Paolo Franzini and Juliet Lee-Franzini

MEMORIAL SYMPOSIUM

19 Aprile 2022
dalle 10:00 alle 17:00
Auditorium Bruno Touschek

19 April 2022
INFN - Laboratori Nazionali di Frascati

The Muon Magnetic Anomaly

Graziano Venanzoni– INFN Pisa

Paolo and Juliet

- As many other colleagues I had the privilege to be in Frascati during the KLOE years, first as a student (in the 90s) and after as a researcher (in the 2000s).
- I was deeply influenced by Paolo and Juliet: their passion for physics, enthusiasm, informal approach, scientific clearness and rigor were always an example and a guide.
- As a co-spoke in g-2 I often think to them when I'm in front of a difficult decision: "What Paolo and Juliet would have done in this case?"
- I miss Paolo and Juliet very much and I'm sure I would have been different without having meet them!

Paolo e Juliet "legacy"

(from Gino's contribution to DIF06 proceedings)

Paolo, Juliet and g-2

- Paolo and Juliet were particularly interesting to g-2 and sigma(had).
- During the years I had almost continuos interactions with them. Often in my office (sorry Erika!) but sometimes in theirs.
- Their contribution/criticism/advice was always very constructive and helpful.
- Juliet was a referee of all the ISR memo’s and Paolo strongly edited the physics (PLB) papers.
- When in 2009 I decided to embark in the g-2 adventure they gave me a strong encourage and support.
- In the last years of my activity at LNF (~2015/16) I met often Paolo and discuss with him the g-2 physics and experiment.

Paolo and Juliet and g-2

$\sigma(e^+e^-\to\text{hadrons}+\gamma)$

Juliet Lee-Franzini

Laboratori Nazionali di Frascati

Cape Cod, June 2003

$g-2$

Paolo Franzini

Rome and Karlsruhe

:arlsruhe - Fall 2001

Measurement of $\sigma(e^+e^-\to\pi^+\pi^-)$ at e^+e^- Colliders

Juliet Lee-Franzini
LNF, INFN, I-00044, Frascati, Italy

2 Mar 2004

Abstract

At the DAΦNE-II workshop a session was devoted to the prospects of measuring the hadronic cross section at the new DAΦNE. The session included six papers, two theoretical and four experimental ones. The theory treatises, one on the muon anomaly and the other on measuring the hadronic cross section using initial state radiation at e^+e^- colliders, set the background for the four experimental discussions. I summarize in the following the salient points of the session.

INTRODUCTION

The electroweak contribution is evaluated to the percent level: $(15.4\pm0.2)\times10^{-10}$. Coming to more uncertain terms, he showed that the sign of the light by light scattering contribution is unambiguously positive but assigned to its value a 50% error: $\delta^{\rm lbl}_{\rm had}a_\mu$=$(8\pm4)\times10^{-10}$. He devoted most of his time to what still remains the most uncertain term, the hadronic vacuum polarization effects. He advocates using the analysis by HMNT which gives, including the corrected CMD2 results, $\delta^{\rm VP}_{\rm had}a_\mu$=$[(692.4\pm6.4)_{\rm lo}-(9.79\pm0.095)_{\rm nlo}]\times10^{-10}$. Adding everything: a_μ=$(11659176.3\pm7.4)\times10^{-10}$ [2]. In conclusion the discrepancy between the experimental measurement and the SM evaluation is now $(32\pm\ 10)\times10^{-10}$, about 3σ.

?????

file=...\g-2.tex

KLOE Memo

Paolo Franzini

13 November 2010

Magnetic moment, magneton, gyromagnetic or Landé g-factor

From the Dirac equation the electron magnetic moment $\mu_{e,\,\rm D}$ is:

$$\mu_{e,\,\rm D}=g\,\frac{e\hbar}{2m_ec}\,\frac{J}{\hbar}$$

with the gyromagnetic, or Landé g-factor, g=2, to lowest order in QED, using Gaussian units. g is dimension-less. J dimensionally is $m\,v\,r$ and is measured in gram×centimeter^2 ×second^{-1}. $J/\hbar$ is the spin in the usual $\hbar$ units. Introducing the Bohr magneton, making explicit the fact that it applies to the electron,

$$\mu_{B,\,e}=\frac{e\hbar}{2m_ec},$$

Please avoid saying that the anomaly, a dimensionless quantity, is a magnetic moment (anomalous or not) which is a dimensionfull quantity! That is a gross conceptual mistake.

Paolo and Juliet and the born of ISR…

- The g-2 physics through the measurement of sigma(had) was part of the KLOE program
- However DAFNE was not optimized for an energy scan…

KLOE Workshop at Karlsruhe 1996

Hadronic Contributions to the Muon g-2

Riccardo Barbieri
Dip. di Fisica, Univ. di Pisa and INFN, Sez. di Pisa
and
Ettore Remiddi
Dip. di Fisica, Univ. di Bologna and INFN, Sez. di Bologna

1991

The obvious target in the domain of the precision measurements of the muon g-2 is the detection of the electroweak corrections due to vector and Higgs boson exchange. The present experimental value of the muon anomaly is [1]

R Measurements at KLOE

a_μ and $\alpha_{QED}(M_Z)$

PAOLO FRANZINI

Tesi di Laurea

Studio di fattibilità di una misura di sezione d'urto adronica con il rivelatore KLOE, finalizzata alla determinazione delle correzioni adroniche al momento magnetico anomalo del muone

Anno Accademico 1995-1996

Candidato:

Giorgio Cabibbo

Relatore interno: Prof. Luciano Paoluzi

Relatore esterno: Prof. Paolo Franzini

THE DAΦNE STUDY GROUP

Then (~1998/99) came the idea of ISR…

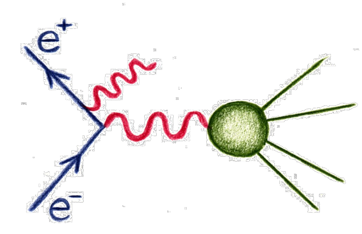
Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Nuclear Physics B (Proc. Suppl.) 181–182 (2008) 280–285
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
www.elsevierphysics.com

Initial State Radiation: A success story

W. Kluge[a*]

[a]Institut für Experimentelle Kernphysik, Universität Karlsruhe, Postfach 3640, D 76021 Germany

The investigation of events with *Initial State Radiation(ISR)* and subsequent *Radiative Return* has become an impressively successful and guiding tool in low and intermediate energy hadron physics with electron positron colliders: it allows to measure hadronic cross sections and the ratio R from threshold up to the maximum energy of the colliders running at fixed energy, to clarify reaction mechanisms and reveal substructures (intermediate states and their decay mechanisms) and to search for new highly excited mesonic states with $J^{PC} = 1^{--}$. While being discussed since the sixties-seventies *ISR* became a powerful tool for experimentalists only with the development of *EVA-PHOKHARA*, a Monte Carlo generator developed over almost 10 years, while increasing its complexity, which is user friendly, flexible and easy to implement into the software of existing detectors.



Physics Letters B 459 (1999) 279–287

Measuring $\sigma(e^+e^- \to \text{hadrons})$ using tagged photons

S. Binner, J.H. Kühn, K. Melnikov [1]

Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany

Radiative return at NLO and the measurement of the hadronic cross-section in electron–positron annihilation

Germán Rodrigo[1a], Henryk Czyż[2,3b], Johann H. Kühn[1,4c], and Marcin Szopa[2]

[1] TH-Division, CERN, CH-1211 Geneva 23, Switzerland.
[2] Institute of Physics, University of Silesia, PL-40007 Katowice, Poland.
[3] Institute of Advanced Study, University of Bologna, I-40138 Bologna,Italy
[4] Institut für Theoretische Teilchenphysik, Universität Karlsruhe, D-76128 Karlsruhe, Germany.

Received: February 1, 2008

Eur. Phys. J. C 6, 637–645 (1999)
DOI 10.1007/s100529800953

THE EUROPEAN PHYSICAL JOURNAL C
© Springer-Verlag 1999

The hadronic contribution to the muon $g-2$ from hadron production in initial state radiation events at the e^+e^- collider DAΦNE

S. Spagnolo[a]

Dipartimento di Fisica dell'Università di Lecce and INFN, Sezione di Lecce, via Arnesano I-73100 Lecce, Italy

KLOE MEMO n°195
August 13, 1999

Measurement of the hadronic cross section $\sigma(e^+e^- \to \pi^+\pi^-)$ from initial state radiative events $\pi^+\pi^-\gamma$ with the KLOE detector

Gabriella Cataldi, Achim Denig, Wolfgang Kluge, Graziano Venanzoni
Institut für Experimentelle Kernphysik, Universität Karlsruhe

From Hadronic Cross Section to the measurement of the Vacuum Polarization at KLOE: a fascinating endeavour

Graziano Venanzoni[1,⋆]
[1] *INFN Sezione di Pisa, Pisa, Italy*

EPJ Web of Conferences **166**, 00021 (2018)

Abstract. The KLOE experiment at the $\phi-$*factory* DAΦNE in Frascati is the first to have employed Initial State Radiation (ISR) to precisely determine the $e^+e^- \to \pi^+\pi^-(\gamma)$ cross section below 1 GeV. Such a measurement is particularly important to test the Standard Model (SM) calculation for the $(g-2)$ of the muon, where a long standing 3σ discrepancy is observed. I will review the ISR activity in KLOE in the last 20 years from the measurement of the hadronic cross section to the first direct determination of the time-like complex running $\alpha(s)$ in the region below 1 GeV.

Measurement of the hadronic cross-section with KLOE using a radiated photon in the initial state

G. Cataldi (Karlsruhe U.), A. Denig (Karlsruhe U.), W. Kluge (Karlsruhe U.), S. Muller (Karlsruhe U.), G. Venanzoni (Karlsruhe U.) (Nov, 1999)

Published in: *Frascati Phys.Ser.* 16 (1999) 569-578 • Contribution to: 3rd Workshop on Physics and Detectors for DAPHNE (DAPHNE 99), 569-578

ISR@Karlsruhe (1999-2000s)

- I was lucky to be in Karlsruhe from 1999-2000 (as EURODAFNEpostdoc) working on ISR at KLOE

Wolfgang Kluge

Achim Denig

Stefan Mueller

Debora Leone

Hans Kuhn

Fred Jegerlehner (Berlin)

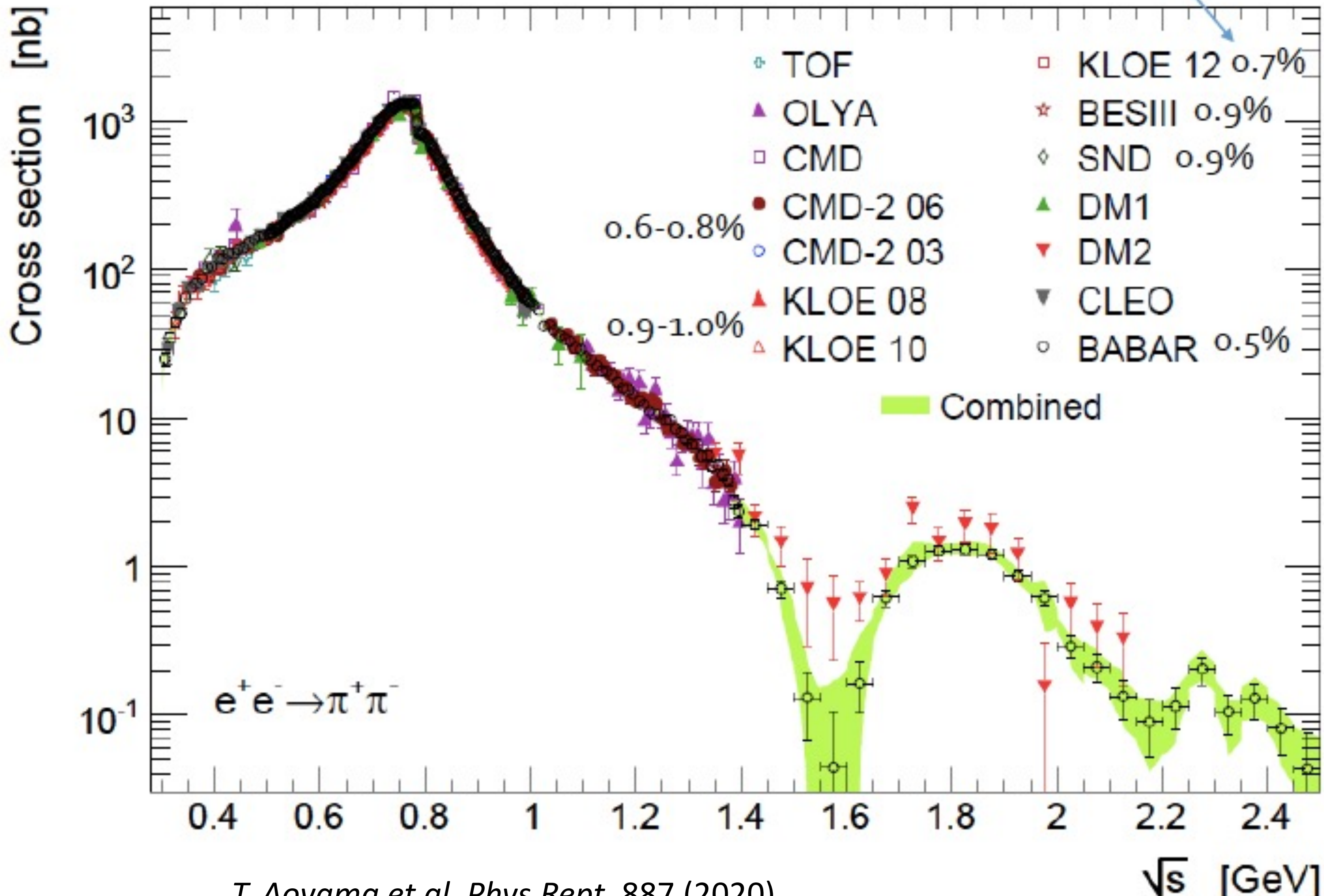
Barbara Valeriani

Paolo Beltrame (Jesuit now)

- Also important for ISR were the contributions of S. Spagnolo (Lecce), F. Nguyen (Roma 3), M. Incagli, S. Di Falco (Pisa), and H. Czyz and G. Rodrigo on theory…and many other (experimental and theory) colleagues joined later

$e^+e^- \rightarrow \pi^+\pi^-$ data

Systematic uncertainties

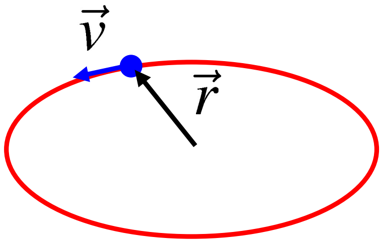


T. Aoyama et al, Phys.Rept. 887 (2020)

The Muon g-2

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

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



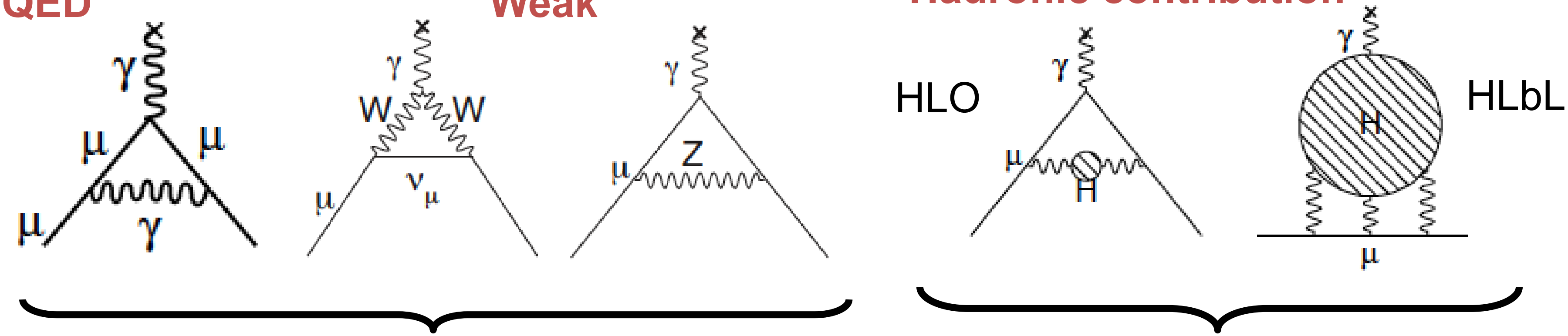
- The ratio μ/(q/2m)L is called giromagnetic ratio g. Classically **g=1**

- 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

In the SM $a_\mu = (g-2)/2$ can be computed very precisely!



Precisely known

Large uncertainty
(significant work going on)

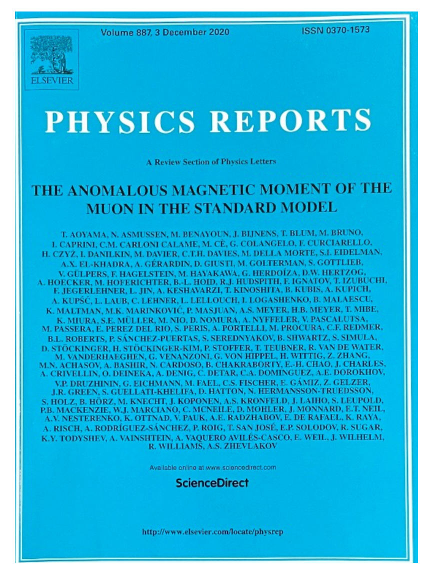
$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

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

$\delta a_\mu^{QED} \sim 1.4\times10^{-12}$ $\quad a_\mu^{Weak} \sim 2\times10^{-11}$ $\quad \delta a_\mu^{HAD} \sim 5\times10^{-10}$

$$a_\mu(\mathrm{SM}) = 116\,591\,810(43)\times10^{-11} \quad (0.37\,\mathrm{ppm})$$

T. Aoyama et al. Phys.Rept. 887 (2020)


Volume 887, 3 December 2020 ISSN 0370-1573

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PHYSICS REPORTS

A Review Section of Physics Letters

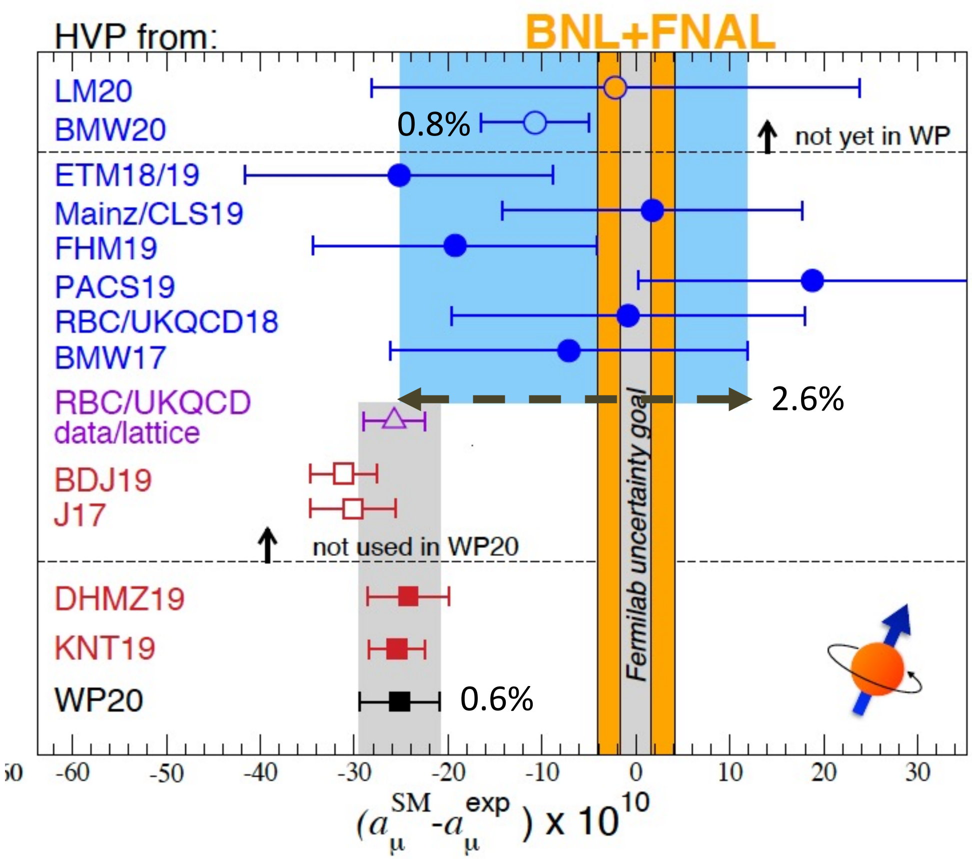
THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL

ScienceDirect

http://www.elsevier.com/locate/physrep

However: a_μ^{HLO}

- Uncertainty SM dominated by HVP (HLO) contribution
- Two approaches:
  - Dispersive (e^+e^-)
  - Lattice
- FNAL measurment is 4.2 σ from SM prediction based on e^+e^-
- However using lattice: **BMW20**
  - **1.5 σ** tra exp e SM
- Hot topic and intensive work going on!
- MUonE experimental proposal at CERN!

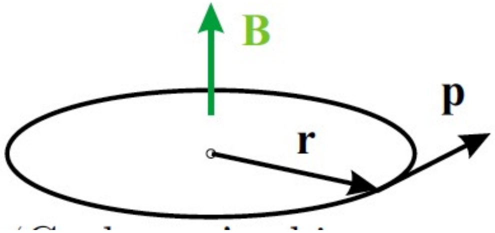


The Muon g-2 Theory Initiative has recently submitted a contribution to 2022 Snowmass Summer Study (https://arxiv.org/pdf/2203.15810.pdf) where they expect a main update in 2023. New results from the two different approaches (lattice and data-driven a_μ^{HLO}) are expected by 2025, possibly with with reduced error

$a_\mu = (g-2)/2$ can also be measured very precisely…

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

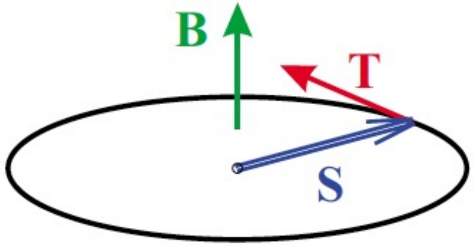
$$\omega_c = \frac{qB}{m}$$



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)

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



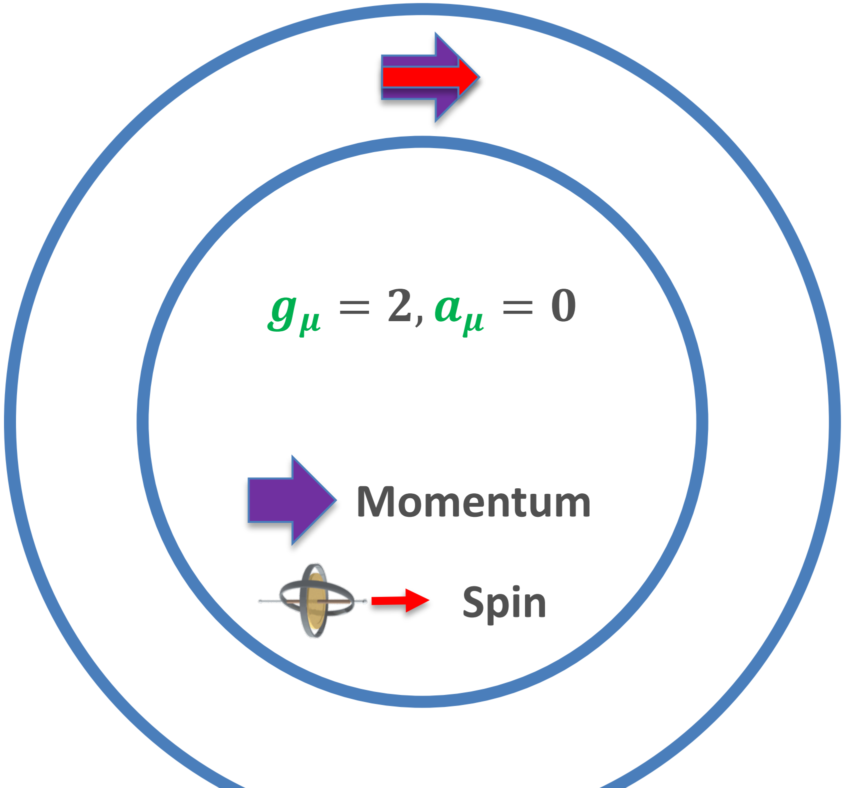
Spin precession, ω_s

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

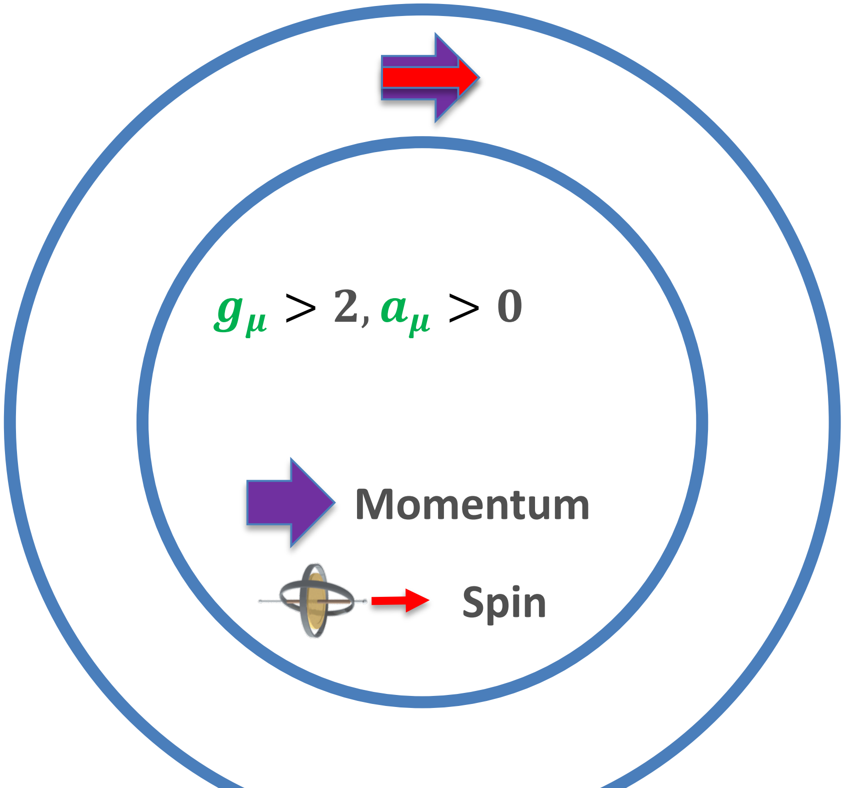


How to measure the muon anomaly?

- 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

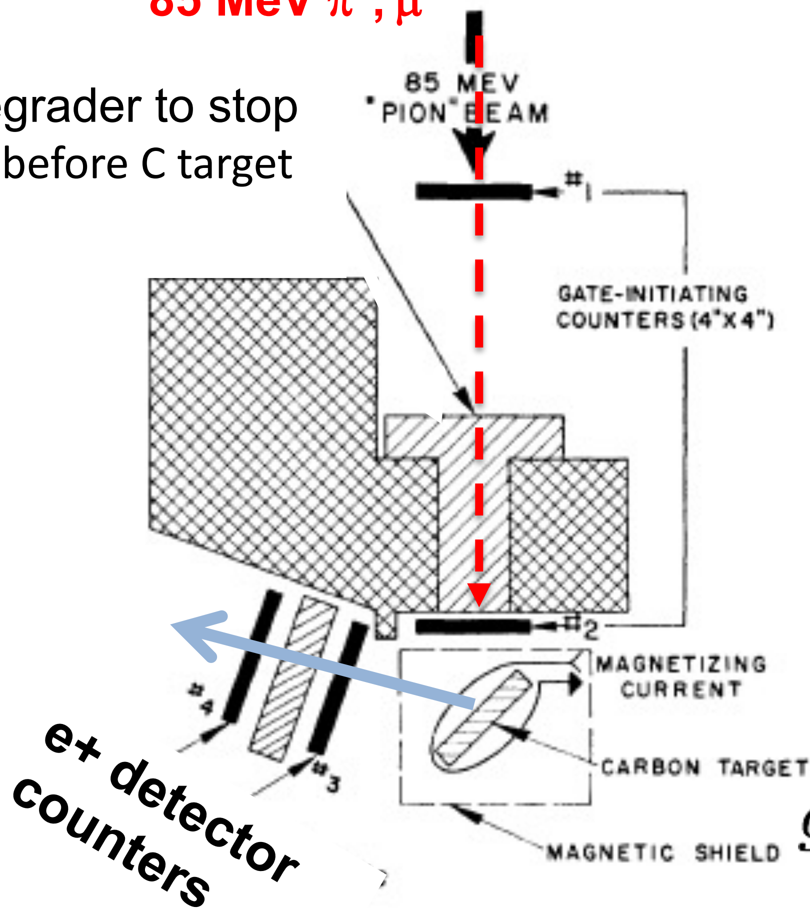
A (brief) history of the muon g-2 experiments

History: the first measurement of g_μ

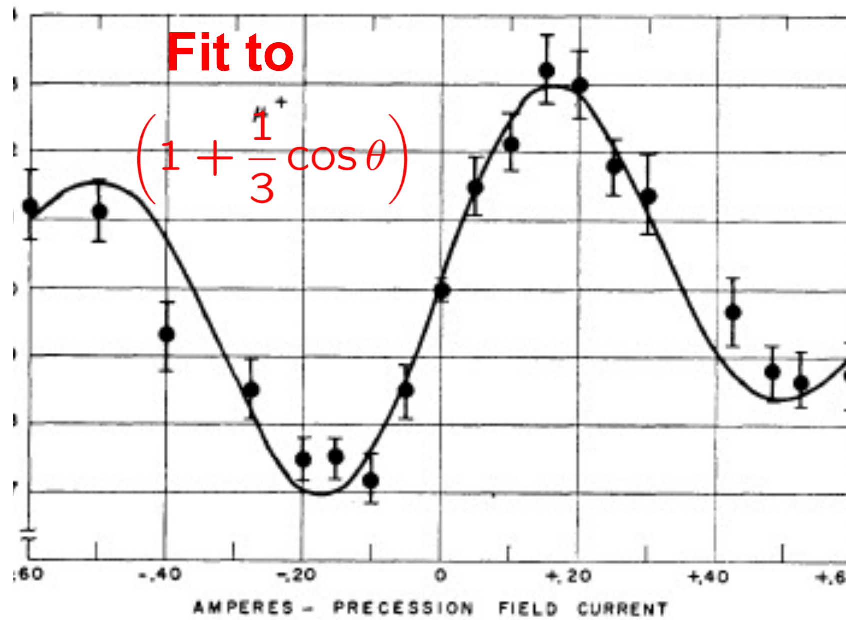
- 1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)

85 MeV π^+, μ^+

degrader to stop π^+ before C target



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

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

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

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

B. Lee Roberts*

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

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.

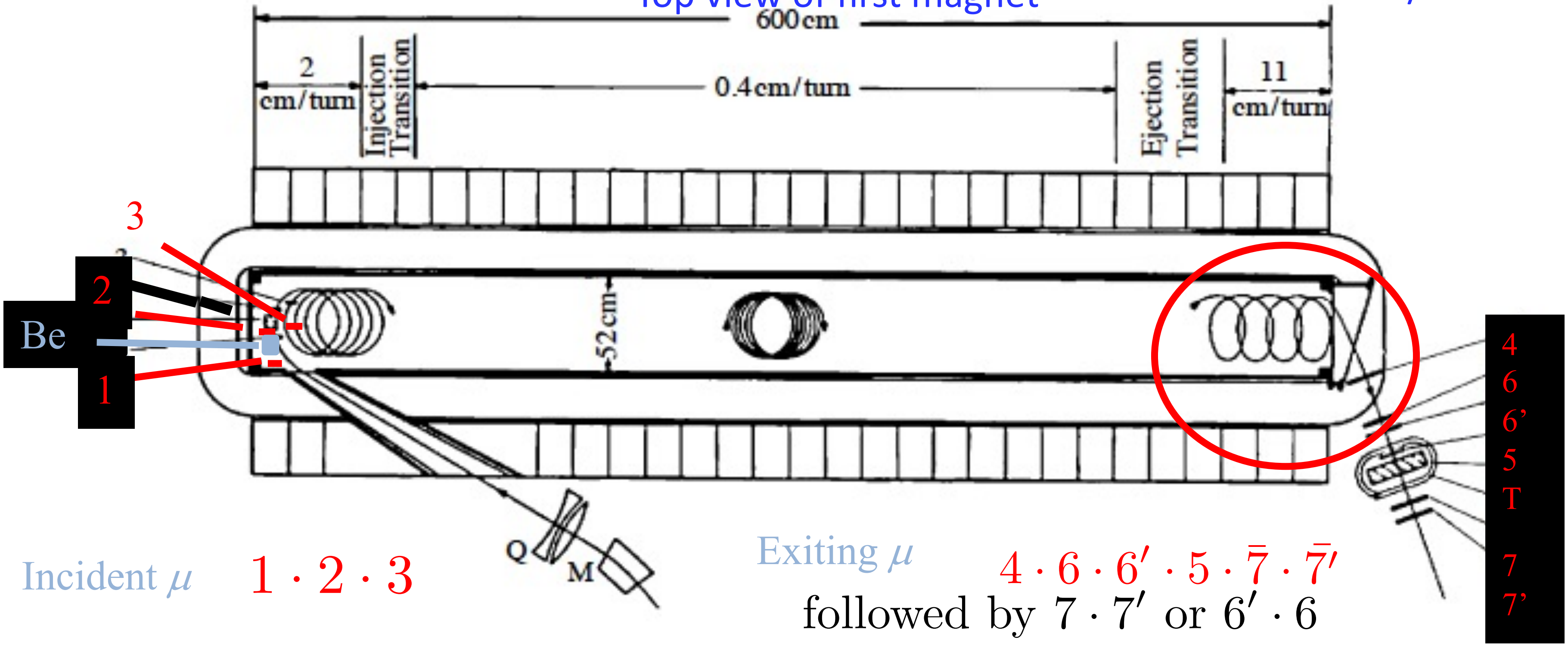
They measure a_μ since the measure the spin relative to the momentum

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

CERN I, 1958-1962

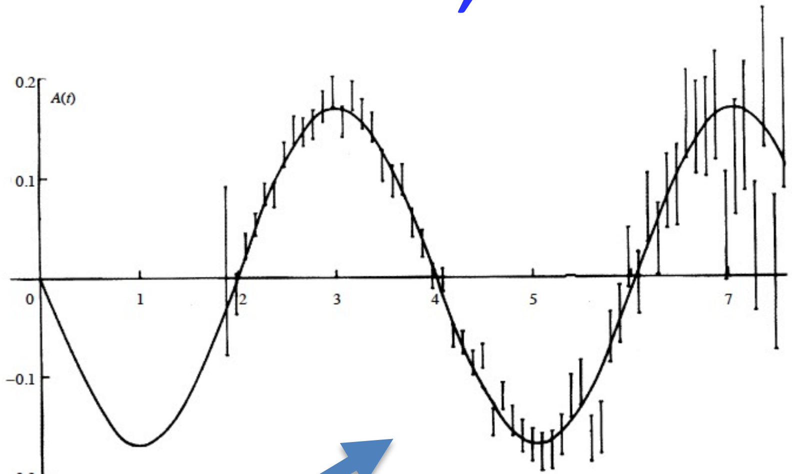
Top view of first magnet

With 100 MeV/c muons



- 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



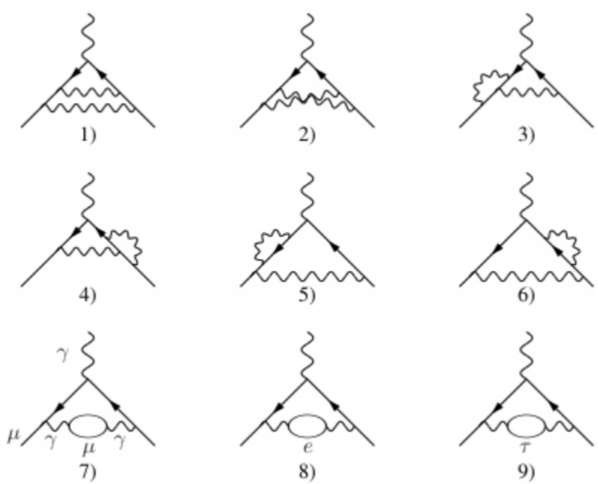
$$A(t) = A_0 \sin(\omega_a t + \varphi)$$

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

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

a_μ(expt) = 0.001162(5) (4300 ppm)

a_μ(theory) = 0.001165



QED, second order

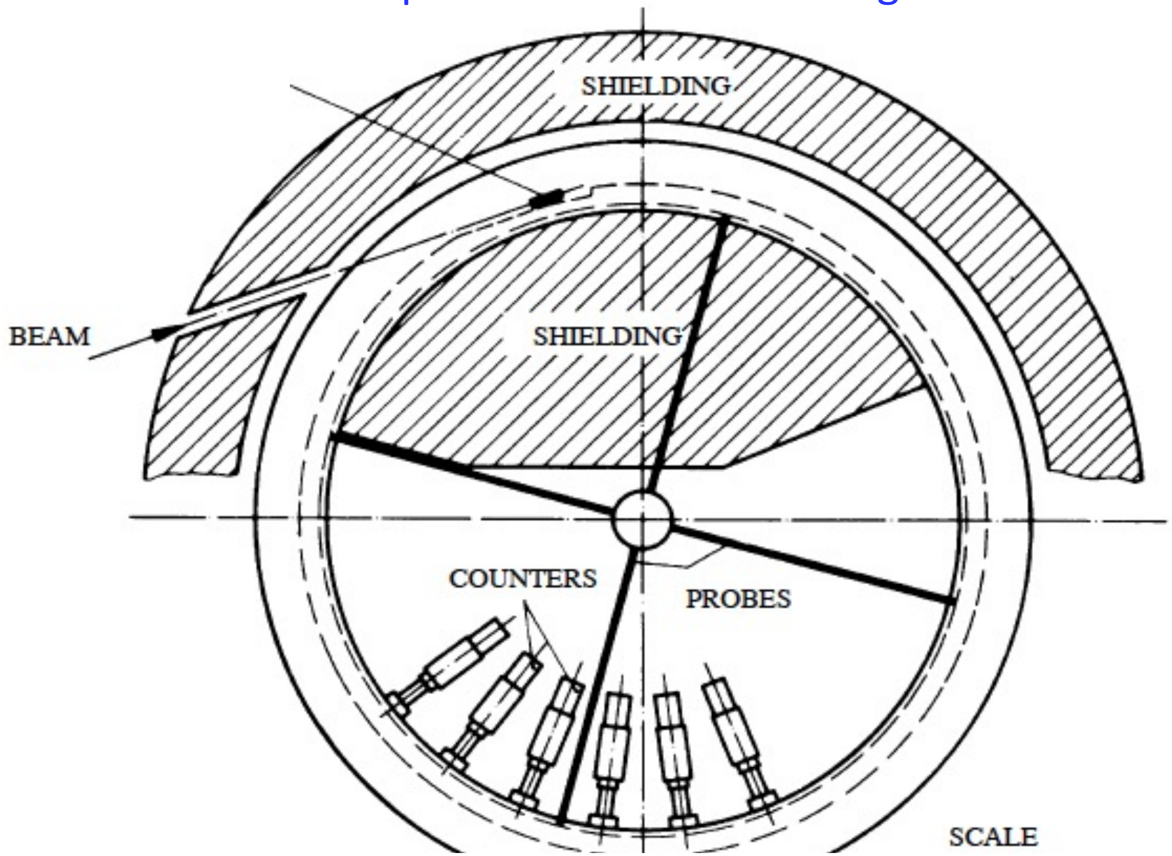
$$a_\mu \approx 0.5\left(\frac{\alpha}{\pi}\right) + 0.766\left(\frac{\alpha}{\pi}\right)^2$$

https://link.springer.com/book/10.1007/978-3-319-63577-4

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

π production target inside

Top view of the second magnet



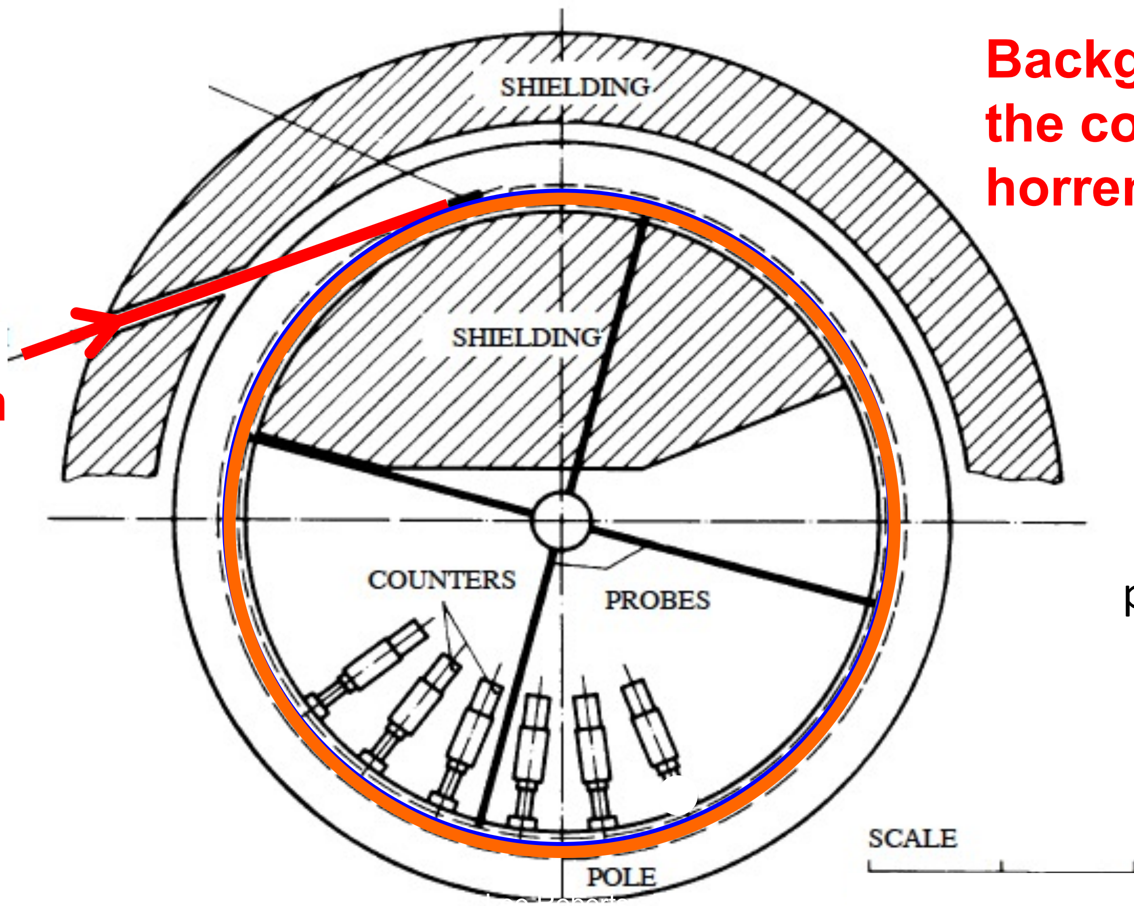
polarization 26%

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**

Background flash in the counters was horrendous!

10.5 GeV/c Proton beam

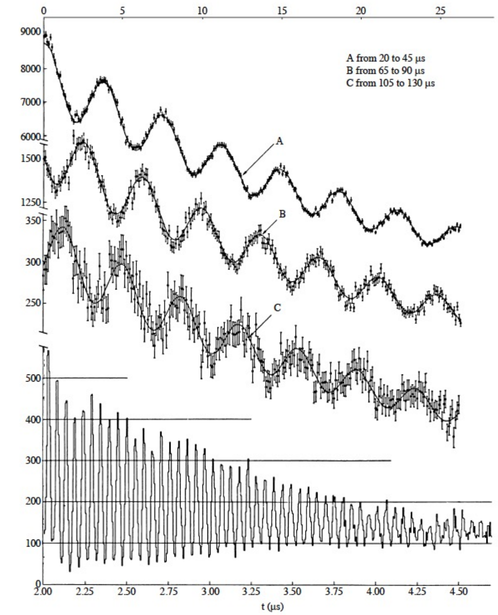


polarization 26%

CERN II, 1962-1968

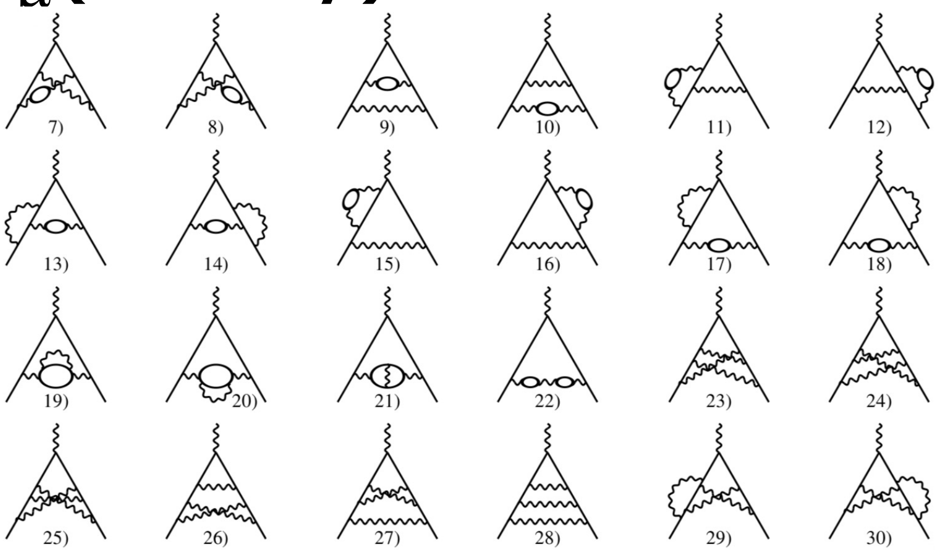
$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

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



a_μ(expt) = 0.00116616(31) (266 ppm)

a_μ(theory) = 0.00116587(3)



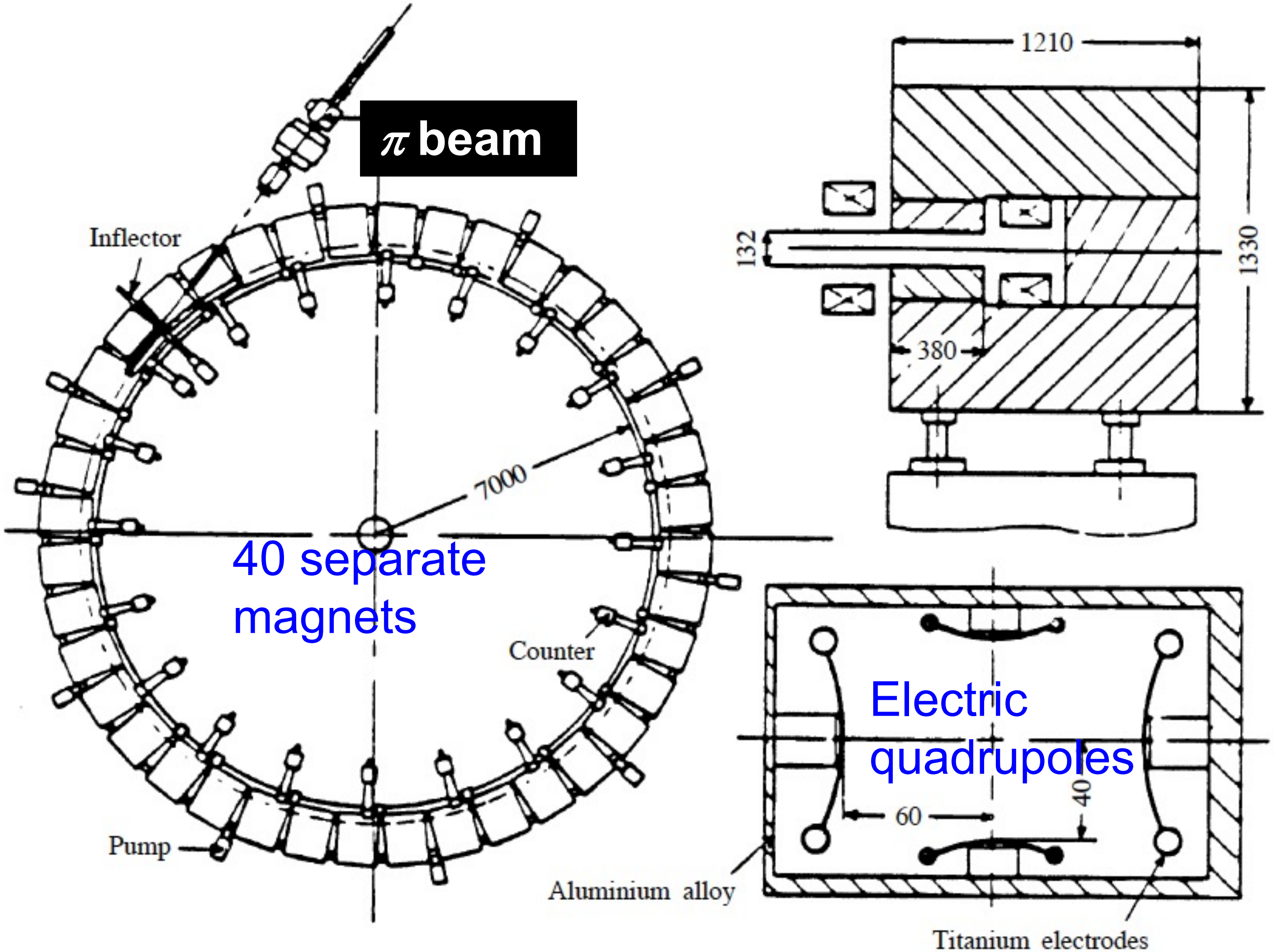
QED, third order

$$a_\mu \approx 0.5\left(\frac{\alpha}{\pi}\right) + 0.766\left(\frac{\alpha}{\pi}\right)^2 + 24.050\left(\frac{\alpha}{\pi}\right)^3$$

https://link.springer.com/book/10.1007/978-3-319-63577-4

CERN III, 1969-1976

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

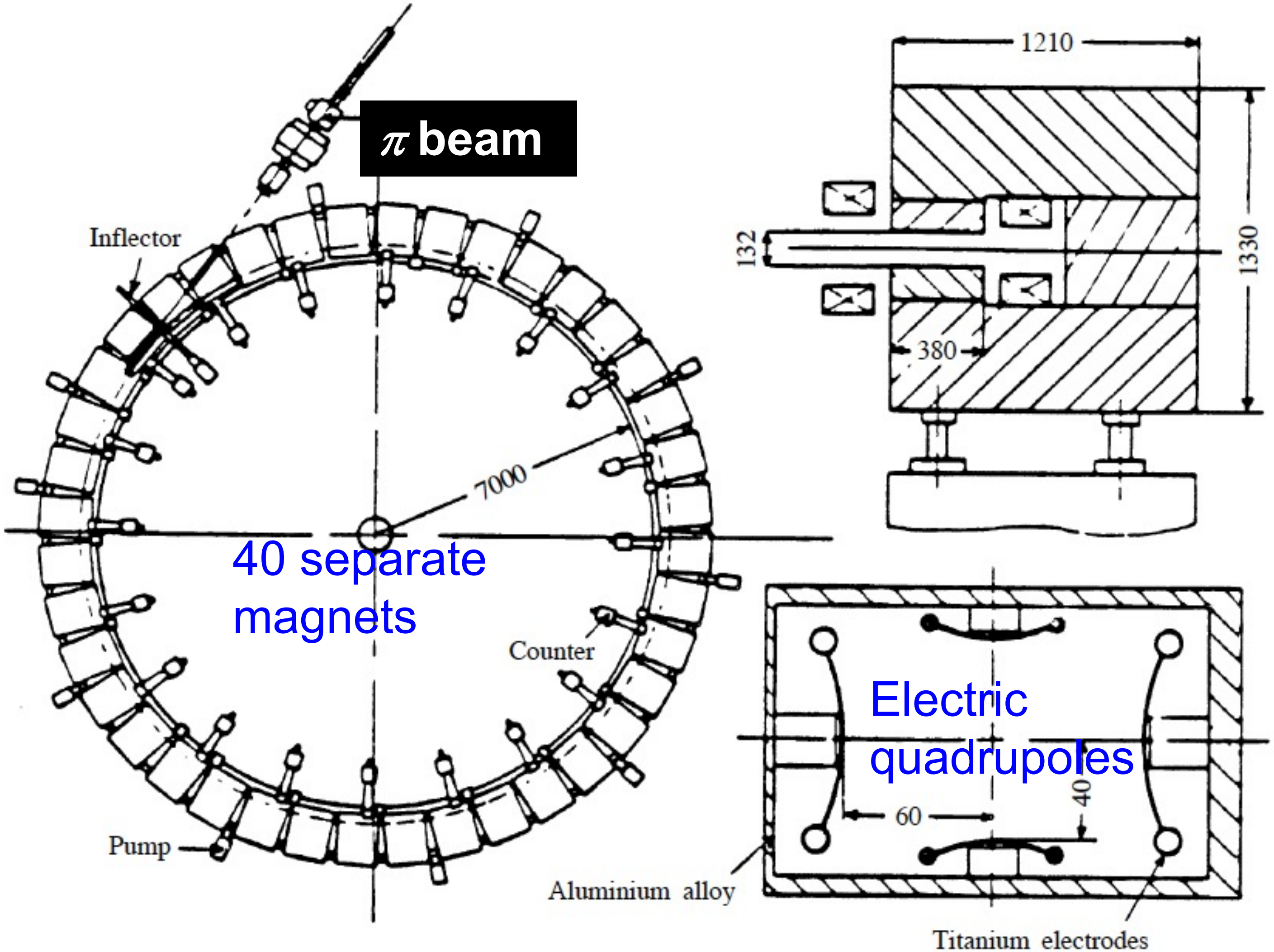


Still have pion flash at injection!

Not as bad as for CERN2

CERN III, 1969-1976

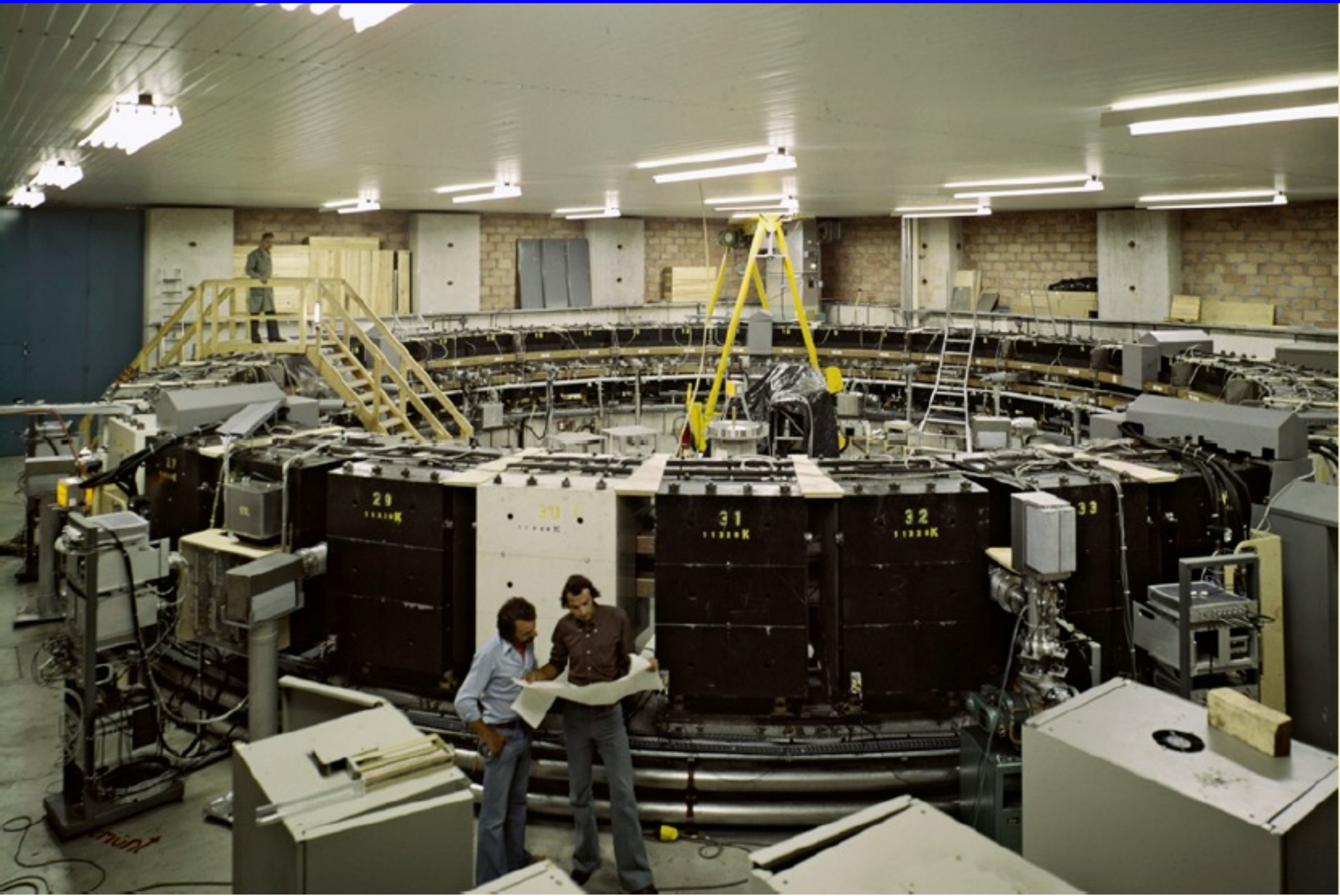
- Inject pions at 3.2 GeV Muon lifetime dilates to 64 μs
- Use $\pi \rightarrow \mu$ decay to kick muons onto stable orbits



Still have pion flash at injection!

Not as bad as for CERN2

3rd Muon g-2 experiment at Cern



CERN III, 1969-1976

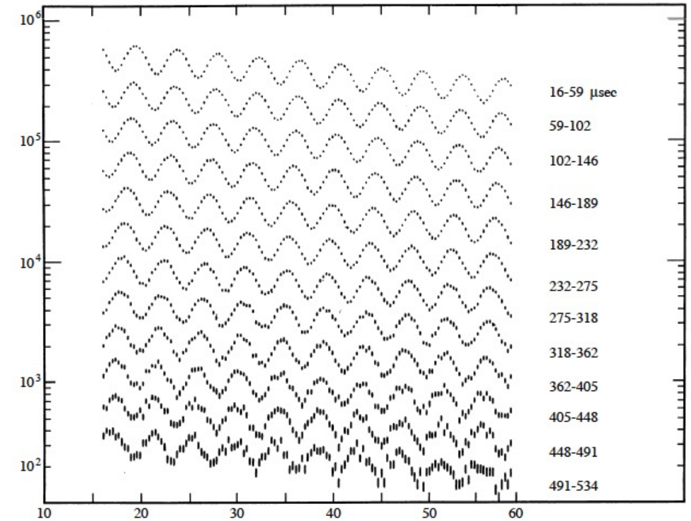
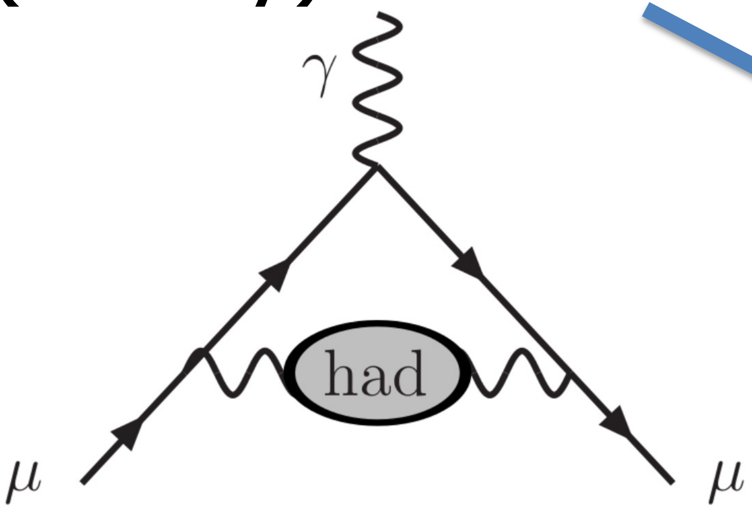


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).

a_μ(expt) = 0.00116592**4(9)** (7.3 ppm)

a_μ(theory) = 0.0011659**21(13)**



HVP (hadronic vacuum polarization)

a_μ^{HAD} ~ 700^{-10} (~60 ppm)

https://link.springer.com/book/10.1007/978-3-319-63577-4

1984-2001: Measurement of a_μ at BNL (E821)

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

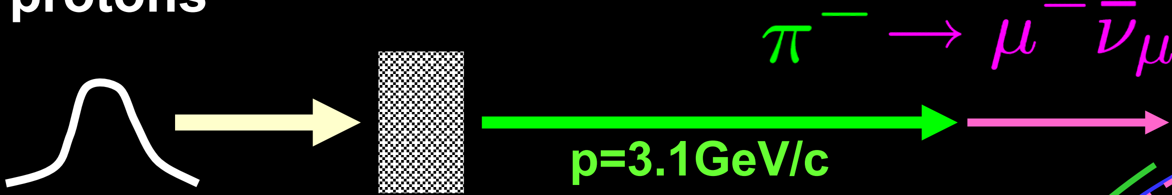
E821 Experimental Technique

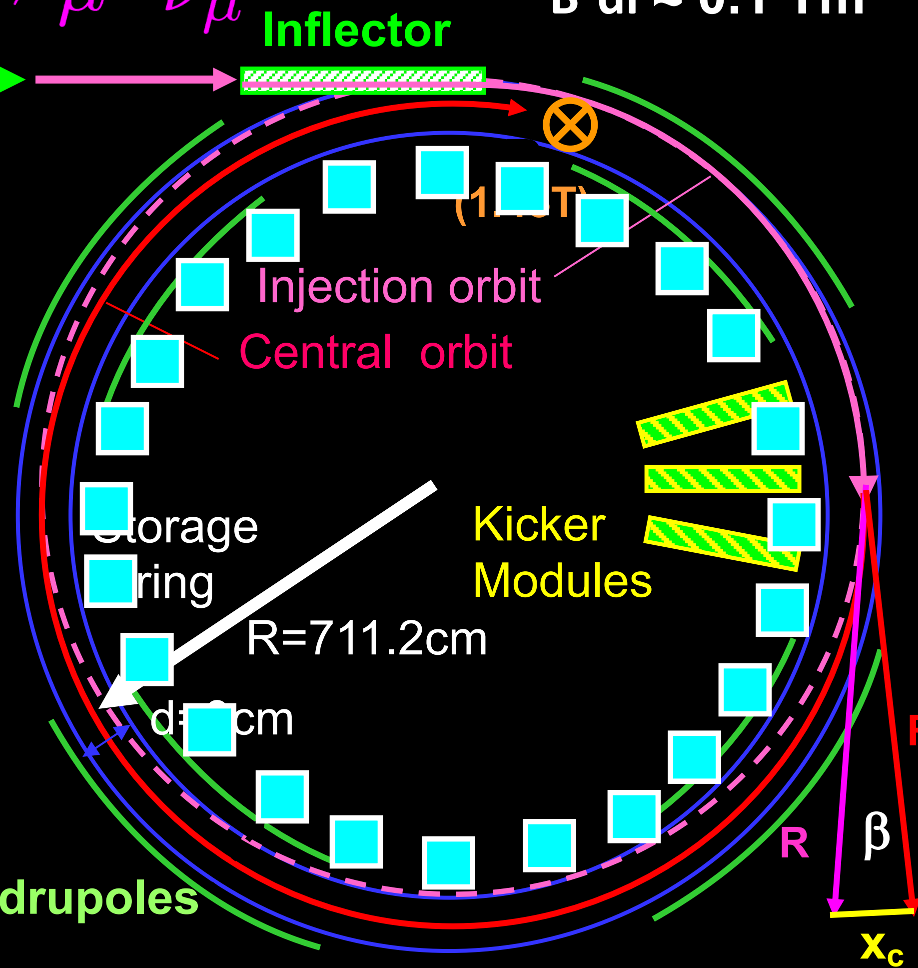
25ns bunch of
$\geqslant$ 1 X 10^{12}
protons

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

B·dl ≈ 0.1 Tm

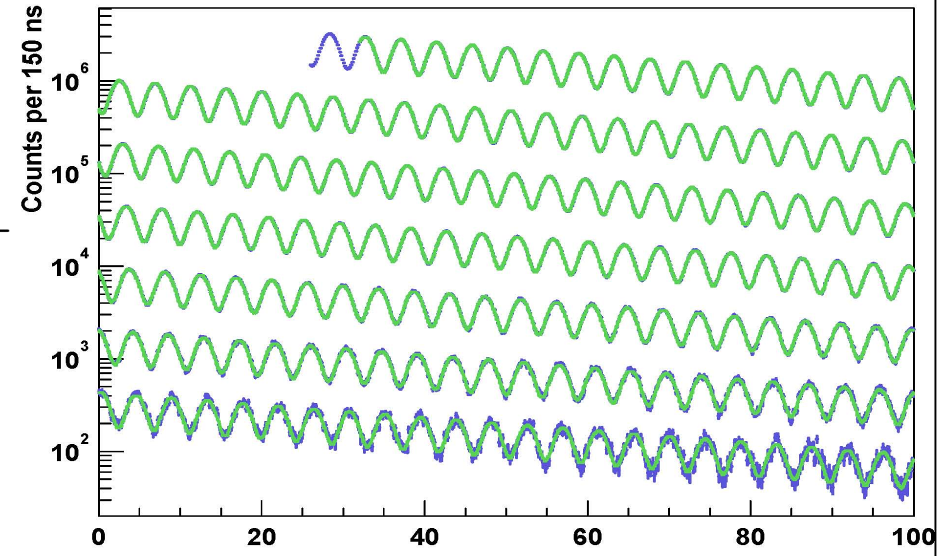




- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

E821, 1984-2001



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

(2006)

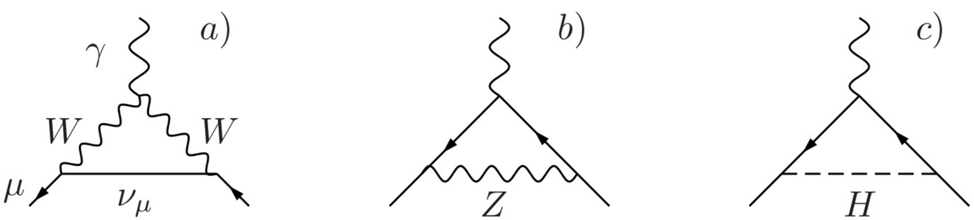
a_μ(expt) = 0.00116592089(63) (0.54 ppm)

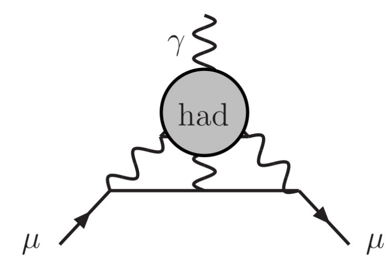
a_μ(theory) = 0.00116591820(73) ~3σ btw TH and EXP!

(HMNT 03)

EW

Hadronic light-by-light





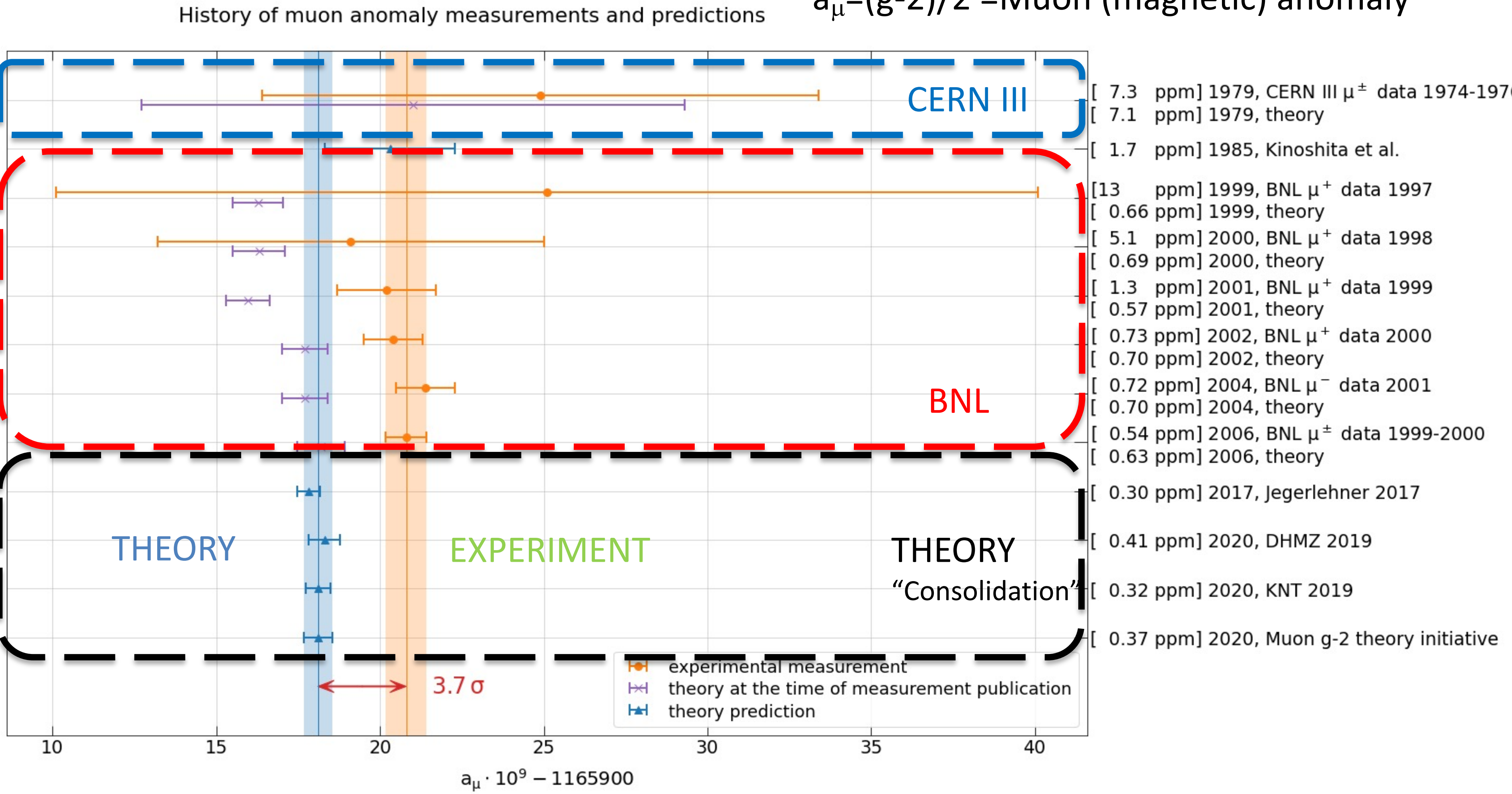
$a_\mu^{EW} \sim 15.3^{-10}$ (~1.3 ppm)

$a_\mu^{HLbL} \sim 9.2^{-10}$ (~0.8 ppm)

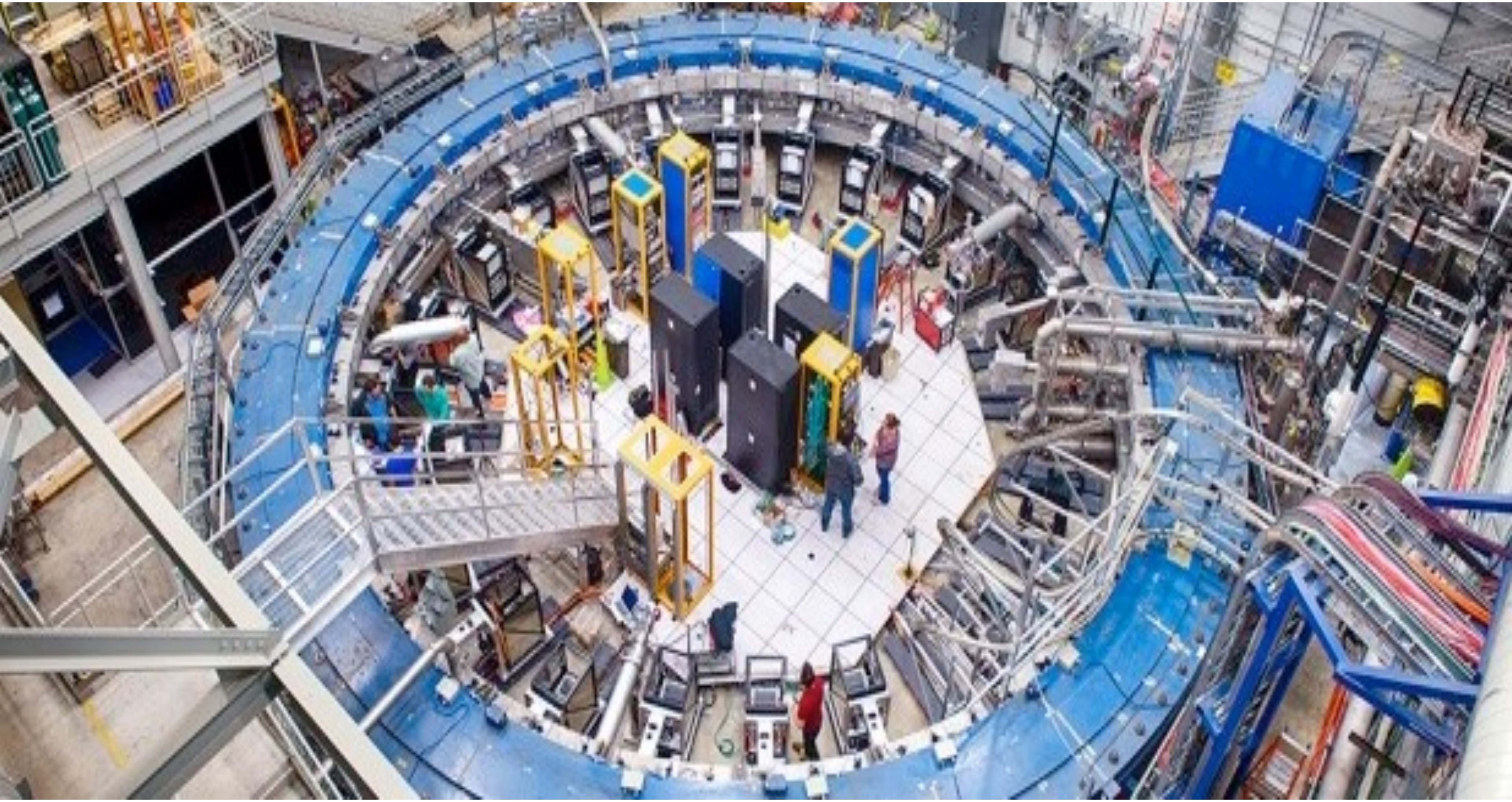
https://link.springer.com/book/10.1007/978-3-319-63577-4

Summary of g-2 theory and measurements (2020)

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



Fermilab Muon g-2 Storage Ring (2009- present)



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**

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

↳ $0.2\omega_a \oplus 0.17\omega_p$

- **E989 at Fermilab**

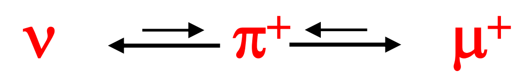
$$\left.\begin{array}{l}\sigma_{stat} = \pm 0.1 \text{ ppm} \\ \sigma_{syst} = \pm 0.1 \text{ ppm}\end{array}\right\} \sigma = \pm 0.14 \text{ ppm}$$

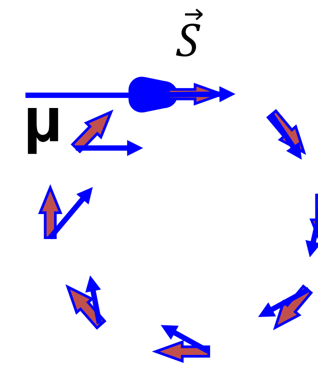
$0.07\omega_a \oplus 0.07\omega_p$

Key ingredients

1) Polarized muons

~97% polarized for forward decay





2) Precession proportional to (g-2)

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

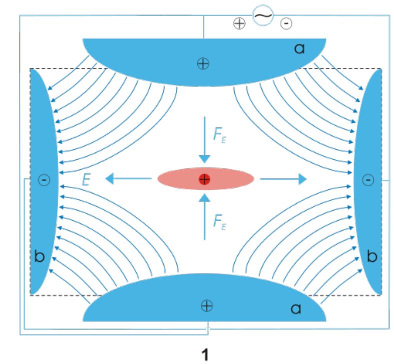
Measure 2 quantities

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

3) P_μ magic momentum = 3.09 GeV/c

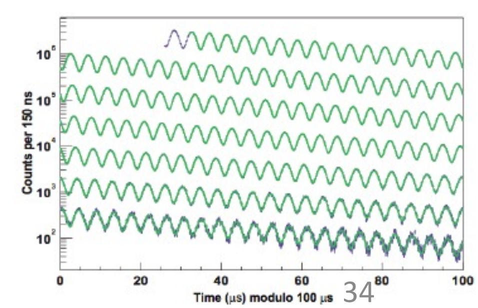
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

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



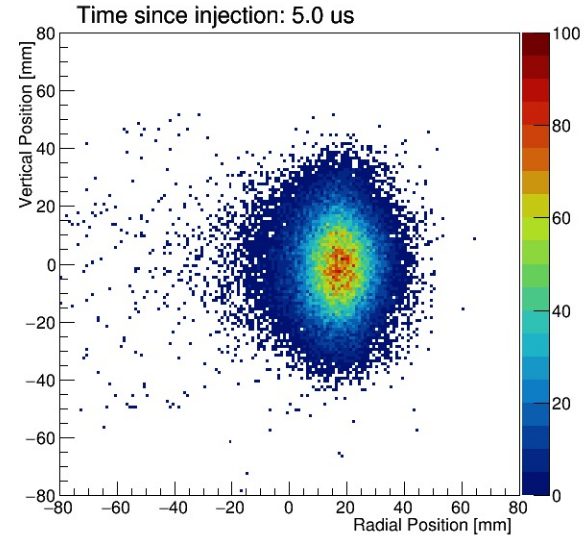
4) Decay e^+ emitted preferably in spin direction of the muon

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



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

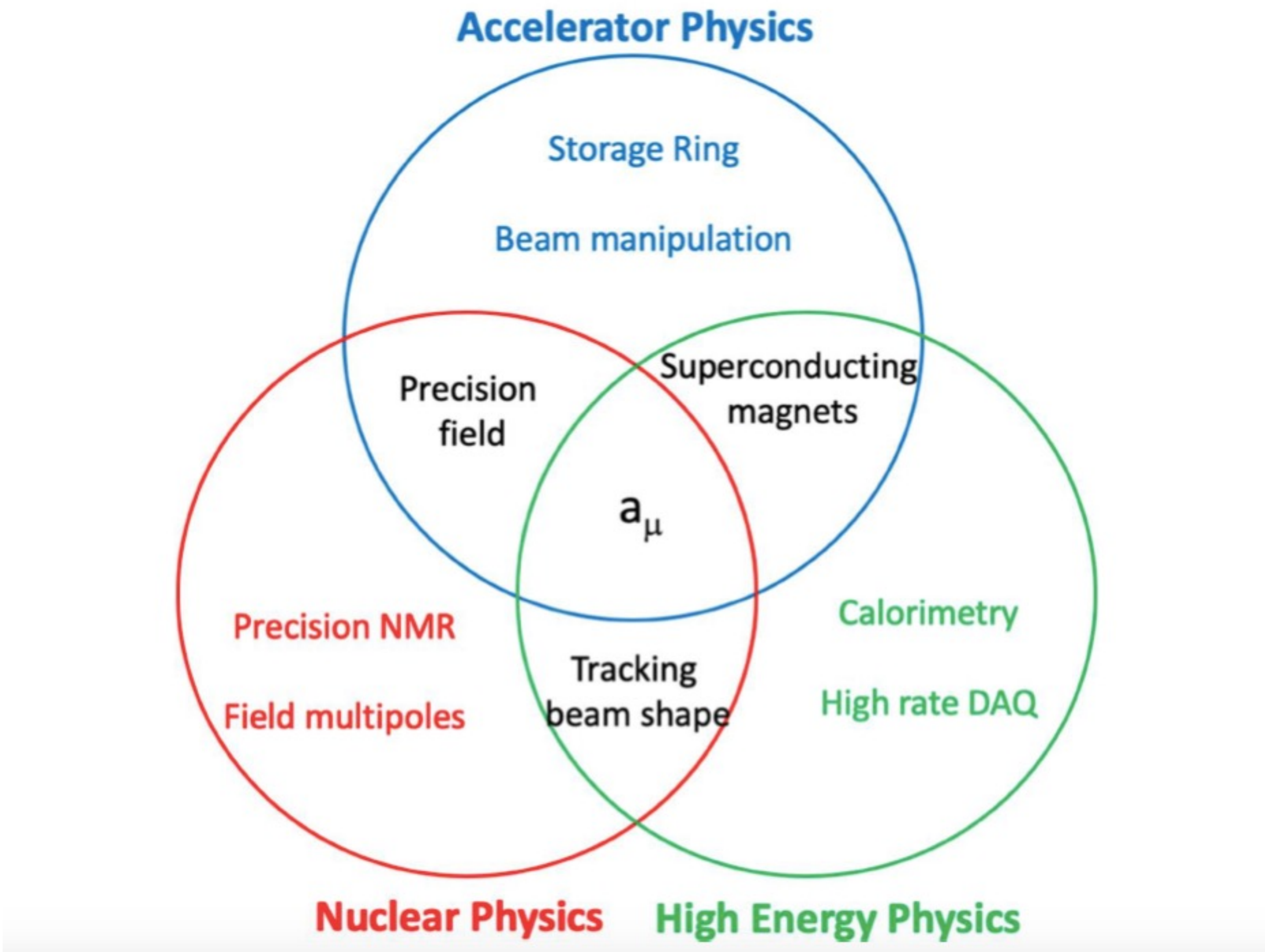
Korea
- CAPP/IBS
- KAIST

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

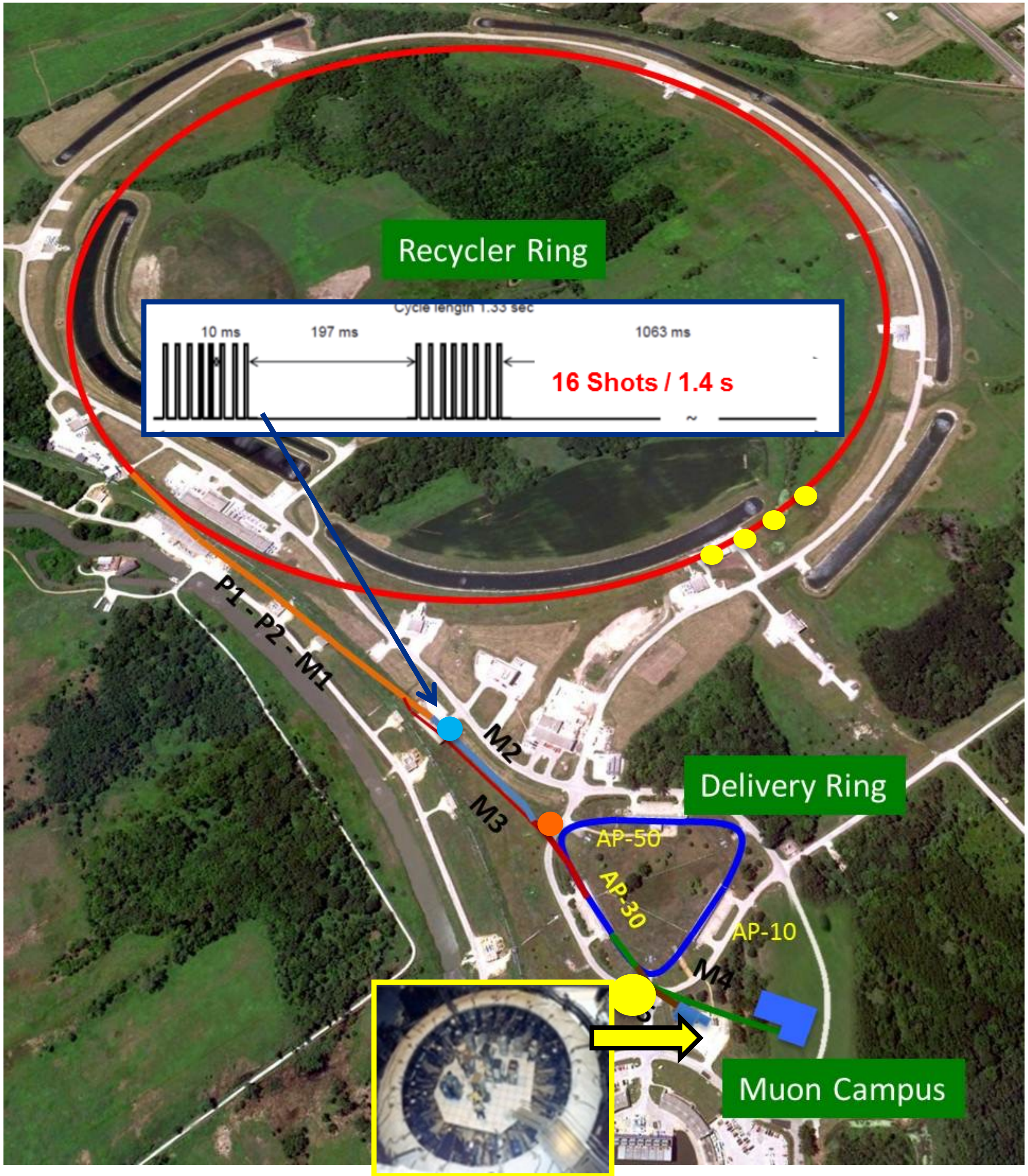


June 2013: The ring leaves from BNL

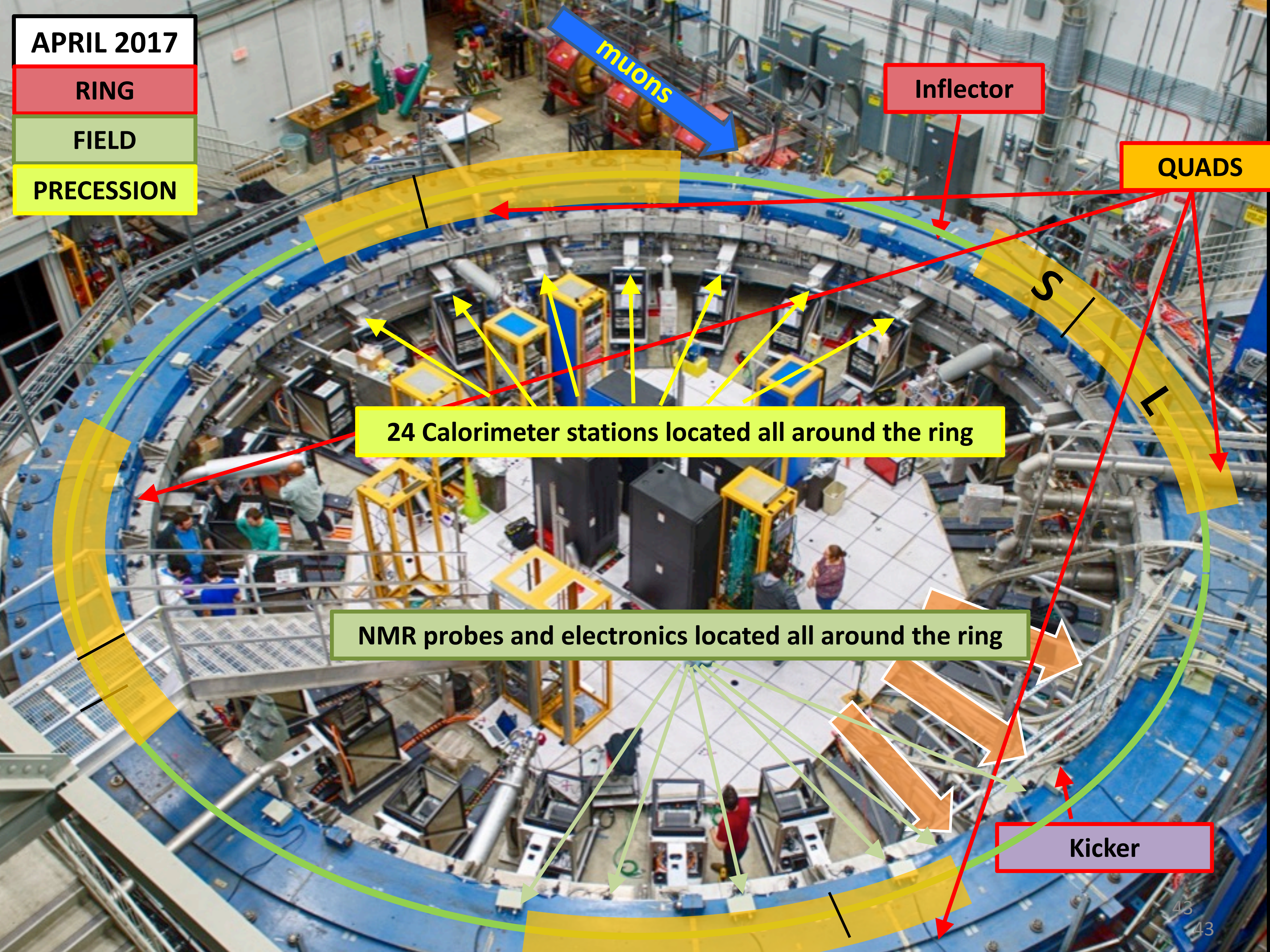
26 July 2013:…the ring arrives to FNAL

[redacted]

Creating the Muon Beam for g-2

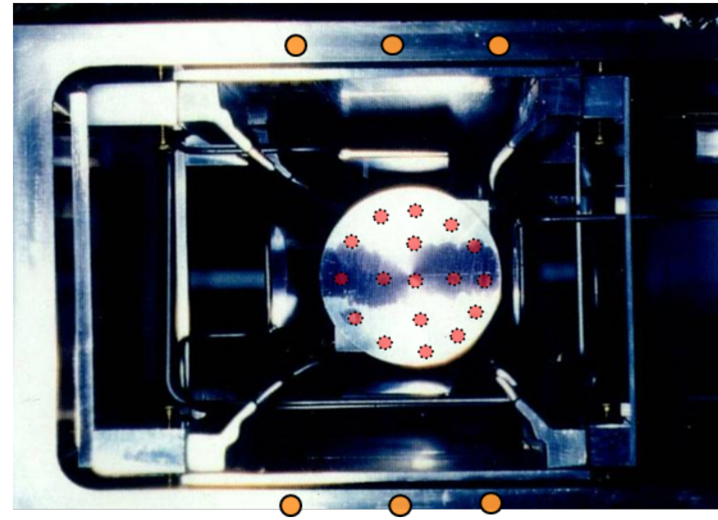


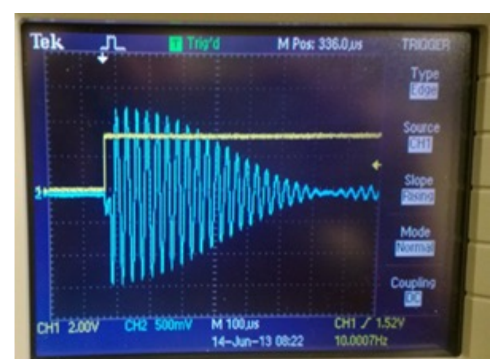
- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- μ enter storage ring


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

Measuring the magnetic field

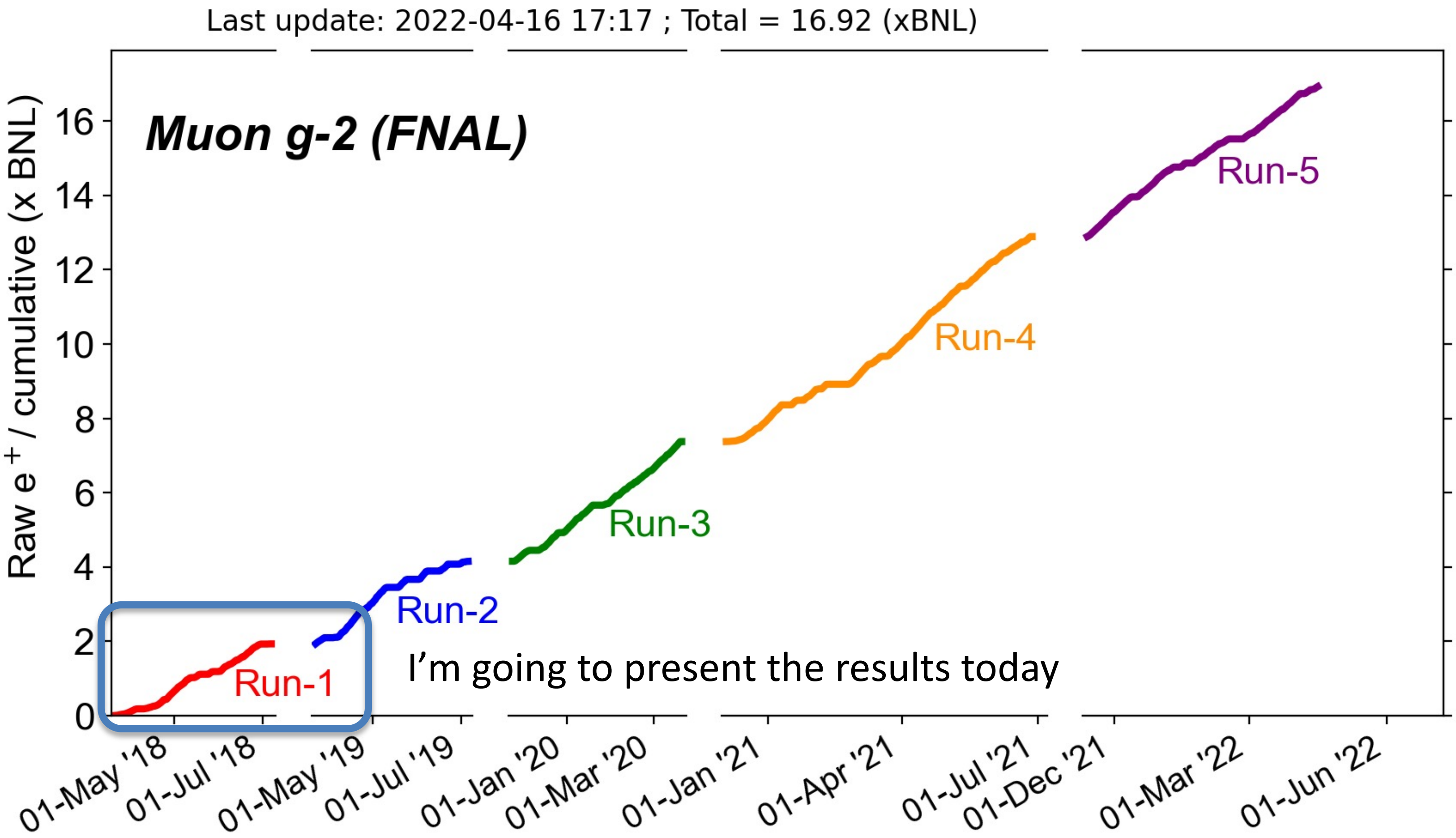
- 378 Fixed probes monitor field 24/7
- 17-probe NMR trolley maps the magnetic field over the muon storage region
  - Trolley runs every 2-3 days
- Free induction decay signal of the probes digitized and analyzed to extract a precession frequency





E989 collected data

We have collected ~16 x BNL over the last 4 years:



I'm going to present the results today

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

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

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

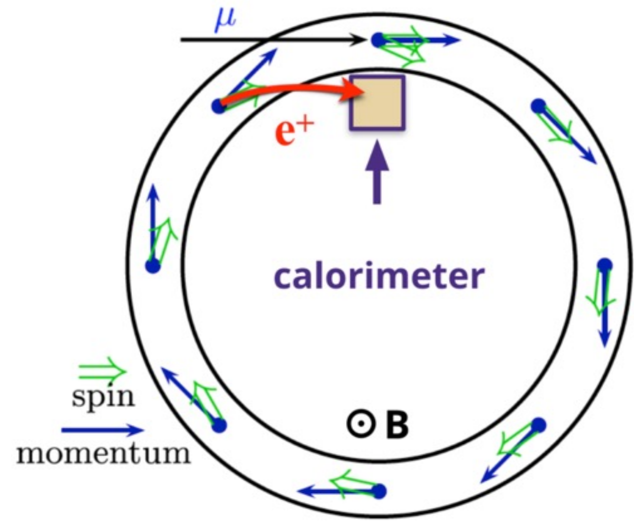
ω_a Measurement

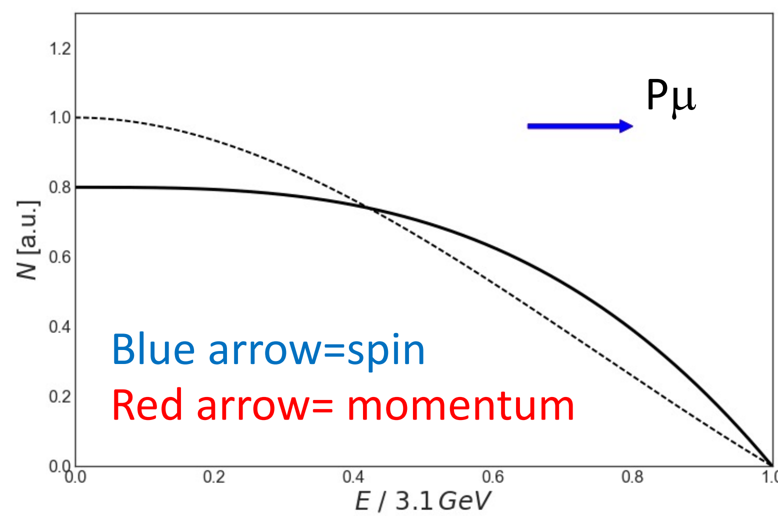
- The number of positrons is modulated by the anomalous precession frequency

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

- 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 fit equation

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

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

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

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

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

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

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

Red = free parameters

Blue= fixed parameters

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

Muon Loss term

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

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

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

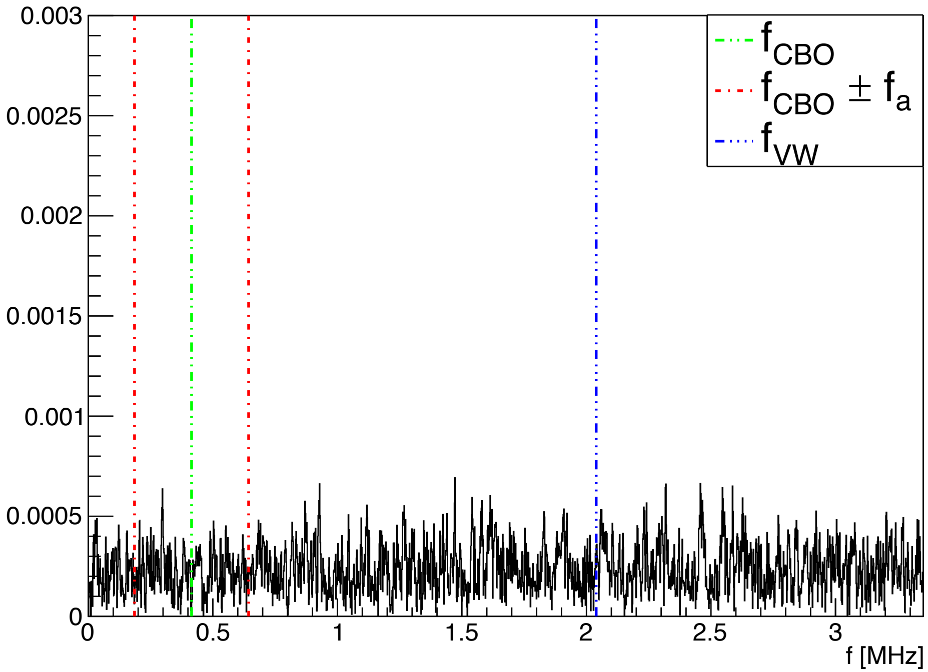
ω_y, ω_{vw} vertical oscillations

ω_{CBO}, ω_{2CBO}, radial oscillation

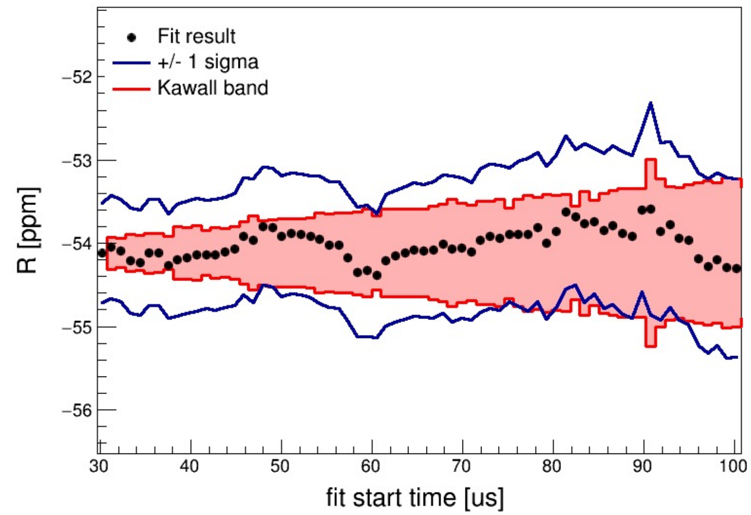
Final Fit

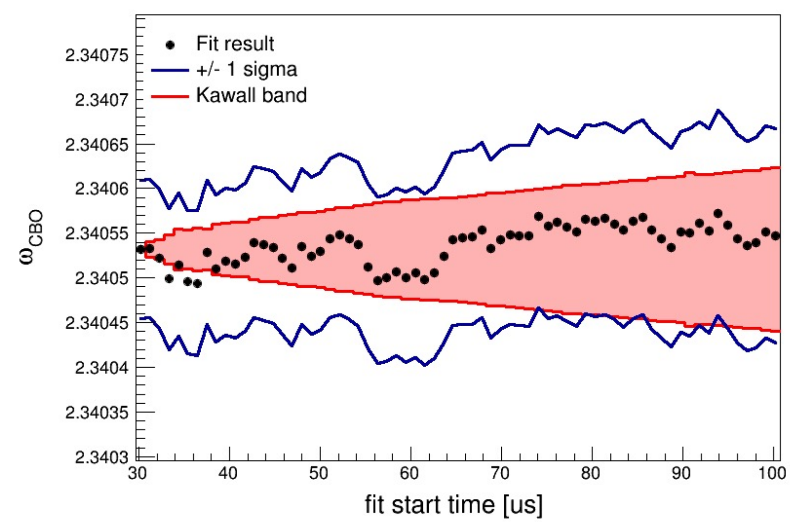
$R_{(blinded)} = \mathbf{(1 + \omega_{blind} / \omega_{ref})\ [ppm]}$

Fourier transform of residuals



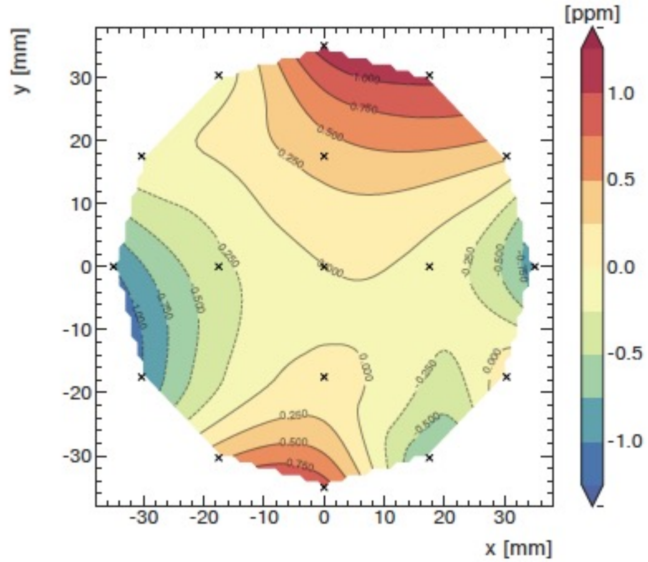
No unaccounted frequencies

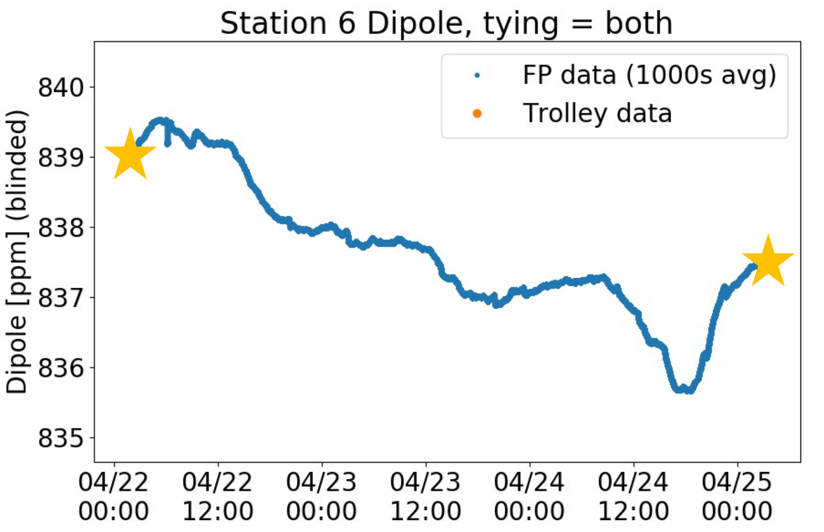




Measuring the magnetic field

- 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

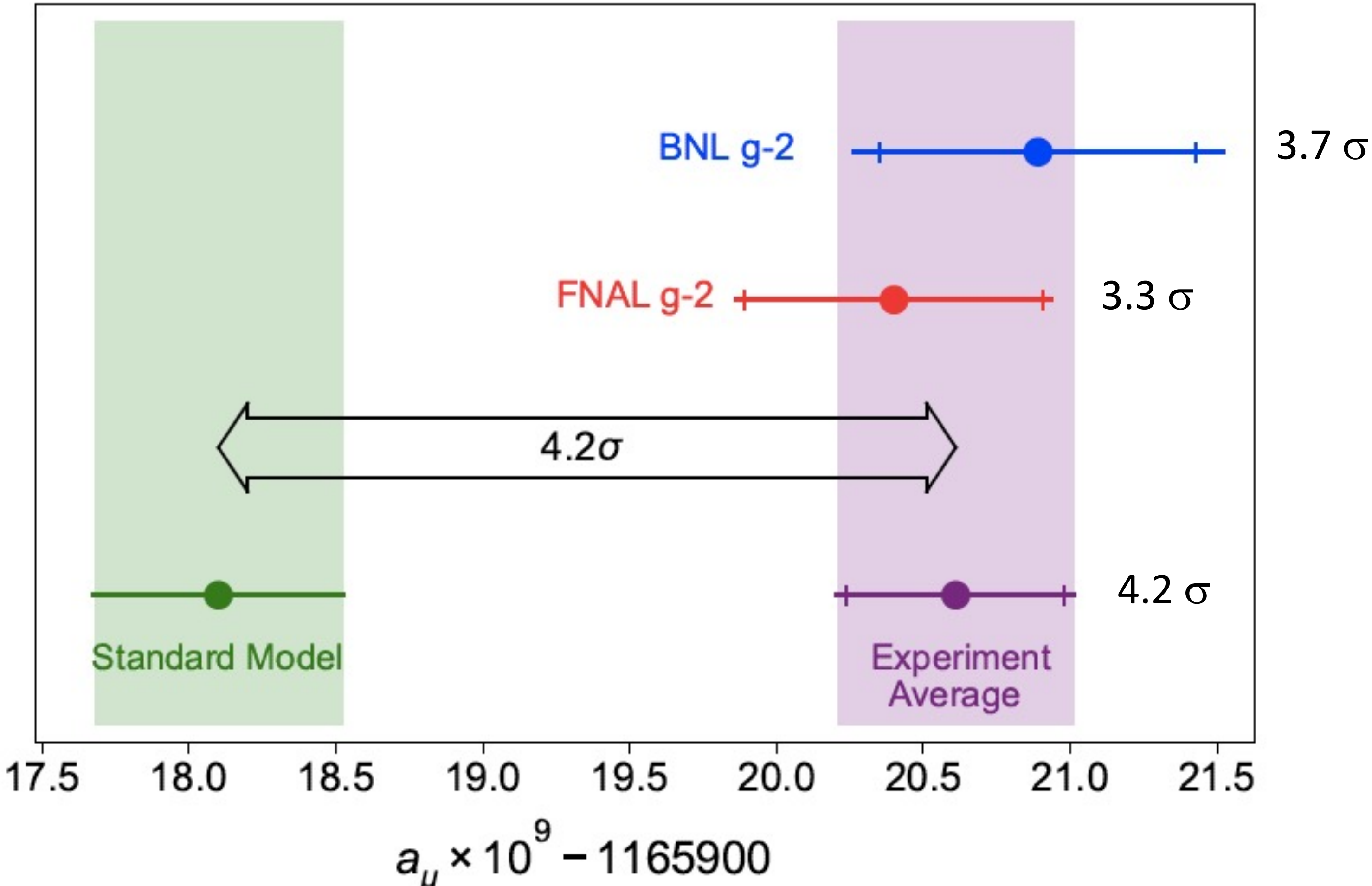




Result

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

$$a_\mu(\text{SM}) = 116\,591\,810(43) \times 10^{-11} \quad (0.37\,\text{ppm})$$ Th. Initiative WP20

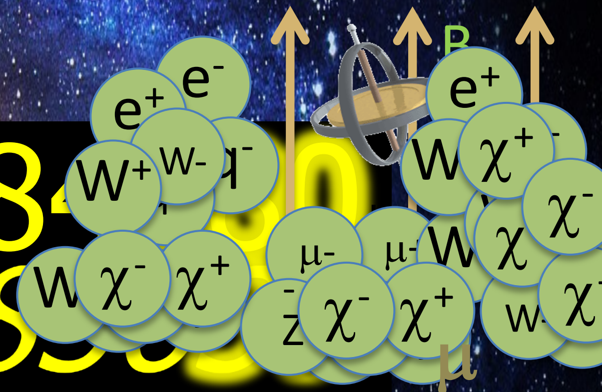


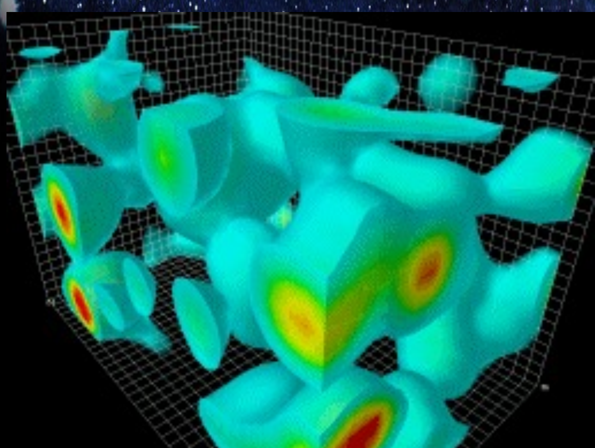
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

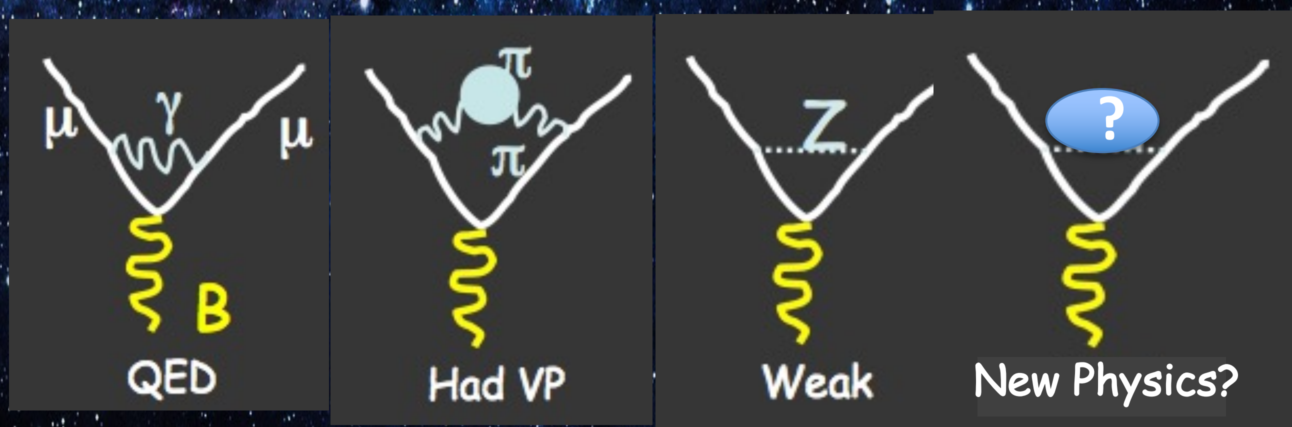
Are we seeing something new ?

g(expt) 2.00233184

g(theory) 2.0023318

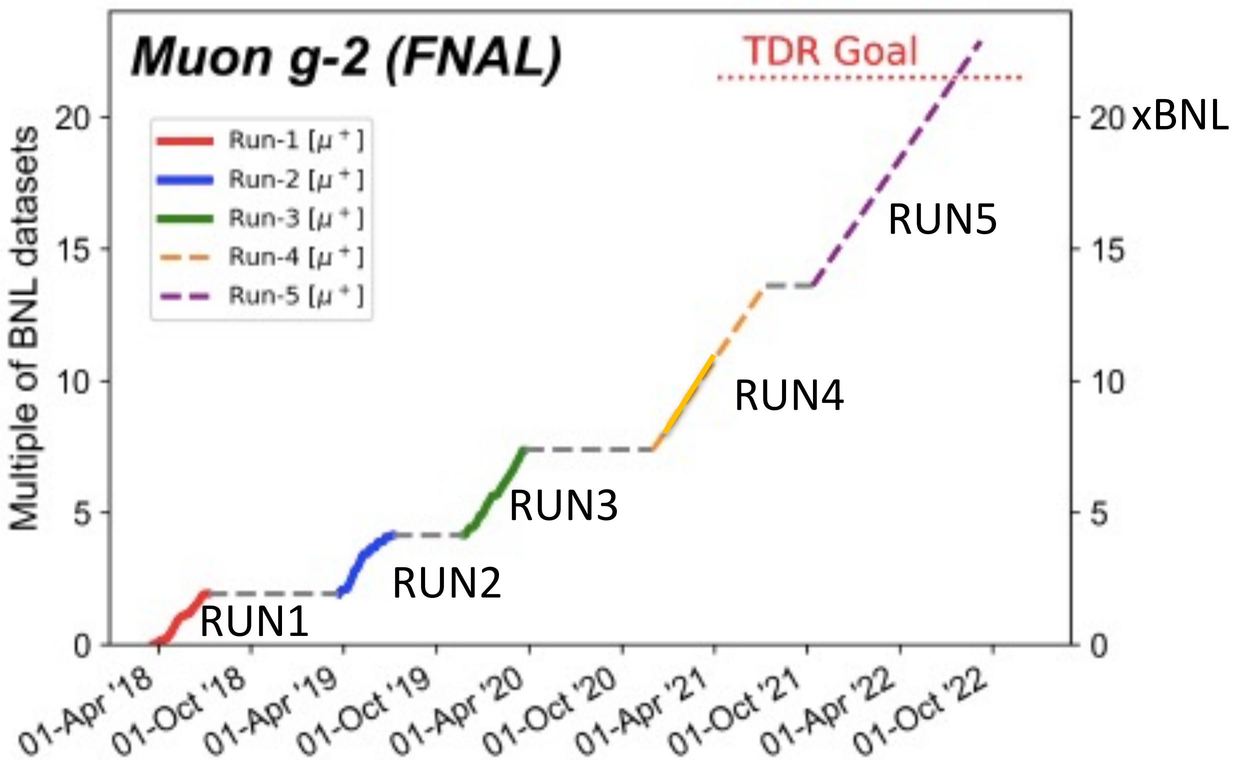




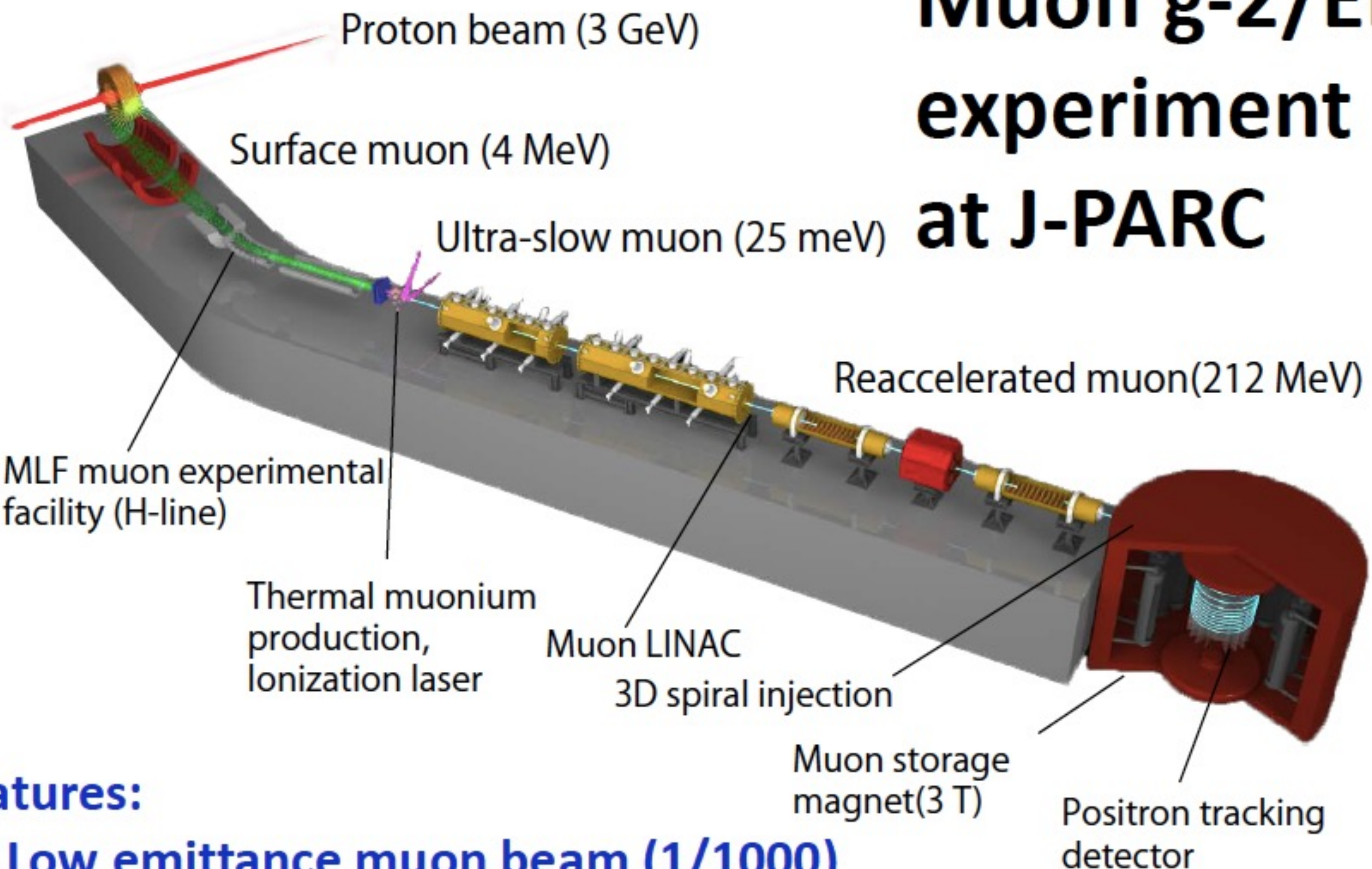


What awaits us

- RUN1 is only 6% of the final dataset
- Analysis of RUN2/3 ongoing. Results expected by early 2023 (~230 ppb uncertainty).
- RUN5 ongoing should allow to achieve the x20 BNL project goal
- RUN6 in 2022-2023 planned with μ-



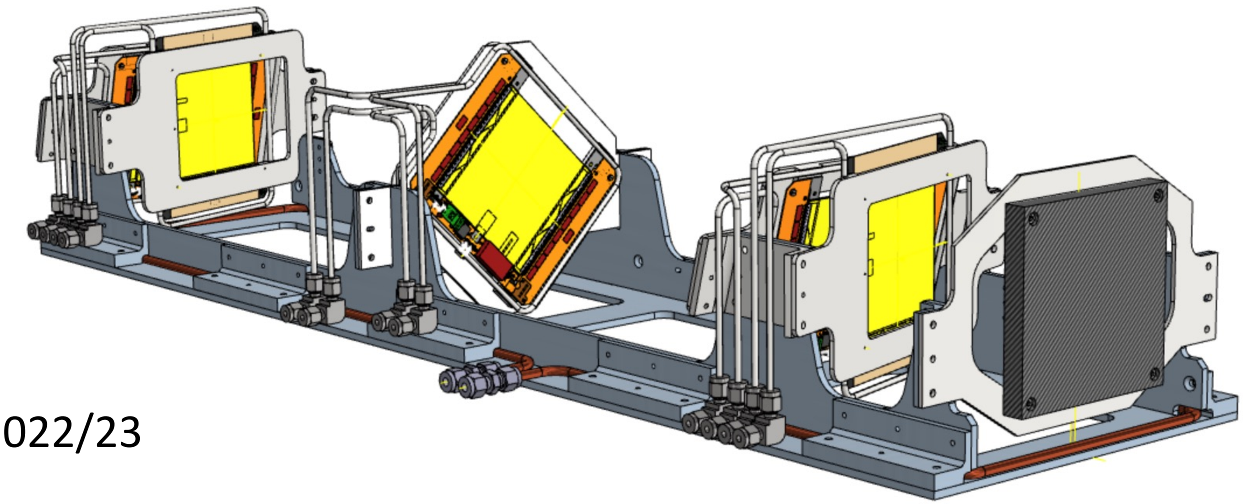
Muon g-2/EDM experiment at J-PARC



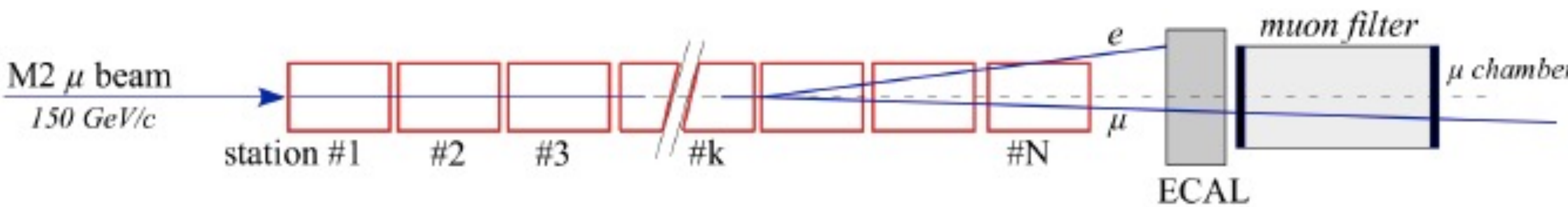
Features:

- **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**

A third way for HVP…MUonE at CERN



Test RUN 2022/23



Alternative measurement of HVP for a_μ

- *-C. M. Carloni Calame et al PLB 746 (2015) 325*
- *-G. Abbiendi et al Eur.Phys.J.C* 77 (2017) 3, 139
- -LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

Conclusions (with Paolo's words)

Paolo's presentation in 2001

Unsatisfactory points:

(4.2 σ (e+e-))

1. 2.6 σ is not very compelling and is also author dependent.
2. M-C is ~3×EW contribution. (~2) What about LEP, $b \to s\gamma$, M_W, M_{top}, $\Re(\epsilon'/\epsilon)$, sin2β...
3. Hadronic corrections difficult, *e.g.* light-by-light (also HVP!)
4. SUSY as a theory is not very precise at the moment. It has too many unknown, free parameters. There is no exp. evidence for it nor a prediction follows from the possible effect in the muon anomaly.

Soon better statistics and both signs muons.

Still very exciting at present.

Thanks!

The Muon g-2 Collaboration (Elba 2019)


ONE THING IS FOR SURE: THE HUNT IS ON, AND NEW DISCOVERIES ARE ON THE HORIZON.
Muon g-2 @ J-Park
Muon g-2 @ Fermilab
MUonE @ CERN
Theory Initiative
Stay tuned!

a_μ: Unblinding

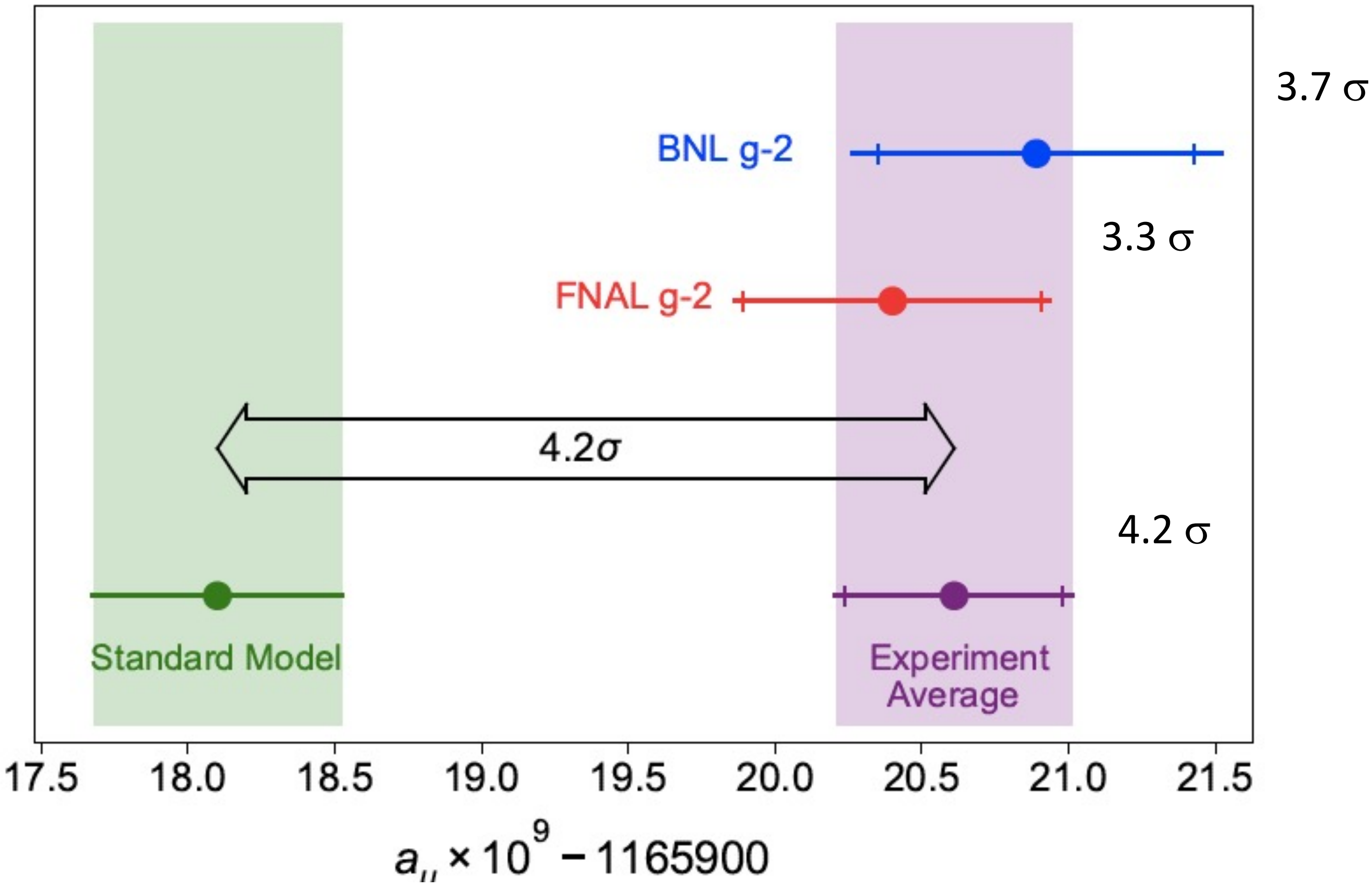
Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{calib}\langle\omega'_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_q	-17	92
B_k	-27	37
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total	–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

434 ppb stat $\oplus$ 157 ppb syst error

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

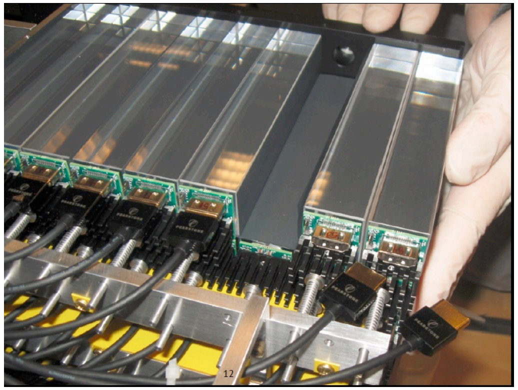
Result

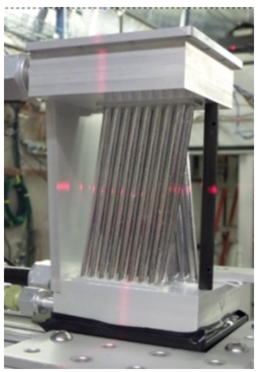
1:40000 chance that the SM is correct!

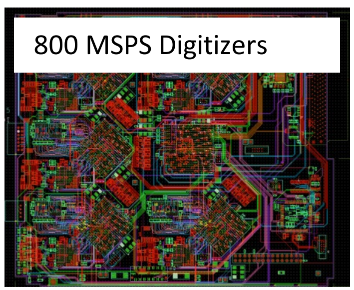


$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

Detector systems

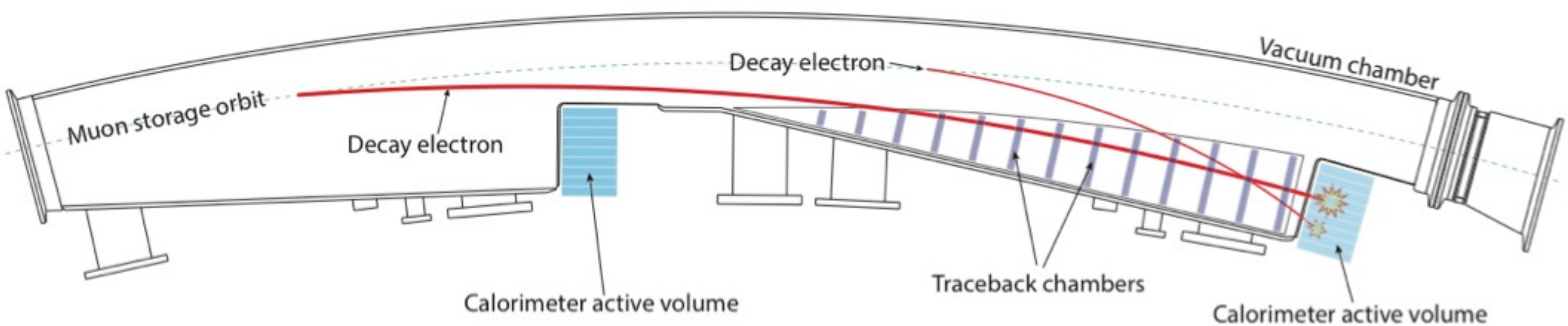






- Calorimeters: fast PbF_2 crystal arrays with SiPM readout → greatly reduce pileup
- State of the art laser calibration system
- WFD electronics → greatly reduced energy threshold
- Two straw tube trackers to precisely monitor properties of stored muons

Top view of 1 of 12 vacuum chambers



Extracting a_μ (more realistic)

Corrections due to beam dynamics

$$R'_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Corrections due to transient magnetic fields

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

What me measure

External inputs (known at 24 ppb)