Muon Precision Experiments

Mexican Workshop on Particles and Fields

21-25 Nov. 2022, Puebla, Mexico

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Outline :

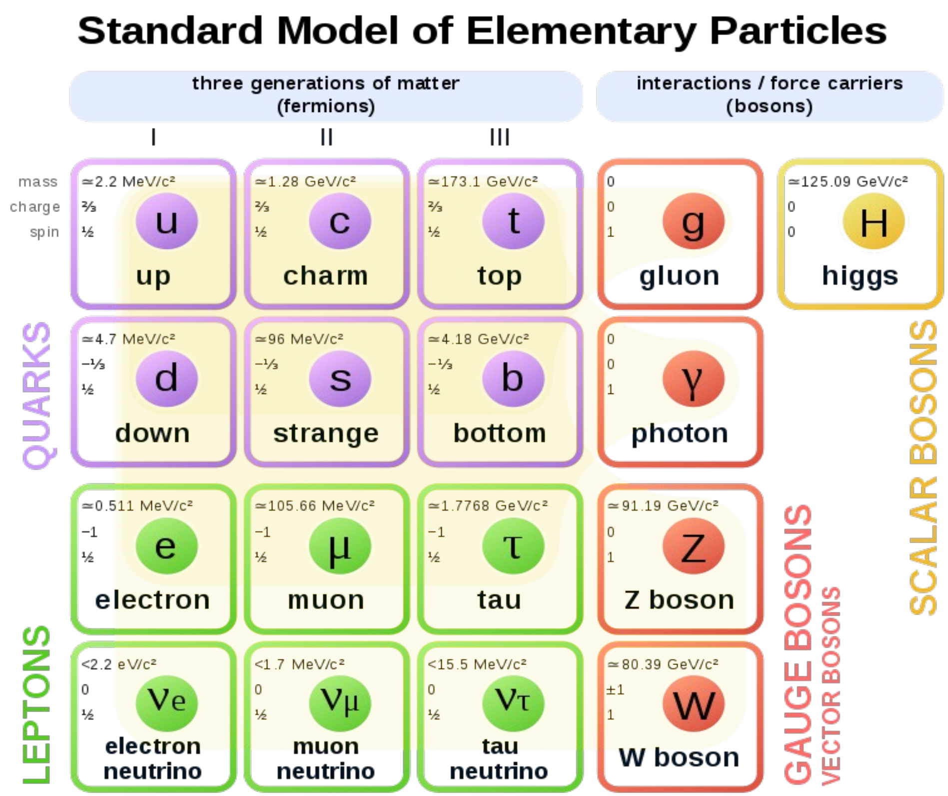
Muon properties
some history
looking for new physics

Muon Precision experiments
g-2, muEDM, CLFV

* I am not part of g-2 collaboration
** some material taken from, Graziano V. and Phillip S-W. workshop on Muon Precision Physics at Liverpool

The Standard Model

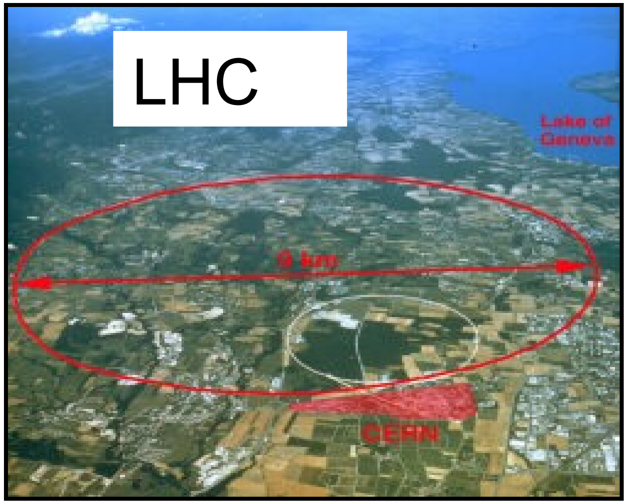
The Standard Model of elementary particles describes all known particles and their interactions via electromagnetic, weak and strong forces.



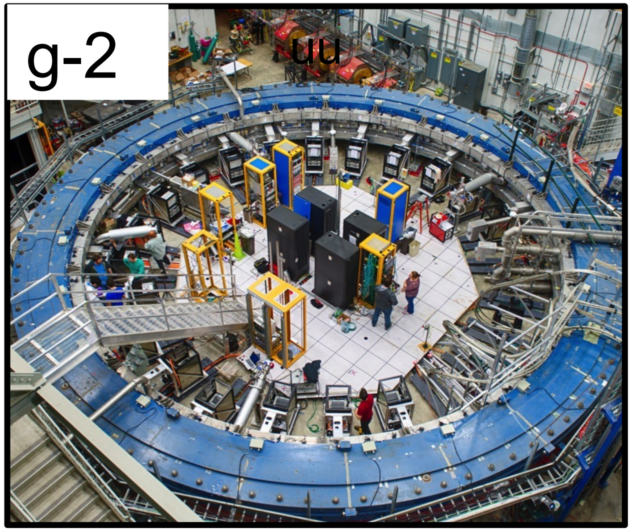
The particles which constitute all known matter are grouped in 3 families **but we do not know why**

Ways of looking for new hysics

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

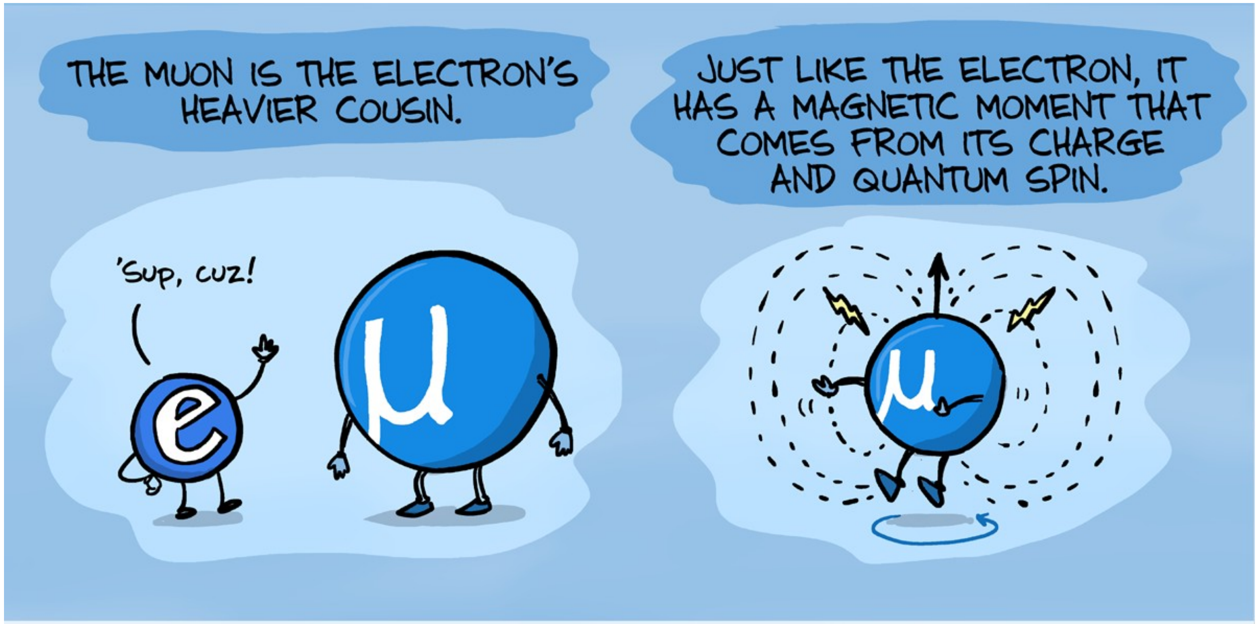


- **High Intensity:** through precision measurements, new low-energy physics effects are sought (deviations from theory). Small scale detectors and collaborations, very high statistics.
(g-2, muEDM, rare decay LFV exp.)



The Muon (μ)

The Muon is an elementary particle with similar characteristics as the electron, same electric charge but is ~200 times heavier. As the electron it has an intrinsic angular and magnetic moment



$m_{\mu} \sim 200\ m_e$, Lifetime ~2.2 μs, $S_{\mu} = 1/2$

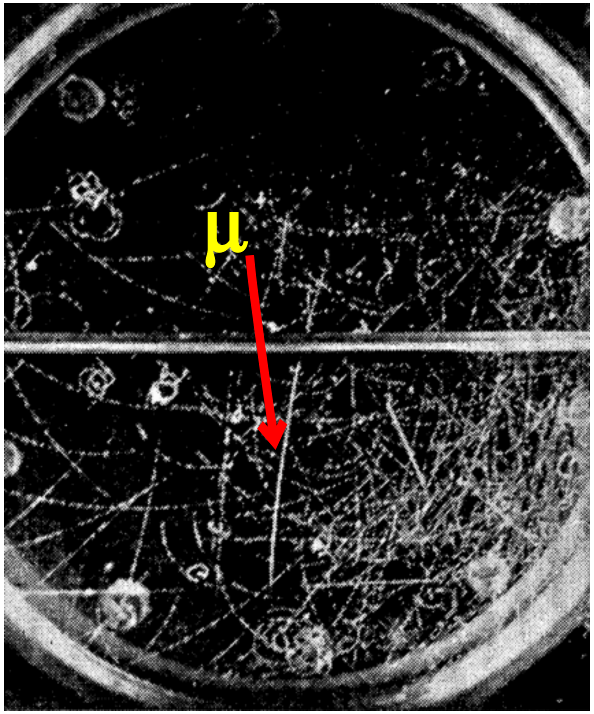
Muon Discovery (1936)

Seeth Neddermeyer

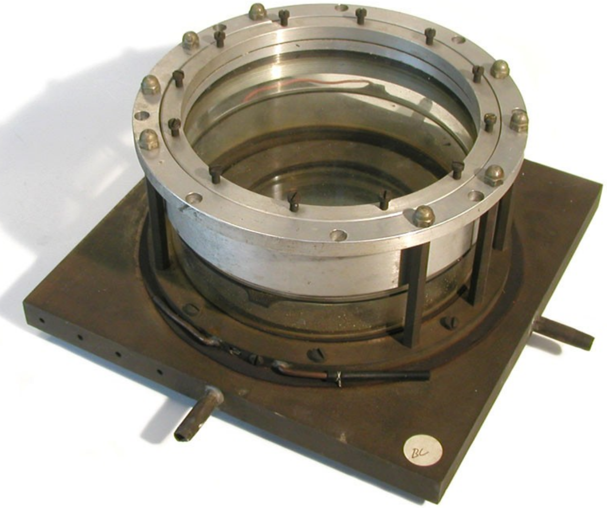
Carl Anderson

First observed in cosmic rays

Pike's Peak, CO



Muon trace in a cloud chamber (Anderson and Neddermeyer 1936)



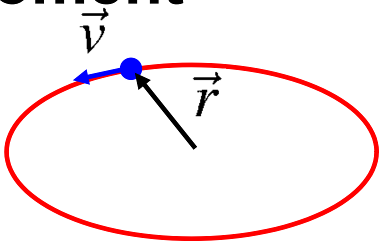
cloud chamber (1935)

For 10 years it was confused with the particle responsible for the nuclear force (Yukawa particle) and it was known as the mesotron

The Magnetic Moment

A charge particle in a plane orbit has:
angular momentum and **magnetic moment**

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



- The ratio $\frac{\vec{\mu}}{\left(\frac{q}{2m}\right)\vec{L}}$ is called gyromagnetic ratio **g**. Classically **g=1**
- For an elementary particle of Spin = 1/2 (e,m) Dirac equation predicts **g = 2**

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

- The **magnetic anomaly** is defined as **a = (g-2)/2.**

g = 2 $\rightarrow$ **a = 0** according to Dirac

Mesurement of g of the electron (1948)

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.

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

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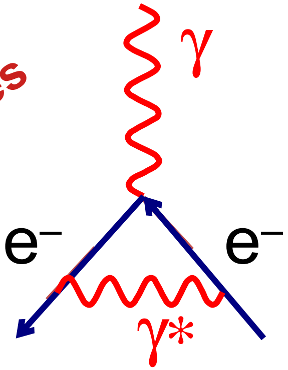
a= 0 according to Dirac

QED prediction
Amazing succes



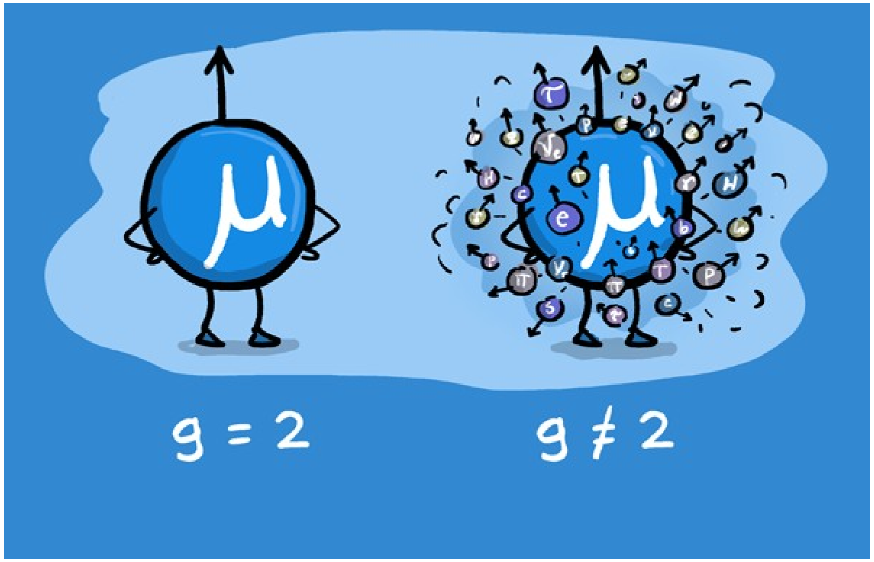
$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$

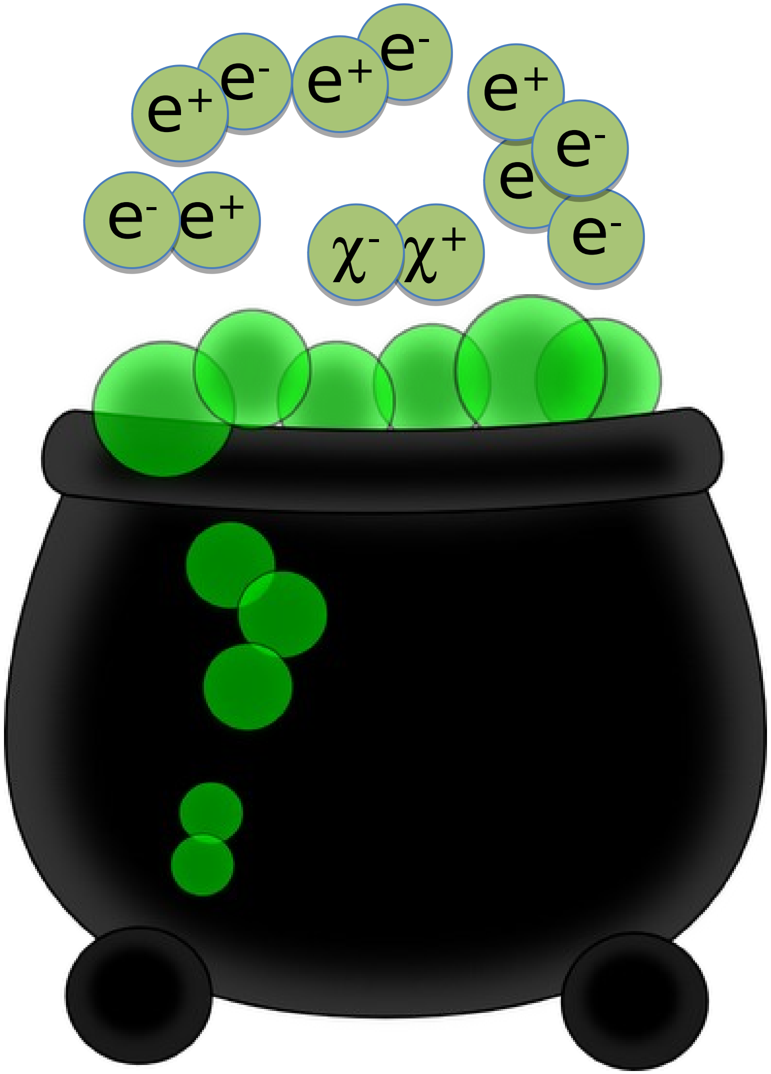
a>0; g>2

Quantum Vacuum

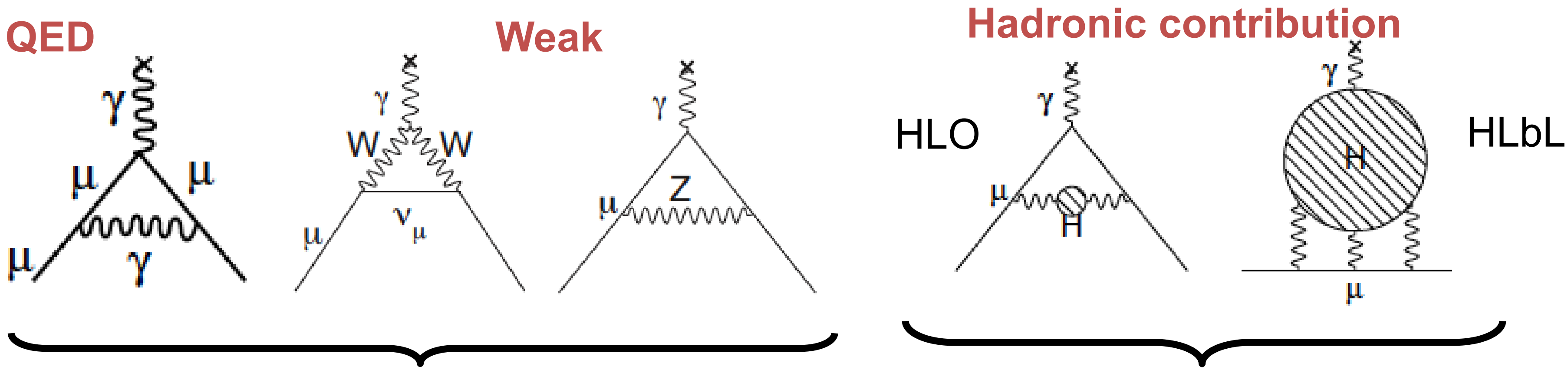
- The vacuum is filled with pairs of particles and antiparticles that exist for a very short time and are therefore called **virtual**.

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





a_μ = (g-2)/2 can be calculated very precisely



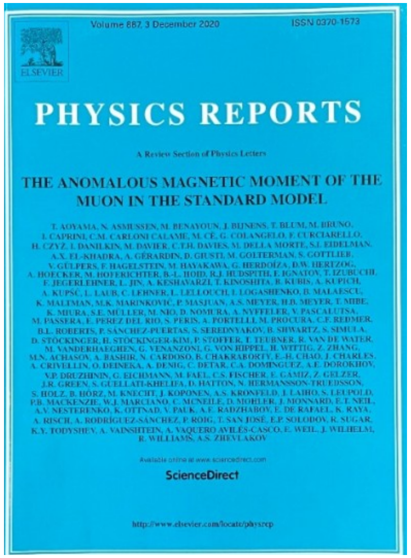
Precisely known

Large uncertainty
(significant work going on)

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

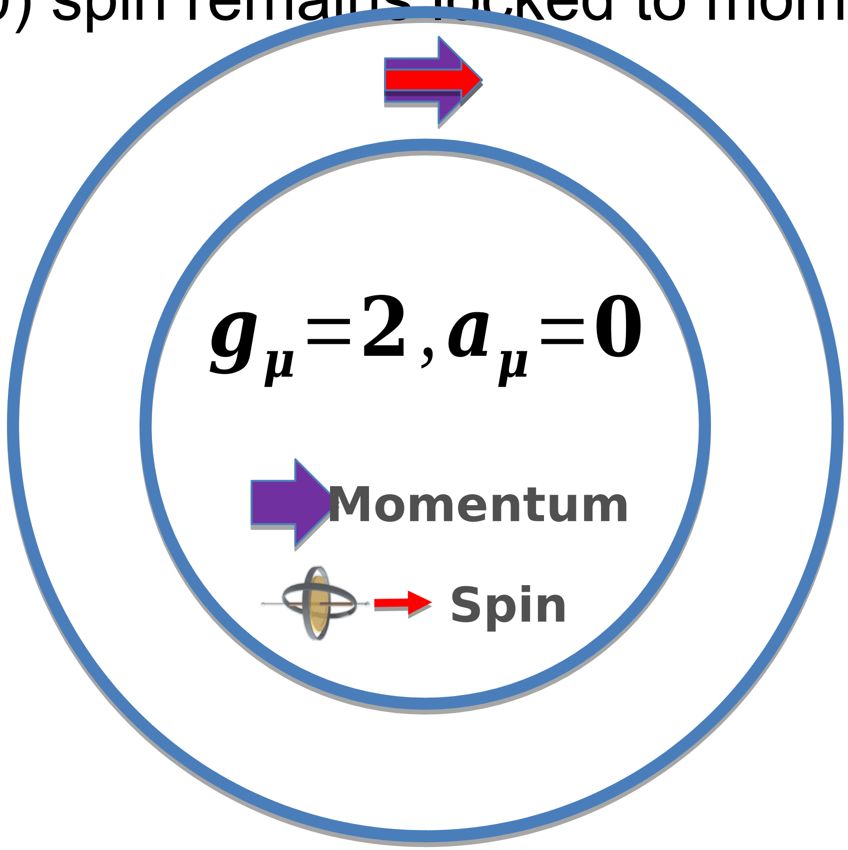
$$a_\mu(\mathrm{SM}) \ = 116\,591\,810(43) \times 10^{-11} \ (0.37\,\mathrm{ppm})$$

Theory Initiative (WP20): T. Aoyama et al. Phys. Rept. 887 (2020)



a_μ can be measured very precisely

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is: $$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$
- If g=2 (a=0) spin remains locked to momentum



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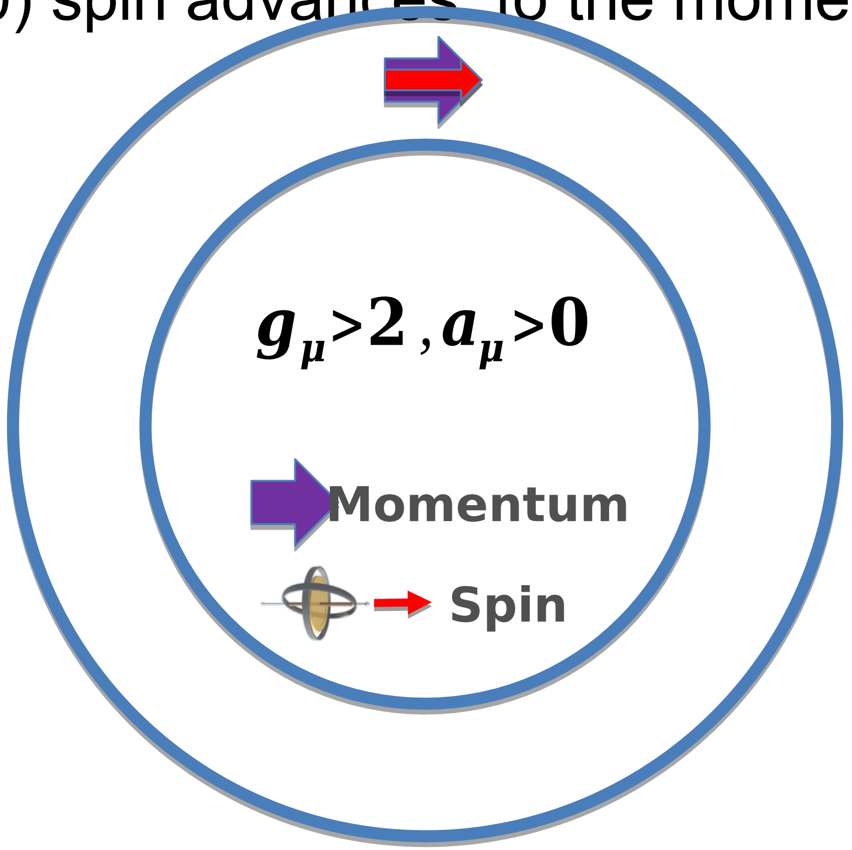
- The frequency with which the spin moves ahead of the momentum in a magnetic field B (anomalous precession frequency ω_a) is: $$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$
- If g>2 (a>0) spin advances to the momentum



Lets have a look at the history of muon g-2 experiments

The Muons in g-2 experiments

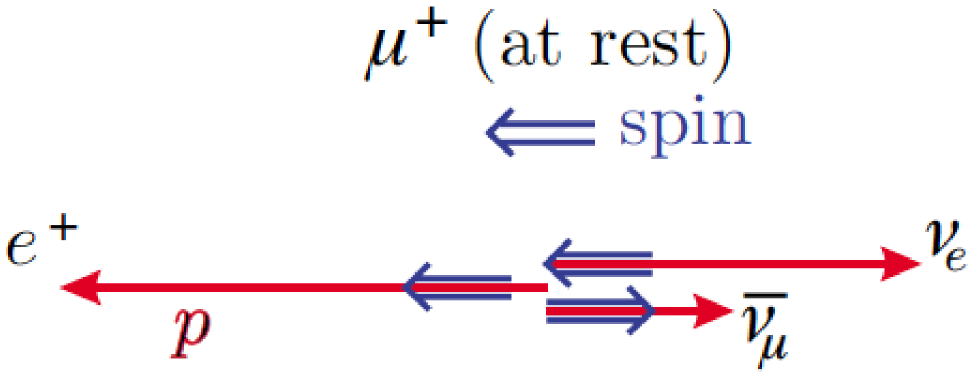
Muons are produced polarized in “forward” direction

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

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^-.

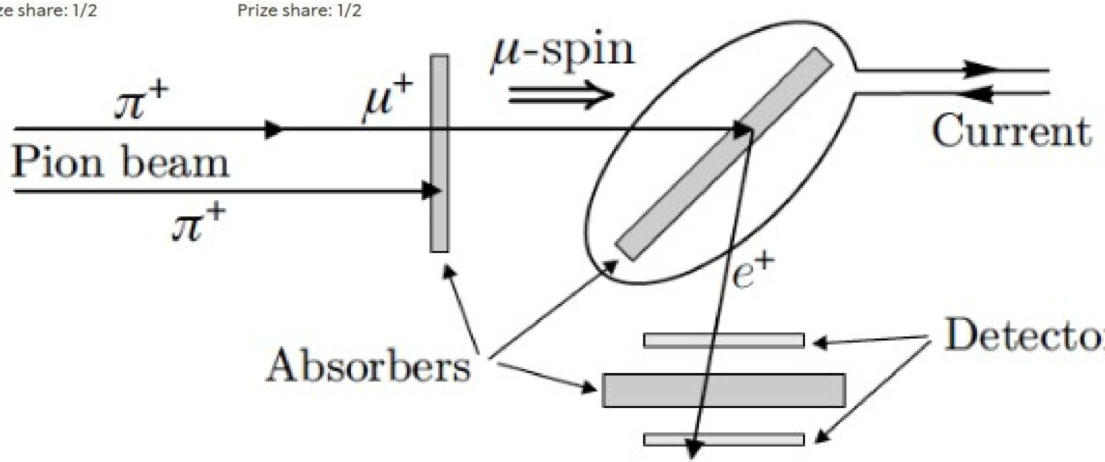
Detect high energy electrons. The time dependence of the signal tracks muon precession.

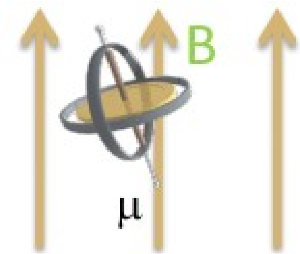
Lee and Yang 1956

Photo from the Nobel Foundation archive.
Chen Ning Yang
Prize share: 1/2

Photo from the Nobel Foundation archive.
Tsung-Dao (T.D.) Lee
Prize share: 1/2

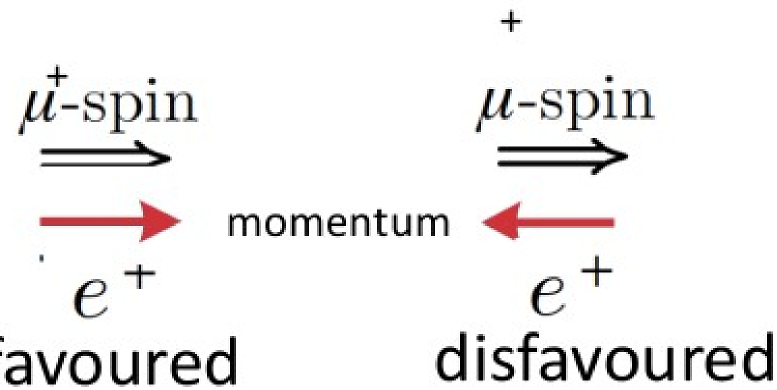
The parity violation in the production and decay of the muon offers a way to measure the muon magnetic moment





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

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

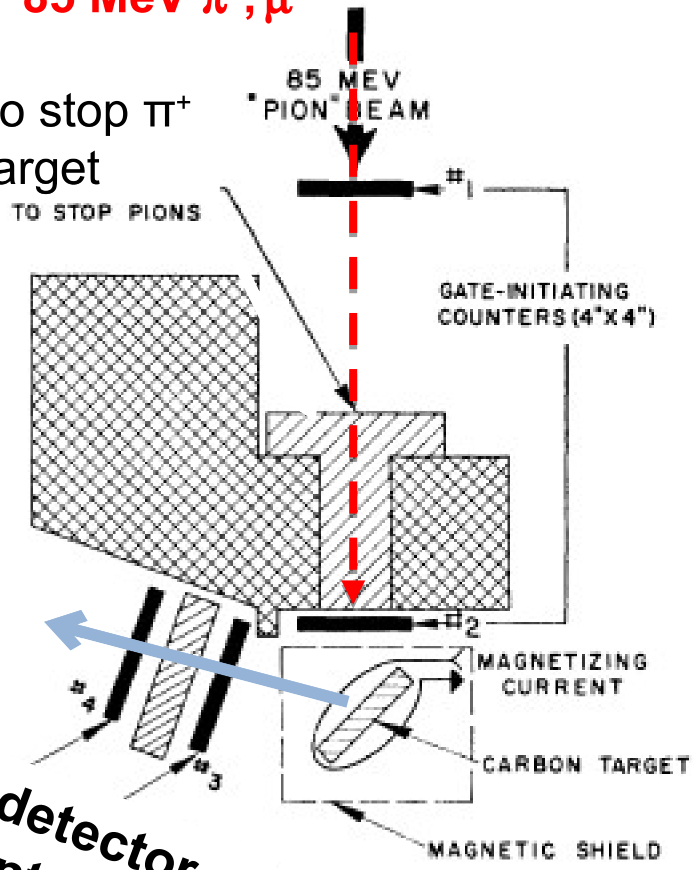


1957 First measurement of g_μ

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

85 MeV π^+, μ^+

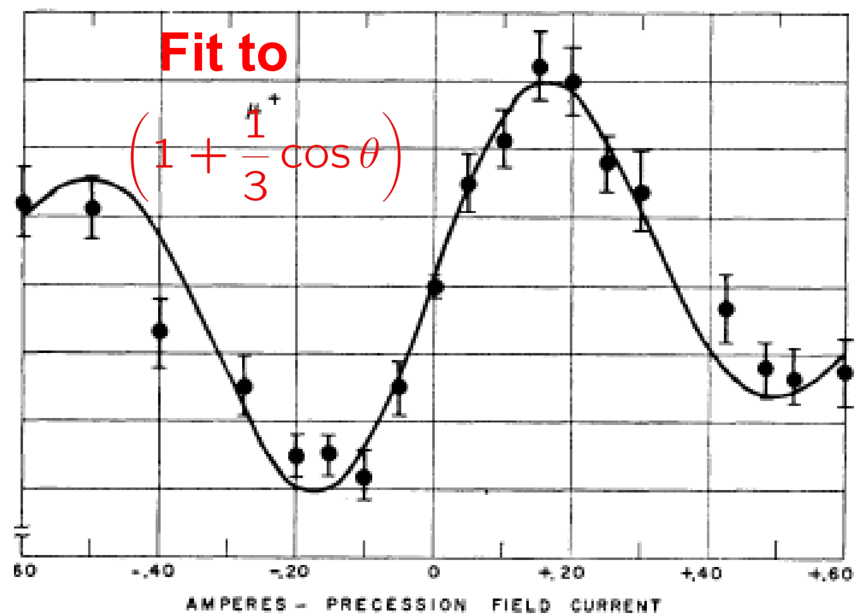
degrader to stop π^+ before C target



e+ detector counters

Direct measurement of g_μ

asym vs field



Fit to

$$\left(1 + \frac{1}{3}\cos\theta\right)$$

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

5% uncertainty

Cassels, et al. (Liverpool)1957

Stopped $\vec{\mu}^+$ from π^+ decays

- Counted e$^+$ decays vs. time in a 100.9 G B field.

$$g_\mu = 2.004 \pm 0.014$$

0.7% uncertainty

stopped μ then decay → e$^+$

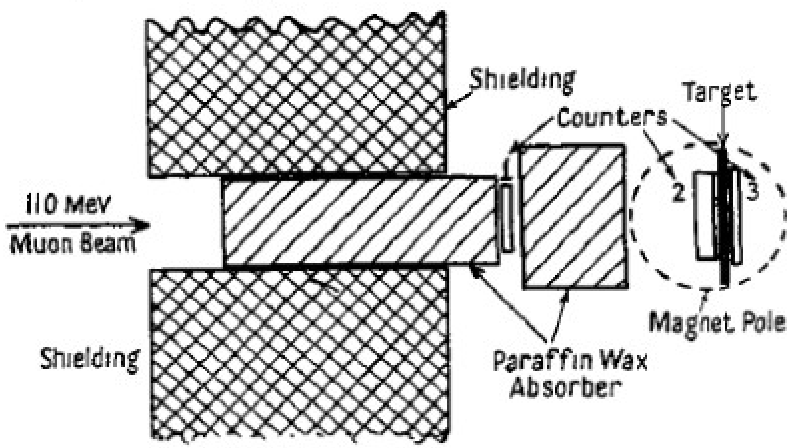
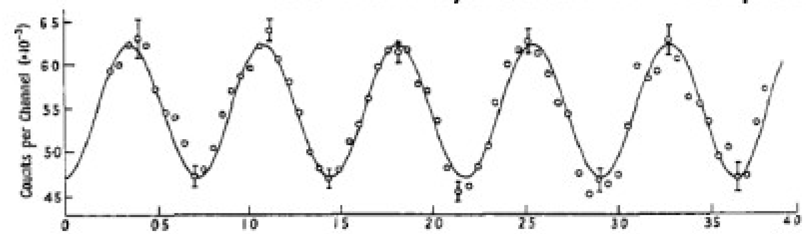


Figure 1 Layout of experimental apparatus

156 inch Cyclotron in Liverpool



exponential from τ_μ divided out

"The value of g itself should be sought in a comparison of the **precession** and **cyclotron** frequencies of muons in a magnetic field. The two frequencies are expected to differ only by the **radiative correction**" → Birth **of Storage Ring** method!

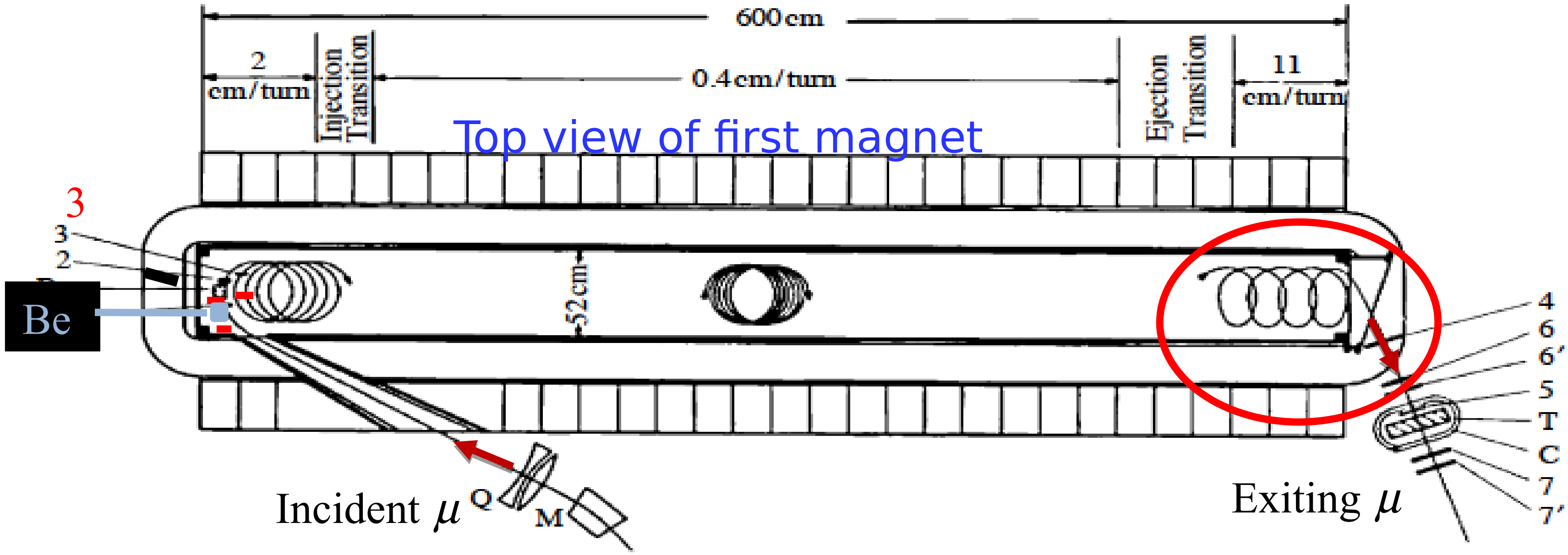
W. E. Bell and E. P. Hincks, Phys. Rev. 84, 1243 (1951)

Muon g-2 CERN experiments (1962-1979) measure the spin relative to the momentum

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

Exp. CERN I, 1958-1962

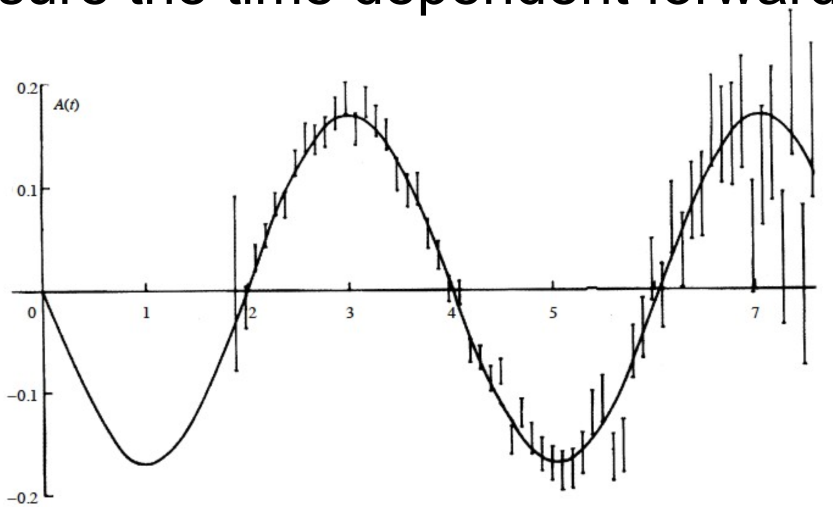
With 100 MeV/c muons



- 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 ms = 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

Exp. CERN I, 1958-1962

Measure the time dependent forward-backward decay asymmetry



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

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

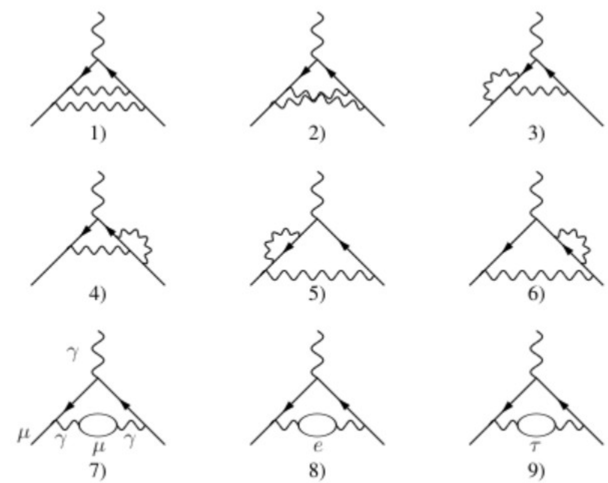
$\simeq 10^3\ \mu^+$ recorded

a_μ(expt) = 0.001162(5) **(4300 ppm)**

a_μ(theory) = 0.001165

Second order QED corrections

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



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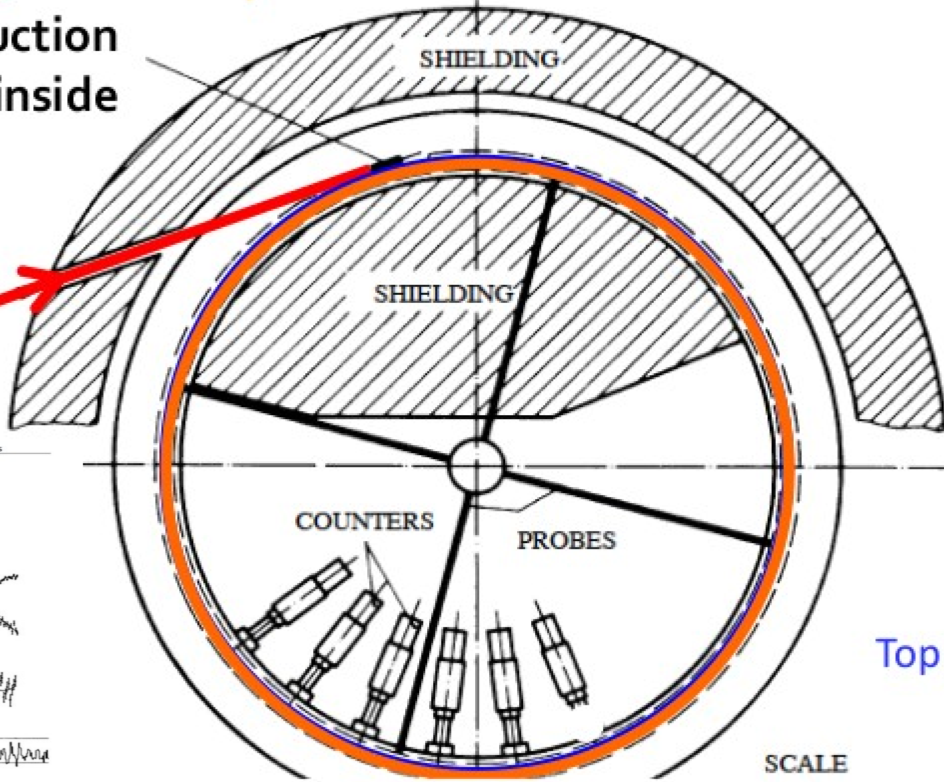
Exp. CERN II, 1962-1968
First Storage Ring

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

π production target inside

10.5 GeV/c Proton beam

Background flash in the counters was horrendous!



polarization 26%

Top view of the second magnet

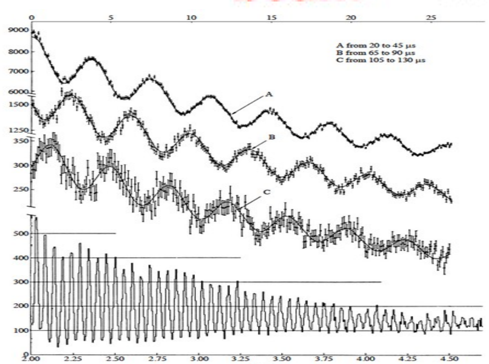


Fig. 17. The first muon storage ring: diameter 5 m, muon momentum 1.3 GeV/c, time dilation factor 12. The injected pulse of 10.5 GeV protons produces pions at the target, which decay in flight to give muons.

The Magic Momentum concept

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

3rd CERN exp. Needs electrostatic quadrupoles - but adds complications

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

$$(p_\mu = 3.09 \text{ GeV}/c)$$

If we choose $\gamma = 29.3$ then coefficient vanishes! The MAGIC momentum!

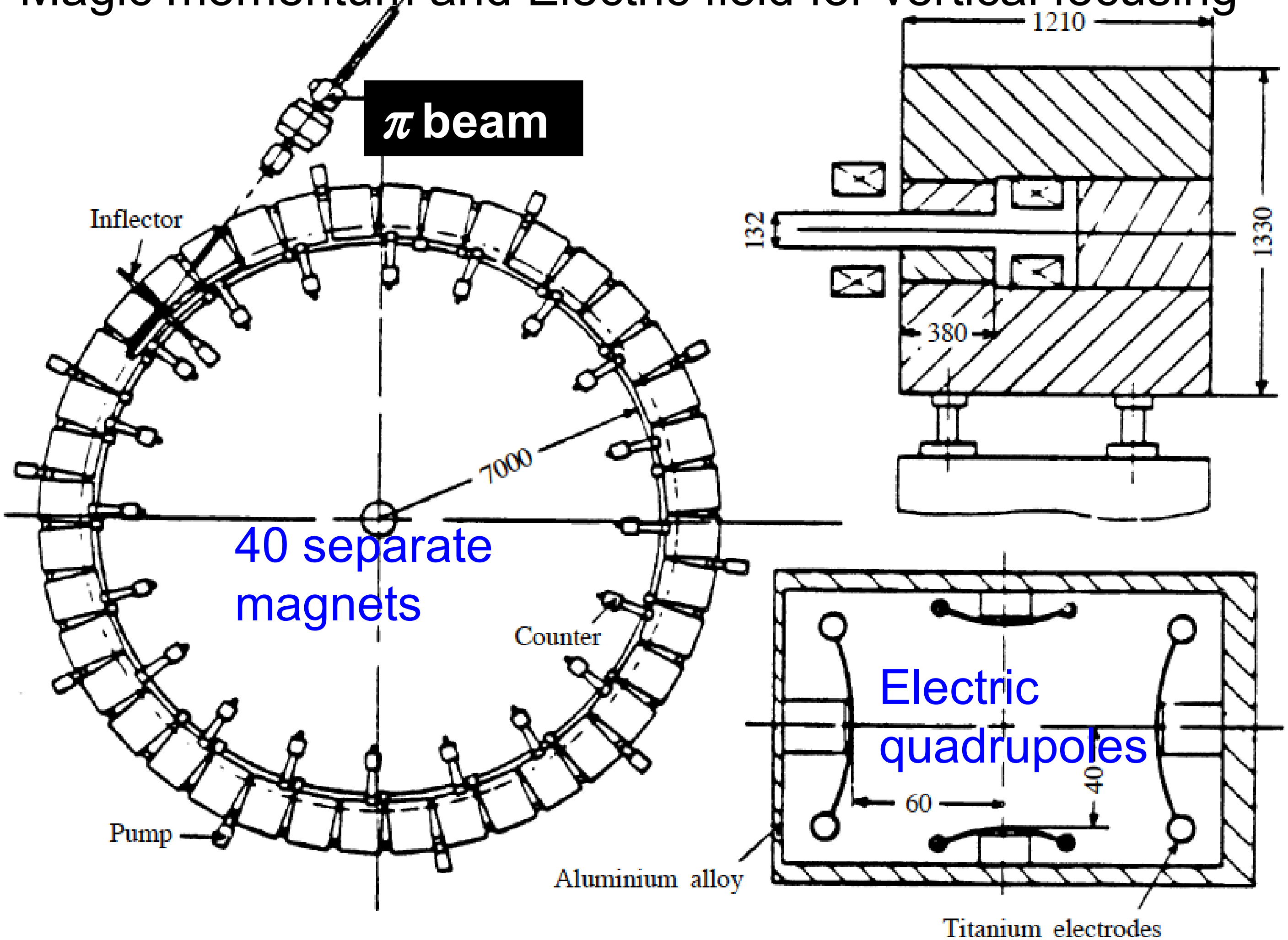
So we can worry less about the electric field (but still will need corrections)

Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

Exp. CERN III, 1969-1976

- Inject pions at 3.2 GeV
- Use $p \to m$ decay to kick muons onto stable orbits
- Magic momentum and Electric field for vertical focusing

Muon lifetime dilates to 64 μs



Still have pion flash at injection!

Not as bad as for CERN2

Exp. CERN III, 1969-1976

a_μ(expt) = 0.001165924(9) **(7.3 ppm)**

a_μ(theory) = 0.001165921(13)

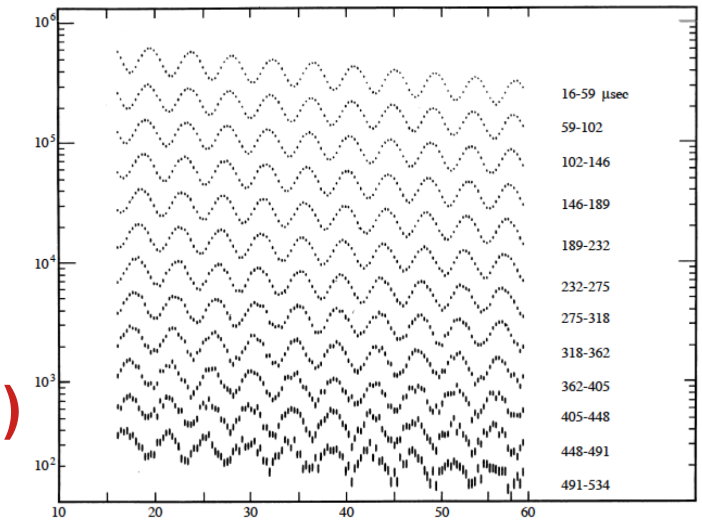
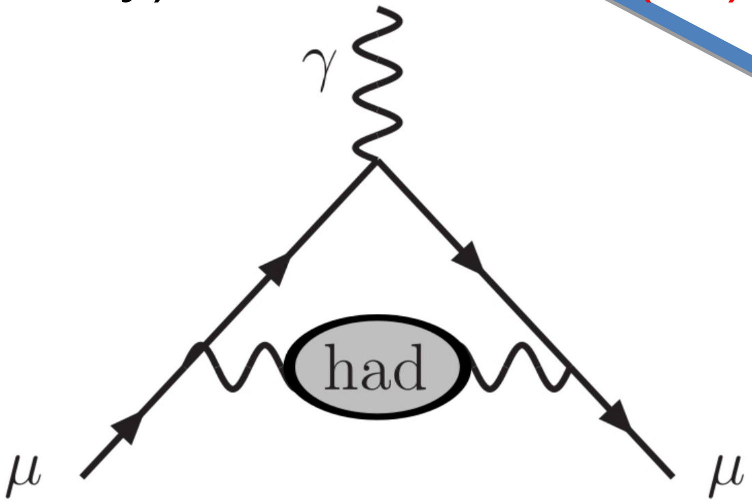


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).



HVP (hadronic vacuum polarization)

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

Muon g-2 experiments
@ BNL E821 (1984-2001)
@ FNAL E989 (2009-present)

Measurement of g-2 at BNL

In 1984 QED was calculated to fourth order
Hadronic uncertainties were greatly reduced
Time for new experiment at Brookhaven at sub ppm

Improvements:

Much higher intensity

3 superconducting coils

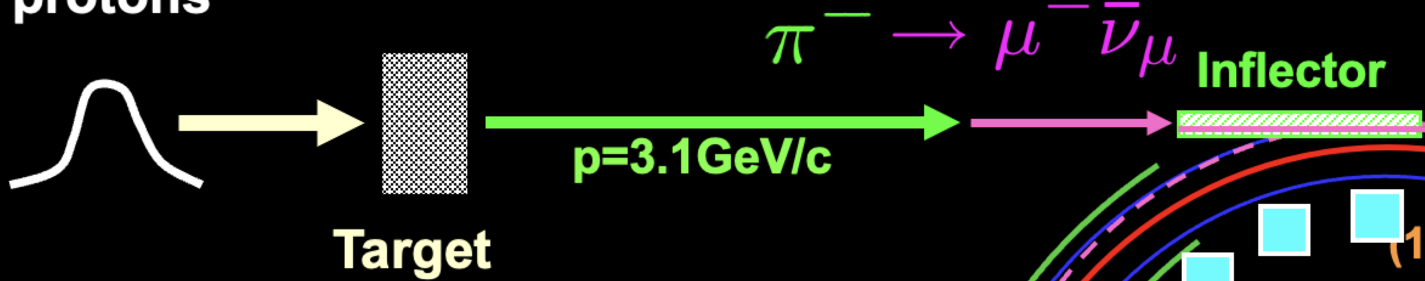
Circular aperture

Inject muons into ring with inflector and kicker

In-situ B measurements with NMR probes

E821 Experimental Technique

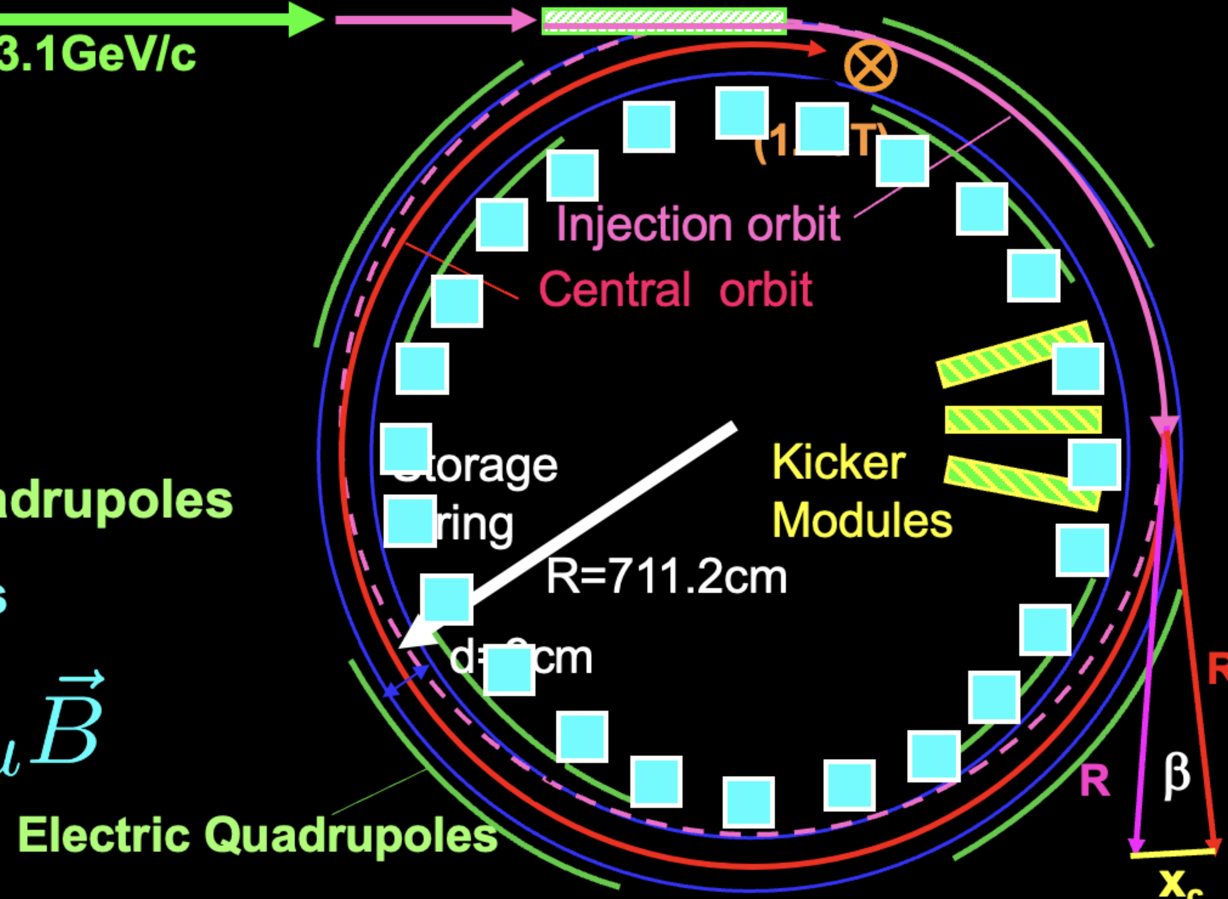
25ns bunch of $\geqslant$ 1 X 10^{12} protons



$x_c \approx$ 77 mm

$\beta \approx$ 10 mrad

B·dl $\approx$ 0.1 Tm

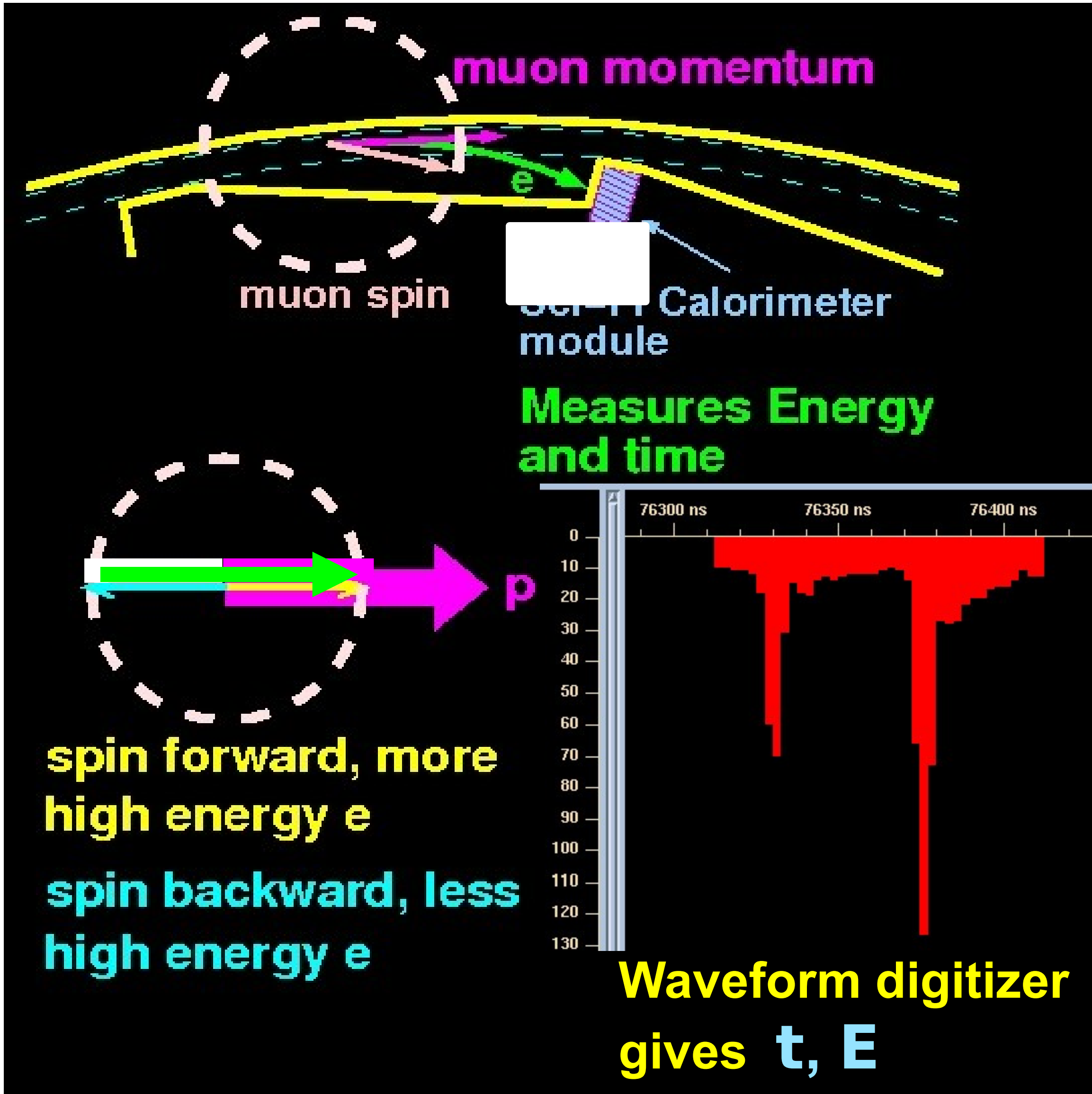


- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

E821 Experimental Technique

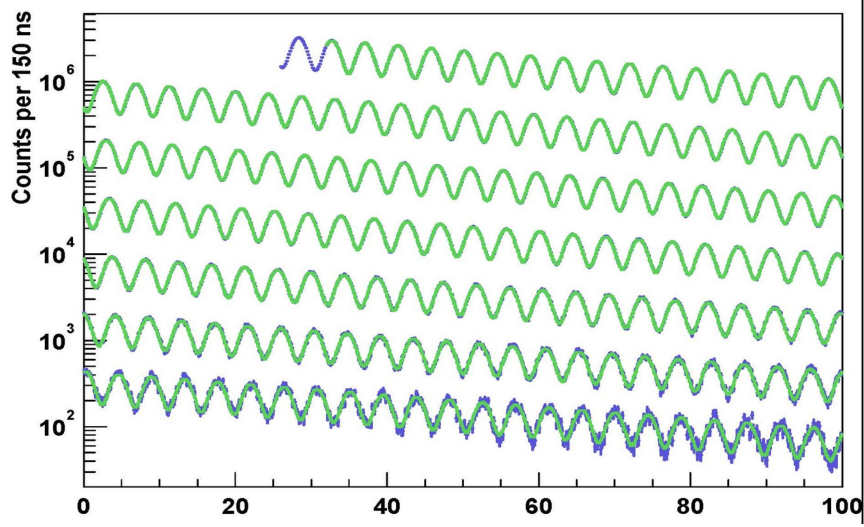
$e^{\pm}$ from $\mu^{\pm} \rightarrow e^{\pm} \nu \bar{\nu}$ are detected



Picture of a Lead-Scifi Calorimeter from E821

E821 at BNL, 1984-2001

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



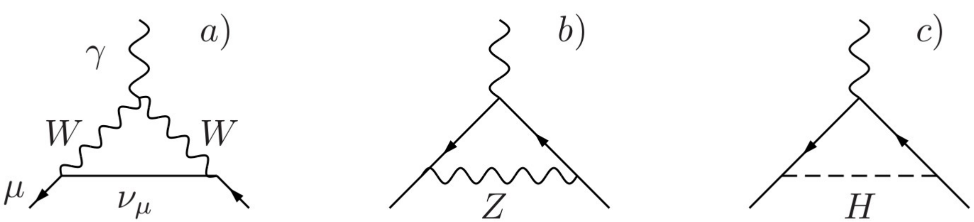
(2006)

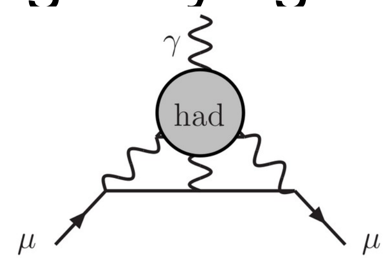
a_μ(expt) = 0.00116592089(63) **(0.54 ppm)**

a_μ(theory) = 0.00116591820(73)
(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)

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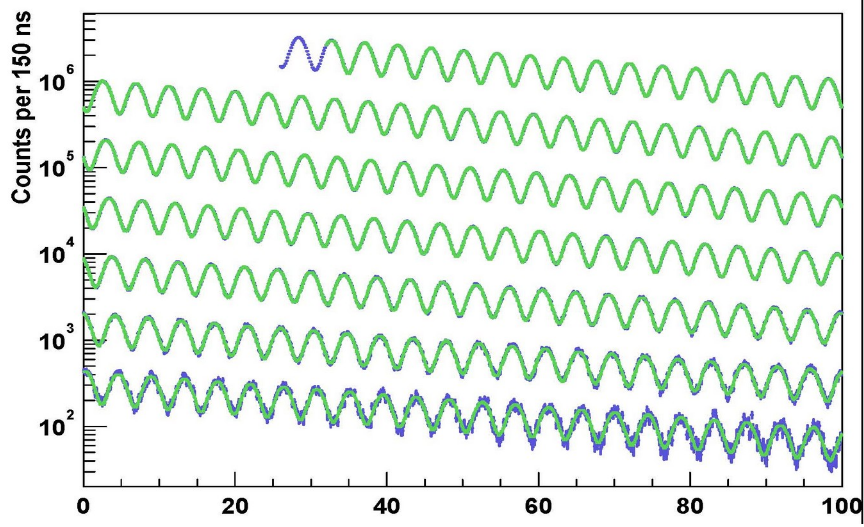
E821 at BNL, 1984-2001

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



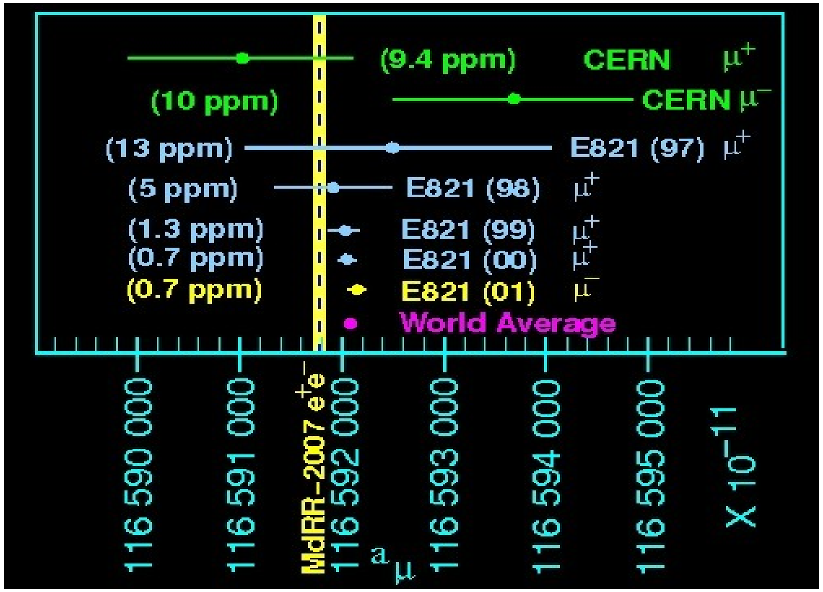
(2006)

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

a_μ(theory) = 0.00116591820(73)
(HMNT 03)

$$a_\mu^{BNL} - a_\mu^{SM} =$$
$$= (279 \pm 76)\times 10^{-11}\ (3.7\sigma)$$

~3 "standard deviations" with SM
→ Hint of new physics?



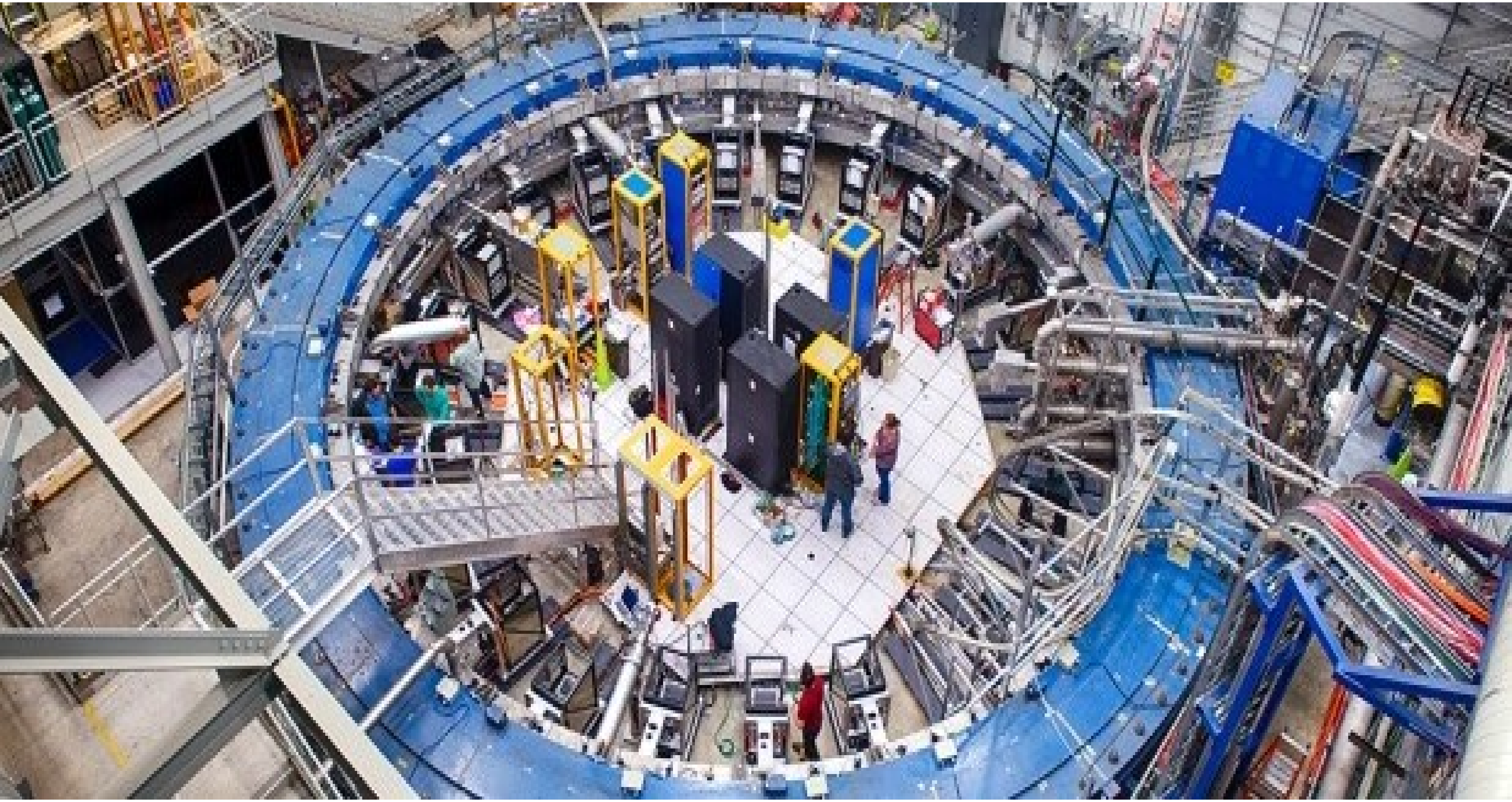
History of muon g-2 experiments (1960-2000)

The storage ring method was developed at CERN and improved at BNL through a series of experiments with increasing precision which allowed to test the SM at the level of strong (CERN) and EW (BNL) effects

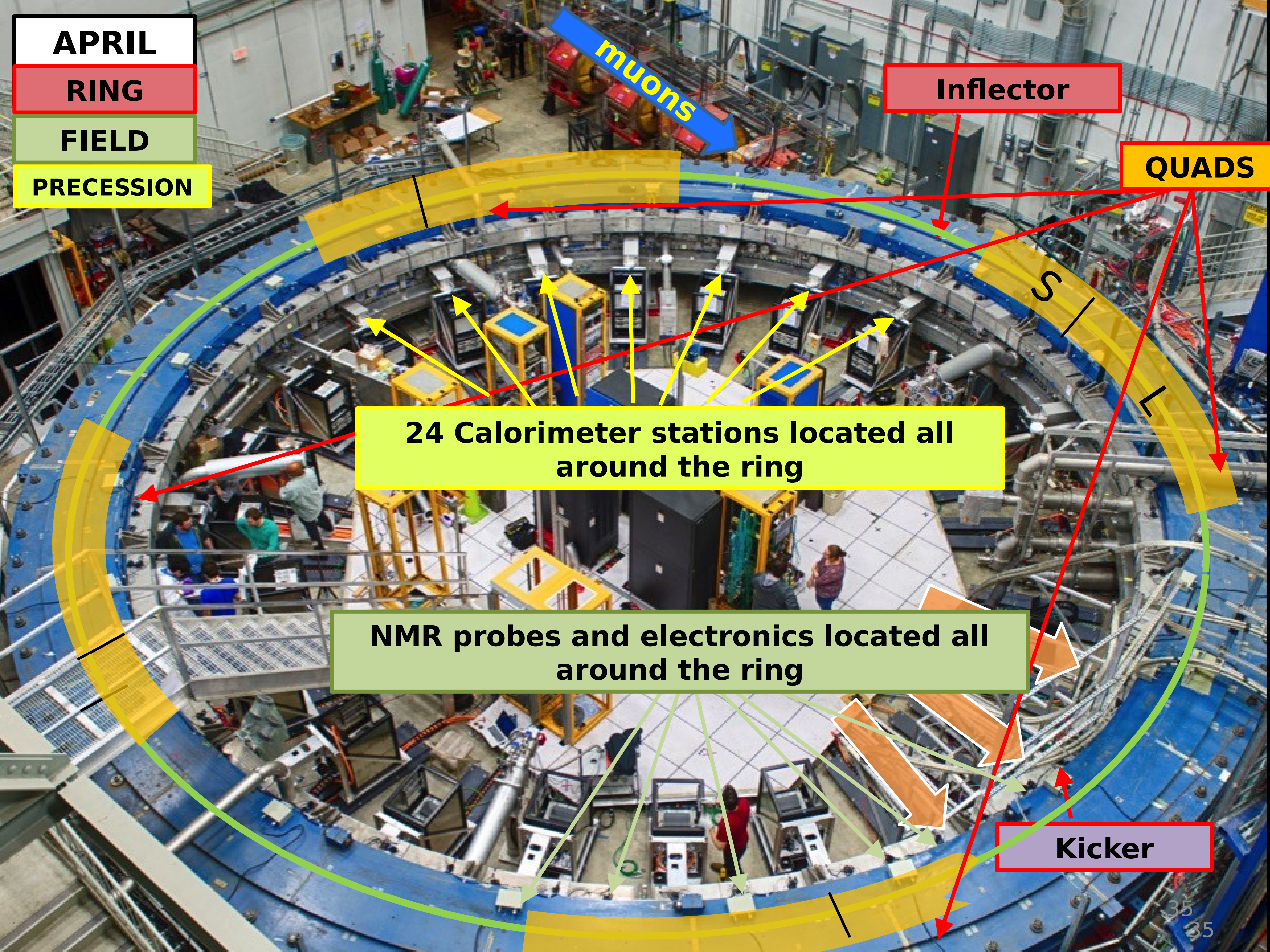
$\pm$	Measurement	σ_{a_μ}/a_μ	Sensitivity	Reference
μ^+	$g = 2.00 \pm 0.10$		$g = 2$	Garwin *et al*[30], Nevis (1957)
μ^+	$0.001\,13^{+0.00016}_{-0.00012}$	12.4%	$\frac{\alpha}{\pi}$	Garwin *et al*[33], Nevis (1959)
μ^+	0.001 145(22)	1.9%	$\frac{\alpha}{\pi}$	Charpak *et al*[34] CERN 1 (SC) (1961)
μ^+	0.001 162(5)	0.43%	$(\frac{\alpha}{\pi})^2$	Charpak *et al*[35] CERN 1 (SC) (1962)
$\mu^\pm$	0.001 166 16(31)	265 ppm	$(\frac{\alpha}{\pi})^3$	Bailey *et al*[36] CERN 2 (PS) (1968)
μ^+	0.001 060(67)	5.8%	$\frac{\alpha}{\pi}$	Henry*et al*[46] solenoid (1969)
$\mu^\pm$	0.001 165 895(27)	23 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[37] CERN 3 (PS) (1975)
$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[38] CERN 3 (PS) (1979)
μ^+	0.001 165 919 1(59)	5 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Brown *et al*[48] BNL (2000)
μ^+	0.001 165 920 2(16)	1.3 ppm	$(\frac{\alpha}{\pi})^4$ + Weak	Brown *et al*[49] BNL (2001)
μ^+	0.001 165 920 3(8)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[50] BNL (2002)
μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51] BNL (2004)
$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51, 26] BNL WA (2004)

J. Miller, E. De Rafael, L. Roberts, Rept. Prog. Phys. 70 (2007) 795

Muon Storage Ring at FNAL, 2009-present



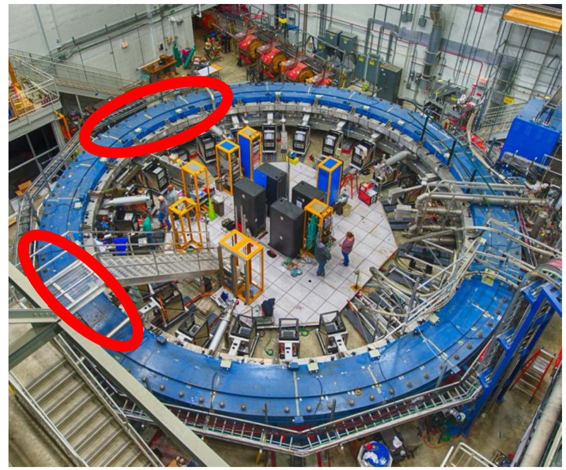
June 2013, Ring leaves BNL for FNAL

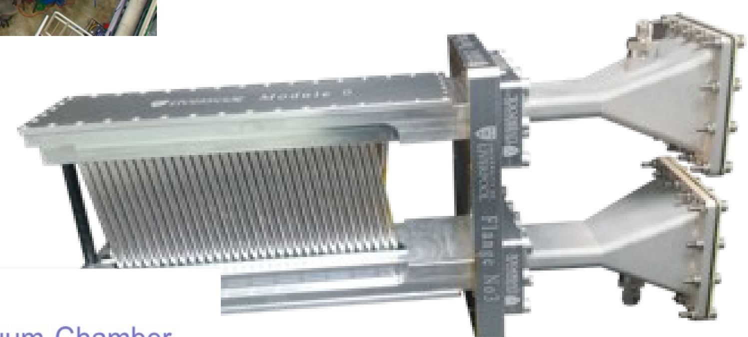

APRIL
RING
FIELD
PRECESSION
muons
Inflector
QUADS
S
L
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

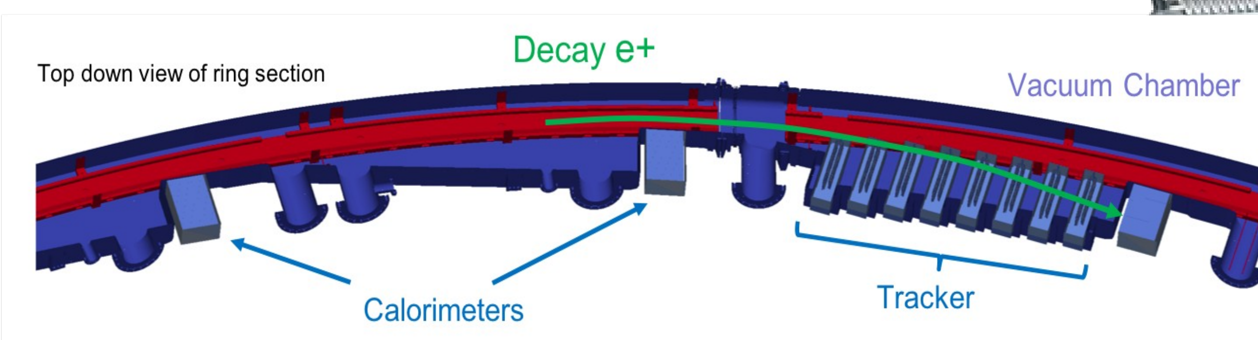
35

Tracking detector

- ➔ Two in-vacuum tracking stations at 180 and 270
- ➔ One station = 8 modules
- ➔ One module = 128 gas-filled straws, arranged in 4 layers
- ➔ Measure trajectory of decay e+ to reconstruct muon beam profile







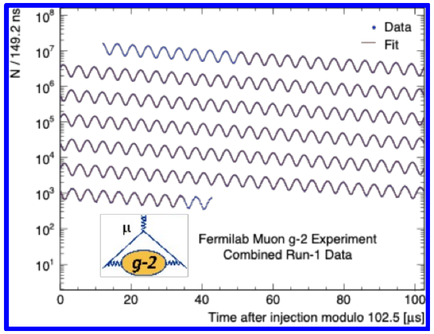
128 straws
10 cm long
15 um Al-coated mylar

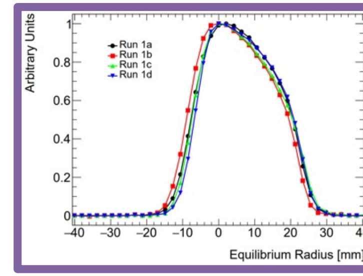
How is g-2 measured?

What we measure

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

Well-known quantities





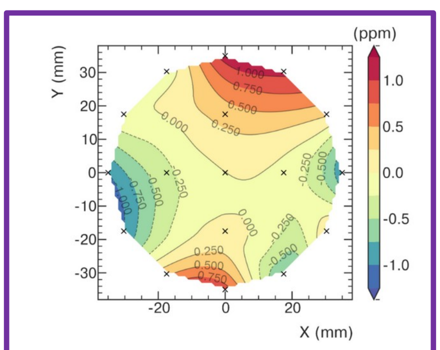
Muon precession frequency

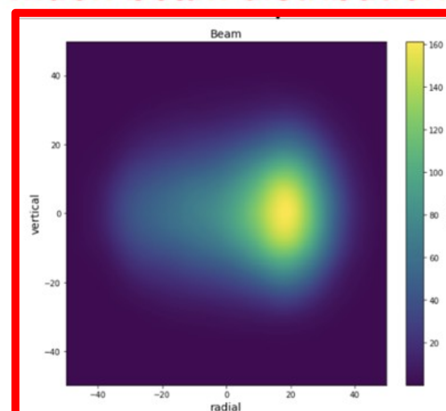
Beam dynamics corrections

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\, \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Magnetic field (proton precession frequency)

Muon beam distribution





Key points for g-2 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

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

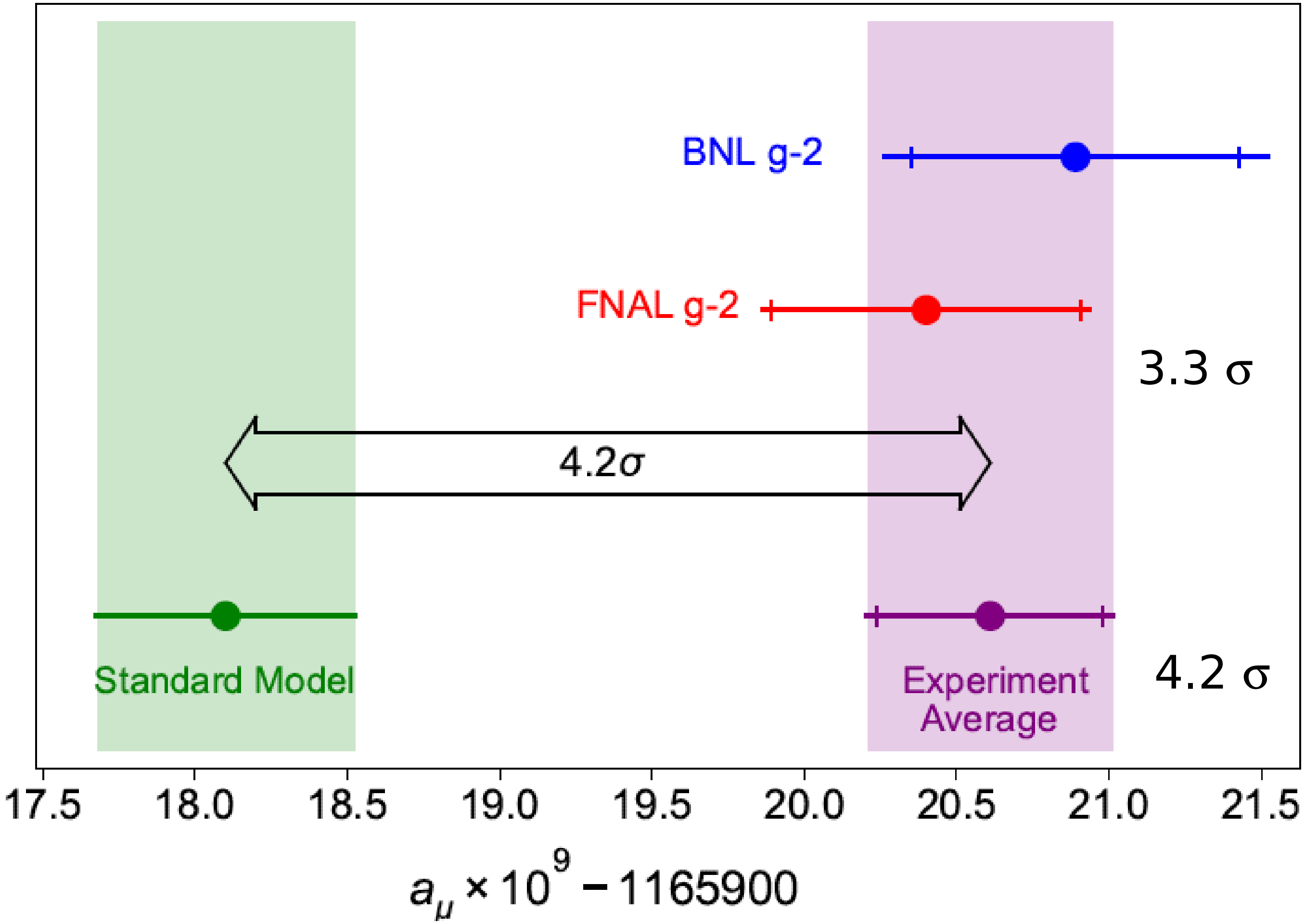
→ $0.2\omega_a \oplus 0.17\omega_p$

E989 at Fermilab

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

$0.07\omega_a \oplus 0.07\omega_p$

April 2021: First results of the g-2 experiment at Fermilab



3.7 σ

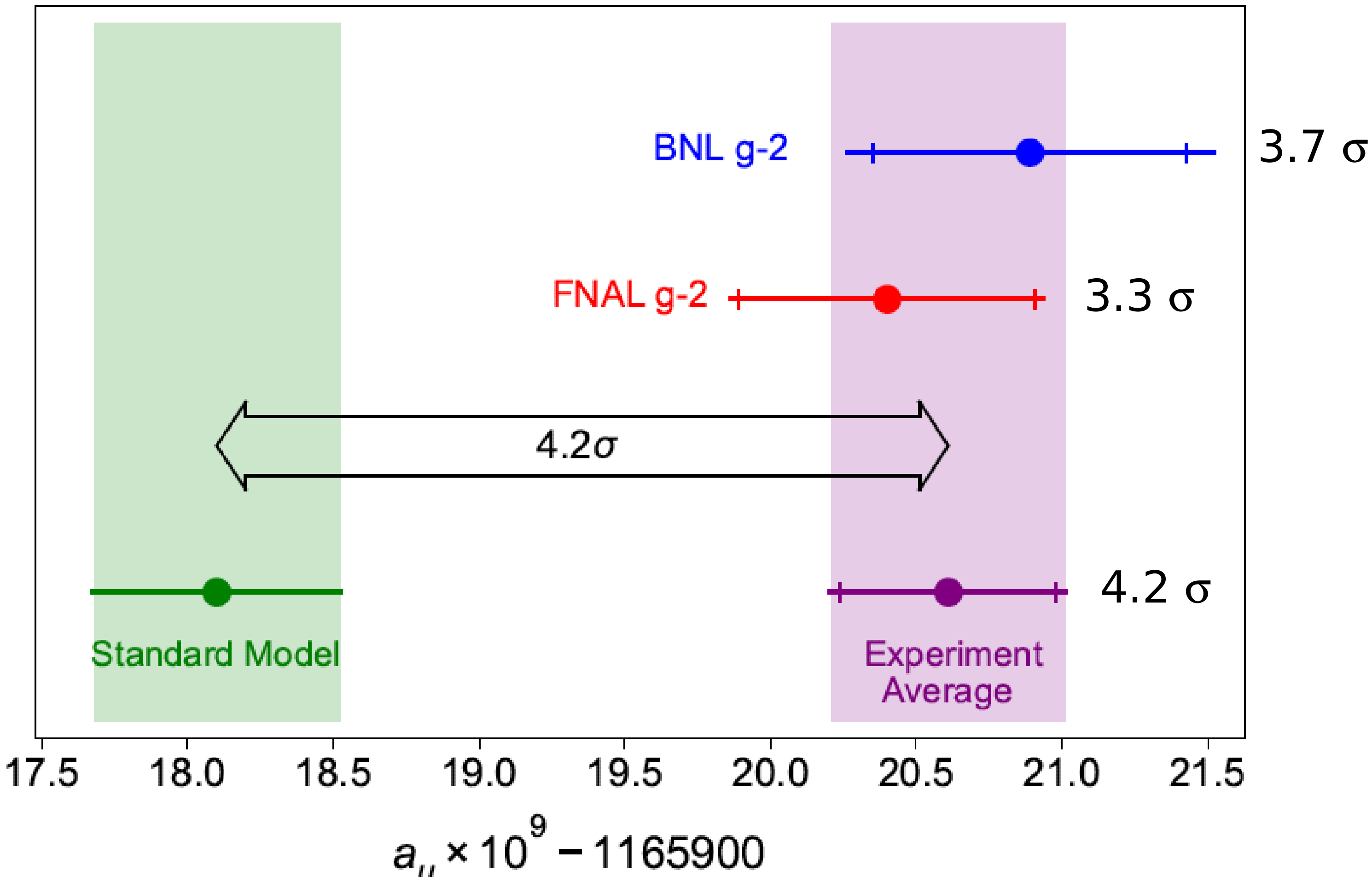
3.3 σ

4.2 σ

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

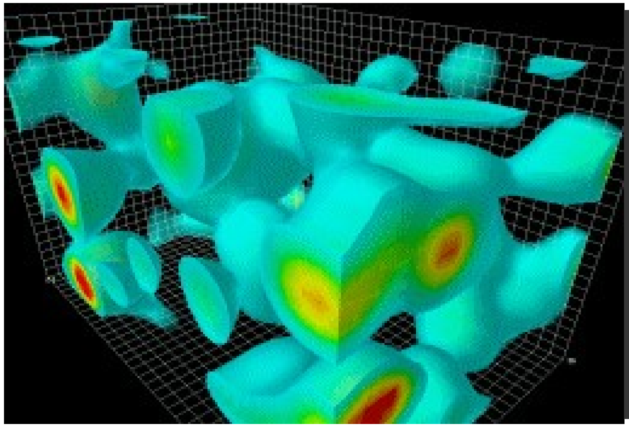
Combined Result

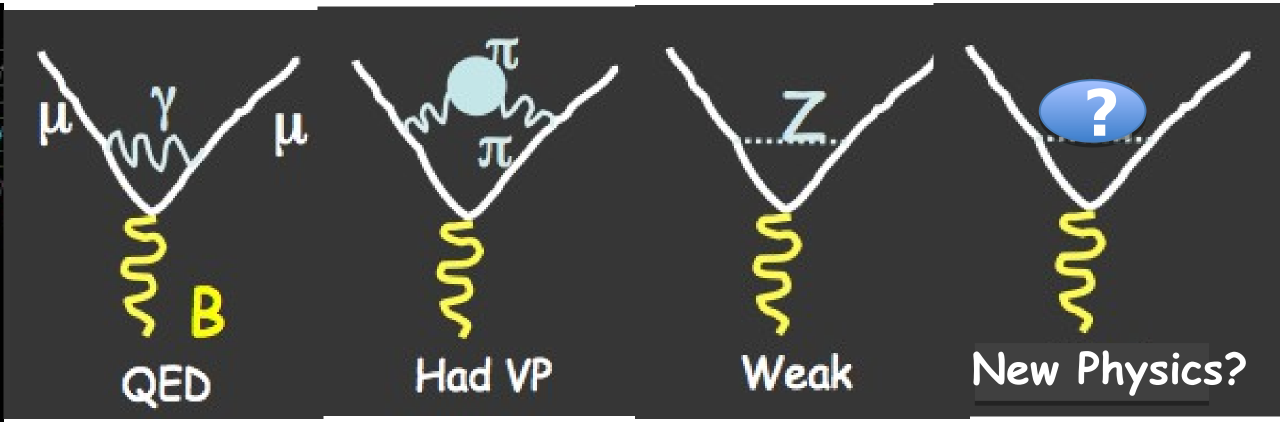
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$$



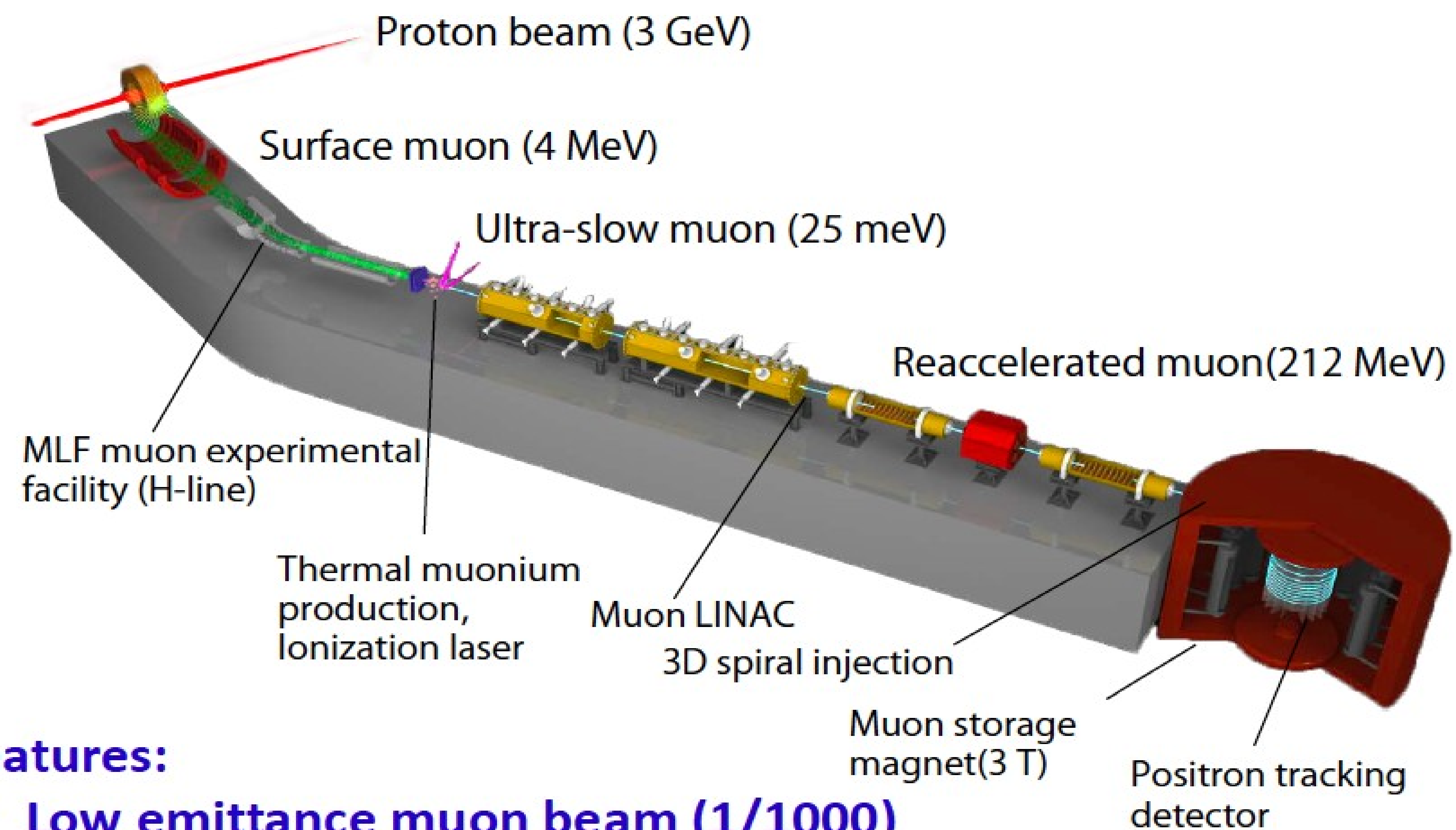
$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

Are we seeing something new ?





Muon g-2/EDM Experiment at J-PARC

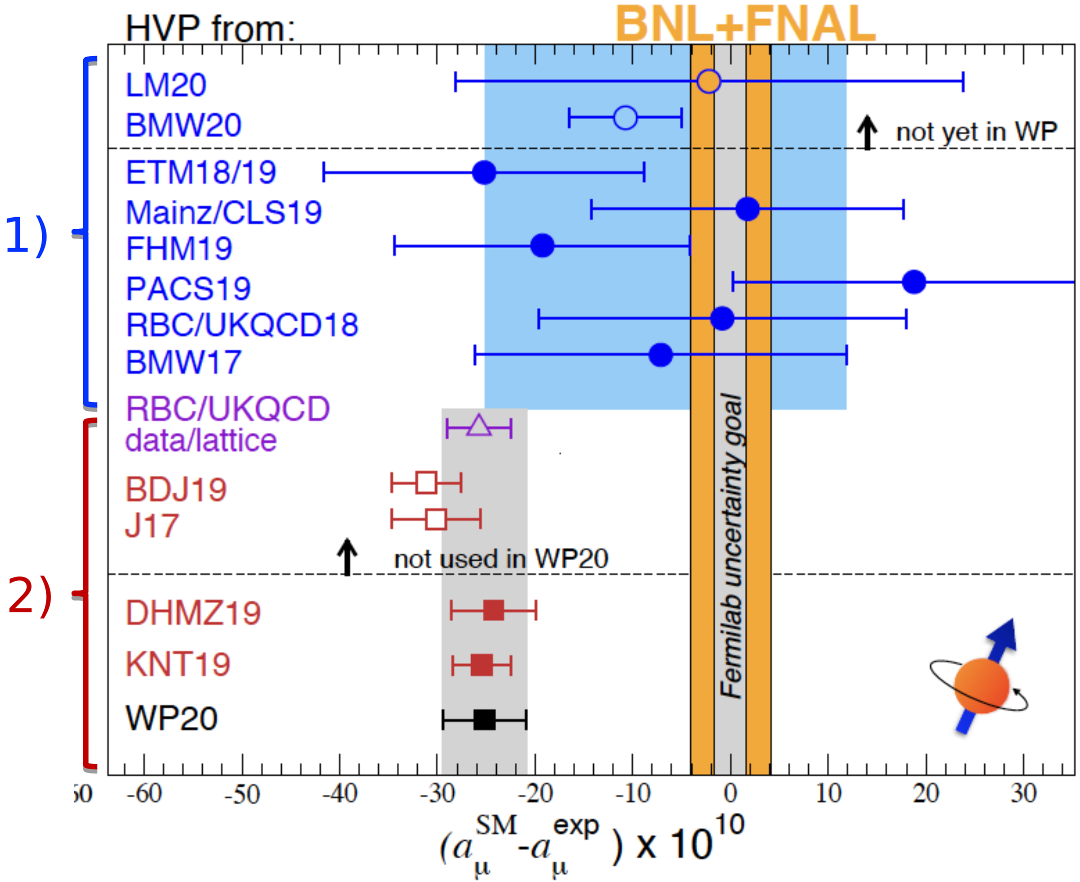


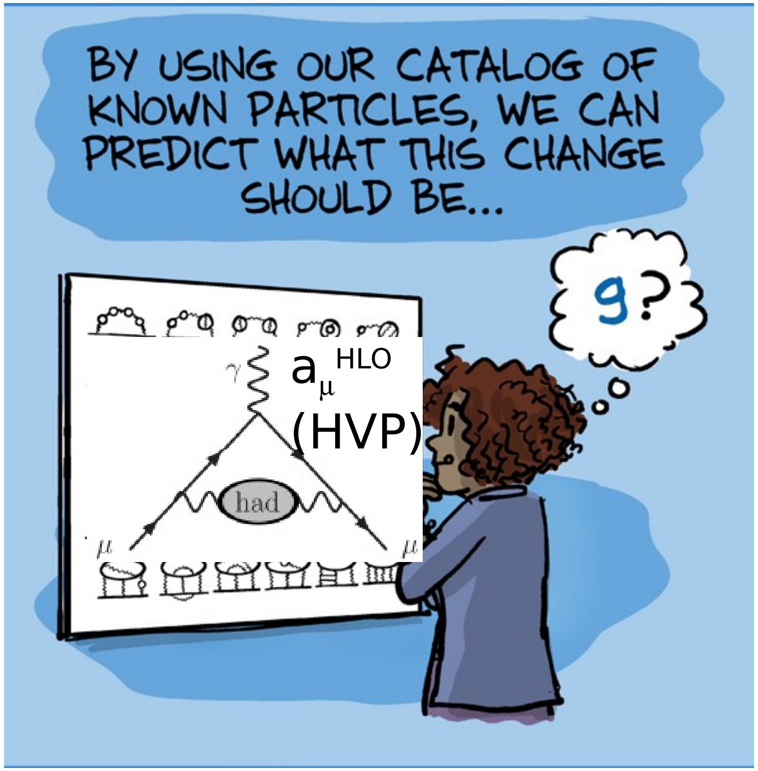
Features:

- **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**

Is the SM calculation correct ?

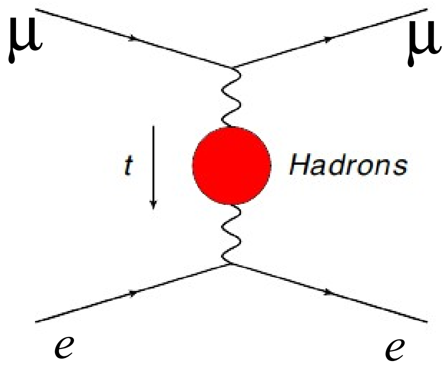
- The contribution from the strong interaction (Hadronic Vacuum Polarization, **HVP**) is challenging
- Tension between two different methods: 1) "lattice calculation"; 2) "dispersive approach"
- Ongoing work to clarify the tension



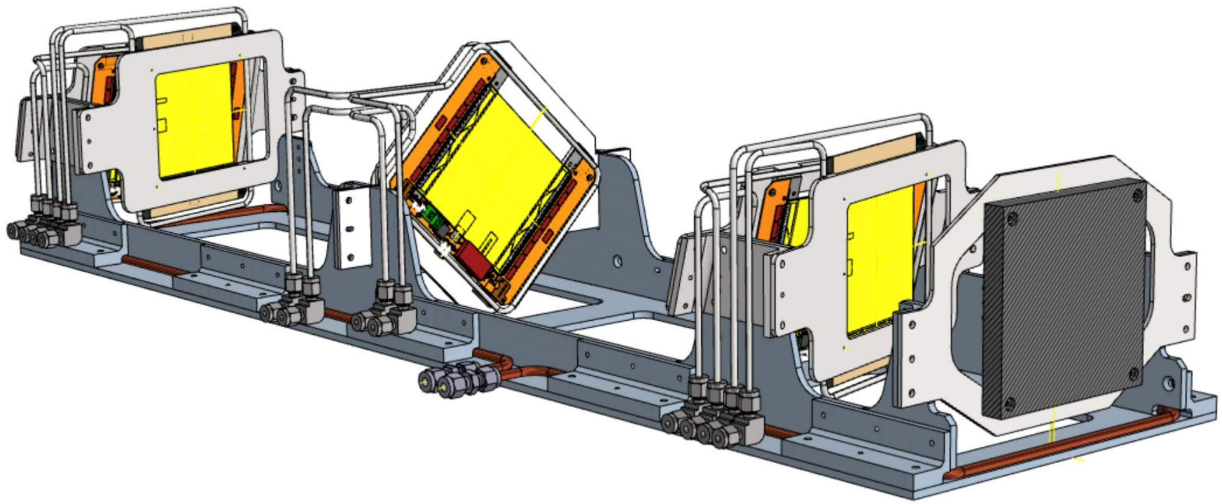


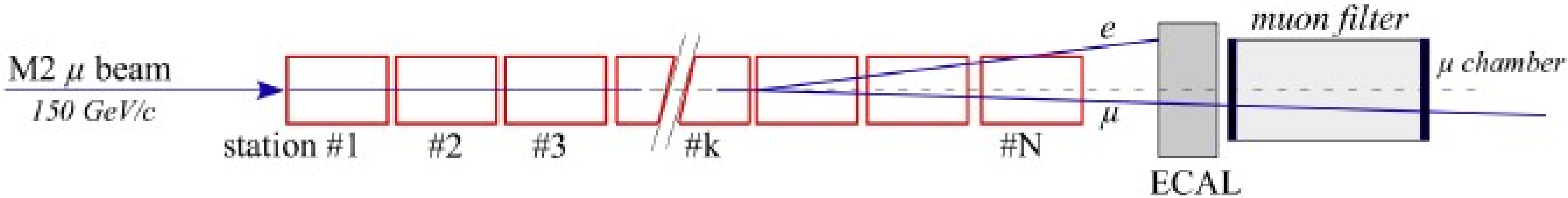
MUonE experiment at CERN

Alternative (competitive) measurement of HVP for a_μ



μe → μe





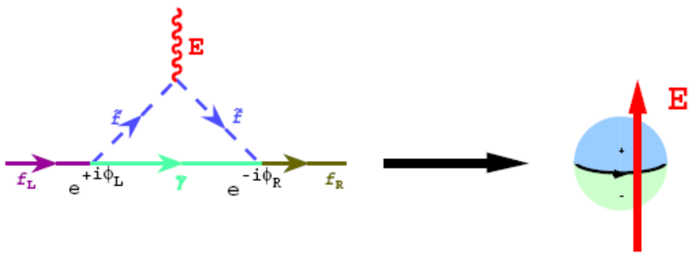
precise measurement of the shape of the differential cross section for the μe → μe elastic process

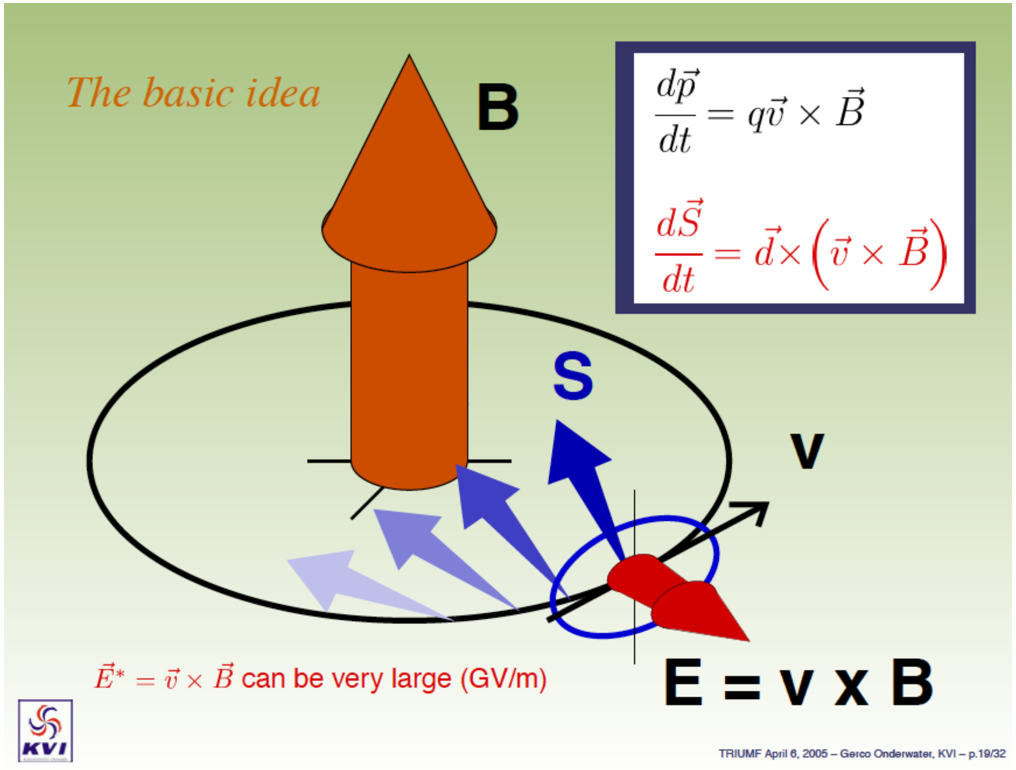
-C. M. Carloni Calame et al PLB 746 (2015) 325
-G. Abbiendi et al Eur.Phys.J.C 77 (2017) 3, 139
-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

Muon EDM Experiments
J-PARC, FNAL storage rings
PSI using frozen spin technique

Muon EDM

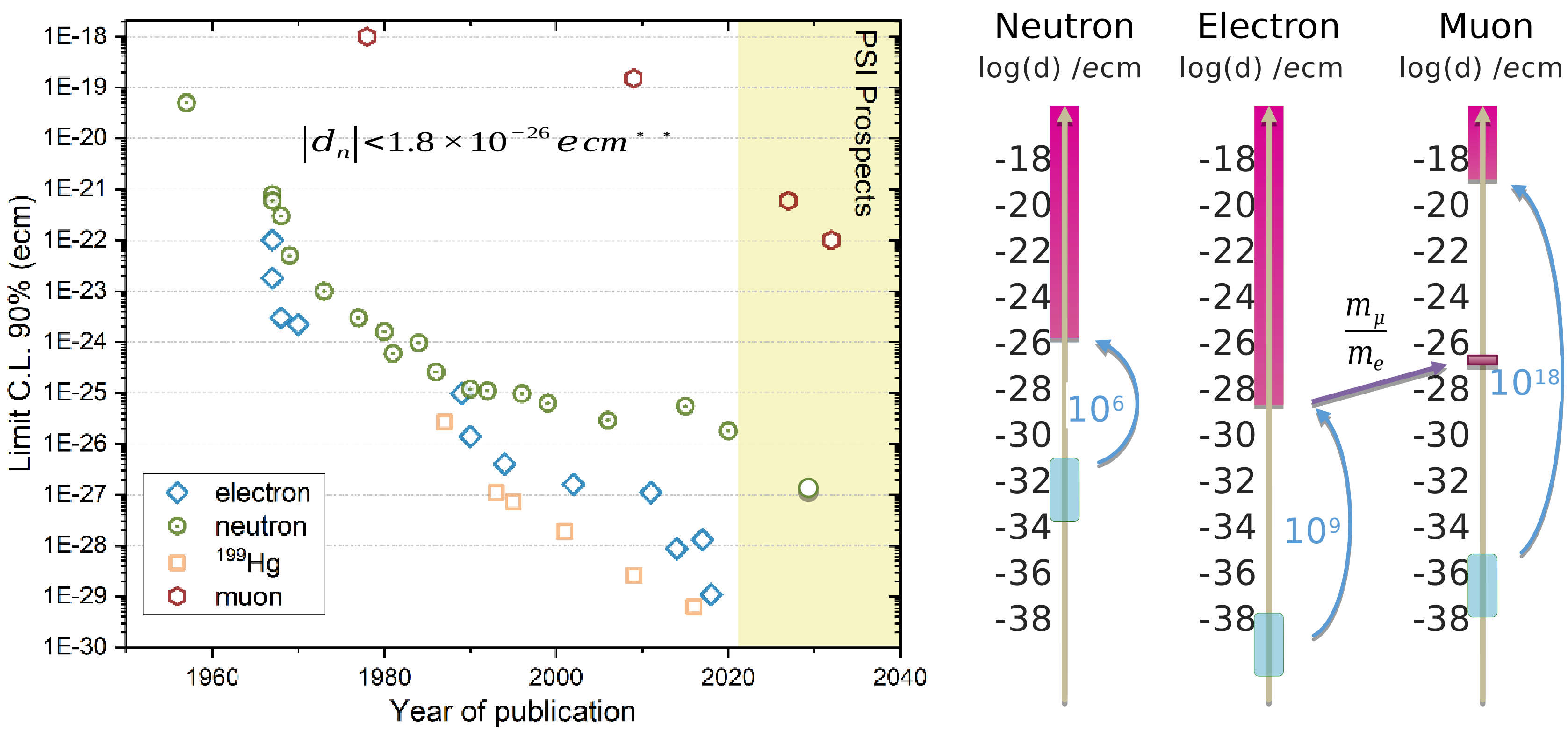
A EDM signal would be a new physics discovery! (No EDM in the SM)
It could explain the matter dominance in the universe
Can be tested at a storage rings and on dedicated experimantal setups.





History of EDM searches

$|d_\mu| < 1.8 \times 10^{-19}\, e\,cm$ *



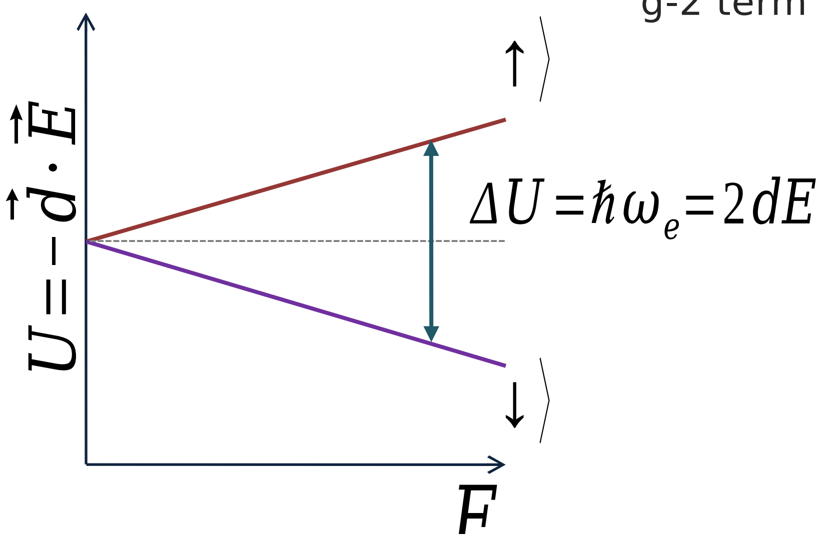
*Bennett et al.,PRD80(2009)052008

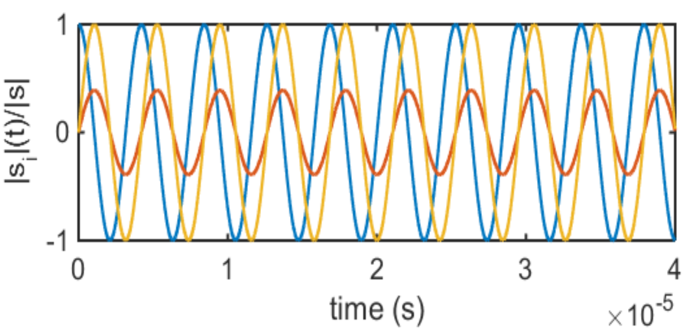
** Abel et al., PRL124(2020)081803

Frequencies under EDM and frozen spin

$$\vec{\omega} = \vec{\omega}_c - \vec{\omega}_L = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

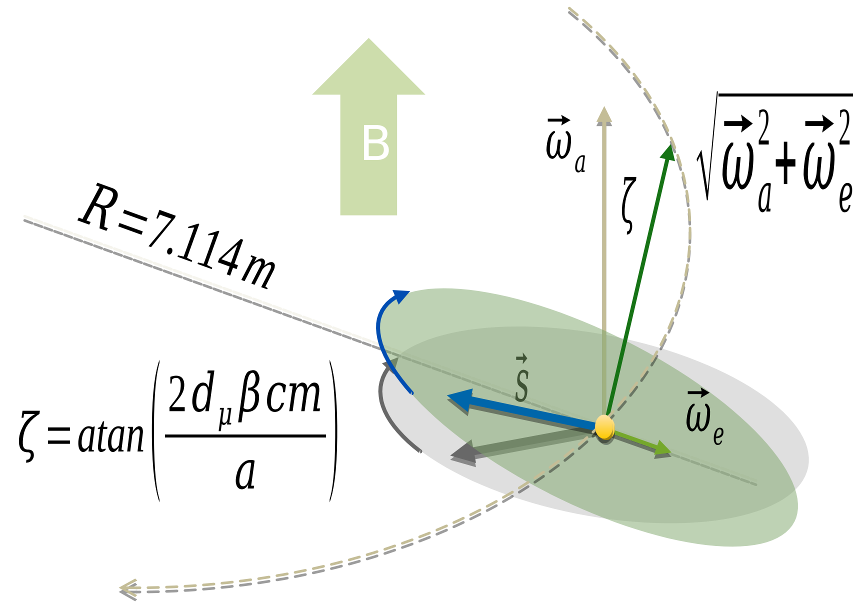
g-2 term





FNAL* &
JPARC**

$$\sigma(d_\mu) \approx 10^{-21}\, e\,cm$$



[*Chislett et al., EPJConf.**118** 01005(2016), **Abe et al., PTEP053C02 (2019)]

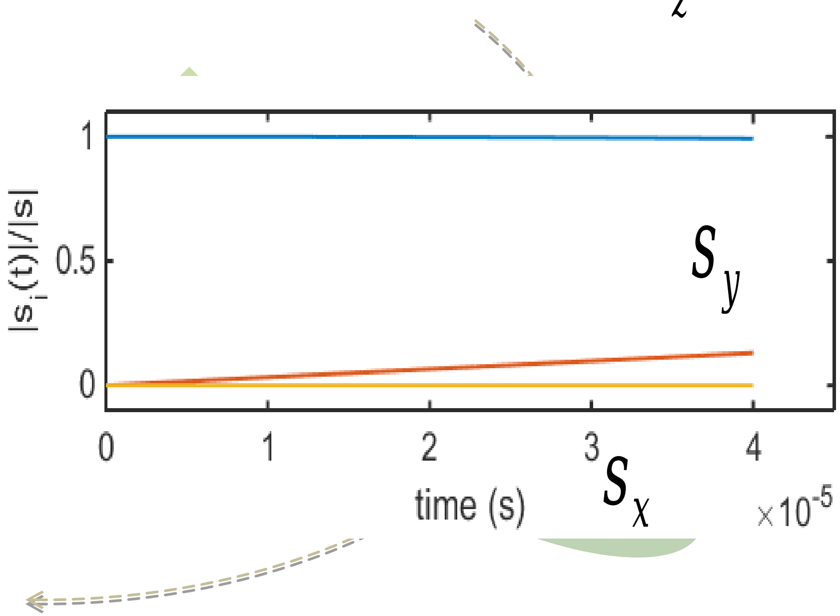
Frequencies under EDM and frozen spin

$$\vec{\omega} = -\frac{q}{m}\left[a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{2\,d_\mu m c}{q\hbar}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

g-2 term

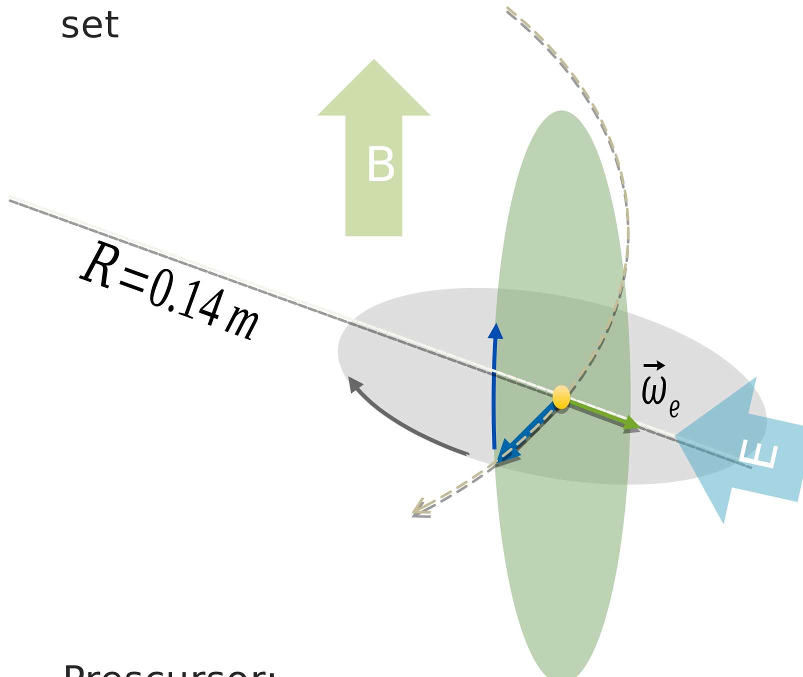
EDM term

FNAL & JPARC $\sigma(d_\mu) \approx 10^{-21}\, e\, cm$



Frozen spin at PSI:

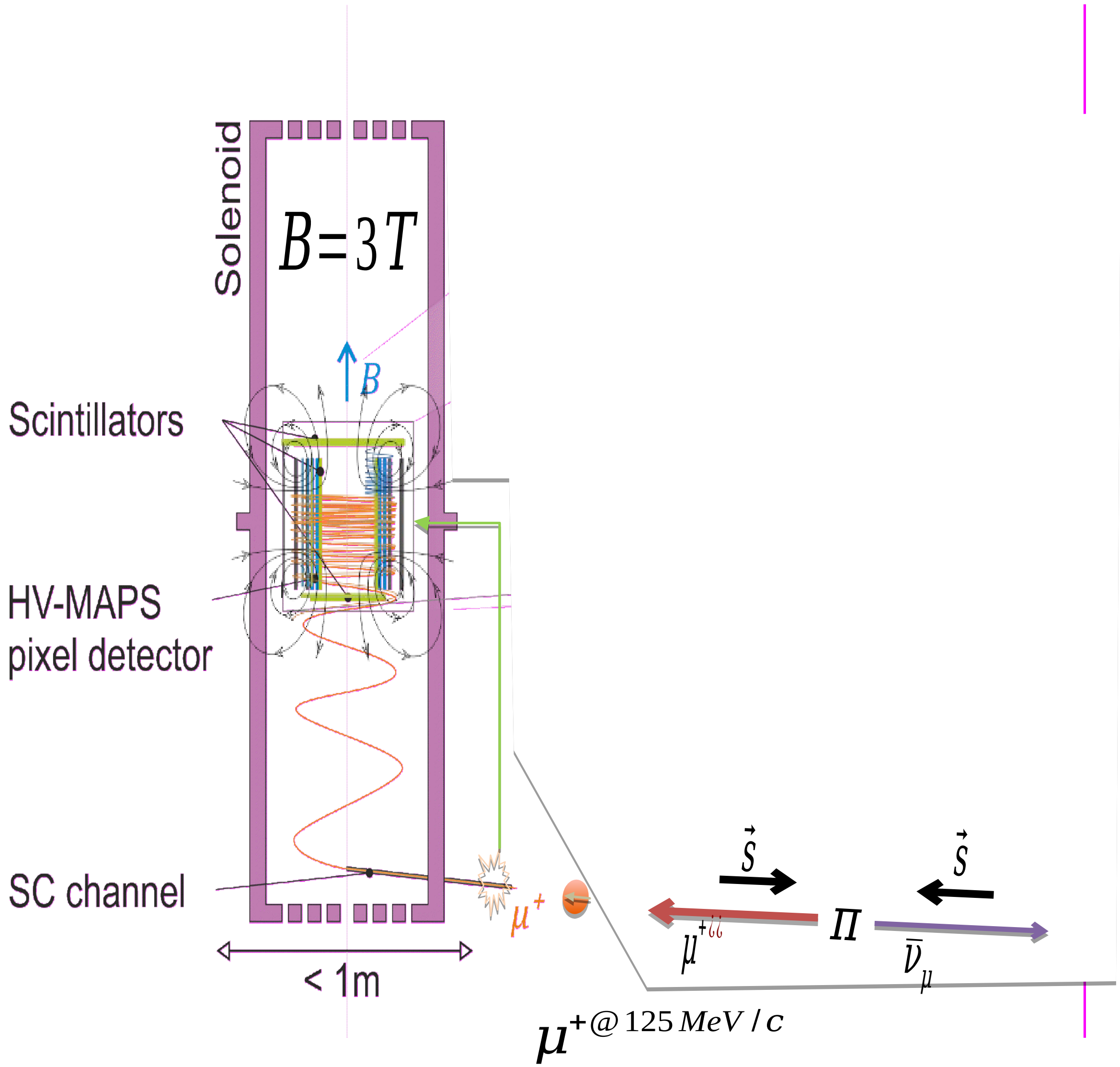
set



Prescursor:

 [*Farley et al,, PRL93 042001 (2004)] ,

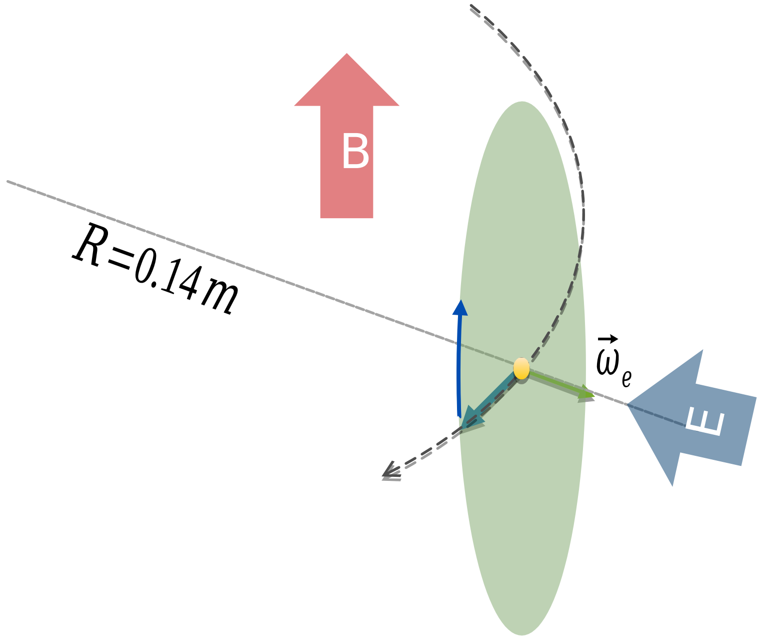
Search for a Muon EDM using Frozen spin

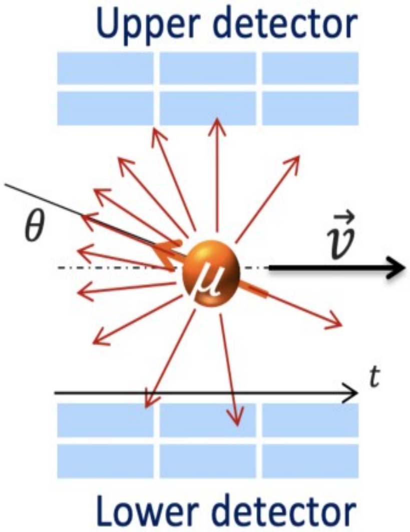


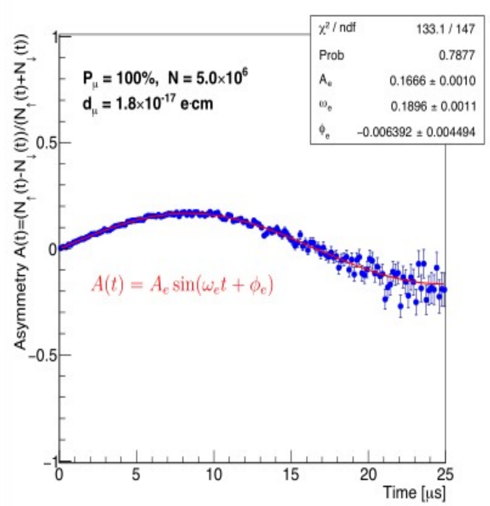
- from Pion-decay → high polarization
- Injection through superconducting channel
- Fast scintillator triggers pulse
- Magnetic pulse stops longitudinal motion of
- Weakly focusing field for storage
- Thin electrodes provide electric field for frozen spin
- Pixelated detectors for
  - tracking

The MuEDM experimental idea

- If the EDM ≠ 0, then there will be a vertical precession out of the plane of the orbit
  - An asymmetry increasing with time will be observed recording decay positrons
- If the EDM = 0, then the spin should always be parallel to the momentum – asymmetry should be zero
- **Some asymmetry could still be observed due to systematic effects**







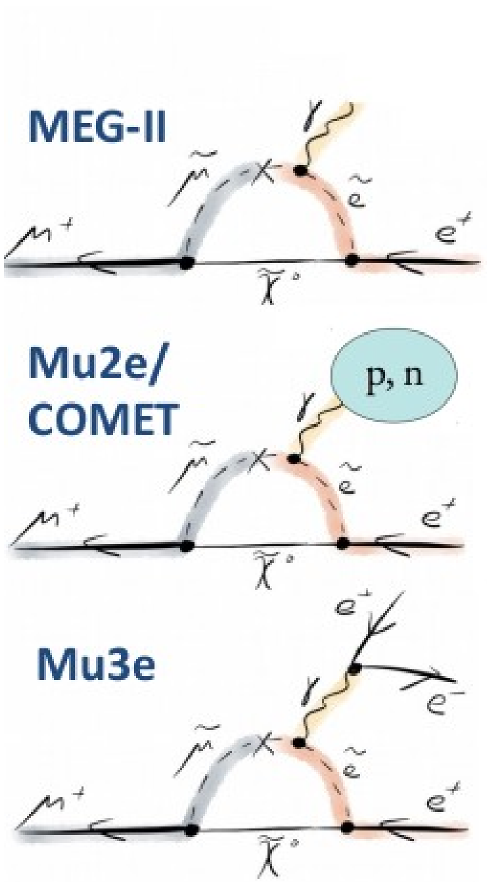
MuEDM collaboration at PSI

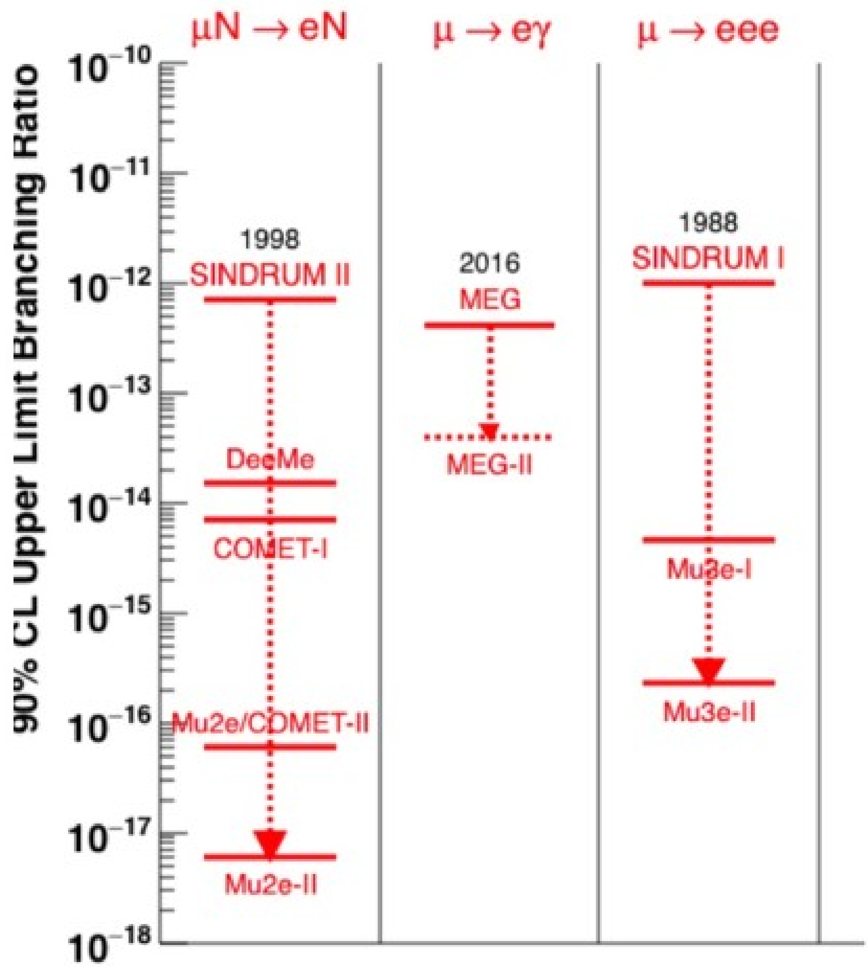
A. Adelmann,[1,2] C. Chavez Barajas,[3] *D. Chouhan,*[4] N. Berger,[4] T. Bowcock,[3]
A. Bravar,[5] C. Calzolaio,[2] L. Caminada,[2,6] G. Cavoto,[7,8] *C. Chen,*[9]
R. Chislett,[10] A. Crivellin,[2,6,11] M. Daum,[2] C. Dutsov,[2] *A. Doinaki,*[2]
F. Fallavollita,[4] M. Giovannozzi,[11] G. Hiller,[12] G. Hesketh,[10] M. Hildebrandt,[2]
M. Hoferichter,[13] *T. Hume,*[2] *T. Hu,*[9] A. Keshavarzi,[14] K.S. Khaw,[9,15]
K. Kirch,[1,2] A. Kozlinsky,[4] A. Knecht,[2] M. Lancaster,[14] B. Märkisch,[15]
F. Méot,[16] *J.K. Ng,*[9] A. Papa,[2,17] *P. Pestlin,*[2] J. Price,[3] F. Renga,[7,8] *M. Sakurai,*[1]
P. Schmidt-Wellenburg,[2] M. Schott,[4] T. Teubner,[3] F. Trillaud,[18] *B. Vitali,*[2,17]
C. Voena,[7,8] J. Vossebeld,[3] and F. Wauters,[4] *Y. Zeng*[9]

Charge Lepton Flavour Violating Experiments
MEG II, Mu2e, COMET, Mu3e

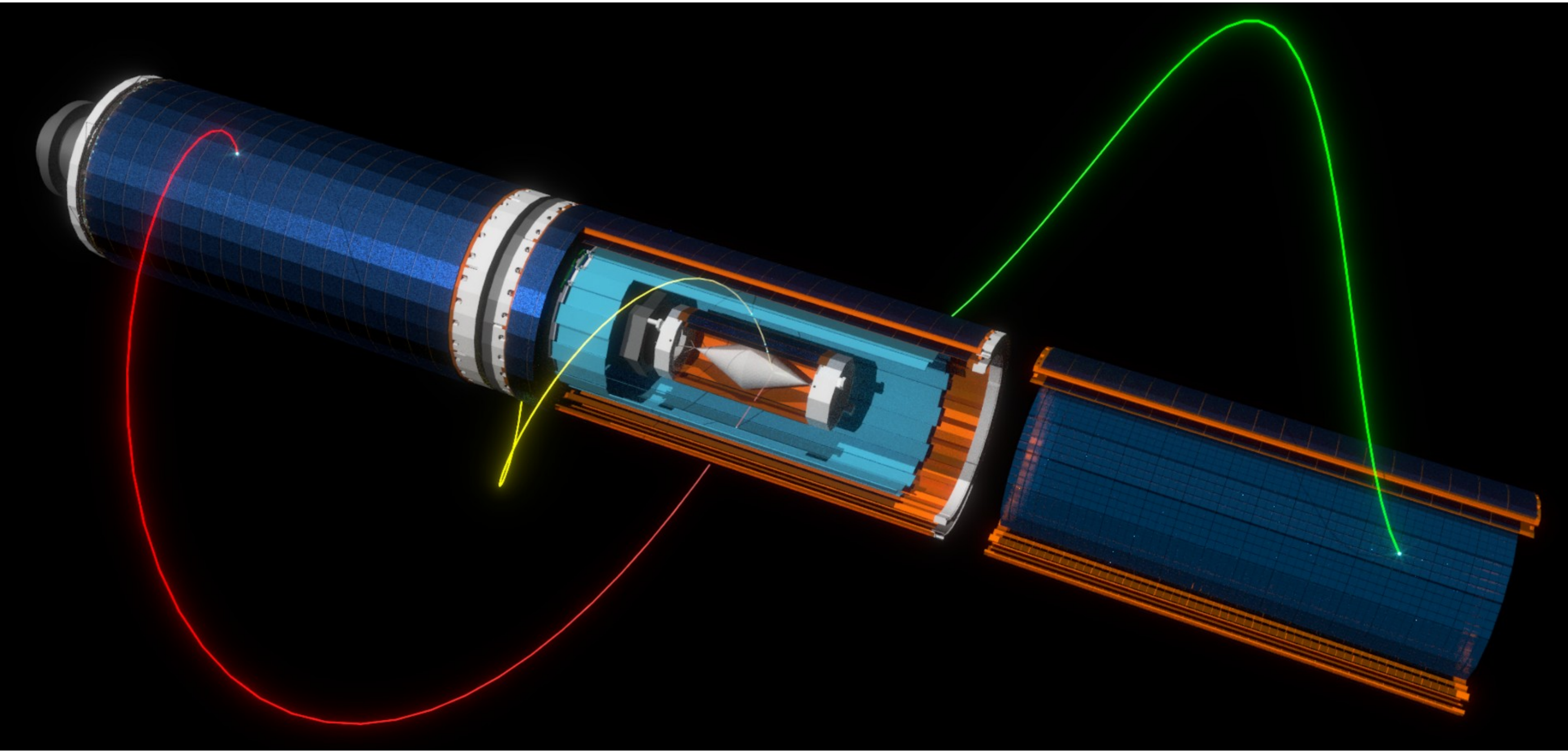
CLFV Experiments

Looking for the neutrinoless decay of a muon to one or more electrons
Significant potential to improve on current limits

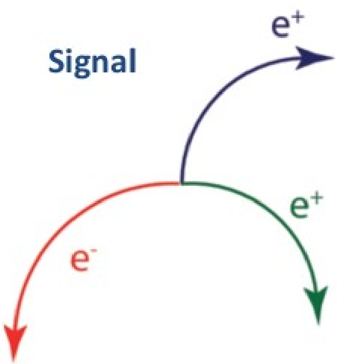




The Mu3e experiment at PSI

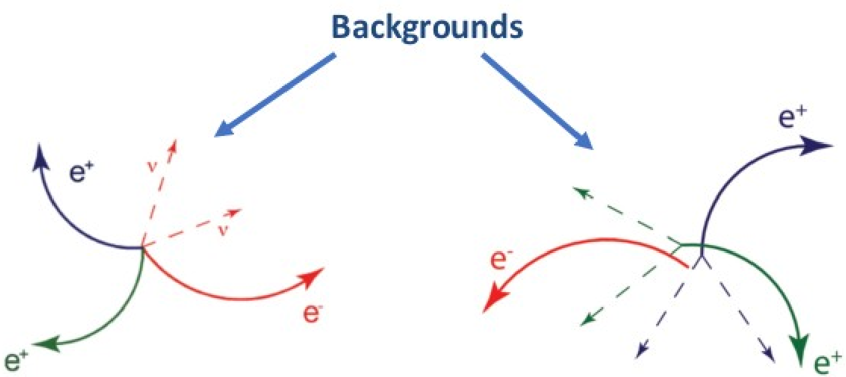


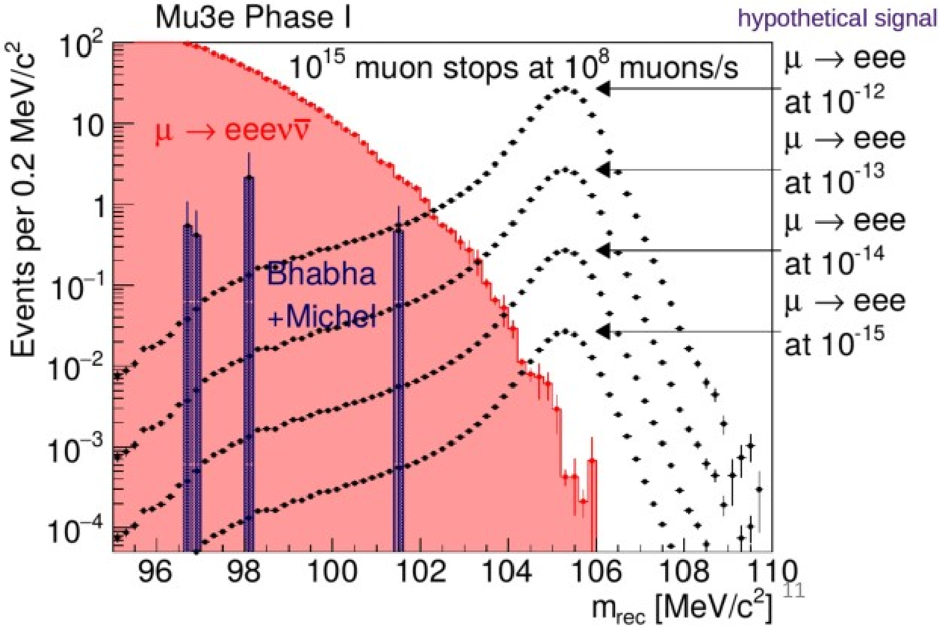
The Mu3e experiment at PSI



Requirements :

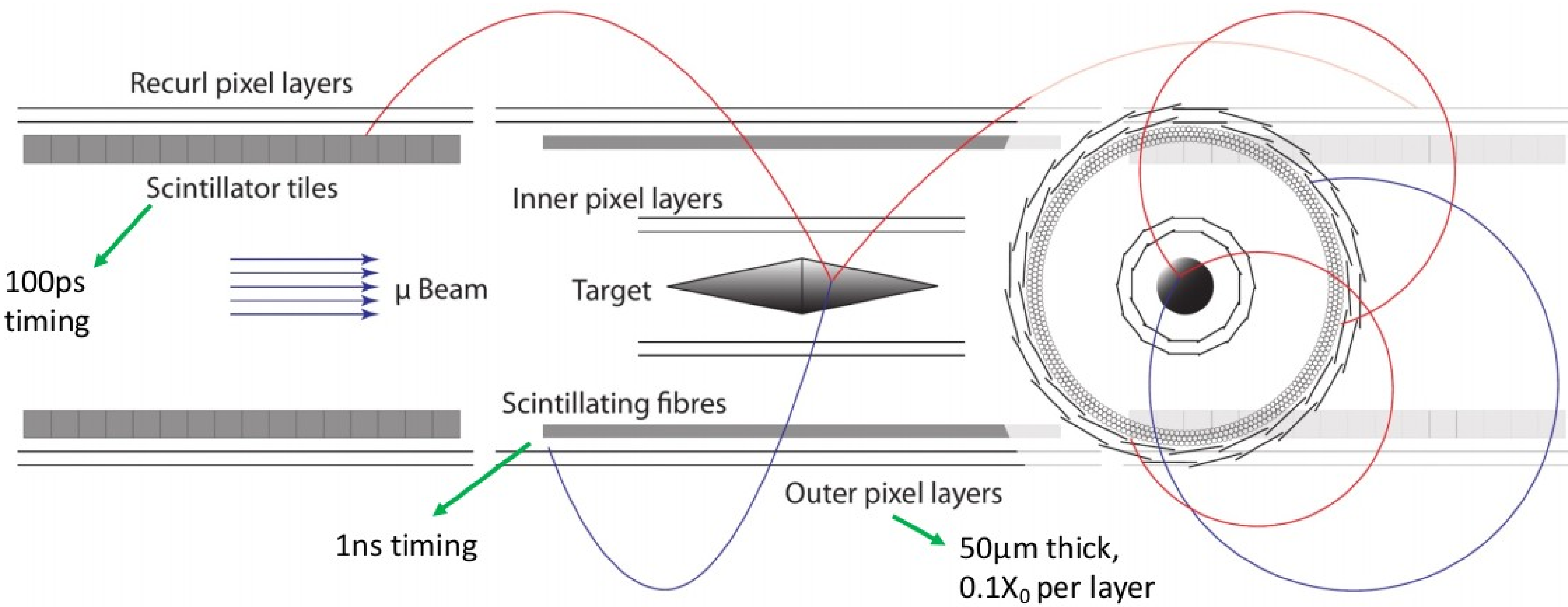
- Excellent timing information (1 ns)
- Good momentum resolution (0.5 MeV at ~53 MeV)
- Well reconstructed vertex (200 µm)
- Minimal material





The Mu3e Experiment at PSI

In Phase 1, PSI provides a constant low momemtum muon beam
With a beam of 10^8 muons per second on target



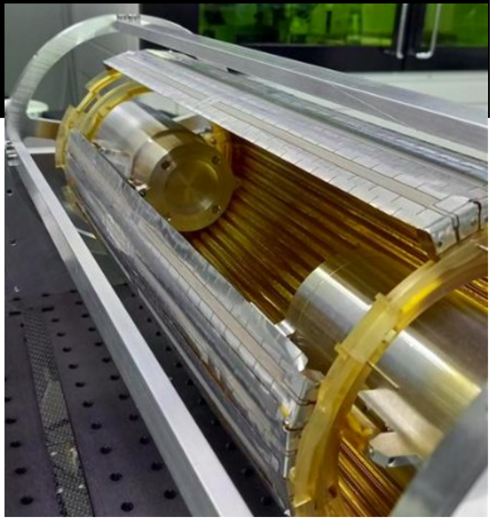
Integration run in 2021, construction of scintillating fibres, tiles and pixel next year.
Completion in 2024 and physics data taking from 2025
Phase I : 1000x improvement in current limit
Phase II: use HIMB to acchieave further factor of 10 in sensitivity

Mu3e Tracking system

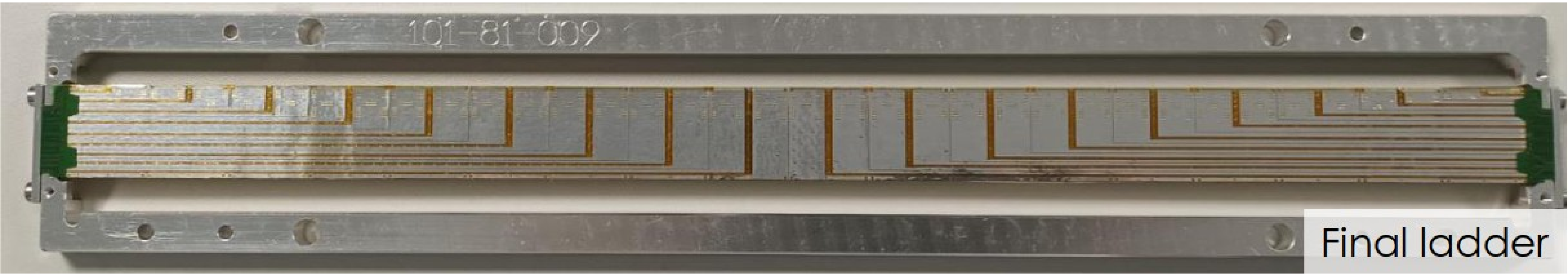
2 inner tracking layers in central station
2 outer tracking layers

minimal mass required:
50 micron thickness HV-CMOS pixel
Aluminum high density interconnect (HDI)
Helium cooling

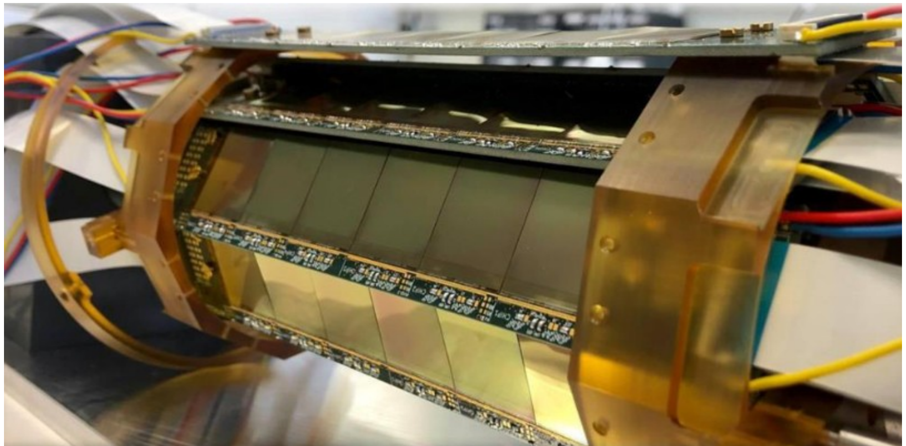
Mockup
System
For cooling
testing



Aluminum HDI shown for outer layer ladder



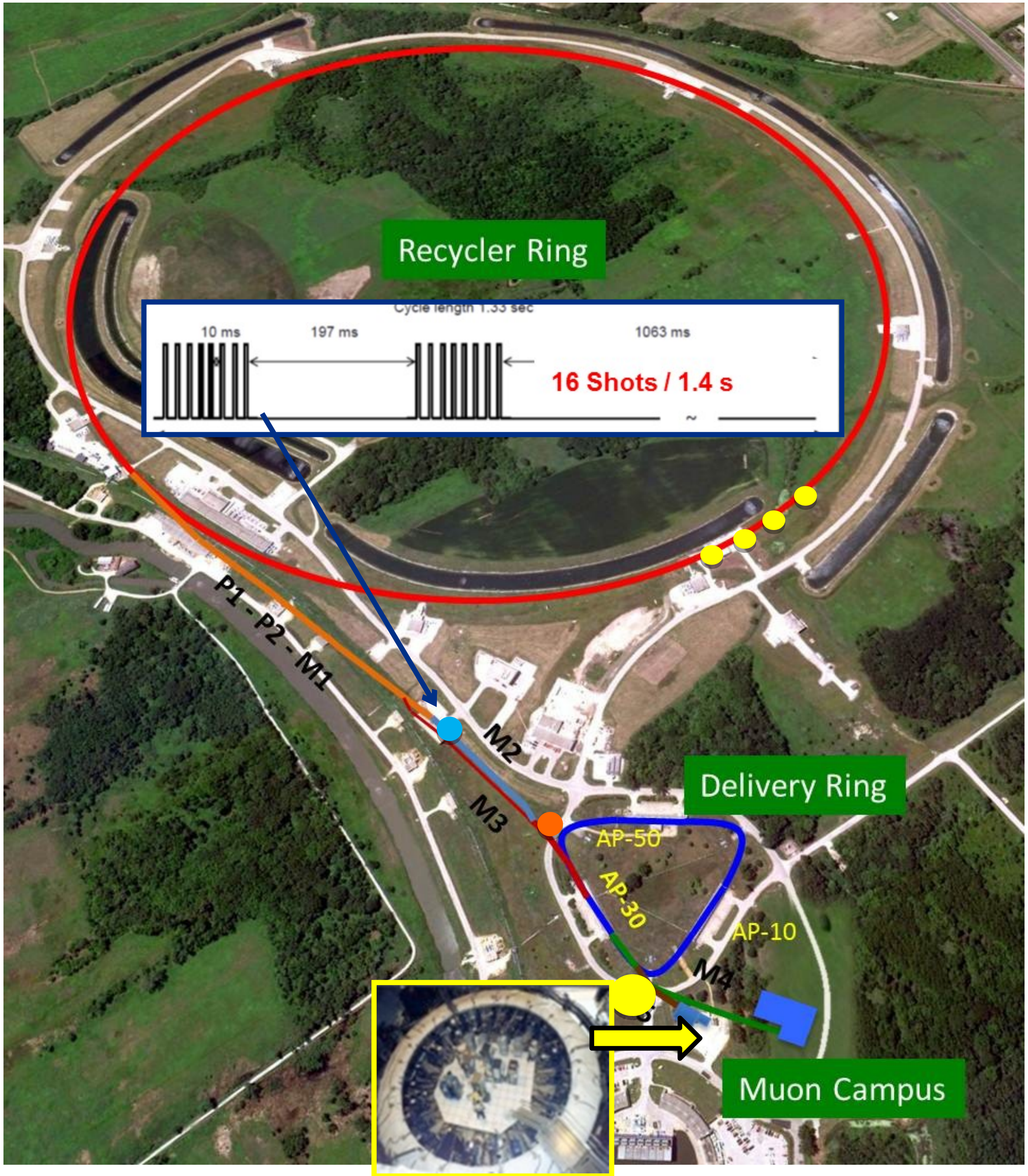
Final ladder



Inner tracker layers
during integration run in 2021


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

END



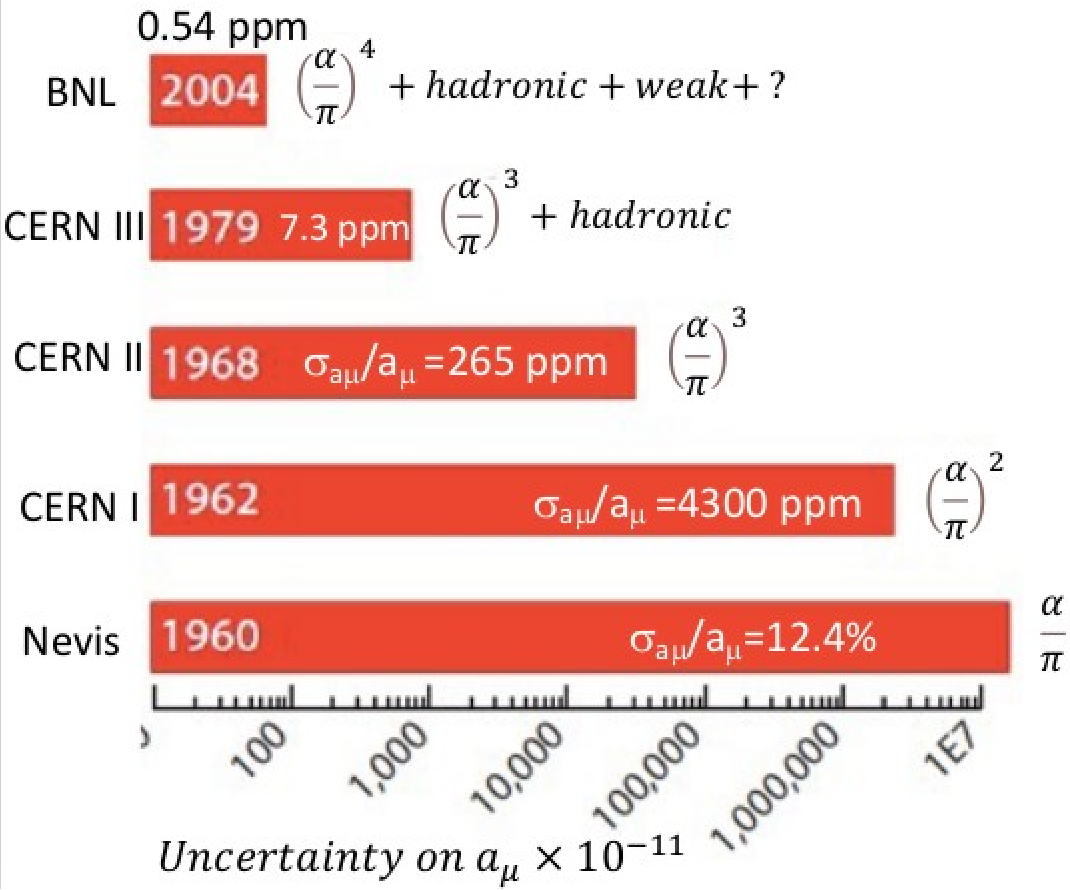
Creating the Muon Beam for g-2

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

History of muon g-2 experiments (1960-2000)

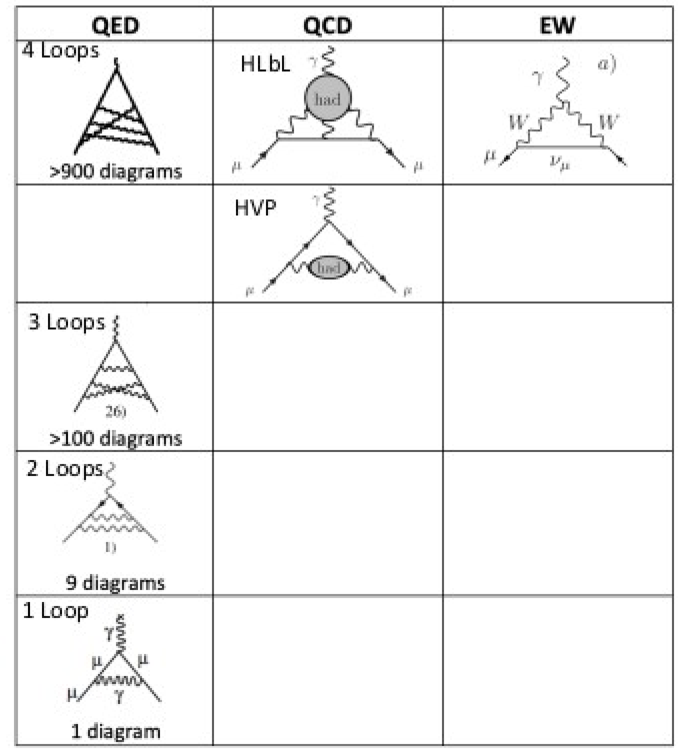
0.54×10^{-6}

$a_\mu^{BNL} = 116\,592\,089\,(63) \times 10^{-11}$ (2001)



contribution to a_μ $(\times 10^{-11})$:

116 584 712...	6937 (44)	153.6(1)
(0.9999...)	(5.9×10^{-5})	(1.3×10^{-6})



Comparisons of g-2 experiments

Comparison of g-2 experiments

JPARC-E34

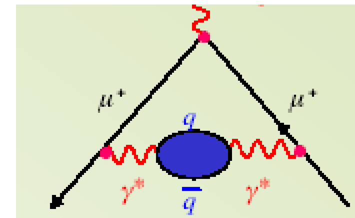
Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

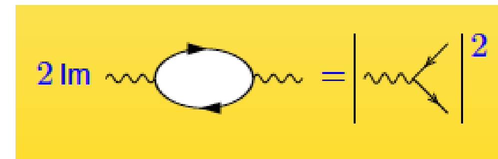
	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected 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.)	$0.2\times10^{-19}\ e\cdot$cm	–	$1.5\times10^{-21}\ e\cdot$cm
(syst.)	$0.9\times10^{-19}\ e\cdot$cm	–	$0.36\times10^{-21}\ e\cdot$cm

	Completed	Running	In preparation

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,…]





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

$a_\mu^{HLO} = (693.1 \pm 4.0)10^{-10}$ (TI)

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