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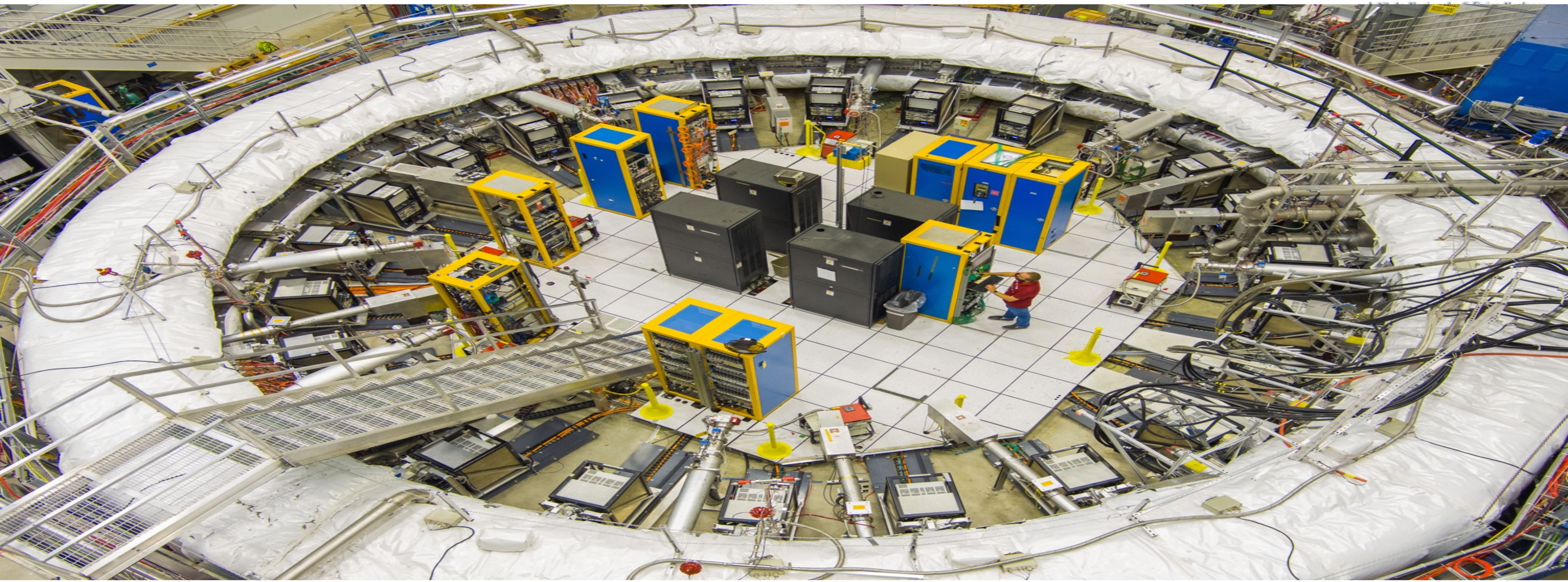


The Muon g-2 Experiment and test of the Standard Model with muons

Graziano Venanzoni
University of Liverpool and Sezione INFN Pisa

XXI Spring School, Frascati, 15/5/24

LEVERHULME TRUST

OUTLINE

- The Muon Physics: A Worldwide frontier research
- The Muon g-2 Experiment at Fermilab and J-Parc
- The MUonE experiment at CERN
- Charged Lepton Flavour Violation experiments:
  - MEG II ($\mu \rightarrow e\gamma$), Mu3e ($\mu \rightarrow 3e$)
  - Mu2e, COMET, DeeMe (μ-e conversion)
- Conclusion

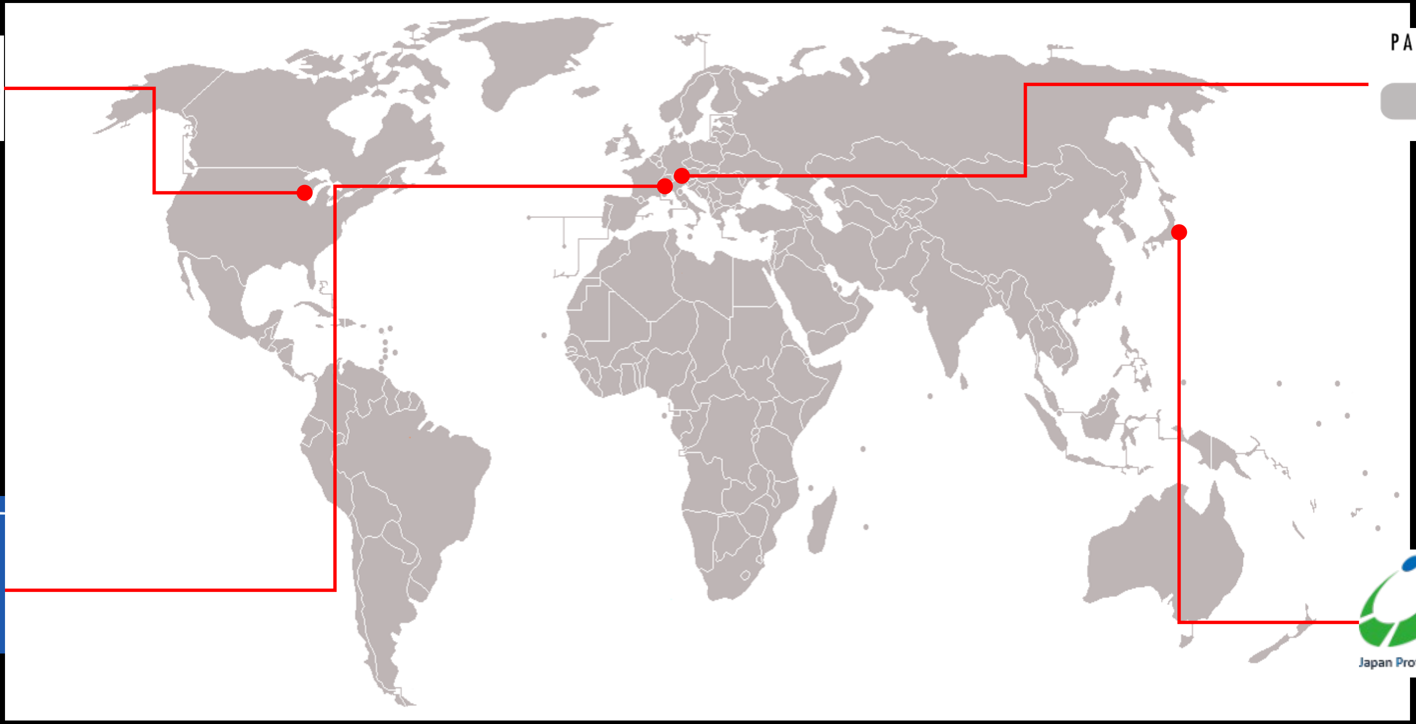
The Muon g-2 & CLFV Physics: A Worldwide frontier research

Fermilab

Muon g-2
Mu2e

CERN

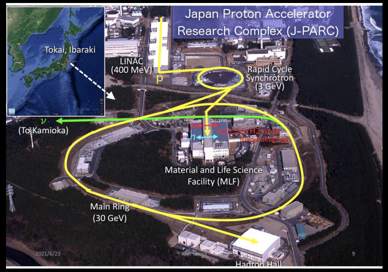
MUonE



PAUL SCHERRER INSTITUT
PSI

Mu3e
MEG

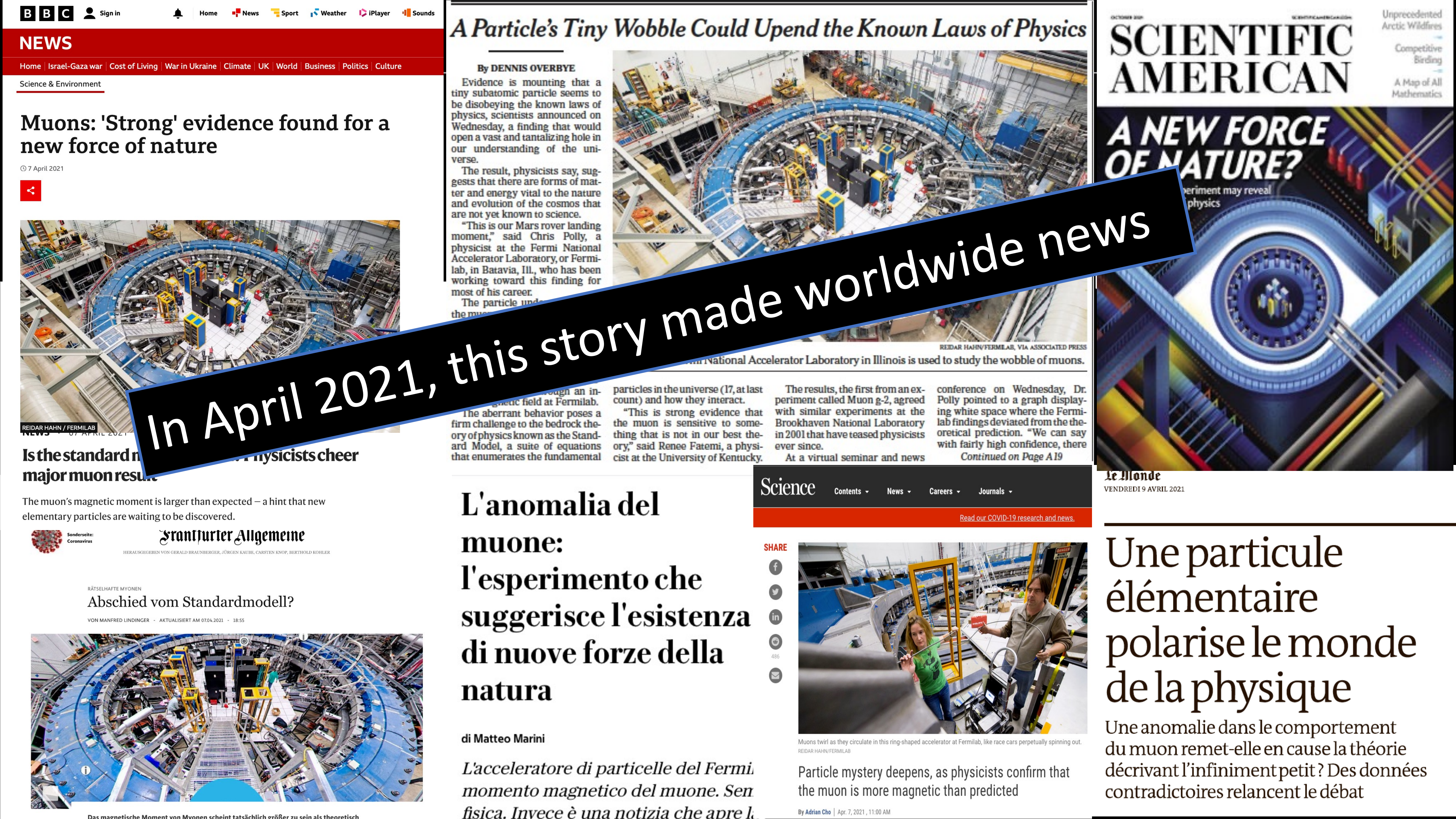
大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex



Muon g-2
COMET
DeeME

- High intensity μ beam & long decay time
  - Large statistics possible & beam transport to target
- Simple kinematics
  - Precise measurements in a high rate background

In April 2021, this story made worldwide news



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Muons: 'Strong' evidence found for a new force of nature

7 April 2021

REIDAR HAHN / FERMILAB

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle un...

REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

...National Accelerator Laboratory in Illinois is used to study the wobble of muons.

...ough an in-...netic field at Fermilab. The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

Continued on Page A19

SCIENTIFIC AMERICAN

Unprecedented Arctic Wildfires

Competitive Birding

A Map of All Mathematics

A NEW FORCE OF NATURE?

...periment may reveal ...physics

Is the standard m... ...hysicists cheer major muon resu...

The muon's magnetic moment is larger than expected – a hint that new elementary particles are waiting to be discovered.

Frankfurter Allgemeine

RÄTSELHAFTE MYONEN

Abschied vom Standardmodell?

VON MANFRED LINDINGER · AKTUALISIERT AM 07.04.2021 · 18:55

Das magnetische Moment von Myonen scheint tatsächlich größer zu sein als theoretisch

L'anomalia del muone: l'esperimento che suggerisce l'esistenza di nuove forze della natura

di Matteo Marini

L'acceleratore di particelle del Fermi... momento magnetico del muone. Sen... fisica. Invece è una notizia che apre l...

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Muons twirl as they circulate in this ring-shaped accelerator at Fermilab, like race cars perpetually spinning out.

REIDAR HAHN/FERMILAB

Particle mystery deepens, as physicists confirm that the muon is more magnetic than predicted

By Adrian Cho | Apr. 7, 2021, 11:00 AM

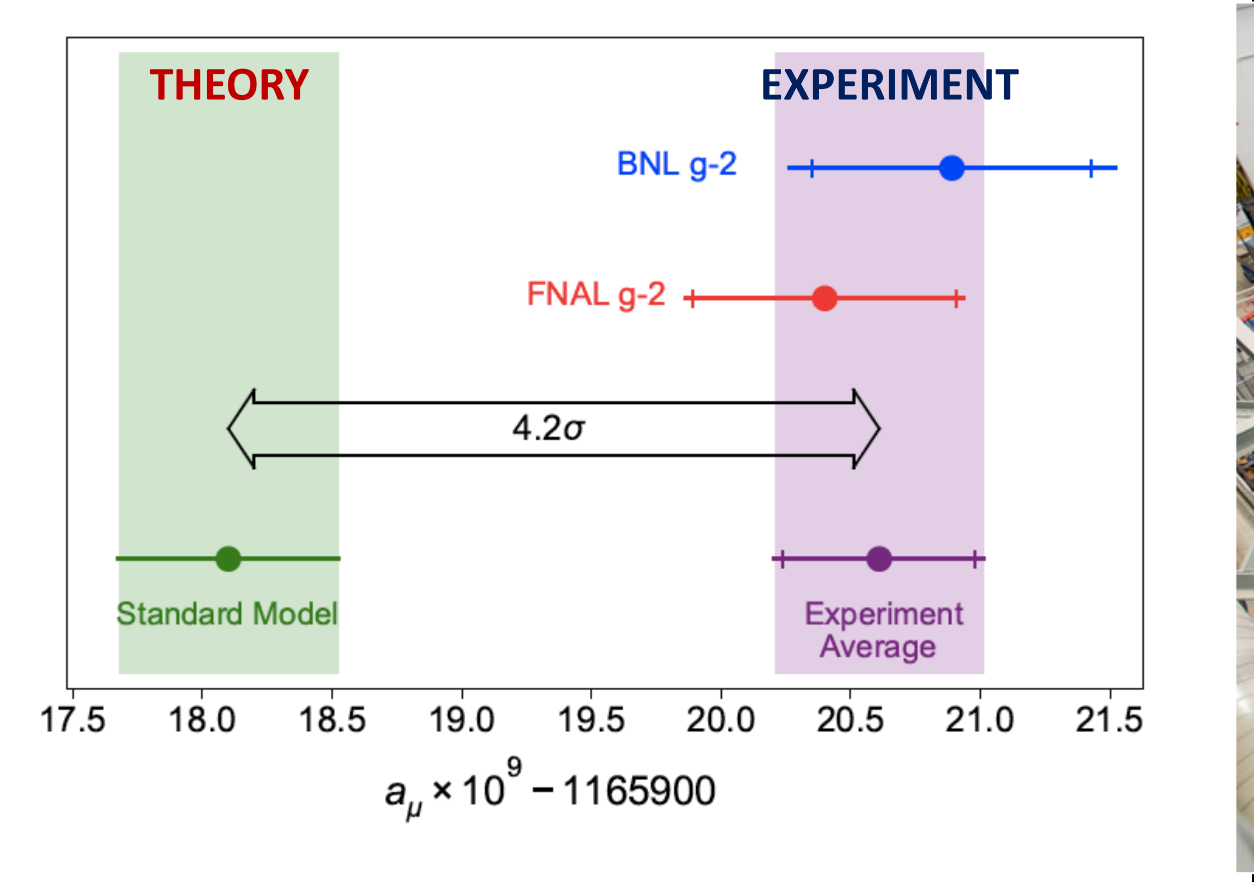
Le Monde

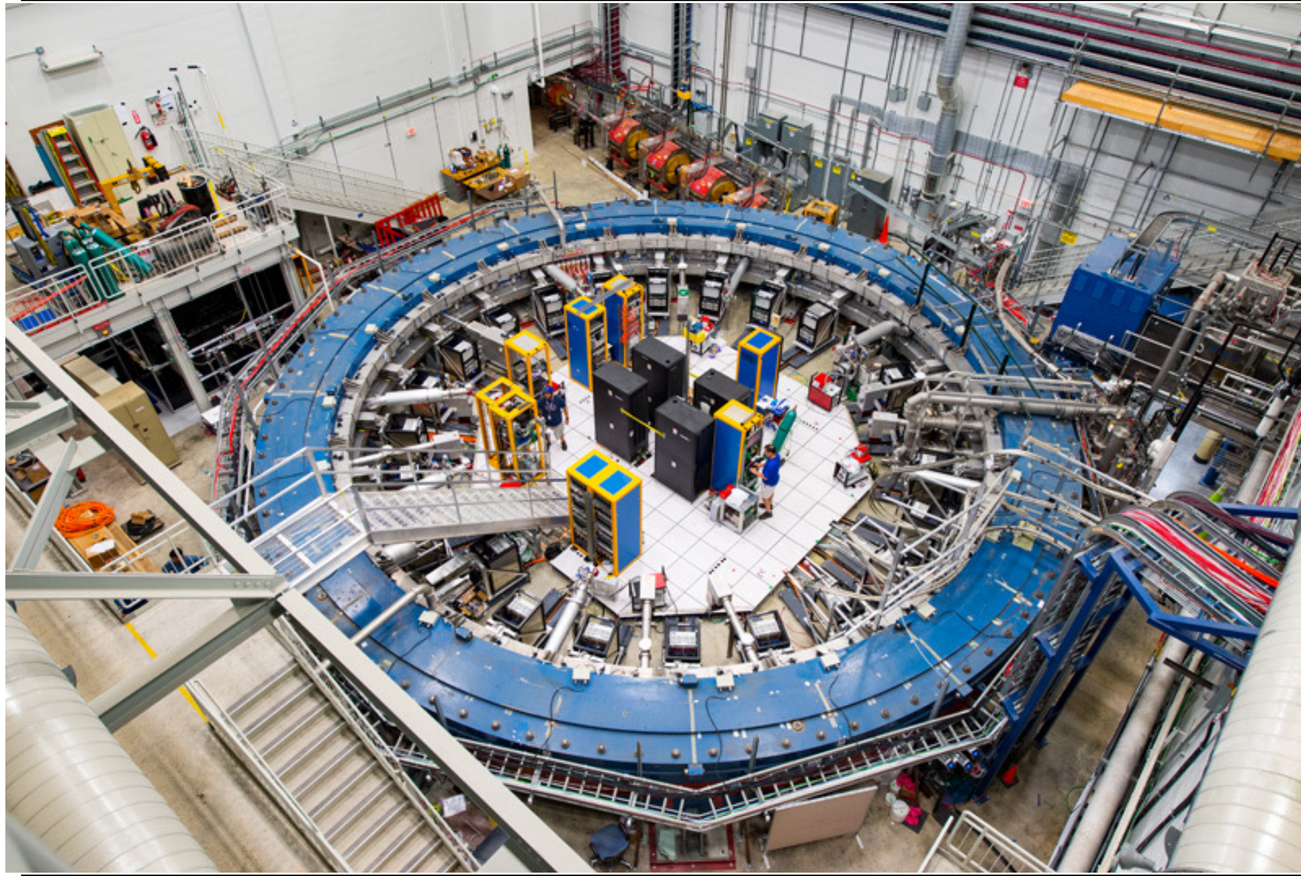
VENDREDI 9 AVRIL 2021

Une particule élémentaire polarise le monde de la physique

Une anomalie dans le comportement du muon remet-elle en cause la théorie décrivant l'infiniment petit ? Des données contradictoires relancent le débat

April 7th 2021:
First results from the Muon g-2 experiment at Fermilab





$g_{experiment}$: 2.00233184122(82)

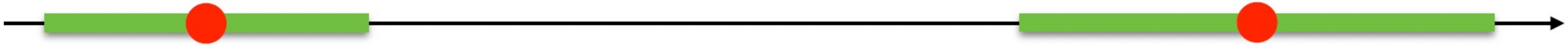
g_{theory} : 2.00233183620(86)

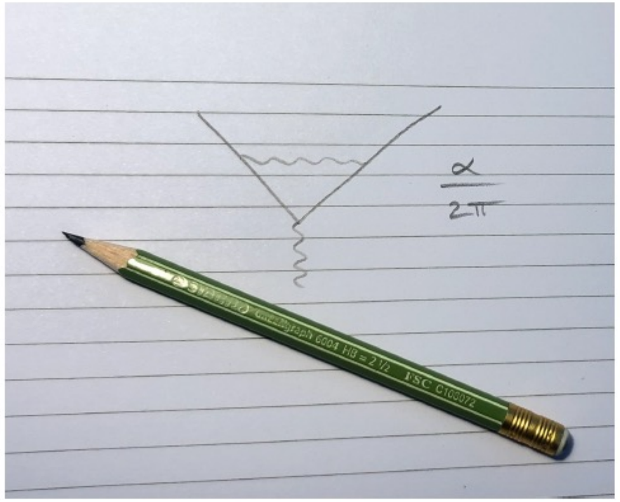
We measured "g-2" with an error of 0.46 part per million (ppm) (0.00 00 00 46)

Like measuring the length of a soccer field with an error smaller than the width of a human hair!

Muon g-2: why are we so excited??

Theory **Experiment**





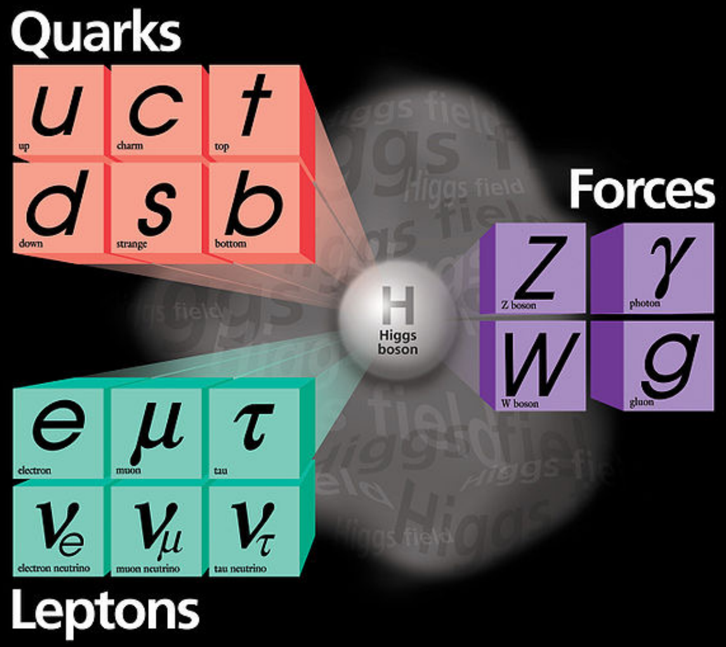
?

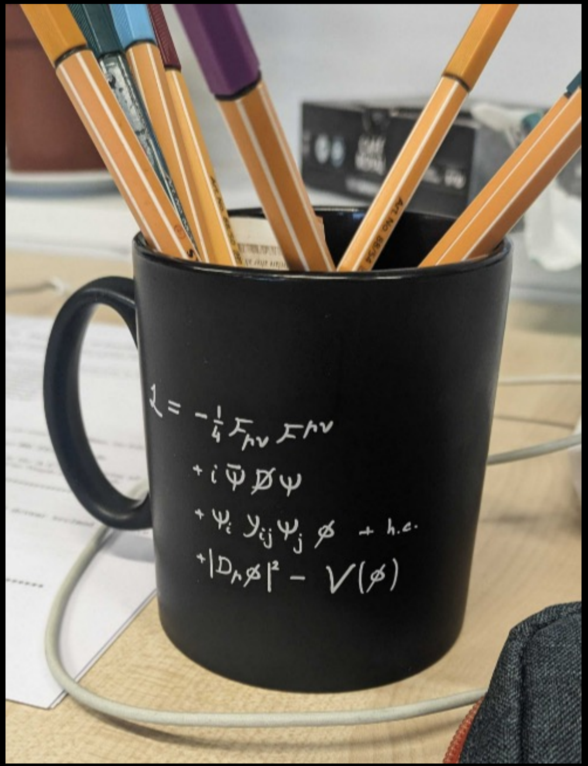
≠

If TH ≠ EXP, there must be new undiscovered particles: New Physics!

Why we expect "New Physics" ?

The Standard Model is a mathematical framework that describes every particle and interaction we've ever measured





It's hugely predictively successful

But…

Gravity

Dark Matter

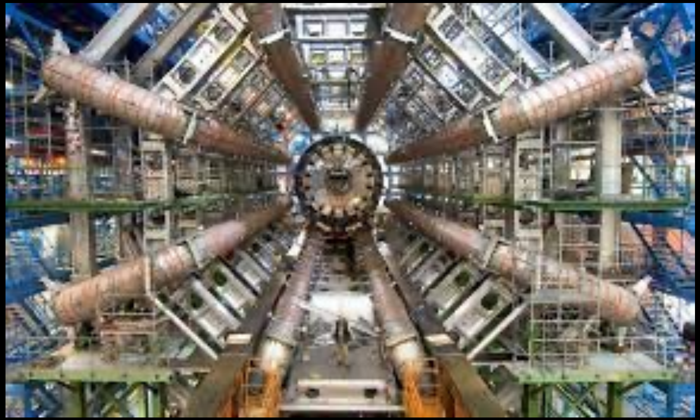
Dark Energy

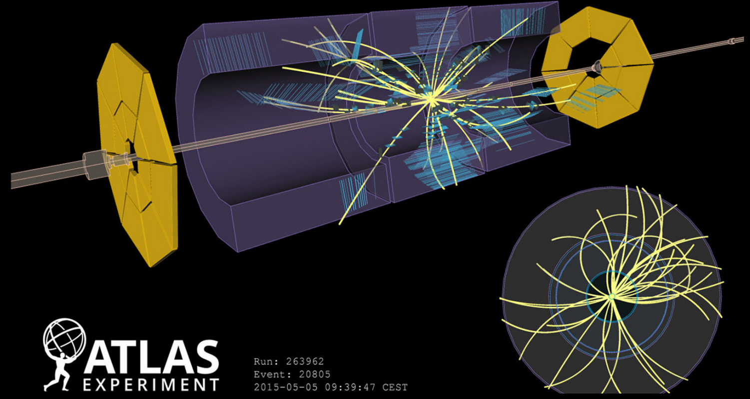
Matter =/= Antimatter

The fact we exist at all is evidence that there must be Physics beyond the Standard Model

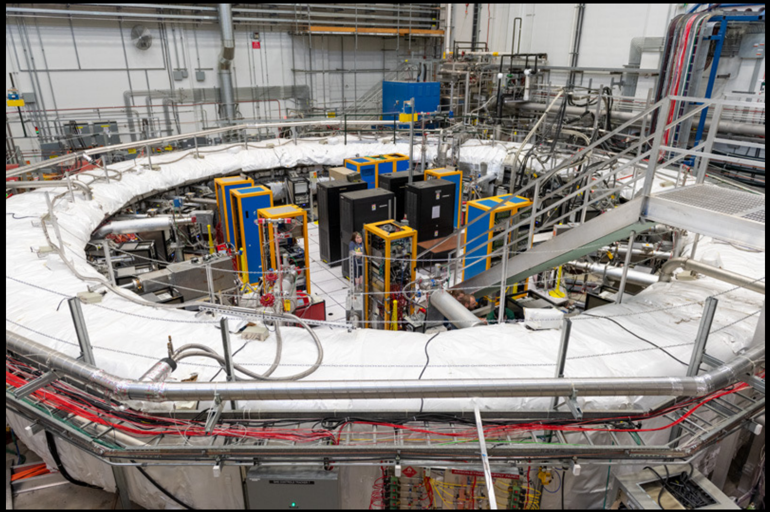
Finding “New Physics”: two options

1. Try and produce new particles directly in high-energy collisions → e.g. Large Hadron Collider

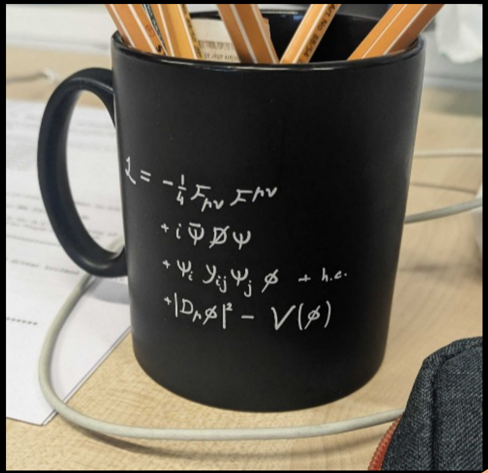




2. Compare ultra-precise SM predictions with ultra-precise measurements

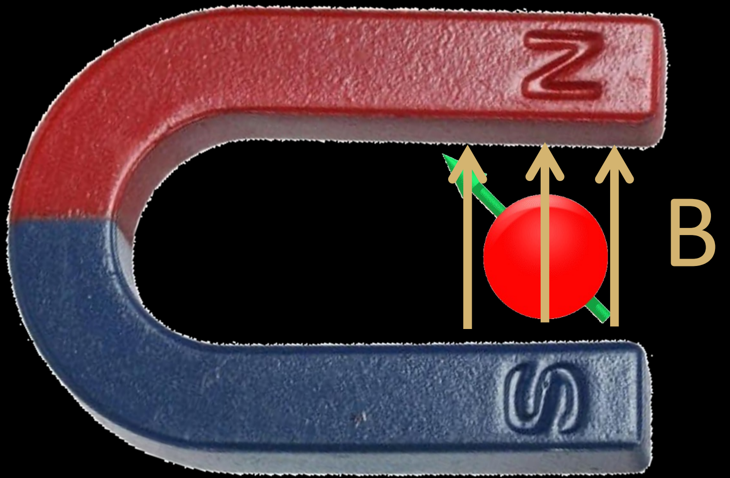


vs



The Muon g-2 as sensitive probe for New Physics

The muons have spin motion…When placed in a magnet, it will precess like a toy top.

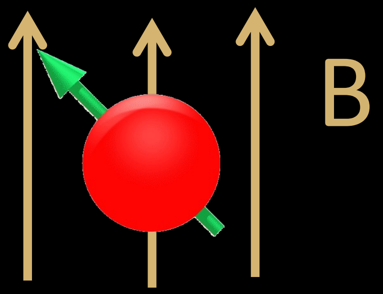


$$\omega_s = g\frac{eB}{m_\mu c}$$

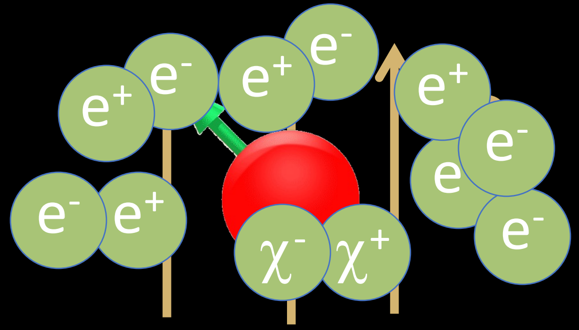
The precession frequency is proportional to *g* (the muon's "magnetic moment", i.e. the strength of the magnetic field)

The Muon g-2 as sensitive probe for New Physics

Heisenberg's uncertainty principle allows, for very short times, the existence of "virtual particles" that lives for a very short time.
These "virtual particles" affects the way in which the muon interact with the magnetic field and this causes **$g \neq 2$**



$g=2$

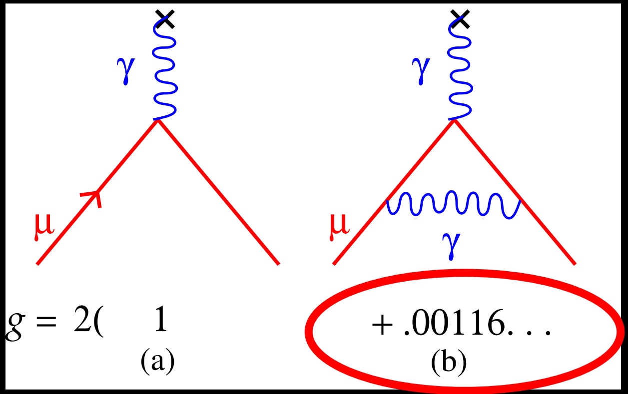


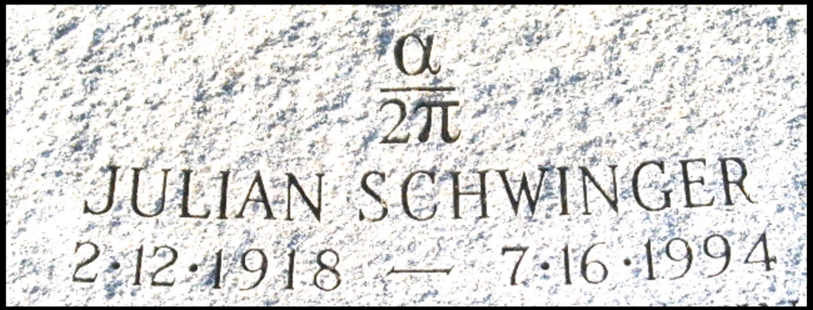
$g \neq 2$

$$a = \frac{g-2}{2} = 0.00116\ldots$$

By measuring precisely g-2 we can be sensitive to each particle in the Universe (the ones that we know but also the ones which we don't know)

1948: The first (mass independent) loop calculation

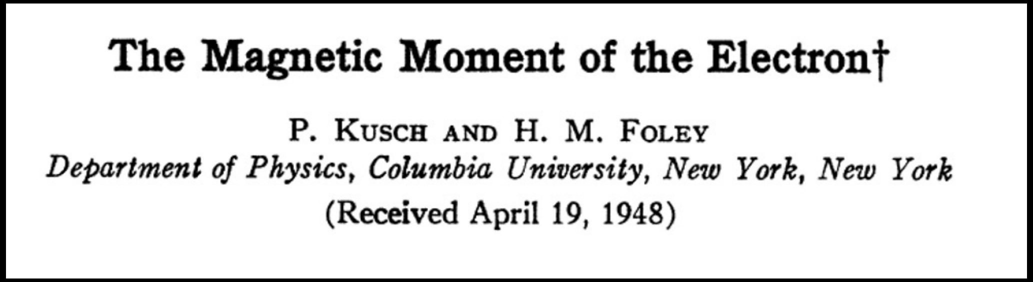




Schwinger, Julian S. *On Quantum electrodynamics and the magnetic moment of the electron*, Phys. Rev.", 73, 1948, 416-417.

$$a = \frac{g-2}{2} = \frac{\alpha}{2\pi} = 0.001162$$

In perfect agreement with Kush & Foley measurement of the electron"g-2"



The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY

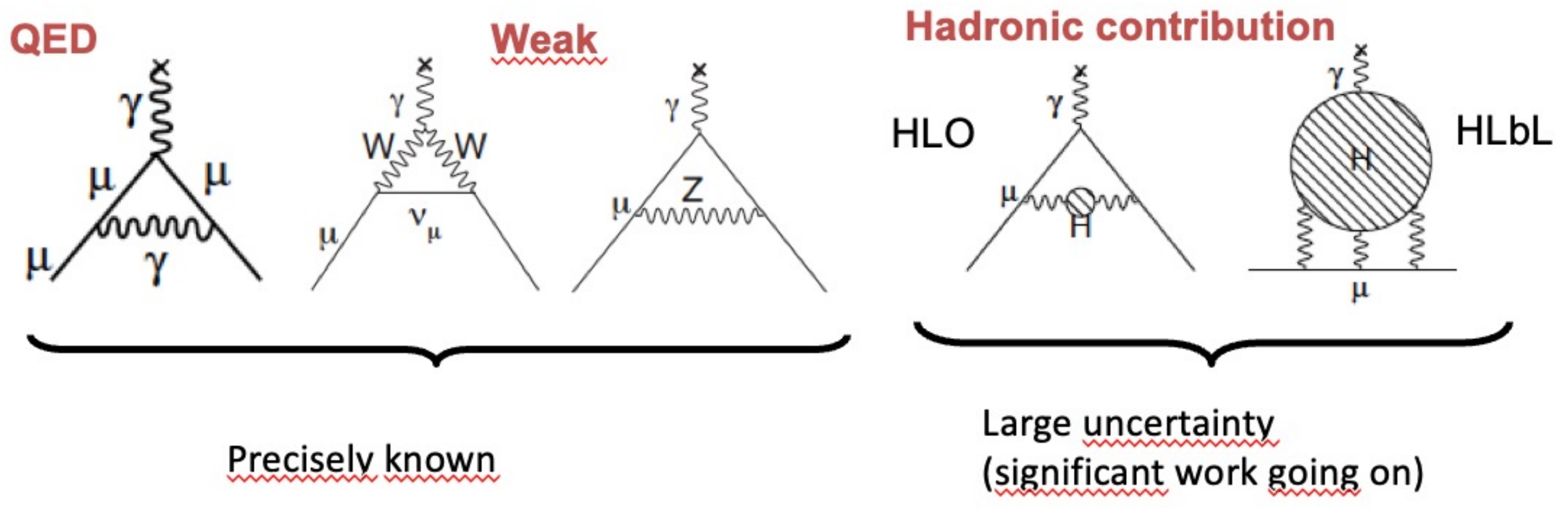
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

a = (g-2)/2 = 0.00119(5)

electron "magnetic moment anomaly"

Nowdays…In the SM a_μ= (g-2)/2 can be computed very precisely!

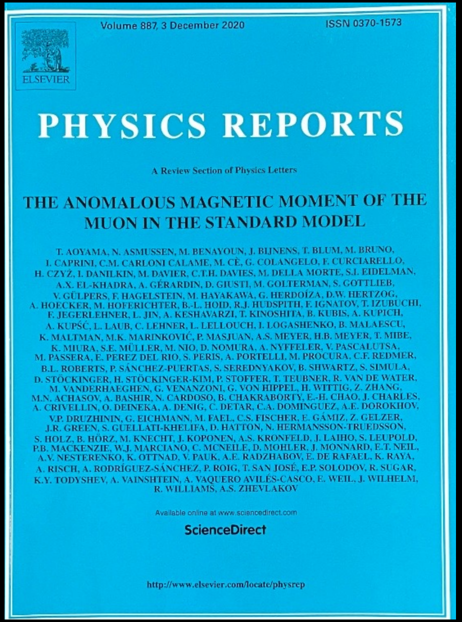


$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

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

$\delta a_\mu^{QED} \sim 1.4\text{x}10^{-12}$ $\delta a_\mu^{HAD} \sim 4\text{x}10^{-10}$ $a_\mu^{Weak} \sim 2\text{x}10^{-11}$

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



Theory Initiative **(wp20):**
T. Aoyama et al. Phys. Rept. 887 (2020)

a_μ^{SM}: the QED contribution

$a_\mu^{QED} = (1/2)(\alpha/\pi)$ Schwinger 1948

$+\ 0.765857426\ (16)\ (\alpha/\pi)^2$

Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; MP '04

$+\ 24.05050988\ (28)\ (\alpha/\pi)^3$

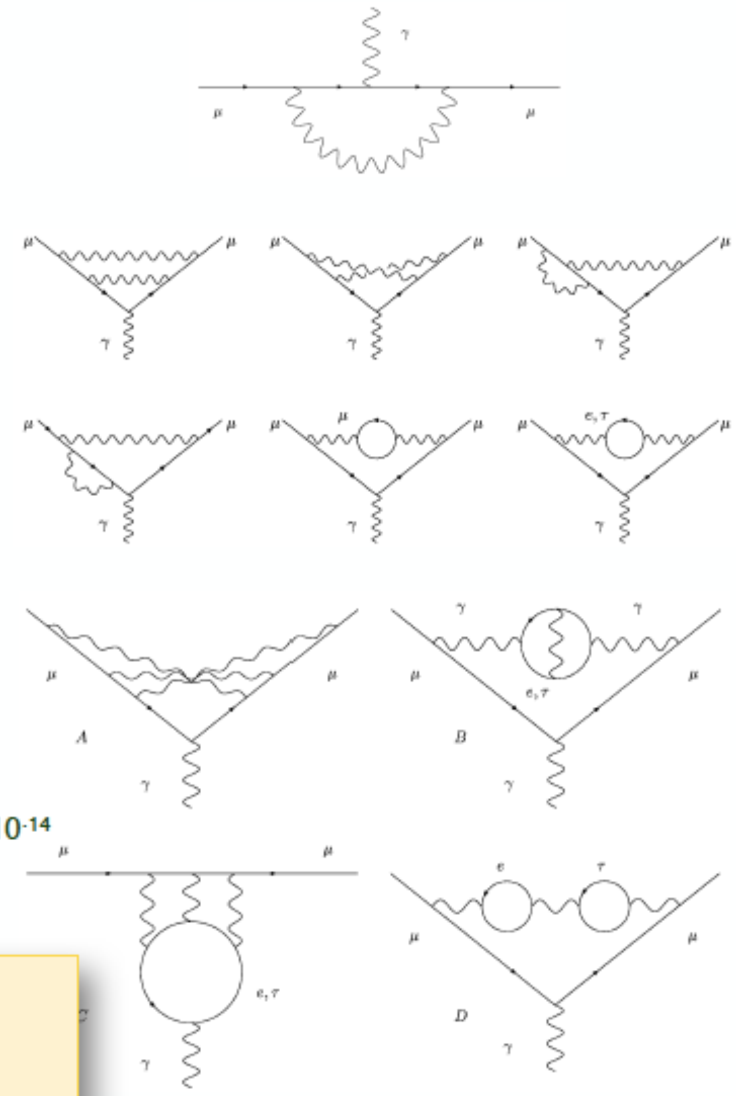
Remiddi, Laporta, Barbieri … ; Czarnecki, Skrzypek '99; MP '04;
Friot, Greynat & de Rafael '05, Ananthanarayan, Friot, Ghosh 2020

$+\ 130.8780\ (60)\ (\alpha/\pi)^4$

Kinoshita & Lindquist '81, … , Kinoshita & Nio '04, '05;
Aoyama, Hayakawa,Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015;
Steinhauser et al. 2013, 2015 & 2016 (all electron & τ loops, analytic);
Laporta, PLB 2017 (mass independent term) COMPLETED²!

$+\ 750.86\ (88)\ (\alpha/\pi)^5$ COMPLETED!

Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,…
Aoyama, Hayakawa, Kinoshita, Nio 2012, 2015, 2017 & 2019.
Volkov 1909.08015: $A_1^{(10)}$[no lept loops] at variance, but negligible $\delta a_\mu \sim 6\times10^{-14}$



Adding up, we get:

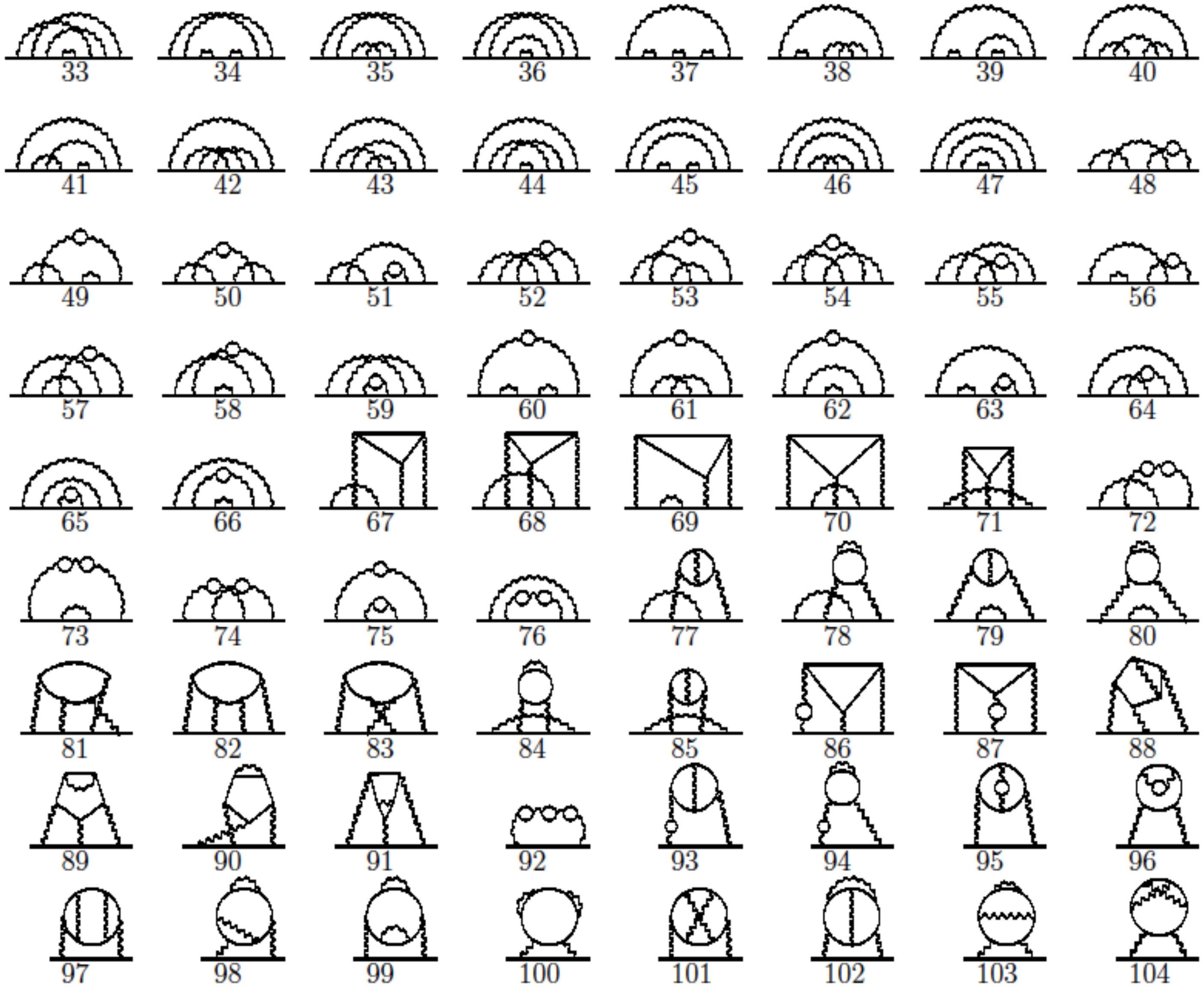
$a_\mu^{QED} = 116584718.931\ (19)(100)(23) \times 10^{-11}$

mainly from 4-loop coeff. unc. — 6-loop — from α(Cs)

$\alpha = 1/137.035999046(27)$ [0.2ppb] Parker et al 2018 — WP20 value

WP20 = White Paper of the Muon g-2 Theory Initiative: arXiv:2006.04822

Impressive calculation…thousands of diagrams

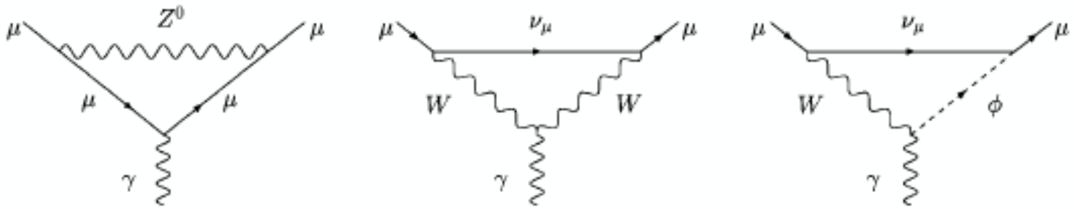


S. Laporta "High-precision calculation of the 4-loop contribution to the electron g-2 in QED" *Phys.Lett.B* 772 (2017) 232

The 4-loop self-mass diagrams.

The electroweak contribution

- **One-loop term:**



$$a_\mu^{\mathrm{EW}}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2+O\left(\frac{m_\mu^2}{M_{Z,W,H}^2}\right)\right] \approx 195\times10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;
Studenikin et al. '80s

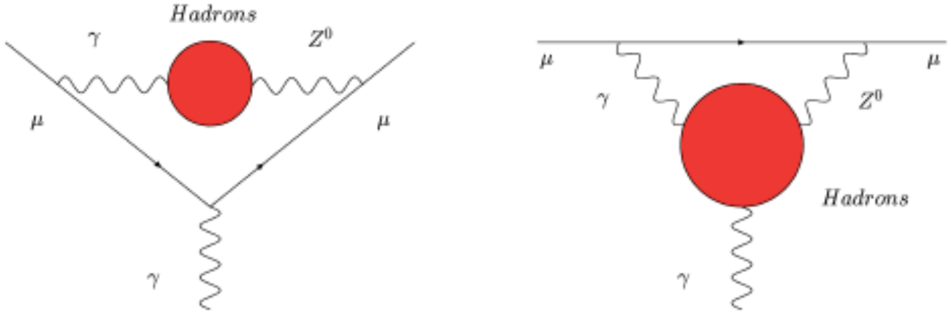
- **One-loop plus higher-order terms:**

$a_\mu^{\mathrm{EW}} = 153.6\ (1.0) \times 10^{-11}$

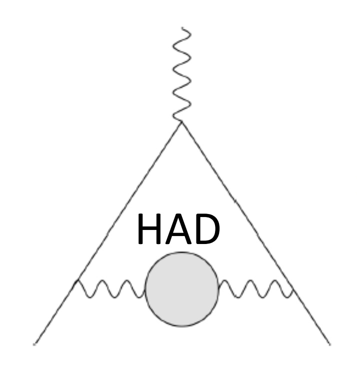
Hadronic loop uncertainties (and 3-loop nonleading logs).

WP20 value

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa, Yasui, 2019.

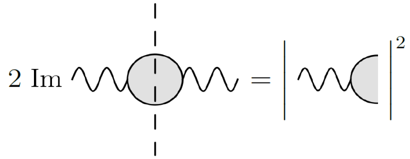


a_μ^{HLO} (HVP) Calculation: Dispersive (e^+e^-) Method



a_μ^{HLO}

- Calculated from data for $\sigma(e^+e^- \rightarrow$ hadrons)



$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty} \frac{K(s)}{s} R(s) ds$$

Hadronic R-ratio (Data Driven)

- Uses **data** from different experiments from **20+ years**
- 1/s weights low energy strongly: 73% from **$\pi^+\pi^-$ channel**

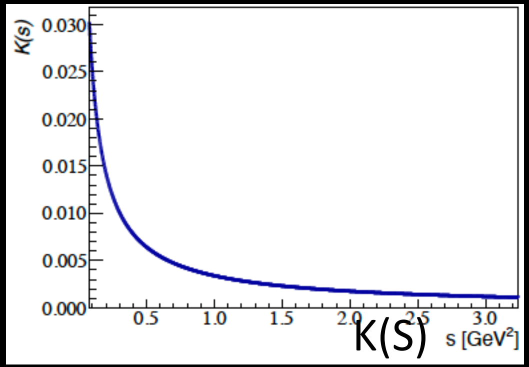
$$\mathbf{R(s)} = \frac{\sigma^0(e^+e^- \to \gamma \to \text{hadrons})}{4\pi\alpha^2/3s}$$

a_μ^{HLO} = 6895 (33) x 10^{-11} F. Jegerlehner, arXiv:1711.06089

= 6939 (40) x 10^{-11} Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921

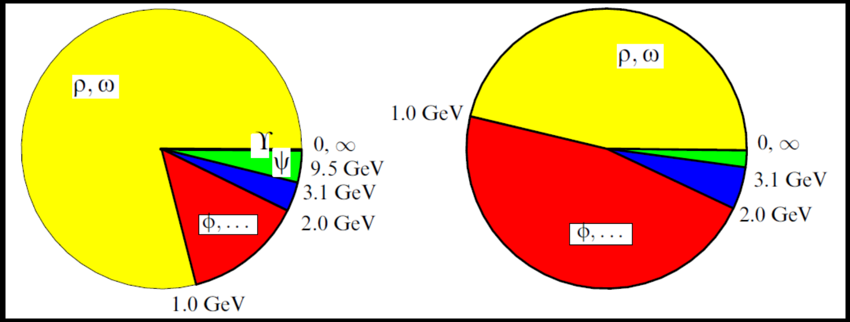
= 6928 (24) x 10^{-11} Keshavarzi, Nomura, Teubner, arXiv:1911.00367

= 6931 (40) x 10^{-11} (0.6%) WP20 value



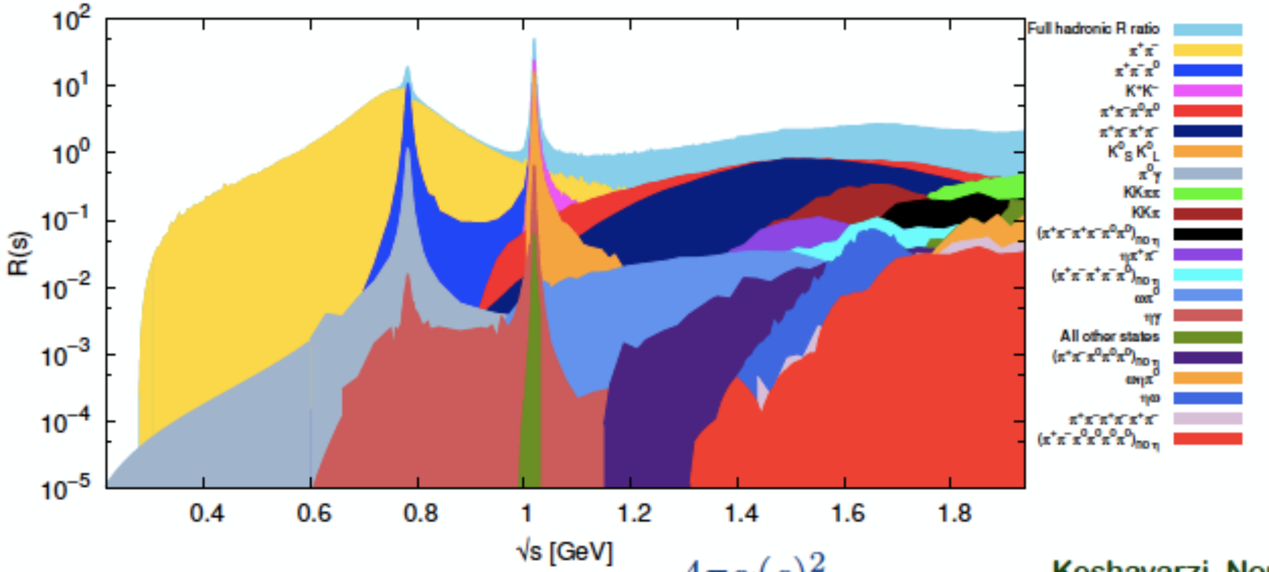
$$a_\mu^{HLO} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} R(s)K(s) \sim \int \frac{R(s)}{s^2} ds$$

the main contribution comes from low energies



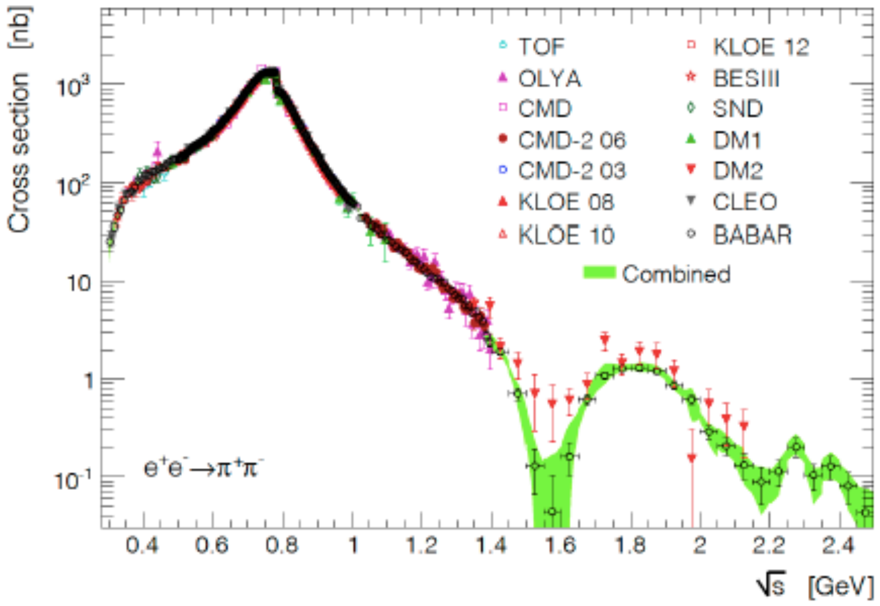
Contribution to the integral Contribution to the error of integral

The low-energy hadronic cross section



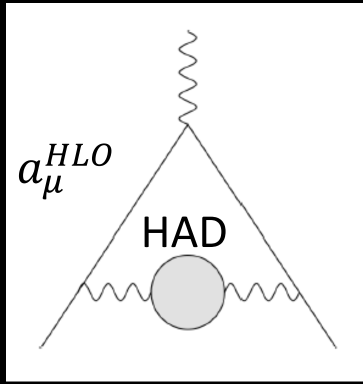
$$R(s) = \sigma(e^+e^- \to \text{hadrons}) / \frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner
PRD 2018



Davier, Hoecker, Malaescu, Zhang
EPJC 2020

a_μ^{HLO} (HVP): Lattice calculation

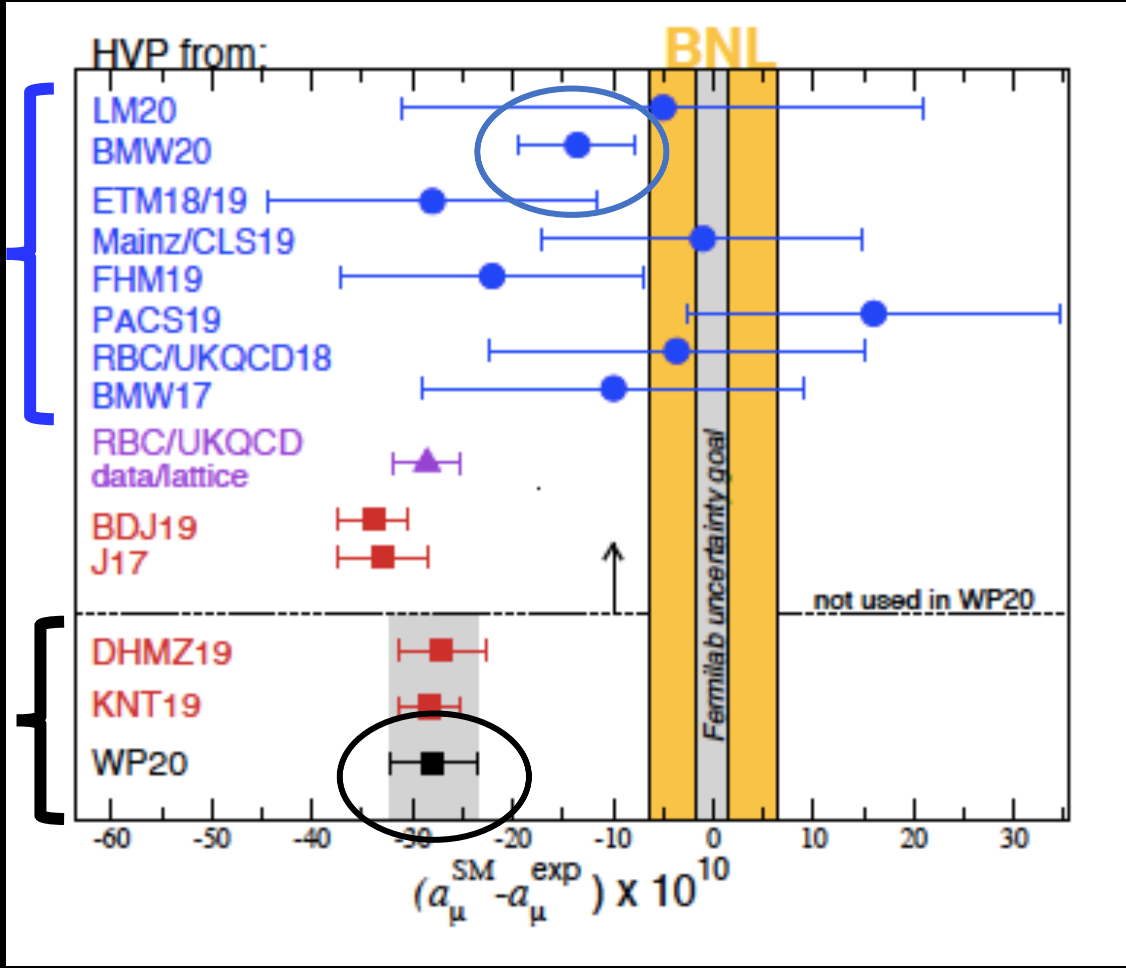


Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision: $a_\mu^{HLO} = 7075(23)_{stat}(50)_{syst} \times 10^{-11}$. Some tension with dispersive evaluations. BMW20

55

LATTICE calculation →

DISPERSIVE approach →



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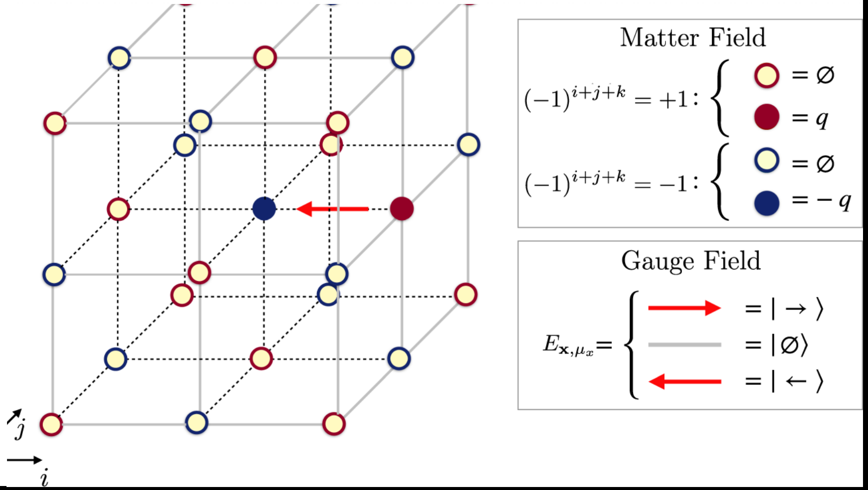
Article | Published: 07 April 2021

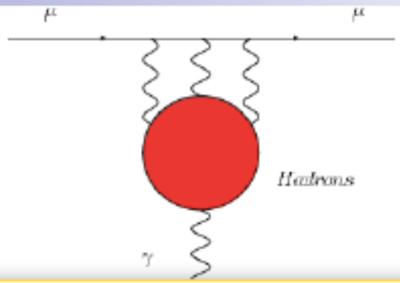
Leading hadronic contribution to the muon magnetic moment from lattice QCD

Sz. Borsanyi, Z. Fodor, J. N. Guenther, C. Hoelbling, S. D. Katz, L. Lellouch, T. Lippert, K. Miura, L. Parato, K. K. Szabo, F. Stokes, B. C. Toth, Cs. Torok & L. Varnhorst

Nature **593**, 51–55 (2021) | Cite this article



The hadronic LbL contribution



- **Hadronic light-by-light at O(α³)**
  - This term had a troubled life! But nowadays:

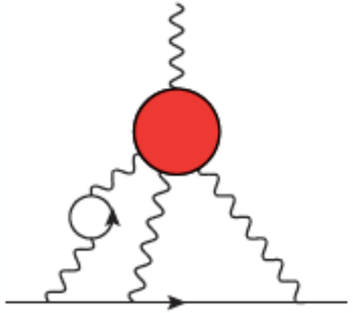
$a_\mu^{HNLO}(lbl)$	=	$80\ (40) \times 10^{-11}$	Knecht & Nyffeler '02
	=	$136\ (25) \times 10^{-11}$	Melnikov & Vainshtein '03
	=	$105\ (26) \times 10^{-11}$	Prades, de Rafael, Vainshtein '09
	=	$100\ (29) \times 10^{-11}$	Jegerlehner, arXiv:1705.00263
	=	$92\ (19) \times 10^{-11}$	WP20 (phenomenology)

  - Significant improvements due to data-driven dispersive approach.
    Colangelo, Hoferichter, Procura, Stoffer, 2014–17; Pauk, Vanderhaeghen 2014.
  - Lattice: RBC: $82(35)\times10^{-11}$ 1911.08123 Mainz: $110(15)\times10^{-11}$ 2104.02632

- **Hadronic light-by-light at O(α⁴)**

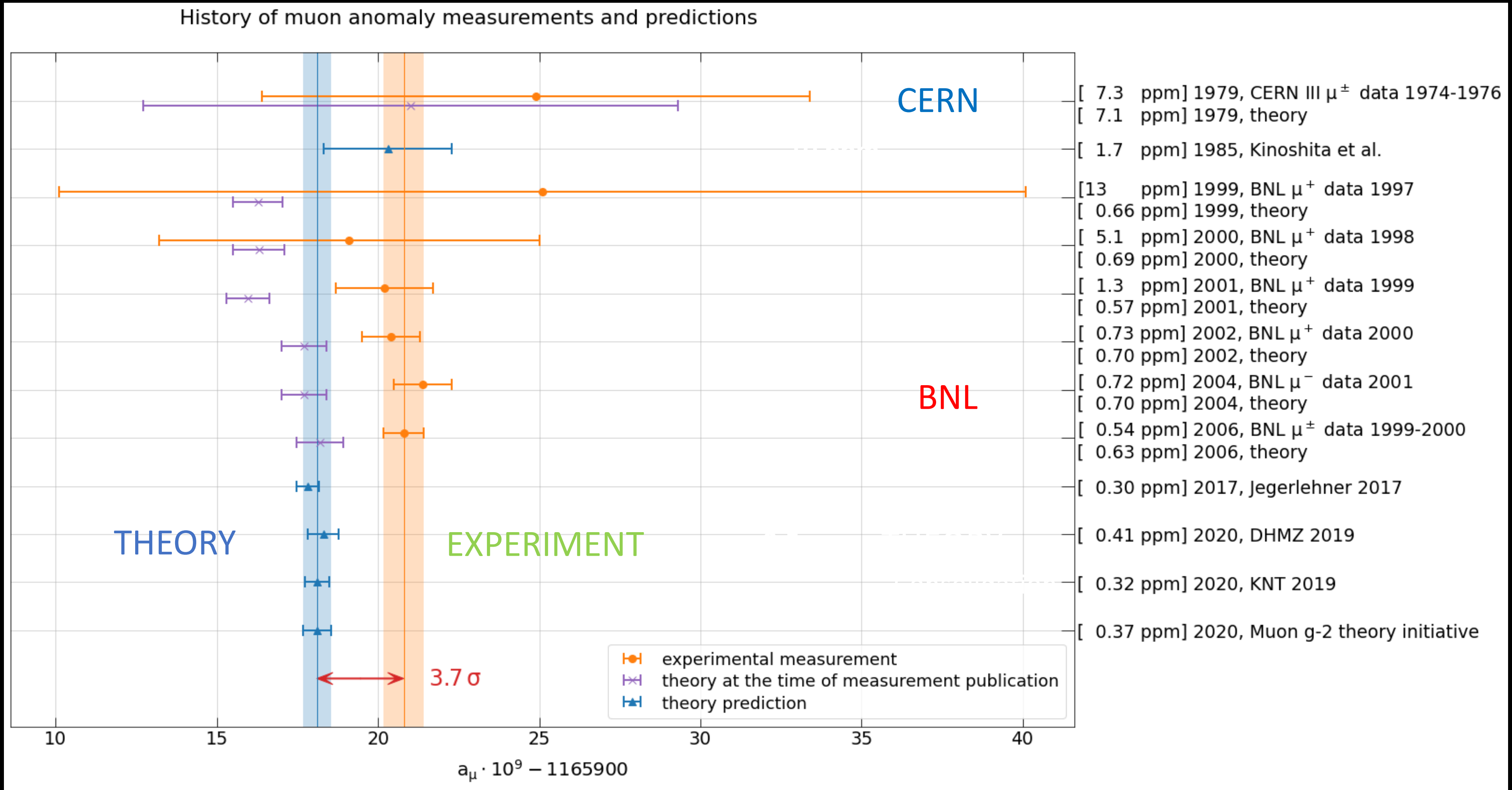
$$a_\mu^{HNNLO}(lbl) = 2\ (1) \times 10^{-11}$$

Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014; WP20



A rich history of g-2 Theory and measurements (year 2000)

a_μ=(g-2)/2 =Muon (magnetic) anomaly



History of the experiments (1950s →2004)

- The storage ring method was developed at CERN around 1960 and improved at BNL (‘90s) through a series of experiments with increasing precision which allowed to test the SM at the level of strong (CERN) and EW (BNL) effects

Storage ring method

$\pm$	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

Pre "g-2" history (1950s)

Lee and Yang (1956)

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

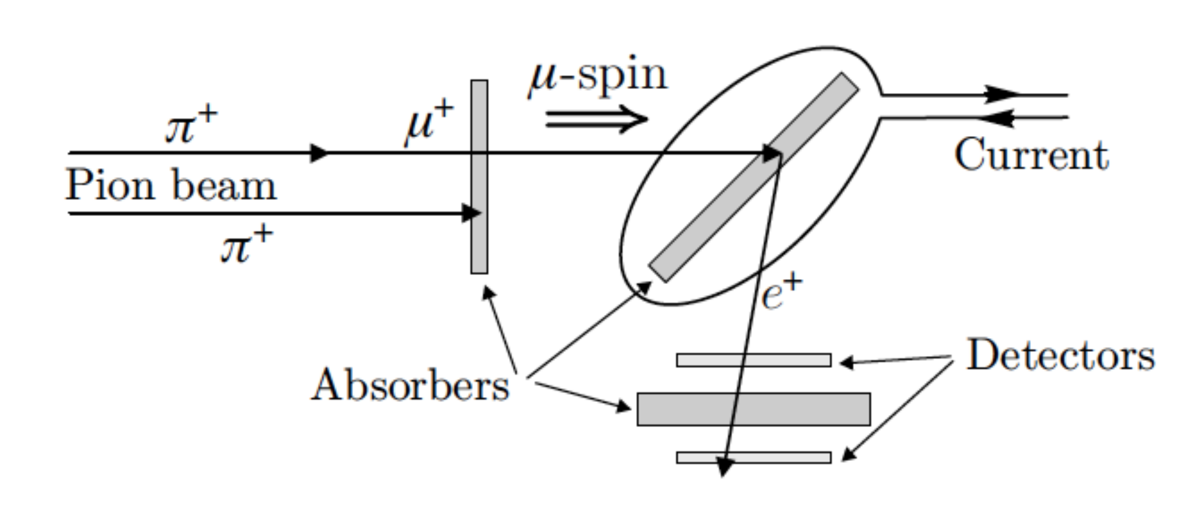
AND

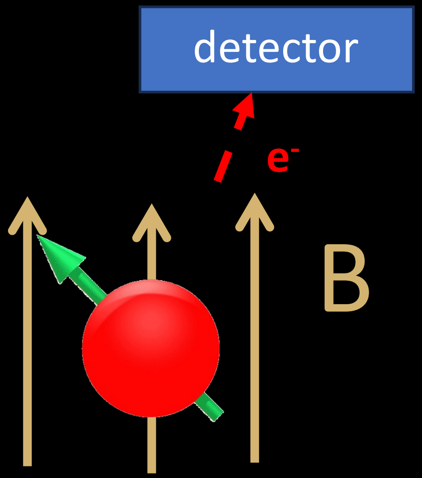
C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

A revolutionary idea (nobel prize 1957)

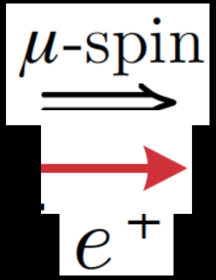
$$\mu^- \rightarrow e^- \ \bar{\nu}_e \ \nu_\mu$$



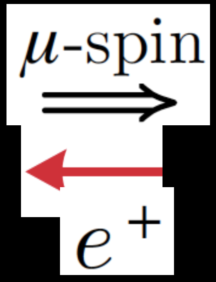


$$\omega_s = g\frac{eB}{2mc}$$

The positron is (preferably) emitted in the direction of the spin. If you count them in a certain direction, its rate is modulated by the precession frequency of the spin (magnetic moment)which depends on ***g***



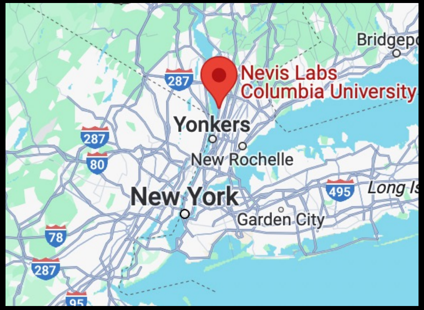
favoured

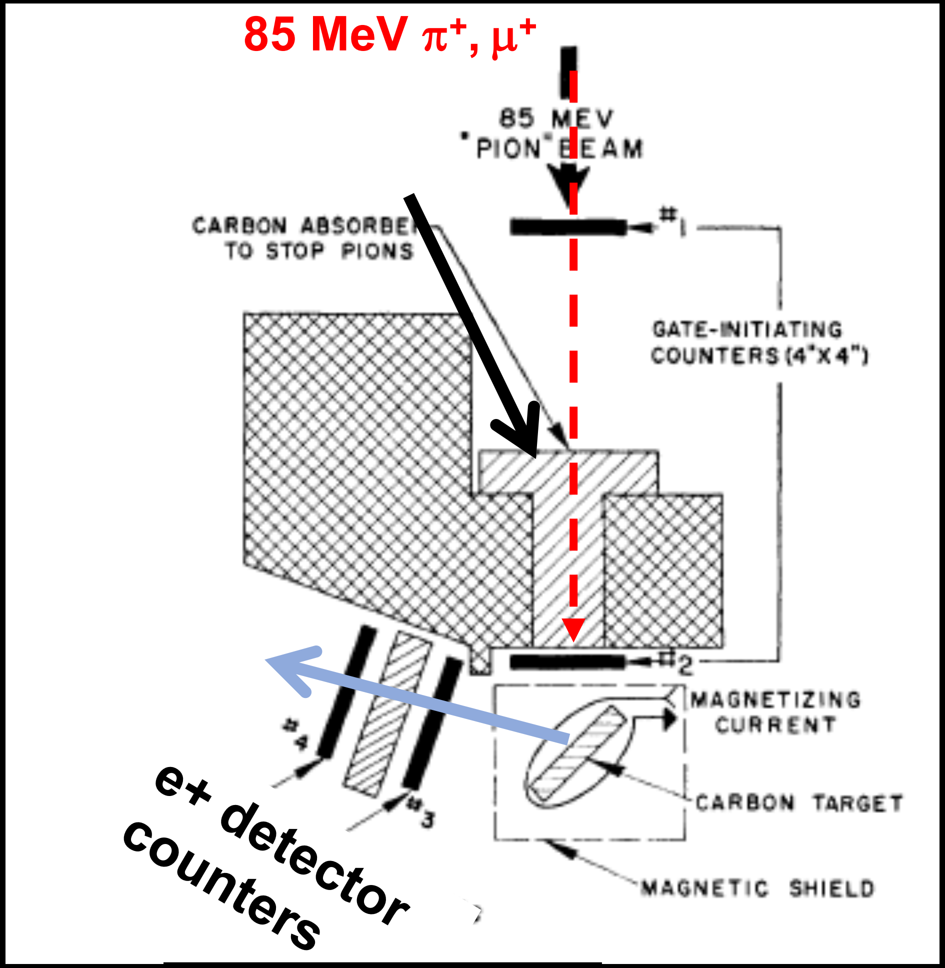


disfavoured

Two experiments measured "g" in the 1950s

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





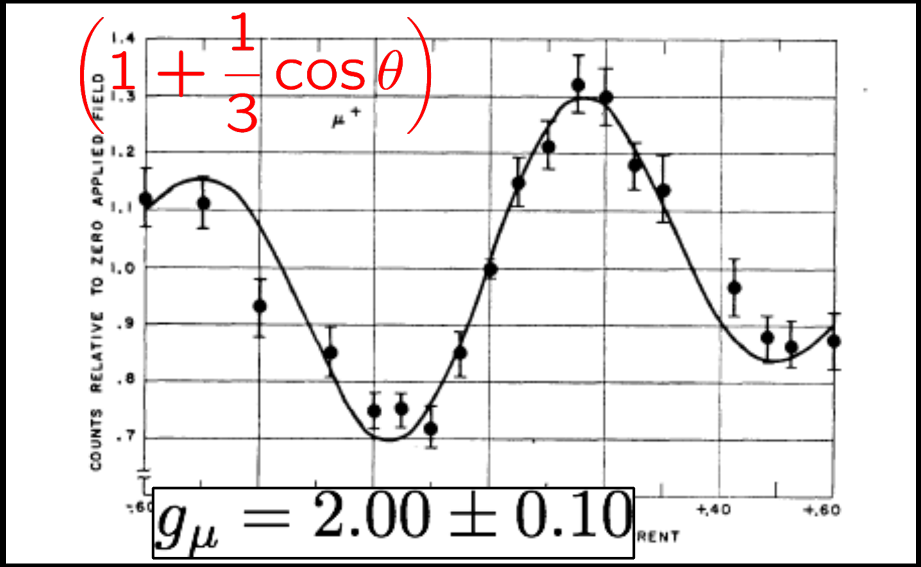
Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

5% uncertainty



muons behave like electrons

Two experiments measured "g" in the 1950s

- 1957: Cassels, et al. (Liverpool) 1957

Experiments with a Polarized Muon Beam

To cite this article: J M Cassels *et al* 1957 *Proc. Phys. Soc.* A **70** 543

stopped μ then decay → e^+

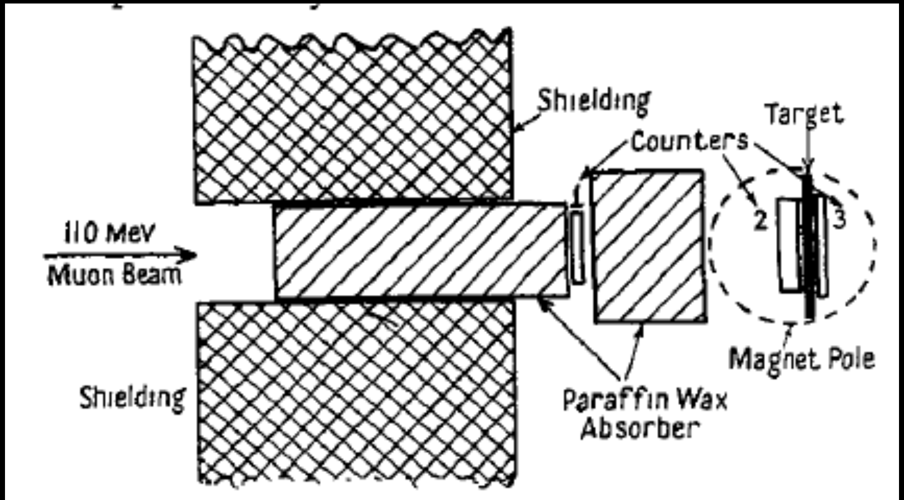
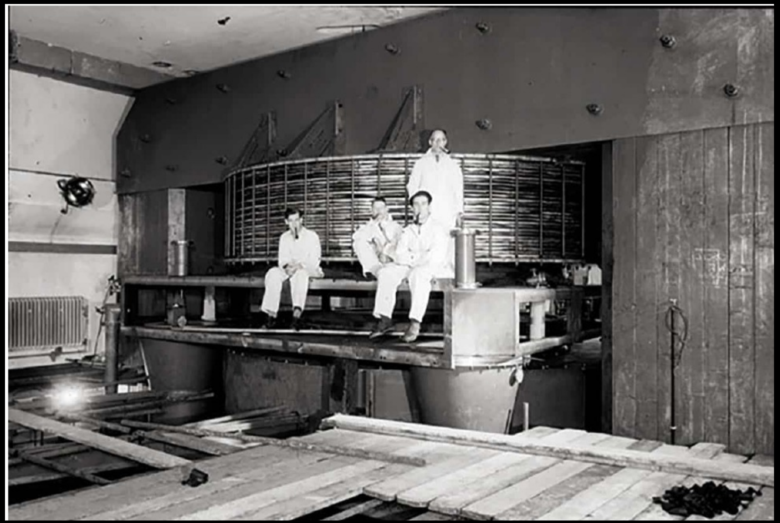
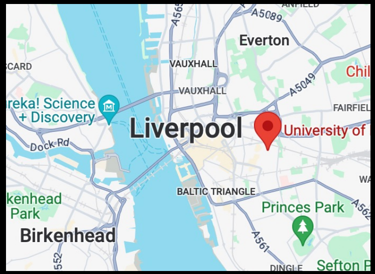


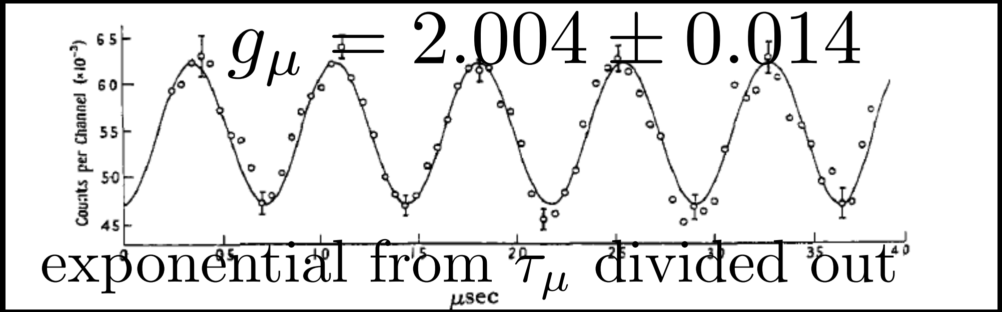
Figure 1 Layout of experimental apparatus





156 inch Cyclotron in Liverpool **0.7% uncertainty**

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



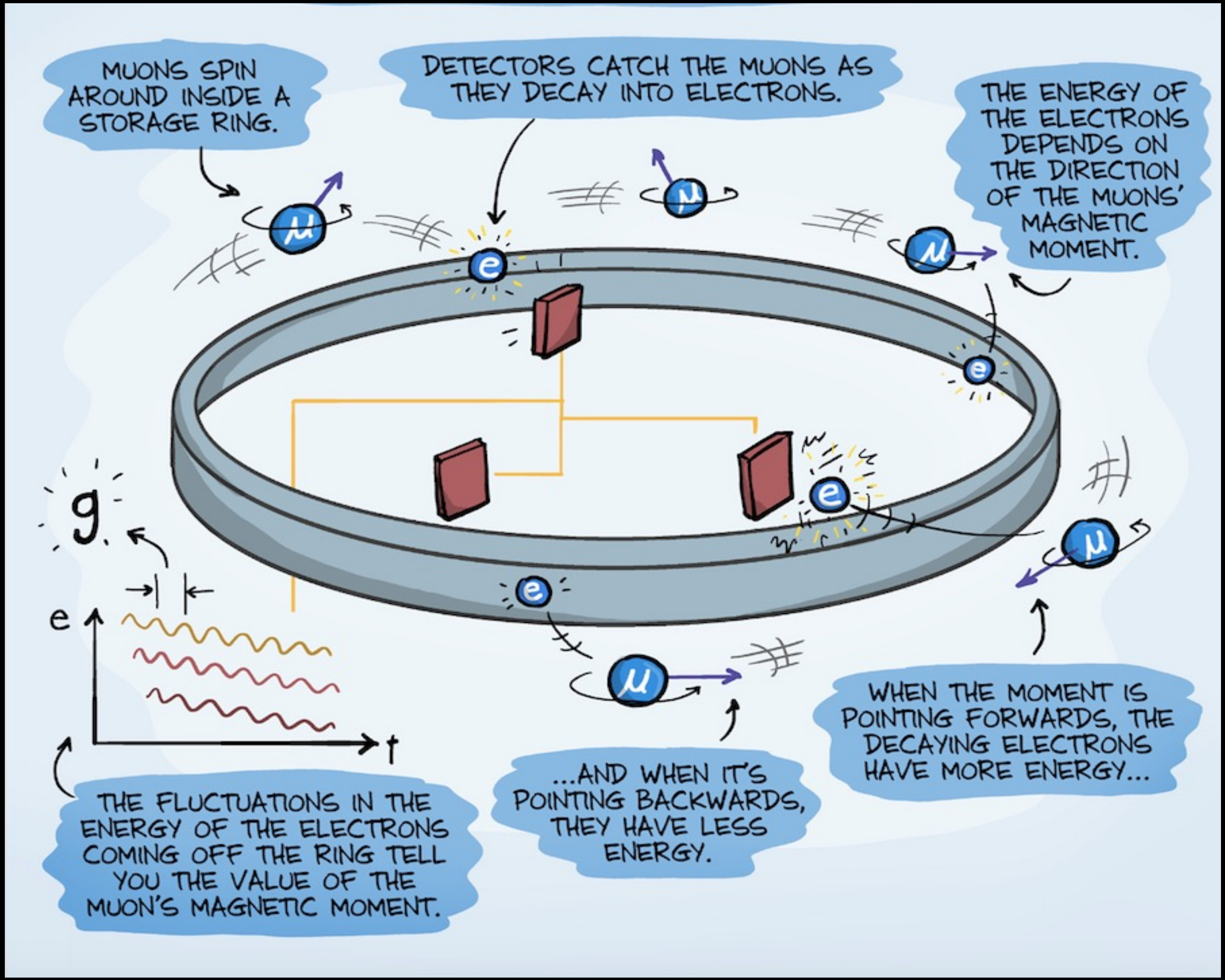
exponential from τ_μ divided out

"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"

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

To improve the accuracy → storage ring!

The Muon “g-2” experiments (1960s to 2023)



Principle of the Muon g-2 experiment

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

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

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

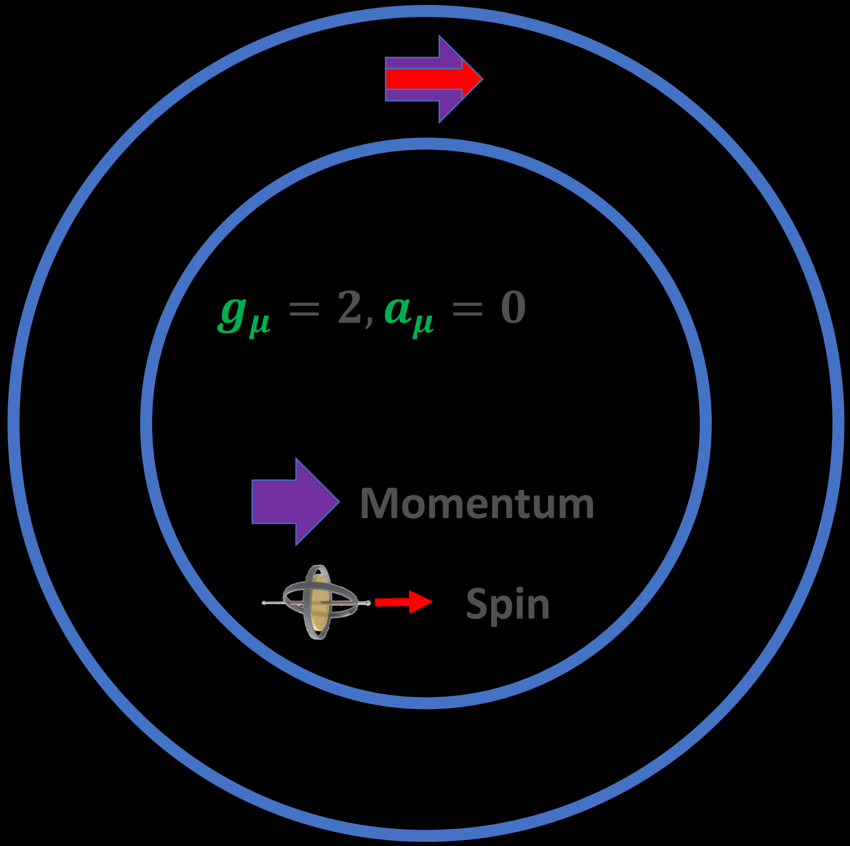
Principle of the Muon g-2 experiment

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

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

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

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



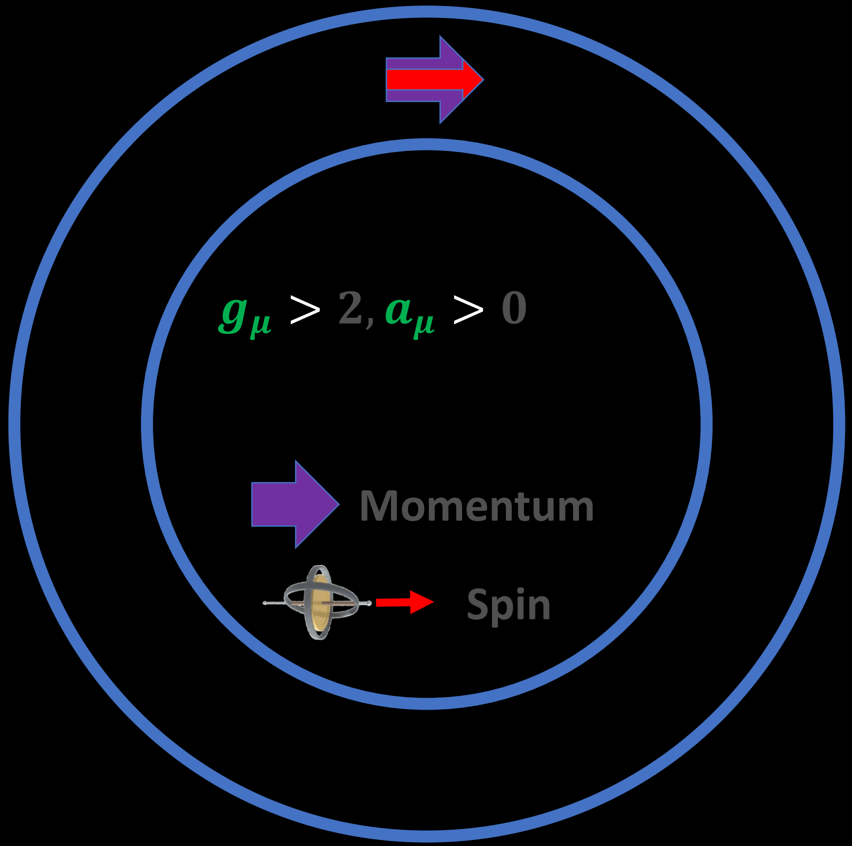
Principle of the Muon g-2 experiment

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

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

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

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



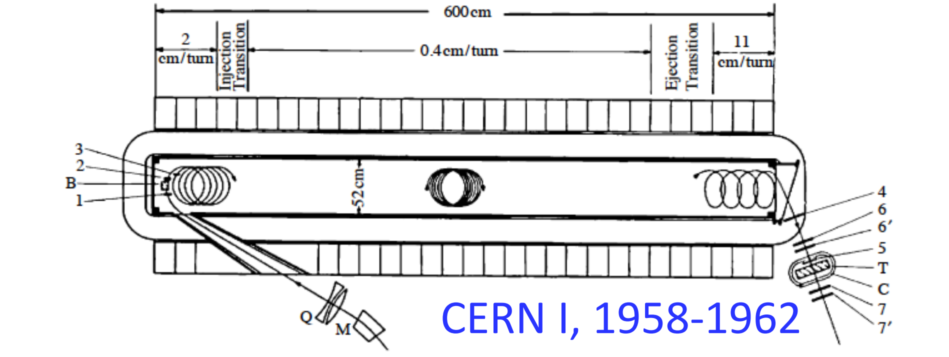
In the muon g-2 experiment we measure very precisely:

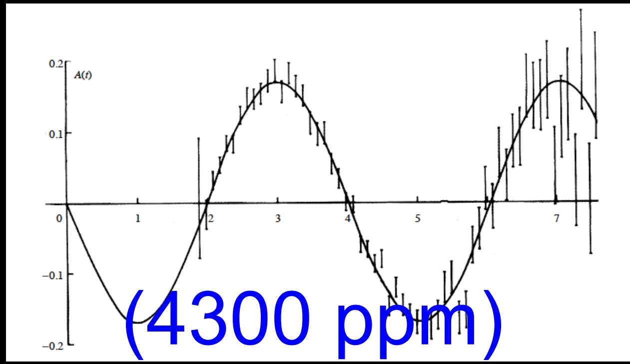
- the frequency of the spin respect to the momentum (ω_a);
- the magnetic field

The CERN experiments I –II (1960s)

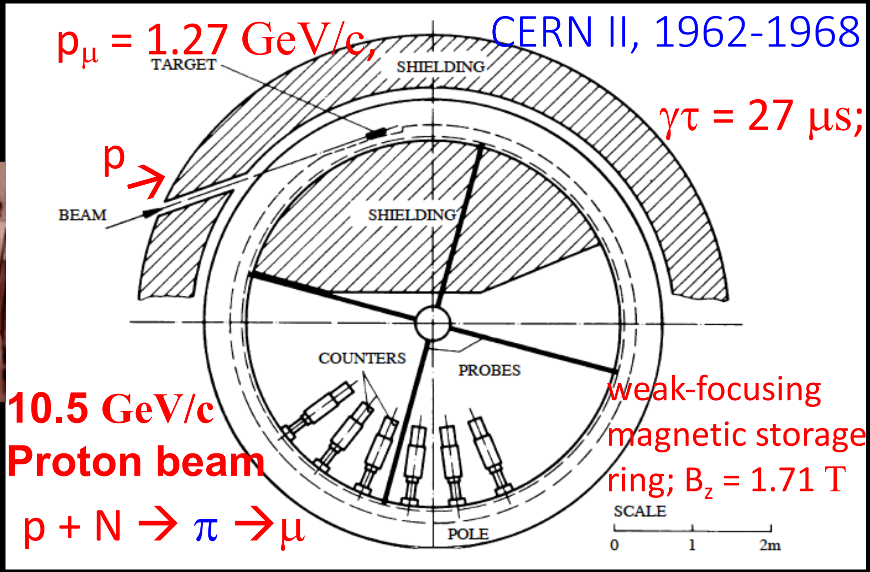
1 ppm (part per million) = 0. 000 001

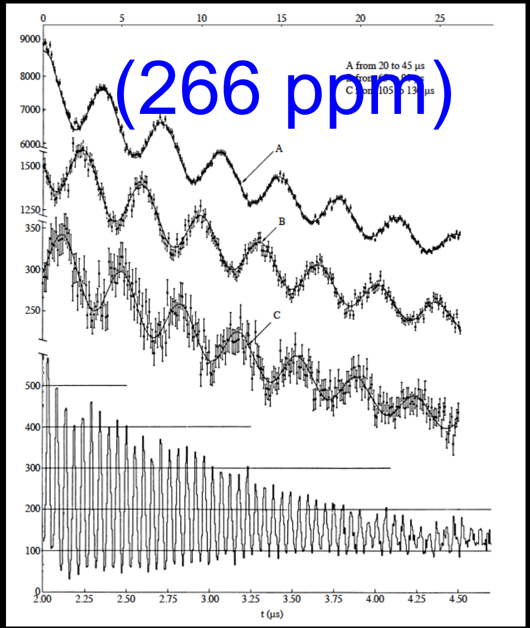
Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.





CERN II (1968): 1st use of a magnetic ring





The concept of magic momentum

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

→ Use electrostatic quadrupoles - but adds complications

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

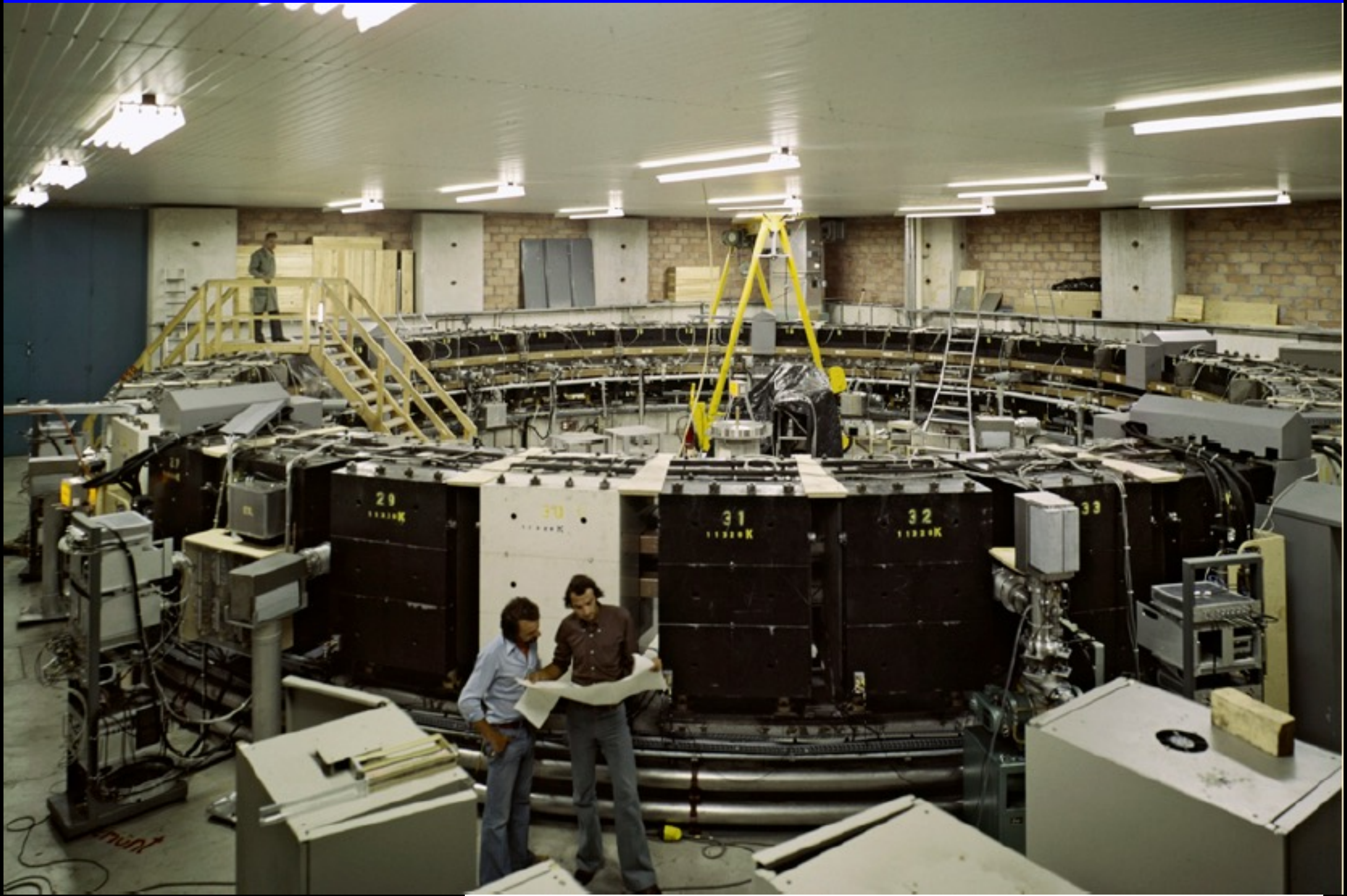
$$(p_\mu = 3.09 \text{ GeV}/c)$$

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)

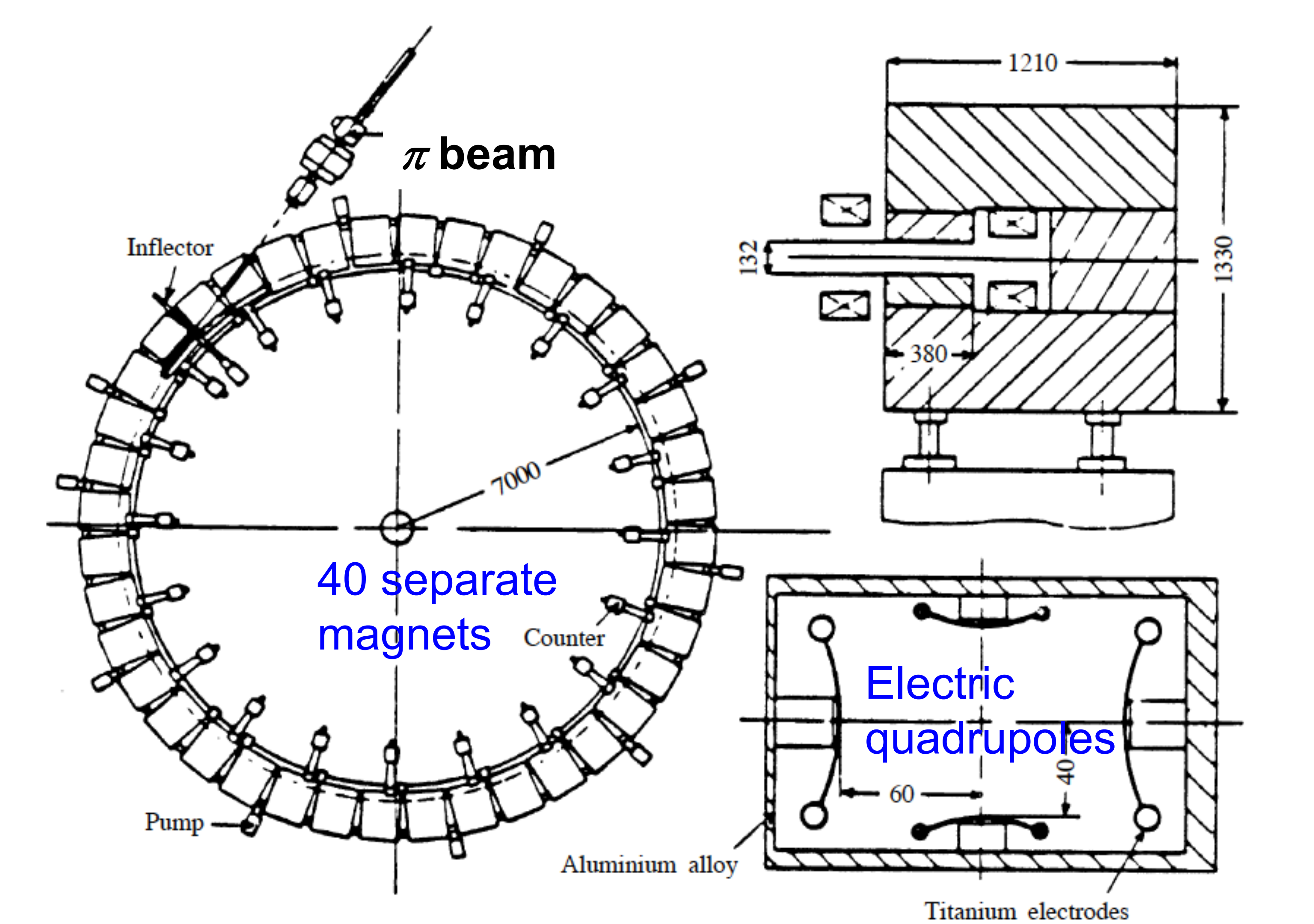
Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

3rd Muon g-2 experiment at Cern



CERN III, 1969-1976

- Inject pions at 3.2 GeV (CERN-II was injecting protons)
- Use $\pi \rightarrow \mu$ decay to kick muons onto stable orbits Muon lifetime dilates to 64 μs
- Magic momentum and Electric field for vertical focusing



Still have pion flash at injection!

Not as bad as for CERN2

CERN III, 1969-1976

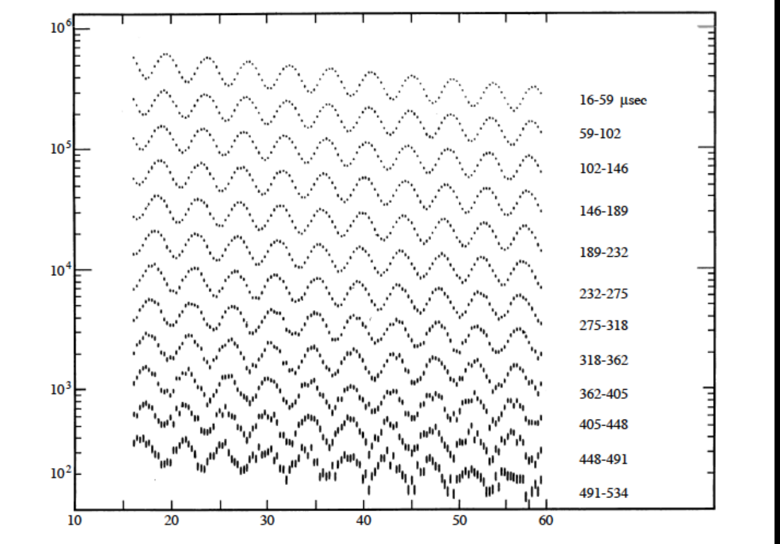
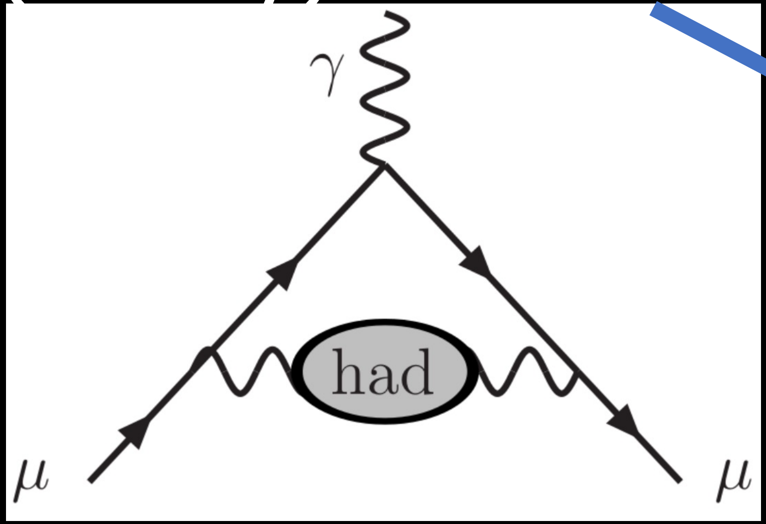


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).

$a_\mu(\text{expt}) = 0.001165924(9)$ **(7.3 ppm)**

$a_\mu(\text{theory}) = 0.001165921(13)$



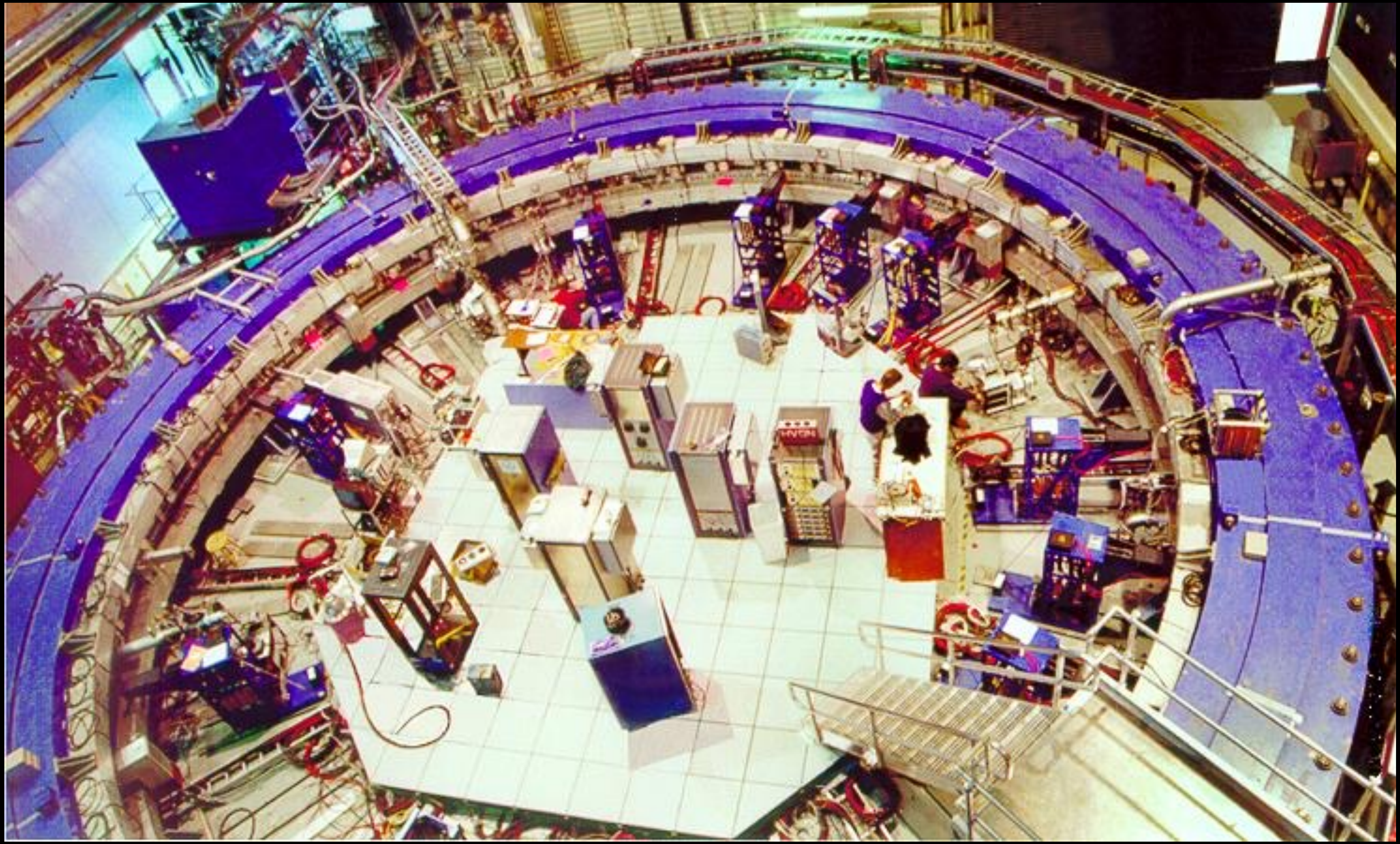
HVP (hadronic vacuum polarization)

$a_\mu^{HAD} \sim 700^{-10}$ (~60 ppm)

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

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)



Improvements:

Much higher intensity

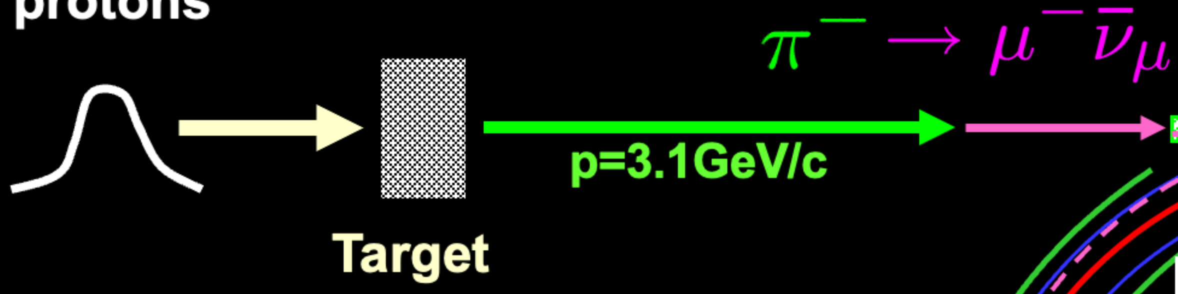
3 superconducting coils

Inject muons into ring with inflector and kicker

In-situ B measurements with NMR probes

E821 Experimental Technique

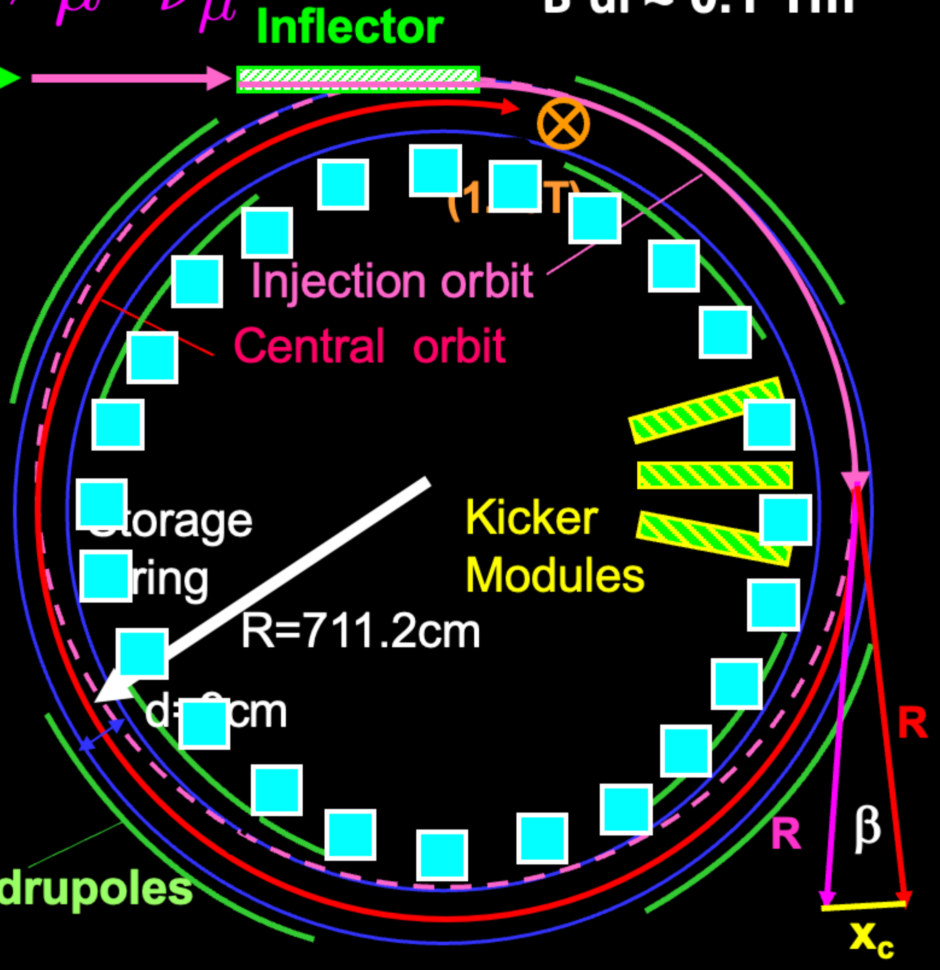
25ns bunch of
$\geqslant$ 1 X 10^{12}
protons



$x_c \approx 77$ mm

$\beta \approx 10$ mrad

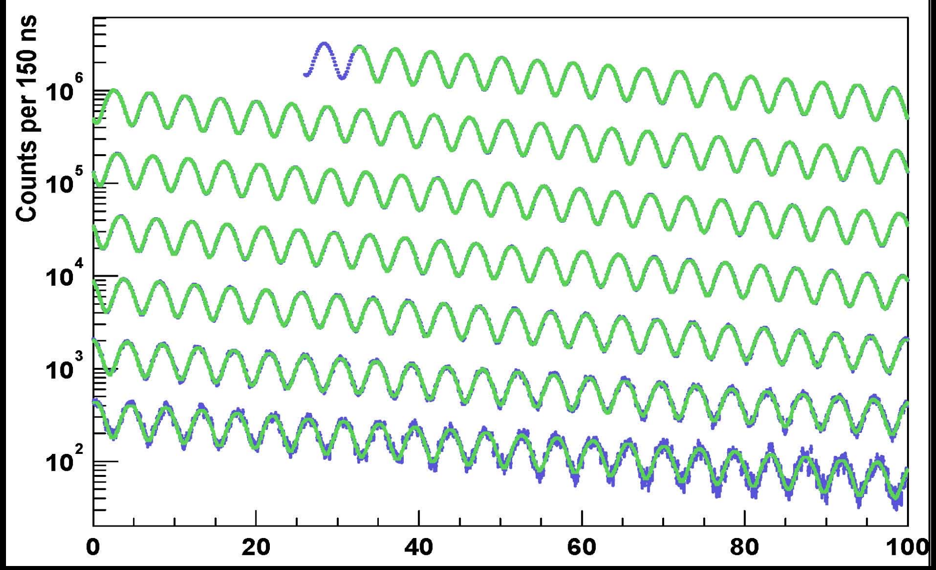
B·dl ≈ 0.1 Tm



- 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



(2006)

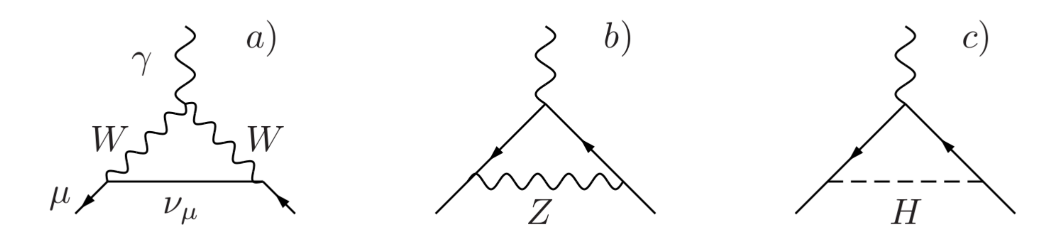
a_μ(expt) = 0.00116592089(63) **(0.54 ppm)**

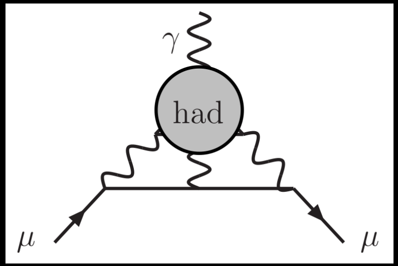
a_μ(theory) = 0.00116591820(73)

(HMNT 03)

EW

Hadronic light-by-light



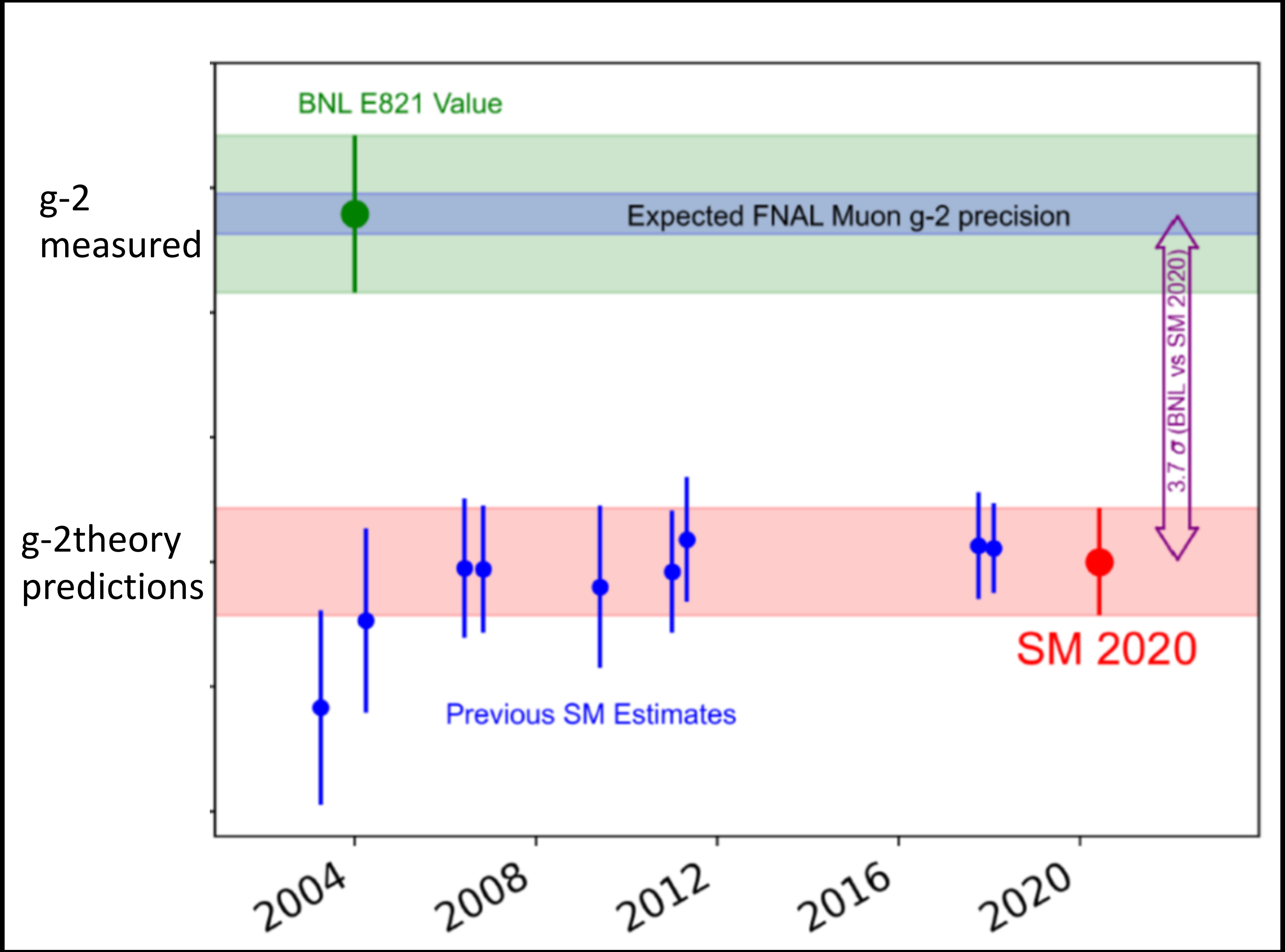


a_μ^{EW} ~ 15.3^{-10} (~1.3 ppm)

a_μ^{HLbL} ~ 9.2^{-10} (~0.8 ppm)

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

Situation after BNL experiment (year 2000s)



Is the measurement wrong?

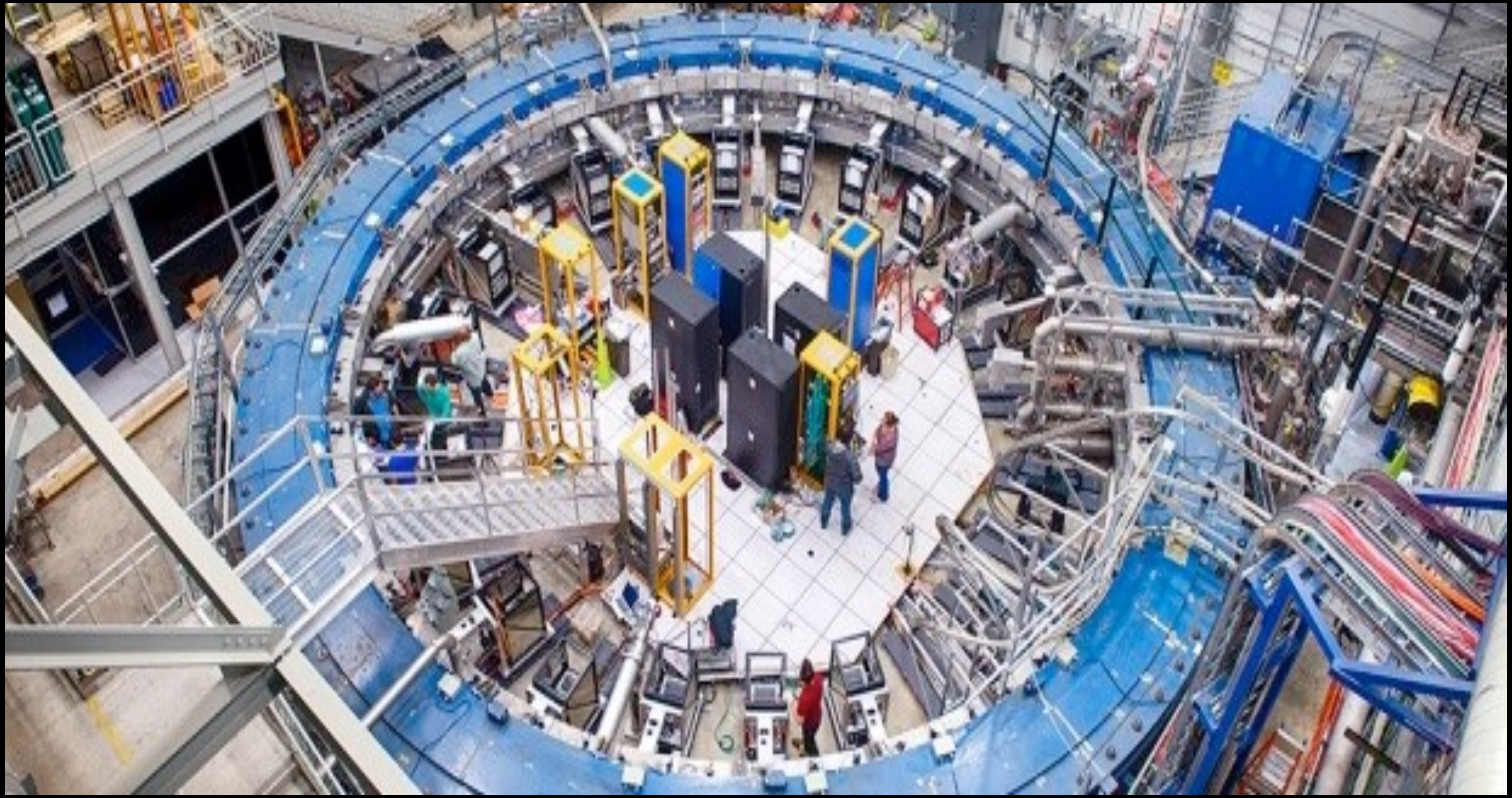
$$a_\mu^{BNL} - a_\mu^{SM} =$$
$$= (279 \pm 76)\times 10^{-11}\ (3.7\sigma)$$

Is Theory wrong ???

→ We need another experiment…

(from D. Hertzog)

The Muon g-2 Experiment at Fermilab (2009 – 2023)



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**

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

↳ $0.2\omega_a \oplus 0.17\omega_p$

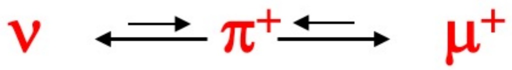
- **E989 at Fermilab**

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

$0.07\omega_a \oplus 0.07\omega_p$

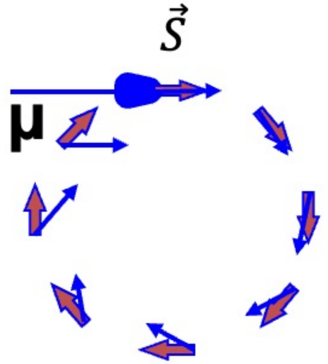
39

Key ingredients



1) Polarized muons

~97% polarized for forward decay



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

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

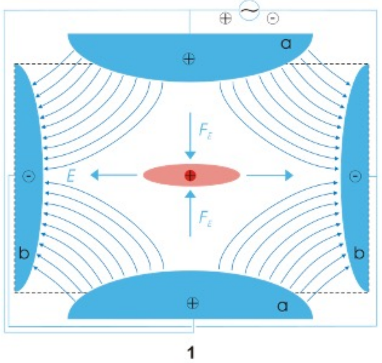
Measure 2 quantities

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

3) P_μ magic momentum = 3.09 GeV/c

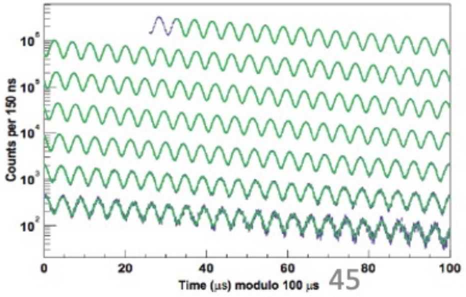
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

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



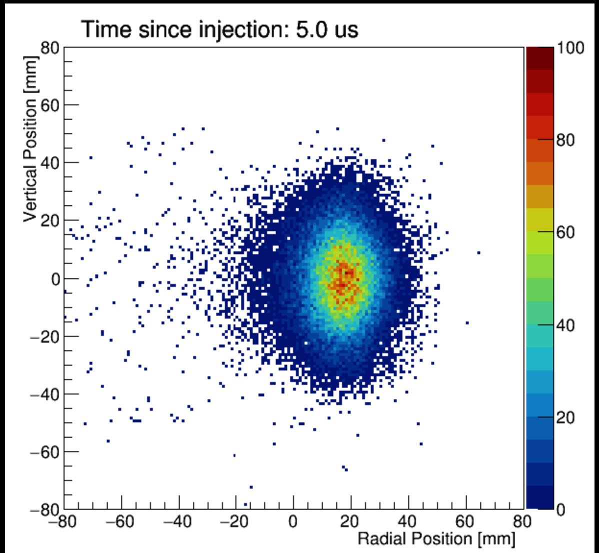
4) Decay e^+ emitted preferably in spin direction of the muon

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



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**

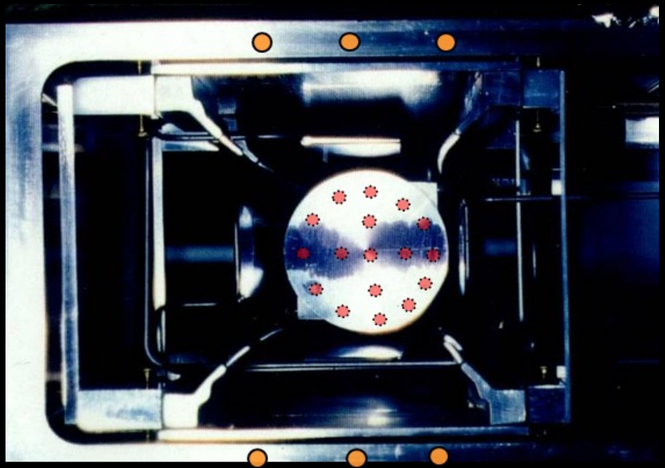
June 2013: The ring leaves from BNL

2013: The Big Move

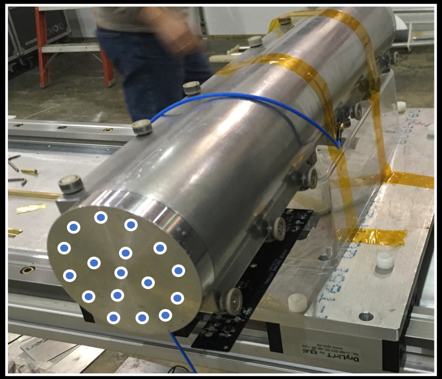
26 July 2013:...the ring arrives to FNAL

The magnetic field is measured using pulsed-proton NMR where the proton "wobble" frequency $\boldsymbol{\omega_p}$ is measured

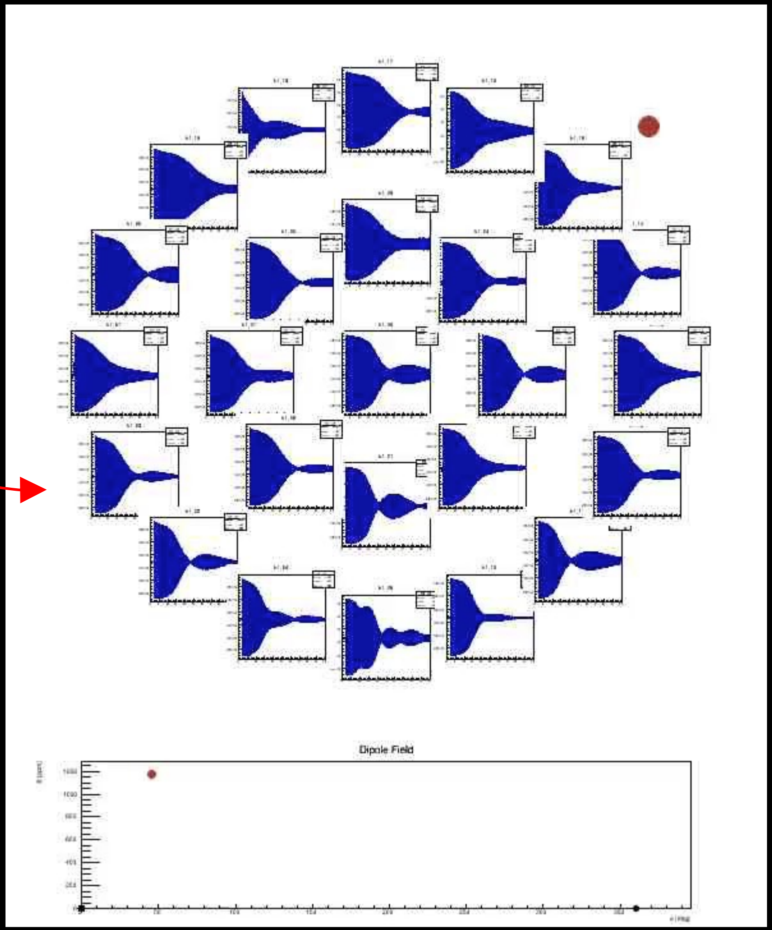
Fixed NMR around the vacuum chamber

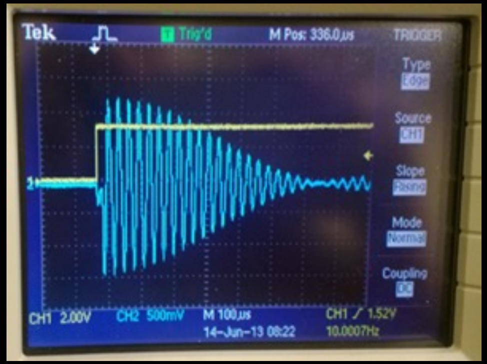


NMR trolley

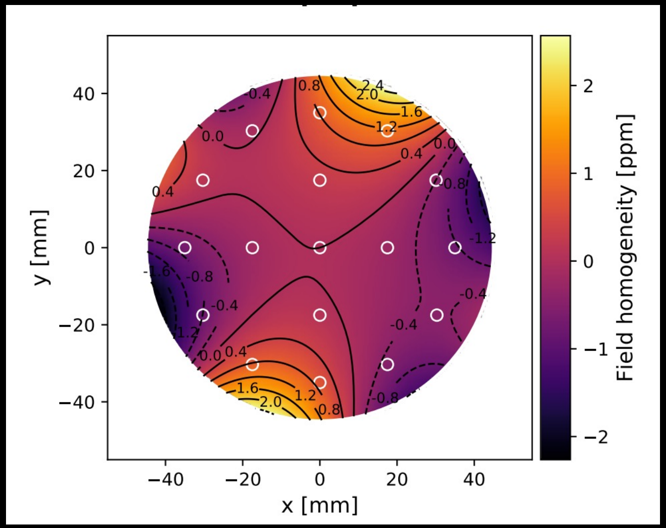


We built a little "NMR Trolley" that goes around the ring and maps the field

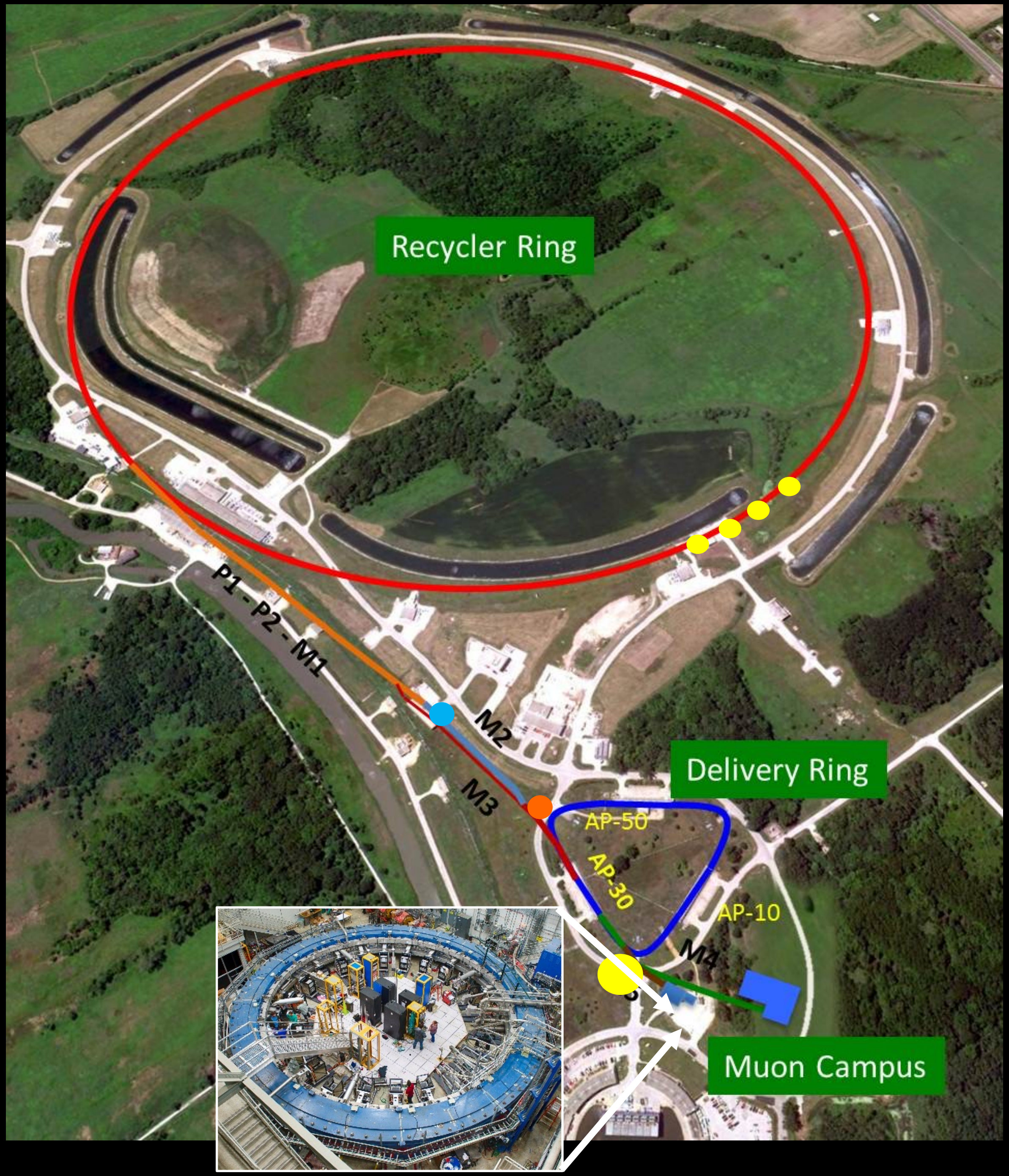




Free induction decay signal of the probes digitized and analyzed



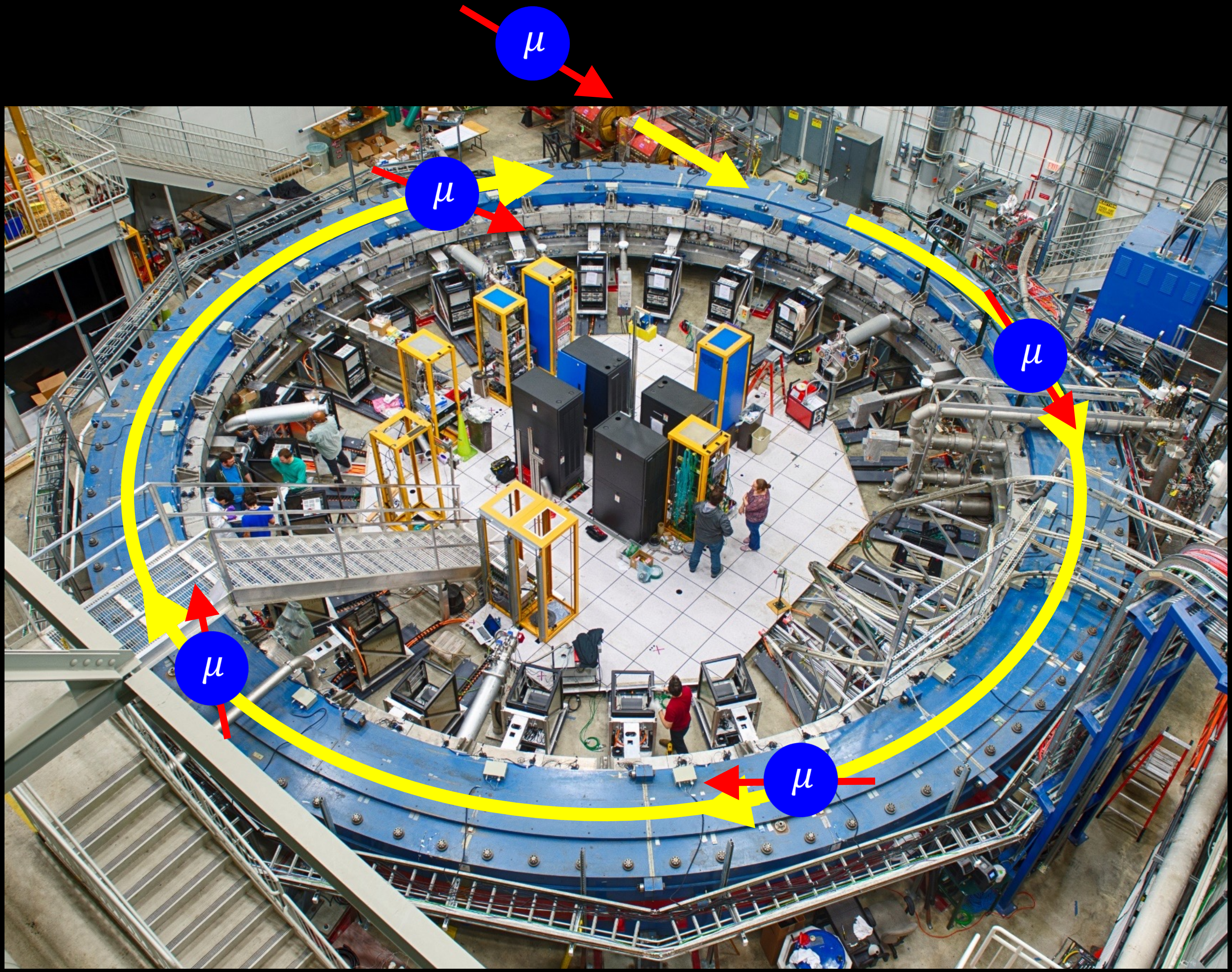
The Final Field is VERY uniform



To create muons, we start with

- A big batch of protons
- Chop them into 4 equal parts
- Shoot 1 batch at a time at a target
- Collect the resulting pions and muons using magnetic lenses
- Run them all around this triangle until only the muons remain
- **Shoot those into the our magnetic storage ring**

The Muons arrive and begin to wobble



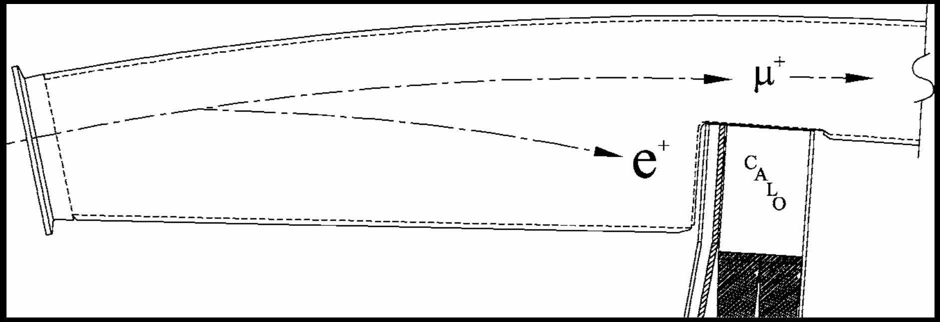
Yellow arrow points in direction of travel

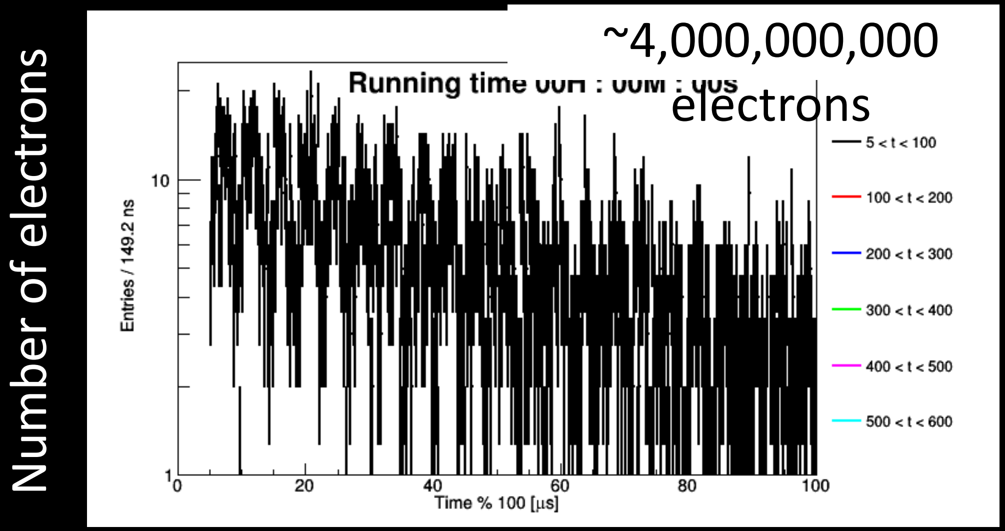
Red arrow points in direction of spin

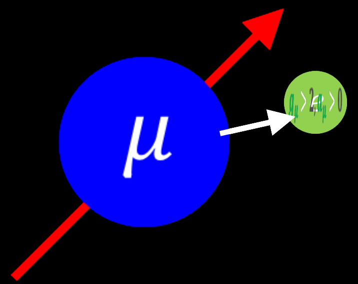
Red arrow is rotating fast than yellow arrow

The difference is proportional to g-2

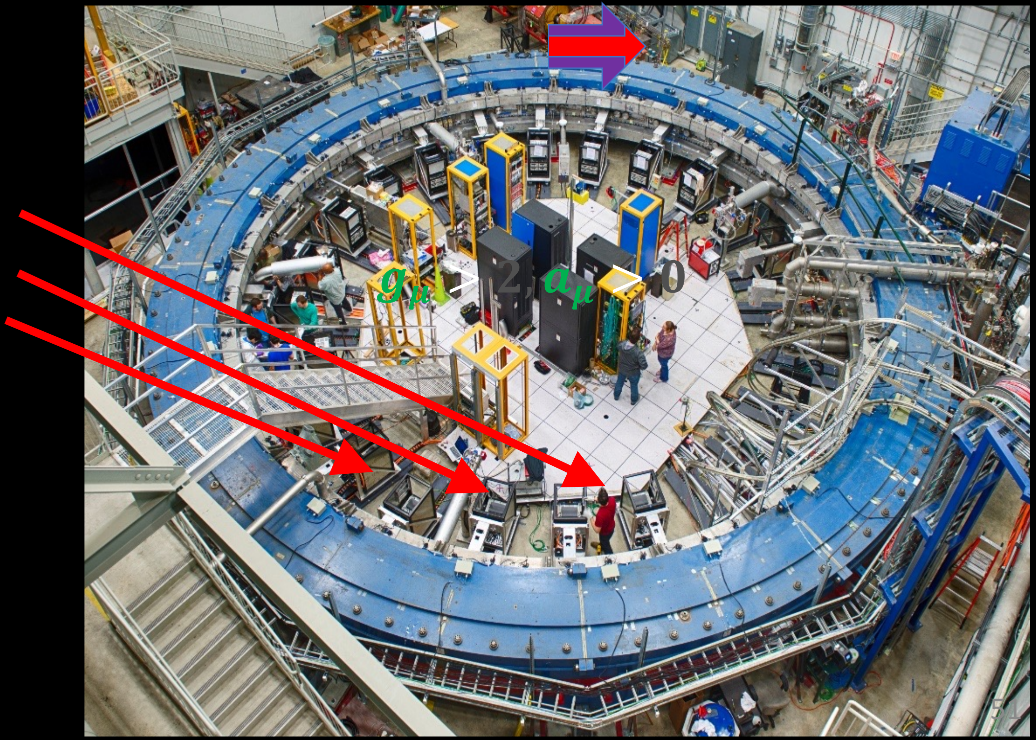
Measuring the wobble frequency







Electromagnetic
Calorimeter

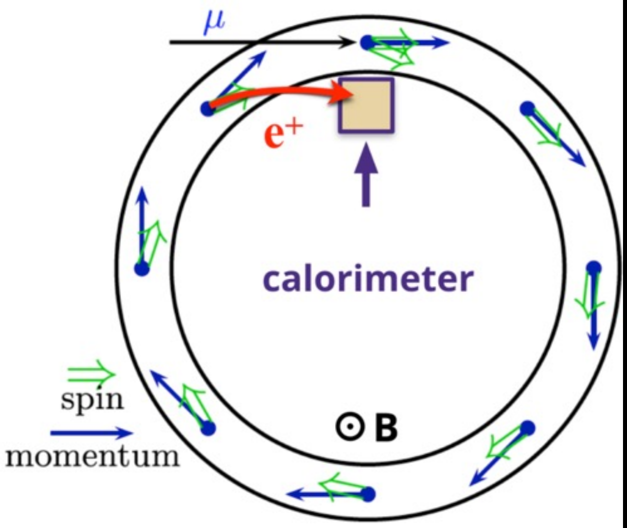


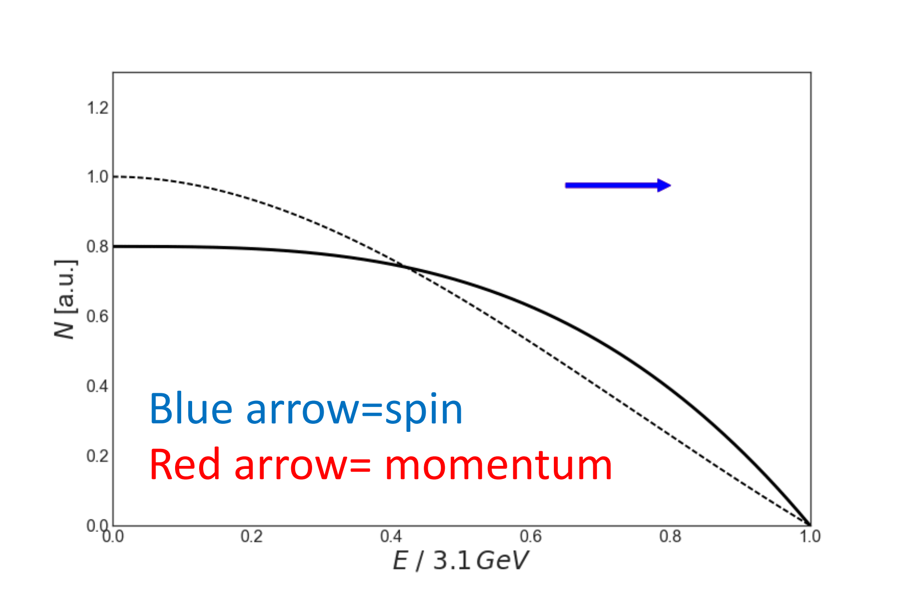
ω_a Measurement

- 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





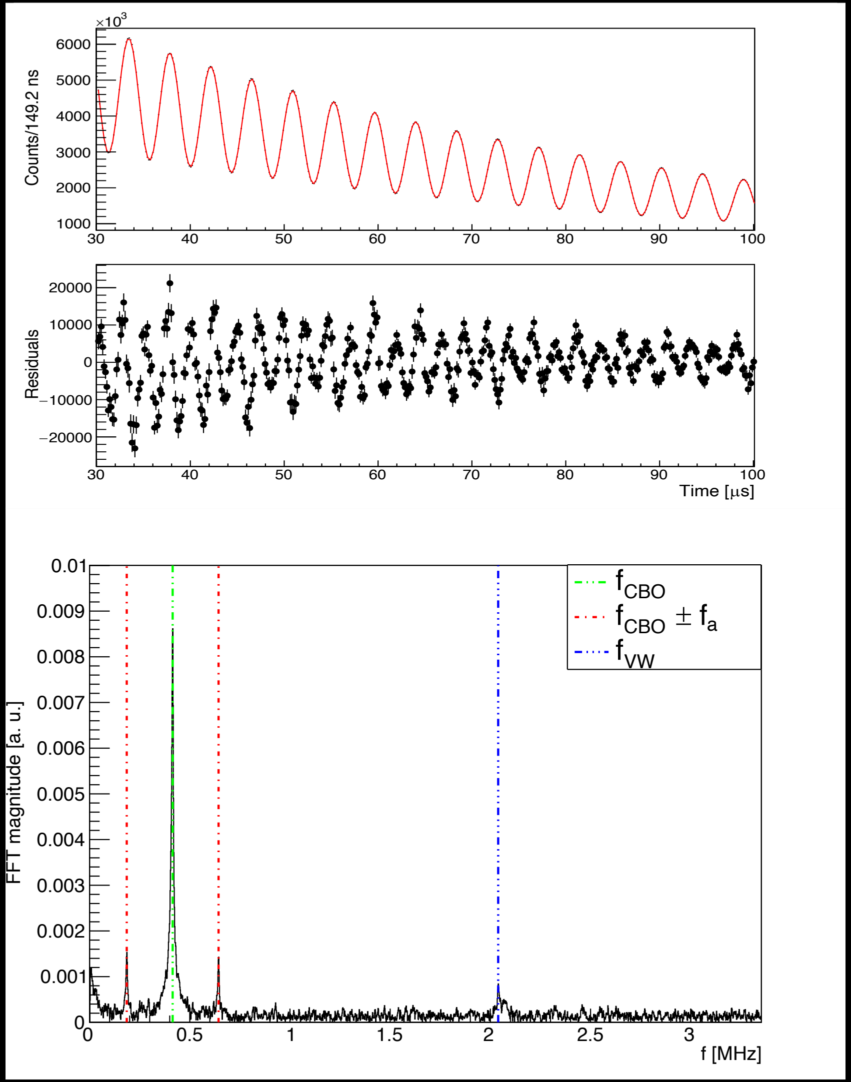
E and t are the measured observables

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



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

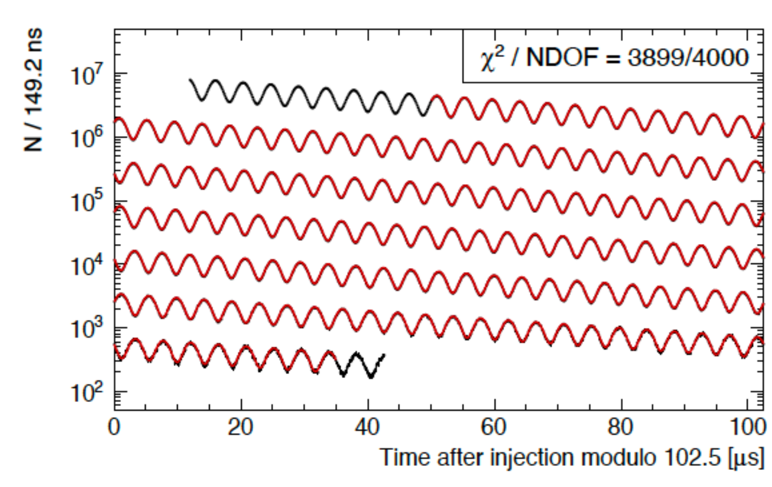
ω_y, ω_{vw} vertical oscillations

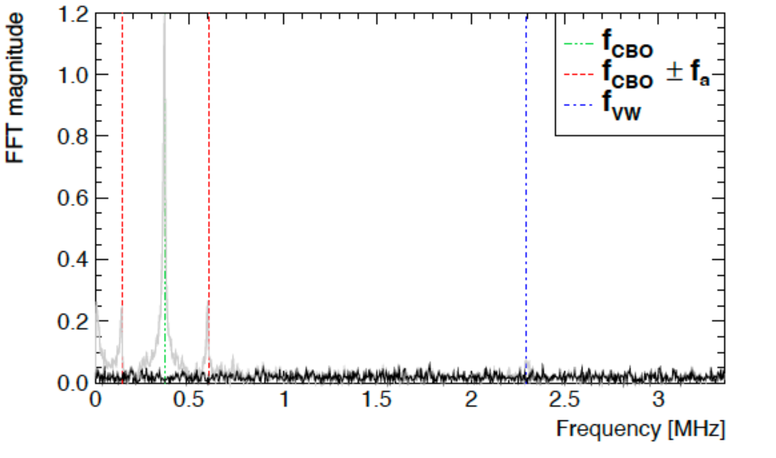
ω_{CBO}, $\omega_{2\mathrm{CBO}}$, radial osc.

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

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

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





RUN1
- **434 ppb** statistical uncertainty (compare to 460 ppb for BNL)
- **56 ppb** systematic uncertainty

The measurements are done entirely "Blind"
We don't know the result until we are done

1. Precision "clocks" are used to determine the frequencies
2. Someone adjusts the clocks to run a bit *faster* or *slower* than nominal
3. Only after the entire data analysis is complete, are we told of the correct clock frequency

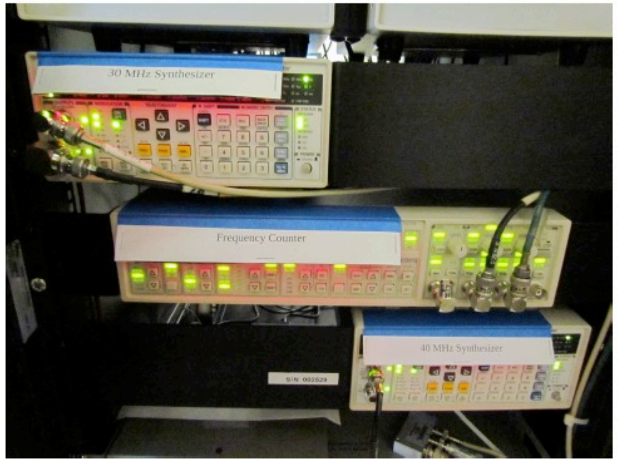
Two outsiders set the Clock frequency and keep the truth in secret envelopes

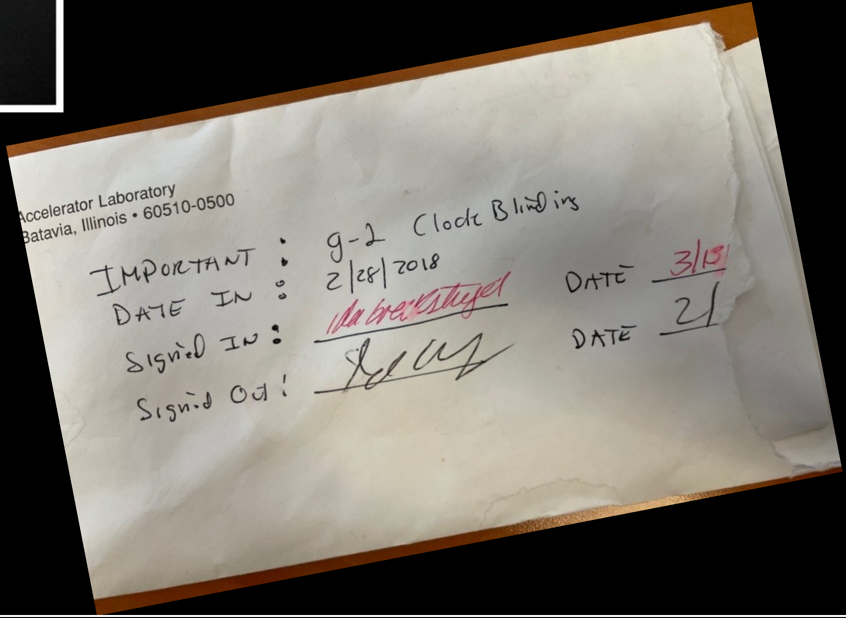
Locked Clock Panel

These folks are NOT in our collaboration….

But we trusted them

Inside the panel





The secret Code with the correct clock frequency was kept in this envelope

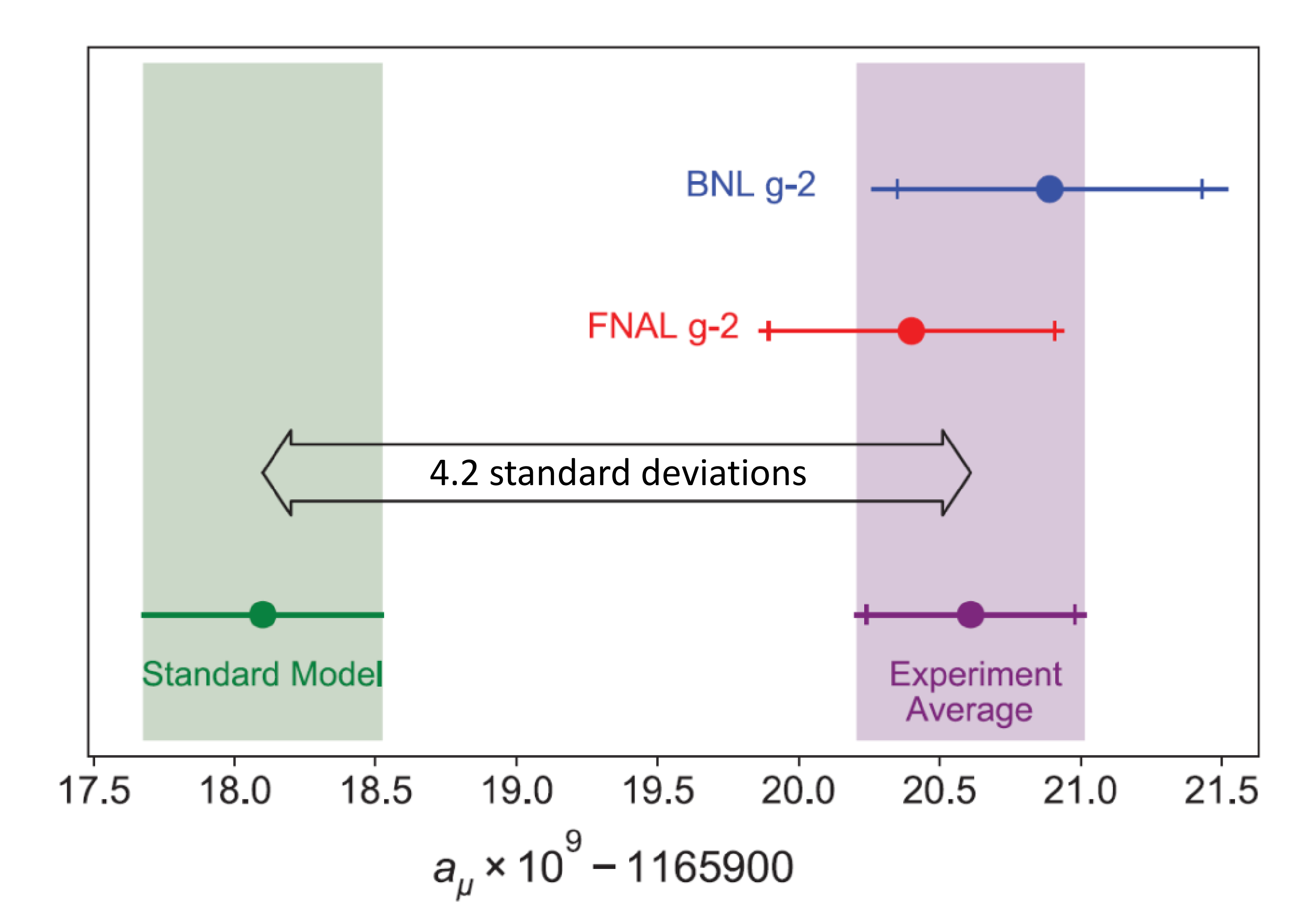
In February 2021 unblinding meeting for our first result

Due to the pandemic the meeting was recorded via zoom

2021 Result

1) We confirmed the result from 20 years ago !!
2) The difference with the SM is 4.2σ

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



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

In August 2023 we presented our second result…

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

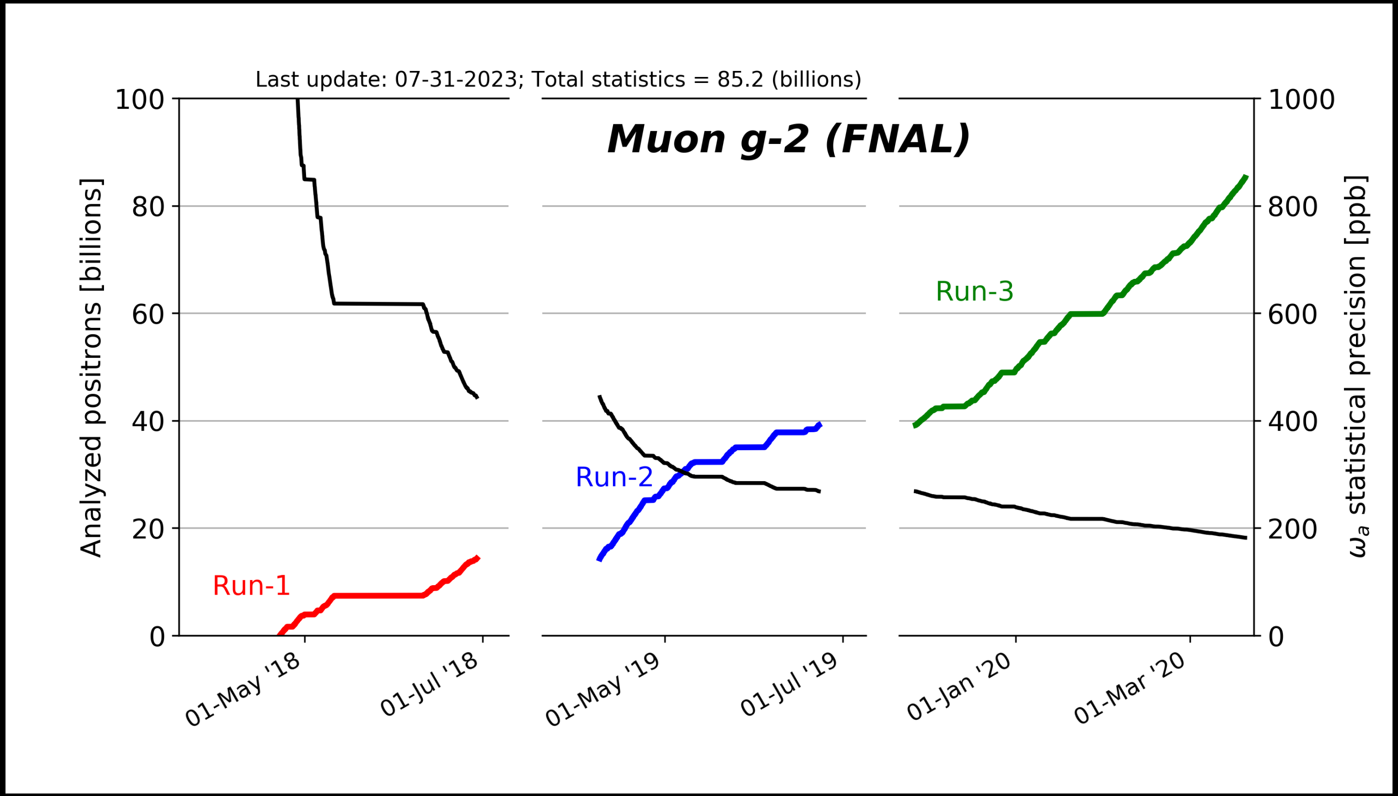
D. P. Aguillard,[33] T. Albahri,[30] D. Allspach,[7] A. Anisenkov,[4,a] K. Badgley,[7] S. Baeßler,[35,b] I. Bailey,[17,c] L. Bailey,[27] V. A. Baranov,[15,d] E. Barlas-Yucel,[28] T. Barrett,[6] E. Barzi,[7] F. Bedeschi,[10] M. Berz,[18] M. Bhattacharya,[7] H. P. Binney,[36] P. Bloom,[19] J. Bono,[7] E. Bottalico,[30] T. Bowcock,[30] S. Braun,[36] M. Bressler,[32] G. Cantatore,[12,e] R. M. Carey,[2] B. C. K. Casey,[7] D. Cauz,[26,f] R. Chakraborty,[29] A. Chapelain,[6] S. Chappa,[7] S. Charity,[30] C. Chen,[23,22] M. Cheng,[28] R. Chislett,[27] Z. Chu,[22,g] T. E. Chupp,[33] C. Claessens,[36] M. E. Convery,[7] S. Corrodi,[1] L. Cotrozzi,[10,h] J. D. Crnkovic,[7] S. Dabagov,[8,i] P. T. Debevec,[28] S. Di Falco,[10] G. Di Sciascio,[11] B. Drendel,[7] A. Driutti,[10,h] V. N. Duginov,[15,d] M. Eads,[20] A. Edmonds,[2] J. Esquivel,[7] M. Farooq,[33] R. Fatemi,[29] C. Ferrari,[10,j] M. Fertl,[14] A. T. Fienberg,[36] A. Fioretti,[10,j] D. Flay,[32] S. B. Foster,[2] H. Friedsam,[7] N. S. Froemming,[20] C. Gabbanini,[10,j] I. Gaines,[7] M. D. Galati,[10,h] S. Ganguly,[7] A. Garcia,[36] J. George,[32,k] L. K. Gibbons,[6] A. Gioiosa,[25,l] K. L. Giovanetti,[13] P. Girotti,[10] W. Gohn,[29] L. Goodenough,[7] T. Gorringe,[29] J. Grange,[33] S. Grant,[1,27] F. Gray,[21] S. Haciomeroglu,[5,m] T. Halewood-Leagas,[30] D. Hampai,[8] F. Han,[29] J. Hempstead,[36] D. W. Hertzog,[36] G. Hesketh,[27] E. Hess,[10] A. Hibbert,[30] Z. Hodge,[36] K. W. Hong,[35] R. Hong,[29] T. Hu,[23,22] Y. Hu,[22,g] M. Iacovacci,[9,n] M. Incagli,[10] P. Kammel,[36] M. Kargiantoulakis,[7] M. Karuza,[12,o] J. Kaspar,[36] D. Kawall,[32] L. Kelton,[29] A. Keshavarzi,[31] D. S. Kessler,[32] K. S. Khaw,[23,22] Z. Khechadoorian,[6] N. V. Khomutov,[15] B. Kiburg,[7] M. Kiburg,[7,19] O. Kim,[34] N. Kinnaird,[2] E. Kraegeloh,[33] V. A. Krylov,[15] N. A. Kuchinskiy,[15] K. R. Labe,[6] J. LaBounty,[36] M. Lancaster,[31] S. Lee,[5] B. Li,[22,1,p] D. Li,[22,q] L. Li,[22,g] I. Logashenko,[4,a] A. Lorente Campos,[29] Z. Lu,[22,g] A. Lucà,[7] G. Lukicov,[27] A. Lusiani,[10,r] A. L. Lyon,[7] B. MacCoy,[36] R. Madrak,[7] K. Makino,[18] S. Mastroianni,[9] J. P. Miller,[2] S. Miozzi,[11] B. Mitra,[34] J. P. Morgan,[7] W. M. Morse,[3] J. Mott,[7,2] A. Nath,[9,n] J. K. Ng,[23,22] H. Nguyen,[7] Y. Oksuzian,[1] Z. Omarov,[16,5] R. Osofsky,[36] S. Park,[5] G. Pauletta,[26,s] G. M. Piacentino,[25,t] R. N. Pilato,[30] K. T. Pitts,[28,u] B. Plaster,[29] D. Počanić,[35] N. Pohlman,[20] C. C. Polly,[7] J. Price,[30] B. Quinn,[34] M. U. H. Qureshi,[14] S. Ramachandran,[1,k] E. Ramberg,[7] R. Reimann,[14] B. L. Roberts,[2] D. L. Rubin,[6] L. Santi,[26,f] C. Schlesier,[28,v] A. Schreckenberger,[7] Y. K. Semertzidis,[5,16] D. Shemyakin,[4,a] M. Sorbara,[11,w] D. Stöckinger,[24] J. Stapleton,[7] D. Still,[7] C. Stoughton,[7] D. Stratakis,[7] H. E. Swanson,[36] G. Sweetmore,[31] D. A. Sweigart,[6] M. J. Syphers,[20] D. A. Tarazona,[6,30,18] T. Teubner,[30] A. E. Tewsley-Booth,[29,33] V. Tishchenko,[3] N. H. Tran,[2,x] W. Turner,[30] E. Valetov,[18] D. Vasilkova,[27,30] G. Venanzoni,[30,l] V. P. Volnykh,[15] T. Walton,[7] A. Weisskopf,[18] L. Welty-Rieger,[7] P. Winter,[1] Y. Wu,[1] B. Yu,[34] M. Yucel,[7] Y. Zeng,[23,22] and C. Zhang[30]

(The Muon $g-2$ Collaboration)

10th August 2023, Fermilab

Run-2/3 Improvement: Statistics

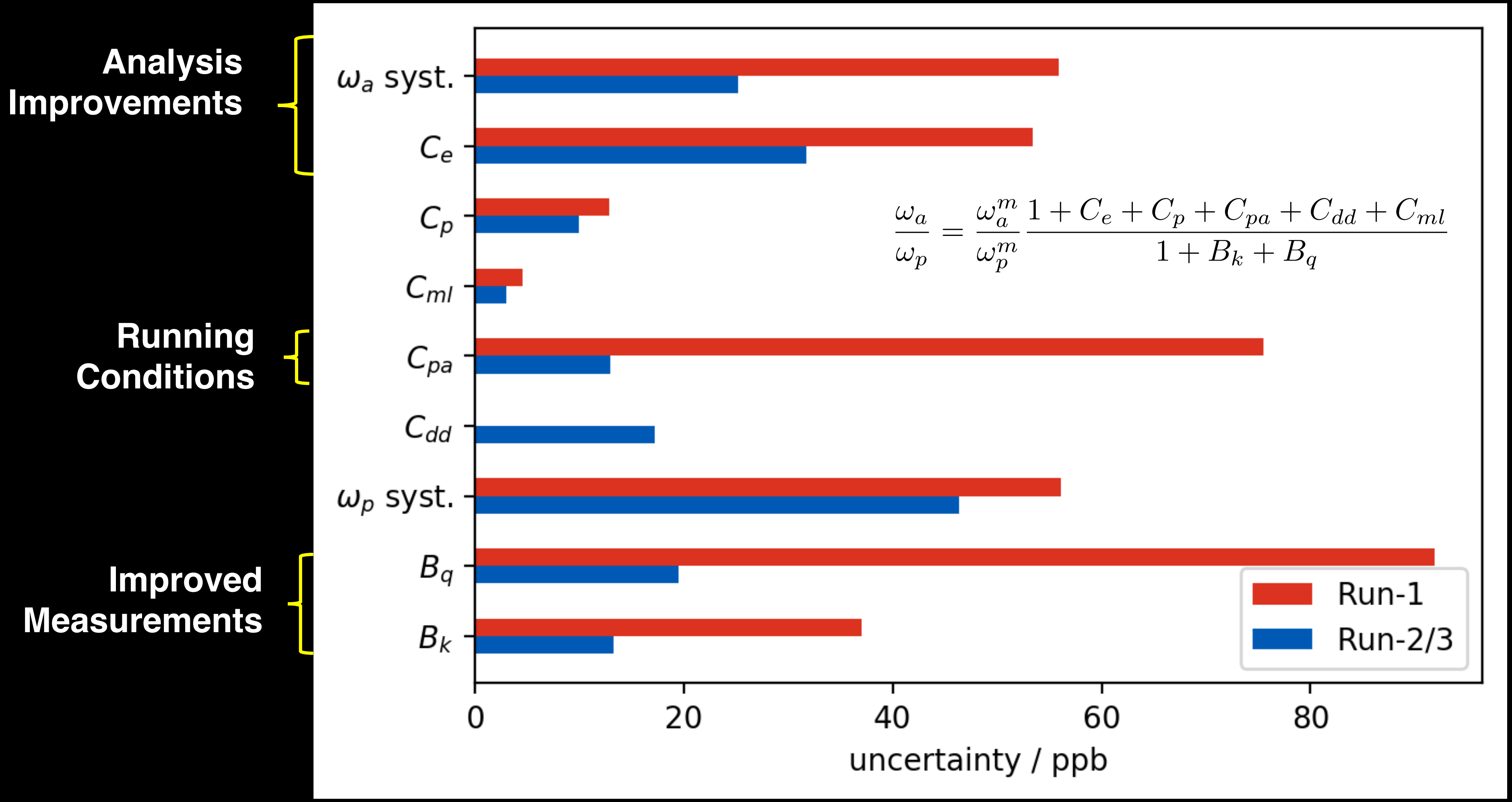
Number of e⁺
with E > 1 GeV
t > 30 µs



- Factor 4.7 more data in Run-2/3 than Run-1

Dataset	Statistical Error [ppb]
Run-1	434
Run-2/3	201
Run-1 + Run-2/3	185

Run-2/3 Improvement: Systematics



Run-2/3 Uncertainties

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\mathrm{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

- Total uncertainty is **215 ppb**

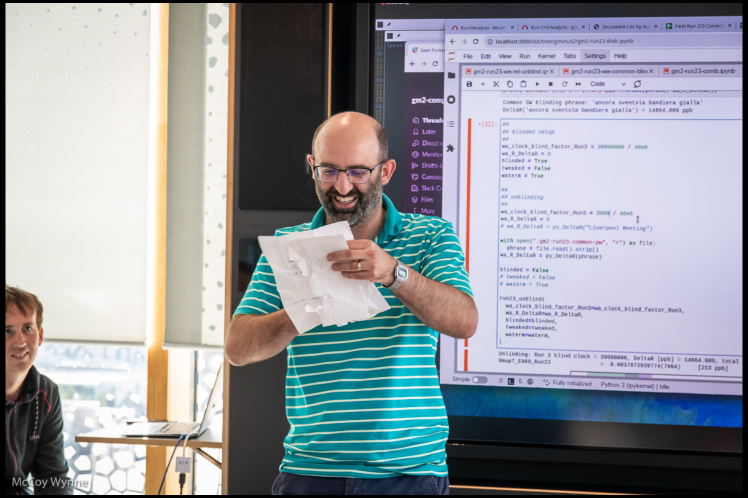
[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- Near-equal improvement: We're still **statistically dominated**

Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!

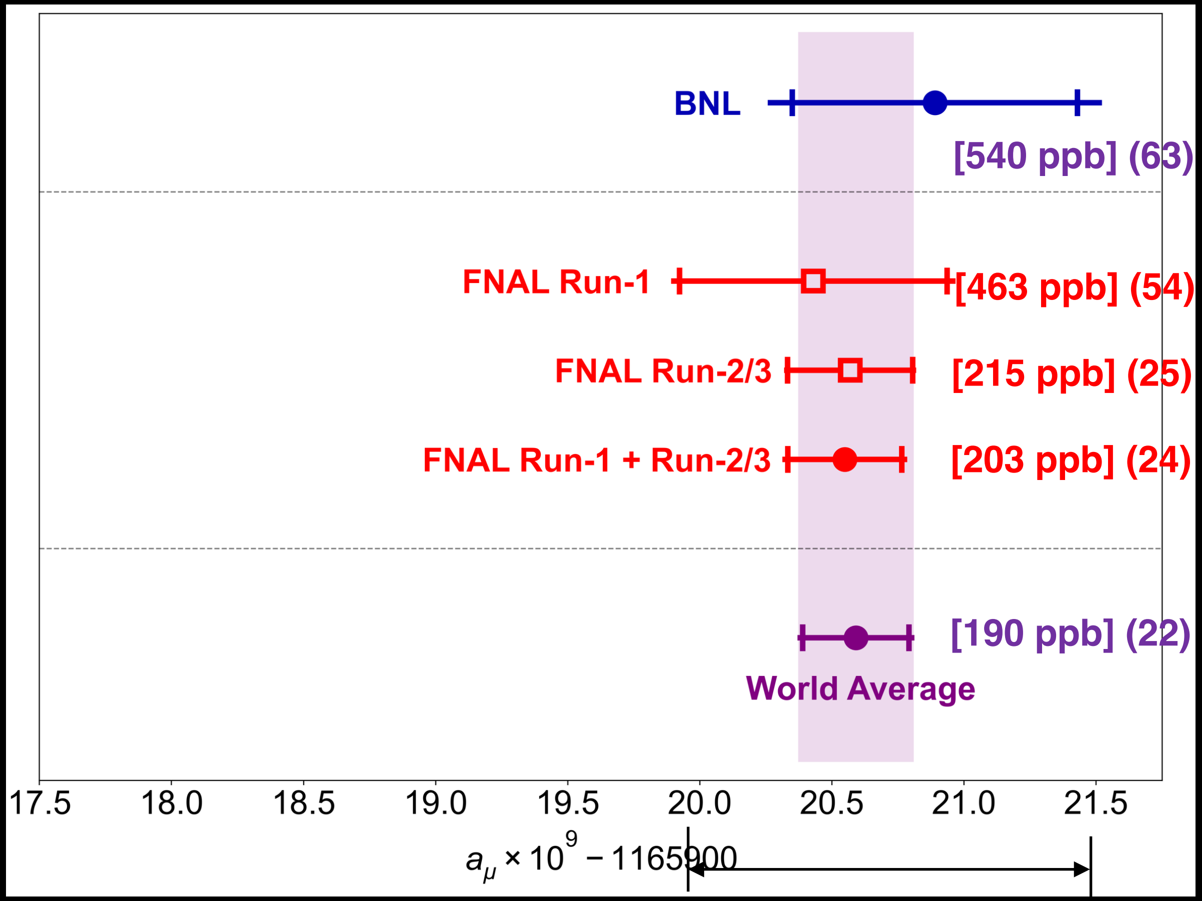
This time the unbinding meeting was in Liverpool

24 July 2023



Run-2/3 Result: FNAL + BNL Combination

a_μ(FNAL) = 116 592 055(24) x10^{-11} [203 ppb]

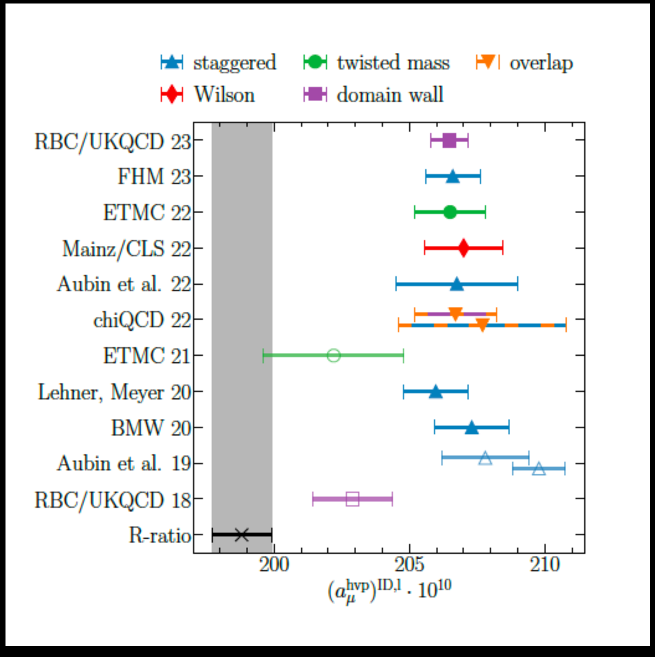


- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** value

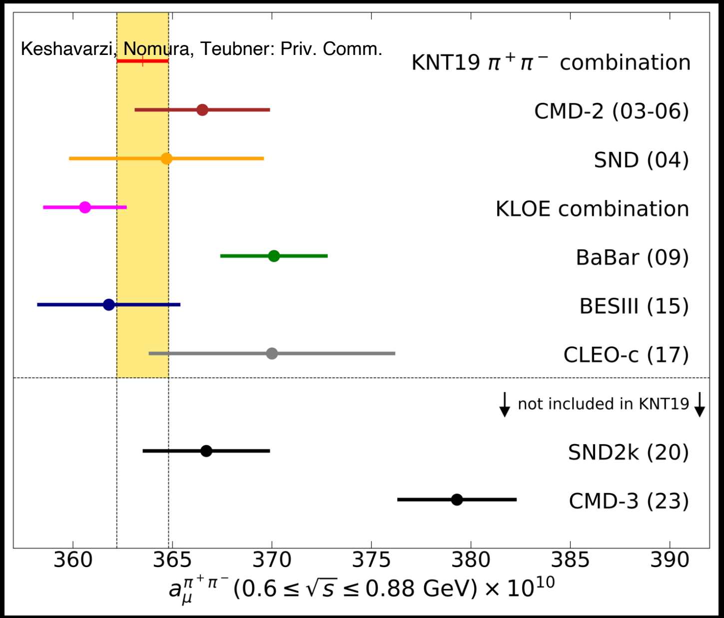
Size of $a_\mu^{EW} = 153.6(1.0) \times 10^{-11}$

a_μ(Exp) = 116 592 059(22) x 10^{-11} [190 ppb]

Comparison with SM prediction (2023)



HVP from **lattice** (intermediate region~ 1/3 $a\mu^{HLO}$)



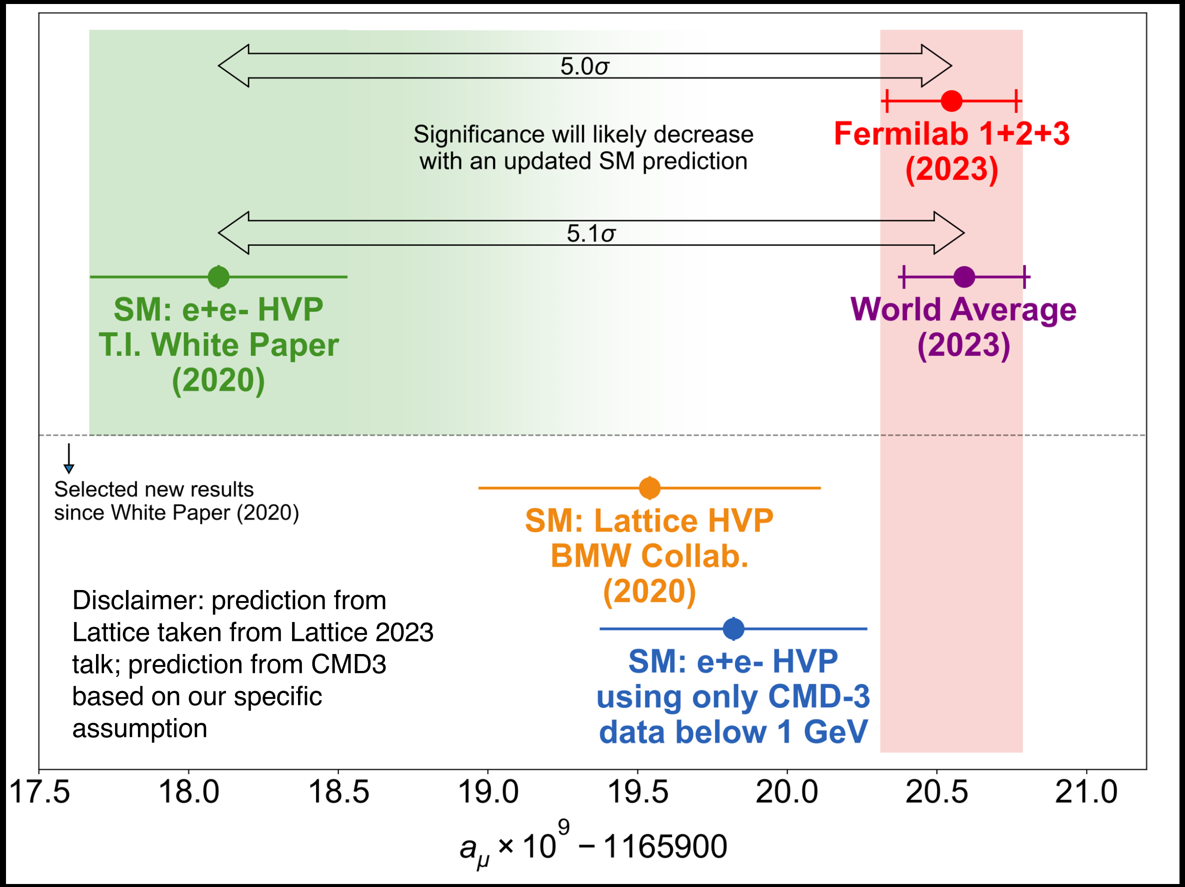
inc. in wp20

HVP from **data** (2π dominant channel)

NOT inc. in wp20

Comparison with wp20

New results after 2020



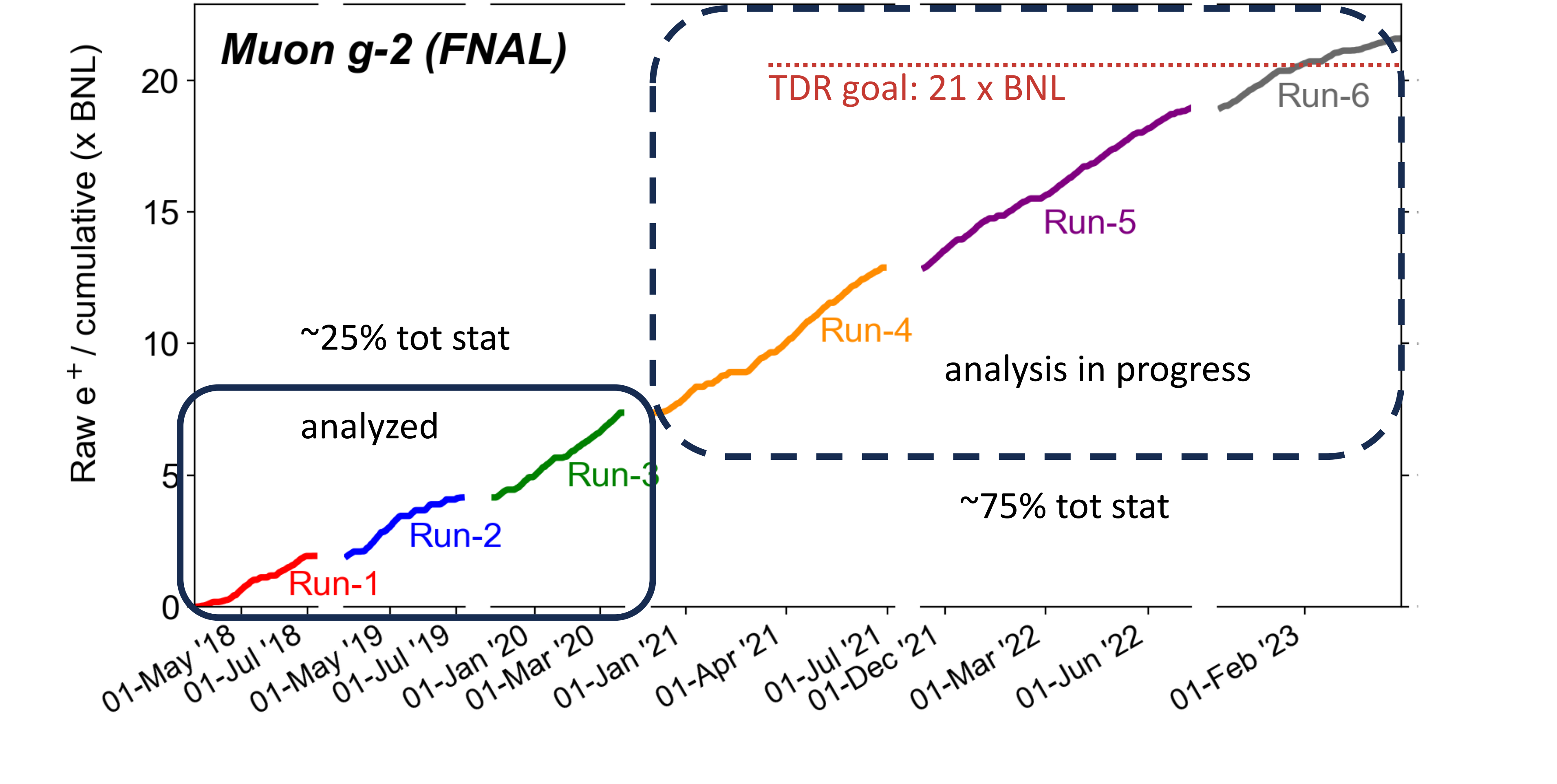
- Comparison of FNAL Run1-3 result with the Theory Initiative's calculation **wp20** is at **5 sigma**
- Waiting for a clarification of the theory (see (https://muon-gm2-theory.illinois.edu/)

Outlook for muon g-2 at Fermilab

Data from **Run-4/5/6 fully produced** and analysis making good progress

With more than 21x BNL statistics on tape we will likely surpass total precision of **140ppb**

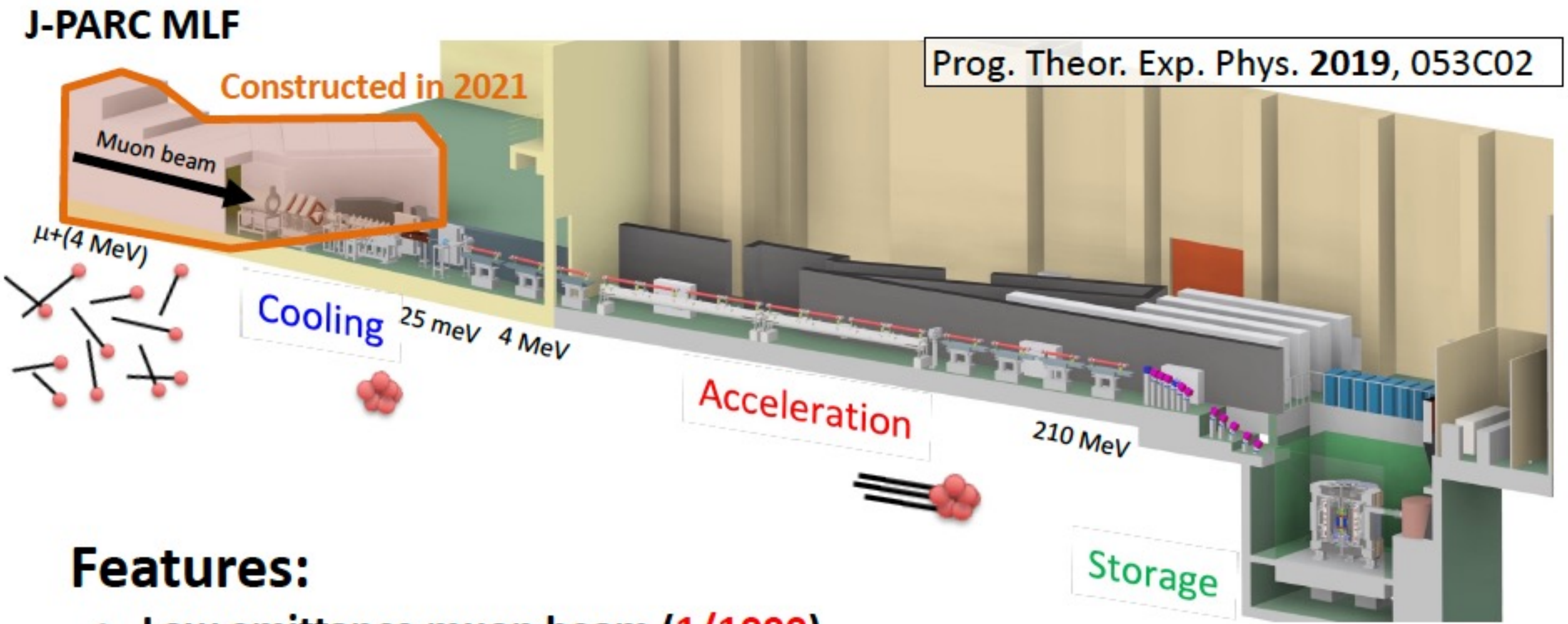
Plan to **publish result of the full dataset in 2025** with twice improved statistical precision



Other analysis ongoing with first results based on Run-1 data expected in 2024:

- Muon Electric Dipole Moment analysis with final sensitivity goal of $\leq 10^{-20}$ e·cm
- BSM searches via CPT/Lorentz violation and Dark Matter

J-PARC muon *g*-2/EDM experiment

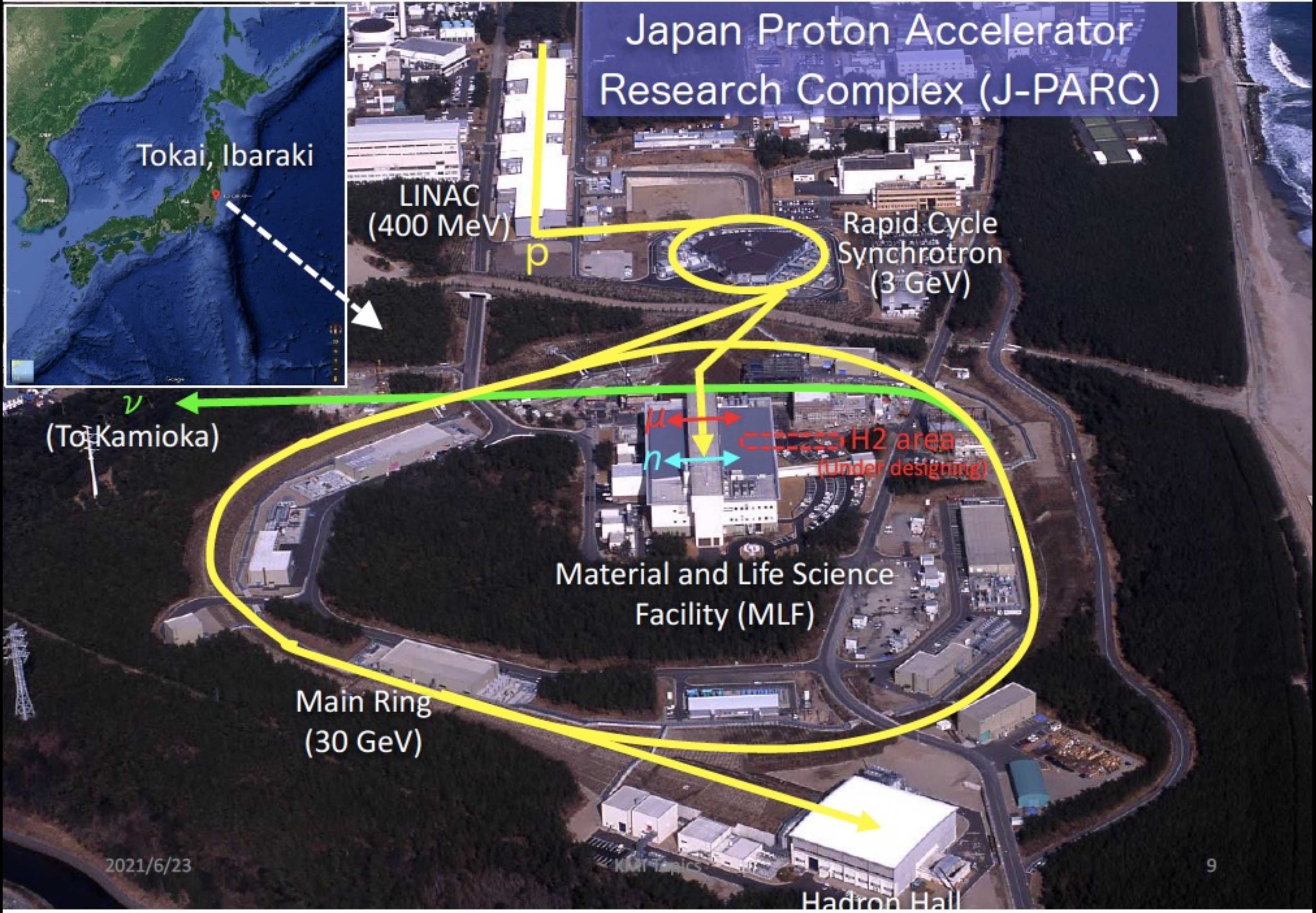


Features:

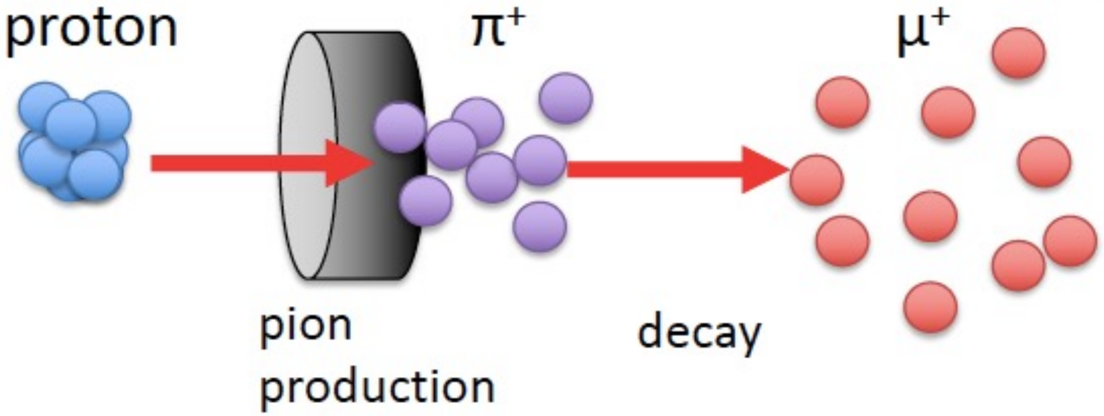
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**

- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

Japan Proton Accelerator Research Complex (J-PARC)



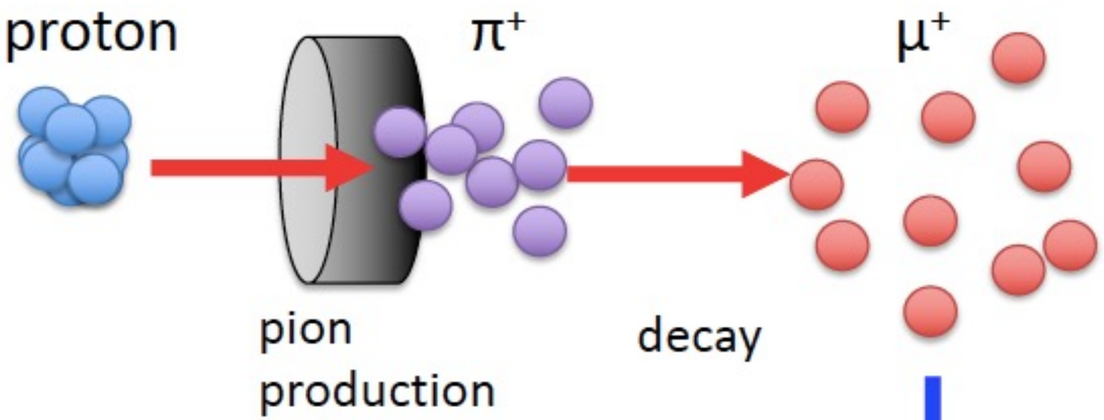
Conventional muon beam (BNL, Fermilab)

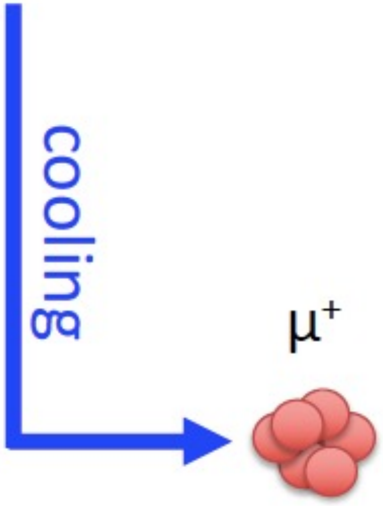


emittance
~1000π mm ▪mrad

Strong focusing
Muon loss
BG π contamination

Muon beam at J-PARC





emittance

~1000π mm·mrad

Strong focusing
Muon loss
BG π contamination

emittance

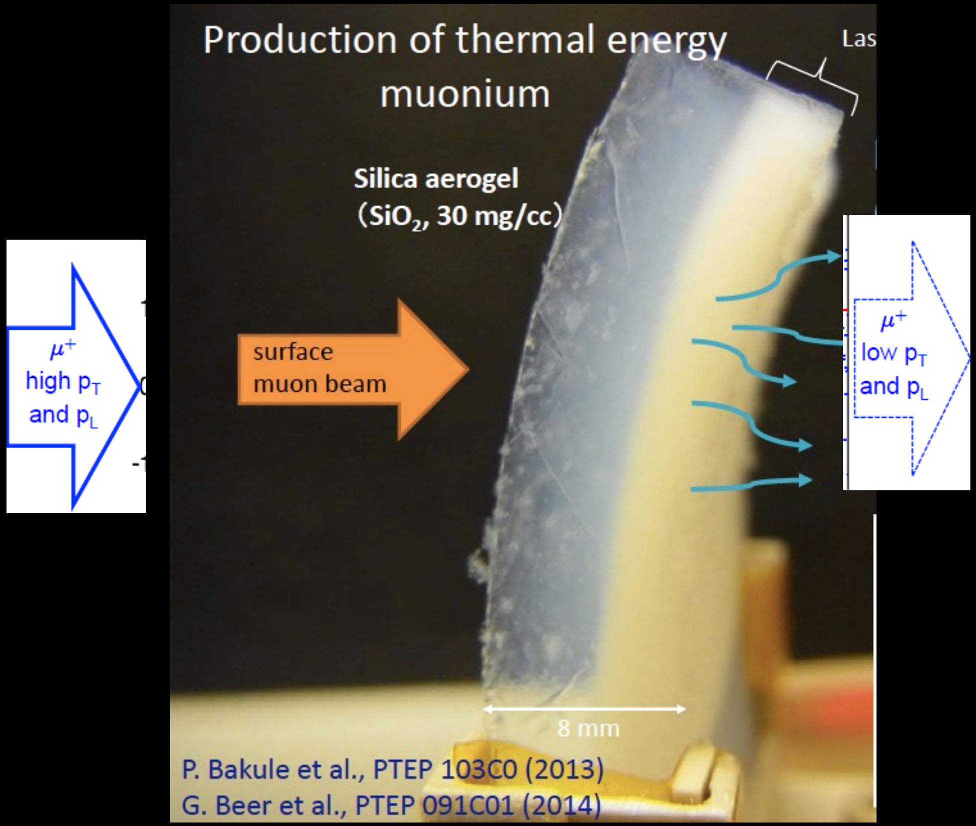
1π mm·mrad

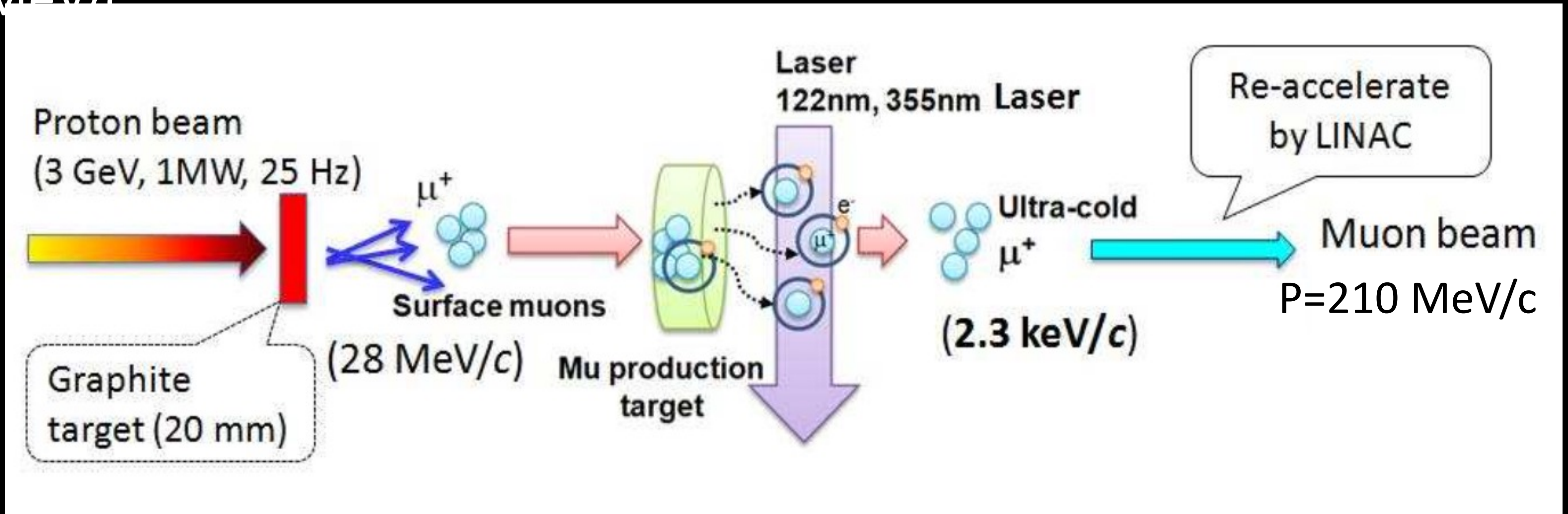
Reaccelerated thermal muon

Free from any of these

Ultra-cold Muons

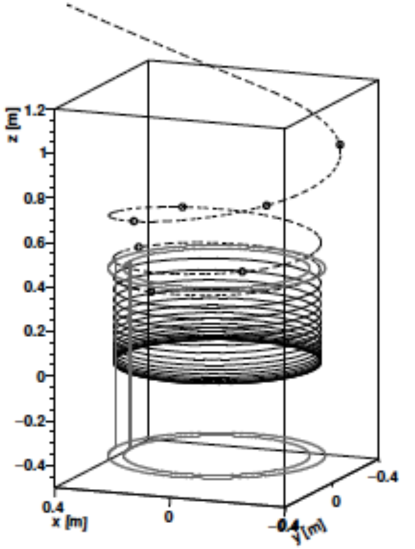
- Surface μ^+
- Stop in Aerogel
- Diffuse Muonium (μ^+e^-) atoms into vacuum
- Ionize
  - 1S → 2P→unbound
  - **Max Polarization 50%**
- Accelerate
  - E field, RFQ, linear structures
  - P = 210 MeV/c





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



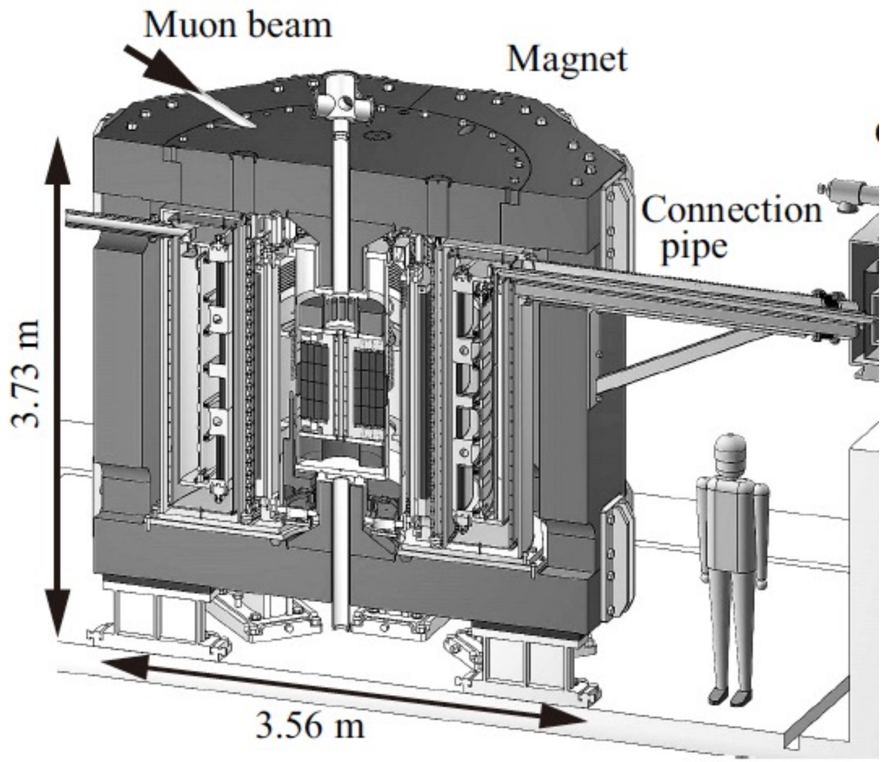
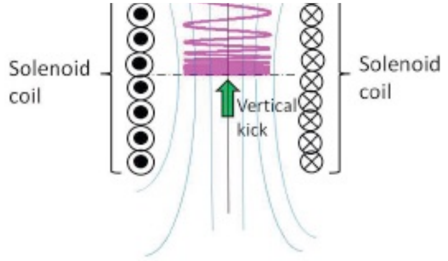


Fig. 8 Overview of the muon storage magnet

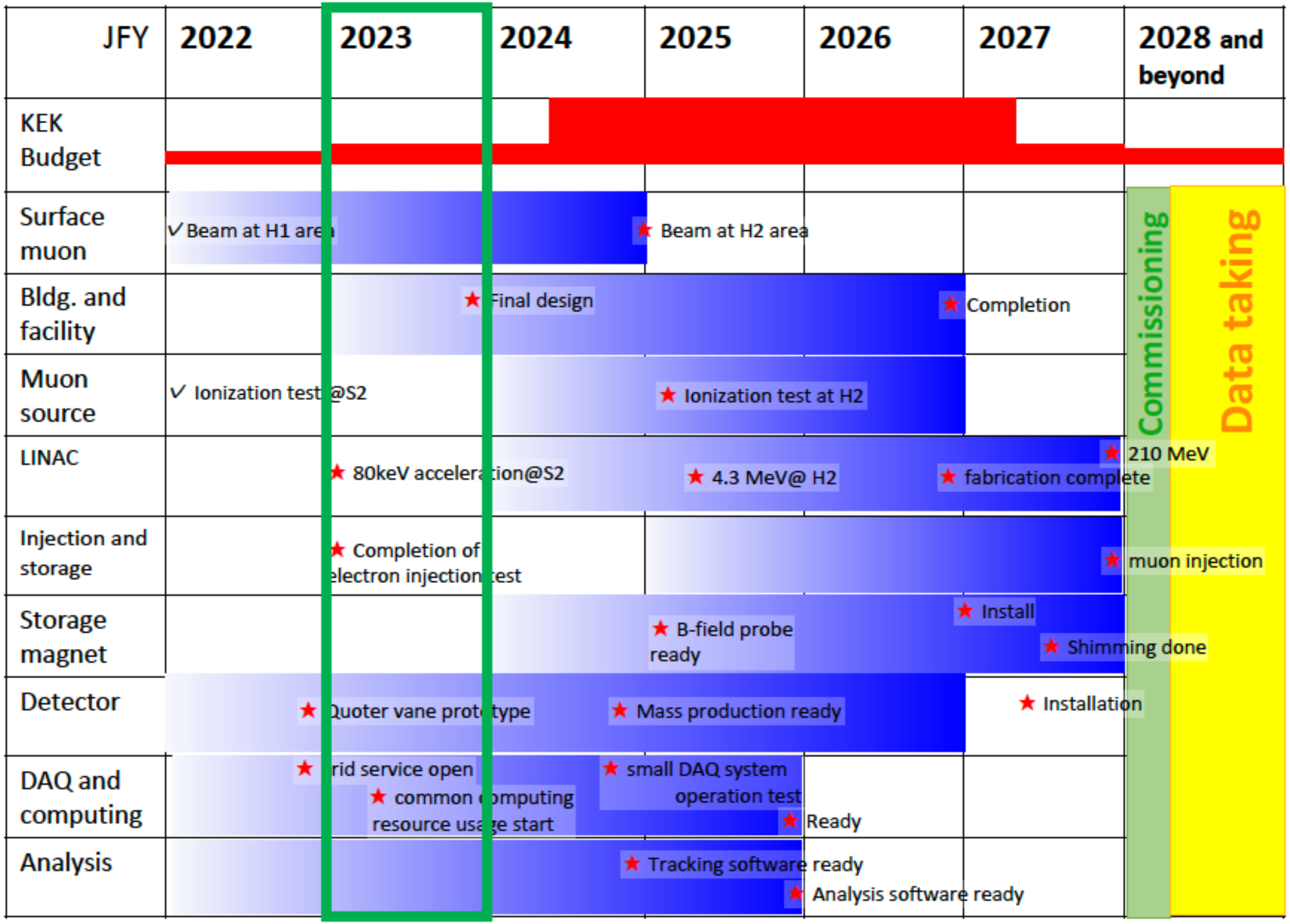


Comparison of g-2 experiments

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.)	$0.2\times10^{-19}\ e\cdot$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

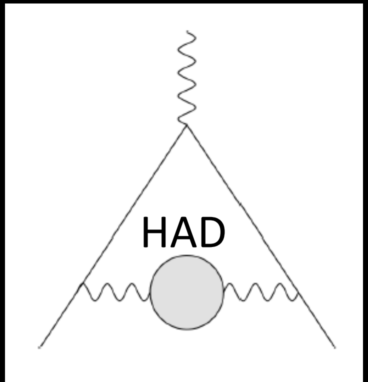
Schedule and milestone



More detailed schedule at https://docs.google.com/spreadsheets/d/102lSO5MvxWnEjrqH4sJGOLmSlQUiPj9p/edit#gid=1381089061

a_μ^{HLO} (HVP) A «Third way»: MUonE at CERN

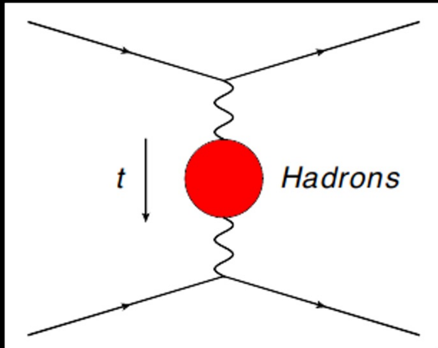
(a space-like approach of a_μ^{HLO})

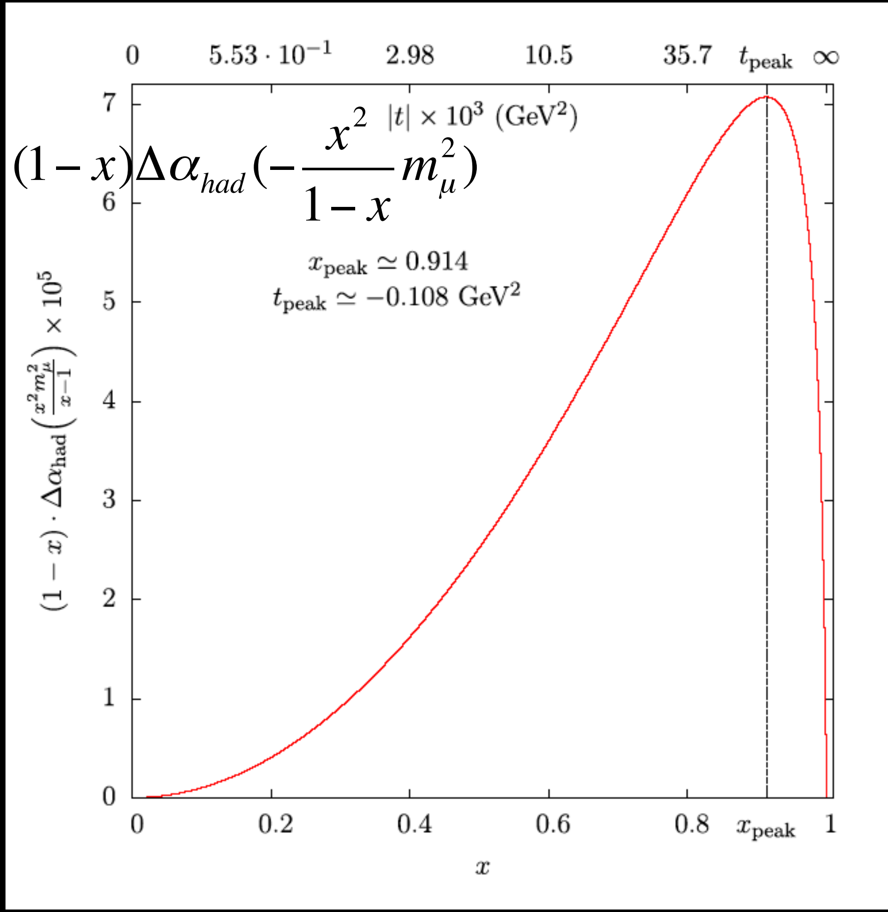


Measurement of $\Delta\alpha_{had}(t)$: hadronic contribution to the running of the electromagnetic coupling constant.

$$a_\mu^{HLO} = \frac{\alpha_0}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{had}[t(x)]$$

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

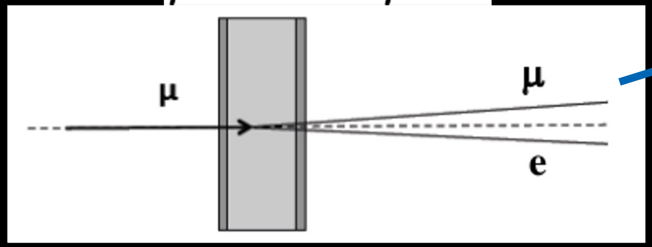




The MUonE experiment

Extraction of $\Delta\alpha_{had}(t)$ from the «shape» of the $\mu^+ e^- \rightarrow \mu^+ e^-$ elastic differential cross section

$\mu\ e \rightarrow \mu\ e$

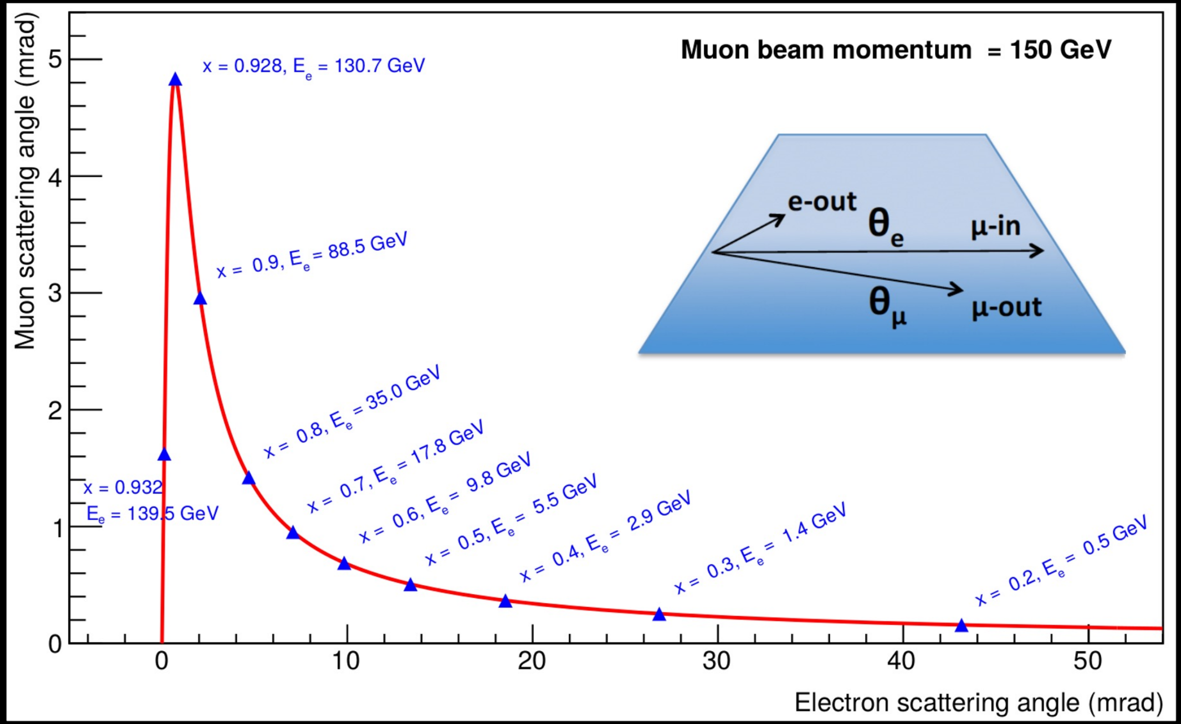


$$\frac{d\sigma_{data}/dt}{d\sigma_{MC}^{\text{no VP}}/dt} = \frac{1}{|1 - \Delta\alpha_{lep}(t) - \Delta\alpha_{had}(t)|^2}$$

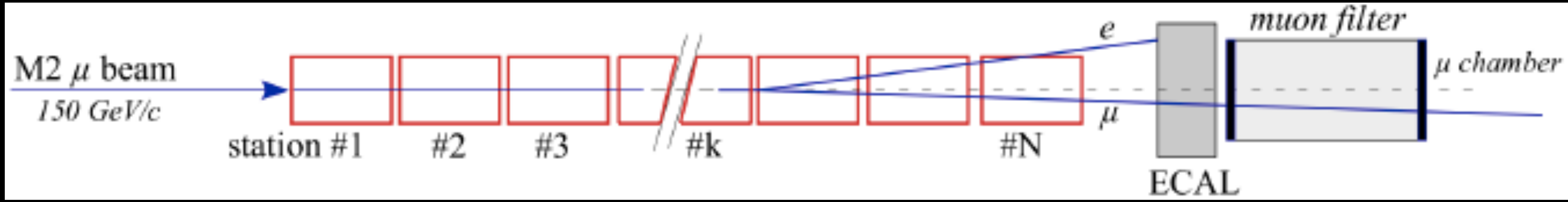
From theoretical calculation

To be measured

- A beam of 160 GeV muons allows to cover the whole a_μ^{HLO}
- Correlation between muon and electron angles allows to select elastic events and reject background (e^+e^- pair production)
- Boosted kinematics: θ_μ < 5 mrad, θ_e < 32 mrad

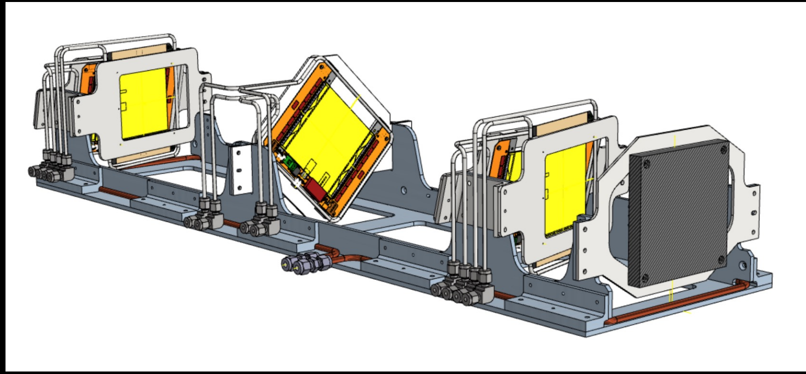


MUonE at CERN: status

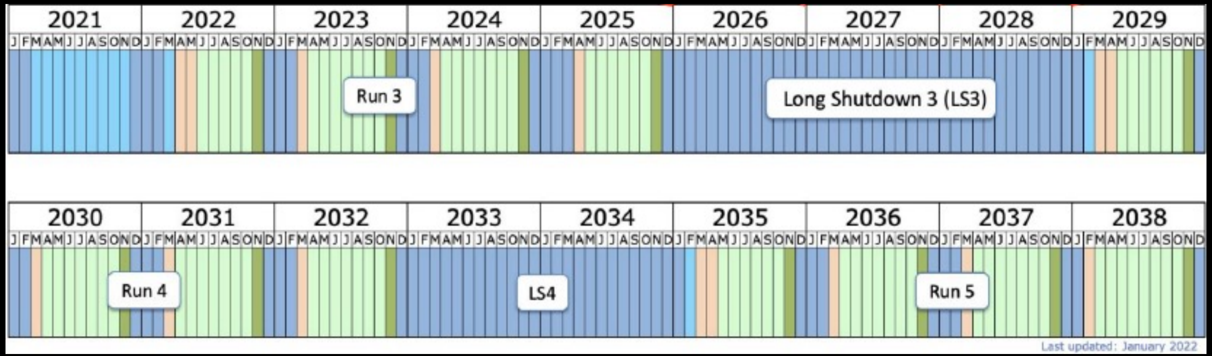


- Many progress in the last years, inc. detector optimization and development of μ-e (N)NLO MC
- 3 weeks Test Run in 2023: proof of concept of the experimental proposal using 2 tracking stations and ECAL. Successful run at 40 MHz
- Staged approach towards the full experiment: 1st phase in 2025 with limited sensitivity to $\Delta\alpha_{had}(t)$; final accuracy after LS3 (>2028) with <0.5% target precision on a_μ^{HLO}

-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



LHC schedule

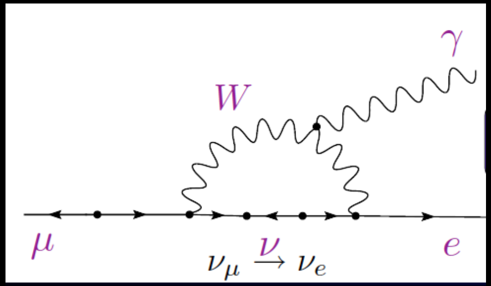


Introduction to CLFV

- Charged Lepton Flavor violation is forbidden in the Standard Model:
  - $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu^- + A \rightarrow e^- + A$,, $\tau \rightarrow e(\mu)\gamma$, $\tau \rightarrow e(\mu)h$, $K_L \rightarrow \mu e$, $K \rightarrow \pi\mu e$, **and many others**
- Neutrino oscillation may induce CLFV but very small (due to GIM-like mechanism and neutrino mass)

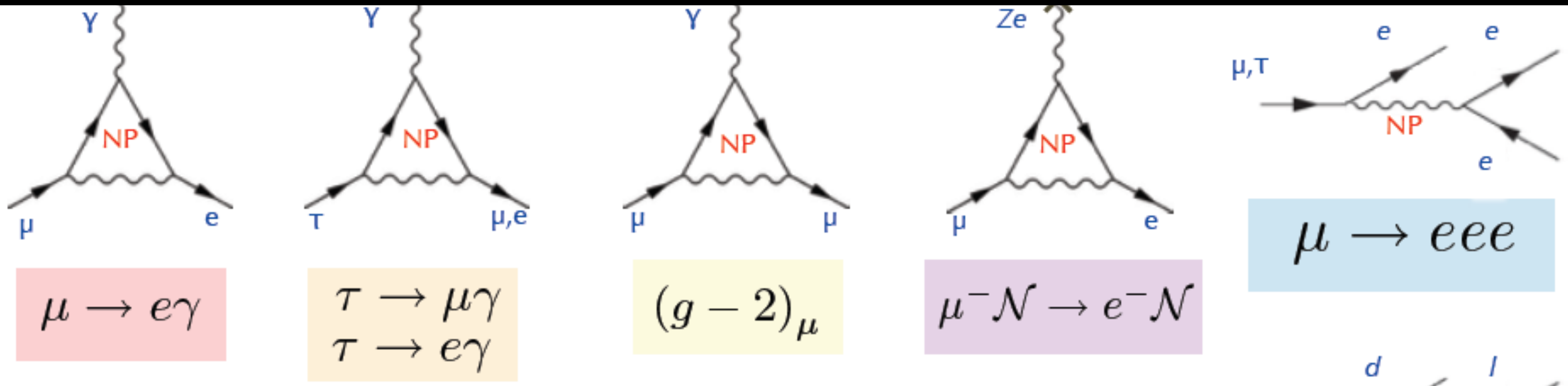
  $BR(\mu \rightarrow e\gamma) \sim O(10^{-54})$ $(BR\ \mu N \rightarrow eN) < 10^{-50}$

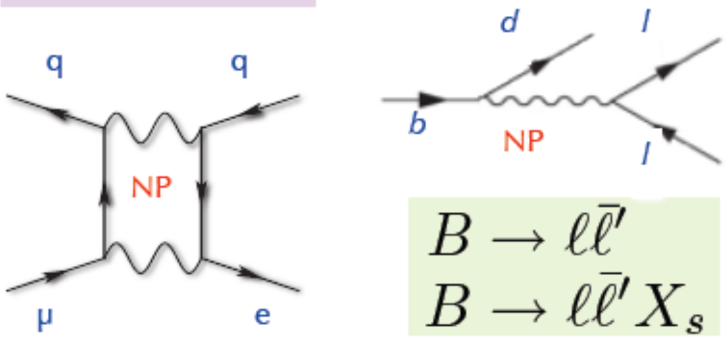
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U^*_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \simeq 10^{-60} \left(\frac{m_\nu}{10^{-2}\,\mathrm{eV}} \right)^4$$



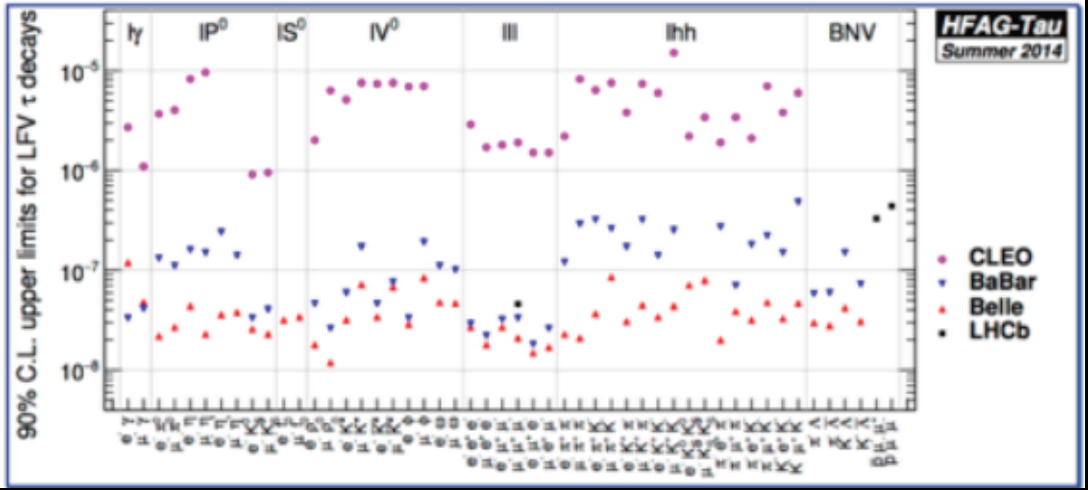
- If CLFV found → Clear evidence of Physics BSM
- Many theories BSM predicts CLFV

NP can contribute to CLFV Processes & g-2





- A **wide field** of research
  - ***LFV decays of leptons***
  - ***Anomalous magnetic moment for the μ***
  - ***Muon-to-electron conversion***
  - ***LFV in meson decays***

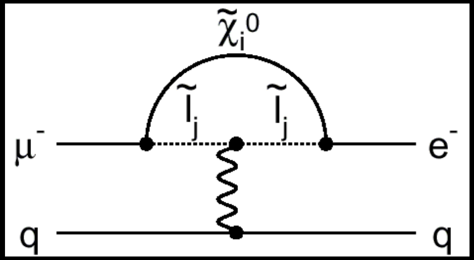


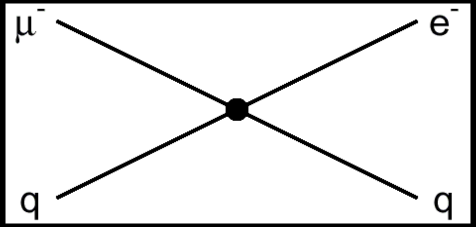
Various models predict CLFV

Sensitivity to different Muon Conversion Mechanism

Supersymmetry

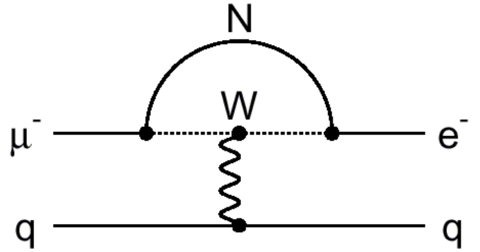
Predictions at 10^{-15}

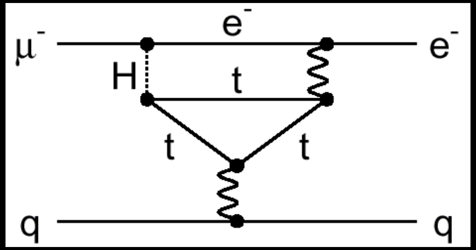




Compositeness

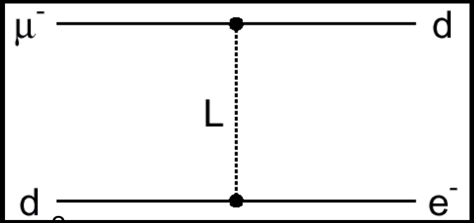
Heavy Neutrinos

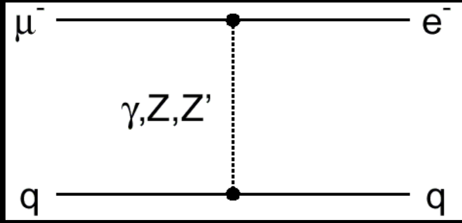




Second Higgs doublet

Leptoquarks

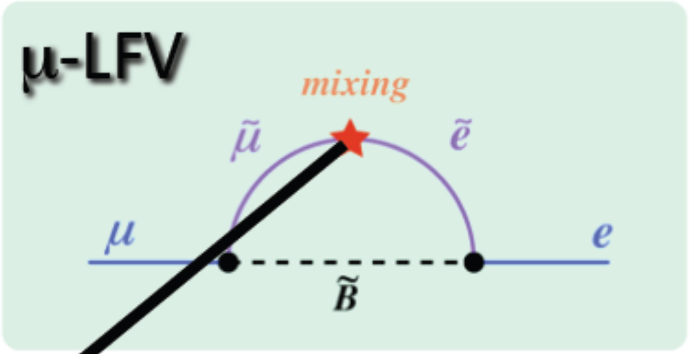


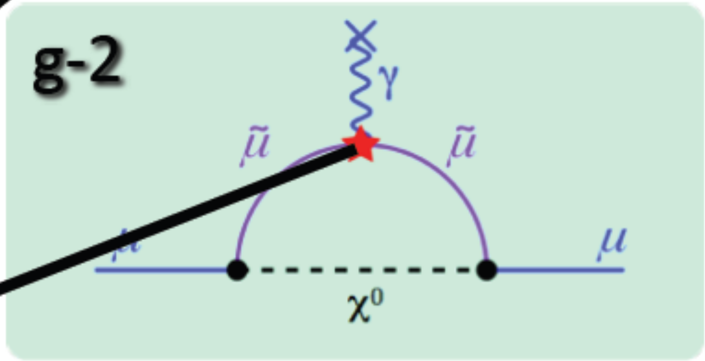


Heavy Z',
Anomalous Z coupling

Supersymmetry as source of CLFV

- Supersymmetry (SUSY)
  - Hierarchy Problem
  - Unification of Force
- If SUSY exists
  → SUSY flavor mixing
  → CLFV



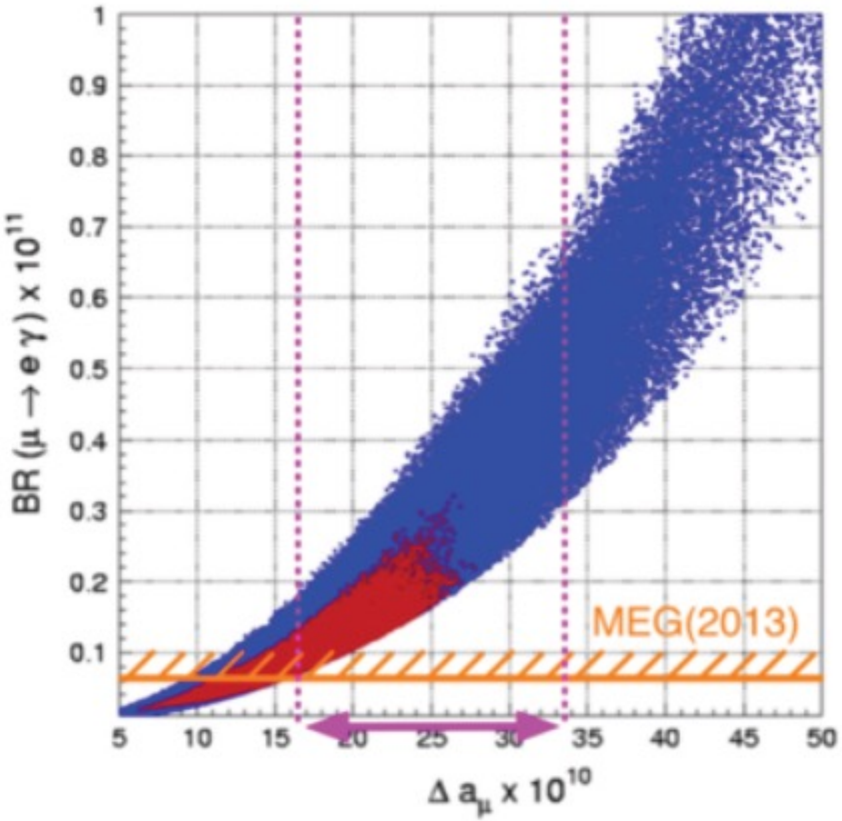


$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

Physics of
slepton mass matrix

Correlations: $\mu \rightarrow e\gamma$ vs $(g-2)_\mu$

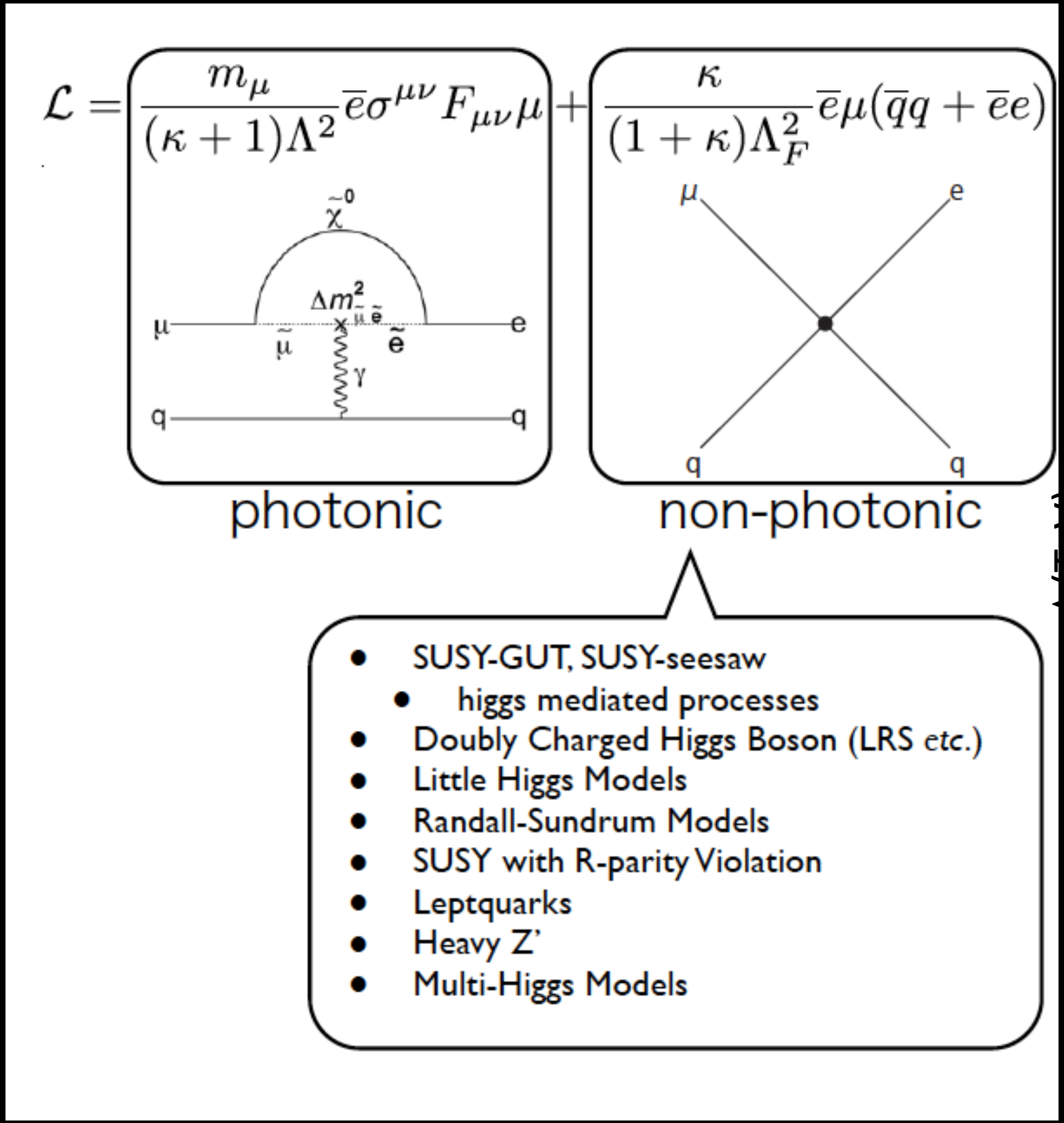
- **3.4 σ discrepancy** w.r.t. Standard Model prediction
  - *possible **hint** of **new physics***
  - *this **would enhance** to **μ->eγ** for example in a **supersymmetric** model*
    - **cLFV coupling $|\delta_{LL}^{12}|^2 \approx 10^{-4}$ almost excluded**
- resolution **improvements** by a **factor 4** from future experiments at **Fermilab** and **J-PARC**
  - *together with **new generation** cLFV **experiments** will be **sensitive** to $|\delta_{LL}^{12}|^2 \approx 10^{-5}$*

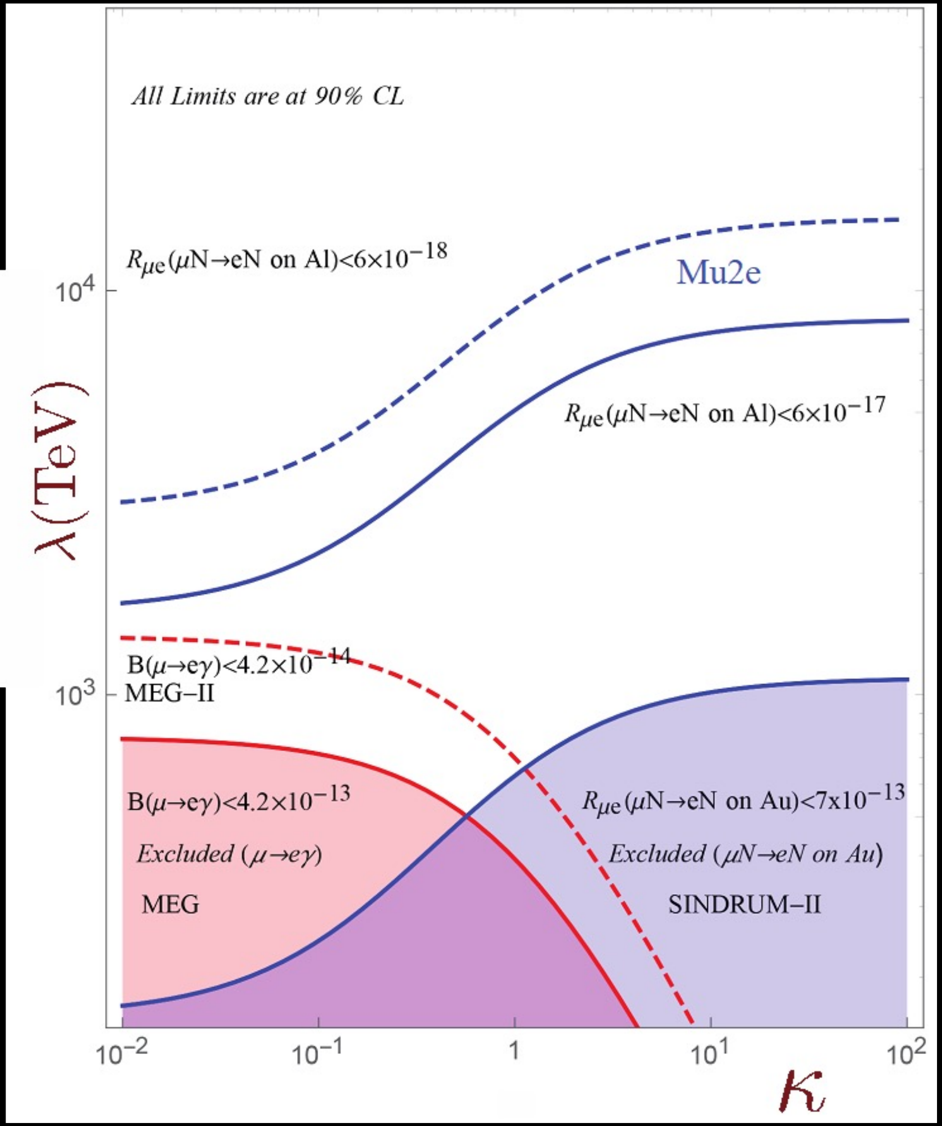


$$\mathcal{B}(\mu \to e\gamma) \approx 10^{-4} \left(\frac{\Delta a_\mu}{200 \times 10^{-11}} \right)^2 |\delta_{LL}^{12}|^2$$

G. Isidori et al., 2007

Correlation μ → eγ & μ-e Conversion





k

photonic-like ⟷ nonphotonic-like

Correlations

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

The pattern of measurement:
★★★ large effects
★★ visible but small effects
★ unobservable effects
is characteristic,
often uniquely so,
of a particular model

GLOSSARY	
AC [10]	RH currents & U(1) flavor symmetry
RVV2 [11]	SU(3)-flavored MSSM
AKM [12]	RH currents & SU(3) family symmetry
δLL [13]	CKM-like currents
FBMSSM [14]	Flavor-blind MSSSM
LHT [15]	Little Higgs with T Parity
RS [16]	Warped Extra Dimensions

CLVF μ-decay status

If charged lepton flavour is violated we might these muon decays:

$\mu \to e\gamma$,

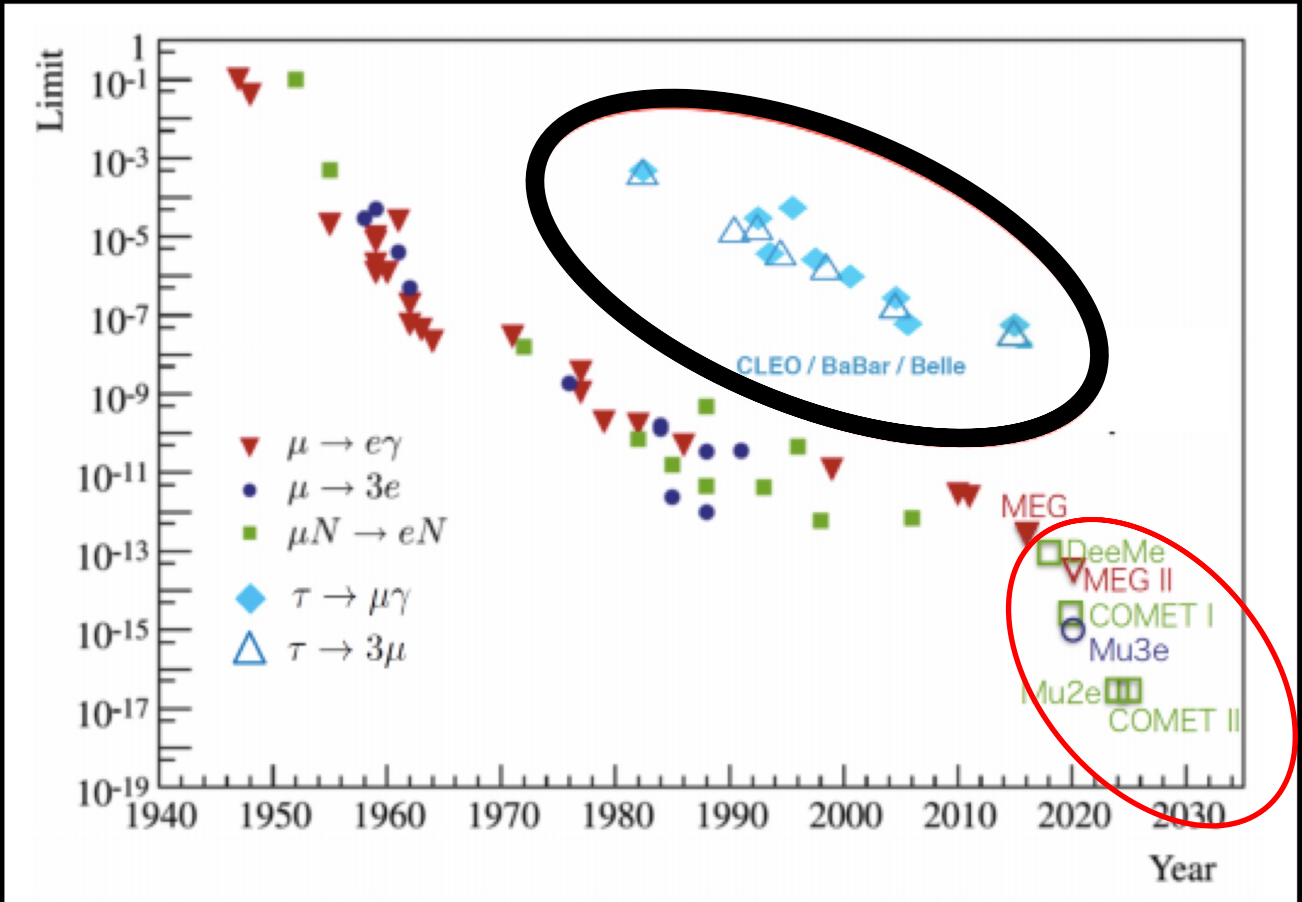
$\mu \to eee$

$\mu N \to eN$

First measurements shortly after discovery muon (showed muon was not an excited electron)

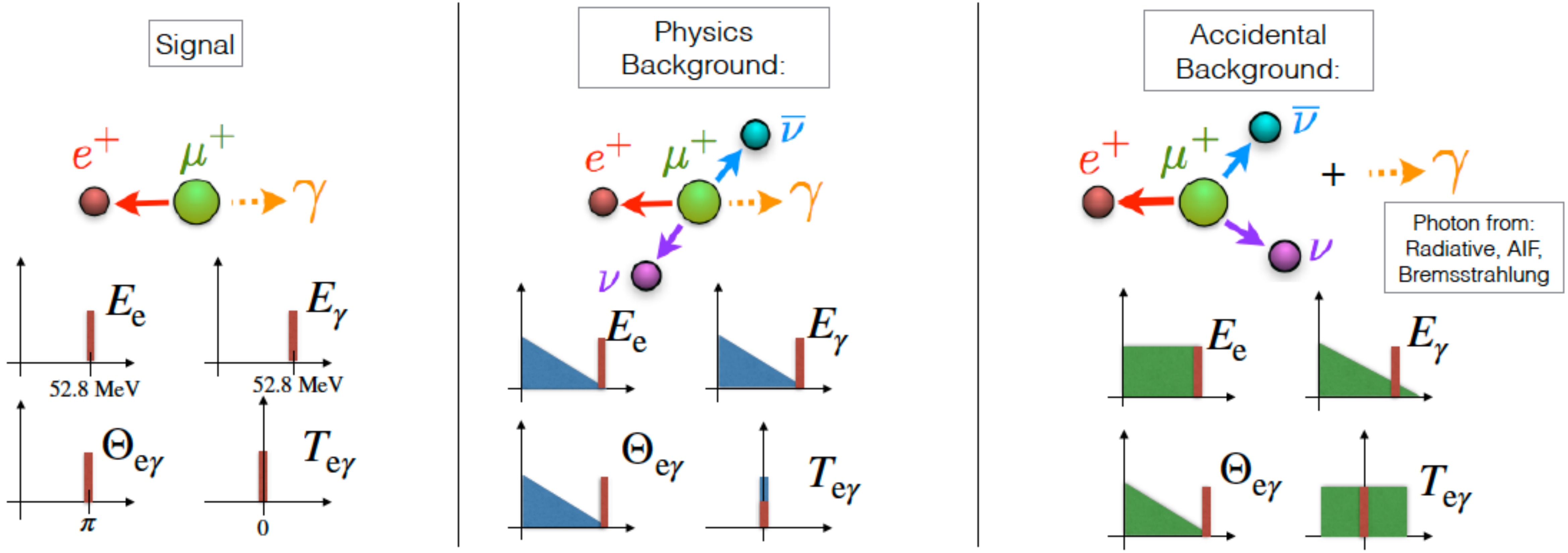
Experiments in preparation will push $\mu \to e$ sensitivity by up to four orders of magnitude over the next 5-10 years. #

This corresponds to at reach for NP up to O(PeV) (10^{15} eV) mass scales, out of reach direct NP searches at colliders.



	Best limits	Projected sensitivities (90%CL)
$\mu \to e\gamma$	< 4.3×10^{-13} MEG (PSI)	6×10^{-14} MEG II (PSI)
$\mu \to eee$	< 1.0×10^{-12} SINDRUM (PSI)	4×10^{-15} Mu3e I (PSI) 1×10^{-16} Mu3e II (PSI)
$\mu N \to eN$	< 7.0×10^{-13} SINDRUM II (PSI) μ Au → e Au	6×10^{-17} Mu2e (FNAL) 7×10^{-15} COMET I (J-PARC) 6×10^{-17} COMET II (J-PARC)

μ→eγ: Signal and Background



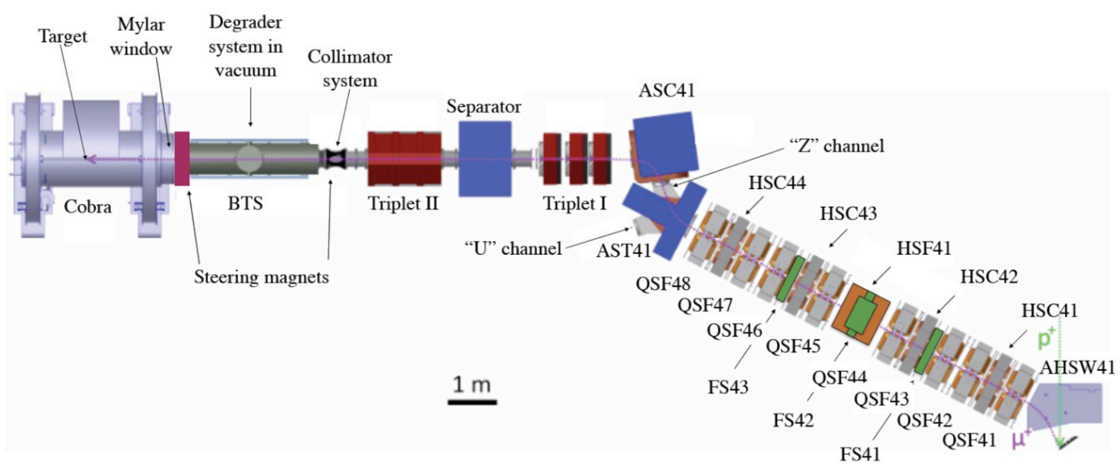
$$R_{\mathrm{Rad}} = R_\mu \, \mathrm{BR}(\mu \rightarrow e\nu\bar{\nu}\gamma \,|\, \Delta E_\gamma, \Delta E_e, \Delta\Theta_{e\gamma})$$

$$R_{\mathrm{Acc}} \approx R_\mu^2 \cdot \Delta E_e \cdot \Delta E_\gamma^2 \cdot \Delta\Theta_{e\gamma}^2 \cdot \Delta T_{e\gamma}$$

Dominating for high muon rates R_μ

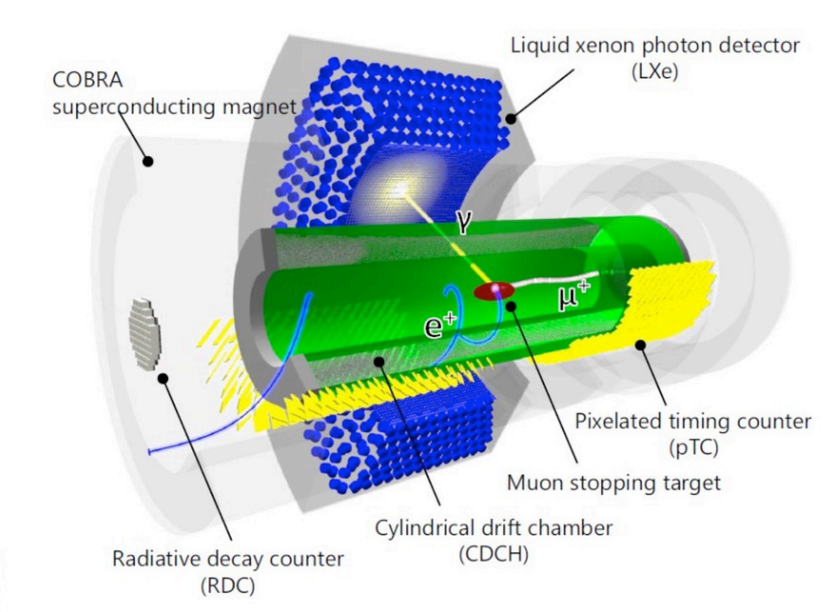
MEG-II: $\mu \to e\gamma$ at PSI

πE5 beam line delivers 28 MeV/c surface muons to experiment target



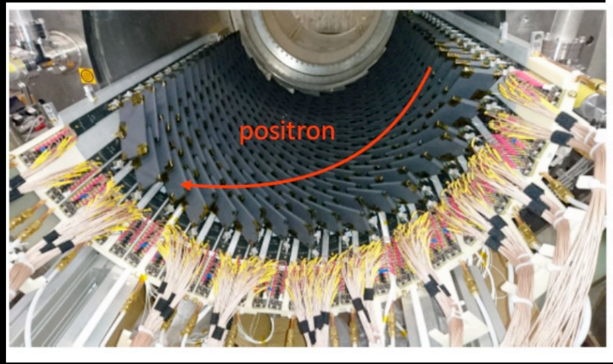
Upgraded (thin, fast, stable) detector:

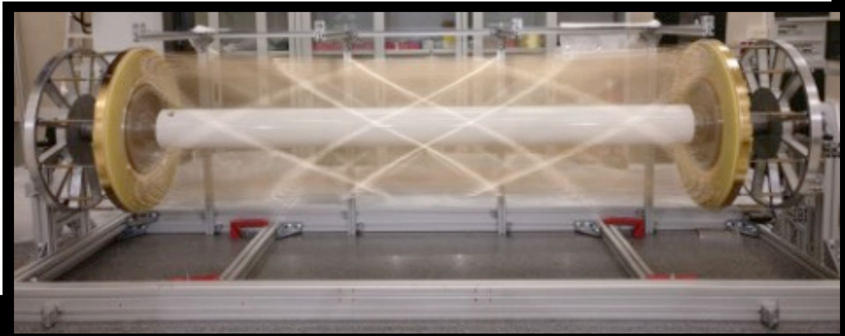
- 2 - 5 x10^{7} μ-decays per second
- 800 liter LXe calorimeter for photon energies
- Cylindrical Drift Chamber for positron momentum
- Scintillating tile timing counters for accidental background rejection



Performance comparison MEG-II vs MEG

Resolutions	Foreseen	Achieved	MEG
E_{e^+} (keV)	100	89	330
ϕ_{e^+}, θ_{e^+} (mrad)	3.7/6.7	4.1/7.1	8.4/9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.75/1.85	1.1/2.5
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	2.4/1.7
$u_\gamma, v_\gamma, w_\gamma$, (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5/5/6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	63	63
ε_{e^+}	65	65	30
ε_{TRG}	≈99	82	





MEG-II status

First MEG-II were published 2023:

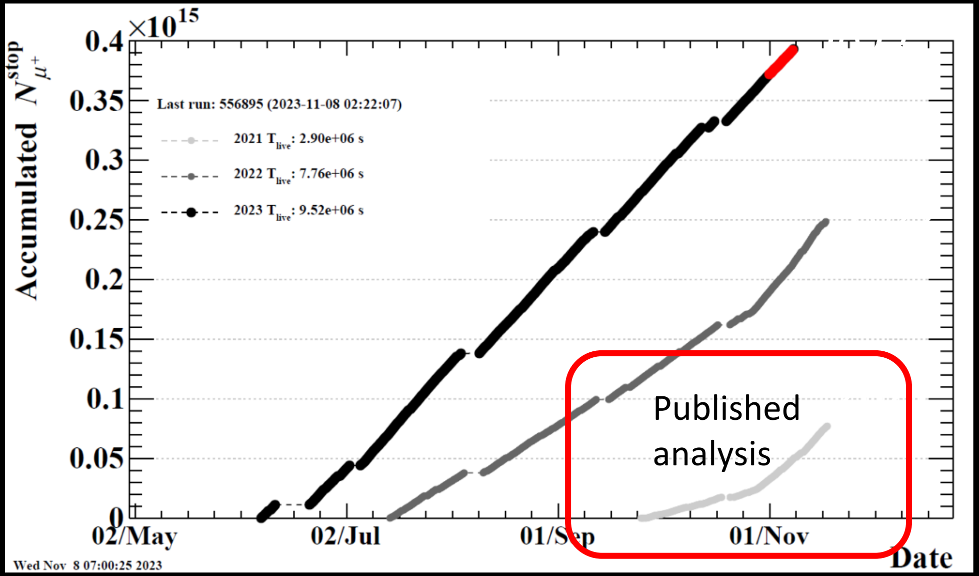
BR($\mu \to e\gamma$) < 7.5 x 10^{-13} (arXiv :2310.12614v2)

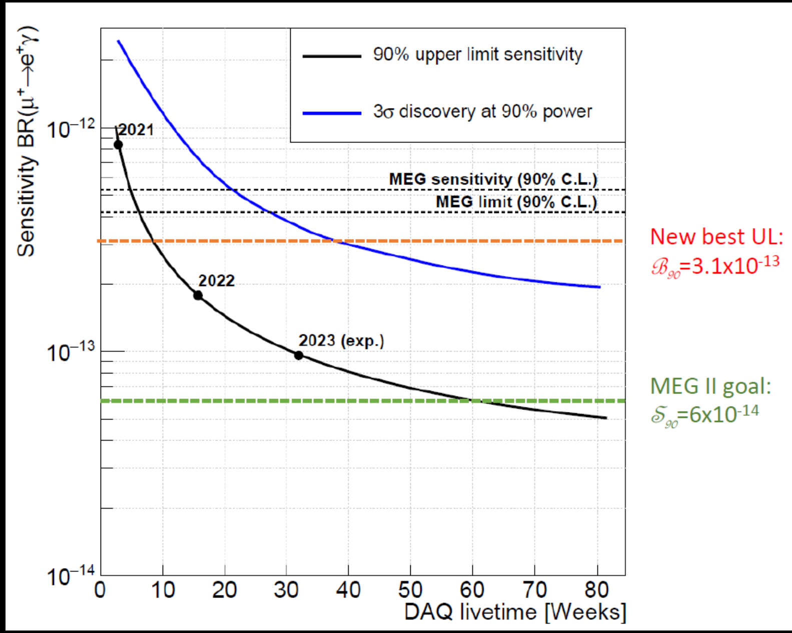
(Combined MEG + MEG-II: BR($\mu \to e\gamma$) < 3.1x10^{-13})

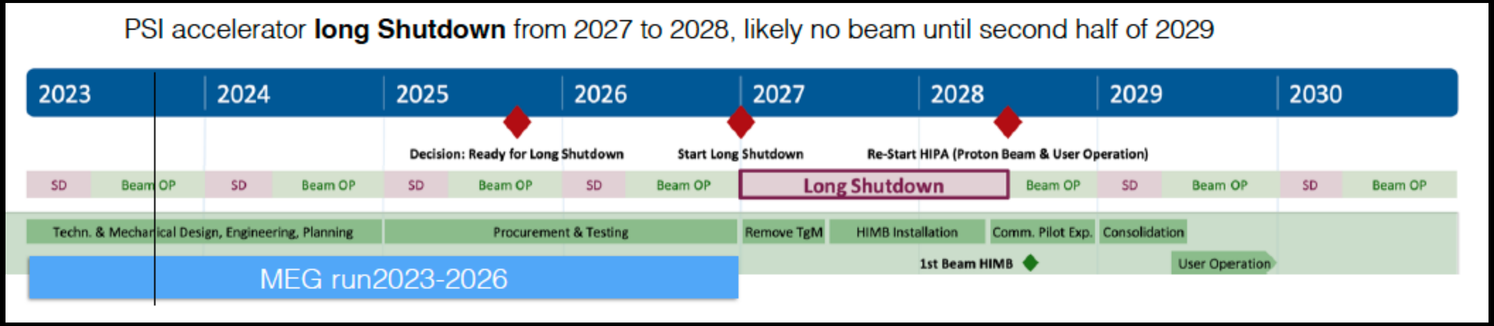
Based on few weeks of data taken in 2021 (10^{14} μ decays)

Continue to run until 2026.

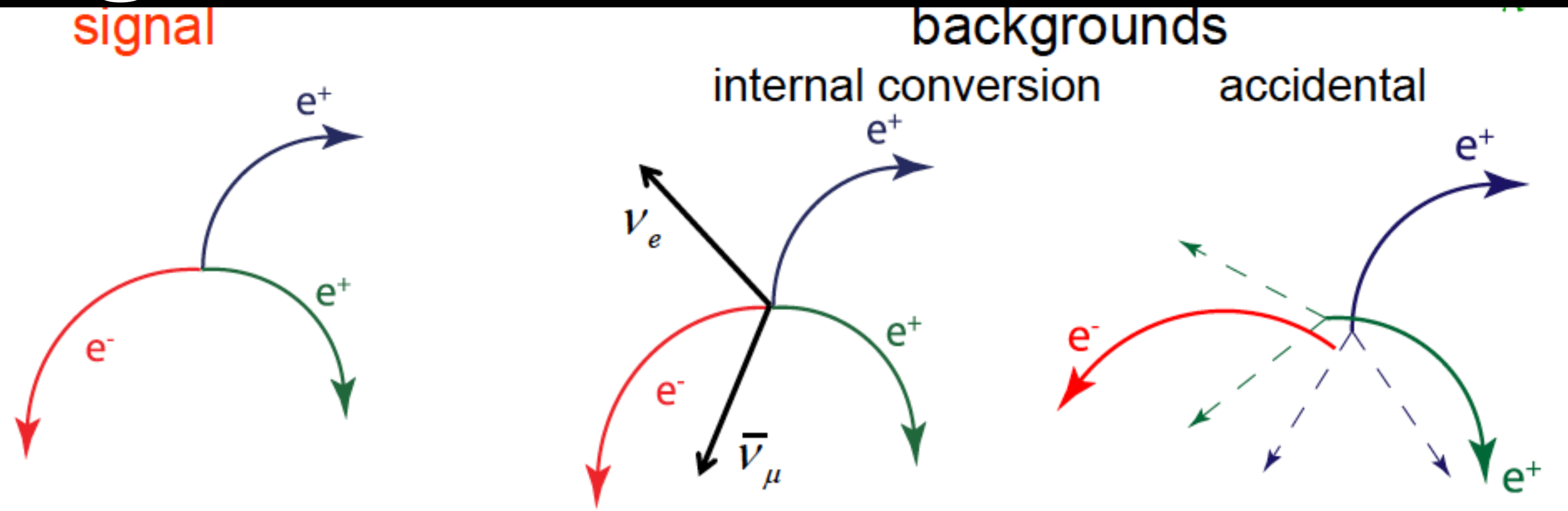
Final sensitivity goal is 6x10^{-14}







Mu3e@PSI



BR ($\mu^+ \rightarrow e^+ e^- e^+ \nu_e \nu_\mu$) = 3.5 x 10^{-5}

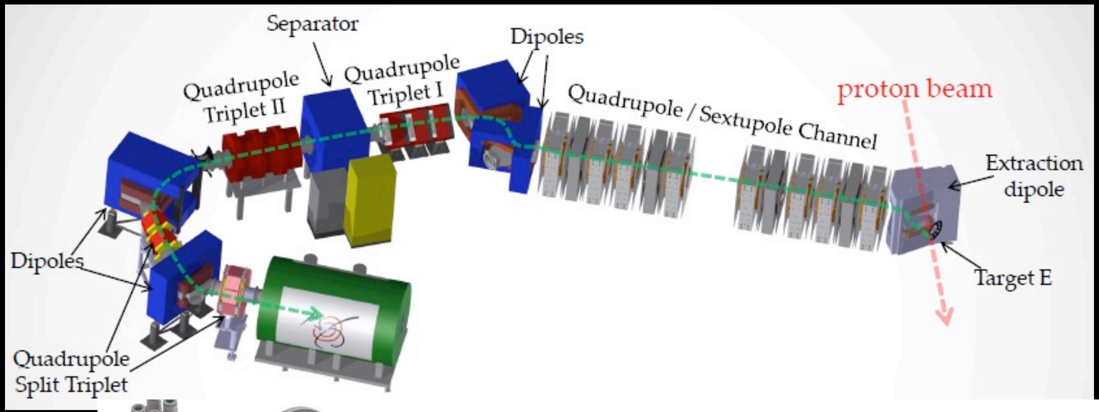
Features

signal	internal conversion	accidental
common vertex	common vertex	no common vertex
$\Sigma \mathbf{p}_i = 0$, $\Sigma E_i = m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i < m_\mu$	$\Sigma \mathbf{p}_i \neq 0$, $\Sigma E_i \neq m_\mu$
in time	in time	out of time

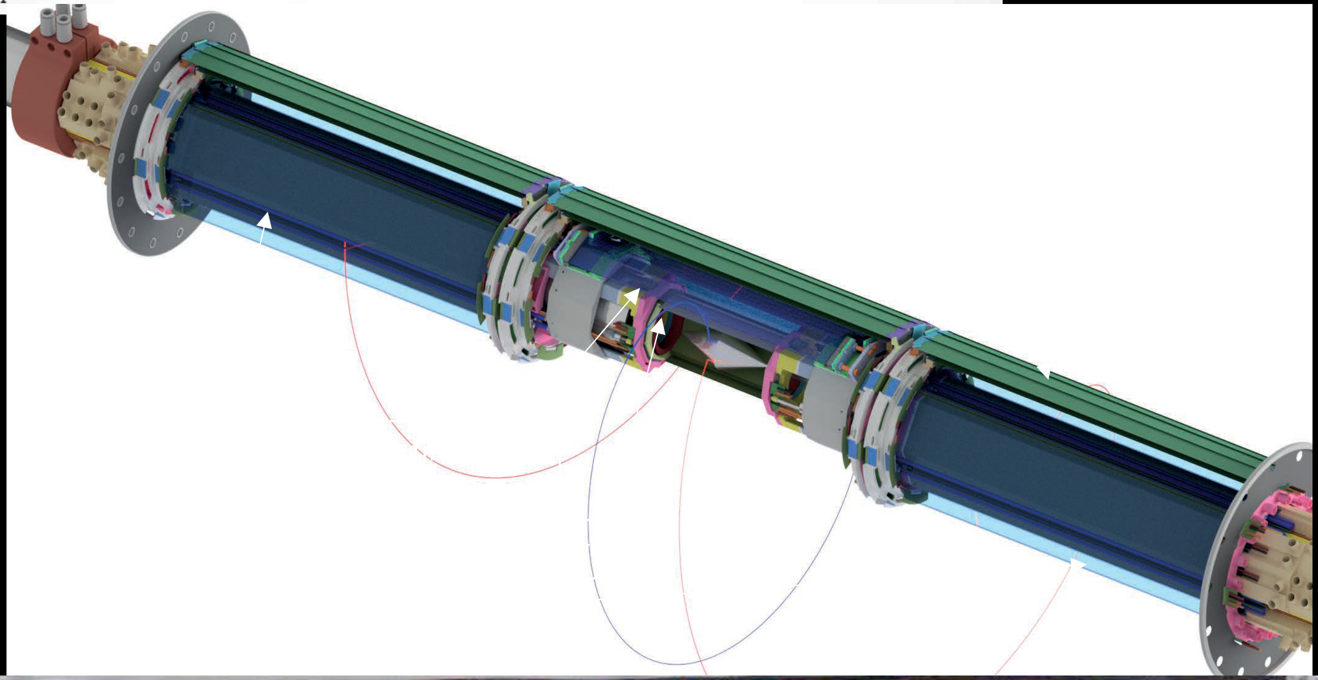
Rejecting the background requires

$\sigma_{vtx} < 300\ \mu m$
$\sigma_p < 0.5$ MeV/c
$\sigma_t < 0.5$ ns

Mu3e: μ→eee at PSI



Inside mu3e up to 2x10[9] μ/s are stopped on thin mylar target.



To achieve high resolution for low energy positrons/electrons (10-50 MeV) requires an ultra-low-mass tracker

- MuPix tracker (~0.1%X_0 per layer)
  - 50 μm HV-CMOS pixel sensors
  - Low mass supports
  - cooled with gaseous Helium
- Recurling track concept (1T B field)

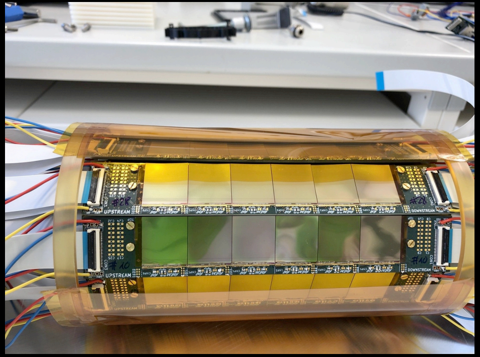
Scintillating fiber and tile detectors crucial for the reduction of combinatoric backgrounds

Mu3e status

Construction of the mu3e experiment is ongoing, to be completed in early 2025.

<u>Phase I experiment </u>(Start of Physics operation in 2026)

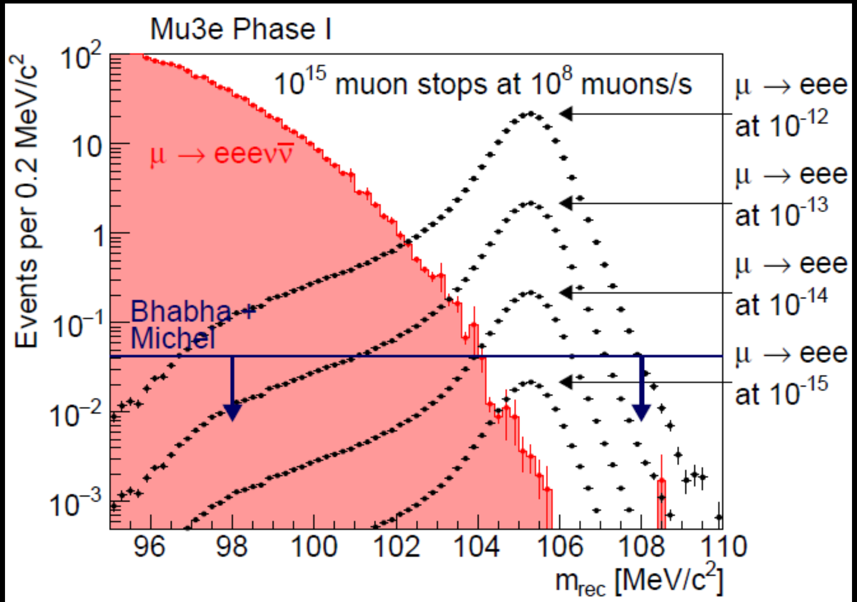
- 10^8 μ/s beam
- substantial improvement on SINDRUM limit (10^{-12}) based on first year of data.
- Completion phase-I around 2030 with sensitivity to BR($\mu\to eee$) < 2×10^{-15}



<u>Phase 2 experiment upgrade</u>

- 2×10^9 μ/s after PSI HIMB upgrade
- Extended acceptance
- Fast silicon to control combinatoric backgrounds
- Sensitivity goal 10^{-16}

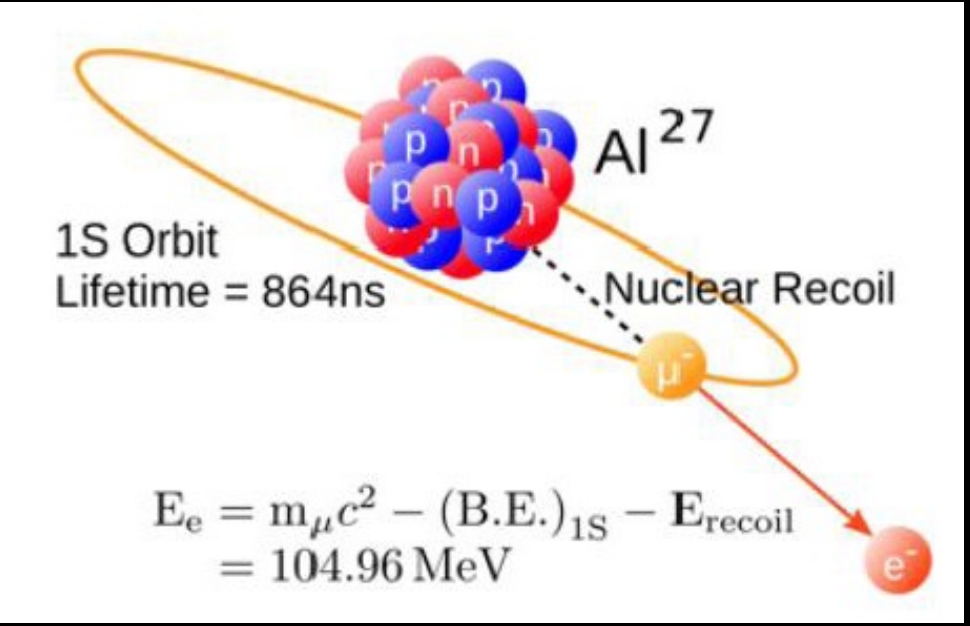
4 order of magnitude improvement respect to SINDRUM BR($\mu\to eee$) < 1×10^{-12}



μ-e Conversion in Nuclear Field

- Muonic Atom (1S state)
  - Muon Capture (MC)

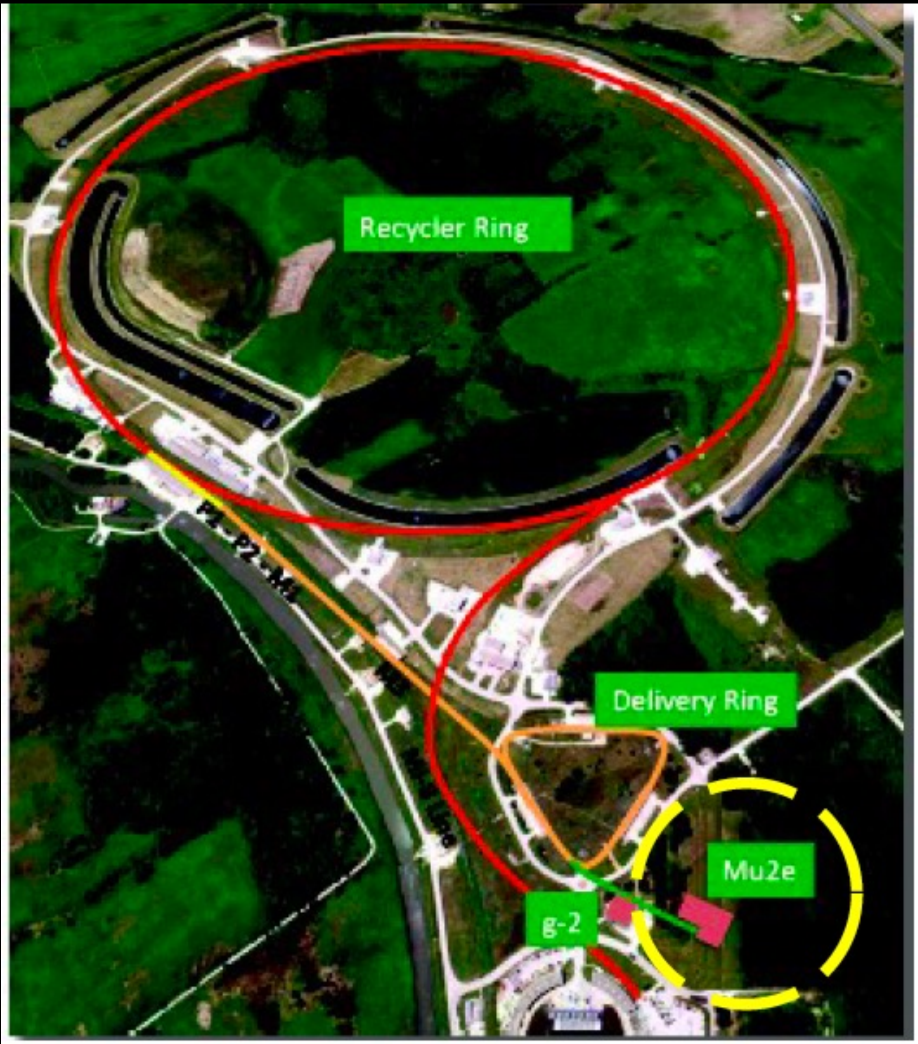
    $\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z-1)$
  - Muon Decay in Orbit (DIO):
    - $\mu^- \rightarrow e^- \nu \nu$
  - MC: DIO = 1:1000(H), 2:1(Si), 13:1(C), 3:2 (Al)
  - τ_μ (Al) = 0.86 μs



- SIGNAL: Charged Lapton Flavor Violation (μ-e conversion in nuclear field) with a monochomatic e- with E~105 MeV
  - $\mu^- + (A, Z) \rightarrow e^- + (A, Z)$

$$BR[\mu^- + (A,Z) \rightarrow e^- + (A,Z)] \equiv \frac{\Gamma[\mu^- + (A,Z) \rightarrow e^- + (A,Z)]}{\Gamma[\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)]}$$

Mu2e



Mu2e at
Fermilab Muon Campus

Mu2e **goal** is to improve by **a factor 10^4** the world's best sensitivity on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

SINDRUM II @PSI (2006, Au)*:

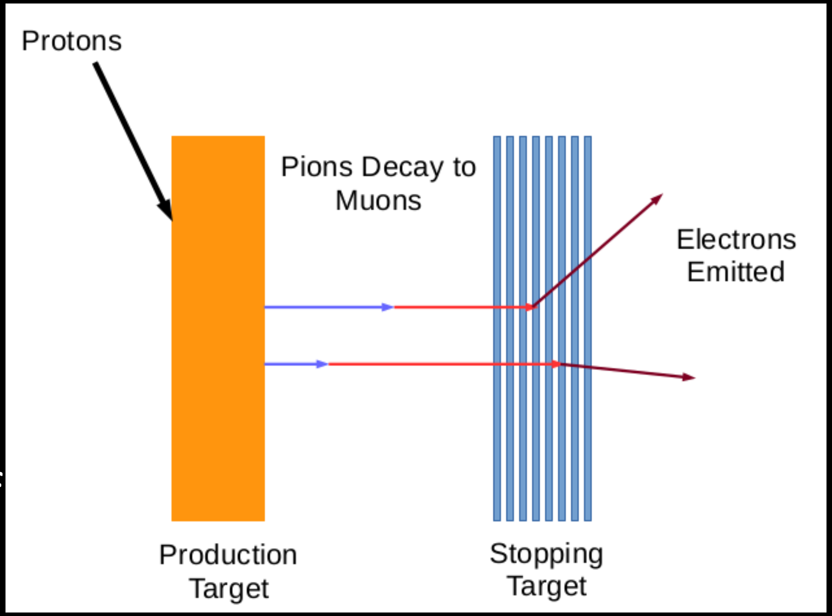
$R_{\mu e} < 7 \cdot 10^{-13}$ (90% CL)

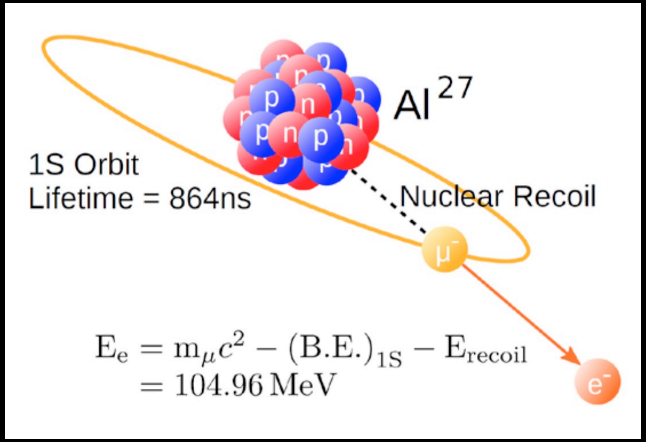
[S. Di Falco, EPS-HEP2023]

Mu2e experiment concept

- Produce a muon beam using a proton beam:
  - Proton beam hitting a production target produces pions
  - Pions decay to muons ($\pi^- \to \mu^- \bar{\nu}_\mu$)
- Low momentum muons captured in a stopping target
  - Instantaneously (~ 10^{-13} s) cascade to 1s state
  - Muonic X-ray emission spectrum gives estimation of number of muons captured
- Muons in muonic atom decay after a certain lifetime:
  - Muon nuclear capture (~61% in Al): $\mu N \to \nu_\mu N'^*$
  - Muon decay-in-orbit (DIO, ~39% in Al): $\mu N \to e N \nu_\mu \bar{\nu}_e$
  - $\mu N \to e N$ conversion: signature of a single monoenergetic electron of ~105 MeV
- Measure ratio of conversions to muon nuclear capture

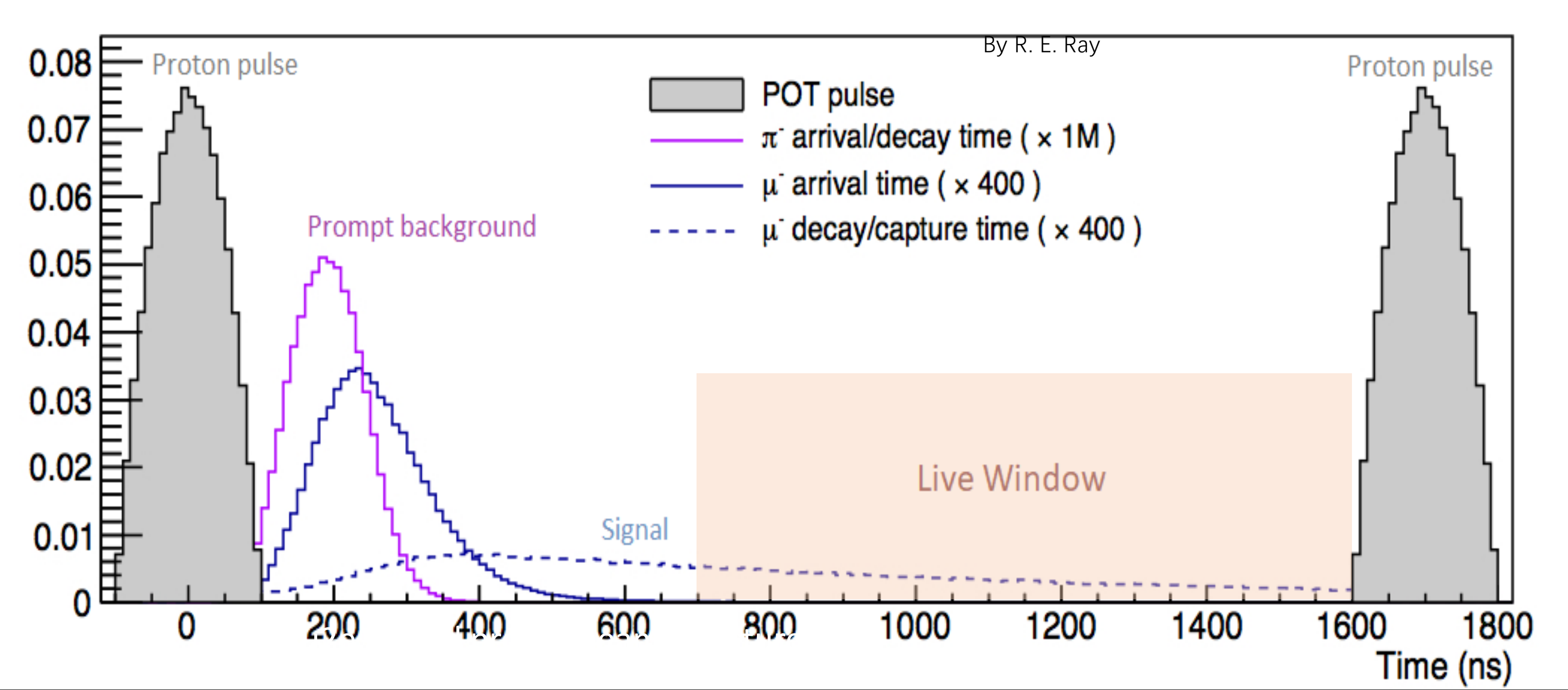
$$R_{\mu e} = \frac{\Gamma[\mu^- + A(Z,N) \to e^- + A(Z,N)]}{\Gamma[\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N+1)]}$$



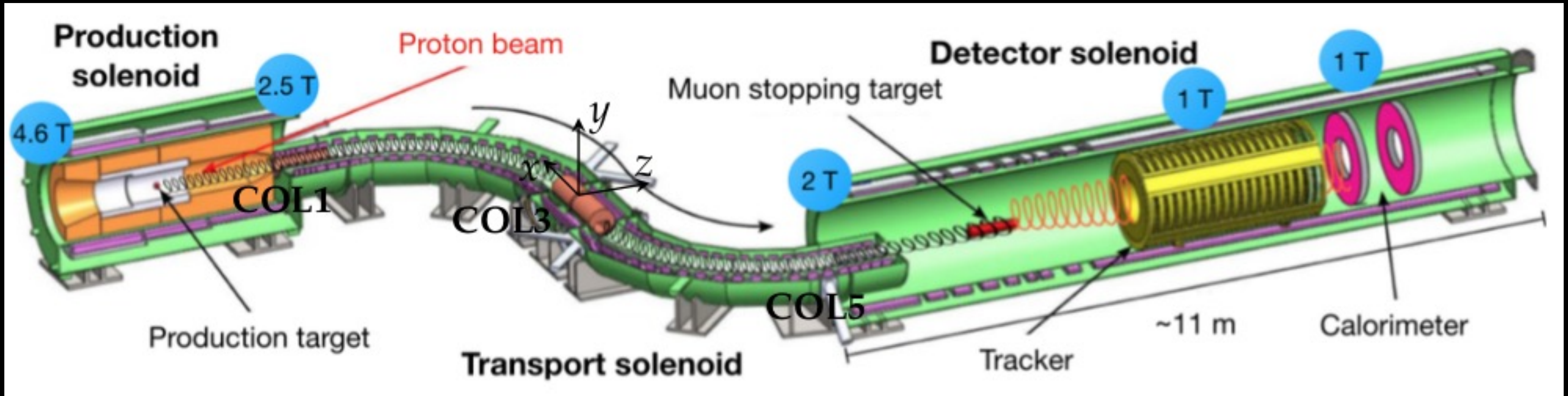


Pulsed proton beam

- Mu2e uses a pulsed proton beam to mitigate backgrounds associated with the primary beam
  - 8 GeV pulsed proton beam from Fermilab booster, re-bunched in the recycler ring, and then transported to the delivery ring
  - Extracted from the delivery ring through resonant extraction (a.k.a., slow extraction)
  - Each pulse: 1695 ns (~2 τ_μ^{Al}), 3.9×10^7 protons (±50%)
  - 900 ns live window starting from 700 ns to suppress prompt background
  - Inter-bunch extinction ratio (fraction out of bunch) < 10^{-10}

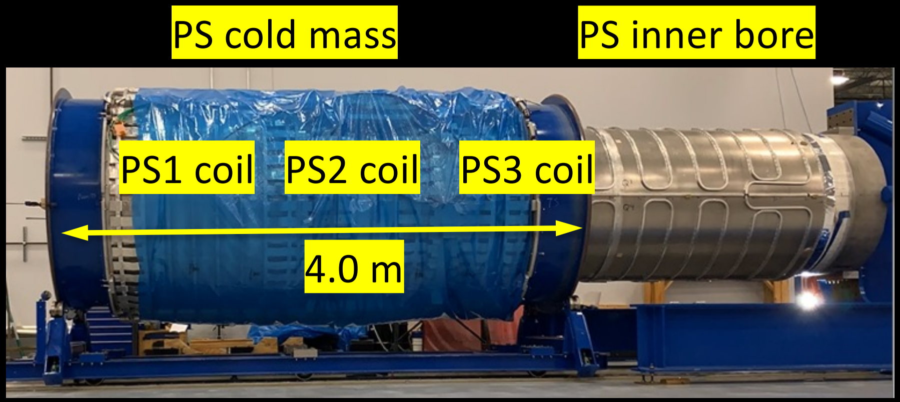


The Mu2e experimental apparatus: the 3 solenoids

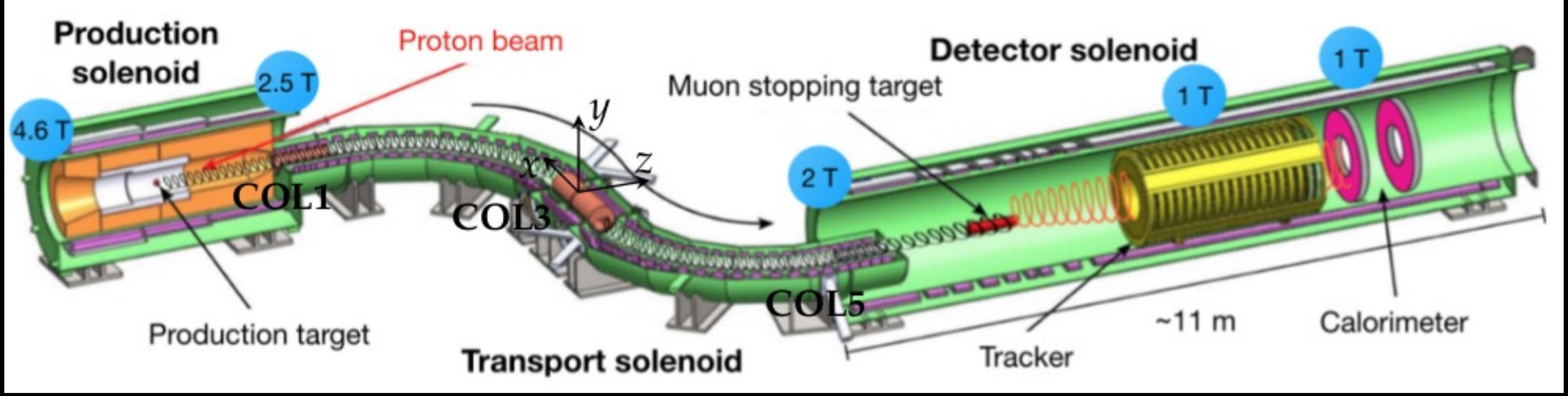


1) Production Solenoid:

- 8 GeV pulsed proton beam entering from the right hits the tungsten target
- a graded magnetic field drives low momentum particles downstream
- Coils assembled with the inner bore
- Preliminary field map obtained

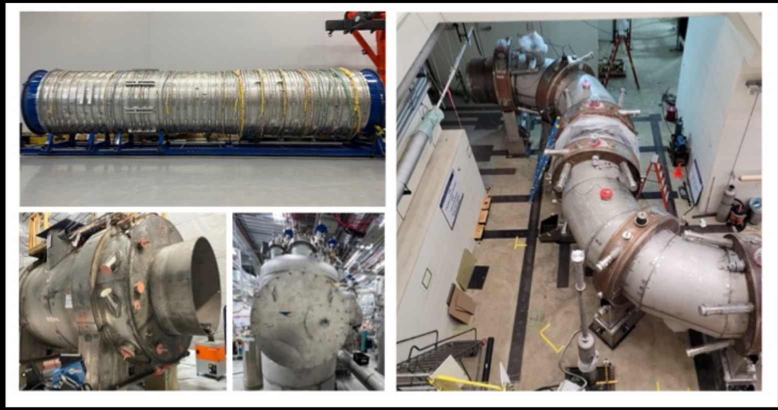


The Mu2e experimental apparatus: the 3 solenoids

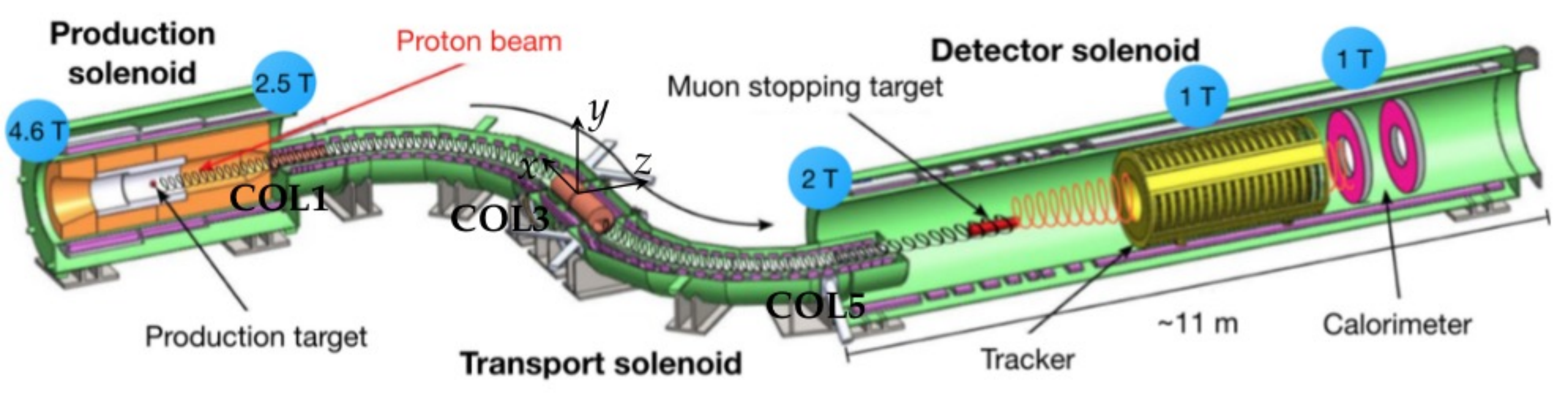


2) Transport solenoid:

- selects -/+ particles of wanted momentum with swivel collimators
- thin absober windows to reduce antiproton background
- small magnetic field gradient to avoid trapped particles
- Installed in the hall !!



The Mu2e experimental apparatus: the 3 solenoids



3) Detector Solenoid (11 coils):

- Contains the Al muon stopping target surrounded by proton/neutron absorbers
- field gradient increases acceptance and suppresses beam electrons
- 1 T uniform field in detectors region
- all 11 coils built, being assembled

A DS coil

μ

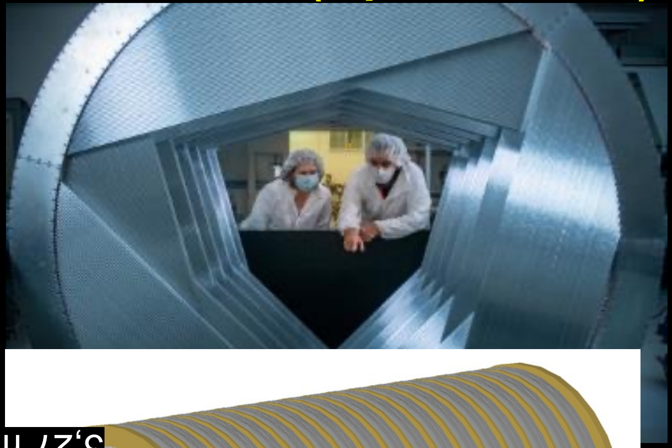
The Aluminum muon stopping target

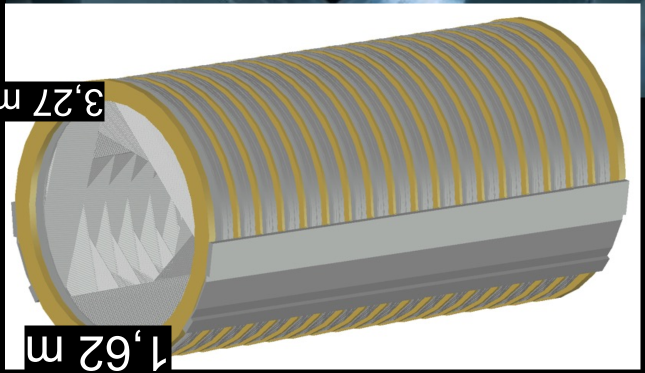
Mu2e detector (main components)

Straw tube tracker provides momentum measurement

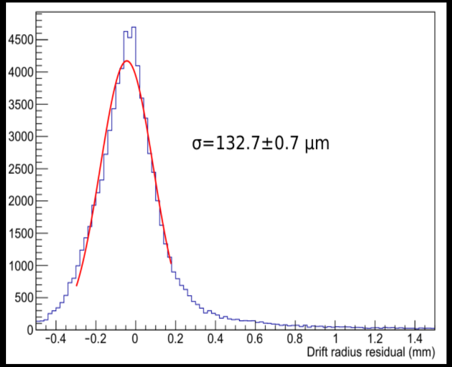
Searching for 105 MeV electrons, with a 180 keV/c momentum resolution

216 panels (made of straws)
36 planes (6 panels each)
18 stations (2 planes each)





Transverse coordinate resolution

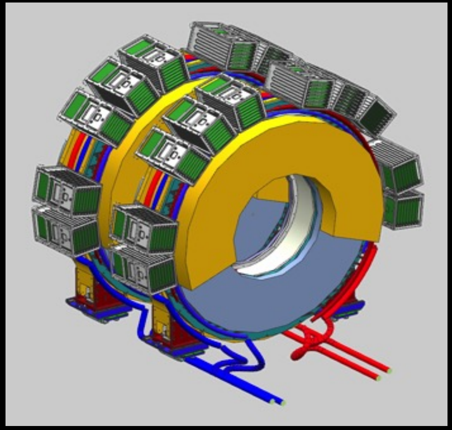


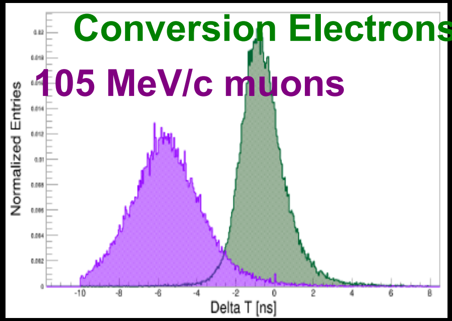
18 stations of 12 panels (~21000 straw tubes)

Expected completion and installation: end of 2024

Electromagnetic calorimeter differentiates particles through energy deposition

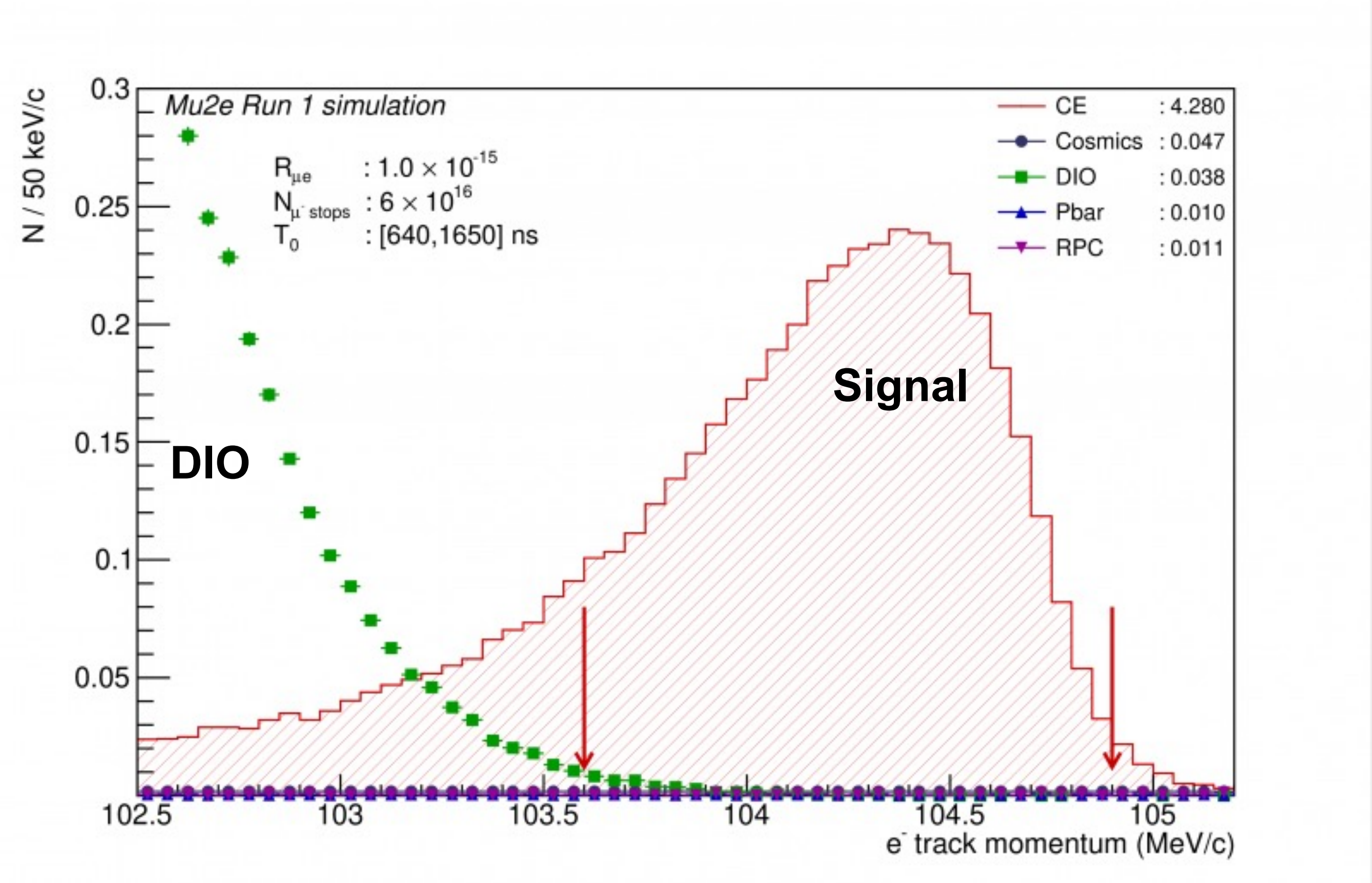
2 disks spaced by 70 cm
674 pure CsI crystals/disk
2 arrays of 6 SiPMs/crystal





Main responsibility of INFN

«signal» window



The **DIO** spectrum falls as $(E_{max}\text{-}E)^5$ close to the end point

Can be suppressed by the momentum window cut

Given the very low background level a **5σ discovery** will require Mu2e to observe just **5 events** of muon conversion

The $R_{\mu e}$ corresponding to a **5σ discovery** in Run 1 is:

$$R_{\mu e} = 1.1 \cdot 10^{-15}$$

Mu2e Run 1
5σ Discovery reach

If no events will be observed the **90% CL limit** will be:

$$R_{\mu e} = 6.2 \cdot 10^{-16}$$

Mu2e Run 1
90% CL limit

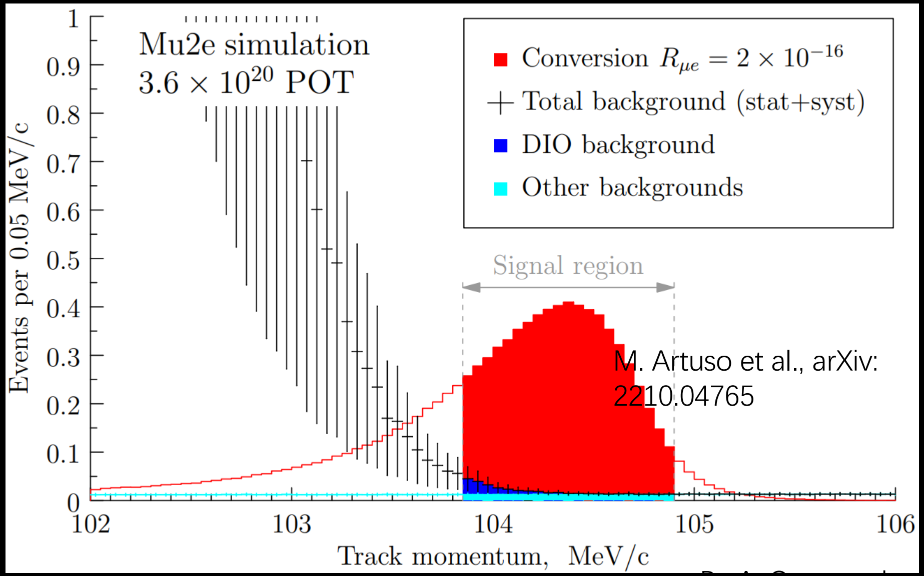
that is more than **x1000** better than current best limit!

[S. Di Falco, EPS-HEP2023]

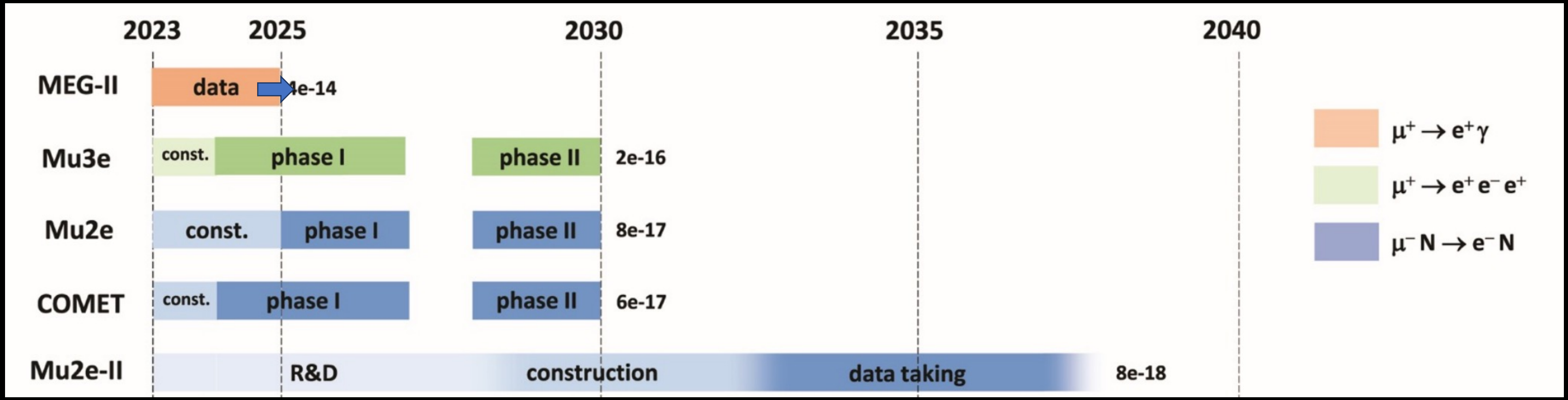
Mu2e schedule

- Run I: End of 2026, before PIP-II/LBNF shutdown
  - 10^3 improvement over SINDRUM-II
- Full data set by the end of the decade, expected $R_{\mu e} < 8\times10^{-17}$ @ 90% CL, 4 orders of magnitude improvement to the current limit
- 2023 P5 Report recommended continued support for Mu2e in the next decade

Simulated Mu2e signal and background



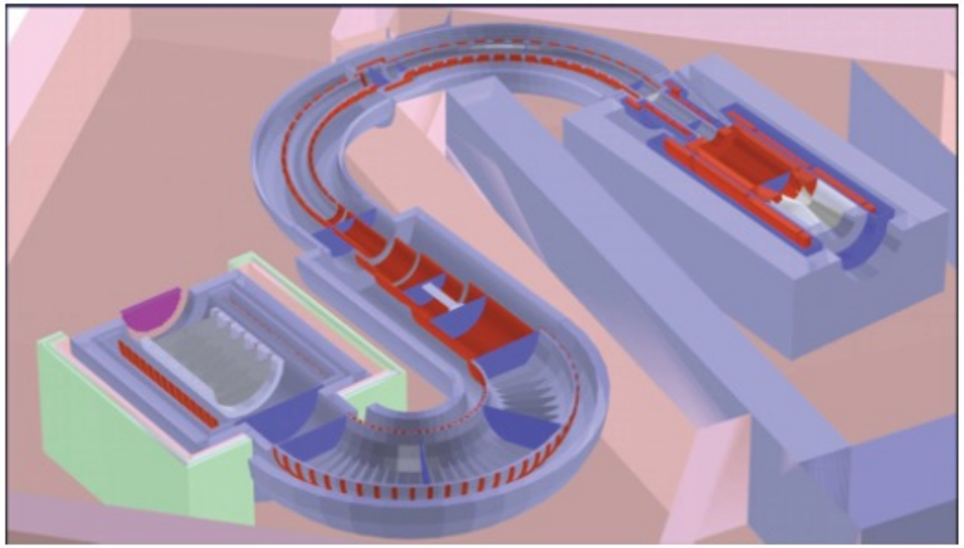
Muon-based CLFV rare decay experiments, expected timeline, and expected 90% CL exclusion power

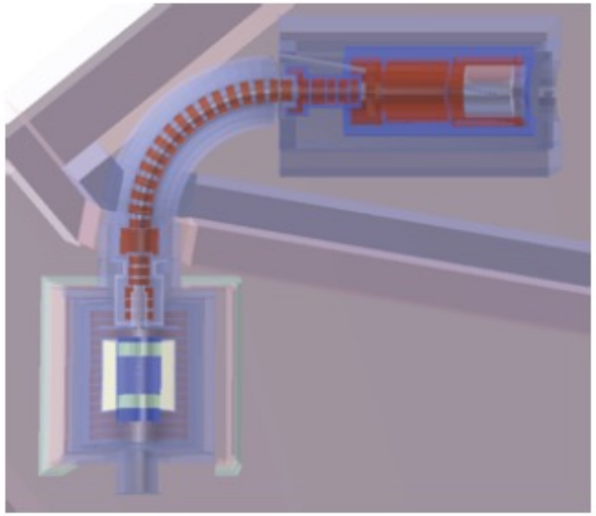


- Discovery reach (5σ): $R_{\mu e} \geq 2\times10^{-16}$
- Exclusion power (90% CL): $R_{\mu e} \geq 8\times10^{-17}$

COMET@JPARC

- a long superconducting solenoid
- Phase-I
  - Beam BG Study
  - S.E.S. = 3×10^{-15}
  - 2018 ~ 2020
- Phase-II
  - S.E.S. = 2.6×10^{-17}
  - 2022 ~

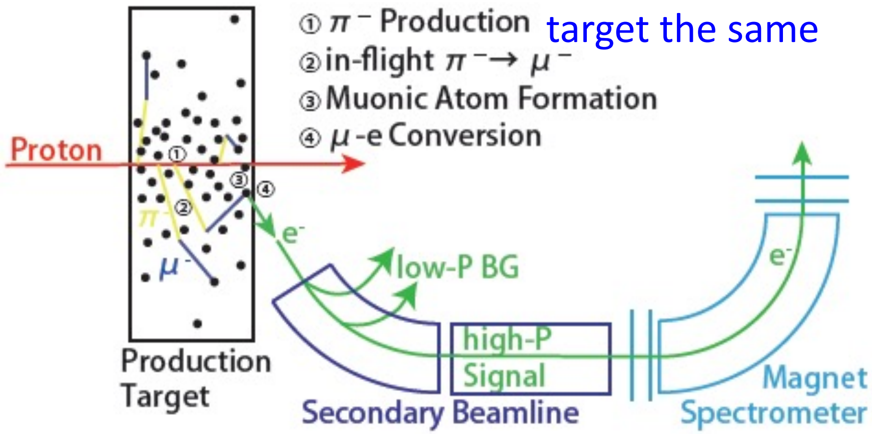


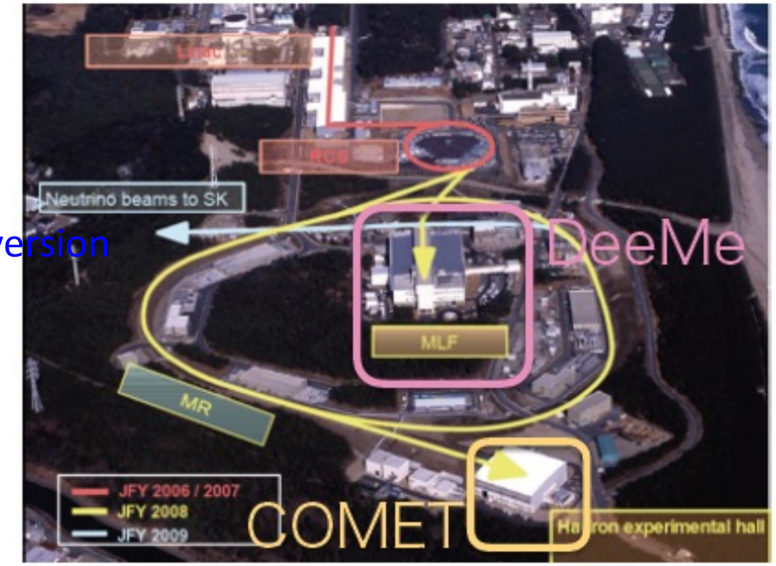


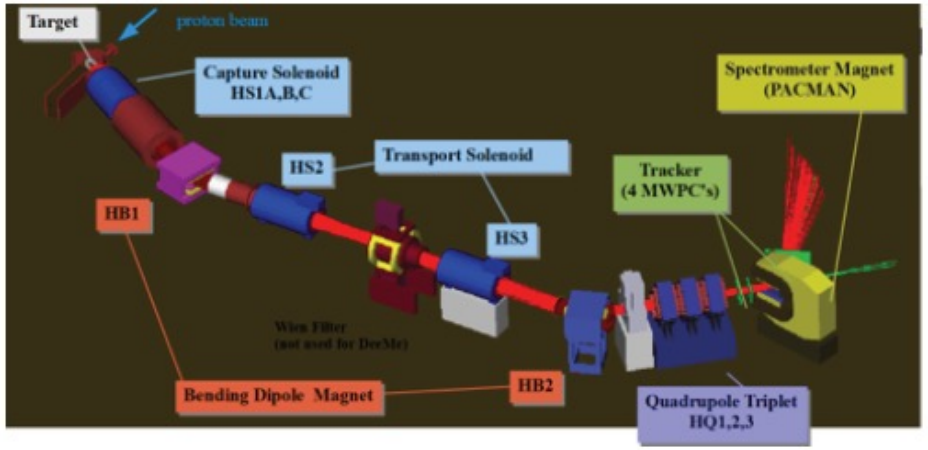
DeeMe@JPARC

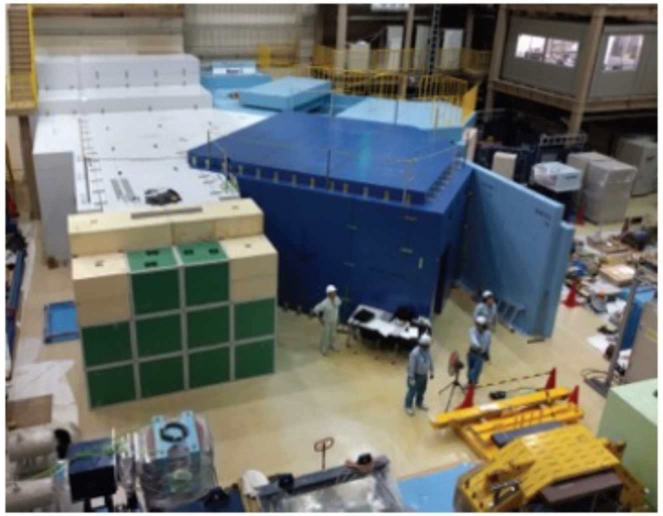
- MELC → MECO → Me2e, COMET
- DeeMe: Completely different idea
- S.E.S. = 10^{-13} (C) ~ 5×10^{-14} (SiC)

Production target and conversion target the same









Conclusions

Exciting muon precision physics programme

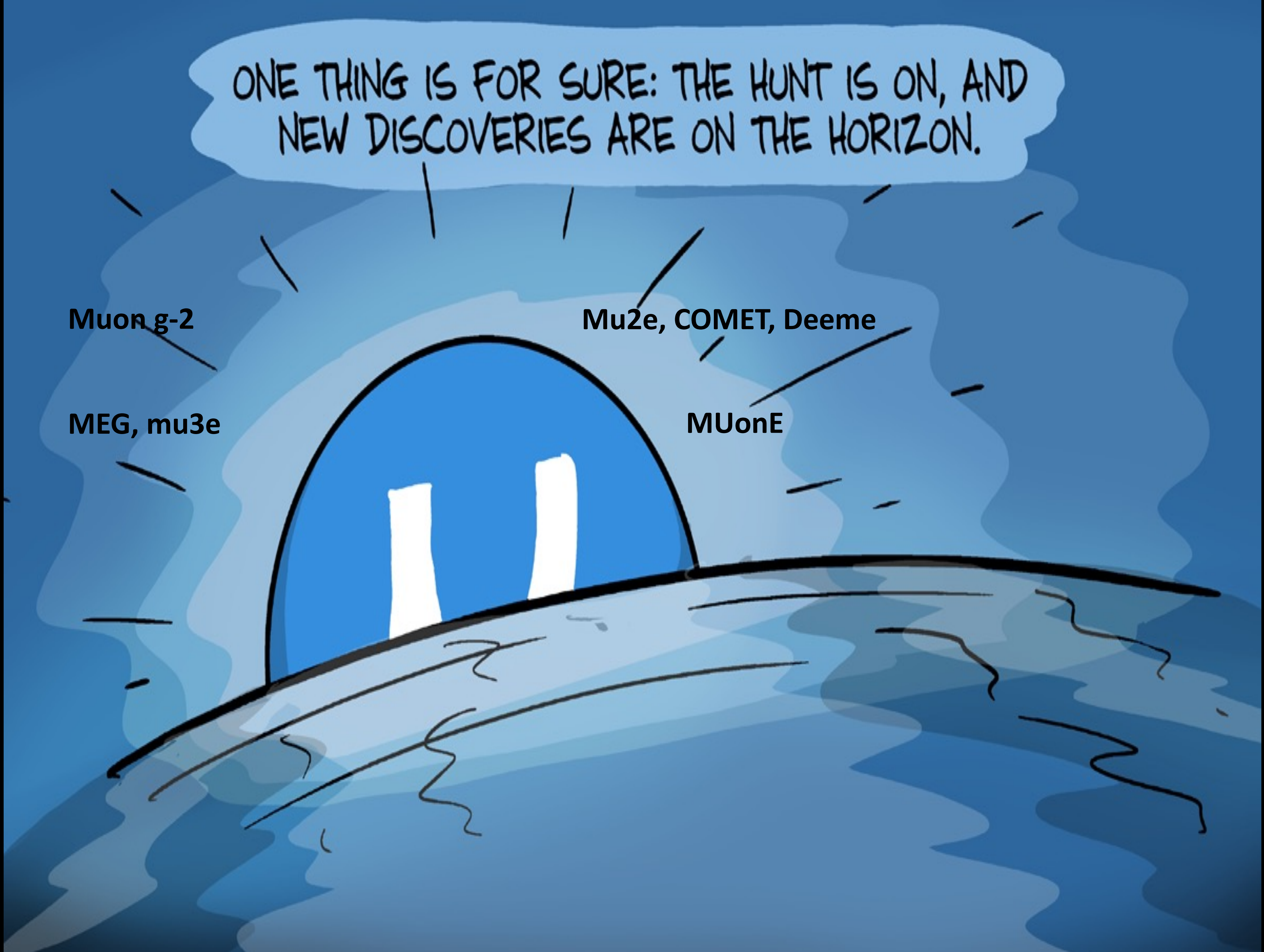
Muon g-2 : successful (70 years) history. Fermilab muon g-2 achieved a precision of 0.2 ppm (→ 0.14 ppm final accuracy). X50 improvement in precision respect to CERN-III **Current** results pose a puzzle that needs resolving. Major focus across theory and new experiments to clarify this

Current experiments and experiments under construction will improve sensitivity to **charged lepton flavour violation in muon decays** by up to four orders of magnitude.

Wide program with with high discovery potential!!

Maybe the final answer will come from one of you!??!

Thank You for the attention!!!


ONE THING IS FOR SURE: THE HUNT IS ON, AND NEW DISCOVERIES ARE ON THE HORIZON.
Muon g-2
Mu2e, COMET, Deeme
MEG, mu3e
MUonE

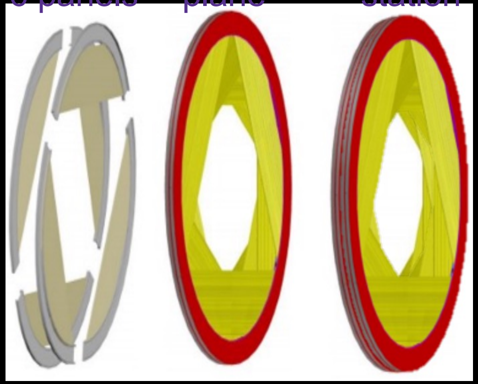
END

2013: The Big Move

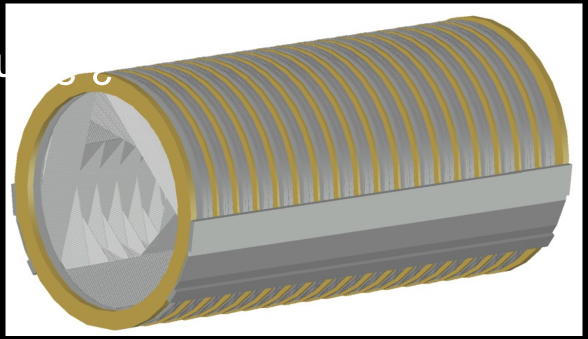
The straw tube tracker

straw tube

5 mm diameter
15μm mylar wall
80:20 $ArCO_2$ gas mixture
25 μm W wire @1450V
ADC & TDC at both ends



216 panels (made of straws)
36 planes (6 panels each)
18 stations (2 planes each)



Tracker structure

18 stations of 12 panels
(~21000 straw tubes)

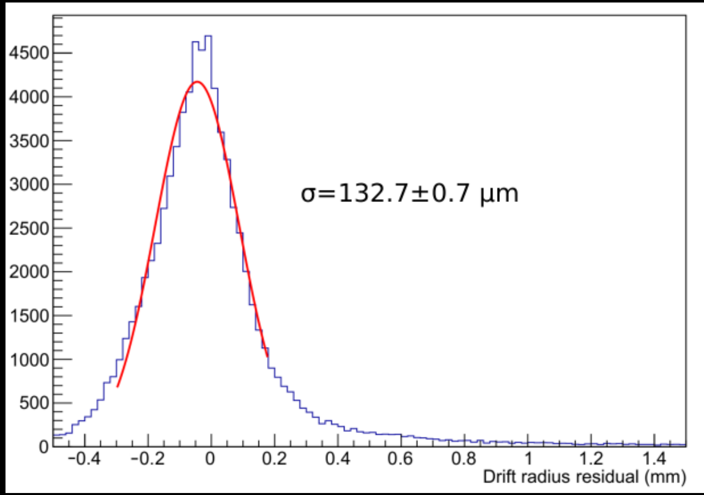
All panels completed
23/36 planes assembled

Leakage test ongoing

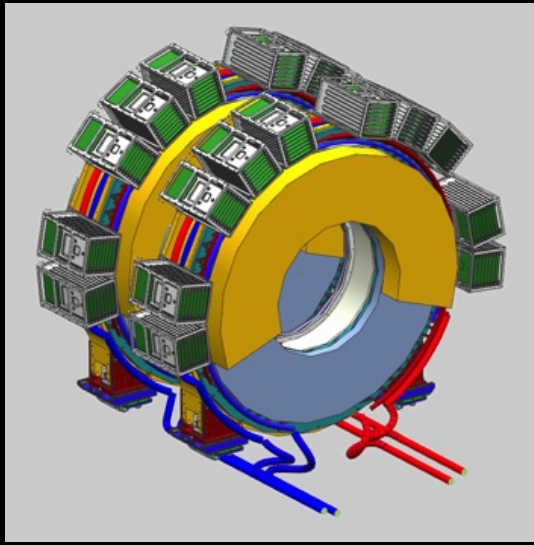
Performances confirm expectations

Expected completion and installation: end of 2024

Transverse coordinate resolution



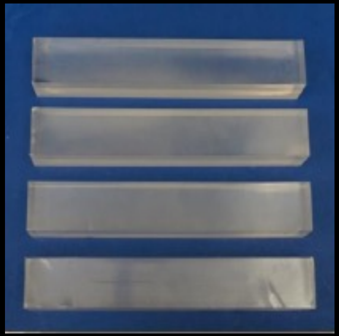
The electromagnetic calorimeter

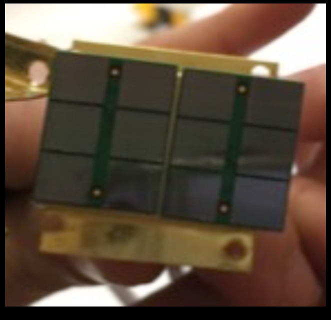


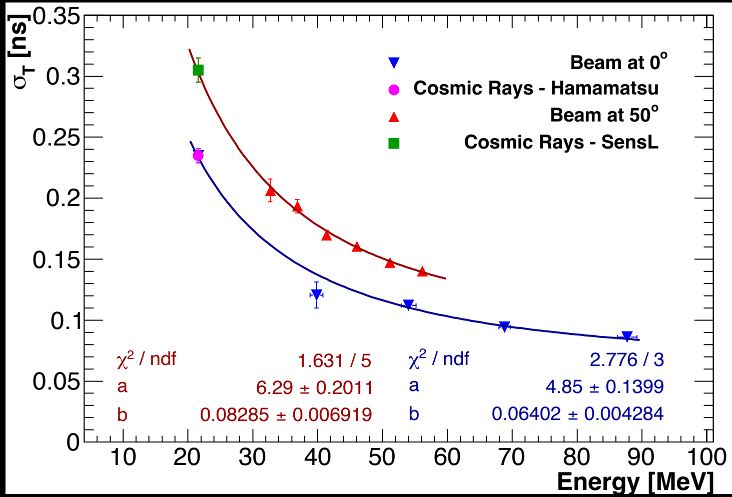
2 disks spaced by 70 cm

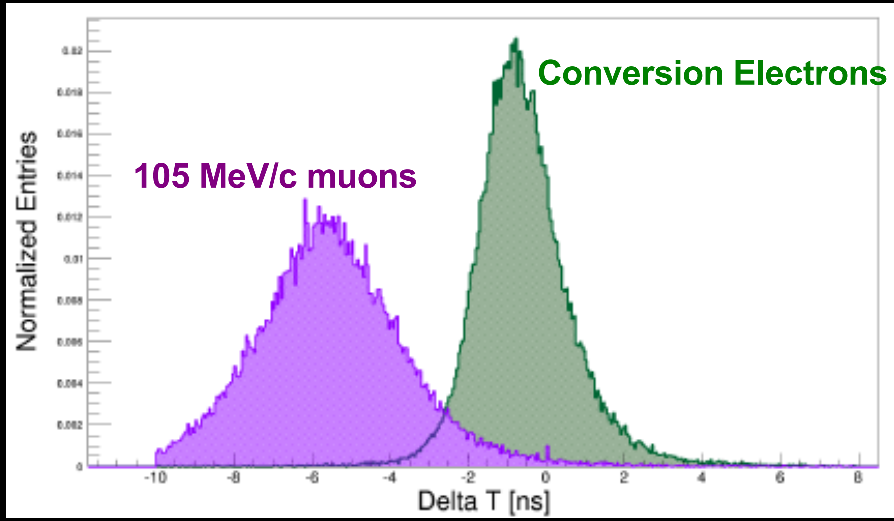
674 pure CsI crystals/disk
2 arrays of 6 SiPMs/crystal

Main goal: e/μ separation



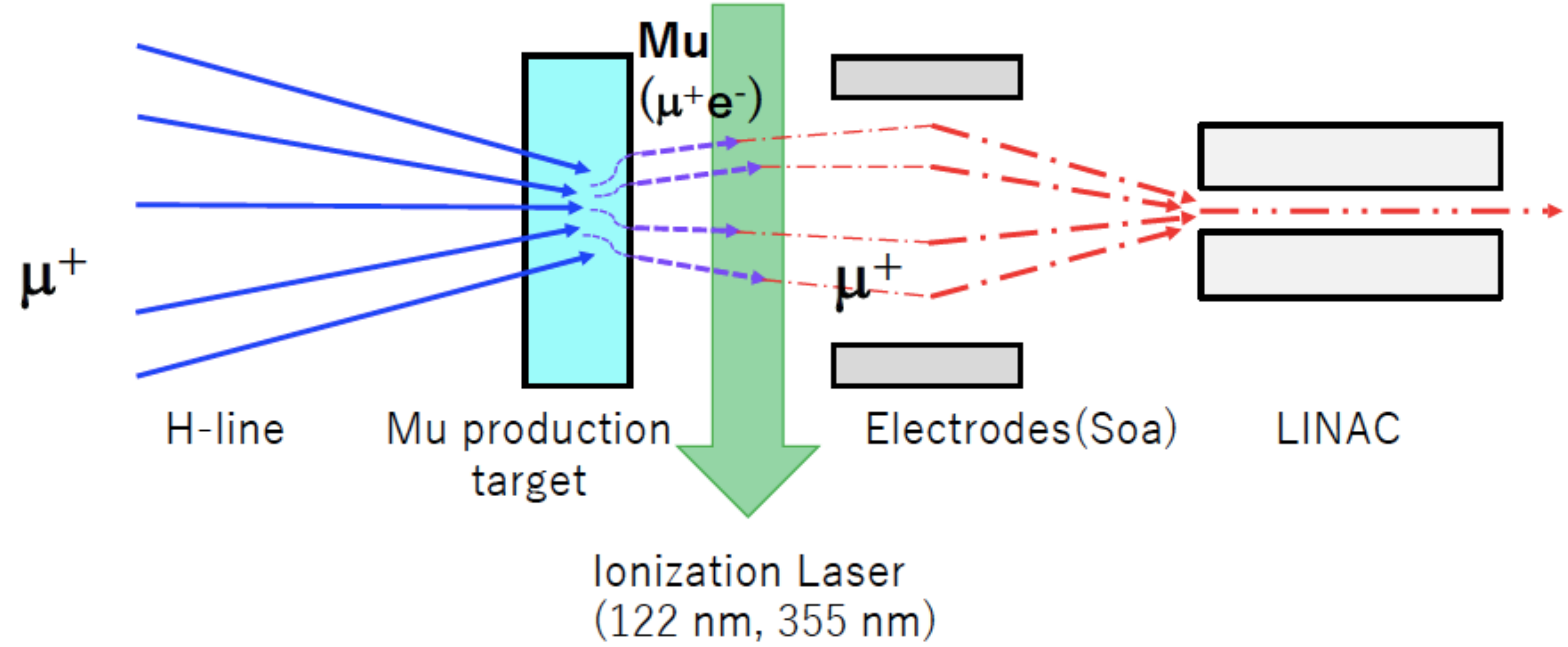






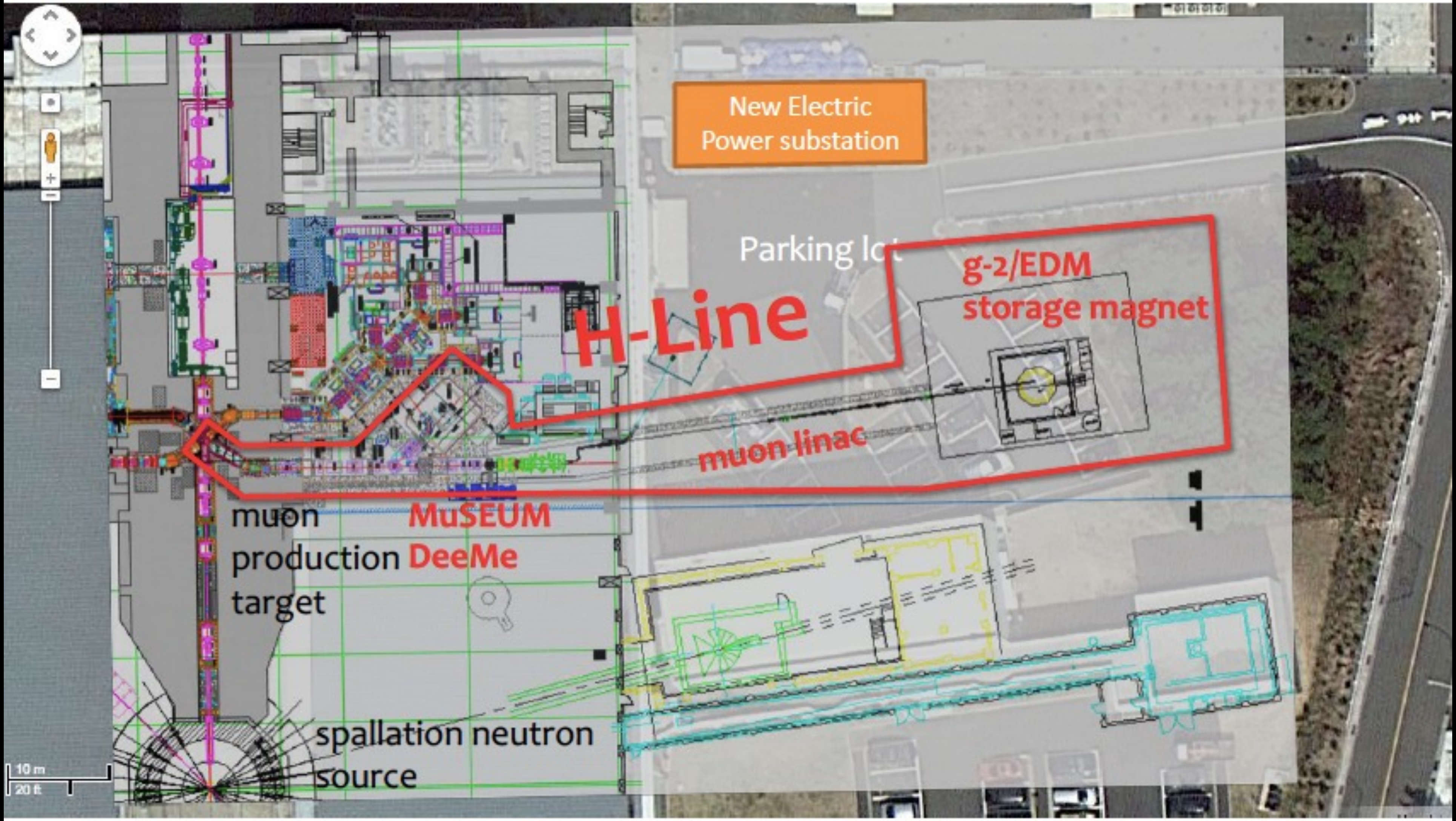
Re-accelerated thermal muon

	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}



Proposed experimental site (H-line)

Material and Life science Facility in J-PARC



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

Sensitivity to the Theory (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})

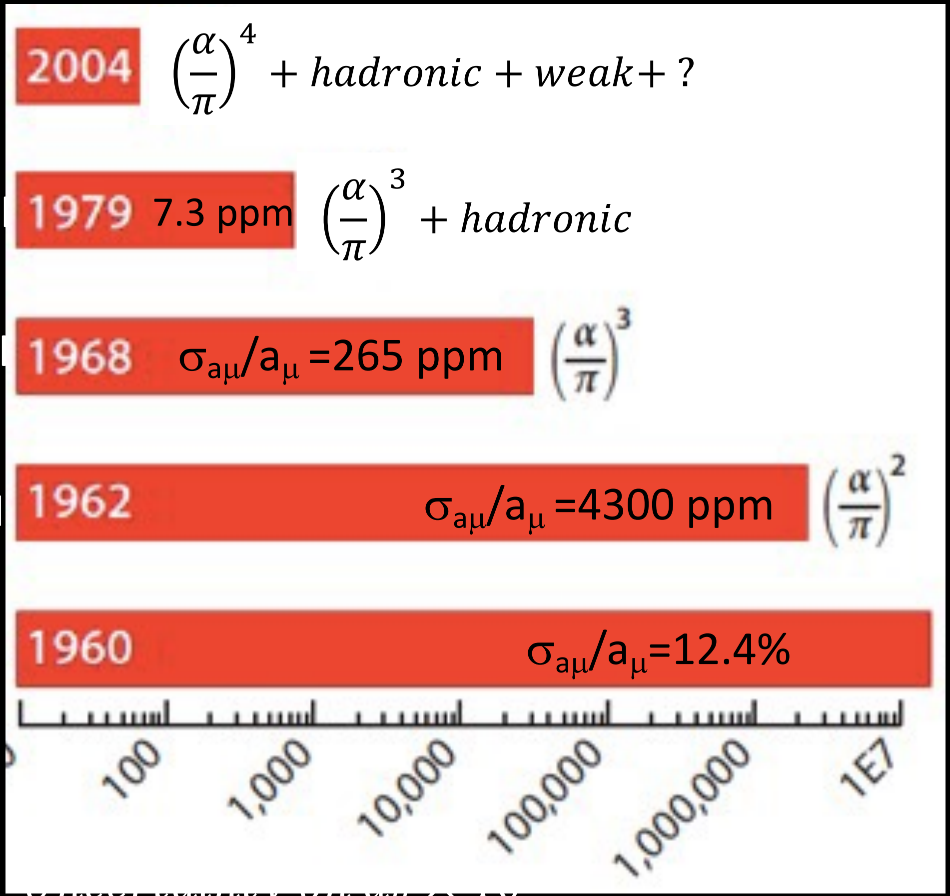
0.54 ppm BNL

CERN III

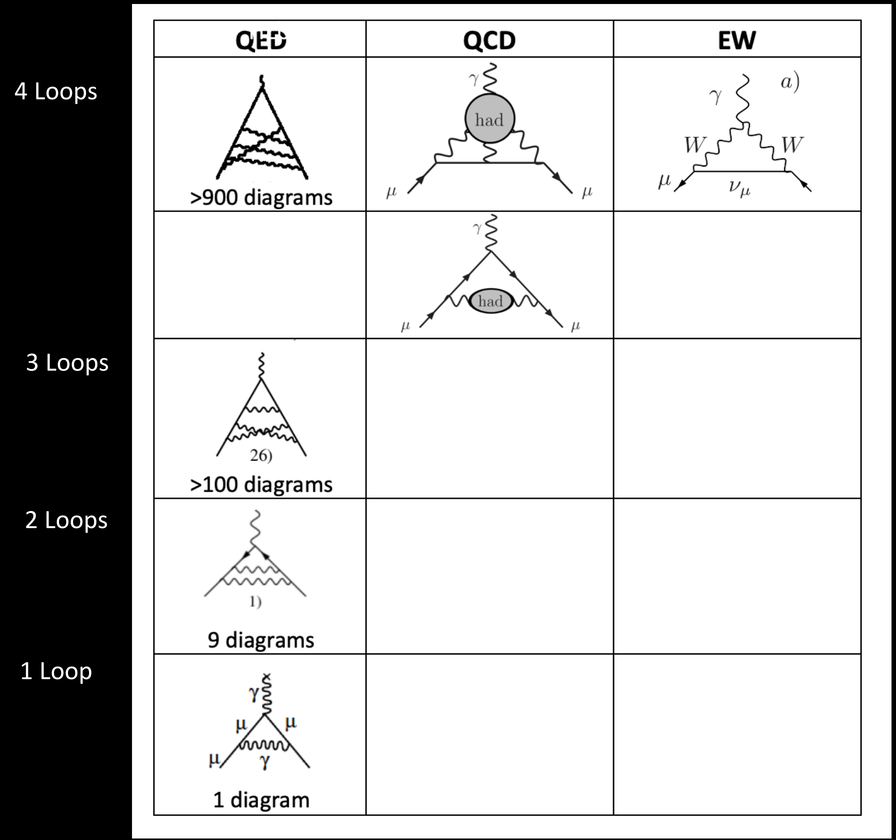
CERN II

CERN I

Nevis



$\frac{\alpha}{\pi}$

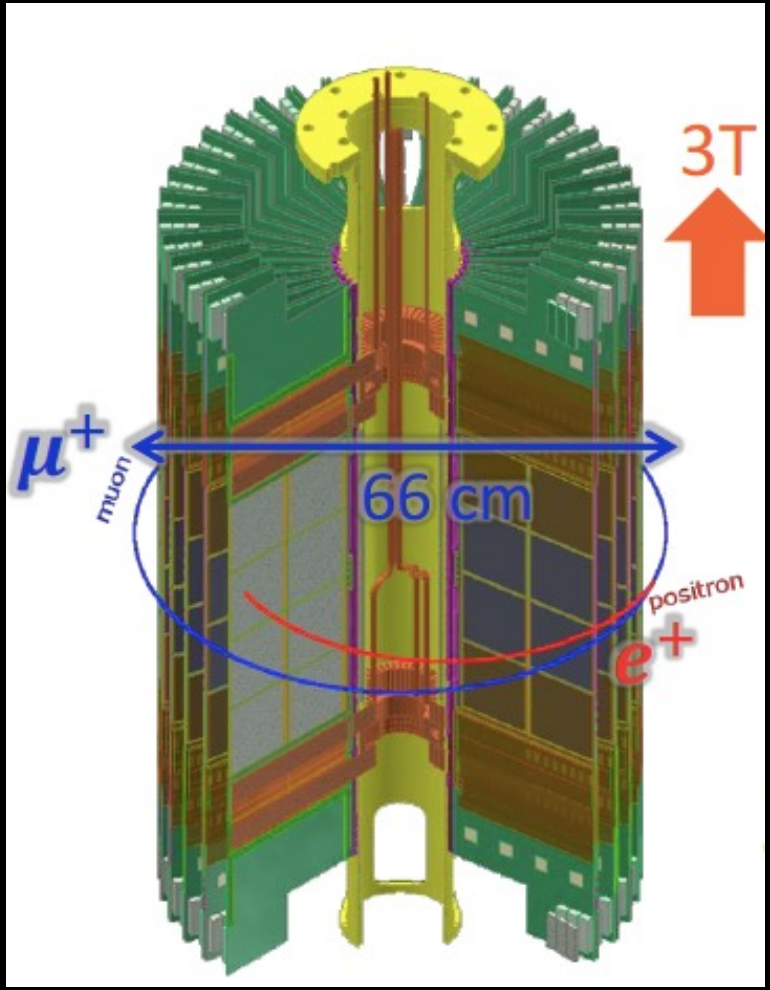


Detector system of silicon trackers

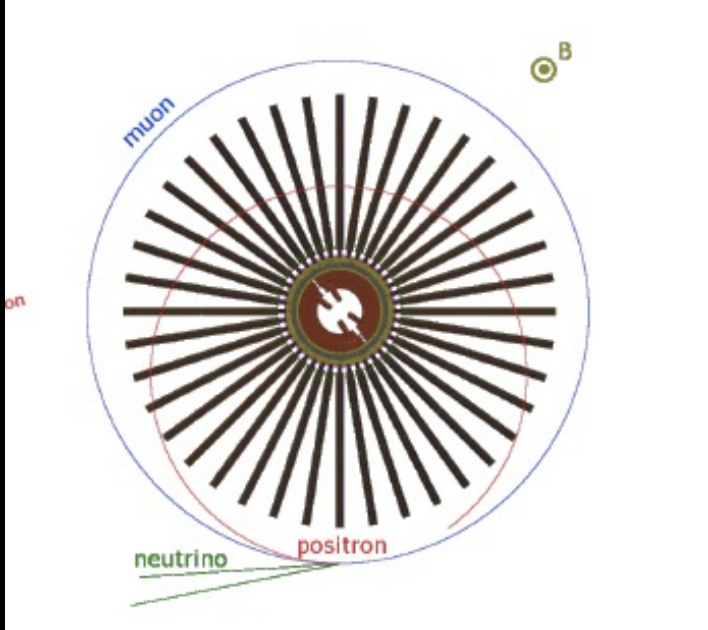
- Requirements
  - Detection of e+ (100<E<300 MeV)
  - Reconstruction of momentum vector
  - Stability over rate changes (1.4 MHz → 14 kHz)

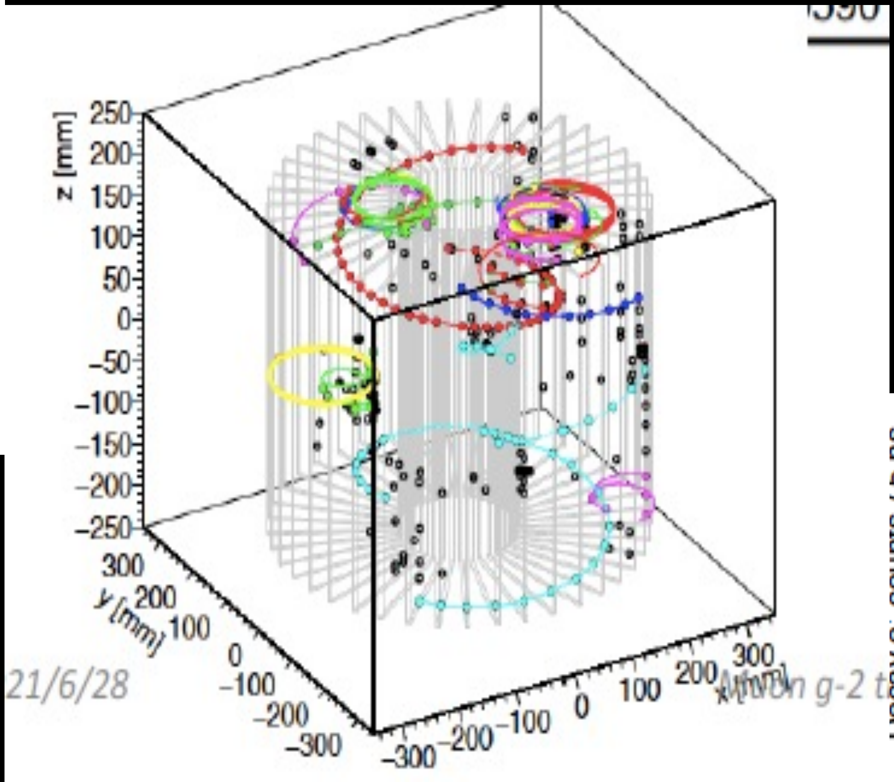
- Specifications
  - Sensor: p-on-n single-sided strip
  - Number of vanes: 40
  - Number of sensors : 640
  - Number of strips : 655,360
  - Area of sensors : 6.24 m^2

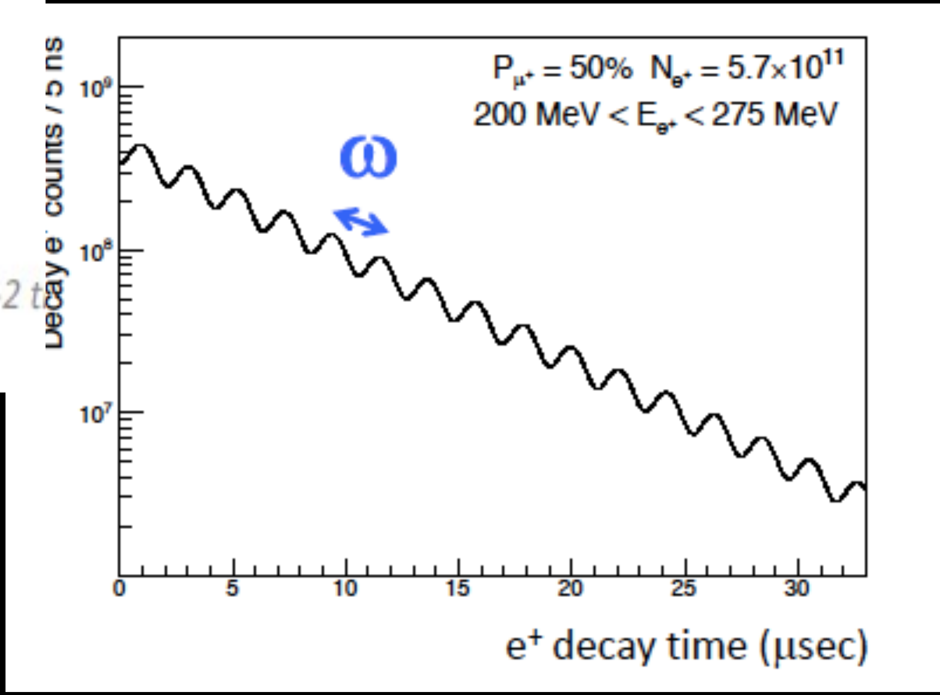
750 mm



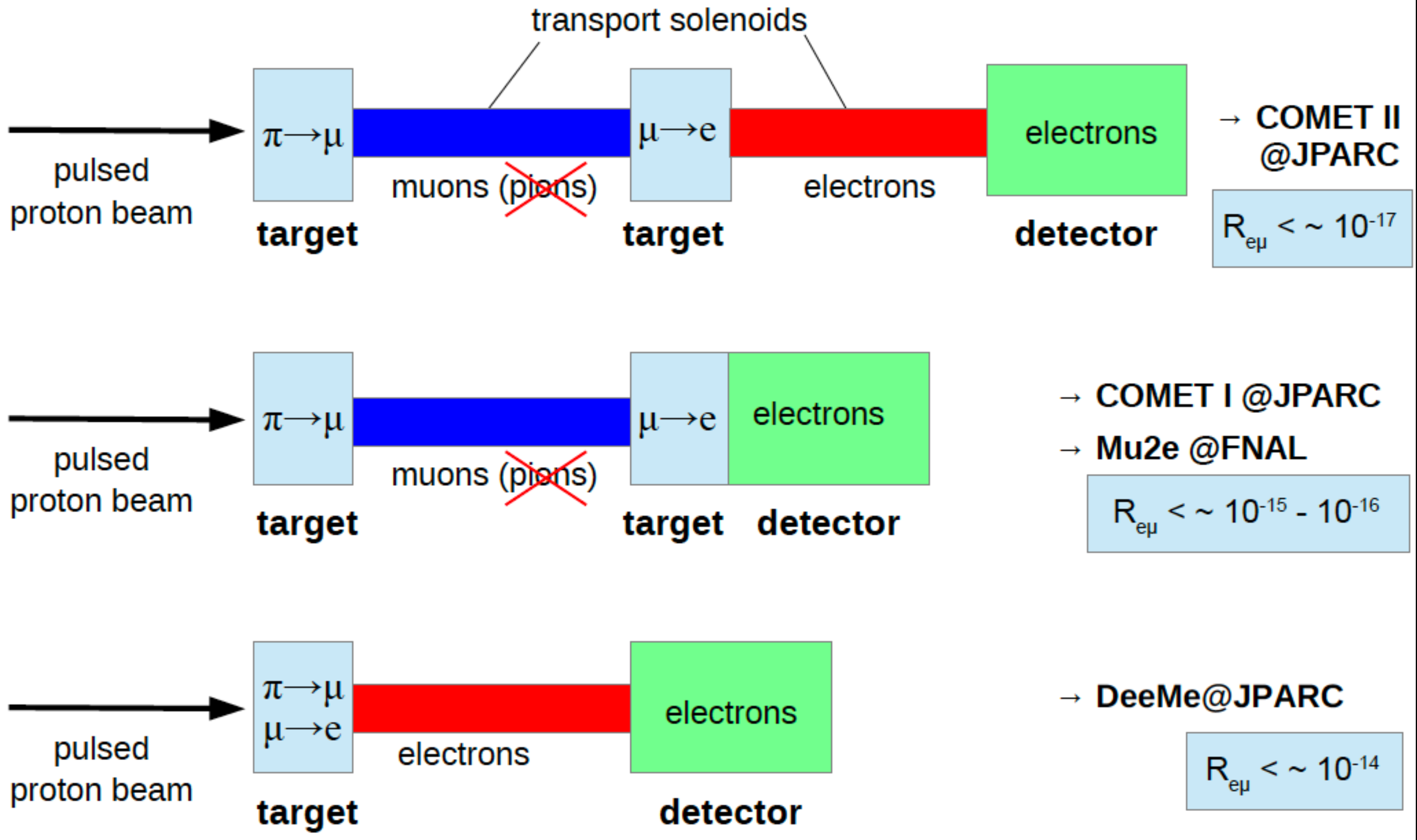
Detector system of silicon trackers







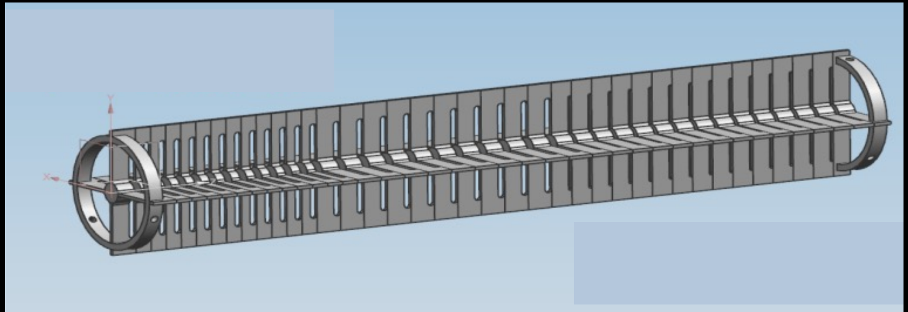
μ-e Conversion in Nuclear Field



[A.Schöning, Heidelberg, Jan 2017]

The Tungsten Production target

Beam



Target Geometry

The production target with its support structure

Must resist to $5.7 \cdot 10^{12}$ protons/s

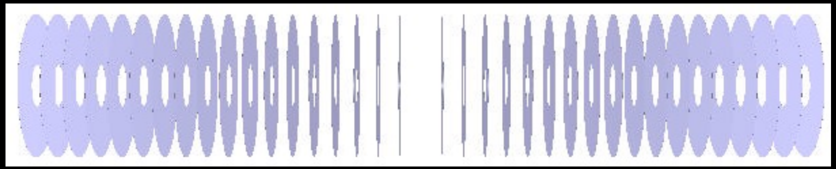
Gaps and fins to help heat dissipation

Maximum T~1100 ^{o}C

The Aluminum muon stopping target

80 cm

beam



μ

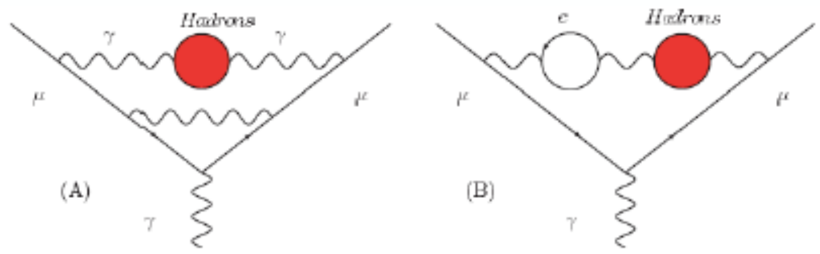
The stopping target:

37 foils of Al
105 μm thick
75 mm radius
22 mm central hole radius

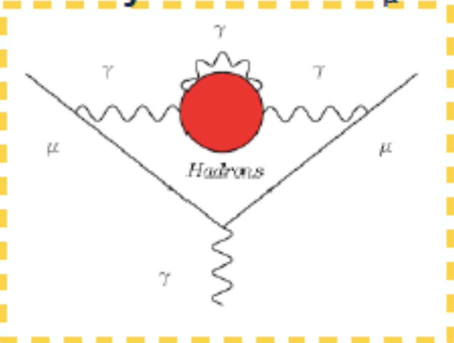
The segmented geometry helps to reduce electron energy losses (improving momentum resolution)

The central hole helps to reduce radiation in the detector

- $O(\alpha^3)$ contributions of diagrams containing HVP insertions:



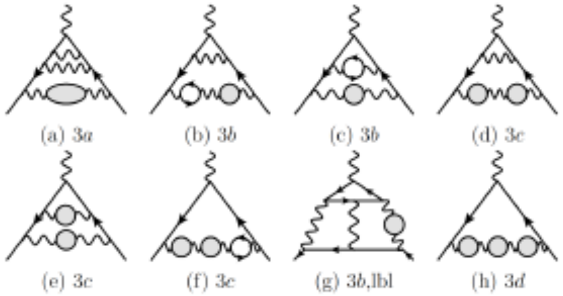
Already included in a_μ^{HLO}



$$a_\mu^{HNLO}(vp) = -98.3\ (7) \times 10^{-11}$$

Krause '96; Keshavarzi, Nomura, Teubner 2019; WP20.

- $O(\alpha^4)$ contributions of diagrams containing HVP insertions:



$$a_\mu^{HNNLO}(vp) = 12.4\ (1) \times 10^{-11}$$

Kurz, Liu, Marquard, Steinhauser 2014