Muon: what is it good for?

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Outline

- Motivation: muon $(g - 2)$
- μ meson $\rightarrow$ muon
- Mirror symmetries and parity violation
- High-energy muons in matter
- Muons from accelerators
- Anomalous magnetic moment
- Muon (g-2) experiments at CERN and at BNL
- Result of BNL: deviation from Standard Model?
- Continue at Fermilab

What makes all this interesting?

The muon anomalous magnetic moment is one of the most precisely measured quantities in particle physics... Since the first results were published, a persisting "discrepancy" between theory and experiment of about 3 standard deviations is observed. It is the largest "established" deviation from the Standard Model seen in a "clean" electroweak observable and thus could be a hint for New Physics to be around the corner.

F. Jegerlehner and A. Nyffeler, "The muon g-2", Phys. Rept. **477** (2009) 1-110.

At present the theoretical and the experimental values are known with a similar relative precision of 0.5 ppm. There is, however, a 3.4 standard deviation difference between the two, strongly suggesting the need for continued experimental and theoretical study.

J. P. Miller, E. de Rafael and B. L. Roberts, "Muon (g-2): Experiment and theory," Rept. Prog. Phys. **70** (2007) 795-897.

$$\mathbf{3.4\sigma \to 3.6\sigma \to 3.5\sigma}$$

Why this talk?

In this paper, the comparison between the theory and the experiment is examined by considering the influence of the spacetime curvature to the measurement on the muon g-2 experiment using the storage ring on the basis of the general relativity up to the post-Newtonian order of O($1/c^2$).

T. Morishima, T. Futamase and H. M. Shimizu,
"Post-Newtonian effects of Dirac particle in curved spacetime - III : The muon g-2 in the Earth's gravity," arXiv:1801.10246 [hep-ph].

It is my melancholy duty to report that these articles are fundamentally flawed in that they fail to correctly implement the Einstein equivalence principle of general relativity. ...the claimed effect is not compatible with explaining the observed experimental anomaly in the anomalous magnetic moment of the muon.

Matt Visser, "Post-Newtonian particle physics in curved spacetime",
arXiv:1802.00651 [hep-ph]

Nuclear forces: Yukawa interaction?

Interaction range $\sim$ proton diameter

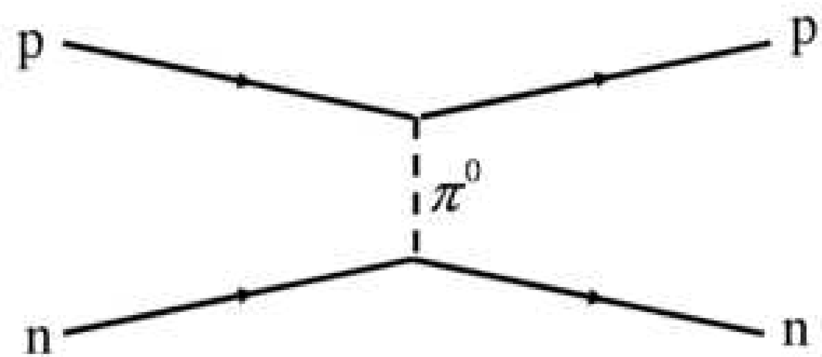
Short range $\rightarrow$ heavy mediator

Yukawa potential:

$V(r) = -g^2 e^{-Mr}/r$

H. Yukawa, 1935: meson

$M \sim 100 - 300$ MeV



C. D. Anderson, 1936: Cosmic μ meson!

Not good, it is a lepton...

C. Powell, 1947: π meson, $M = 140$ MeV

Nobel prizes: Anderson, 1936 (e^+); Yukawa, 1949; Powell, 1950

Pion exchange is still good approximation in nuclei

Does not work at high energies $\Rightarrow$ QCD

Who needs the muon?

Muon = big brother of the electron at $M_\mu \sim 200 \times M_\mathrm{e}$

Sheldon Glashow in 2007, about the questions to be solved by the LHC:

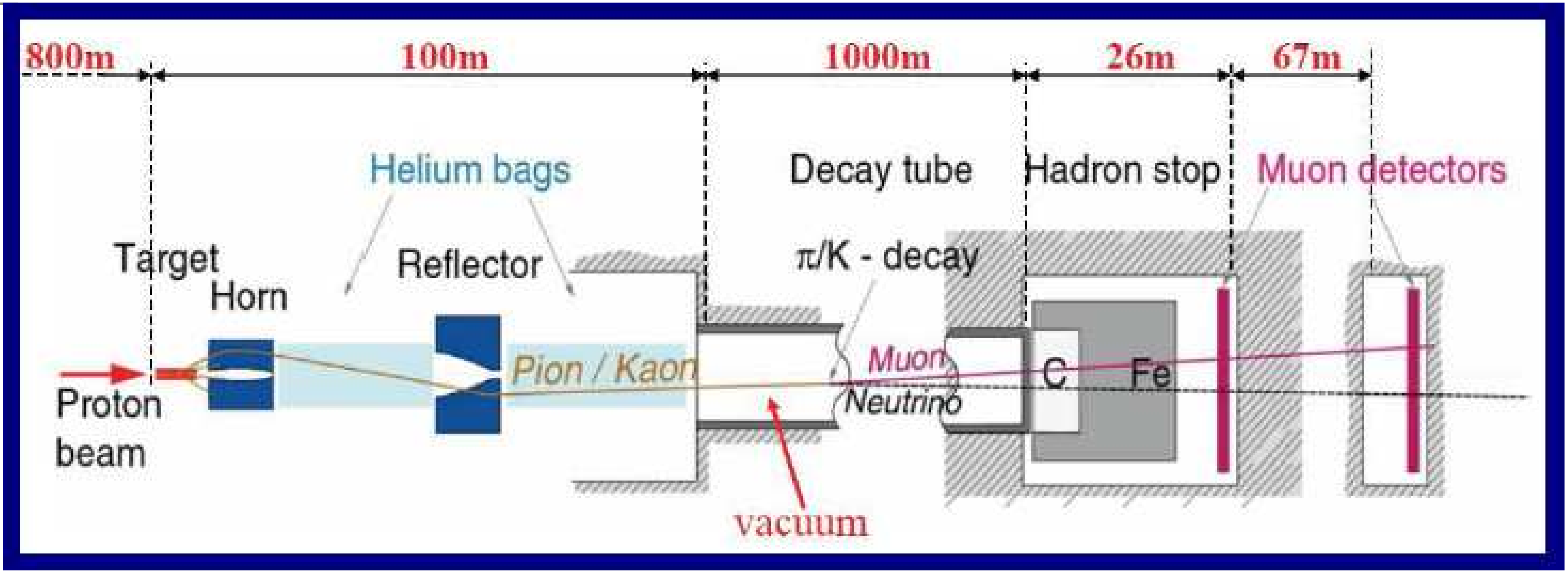
And why is the muon, a silly particle that was first seen in the 1930s, why is the muon 200 times heavier than the electron, and indeed, why is it there? Who needs the muon?

(http://www.pbs.org/wgbh/nova/sciencenow/3410/02-bigd-text.html)

High energy physics needs the muon!

- Time dilatation by special relativity was proven by the survival of cosmic muons to be detected on the surface of Earth.
- Muons helped to observe parity violation, neutrino oscillation, Higgs boson the first time.
- Muons are the most penetrative charged particles, the best messengers of new physics everywhere.
- All HEP experiments encircle their apparati with enormous muon detection systems. In CMS (Compact Muon Solenoid) it weighs 10 k tons.
- Muons facilitate to produce neutrino beams at proton accelerators via letting collimated relativistic pions decay in flight: $\pi \to \mu + \nu_\mu$ with a subsequent absorption of the muons in earth.

CERN Neutrinos to Gran Sasso



Proton ⇒ pion, kaon $K \rightarrow \pi$, $\pi^{\pm} \rightarrow \mu^{\pm} \nu_{\mu}$ K, π stop $\mu^{\pm}$ detection

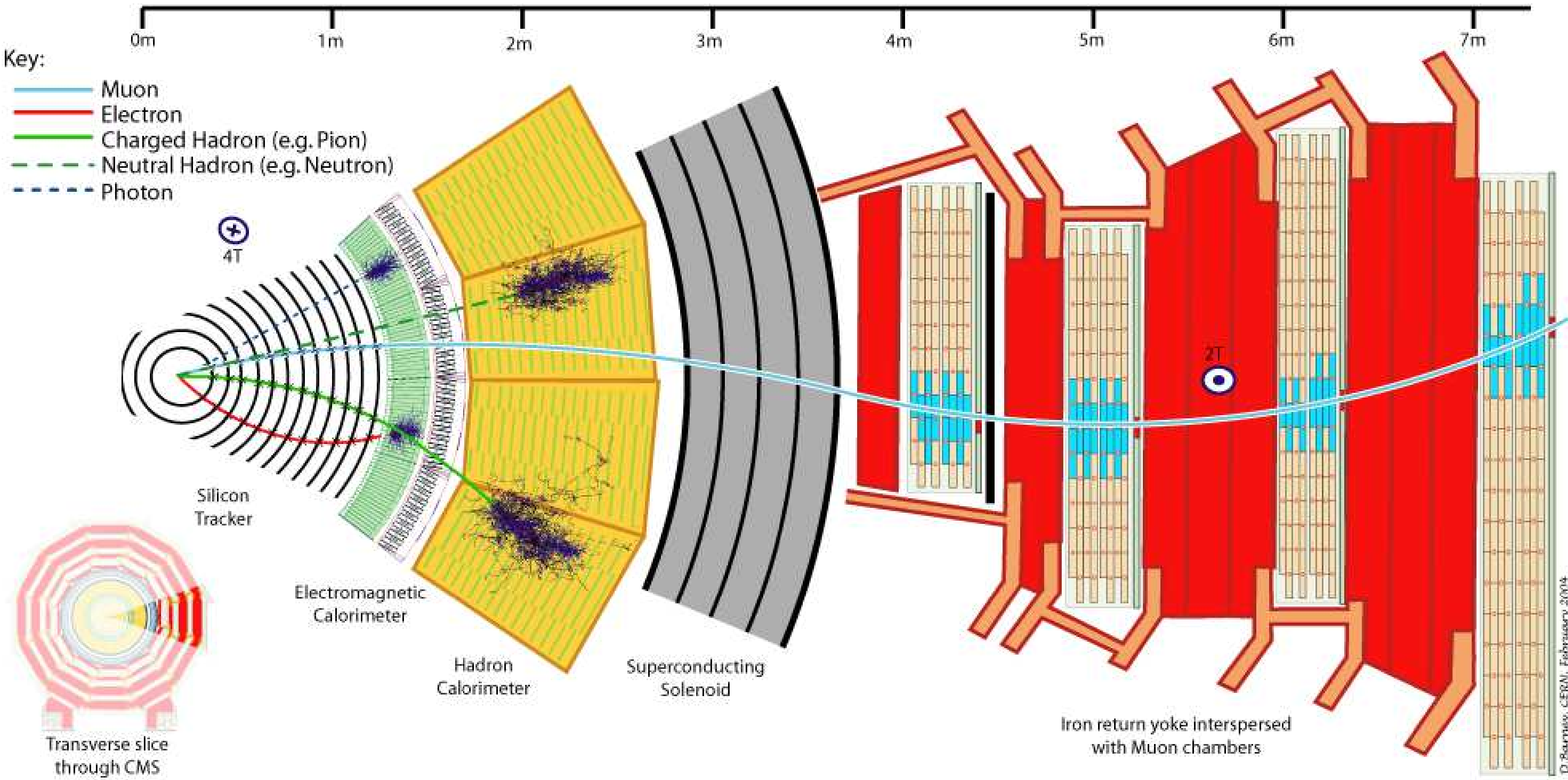
All particles are relativistic.

Muon slows down and decays, $\mu \rightarrow e \nu_{\mu} \nu_{e}$ its neutrinos scatter out

Muon neutrino from pion decay flies forward.

ν_{μ} beam spreads out on 732 km, at LNGS FWHM = 2.8 km

CMS: Compact Muon Solenoid



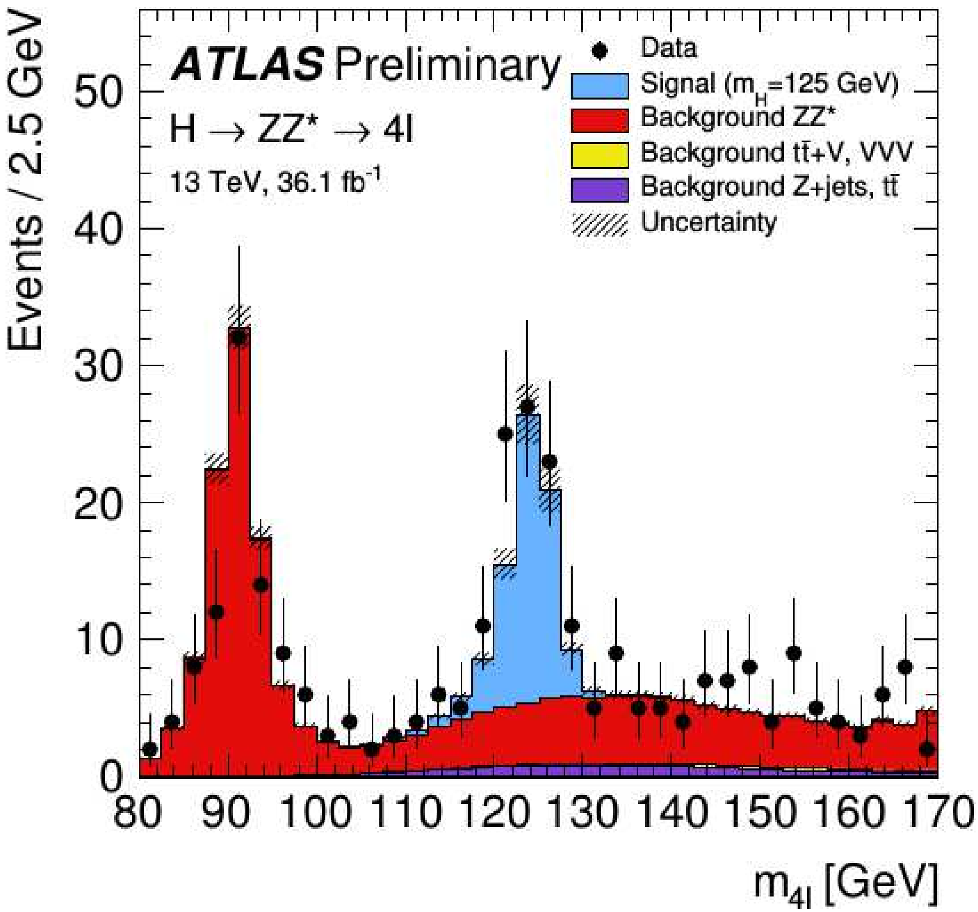
14000 ton digital camera:

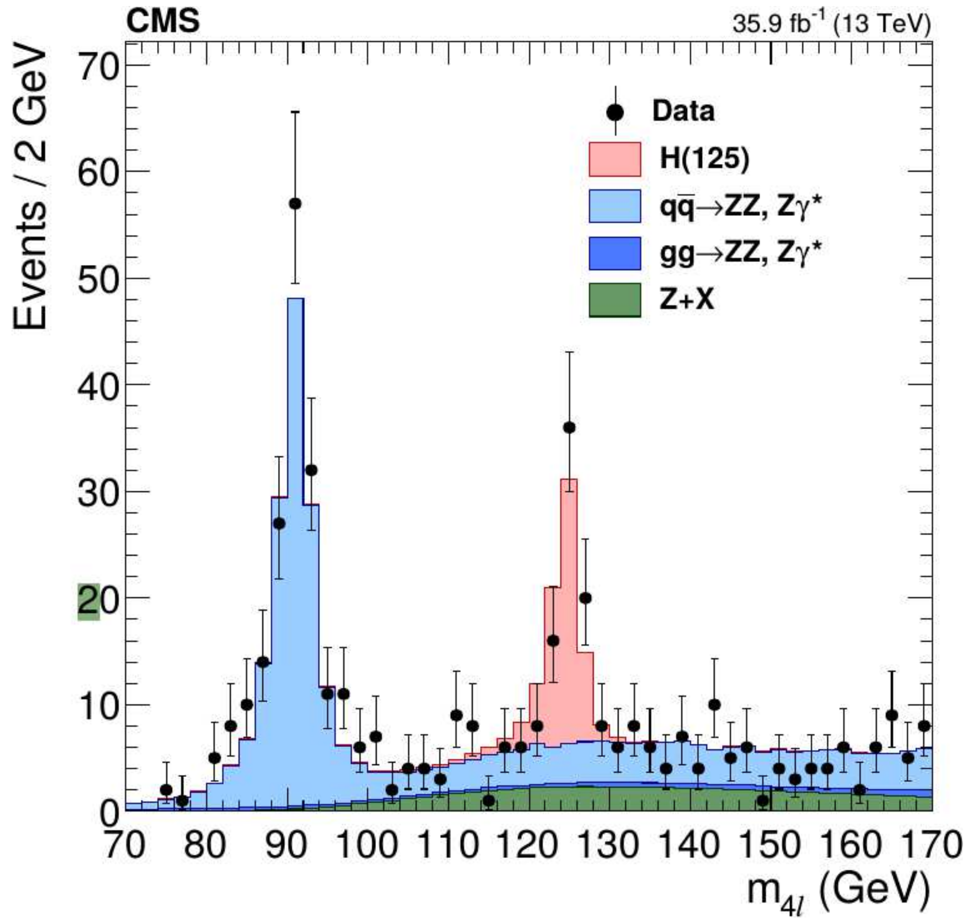
200 M pixel, 40 M pictures/sec, 1000 GB/sec data

Processes cc. 1000 pictures/sec ⇒ intelligent filter!!

$\mathbf{H \to 4\ell\ (\ell = \mu^\pm,\ e^\pm)}$

Invariant mass spectra at $\sqrt{s} = 13$ TeV





$\mathbf{124.88 \pm 0.37}$(stat) $\pm$ $\mathbf{0.05}$ (syst) | $\mathbf{125.26 \pm 0.20}$(stat) $\pm$ $\mathbf{0.08}$ (syst)

ATLAS-CONF-2017-046 | CMS-HIG-16-041

Both statistically limited.

CPT Invariance

Charge conjugation: $C|\mathrm{p}(r,t)\rangle = |\overline{\mathrm{p}}(r,t)\rangle$

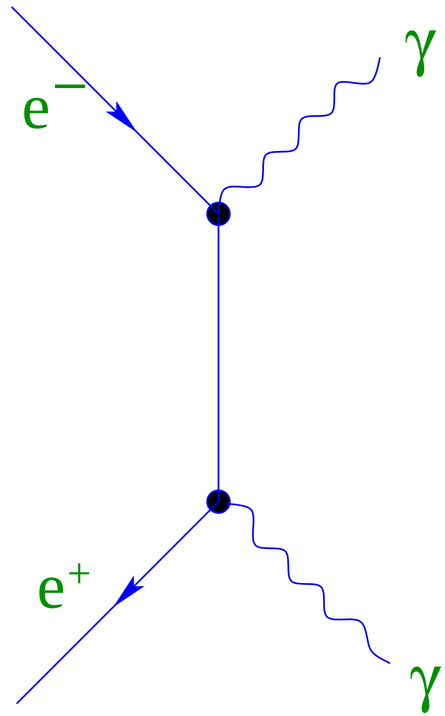
Space reflection: $P|\mathrm{p}(r,t)\rangle = |\mathrm{p}(-r,t)\rangle$

Time reversal: $T|\mathrm{p}(r,t)\rangle = |\mathrm{p}(r,-t)\rangle K$

Basic assumption of field theory:

$CPT|\mathrm{p}(r,t)\rangle = |\overline{\mathrm{p}}(-r,-t)\rangle \sim |\mathrm{p}(r,t)\rangle$

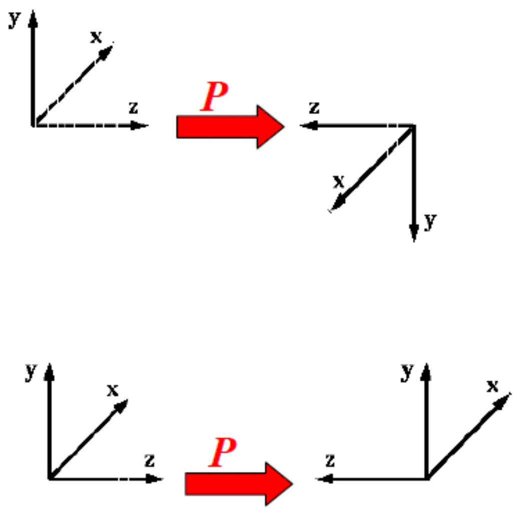
meaning free antiparticle $\sim$ particle going backwards in space and time.



Giving up CPT one has to give up:

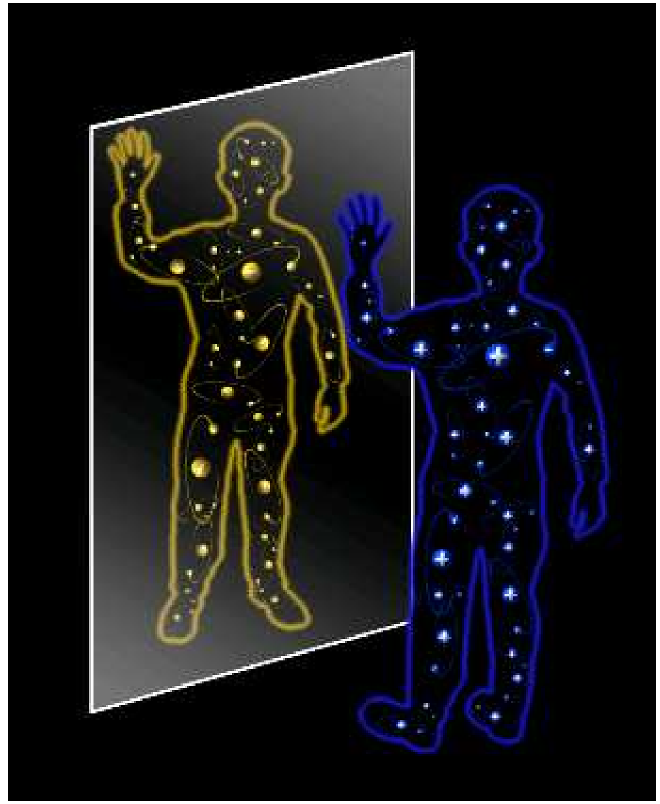
- locality of interactions $\Rightarrow$ causality, or
- unitarity $\Rightarrow$ conservation of matter, information, ... or
- Lorentz invariance

Space reflection: parity



Mirror reflection of all coordinates:

right handed $\Rightarrow$ left handed rendszer



D. Kirkby, APS, 2003

$$f(x) = \frac{1}{2}[f(x) + f(-x)] + \frac{1}{2}[f(x) - f(-x)]$$

$$f(x) = \sum_{k=0}^{\infty} \frac{d^{2k} f(x)}{dx^{2k}} \frac{x^{2k}}{(2k)!} + \sum_{k=0}^{\infty} \frac{d^{2k+1} f(x)}{dx^{2k+1}} \frac{x^{2k+1}}{(2k+1)!}$$

even function. odd function

A Nobel-winner article

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 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)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

How many papers for a Nobel prize?

Parity violation in pion decay

Pion decay:

$\pi \rightarrow \mu\nu$

Only B realized ⇒ maximal parity violation

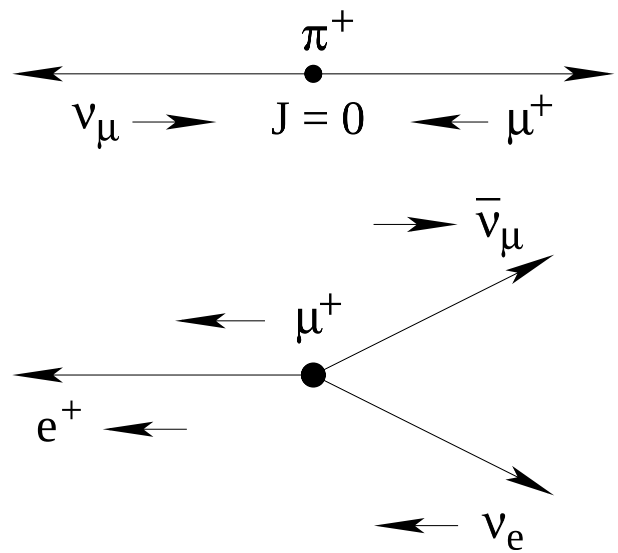
Muon production:

$\pi^+ \rightarrow \mu^+ \nu_\mu$

Muon decay:

$\mu^+ \rightarrow \mathrm{e}^+ \nu_\mathrm{e} \overline{\nu}_\mu$

μ spin resonance



Parity violation of weak interaction: V–A theory

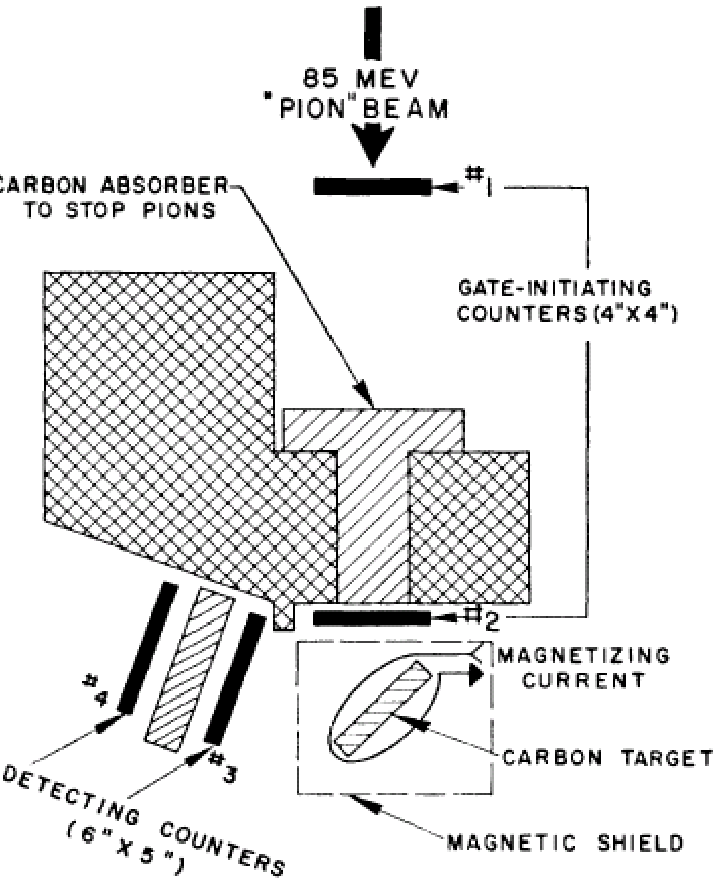
Vector – axial vector: $\overline{\psi}(1 - \gamma^5)\gamma^\mu \psi$

Left-handed particles ⇔ right-handed antiparticles

Lederman's experiment

R.L. Garwin, L.M. Lederman, M. Weinrich: Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon *Phys. Rev.* 105 *(1957) 1415-1417*

$$\pi^+ \to \mu^+ \nu_\mu ; \quad \mu^+ \to e^+ \nu_e \overline{\nu}_\mu$$



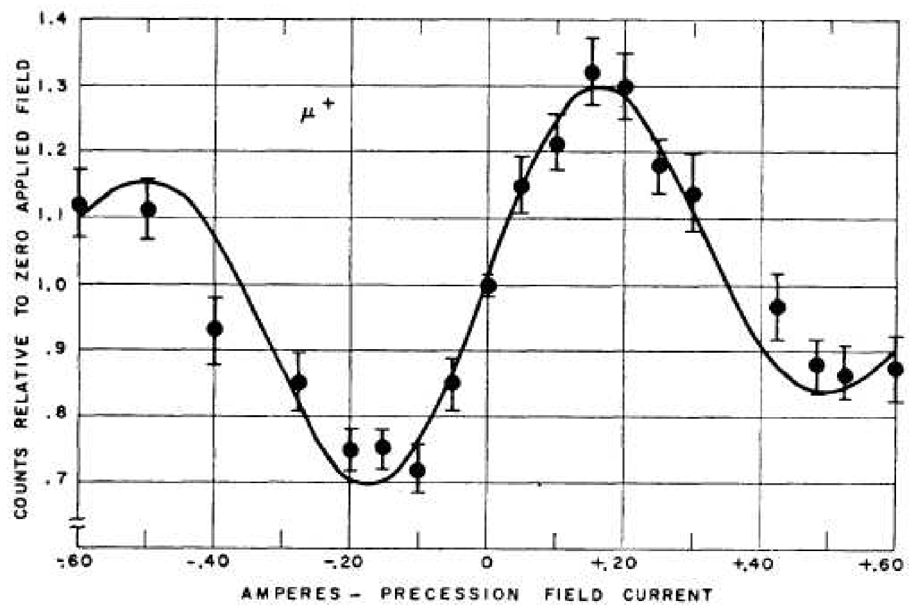


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

Discovery of parity violation

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

The inspiring discussions held with Professor T. D. ee and Professor C. N. Yang by one of us (C. S. Wu) re gratefully acknowledged.

Phys. Rev. 105 *(1957) 1413-1414*

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)

The authors wish to acknowledge the essential role of Professor Tsung-Dao Lee in clarifying for us the papers of Lee and Yang. We are also indebted to Professor C. S. Wu[6] for reports of her preliminary results in the Columbia discussions immediately preceding this experiment.

Phys. Rev. 105 *(1957) 1415-1417*

Nice example of scientific ethics:

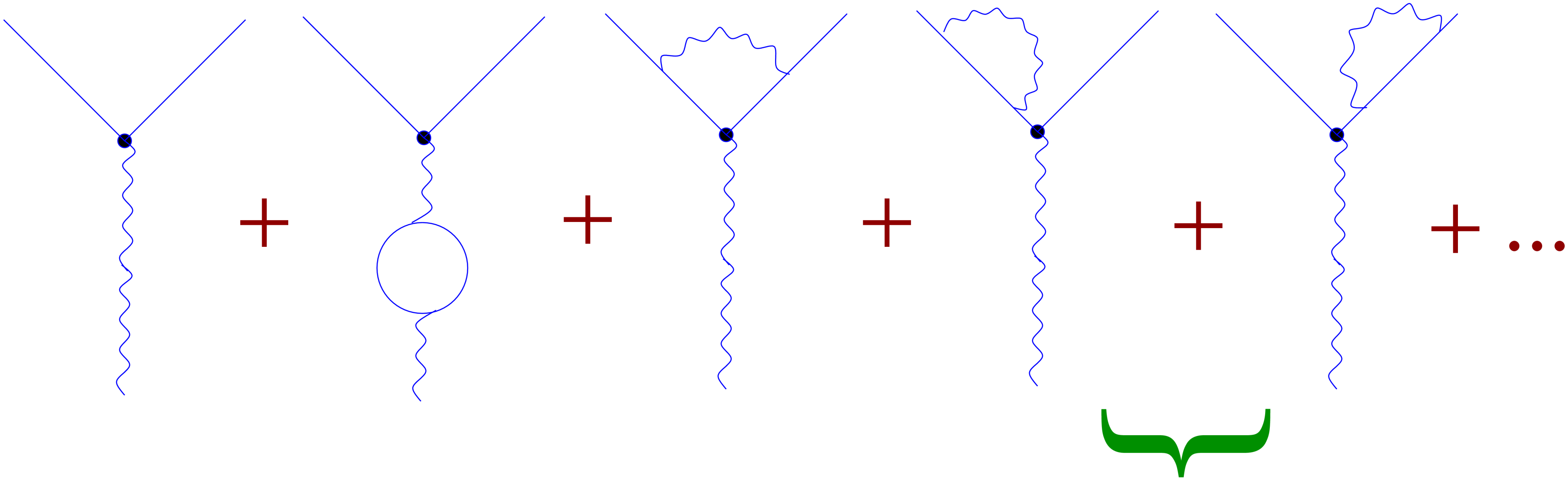
Wu's group worked several months on this experiment.

Lederman's spent 1 day for data taking, 1 week for analysis, then waited for the Wu result to become public

Lederman received a Nobel prize: ν_μ, 1963; Wu did not.

Magnetic moment of the electron

$$\vec{\mu}_e = -g \frac{e}{2m_e} \vec{S}$$



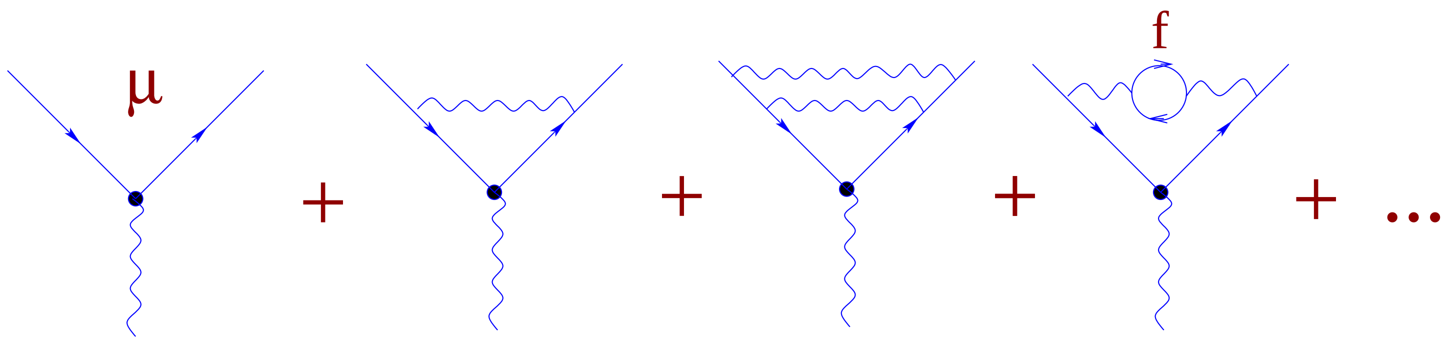
$$e_R \;=\; e \;+\; (e_R^{(1)} - e) \;+\; \Delta e_R^{(1)} \;-\; \Delta e_R^{(1)'} \;+-\; \ldots$$

$$g_e = 2 + \frac{\alpha}{\pi} \pm \ldots$$

e_R contains first 2 terms, 3+4 reduces 2

Magnetic moment of the muon

$$\vec{\mu}_\mu = -g\frac{e}{2m_\mu}\vec{S}$$

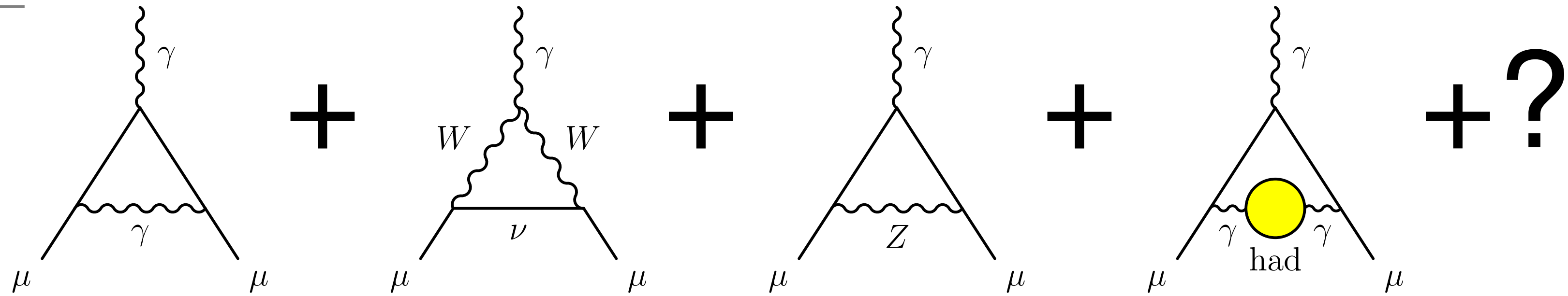


$g = 2 \quad + \quad O(\alpha) \quad + \quad O(\alpha^2) \quad + \quad \dots$

Point-like Dirac fermion: $g = 2$

Anomalous part: $a = \frac{g-2}{2}$

Anomalous m.m.: interesting?



$$a_\mu(\mathrm{SM}) = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{weak}) + a_\mu(\mathrm{hadr}) + a_\mu(??)$$

Deviation: new physics or incorrect calculation

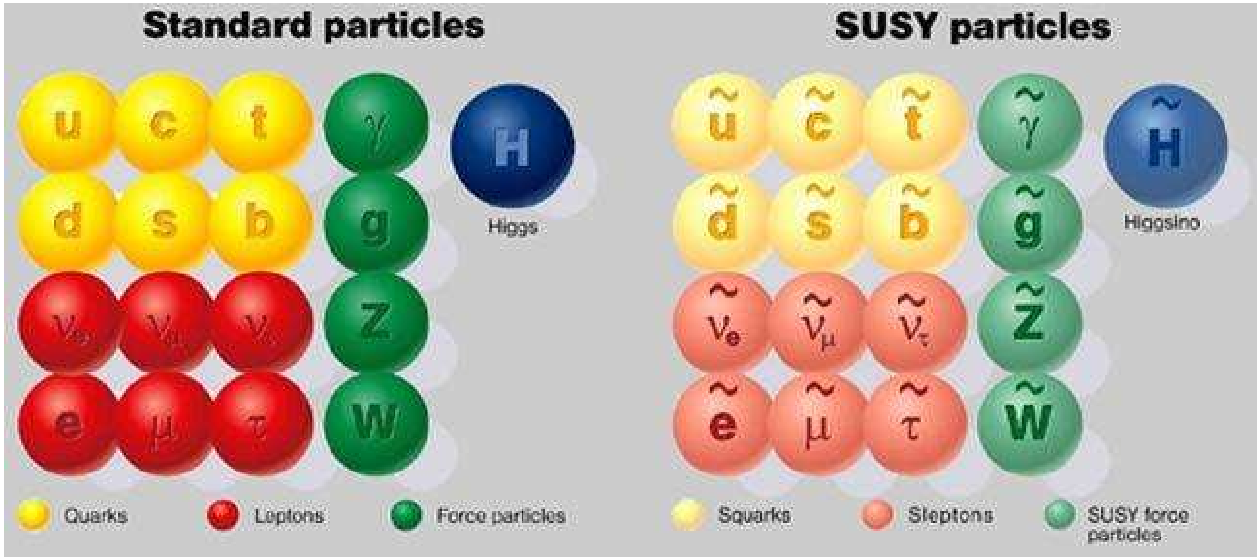
Particle Data Group, 2017:

	$a_e \times 10^9$	$a_\mu \times 10^9$
QED prediction	1159652.4 (4)	1165847.1895 (8)
hadron corrections	—	1165918.23 (1) (34) (26)
experiment (BNL)	1159652.186 (4)	μ^+: 1165920.4 (6) (5) μ^-: 1165921.5 (8) (3)

$$(\overline{a}_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}) = (268 \pm 63 \pm 43) \times 10^{-11} \ (3.5\sigma\ !)$$

Muon (g-2) deviation: SUSY ?

Supersymmetry: many new particles?



Partners for SM fermions + 5 Higgs-bosons

$$a_\mu^{\mathrm{SUSY}} \approx \pm 130 \cdot 10^{-11} \cdot \left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2 \tan\beta$$

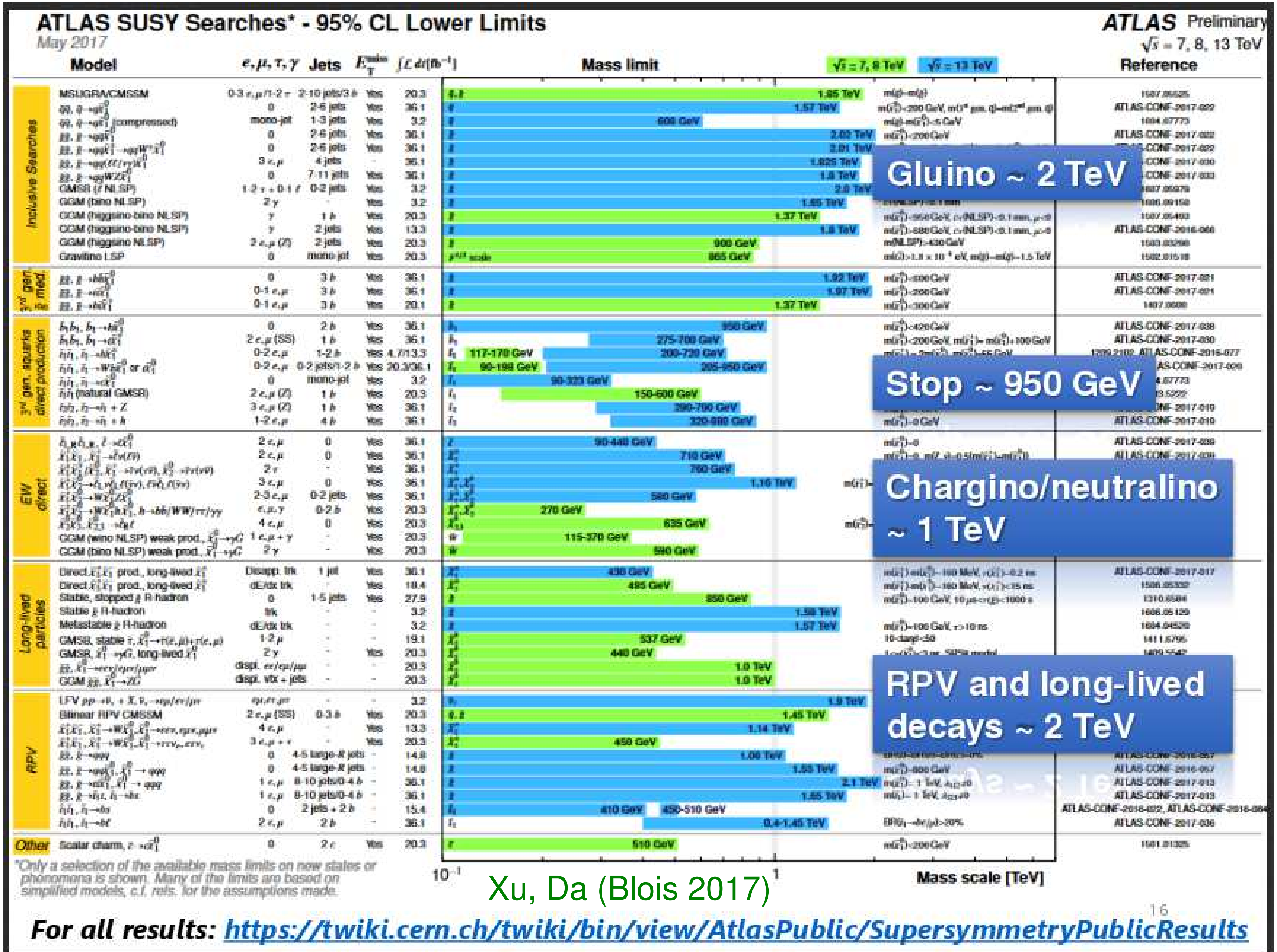
m_{SUSY}: SUSY mass scale; $\tan\beta = v_1/v2 \approx 3\ldots40$

SUSY particles of $m = 100\ldots500$ GeV could explain the deviation

No evidence for them at LHC

Dark photon of $m = 10\ldots100$ MeV in mixing with photon??

ATLAS SUSY summary plot



$(g-2)_\mu$ measurements

Spin magn. mom.: $\vec{\mu} = g\frac{e\hbar}{2mc}\vec{S}$

Dirac equation: $g = 2$

Larmor precession (non-relativistic, Pauli):

$$\omega_s = \frac{g}{\hbar}\left(\frac{e\hbar}{2mc}\right)B = \frac{eB}{mc}\cdot\frac{g}{2} = \frac{eB}{mc}\left(1+\frac{g-2}{2}\right) = \frac{eB}{mc}(1+a)$$

Precession of $S = \frac{1}{2}$ particle around its momentum in a $\vec{B}$ field:

spin freq – cyclotron freq = $\omega_a = \omega_S - \omega_c = \omega_S - \frac{eB}{mc} = a\frac{eB}{mc}$

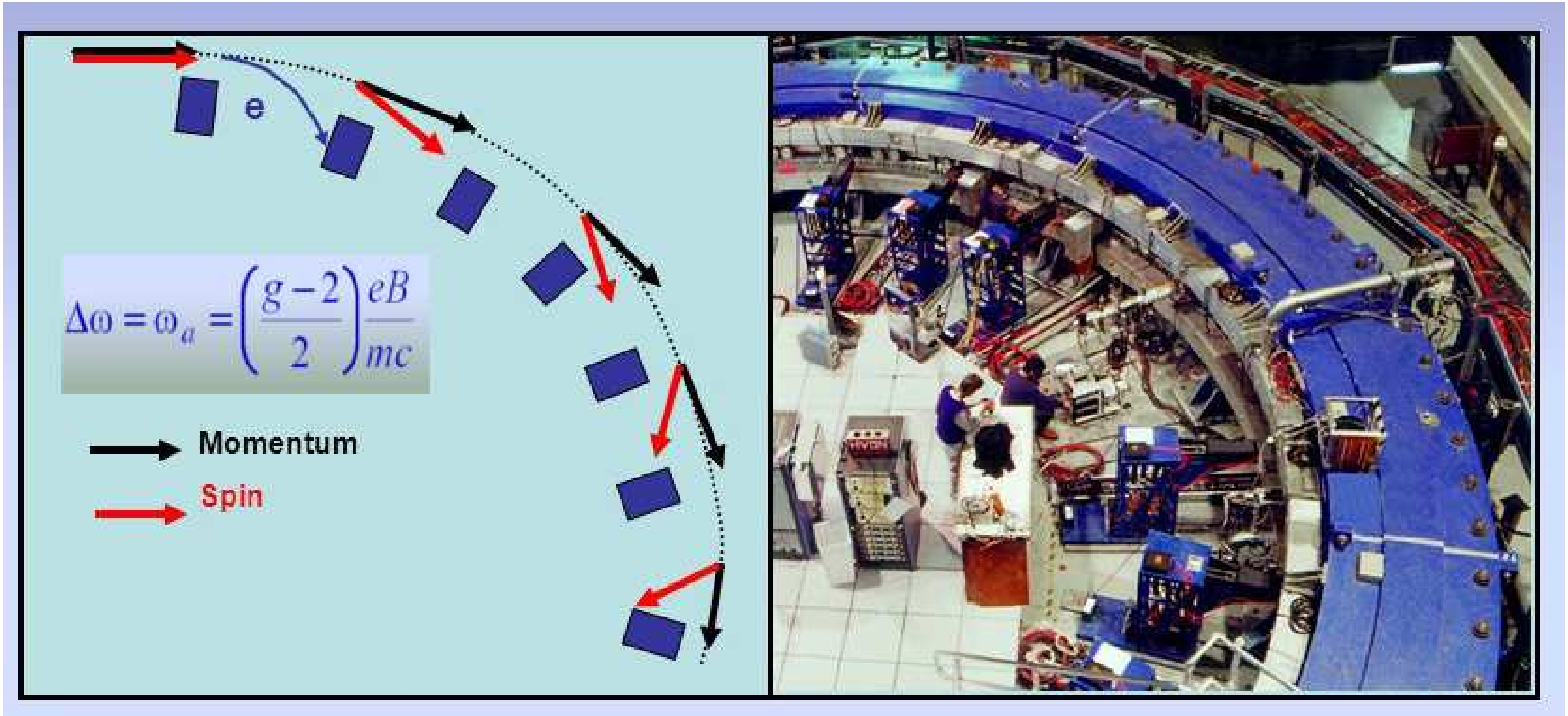
Muon in storage ring: $\mu^+ \to e^+\nu_e\overline{\nu}_\mu \quad \vec{v}(e^+) \sim \vec{S}(\mu^+)$

G. Charpak et al., CERN, 1965:

Time spectrum: $N(t) = N_0 e^{-\frac{t}{\tau}}[1 - A\cos(\omega_a t + \phi)]$

$\tau = 2.2\mu s$, $p_\mu = 90$ MeV/c, B=1.6 T $\Rightarrow a_\mu = 1162(5)\times 10^{-6}$

Muon (g-2) principle



Using relativistic muons

Longer lifetime ⇒more precise measurement

Larmor + Thomas-precession: $\omega_s = g\frac{eB}{mc} + (1-\gamma)\frac{eB}{mc\gamma}$

Cyclotron frequency: $\omega_c = \frac{eB}{mc\gamma}$; $\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$

$$\omega_a = \omega_s - \omega_c = \frac{eB}{mc}[\frac{g}{2} + \frac{1-\gamma}{\gamma} - \frac{1}{\gamma}] = a\frac{eB}{mc}$$

J. Bailey et al., CERN, 1972:

$p_\mu = 1.9$ GeV/c; $\gamma = 12$; $\gamma\tau_\mu = 26\mu$s

$B = 1.7$ T, inhomogeneous ⇒ focusing, but broadening

Result: $a_\mu = 116616(31) \times 10^{-8}$

Focusing in electric field

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

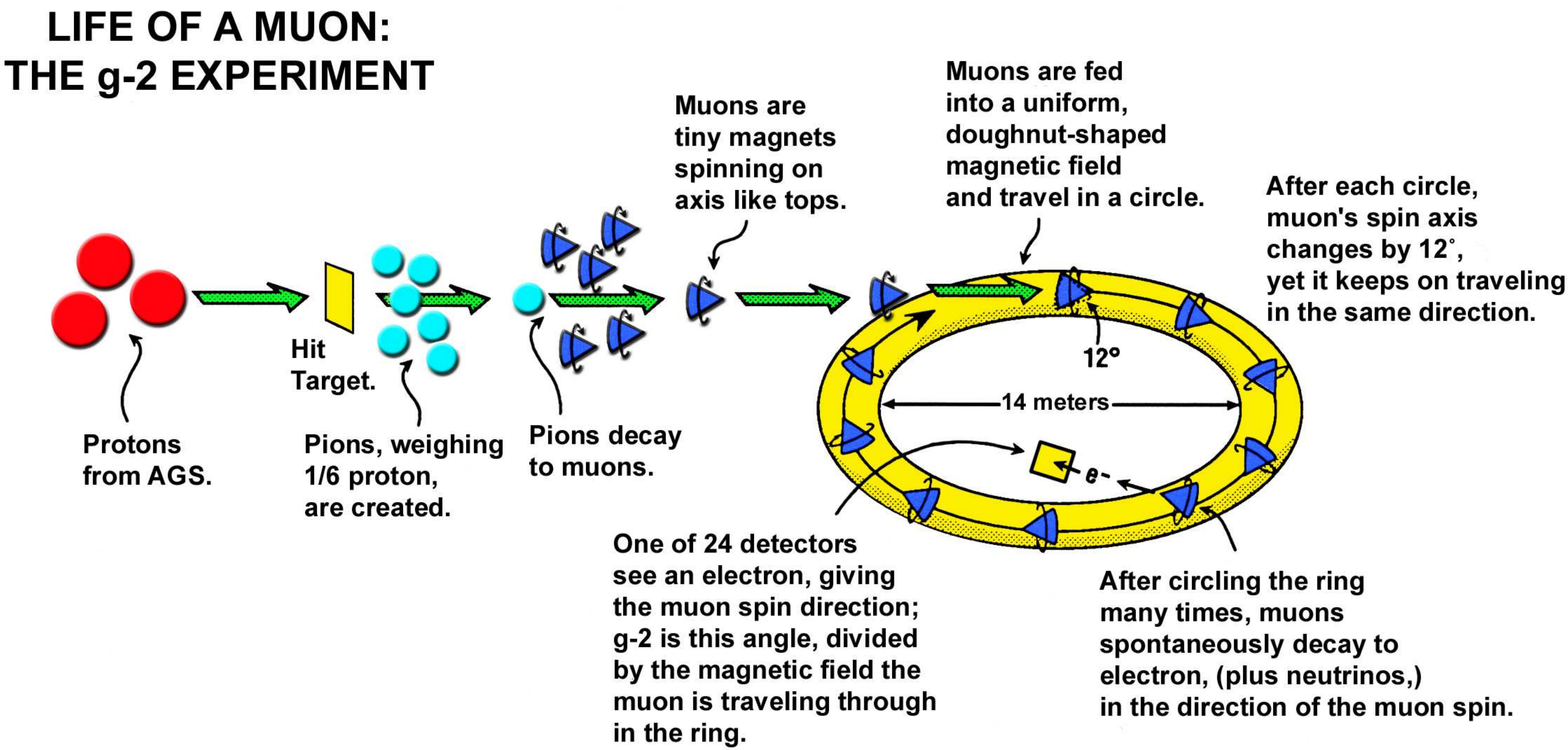
Magic γ: $a - \frac{1}{\gamma^2-1} = 0 \Rightarrow \vec{E}$ term eliminated

J. Bailey et al., CERN, 1979:

$p_\mu = 3.094$ GeV/c; $\gamma_\mu = 29.37$; $\gamma\tau_\mu = 64.4\mu$s
$B = 1.5$ T, homogeneous, el-static focusing
$a_\mu = 1165924(85) \times 10^{-9}$

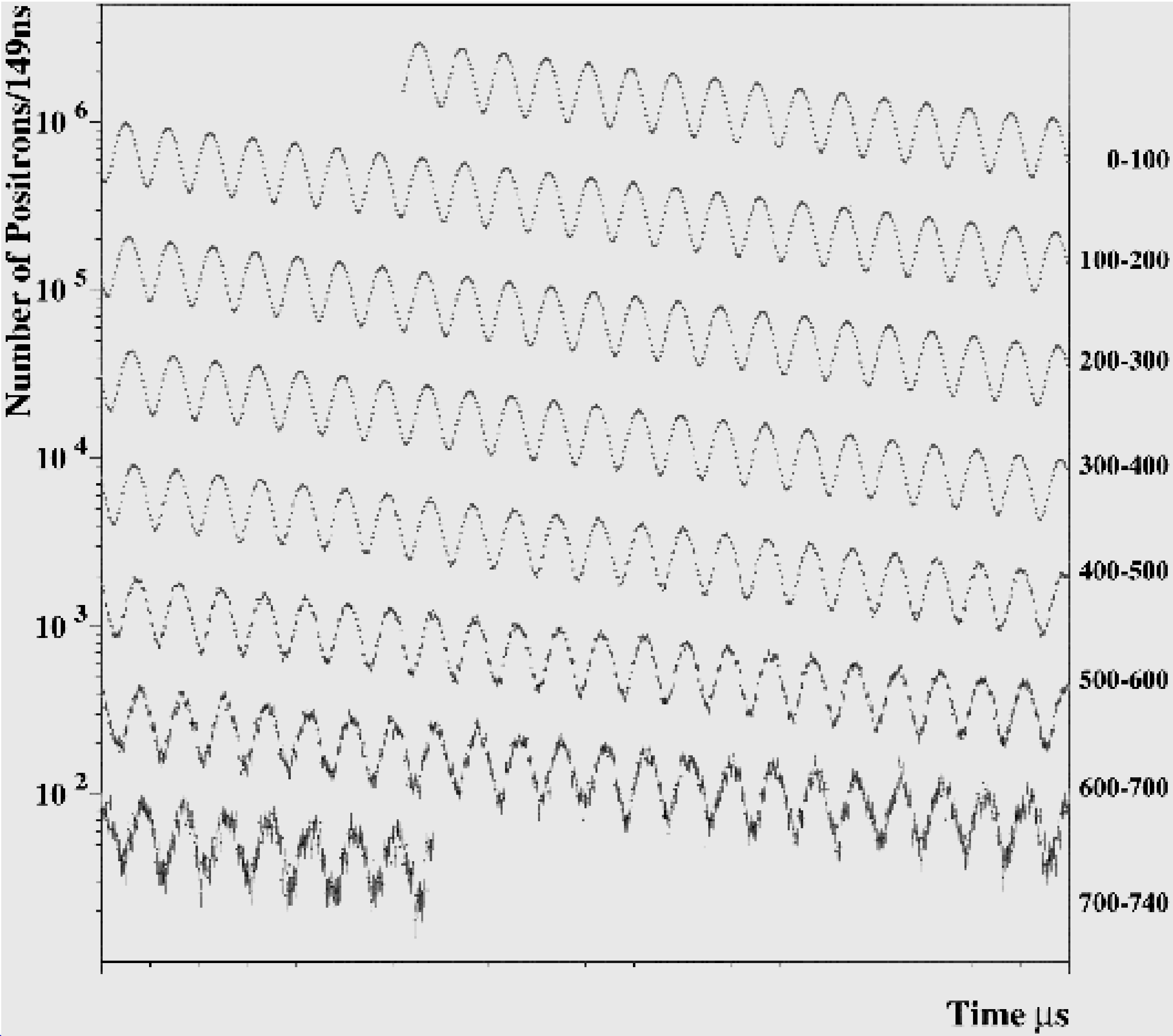
Brookhaven (g-2) experiment: 1999 - 2006

Brookhaven (g-2) experiment

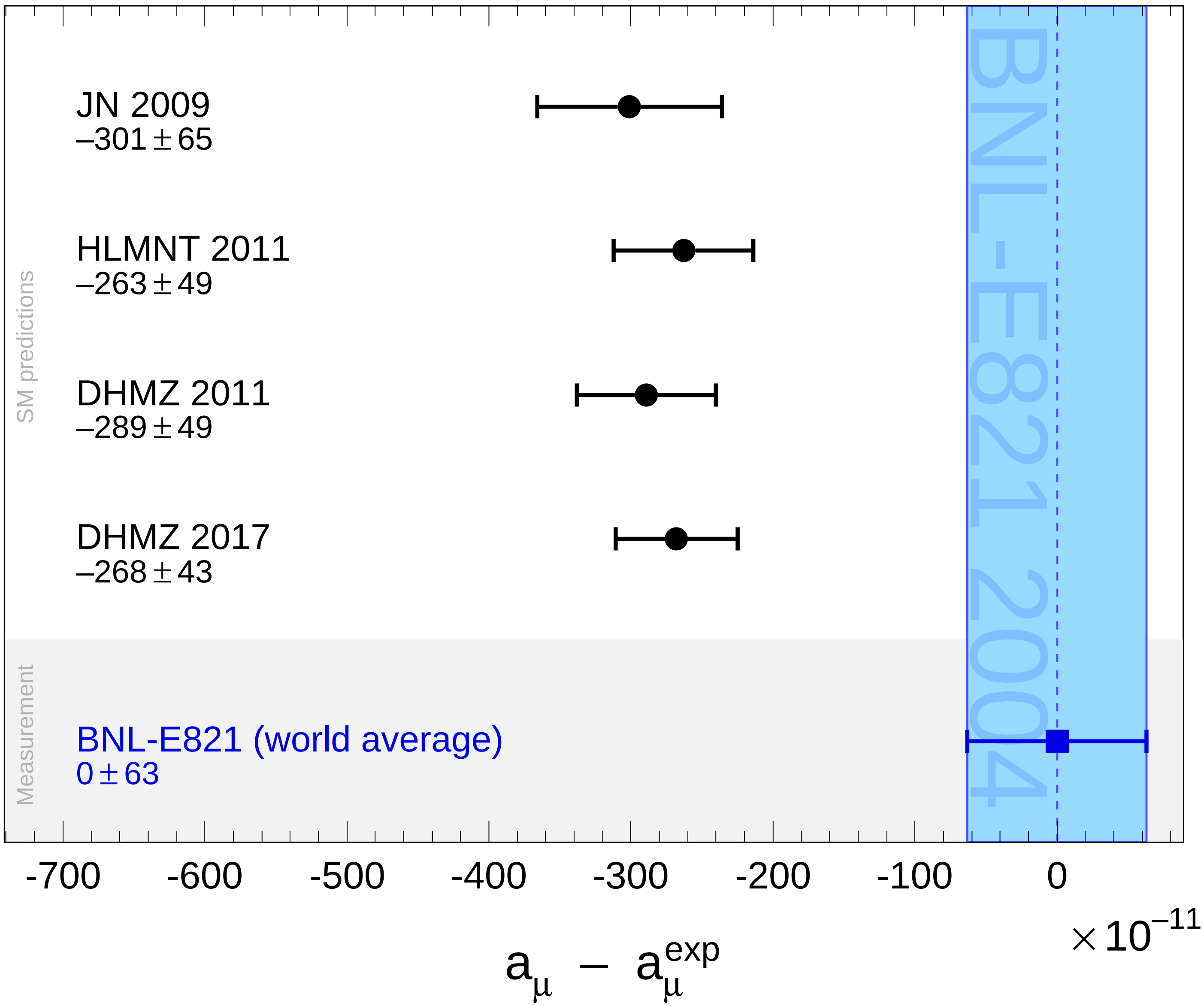


Brookhaven (g-2) experiment

Brookhaven (g-2) spectrum



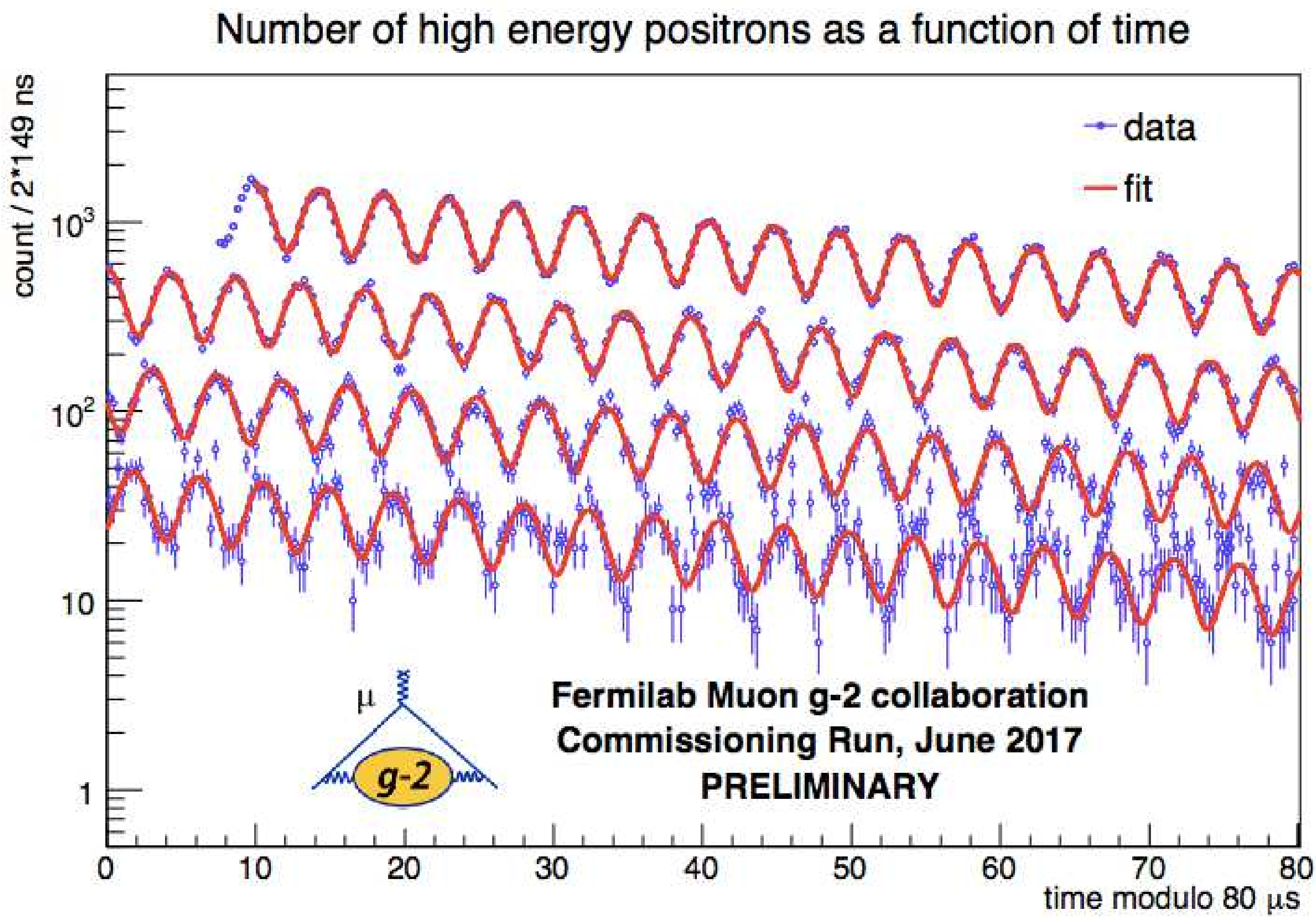
BNL (g-2) result (PDG, 2017)



Way of $(g-2)$ ring to Fermilab

Muon g-2 ring
BNL to FNAL, 2013

Muon (*g*-2) started at Fermilab



Aim: 21× statistics, 1/4× systematics, up to 7σ (if!!)

Summary (not conclusion!)

- There is a 3.5σ difference between theory and experiment for the muon (g–2)
- Its source is not known.
- There were many attempts to explain it, mere speculations or refuted.
- Fermilab hopes to measure it at higher precision.
- We always hope for devations from the Standard Model: new physics!

Thanks for your attention!