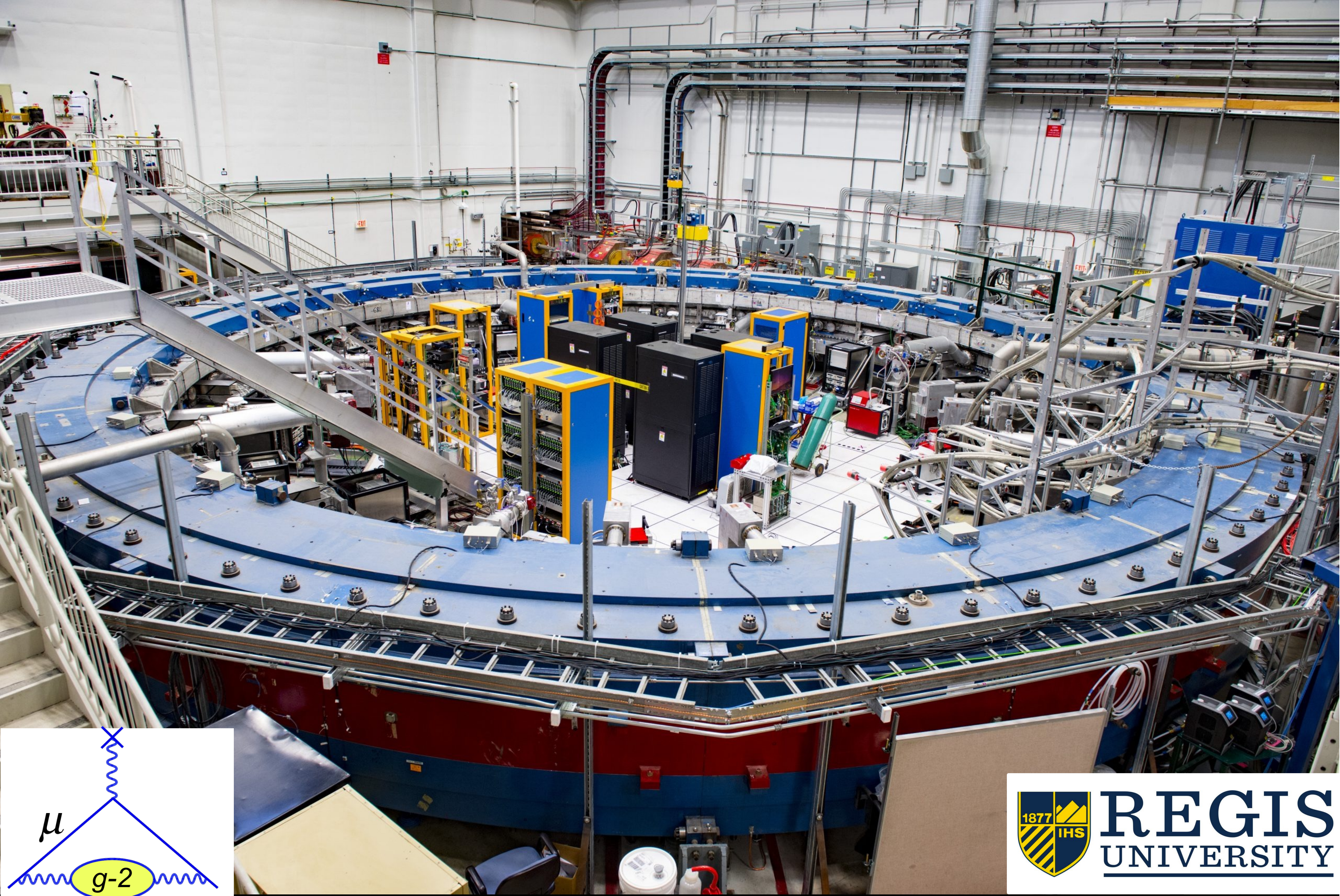


REGIS UNIVERSITY

Fred Gray, Regis University – for the Fermilab Muon g-2 Collaboration
Seminar for Universidade Federal de Santa Catarina, Florianópolis – August 13, 2021

What is it all made of?
How did we get here?

Image from http://www.skyandtelescope.com/astronomy-information/

"What is it all made of?" = Standard Model

- Three generations of quarks:

up	**charm**	**top**
down	**strange**	**bottom**

…from which baryons (like proton and neutron) and mesons (like pion) are built.

- Three generations of leptons:

electron neutrino (ν_e)	**muon neutrino (ν_μ)**	**tau neutrino (ν_τ)**
electron	**muon (μ)**	**tau (τ)**

- Gauge bosons (integer spin) as force carriers:

Electromagnetic	**Weak**	**Strong**
Photon (γ)	**$W^{\pm}$, Z^0**	**Gluon**

- Higgs boson as generator of mass for fundamental particles.

“What is it all made of?” = Standard Model

- Explains almost everything ever observed in particle physics experiments.
  - with few exceptions: our experiment, and recent measurements of B meson decay to muons vs. electrons.

- Doesn’t explain matter/antimatter asymmetry.
  - the BIG “how did we get here?” question.

- Doesn’t explain dark matter.
  - 5.5 times normal matter!
  - Doesn’t even have the right words to talk about dark energy.

- Doesn’t explain hierarchy problem.
  - why is gravity so weak (compared to other forces)?
  - why is the Higgs mass so small (vs. the Planck scale)?

Direct searches have not yet uncovered “new physics”: we’re searching for indirect hints in the form of subtle effects of virtual particles.

We use muons as probes to test the Standard Model

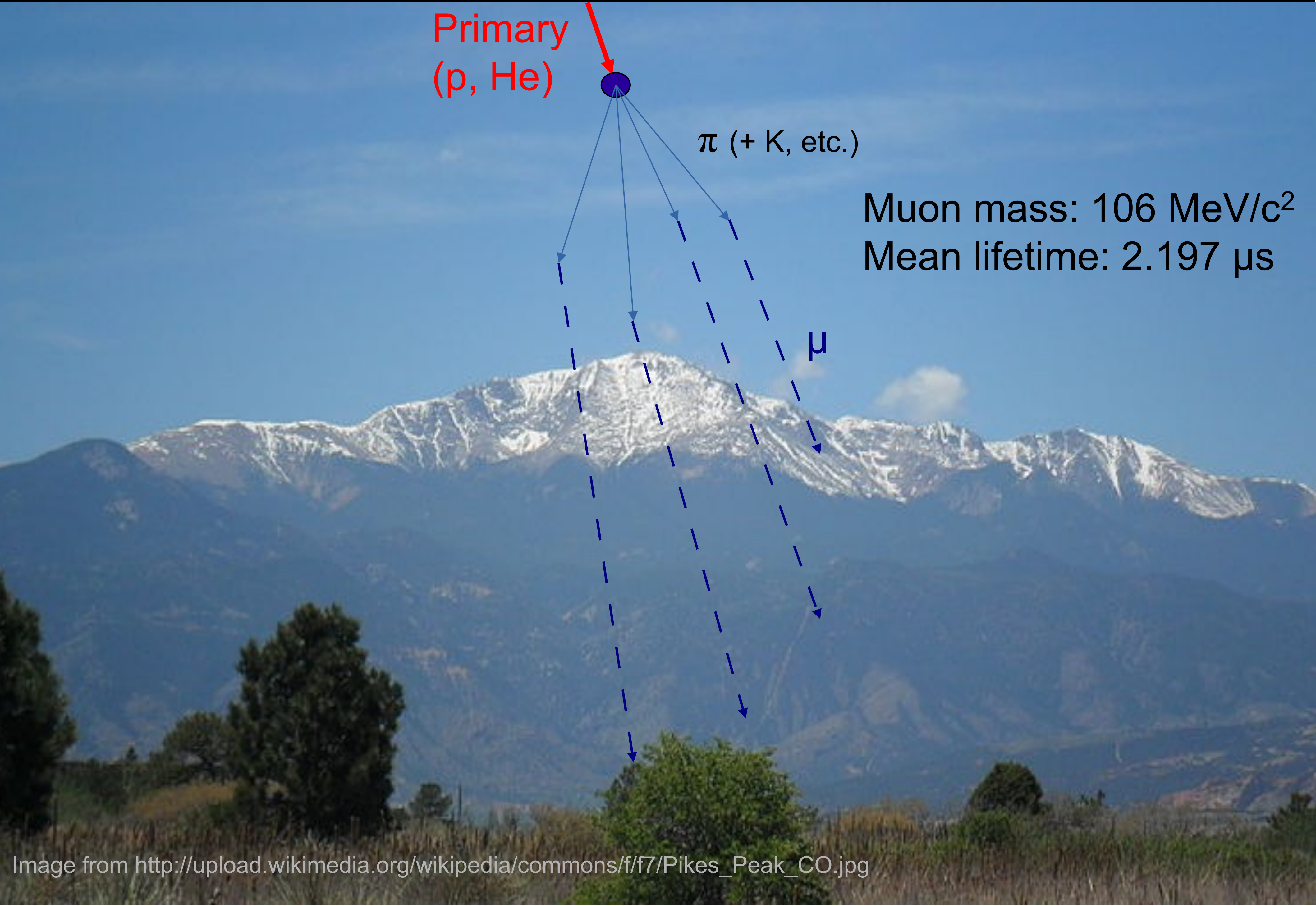
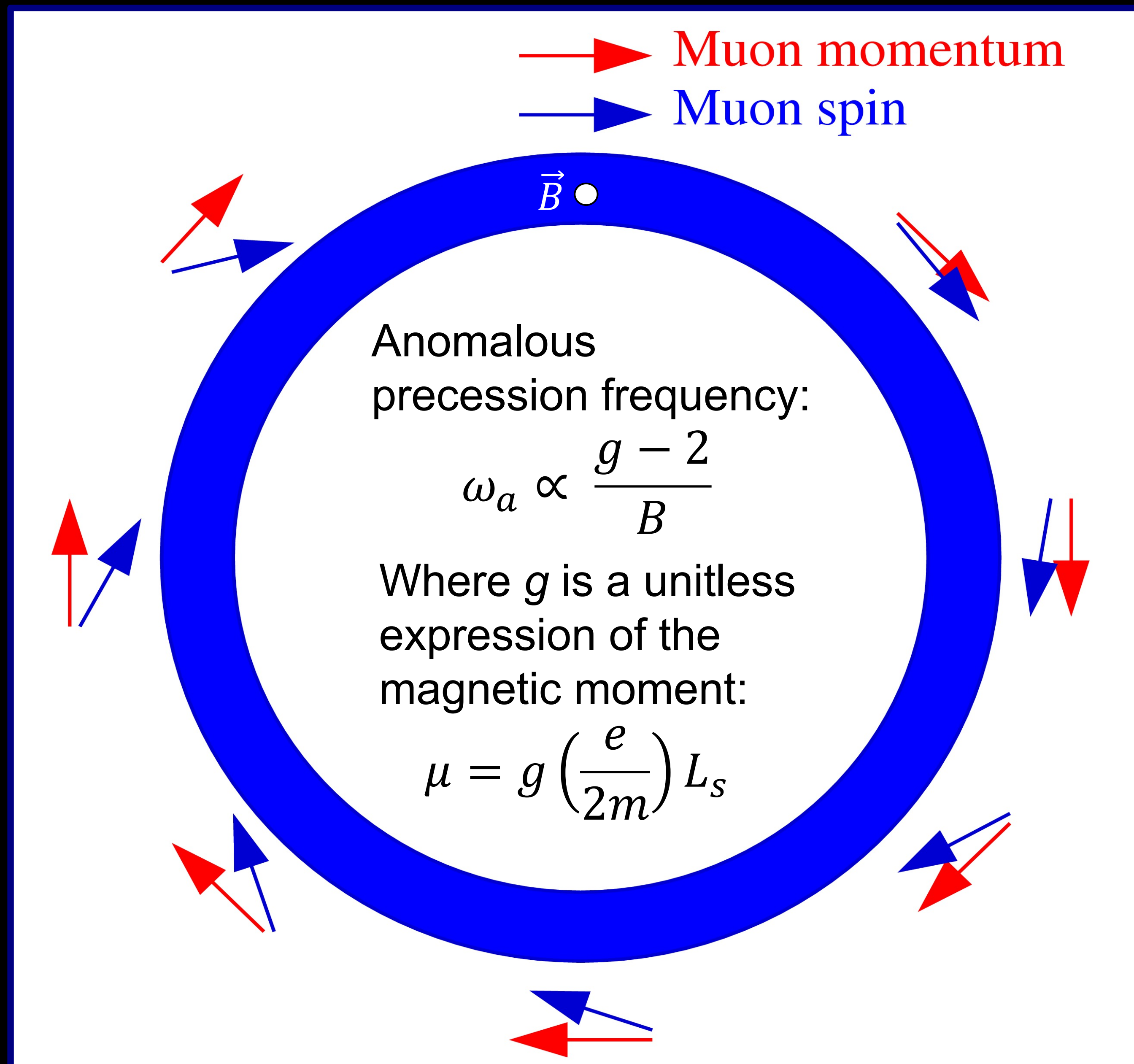
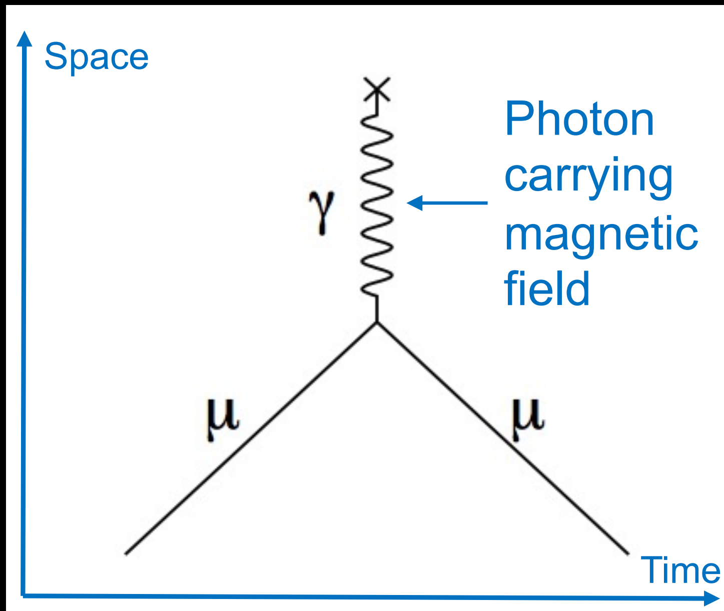


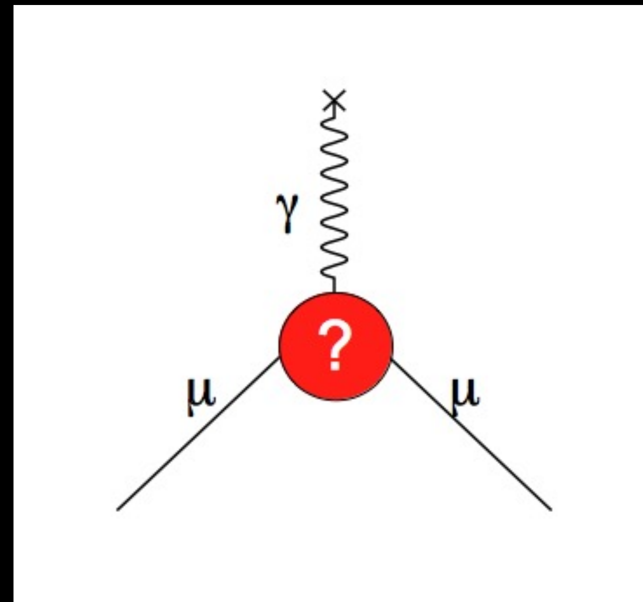
Image from http://upload.wikimedia.org/wikipedia/commons/f/f7/Pikes_Peak_CO.jpg

Basic principle of Muon g-2 Experiment



We store a polarized beam of muons in a uniform magnetic field and observe the spin precession.





$g = 2$

from Dirac equation

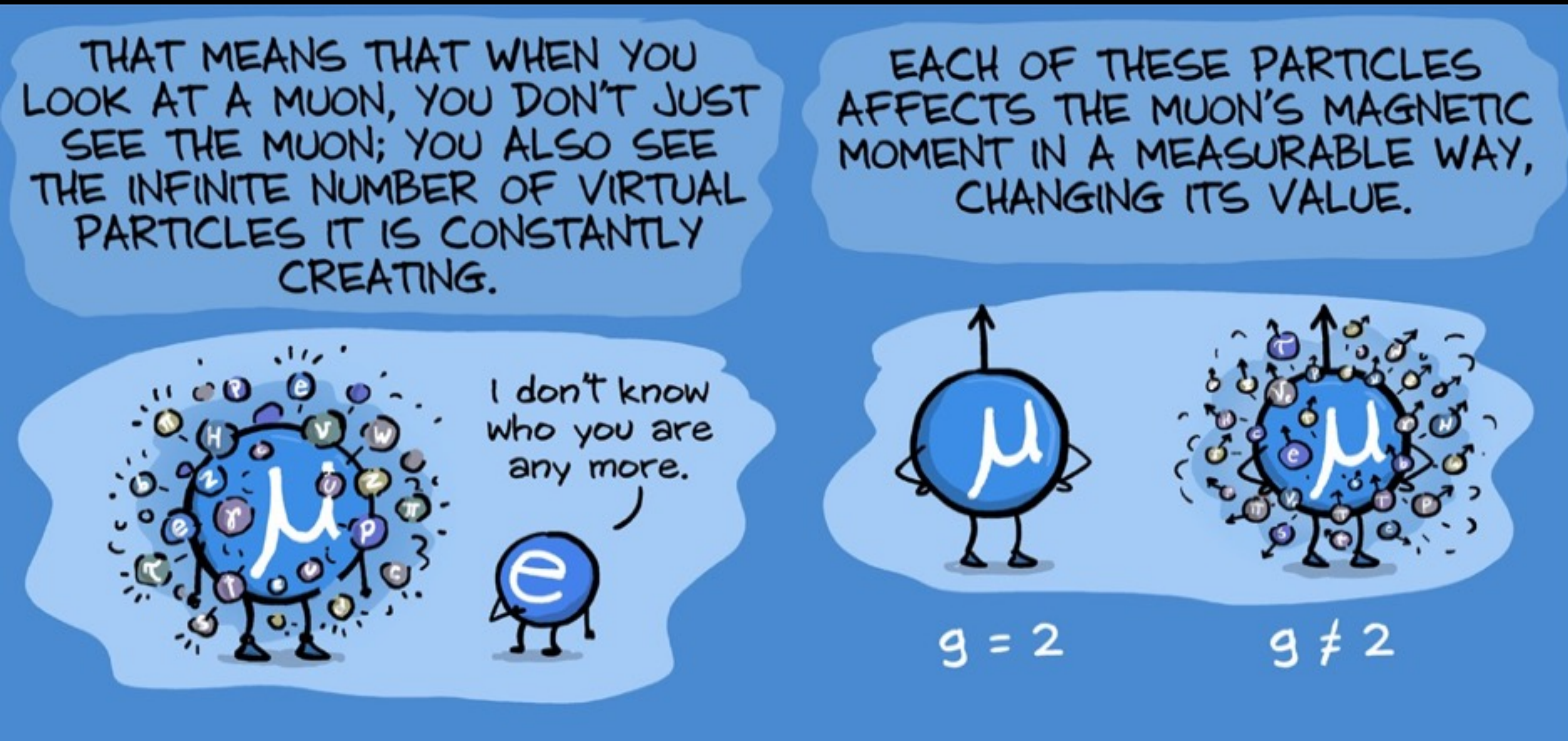
(...which would give no precession)

$$a = \frac{g}{2} - 1$$

anomalous part

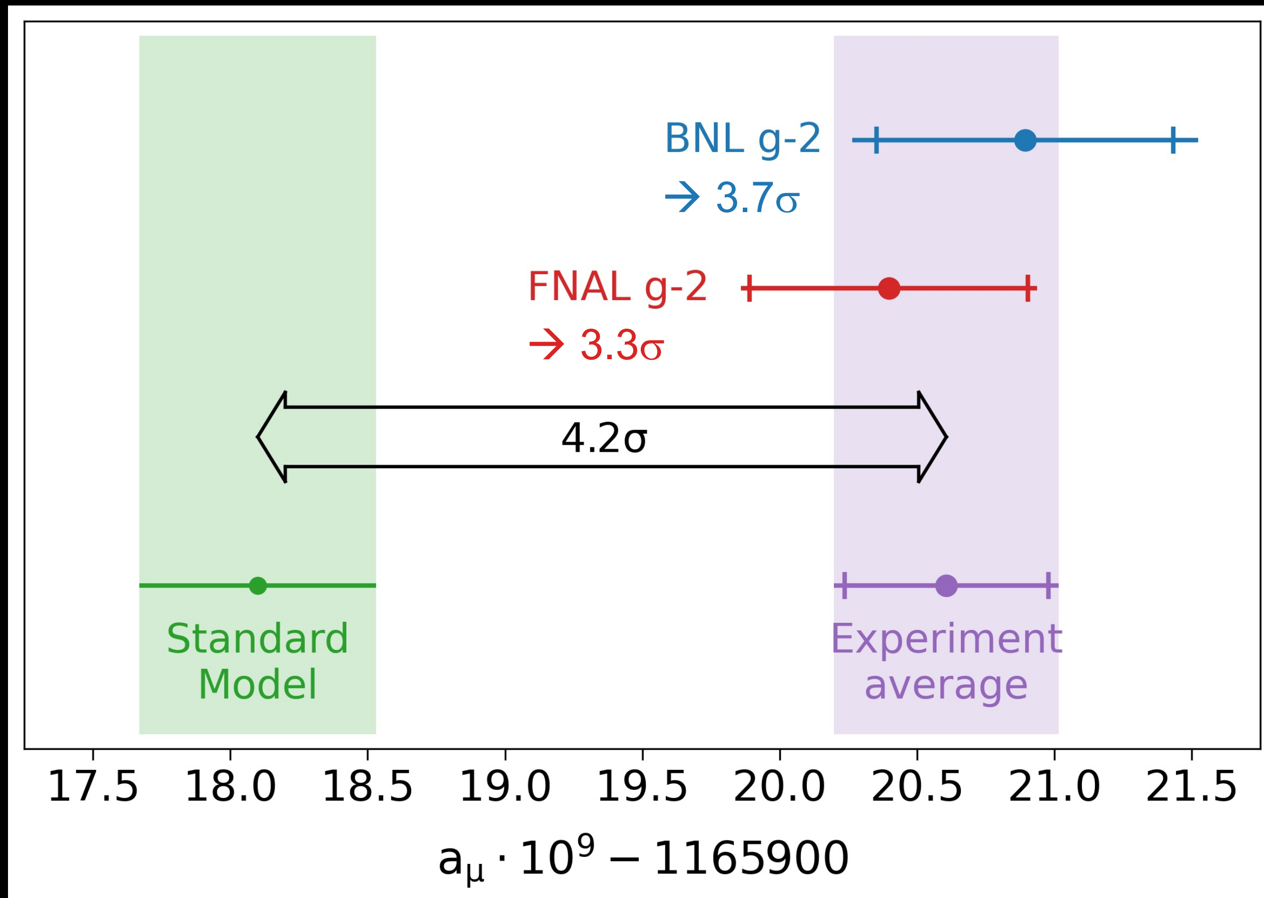
Describes substructure and interactions with virtual particles:

For both electron and muon: $g \approx 2.00233$, $a \approx 0.00116$



Jorge Cham, https://physics.aps.org/articles/v14/47

- The Standard Model makes a very precise prediction of the value of a_μ based on known particles and interactions.
- Our collaboration has made a very precise experimental measurement of a_μ.
- If they don't agree, the difference could be caused by not-yet-discovered particles and interactions.

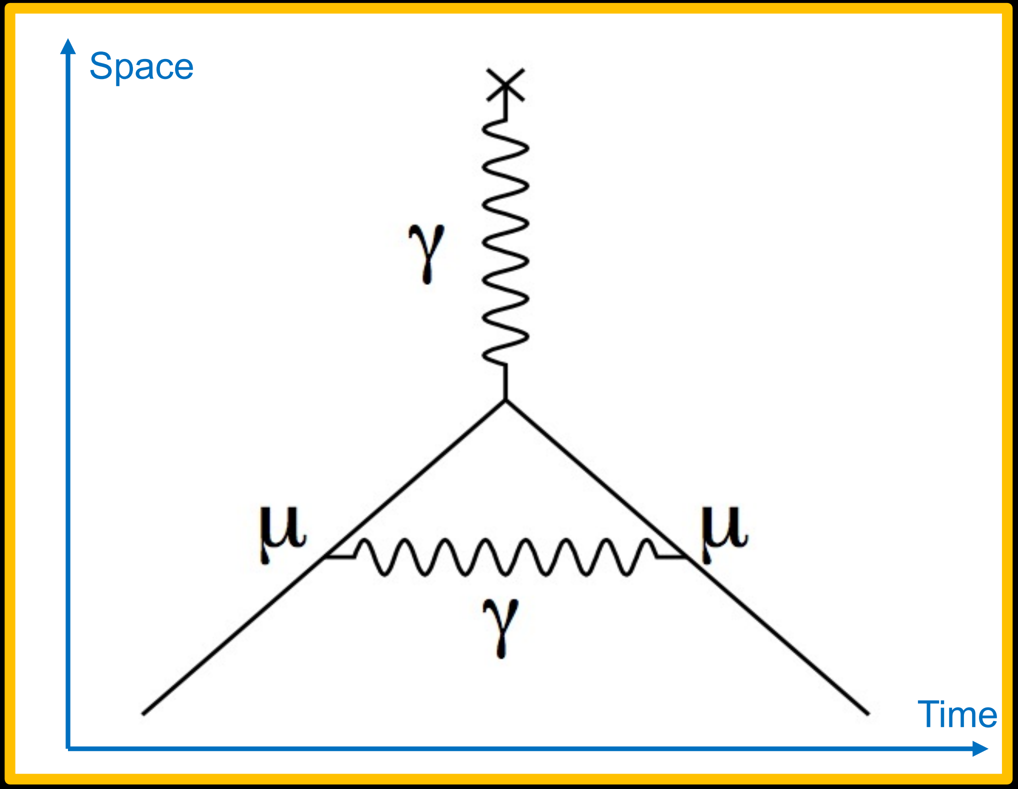


$a_\mu(SM) = (116591810 \pm 43) \times 10^{-11}$ → 368 ppb

$a_\mu(BNL) = (116592089 \pm 63) \times 10^{-11}$ → 540 ppb
$a_\mu(FNAL\ Run\ 1) = (116592040 \pm 54) \times 10^{-11}$ → 463 ppb
$a_\mu(Expt.\ Average) = (116592061 \pm 41) \times 10^{-11}$ → 350 ppb

$a_\mu(Expt.\ Average) - a_\mu(SM) = (251 \pm 59) \times 10^{-11}$

Simplest anomalous part: Electromagnetic interaction with one virtual photon



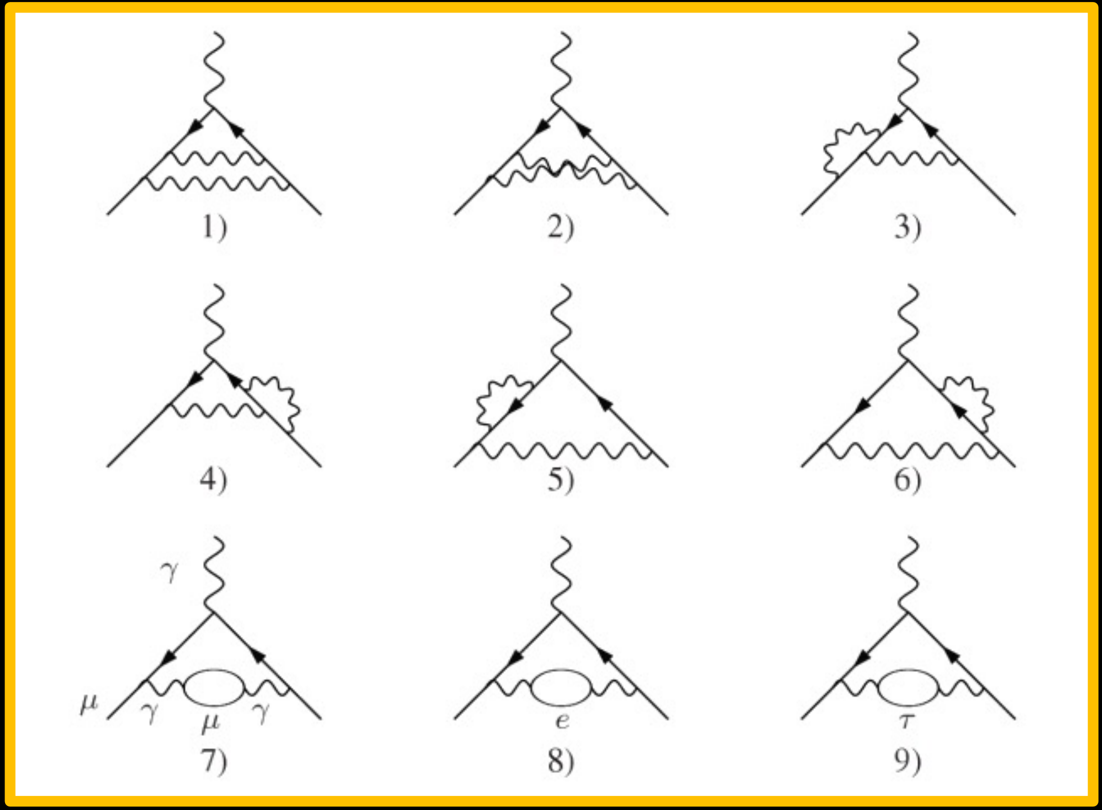
$$a_\mu \approx \frac{\alpha}{2\pi} \approx 0.00116$$

(99.6% of muon anomalous magnetic moment)

Same for electron and muon because photon is massless.
Contributions from massive particles produced in loops scale as m^2.

Higher-order quantum electrodynamics (QED) diagrams

Some of the two-loop diagrams:

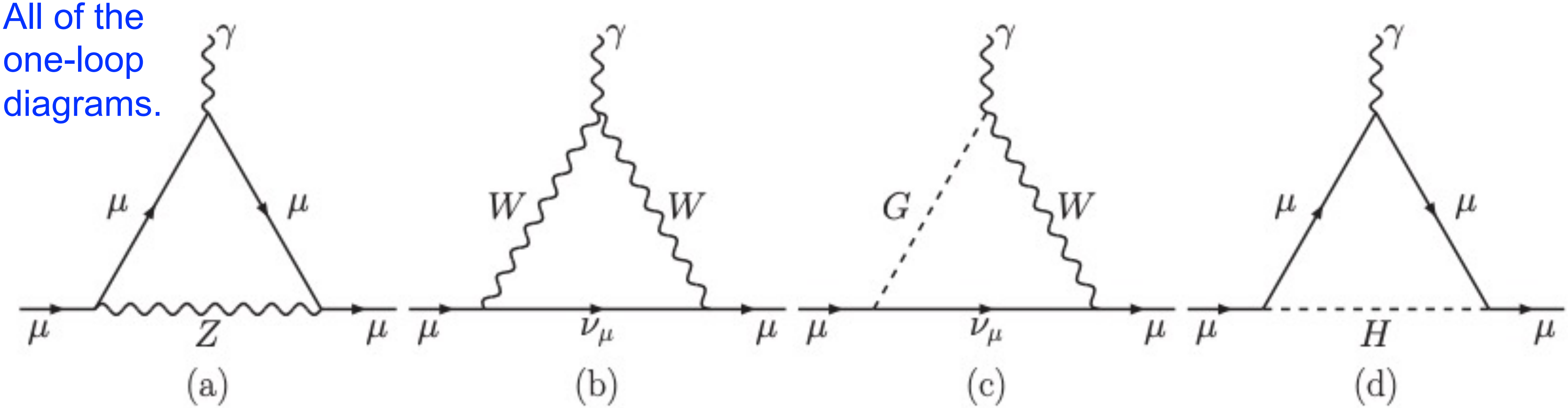


Loops	Diagrams	Value	Value x 10^{11}
1	1	$0.5\ (\alpha/\pi)$	116 140 973.301
2	9	$0.765857410\ (\alpha/\pi)^2$	413 217.621
3	72	$24.050\ 509\ 65\ (\alpha/\pi)^3$	30 141.902
4	1360	$130.8105\ (\alpha/\pi)^4$	380.807
5	12672	$663\ (\alpha/\pi)^5$	4.483

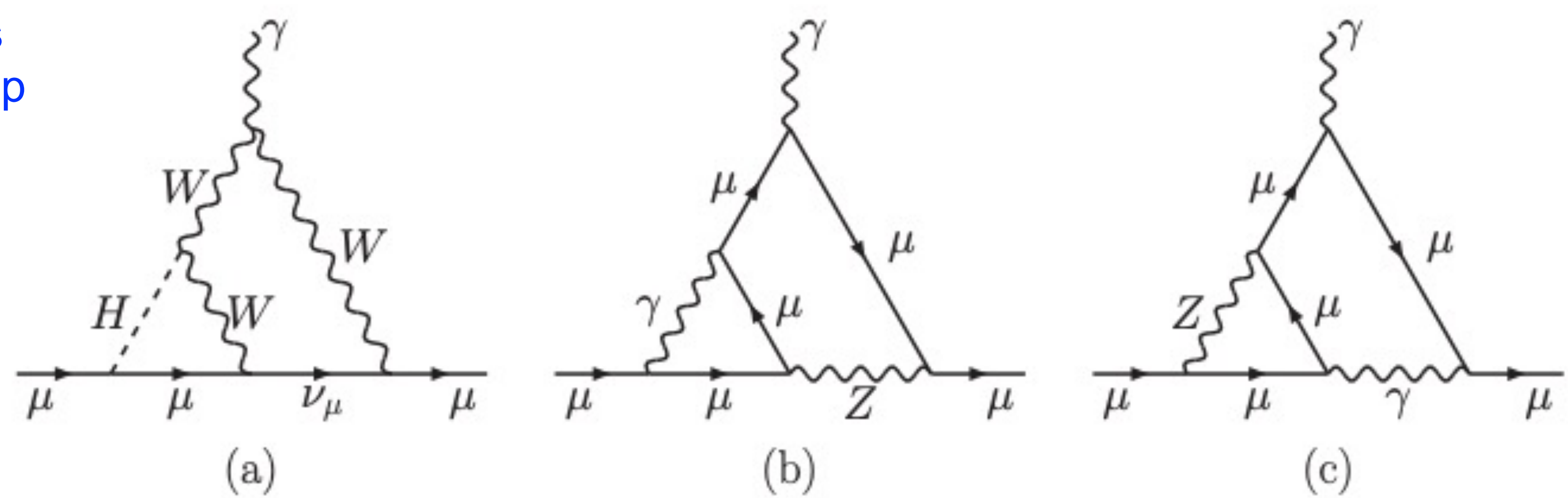
from F. Jegerlehner, *The Anomalous Magnetic Moment of the Muon* (Springer, 2008)

Weak-interaction and electroweak terms can be calculated in much the same way.

All of the one-loop diagrams.



Examples of two-loop diagrams

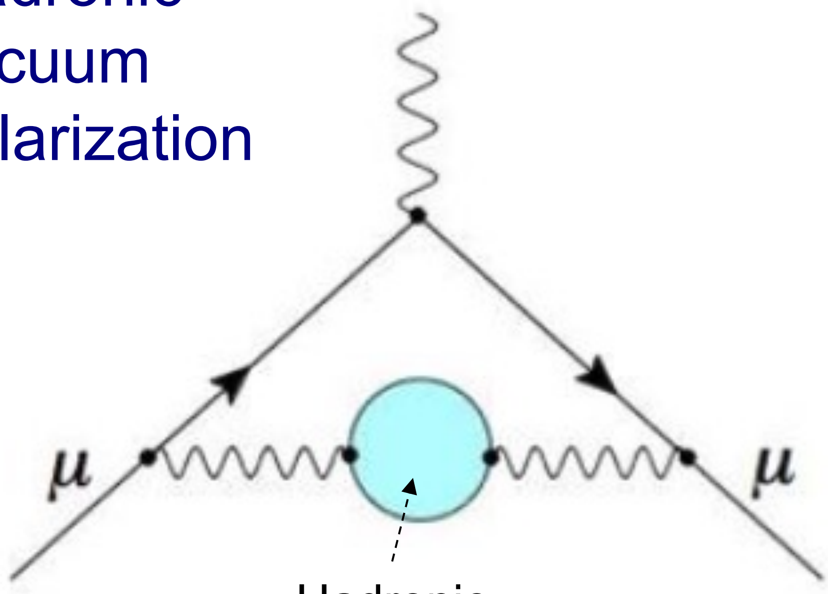


Images from T. Aoyama et al., Phys. Rept. 887 (2020) 1-166, https://arxiv.org/abs/2006.04822

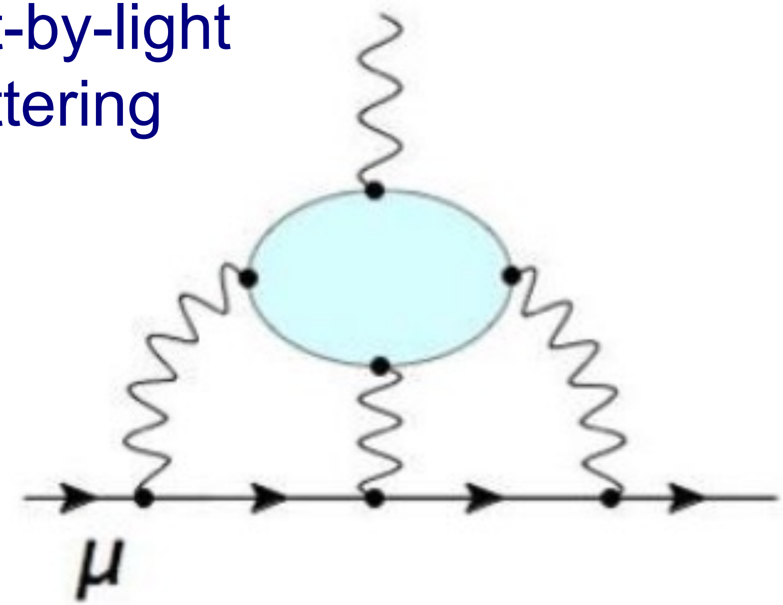
Total electroweak contribution (through two loops): $(153.6 \pm 1.0) \times 10^{-11}$

Quantum chromodynamics (QCD) is not as easy

Hadronic vacuum polarization



Hadronic light-by-light scattering



Recommended values from Muon g-2 Theory Initiative:

	Value x 10^{11}	Uncertainty x 10^{11}
Quantum electrodynamics	116 584 718.931	0.104
Weak interaction	153.6	1.0
Hadronic vacuum polarization	6845	40
Hadronic light-by-light	92	18
TOTAL	***116 591 810***	***43***

Images from https://muon-gm2-theory.illinois.edu/white-paper/

Muon g-2 Theory Initiative

The anomalous magnetic moment of the muon in the Standard Model

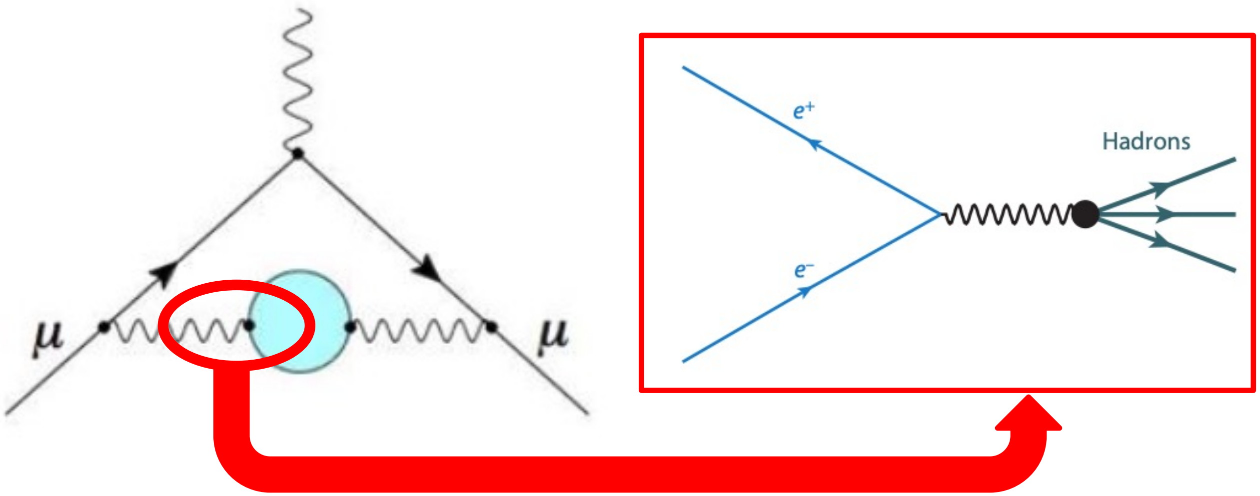
T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

- Theory community consortium to compile theoretical input and make recommendations on Standard Model value.

- “White paper” released June 10, 2020 based on six workshops held from 2017-2020
- 132 authors, 82 institutions, 21 countries
- Published in *Physics Reports*

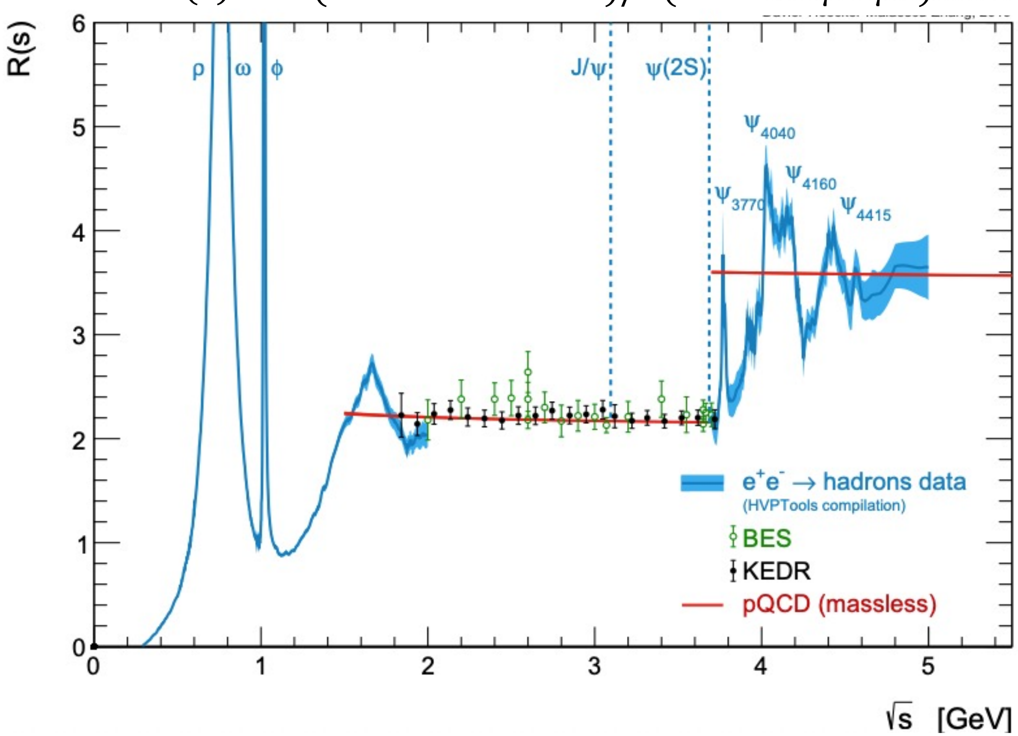
Hadronic vacuum polarization: data-driven dispersion integral relations

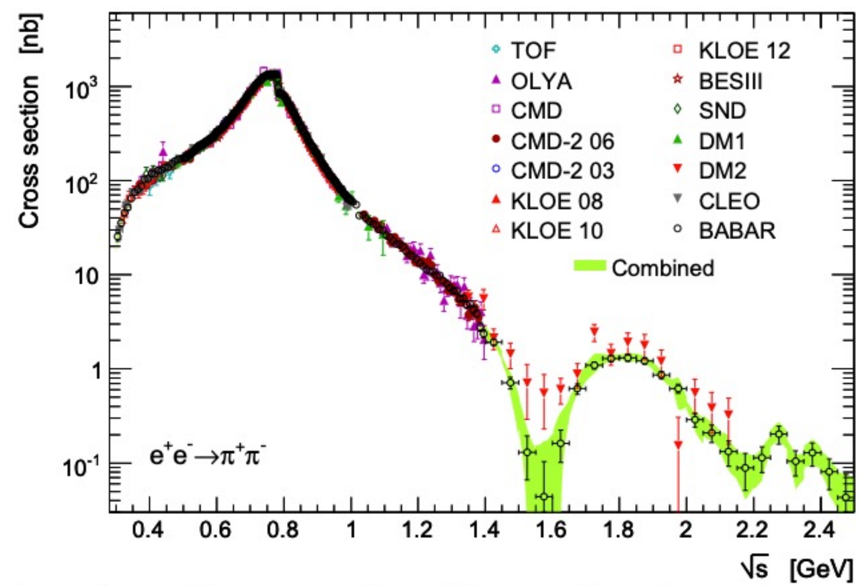


$$a_\mu^{\text{HVP, LO}} = \frac{\alpha^2}{3\pi^2}\int_{M_\pi^2}^{\infty}\frac{K(s)}{s}R(s)\,ds$$

with $K(s) \sim \frac{m_\mu^2}{3s}$

$$R(s) = \sigma(e^+ e^- \to \text{hadrons})/\sigma(e^+ e^- \to \mu^+ \mu^-)$$

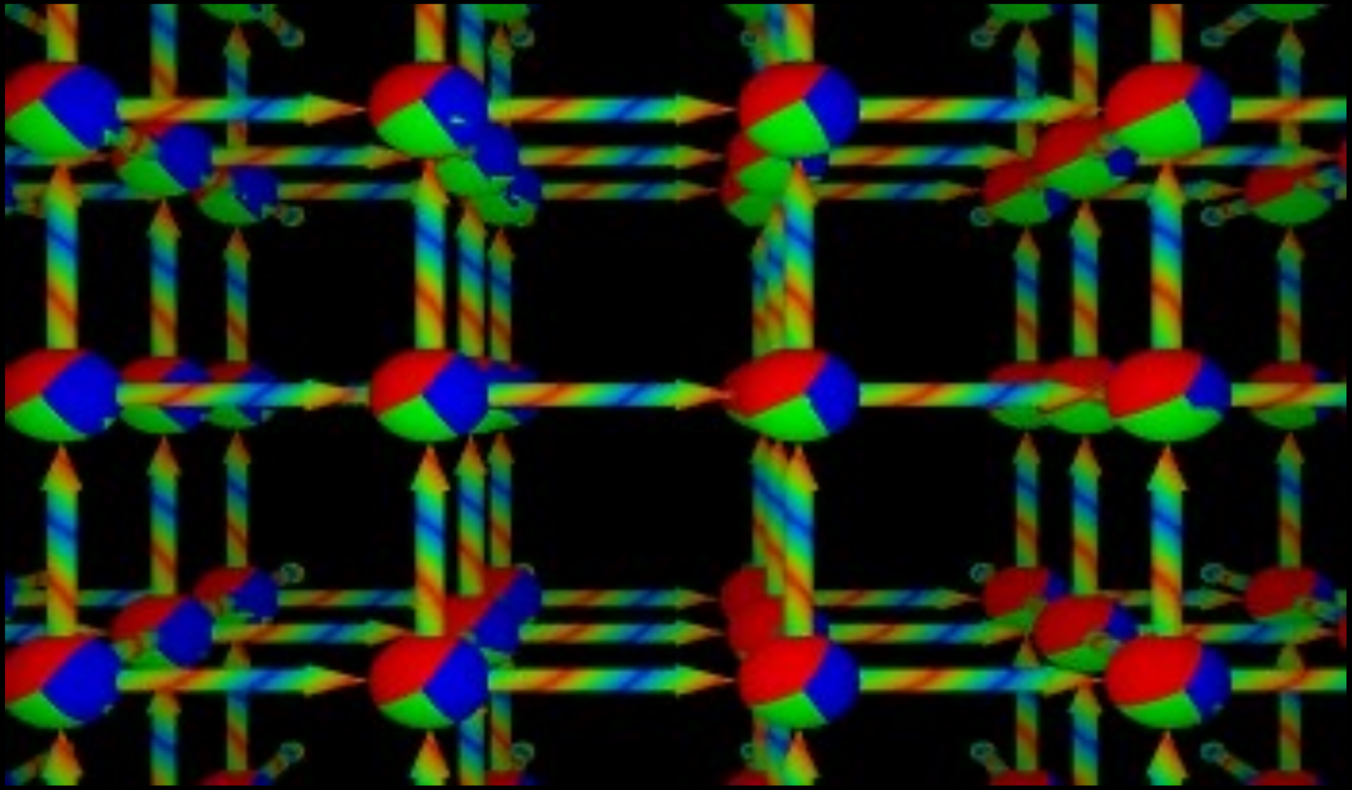




Dispersion integral heavily weights low-energy region that is dominated by two-pion production.

Images from T. Aoyama et al., Phys. Rept. 887 (2020) 1-166, https://arxiv.org/abs/2006.04822

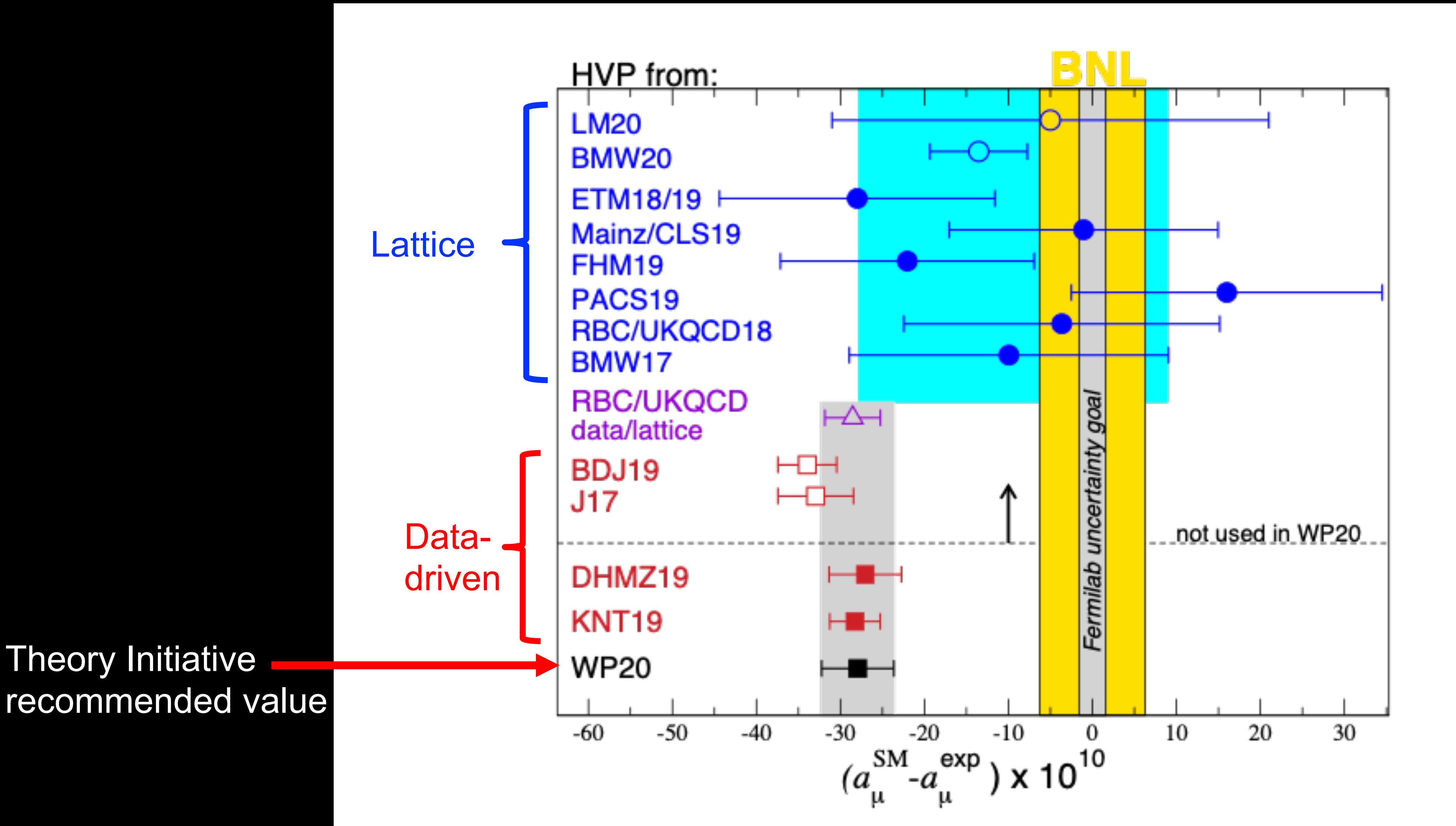
Lattice QCD calculations



- Model interactions at quark+gluon level with discrete space and time variables.
- Vary lattice spacing, find limit as space and time become continuous.

- Requires extensive computing resources.

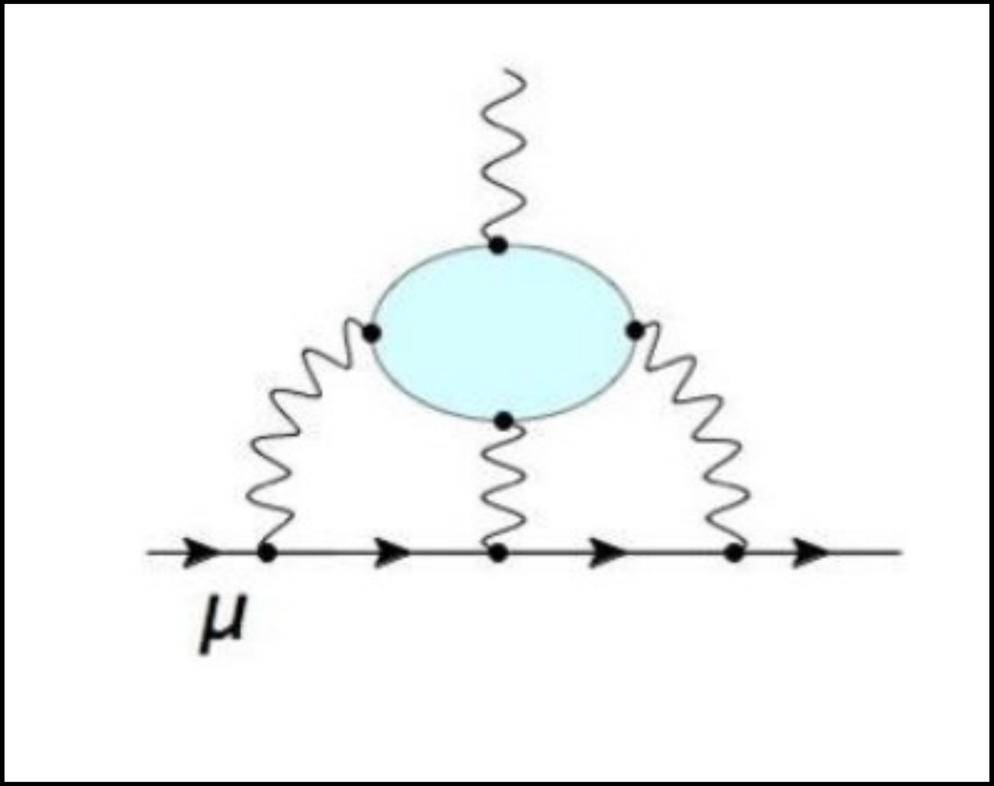
Image from https://www.tpi.uni-jena.de/~gbergner/projects.html

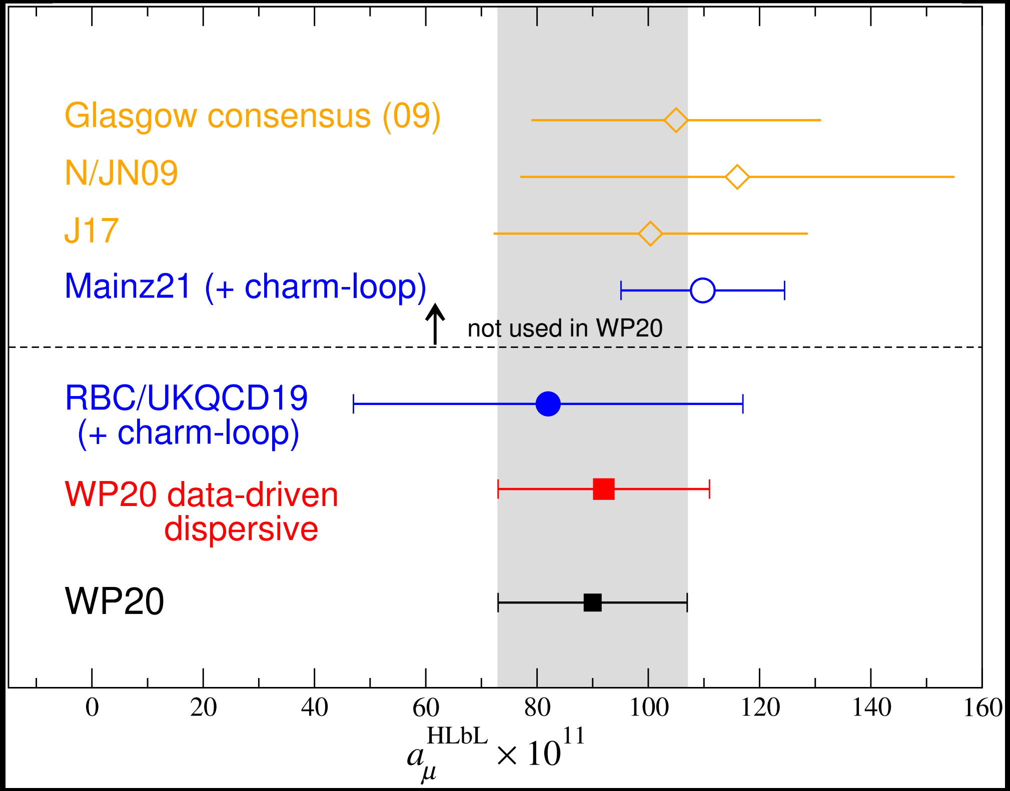


- Lattice QCD calculations of hadronic vacuum polarization are starting to reach < 1% level of precision.
- At this point, Muon g-2 Theory Initiative white paper recommends a value based only on data-driven evaluations.

Images from T. Aoyama et al., Phys. Rept. 887 (2020) 1-166, https://arxiv.org/abs/2006.04822

Hadronic light-by-light scattering





- Historically, relied on phenomenological nuclear models

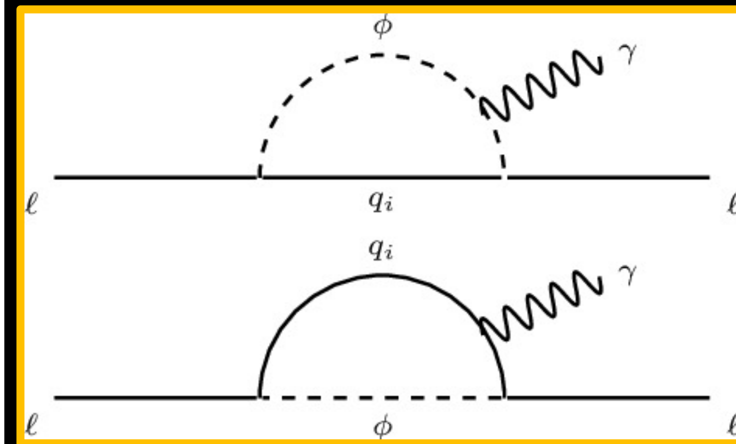
- Two new approaches in good agreement:
  - lattice calculations
  - data-driven dispersion relations

Beyond the Standard Model – what could it be?

Supersymmetry?

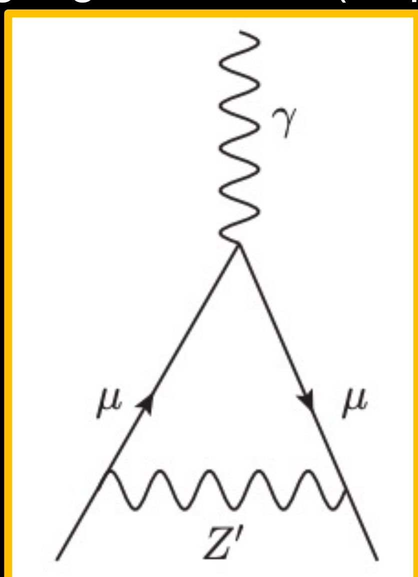
- For every boson we know, a new fermion.
- For every fermion we know, a new boson.
- Strong constraints from absence at LHC, but some scenarios still possible.

Leptoquarks?



from I. Bigaran and R. R. Volkas, arXiv:2002.12544

Extra gauge bosons? (“Z-prime")



from A.P. Morais, R. Pasechnik, J.P. Rodrigues, arXiv:1912.11882

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

Muon g-2 Collaboration • B. Abi (Oxford U.) et al. (Apr 7, 2021)

Published in: *Phys.Rev.Lett.* 126 (2021) 14, 141801 • e-Print: 2104.03281 [hep-ex]

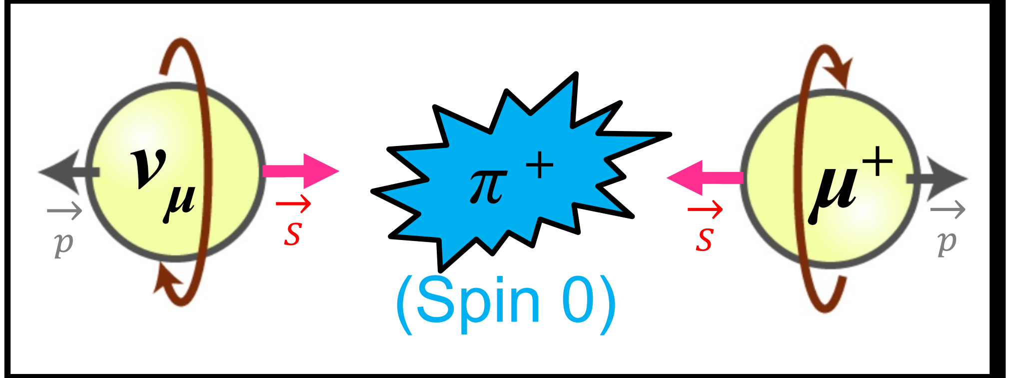
pdf links DOI cite 238 citations

https://inspirehep.net/literature/1856627

What if we tried to measure the muon *g* factor with stopped cosmic ray muons?

Positive muons produced with spin polarized opposite to momentum:

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$



Only left-handed neutrinos...

To conserve angular momentum, only left-handed muons (in pion rest frame).

What if we tried to measure the muon *g* factor with stopped cosmic ray muons?

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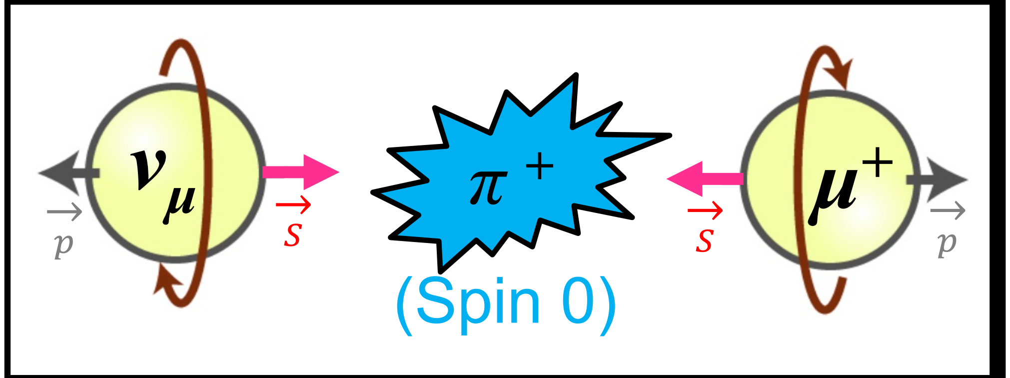


Only left-handed neutrinos...

To conserve angular momentum, only left-handed muons (in pion rest frame).

After stopping in experiment, muon spin precesses around applied magnetic field:

$$\omega_s = g\left(\frac{e}{2m}\right)B$$

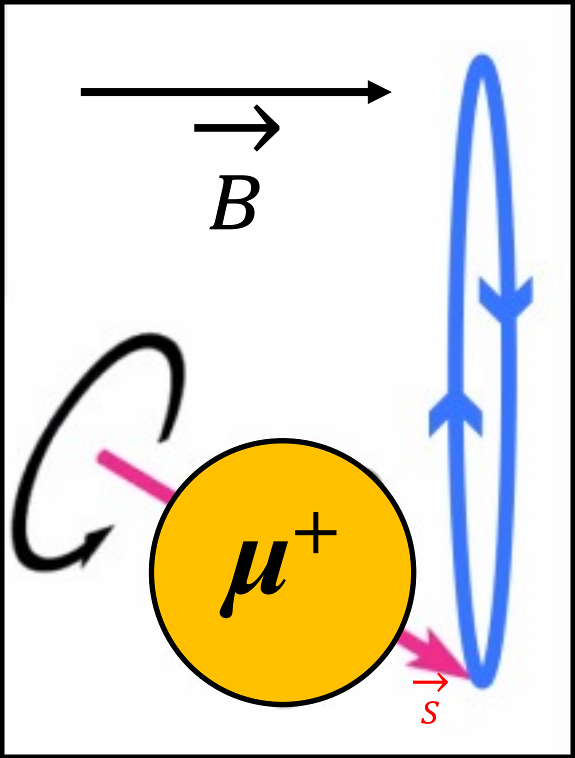
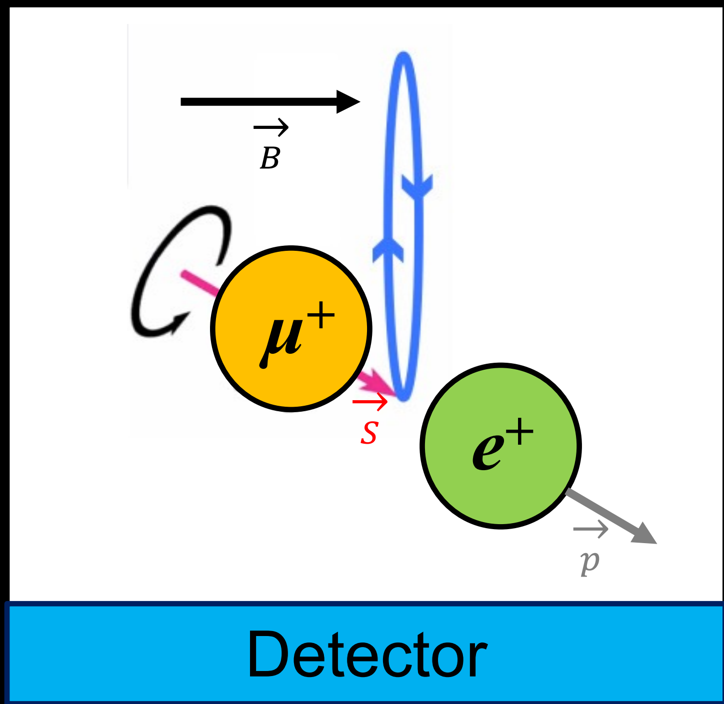


Image derived from http://mriquestions.com/why-precession.html

Measuring the muon *g* factor with cosmic rays



- Positron in $\mu^+ \longrightarrow e^+ + \nu_e + \overline{\nu}_\mu$ preferentially follows muon spin direction.

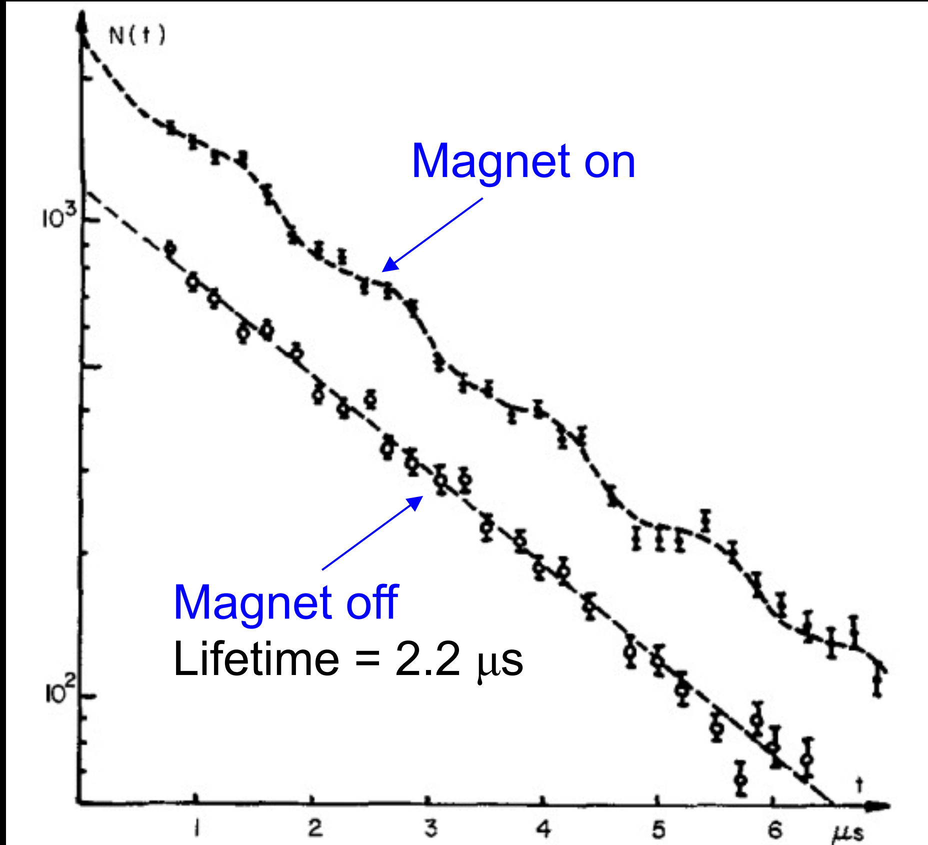


FIG. 3. Experimental results: The upper spectrum was obtained with a field of 55 G (~17 500 events), the lower spectrum with field off (~9000 events). The curves are computer fits.

C. Amsler, *Am. J. Phys.* 42, 1067 (1974)

(Modulated at rate proportional to *g*)

Measuring muons in flight: *g* - 2 rather than *g*

- For muons at rest: $\vec{\omega}_s = g_\mu \left(\frac{e}{2m_\mu}\right)\vec{B}$
- In flight, add a relativistic correction:

$$\vec{\omega}_s = g_\mu \left(\frac{e}{2m_\mu}\right)\vec{B} + \left(\frac{1}{\gamma} - 1\right)\left(\frac{e}{m_\mu}\right)\vec{B}$$

- Subtract the frequency of orbits around the ring: $\vec{\omega}_c = \left(\frac{e\vec{B}}{m_\mu \gamma}\right)$
- The difference is proportional to *a*, not *g*:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \left(\frac{g_\mu}{2} - 1\right)\left(\frac{e}{m_\mu}\right)\vec{B} = \frac{e}{m_\mu} a_\mu \vec{B}$$

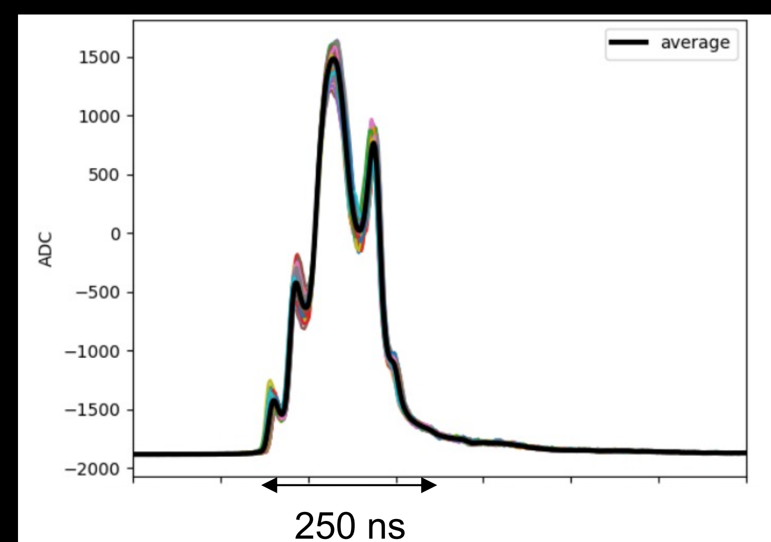
If we measure a_μ = 0.001165921, then g_μ = 2.002331842.
That's three more digits of precision!

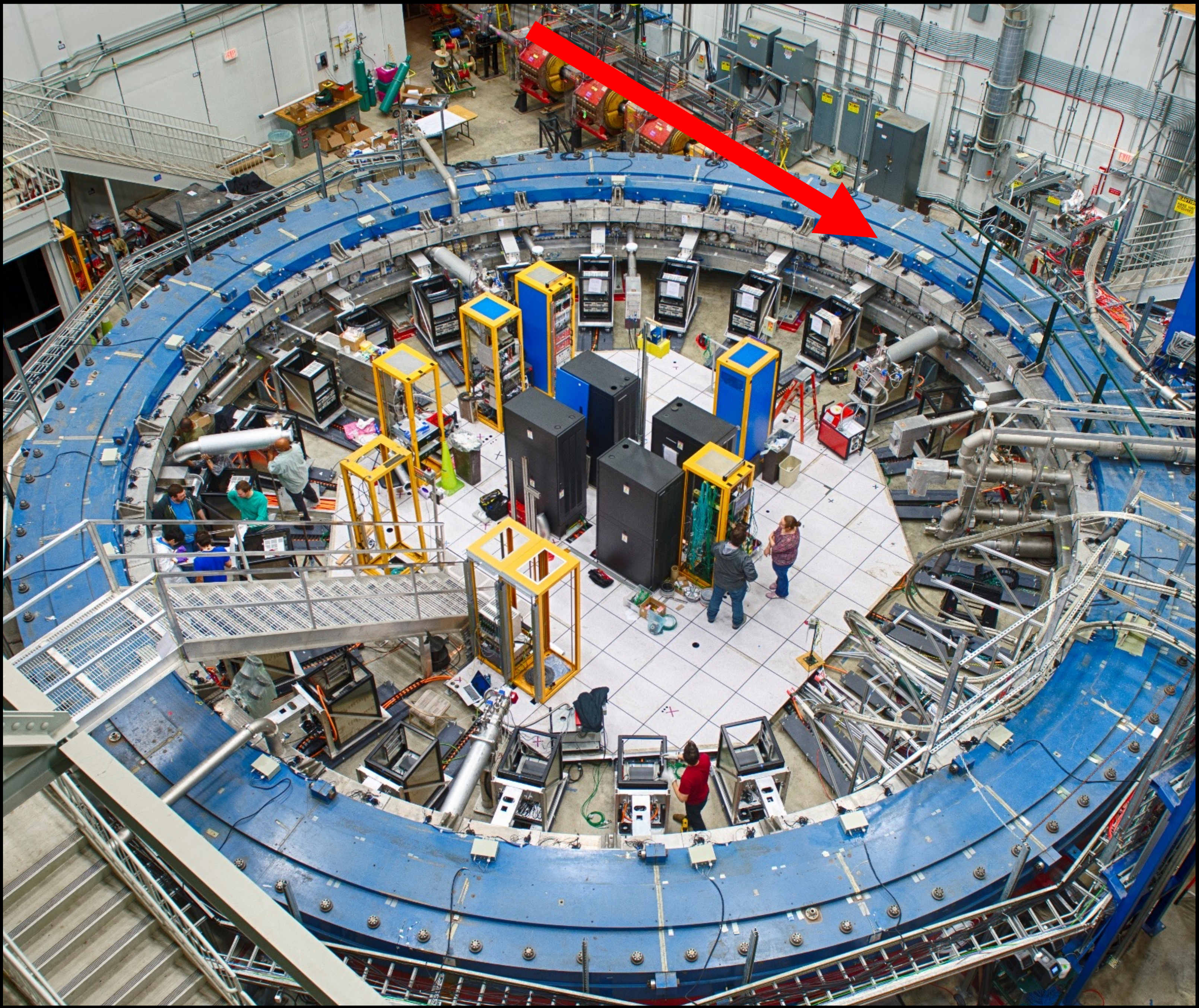
* We are ignoring electric fields and assuming that the motion is in a plane perpendicular to $\vec{B}$

Fermilab Muon Campus

- 8 GeV protons from Booster
- Rebunched into 16 fills per 1.33 s supercycle.

- > 2000 m pion decay path.
- Proton removal after 3 turns in Delivery Ring.



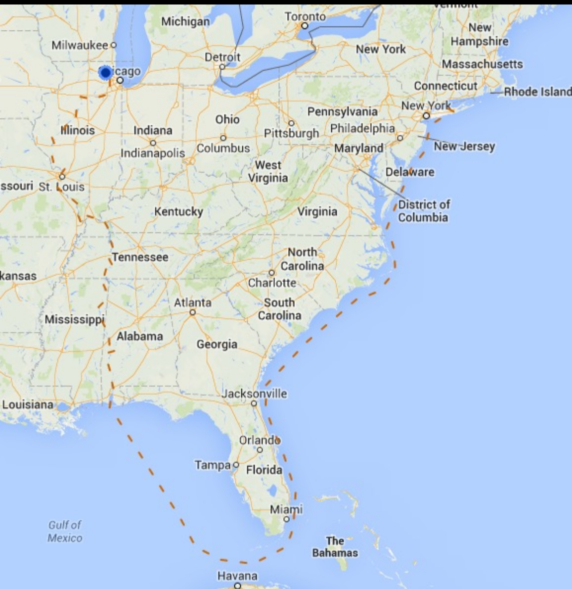


r = 7.112 m
B = 1.45 T

p_μ = 3.09 GeV/c (“magic”)
τ_c = 149 ns

$\gamma\tau$ = 64.4 μs
τ_a = 4.37 μs

Built on the foundations of Brookhaven experiment 821
(which was intellectually descended from mid-1970s CERN III experiment)



Some major components reused (after refurbishing):

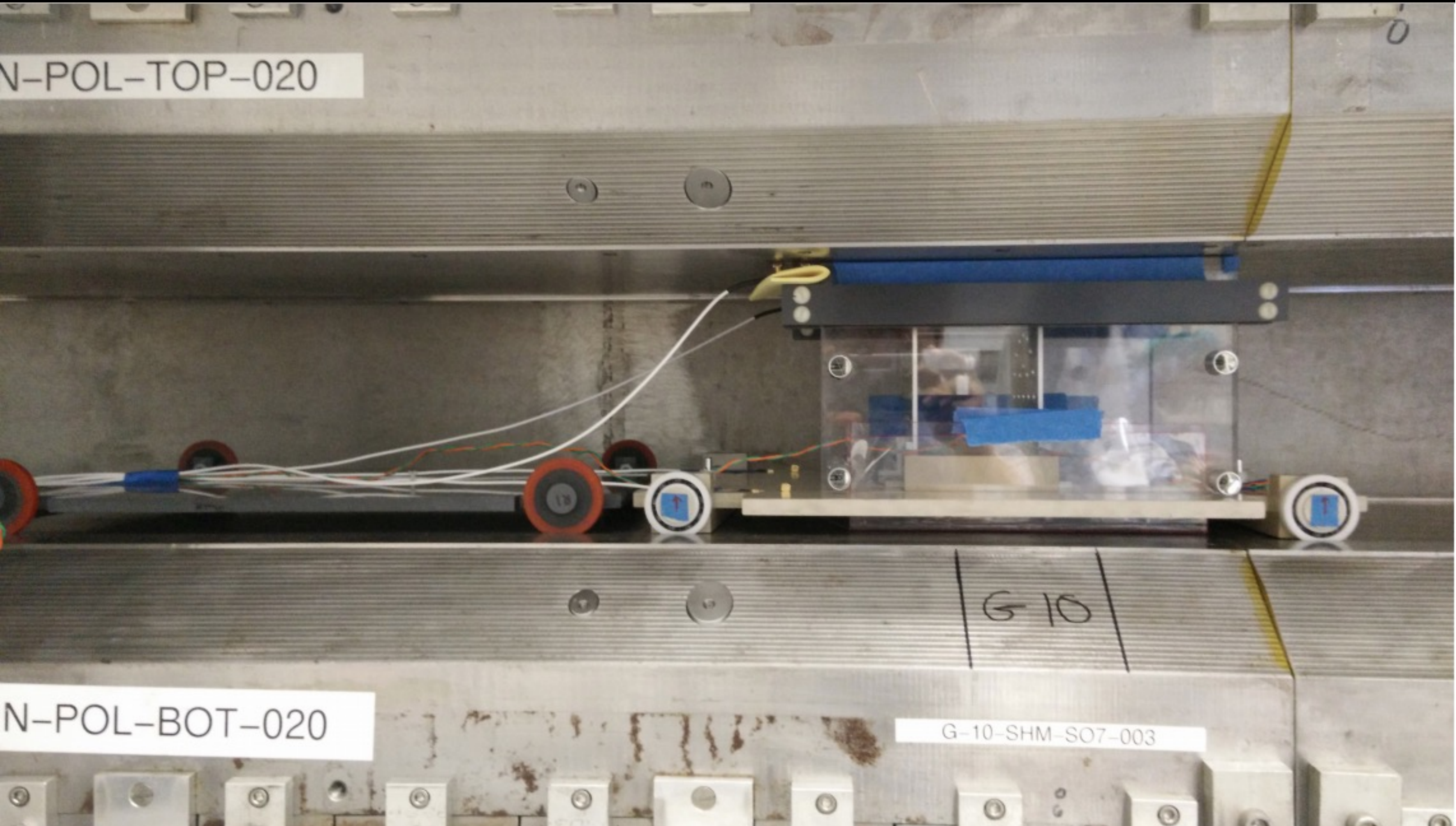
- Magnet
- Vacuum chambers
- Inflector

But also many new designs:

- Beamline
- Kicker
- Detectors: Calorimeter and Tracker
- Electronics
- DAQ/Computing

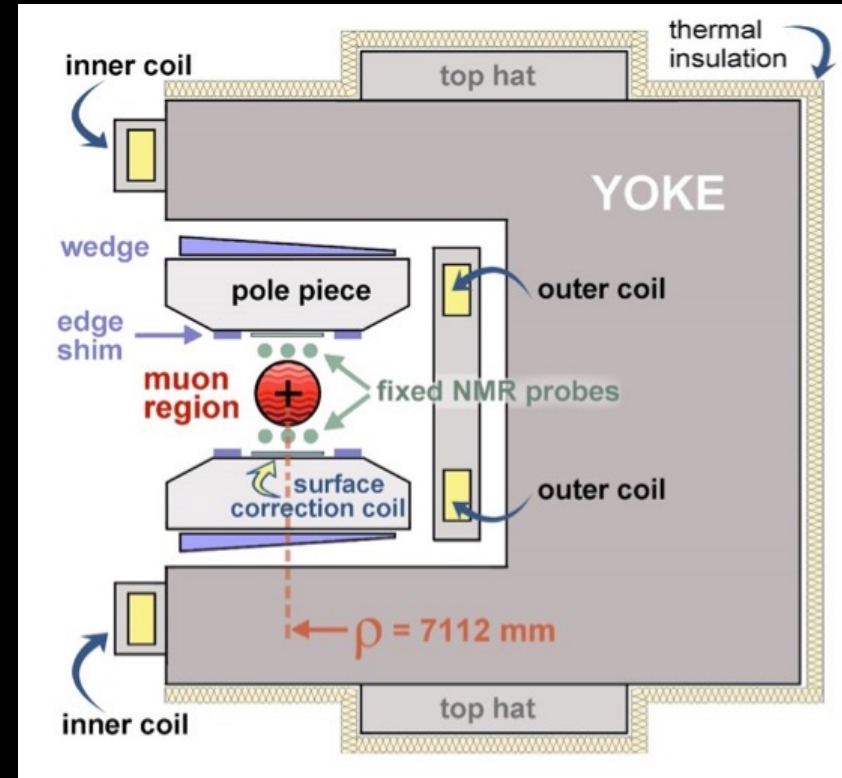
Only 11 of the 190 collaborators worked on Brookhaven experiment.

After reassembling the magnet, time to re-shim

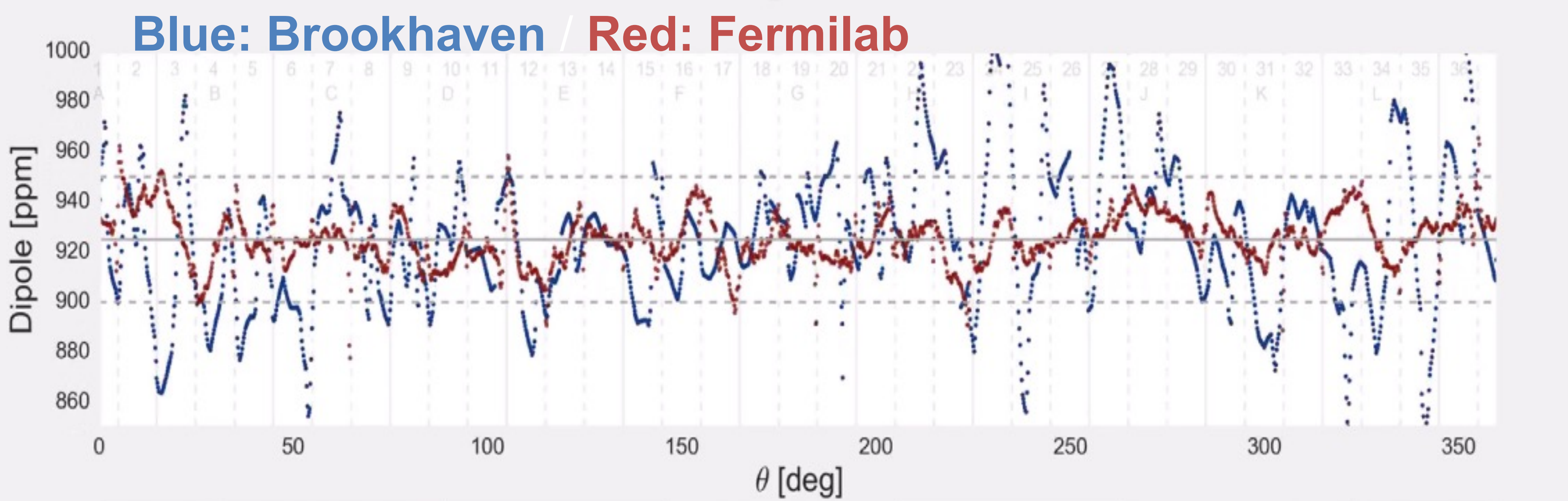


- Azimuthal uniformity “out of the box” was about 1 order of magnitude worse than final Brookhaven result.

- Adjustment of pole pieces, "top hats" and wedge shims
- New iron foil laminations

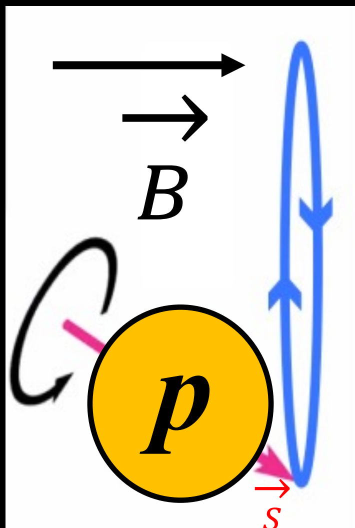


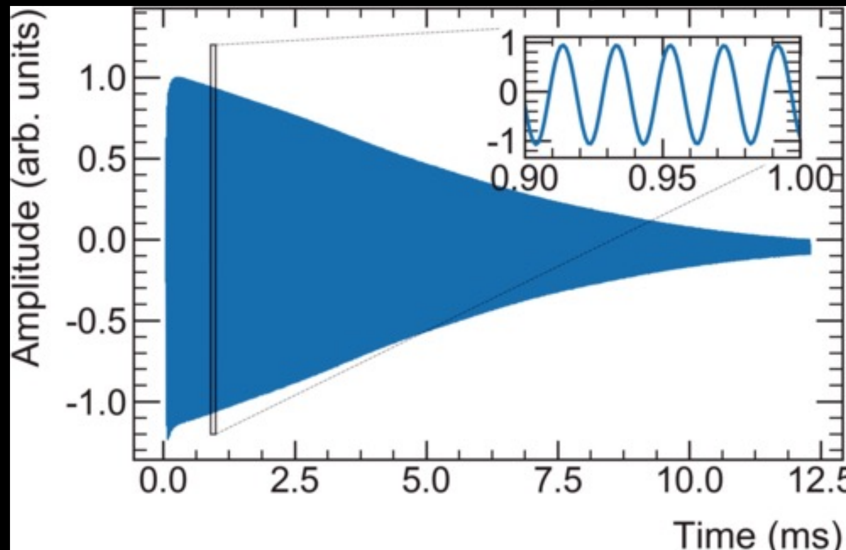
g-2 Magnet in Cross Section



Magnetic field measured with NMR

- Proton spin precession frequency ω_p :





- Precise method to determine $a_\mu = \frac{m_\mu}{e}\frac{\omega_a}{B}$:

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

We measure this ratio

10.5 ppb

Exact

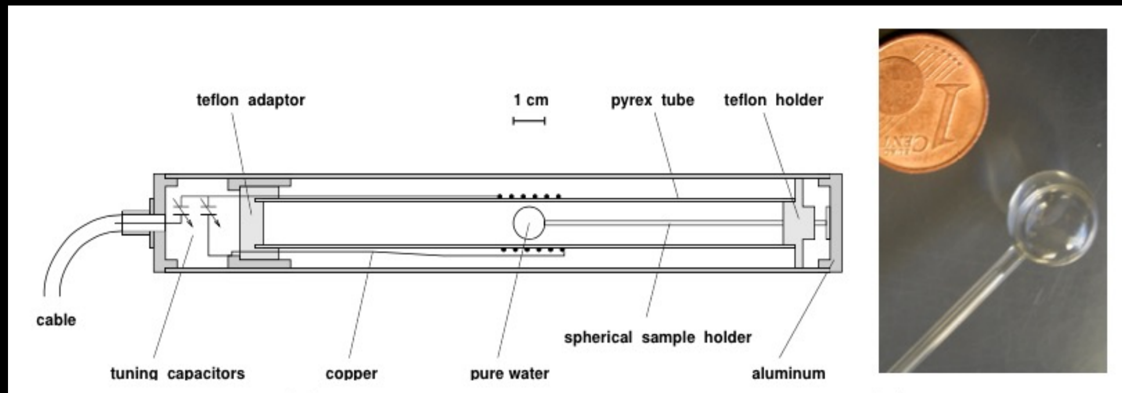
22 ppb

0.28 ppt

~ : weighted by muon population
′ : in spherical water sample
T_r : reference temperature (34.7° C)
H : in hydrogen atom

Magnetic field calibration

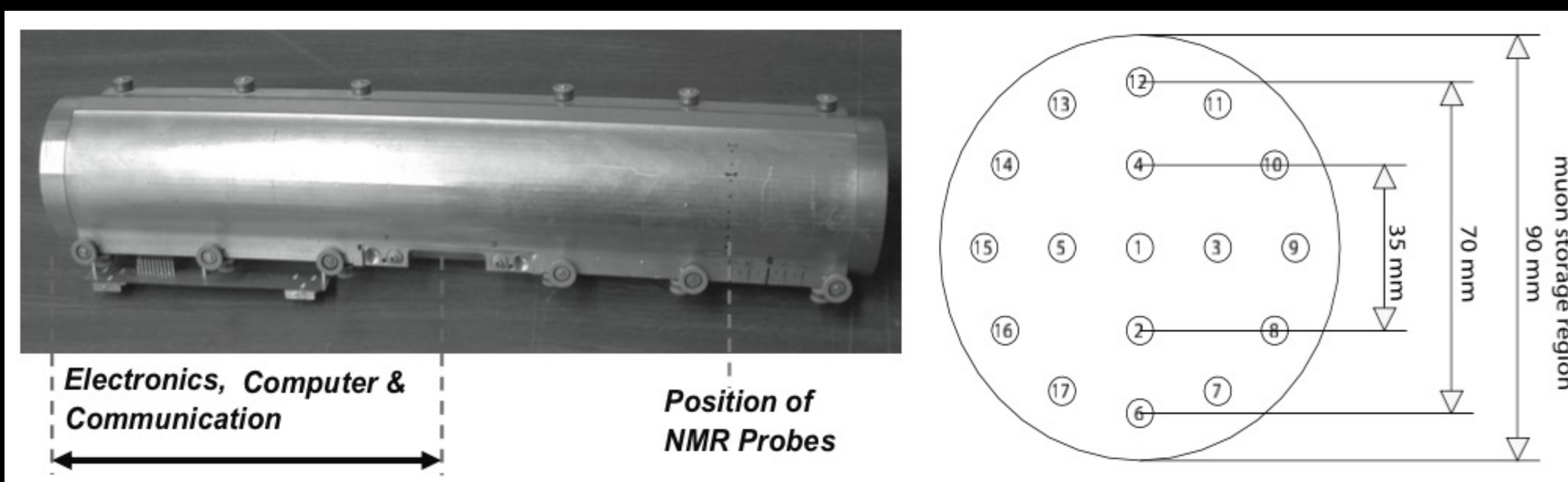
- Absolute calibration standard: spherical H_2O probe



(a) Absolute calibration probe

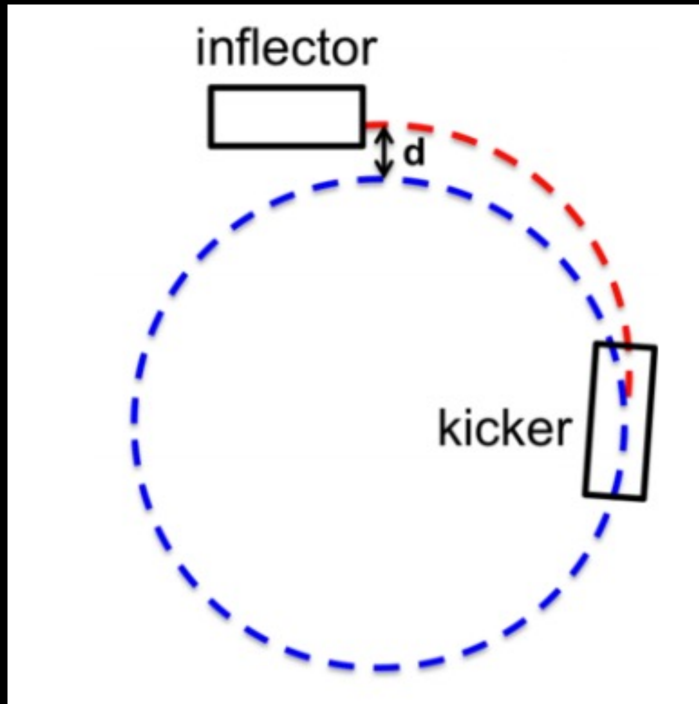
(b) Spherical Pyrex container

- Absolute calibration confirmed with second standard: ^{3}He probe
- Calibration transferred to trolley probes via x-y plunging probe:

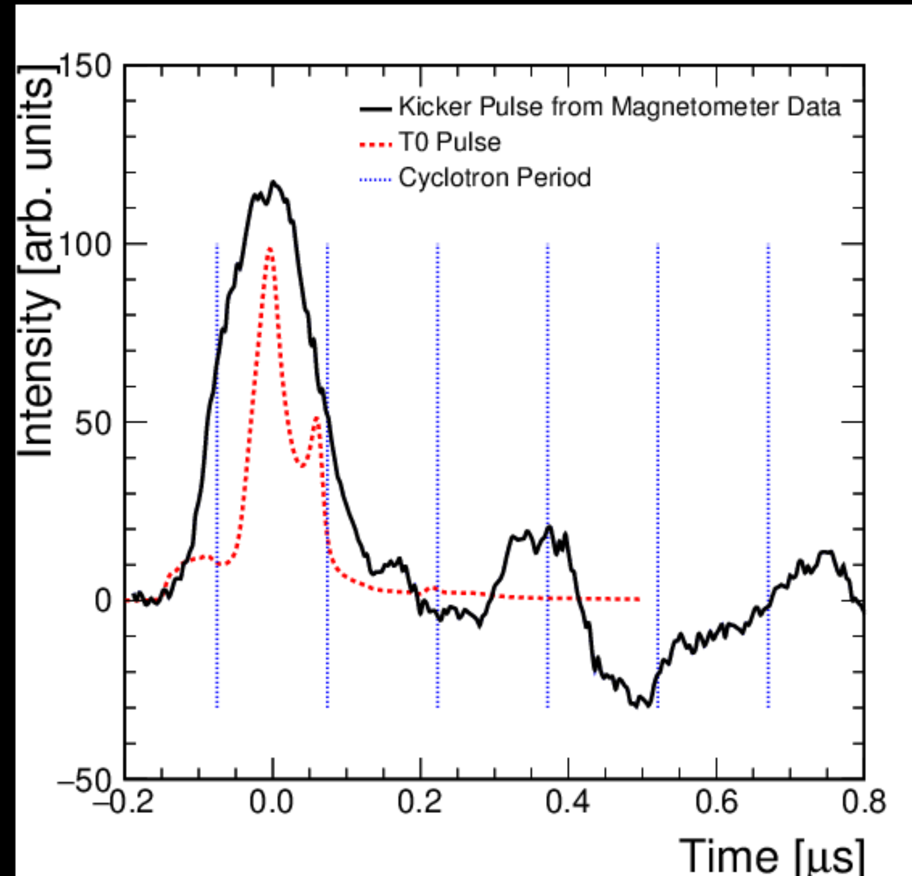


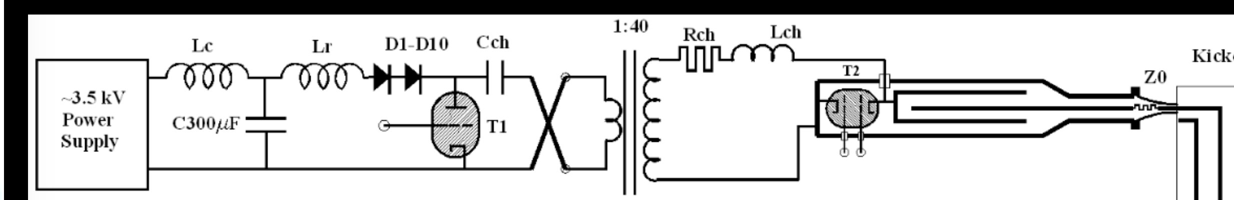
- Interpolated between trolley runs with 378 fixed probes in grooves on outside of vacuum chambers.

Injection: orbit displaced by fast magnetic kicker



d = 77 mm





Blumlein Pulse Forming Network

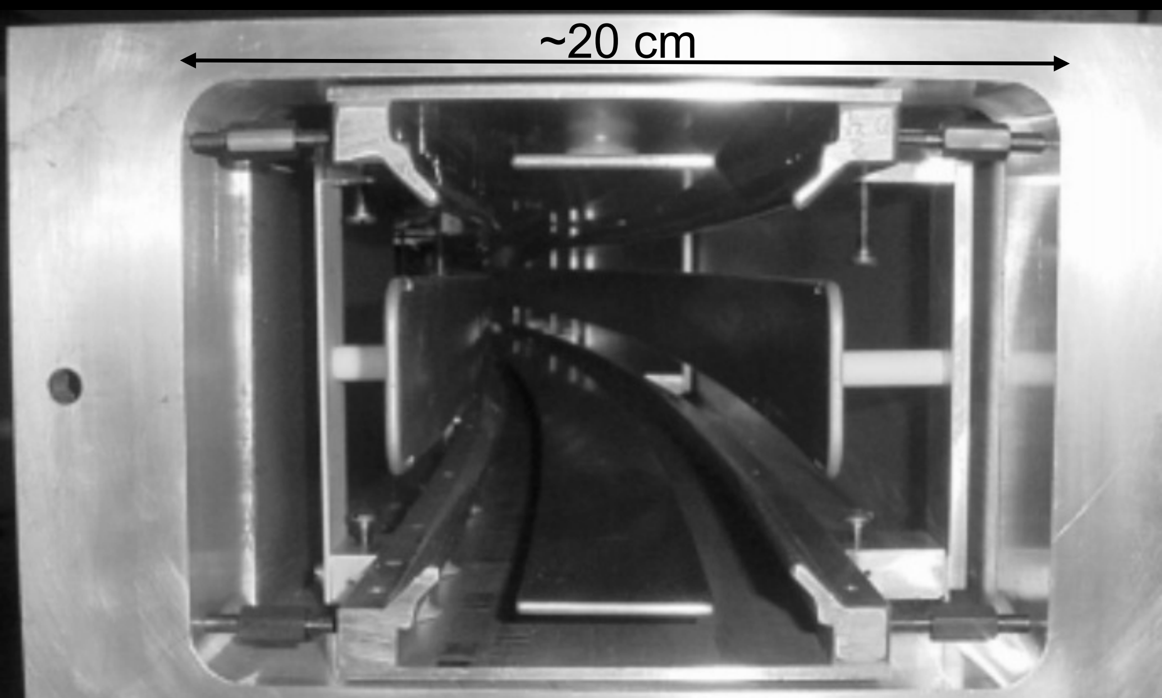
Electrostatic focusing

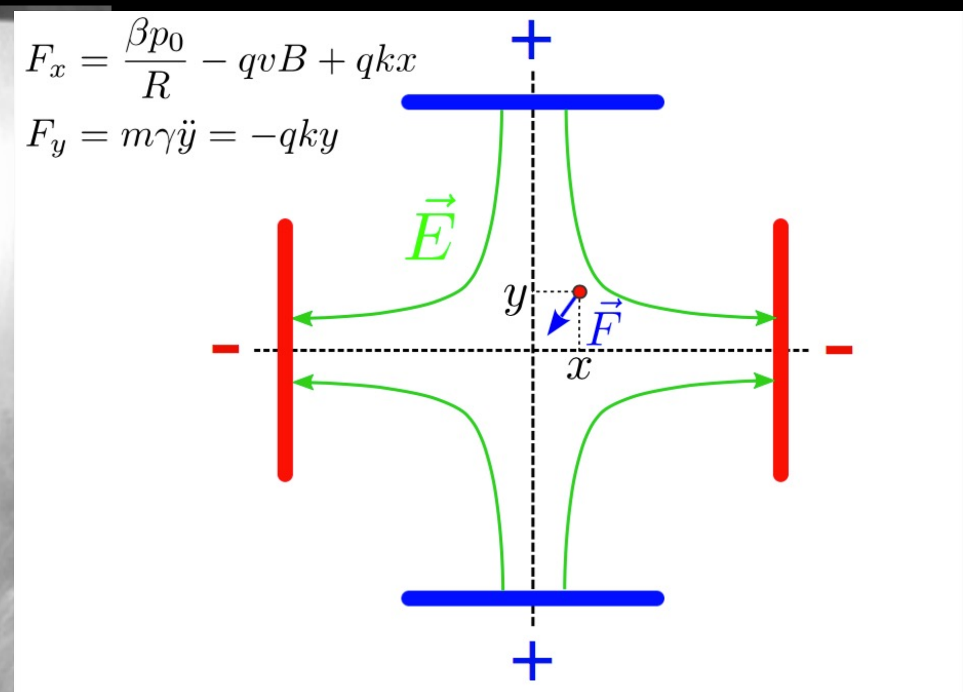
If we recalculate the spin precession rate including the electric field:

(still assuming motion in a horizontal plane with a vertical magnetic field)

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

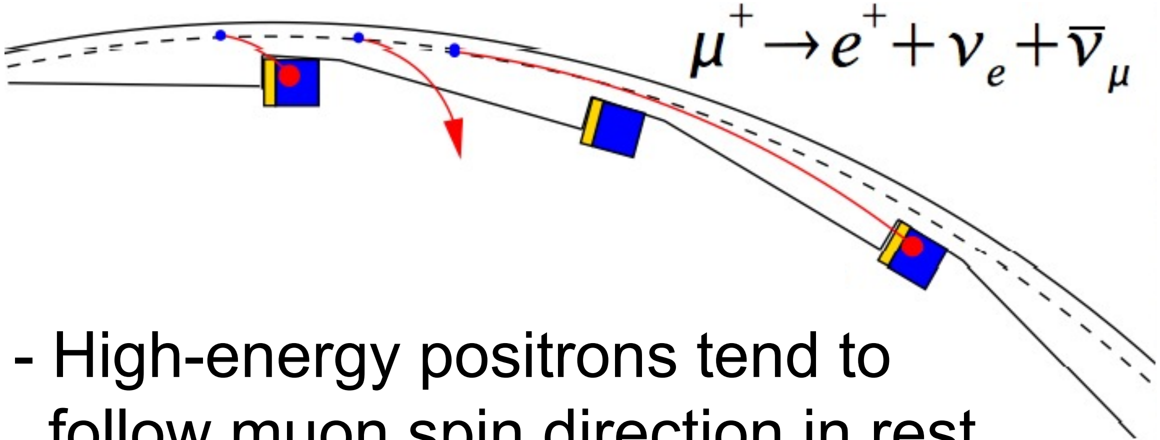
...this part is 0 for $\gamma = 29.3$, $p = 3.09$ GeV/c, $v = 0.9994c$ allowing large E fields at this "magic" γ.





Vertical electrostatic focusing + radial weak focusing

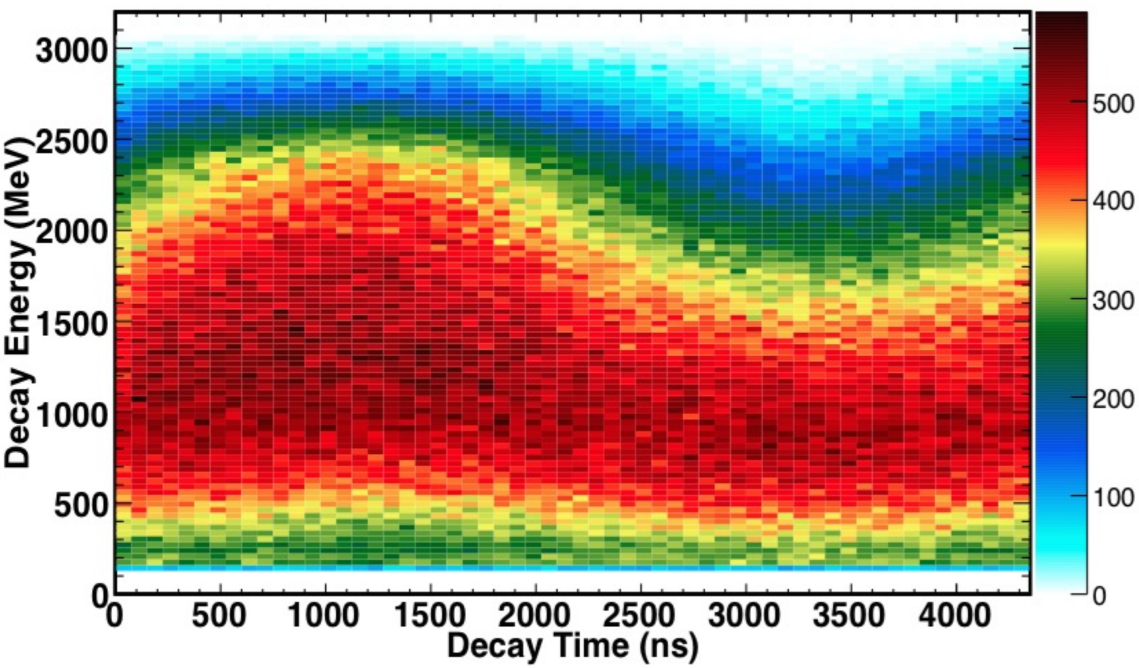
Trolley video from Simon Corrodi, Jimin George, Joe Grange



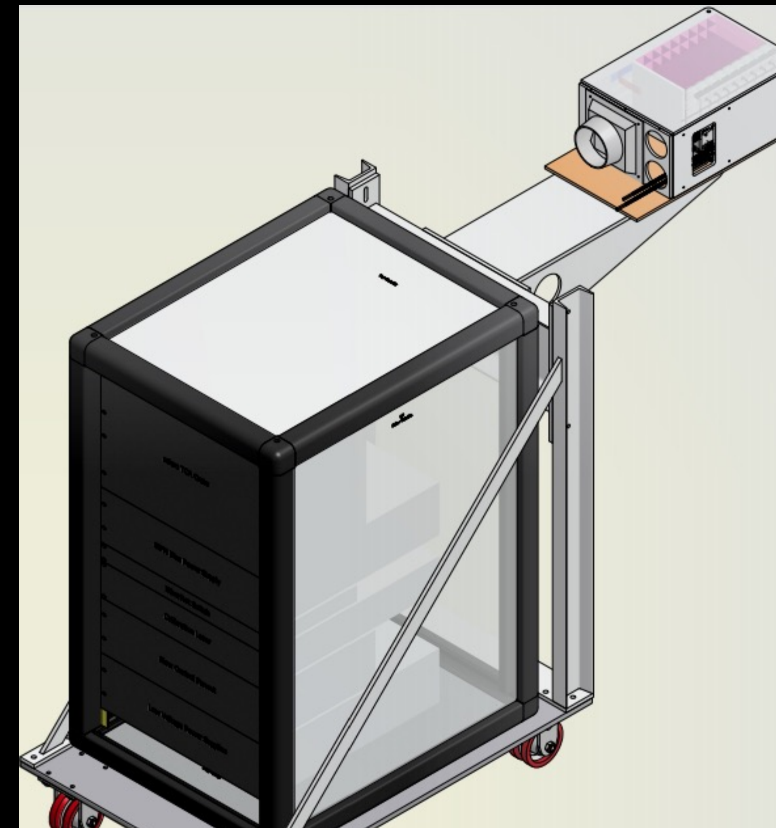
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- High-energy positrons tend to follow muon spin direction in rest frame.

- After boost to lab frame:



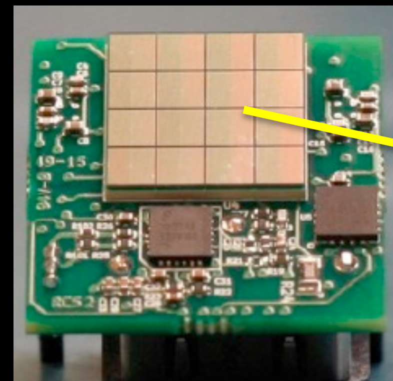
- Modulated at precession frequency ω_a

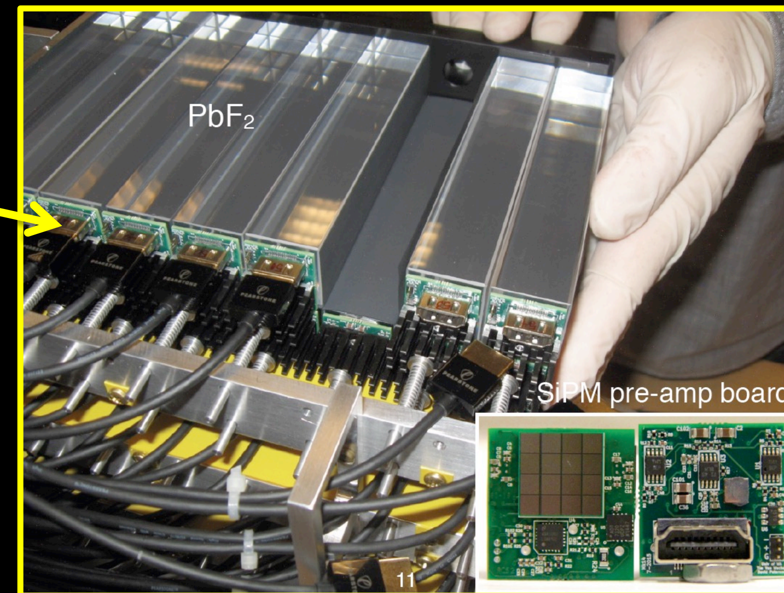


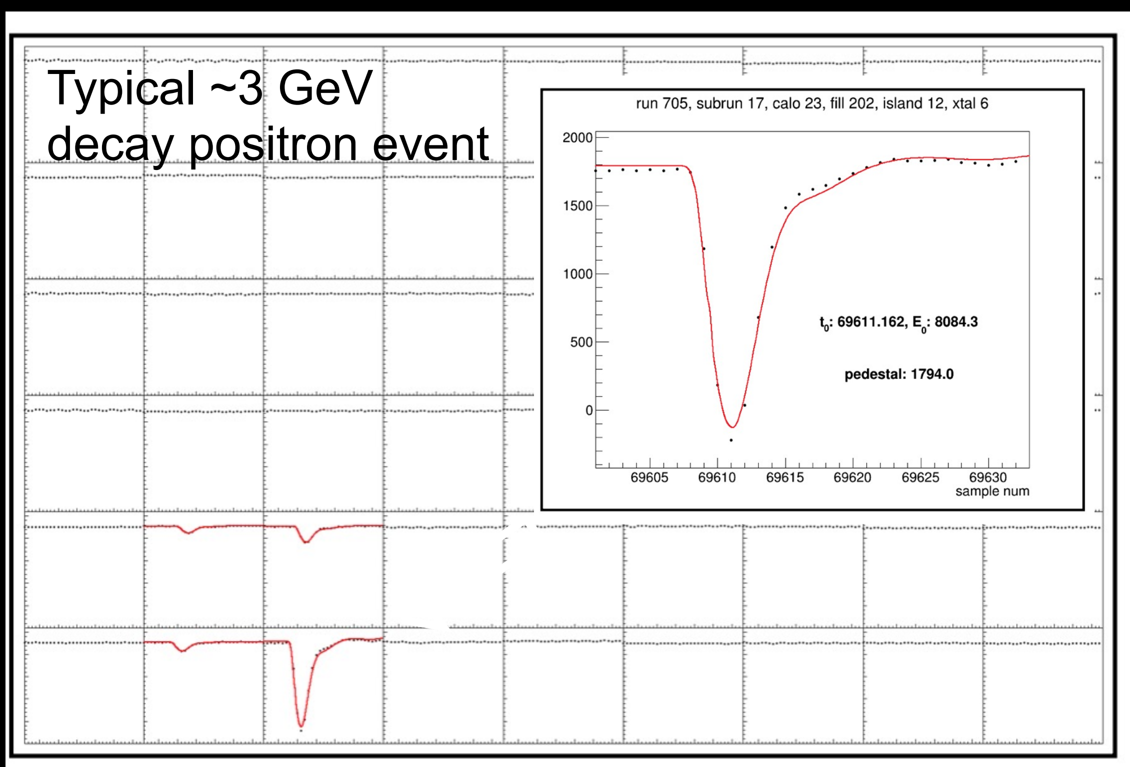
Positrons detected in 24 calorimeters around inner circumference of ring.

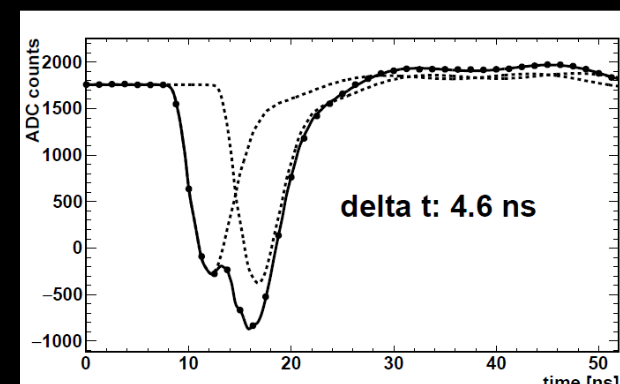
Calorimeters: pulse separation in space and time

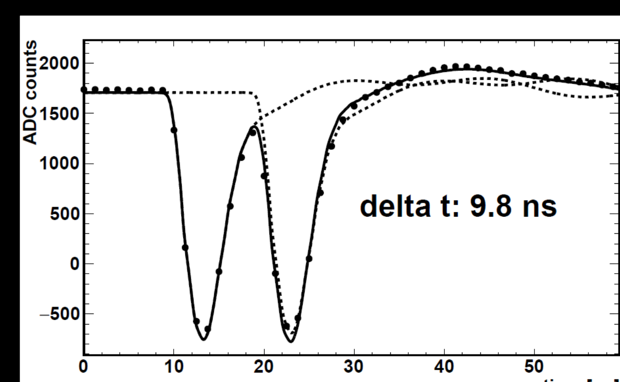
- 24 calorimeters
- Each segmented into 9x6 array of PbF_2 Cerenkov crystals.
- Instrumented with silicon photomultiplier (MPPC) arrays.
- Continuously digitized with 800 MSPS sampling.
- Pulses selected and recorded by algorithms in online GPU (graphics processing unit) cluster.



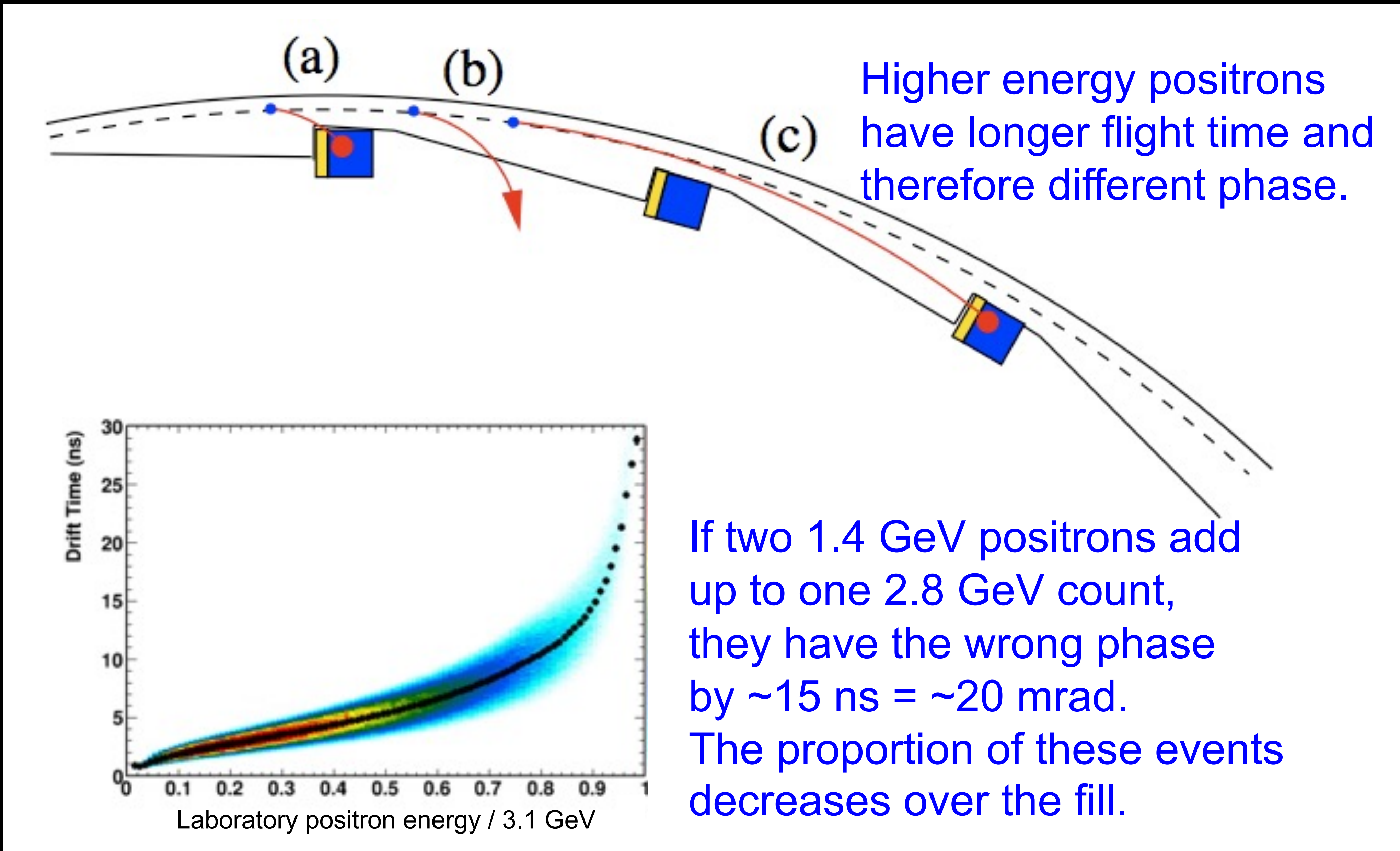






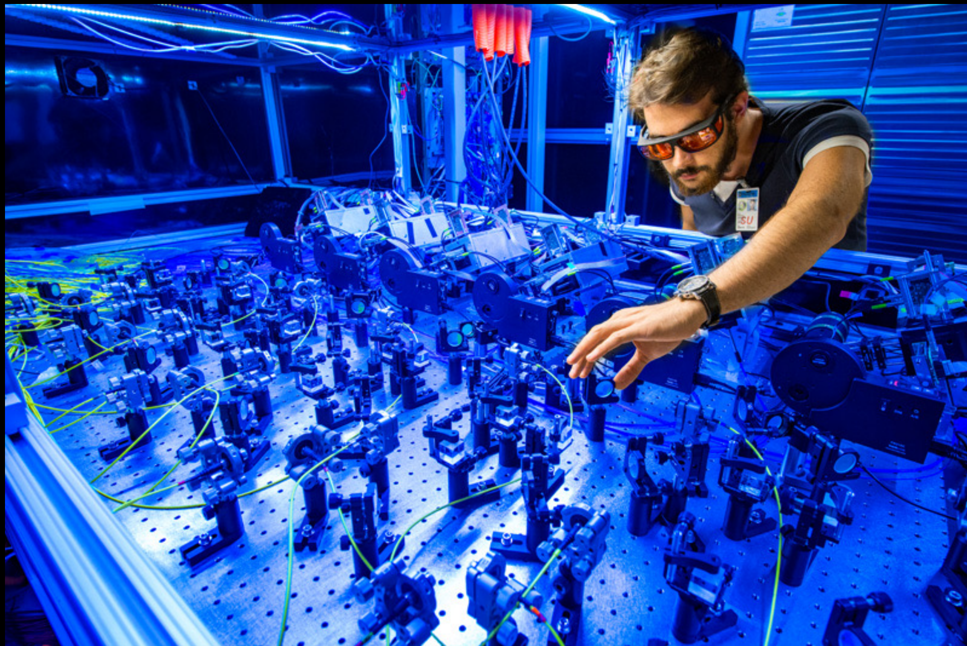


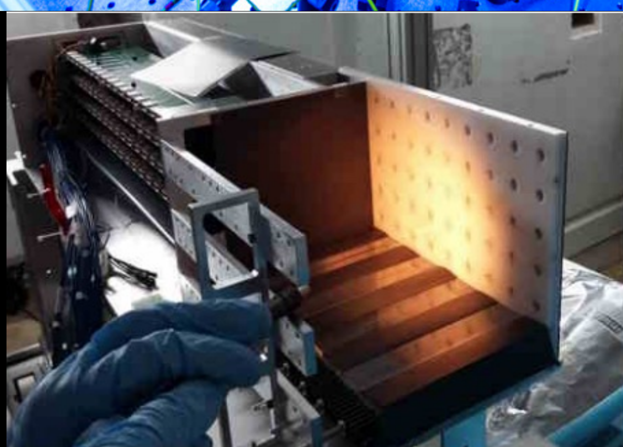
Overlapping pulses ("pileup")

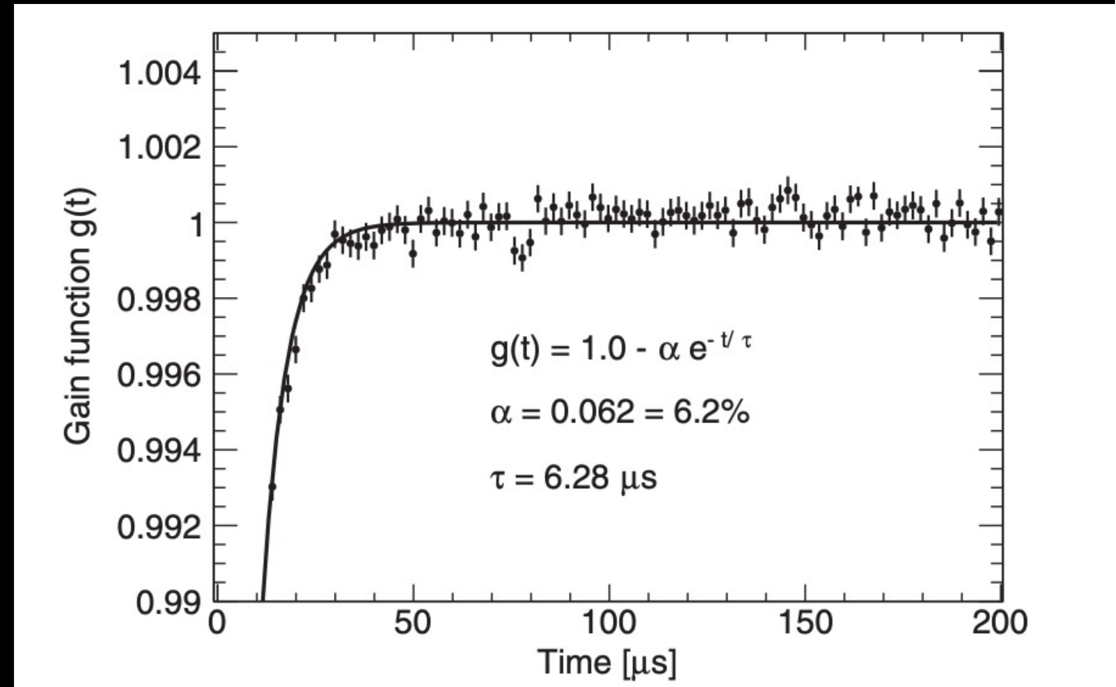


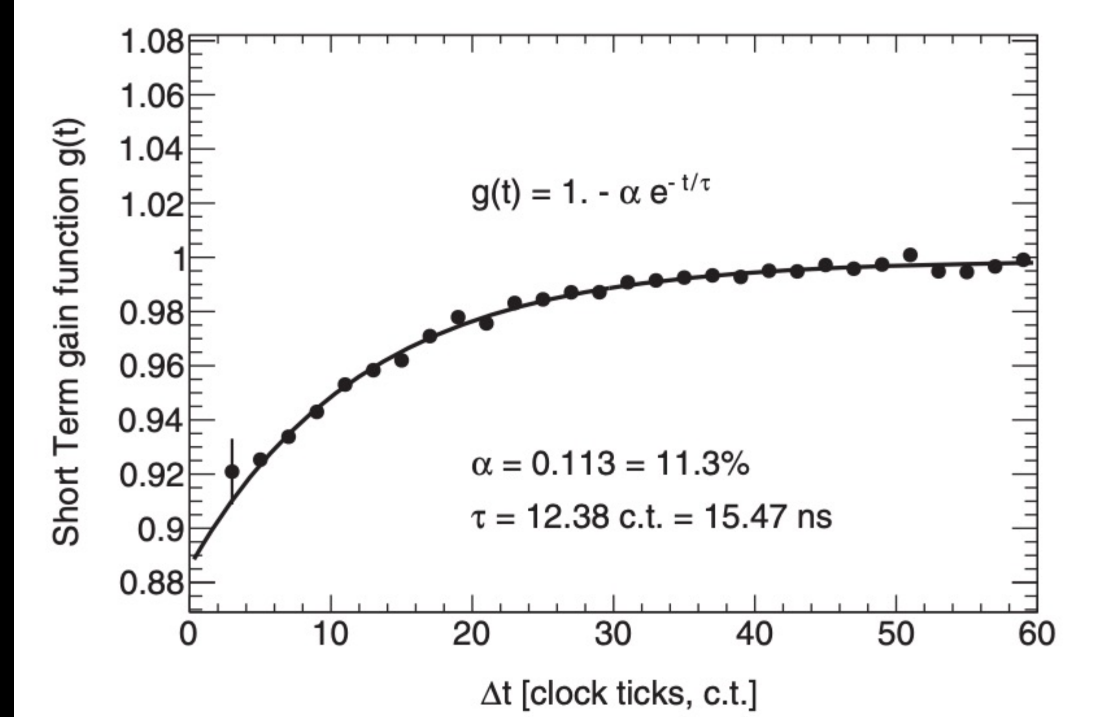
Early-to-late phase shift alters the fitted frequency, so spectrum is corrected for pileup before fitting.

Gain of each crystal corrected with laser pulses

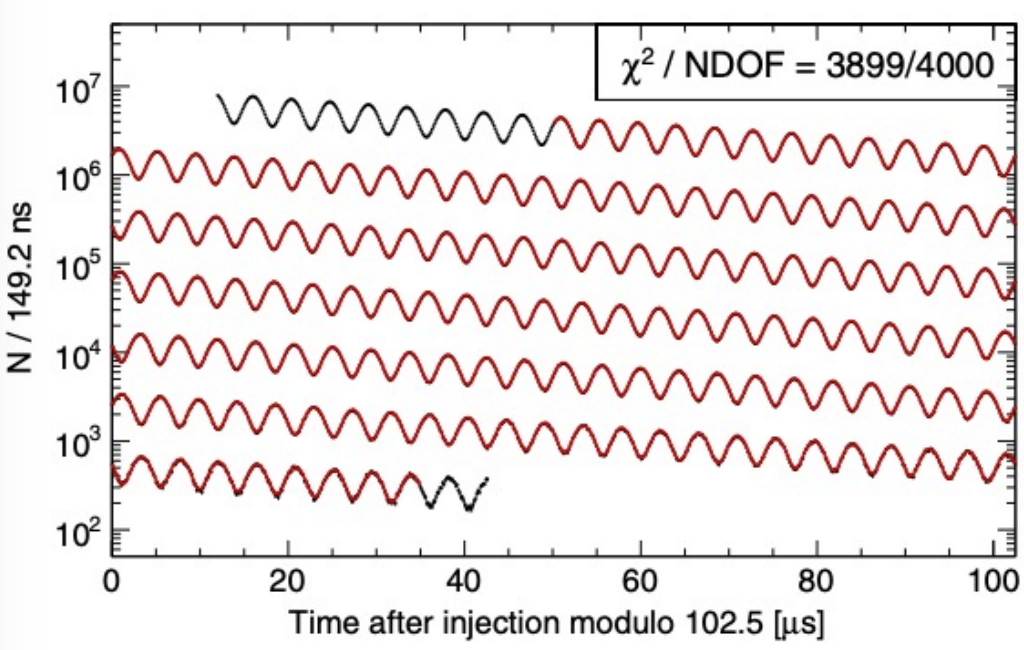




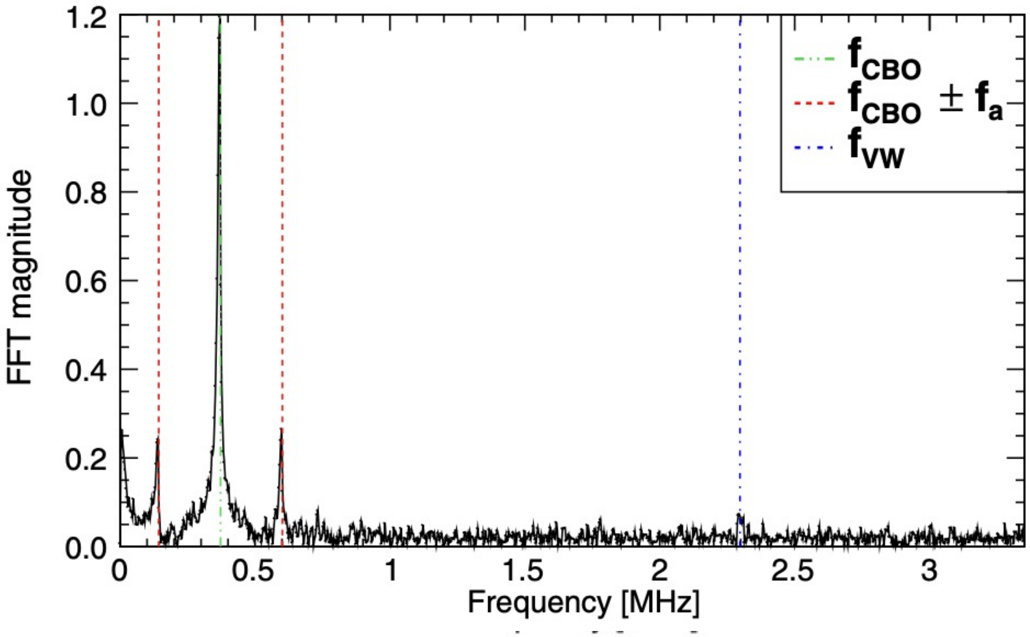




High-energy (> 1.7 GeV) positron times



Fourier transform of residuals after fit

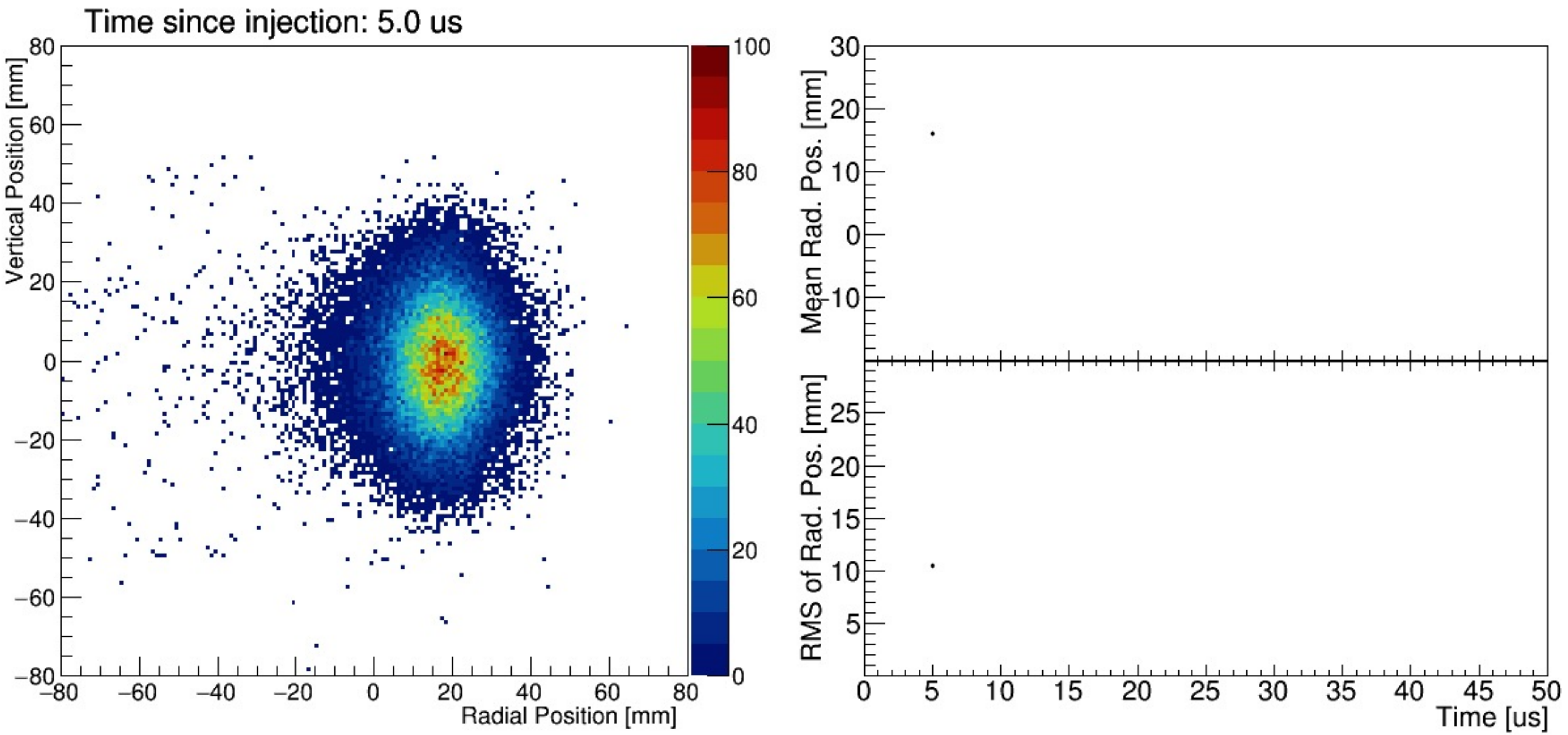


- By eye, seems to fit to a simple five-parameter model

$$N(t) = N_o e^{-t/\gamma\tau}[1 + A\ \cos(\omega_a t + \varphi_o)]$$

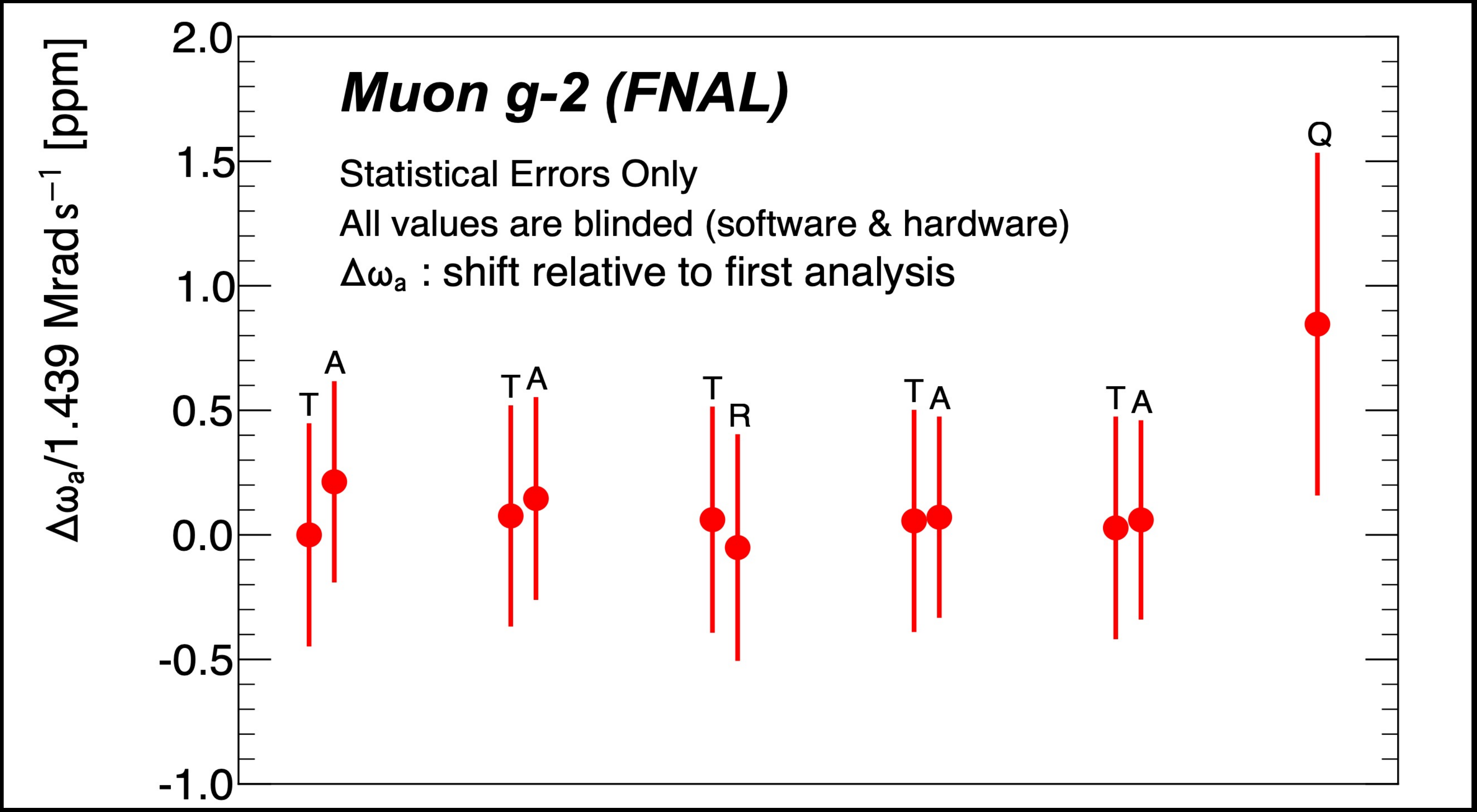
- Requires additional terms for coherent betatron oscillations (CBO) and muon losses to obtain acceptable χ^2/dof.

Coherent betatron oscillations: Electrostatic focusing + less-than-ideal kick in run 1



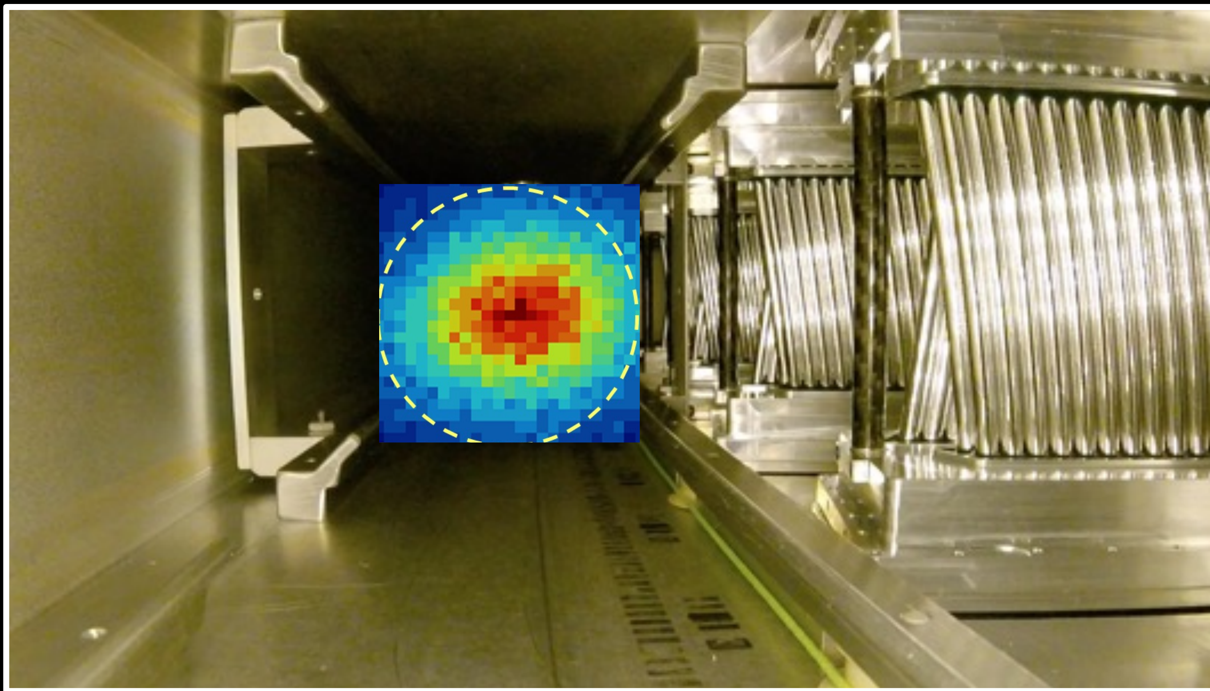
- Beam only fills part of the phase space of storage ring.
- Stroboscopic observation of oscillations at $\omega_{CBO} = \omega_x - \omega_c$
- Kicker voltage increased in more recent datasets to properly center beam.

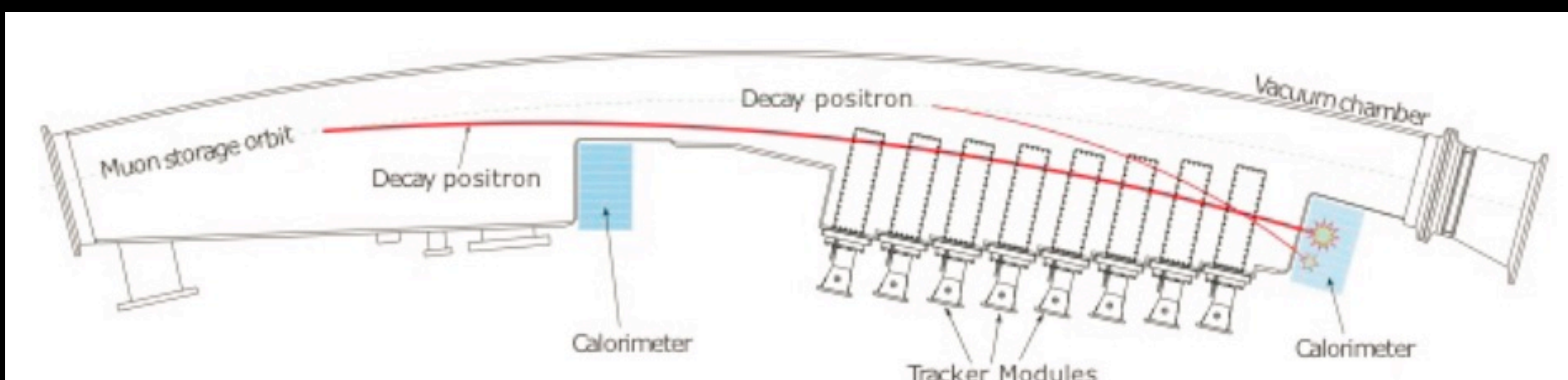
Independent analyses with different methods agreed



- T method: accept pulses with energy > 1.7 GeV
- A method: weight pulses by asymmetry *A(E)*
- R method: cancel out slow variations with ratio technique
- Q method: total energy vs. time

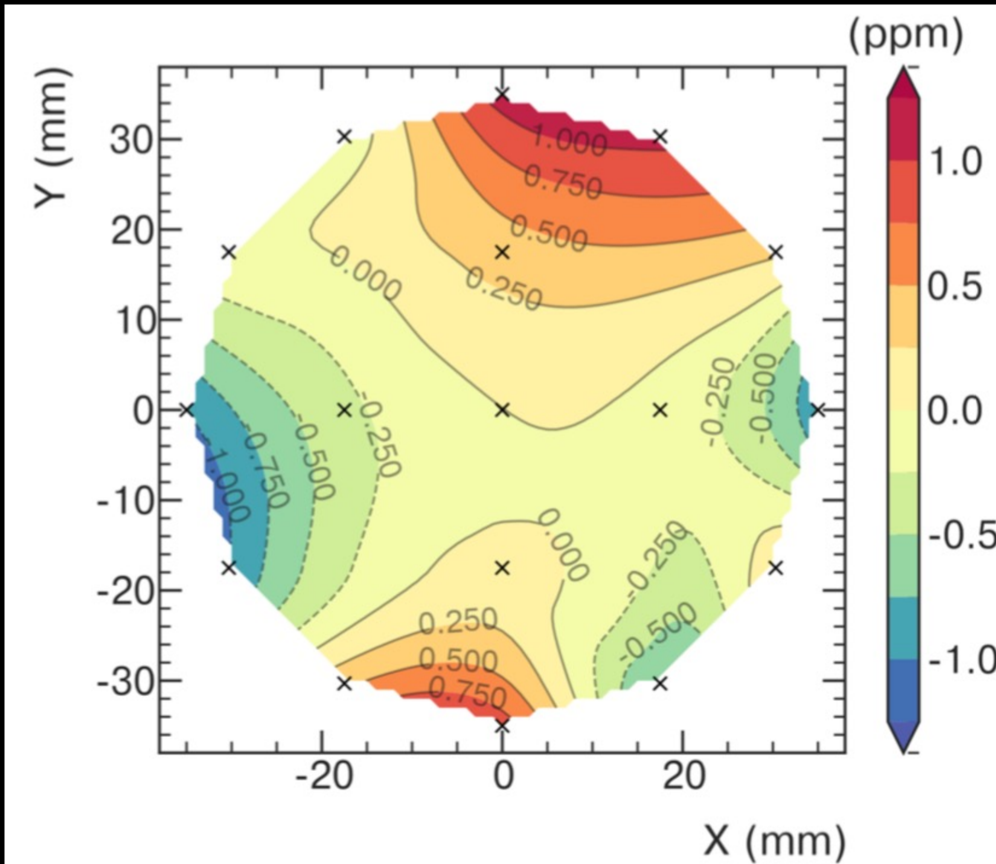
Visualization was based on data from straw trackers

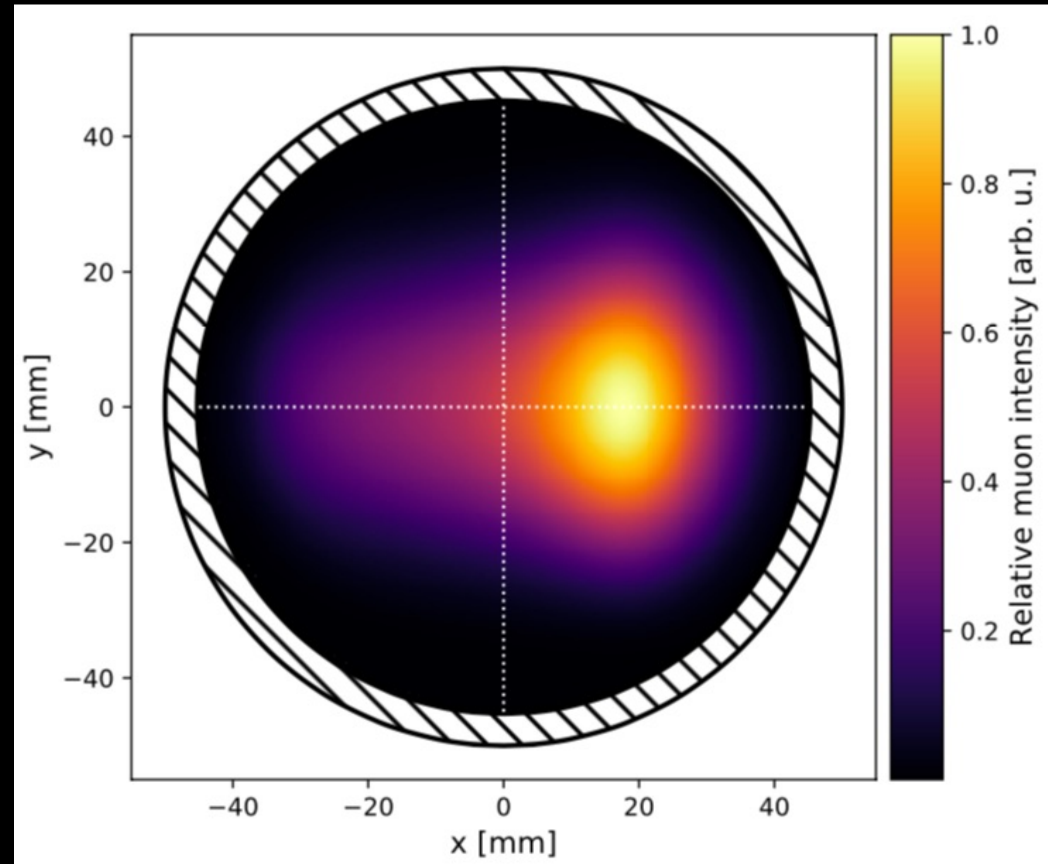




- At two locations in ring (180^o and 270^o from injection point)
- Used to determine muon distribution for weighting with magnetic field

Magnetic field weighted by muon distribution





$$\frac{\omega_a}{\tilde{\omega}_p} = \left(\frac{f_{clock}\,\omega_a\,(1 + C_e + C_p + C_{ml} + C_{pa})}{(1 + B_{QT} + B_{Eddy})\; f_{field}\,\omega_p \otimes \rho(\mathbf{r})} \right)$$

E-field & pitch corrections ($C_e + C_p$)

Muon loss & phase acceptance corrections ($C_{ml} + C_{pa}$)

Field transients ($B_{QT} + B_{Eddy}$)

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} \right]$$

Pitch correction (the $a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta}$ term)

Electric field correction (the $\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}$ term)

- Systematic errors associated with every term have been studied in considerable detail.

Systematic errors

TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ correction terms in Eq. (4), and uncertainties due to the constants in Eq. (2) for a_μ. Positive C_i increase a_μ and positive B_i decrease a_μ.

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	⋯	434
ω_a^m (systematic)	⋯	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	⋯	56
B_k	−27	37
B_q	−17	92
$\mu'_p(34.7°)/\mu_e$	⋯	10
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic	⋯	157
Total fundamental factors	⋯	25
Totals	544	462

Muon spin precession frequency

Beam dynamics corrections

Magnetic field experienced by muon distribution

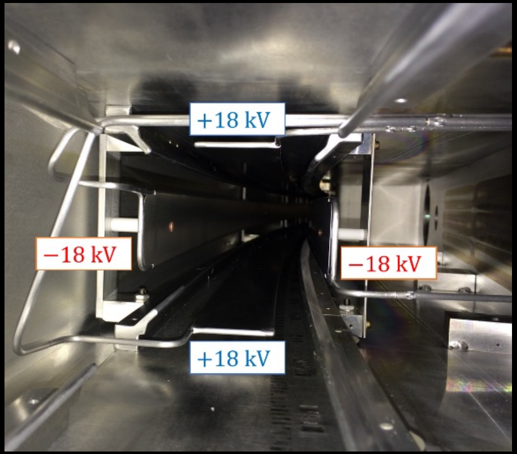
External constants

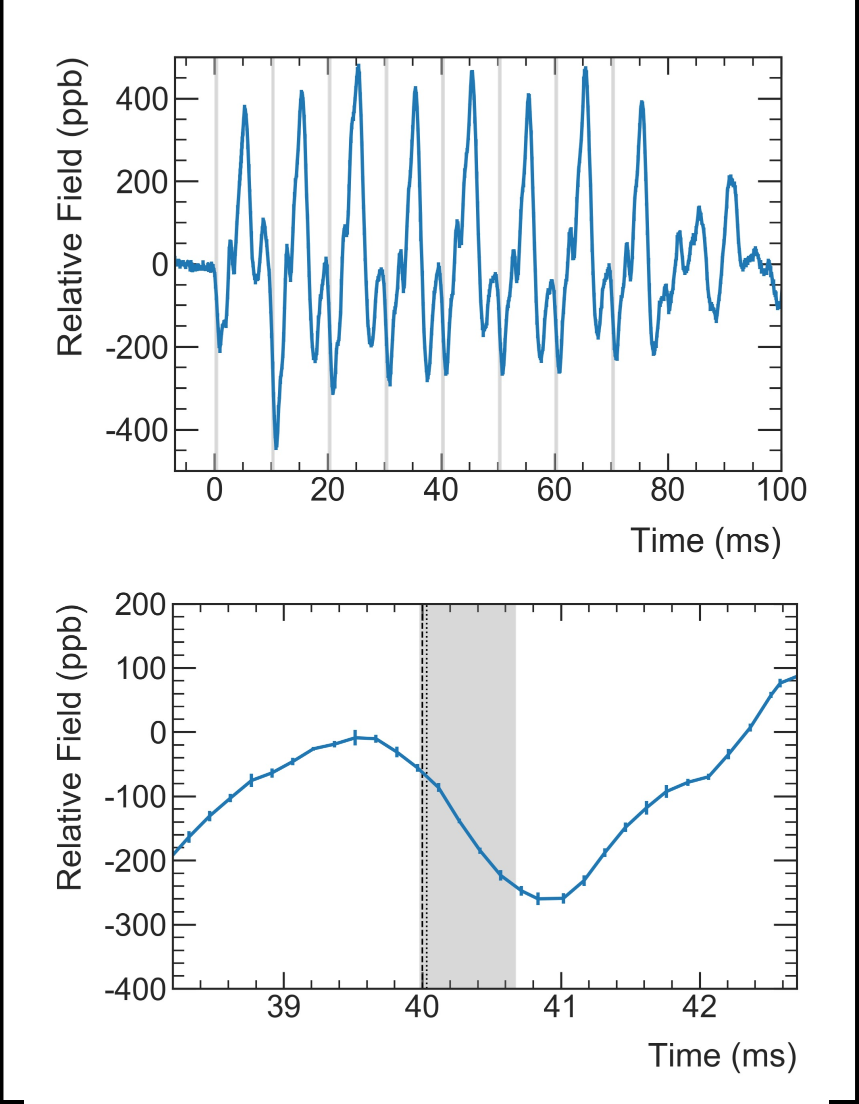
Goal for final result: statistical and systematic uncertainties each < 100 ppb

B. Abi et al., *Phys. Rev. Lett.* 126, 141801 (2021)

B_Q: Quadrupole transient field

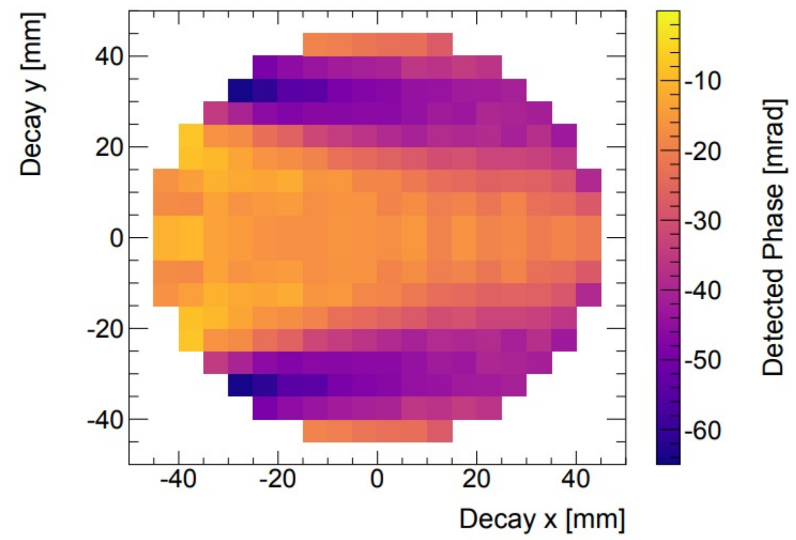
- Mechanical vibrations from pulsing electric quadrupoles induce a magnetic field
- Beam structure (10 ms between pulses) near ~100 Hz mechanical resonance
- -17 ppb correction, 92 ppb uncertainty because azimuthal map is not yet complete.
- Should be reduced by a factor of 2 to 3 for future runs.

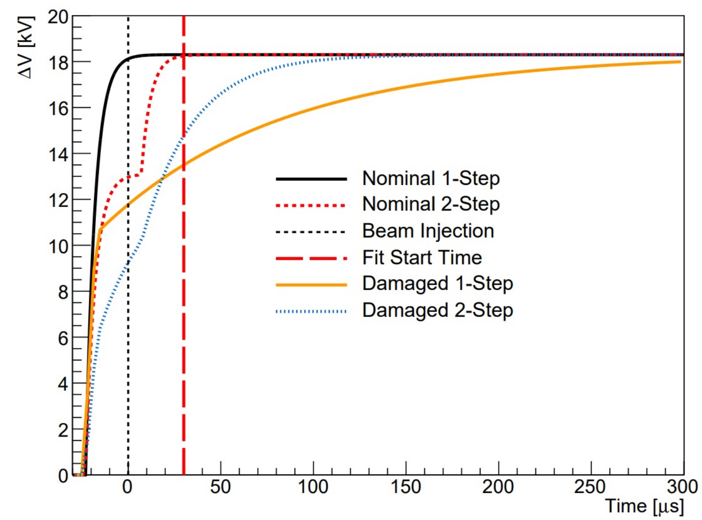


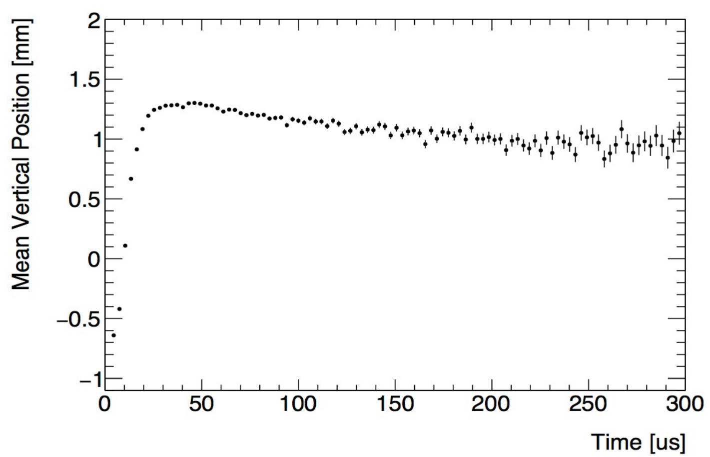


C_{PA}: Phase-acceptance correction

- Precession phase depends on muon decay position (*x,y*) as well as positron energy.
- Two quadrupole charging resistors were damaged, causing vertical drift of beam during measuring time.
- Correction of -158 ppb with a 75 ppb uncertainty for run 1.
- Resistors replaced for later runs.







USA

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

USA National Labs

- Argonne
- Brookhaven
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- Shanghai Jiao Tong

Germany

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Russia

- Budker/Novosibirsk
- JINR Dubna

United Kingdom

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

7 countries
35 institutions
190 collaborators

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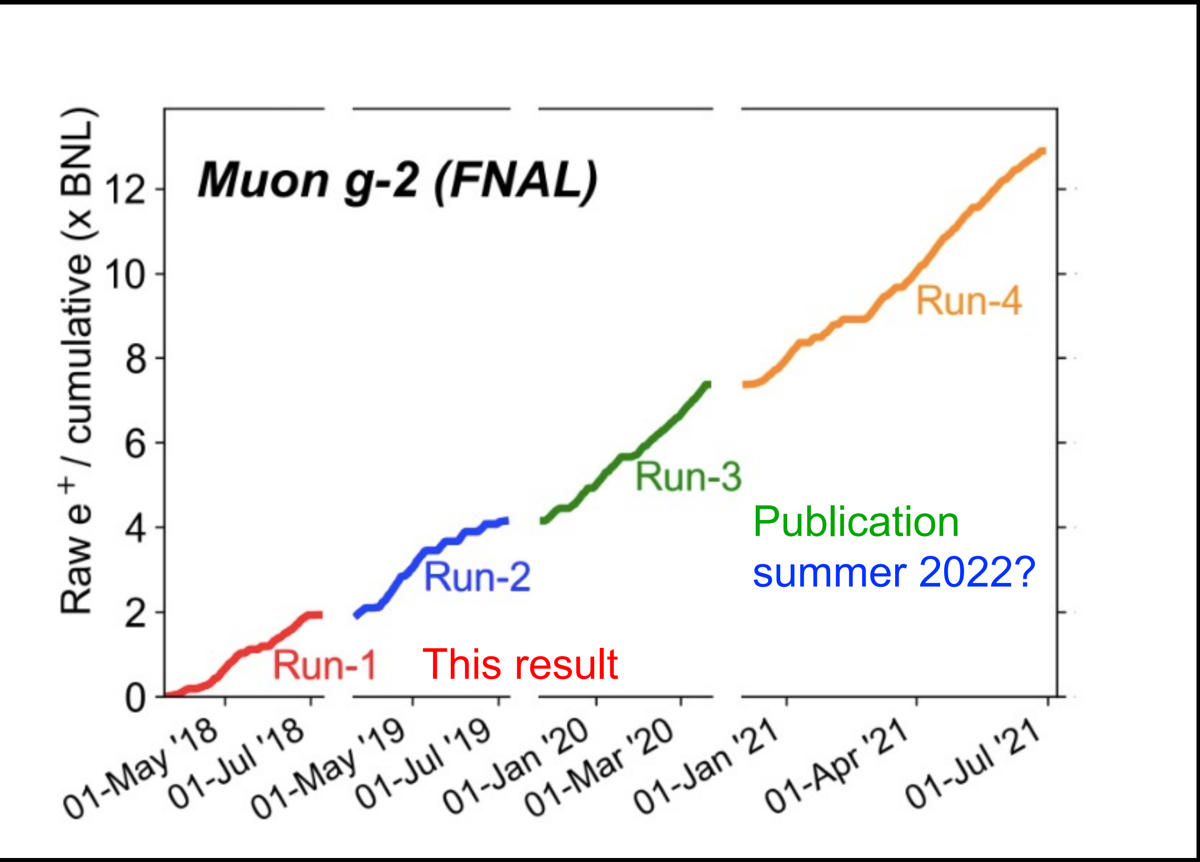
Future Outlook



Run 1 is only ~6% of final dataset! (Plan for 21xBNL.)

Eventual goal of 140 ppb precision (100 ppb statistics, 100 ppb systematics)

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