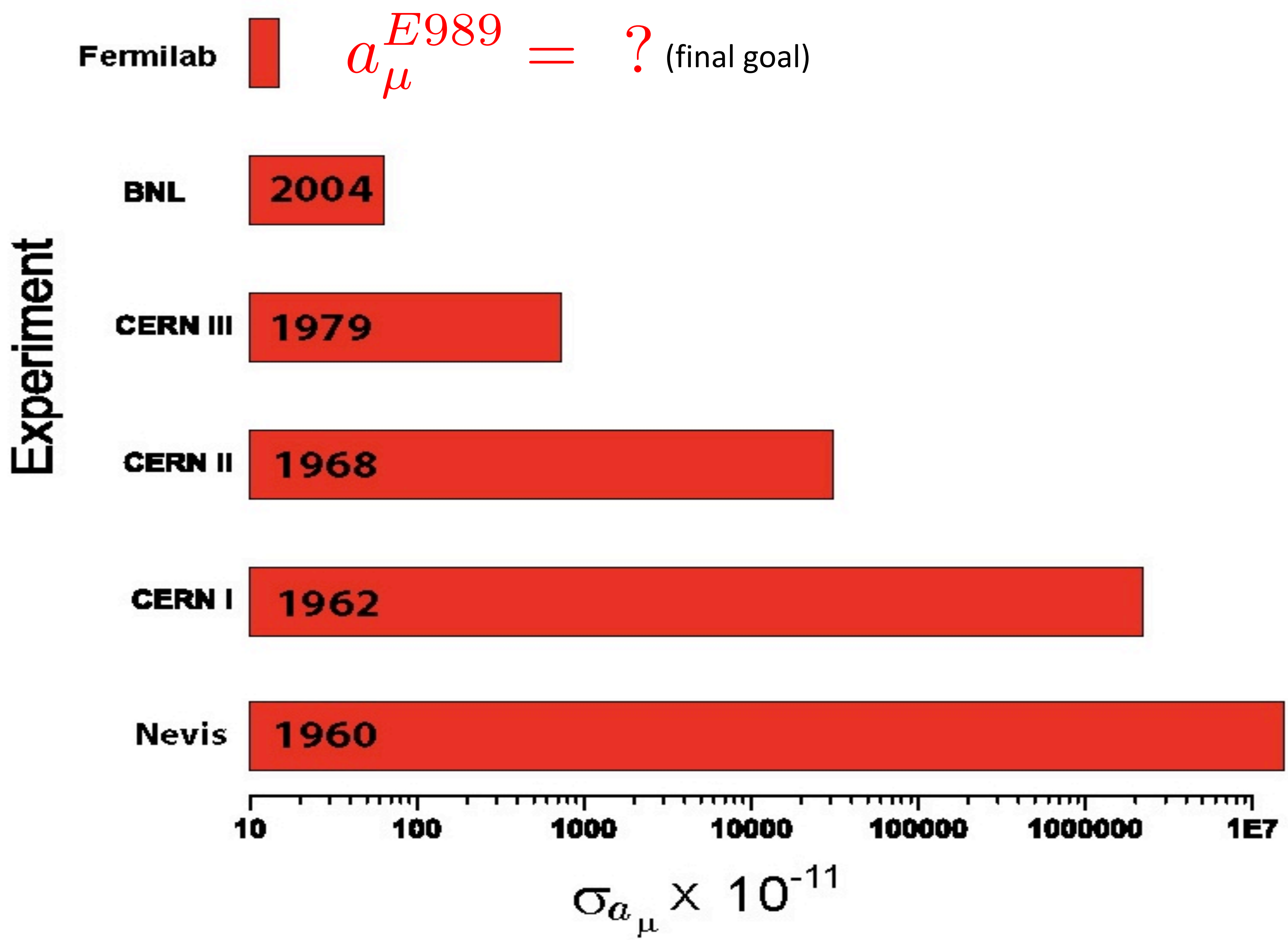
- A +60years rich history of the muon g-2 experiments which allowed to test the SM at <0.5 ppm precision.
- An intriguing discrepancy is present. Possible a sign of new Physics?
- New (and current) experimental (and theory) initiatives ongoing at Fermilab (E989), JPARC (E34) and CERN (MUonE)
- In the next years we (probably) will know if the current discrepancy is a real sign of new physics or not

STAY TUNED!

References

- **”Storage Ring” Muon g-2** (Reviews, only a subset):
  - F. Farley, E. Picasso “The Muon (g−2) Experiments at CERN», Ann.Rev.Nucl.Part.Sci. 29 (1979) 243-282
  - F. Farley, Y. Semertzidis «The 47 years of muon g-2», Prog.Part.Nucl.Phys. 52 (2004) 1-83
  - J. Miller, E. de Rafael, B. L. Roberts, D. Stockinger, «Muon (g-2): Experiment and Theory», *Ann.Rev.Nucl.Part.Sci.* 62 (2012) 237-264
  - D. Hertzog, «Next Generation Muon g-2 experiments», *EPJ Web Conf.* 118 (2016) 01015 e-Print: https://arxiv.org/abs/1512.00928
  - B. L. Roberts «The History of the Muon (g-2) experiments», *SciPost Phys.Proc.* 1 (2019) 032, https://arxiv.org/abs/1811.06974
- **JPARC Muon g-2:**
  - M. Abe et al, «A New Approach for Measuring the Muon Anomalous Magnetic Moment and Electric Dipole Moment», *PTEP* 2019 (2019) 5, 053C02, https://arxiv.org/pdf/1901.03047.pdf
  - Y. Sato «J-PARC muon g - 2/EDM experiment» JPS Conf. Proc., 011110 (2021)
- **MUonE at CERN:**
  - C.M. C. Calame et al, “A new approach to evaluate the leading hadronic corrections to the muon g-2”Phys. Lett. B 746 (2015) 325
  - G. Abbiendi et al. “Measuring the leading hadronic contribution to the muon g-2 via μe scattering” , Eur.Phys.J.C 77 (2017) 3, 139
  - MUonE LoI: https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf (2020)
  - G. Abbiendi «Status of the MUoNE experiment», PoS ICHEP2020 (2021) 223, https://arxiv.org/abs/2012.07016

Thanks!



Fermilab
$a_\mu^{E989} = ?$ (final goal)
BNL
2004
CERN III
1979
CERN II
1968
CERN I
1962
Nevis
1960
Experiment
10
100
1000
10000
100000
1000000
1E7
$\sigma_{a_\mu} \times 10^{-11}$