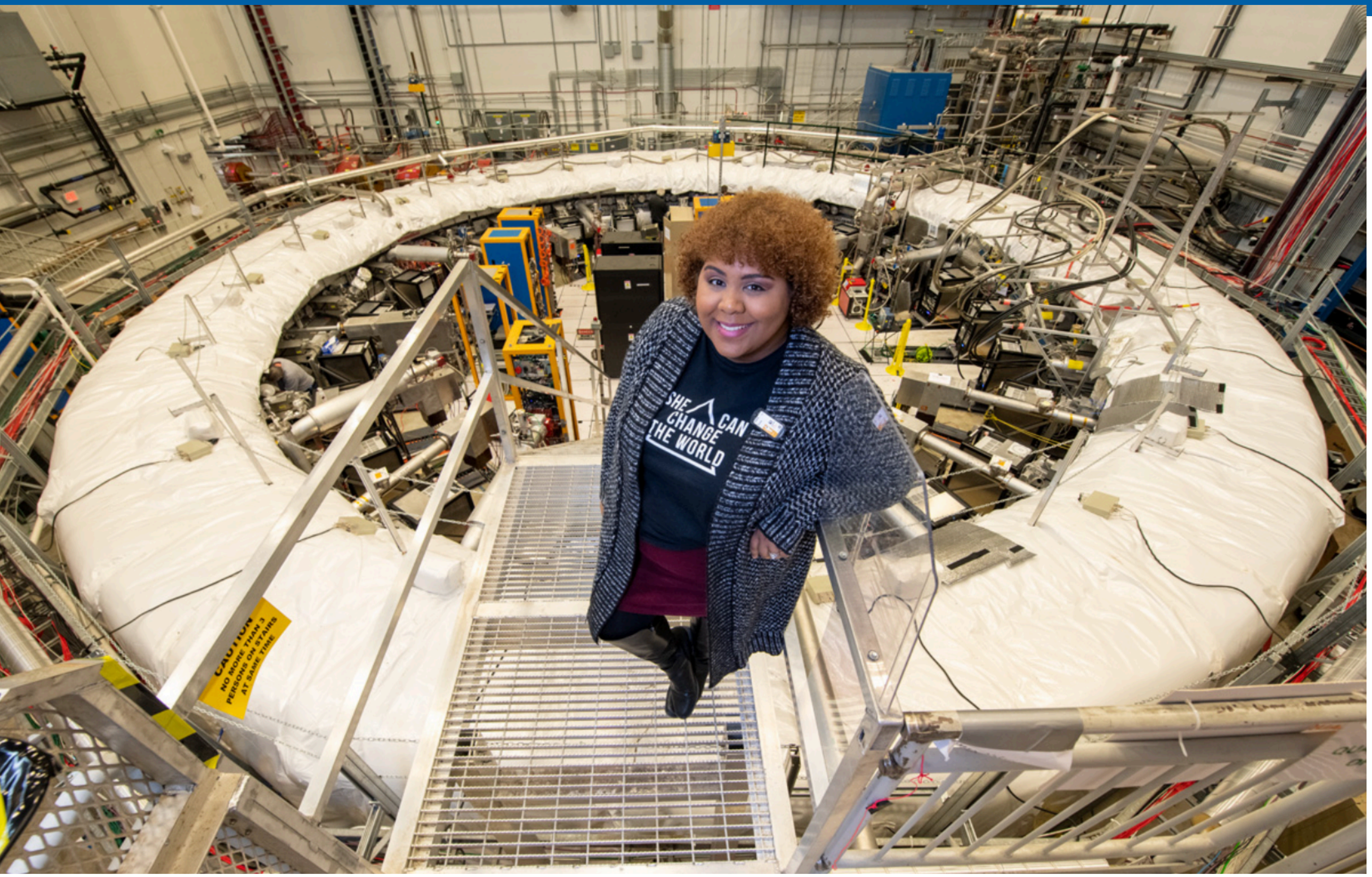
Fermilab U.S. DEPARTMENT OF ENERGY Office of Science



Muon Physics at Fermilab

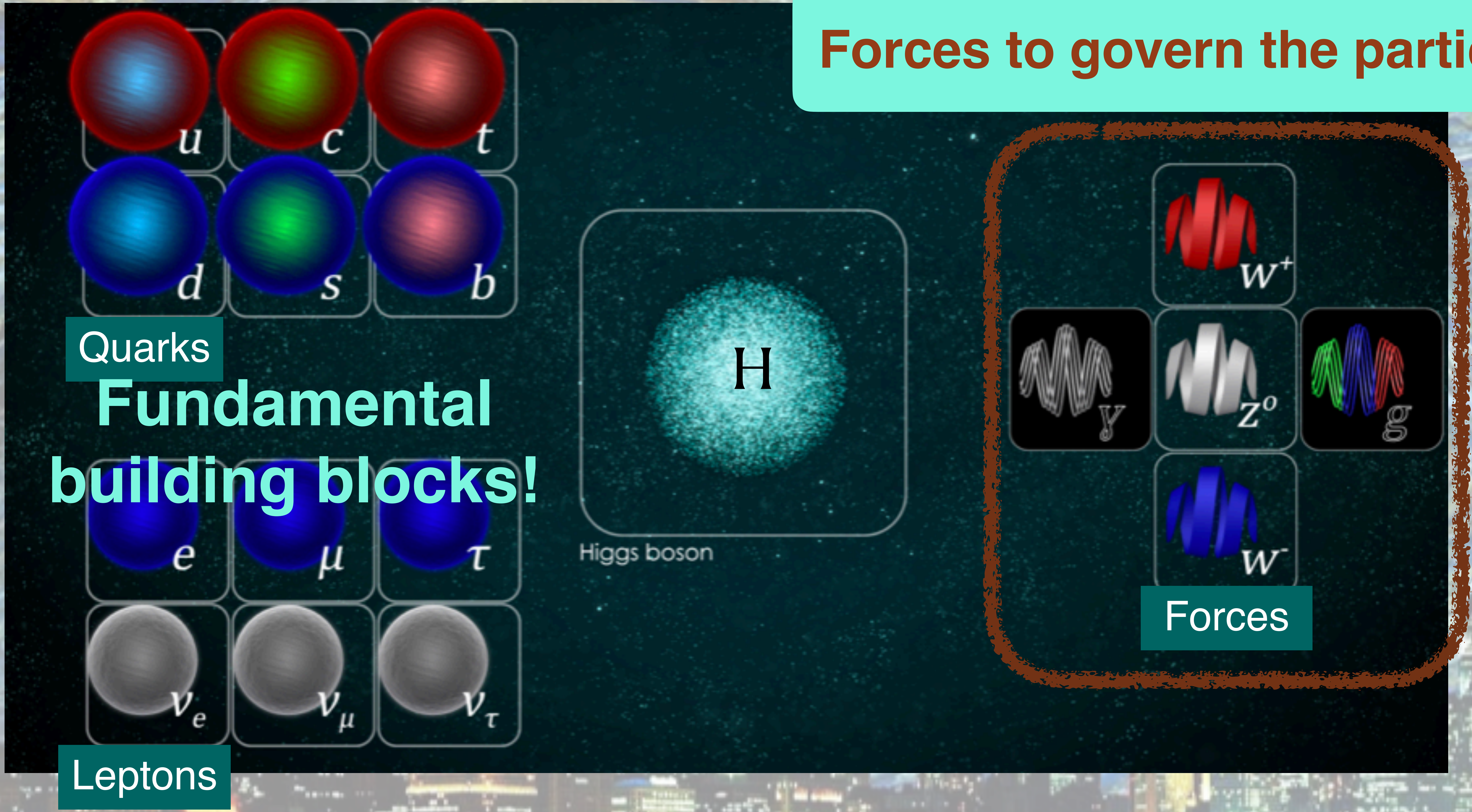
Sudeshna Ganguly

Fermilab Undergraduate Lecture Series

16 June, 2020

Standard Model of Particle Physics (SM)

Forces to govern the particles!



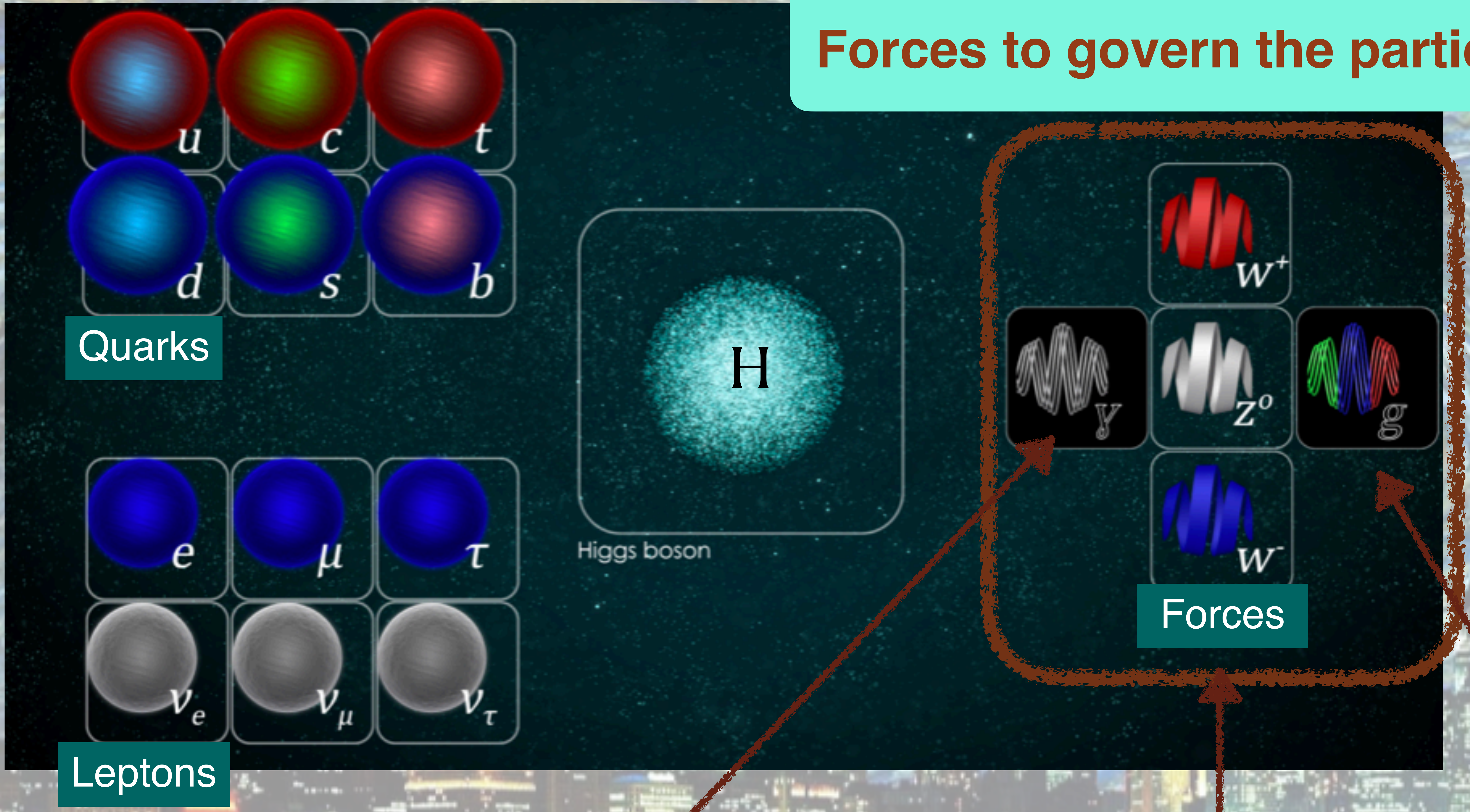
Fundamental building blocks!

Does the Standard Model grasp the whole picture?

Are there puzzle pieces to Universe that Standard Model does not quite place?

Standard Model of Particle Physics (SM)

Forces to govern the particles!

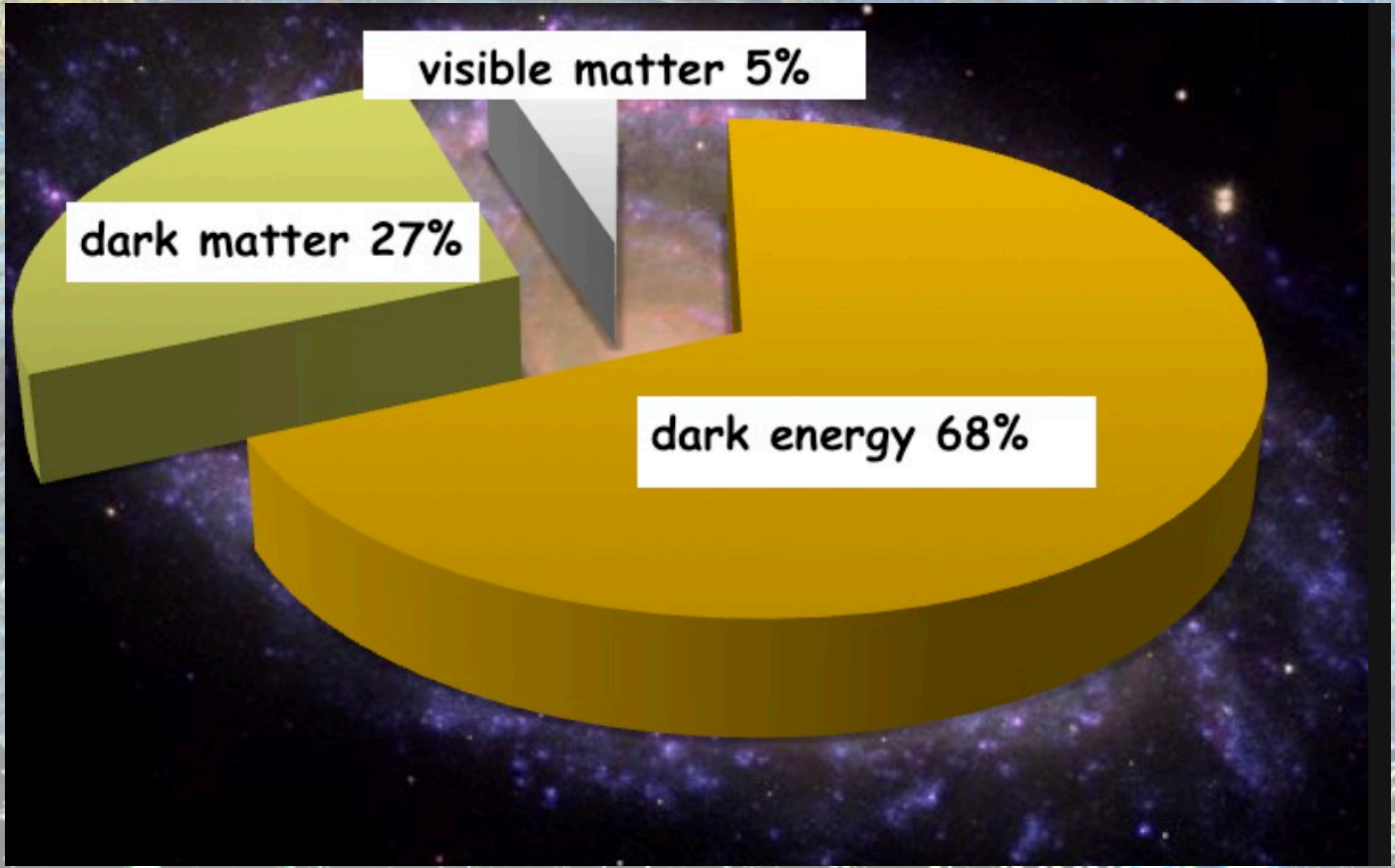


Electromagnetic

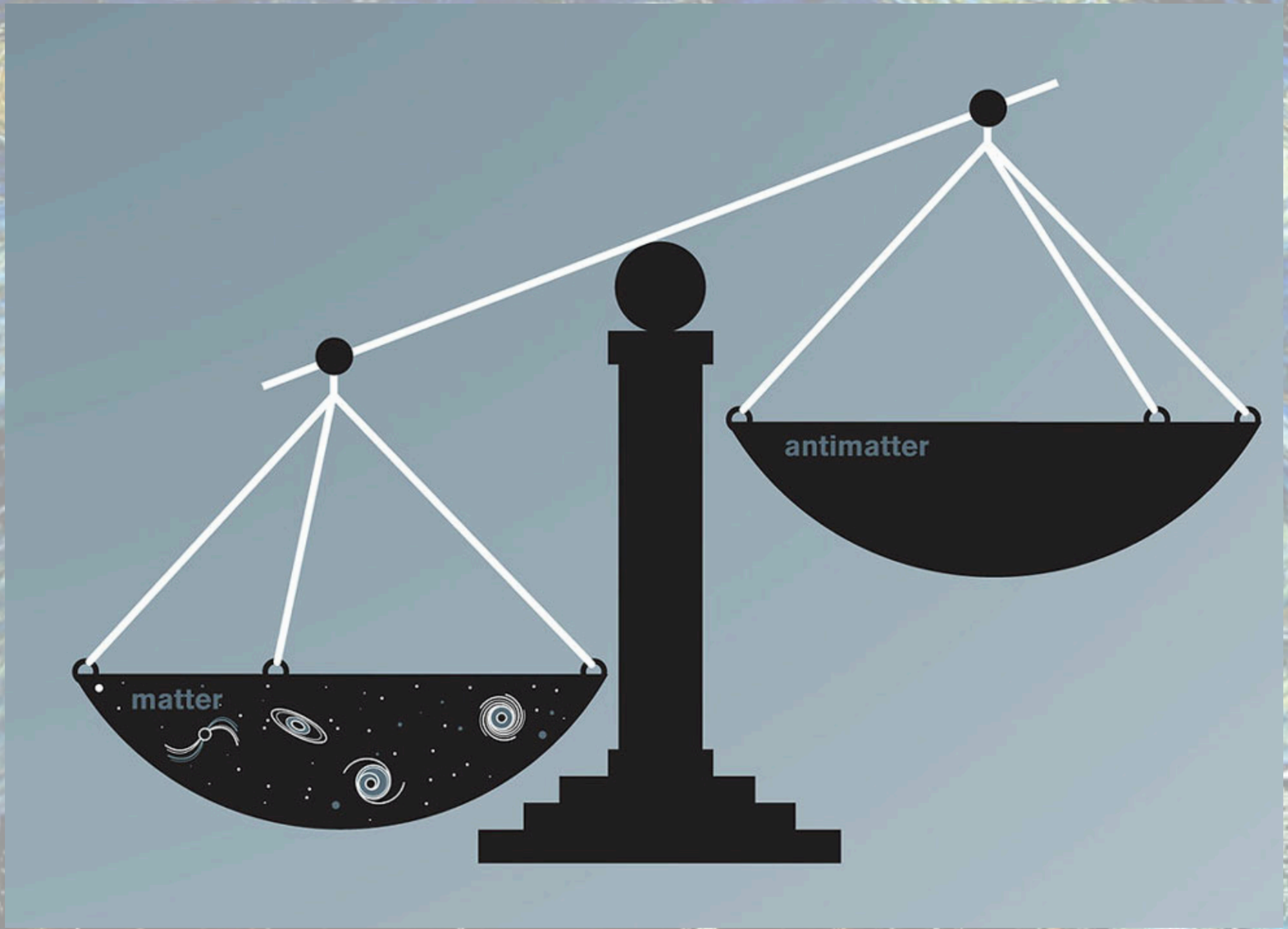
Weak

Strong

Gravity is the most familiar force in our lives, but it is not part of the Standard Model!



Normal matter consists of atoms that make up stars, planets, human beings and every other visible object in the Universe but normal matter is only a tiny part of the universe!



Big Bang should have created equal amounts of matter & anti-matter at the early universe.

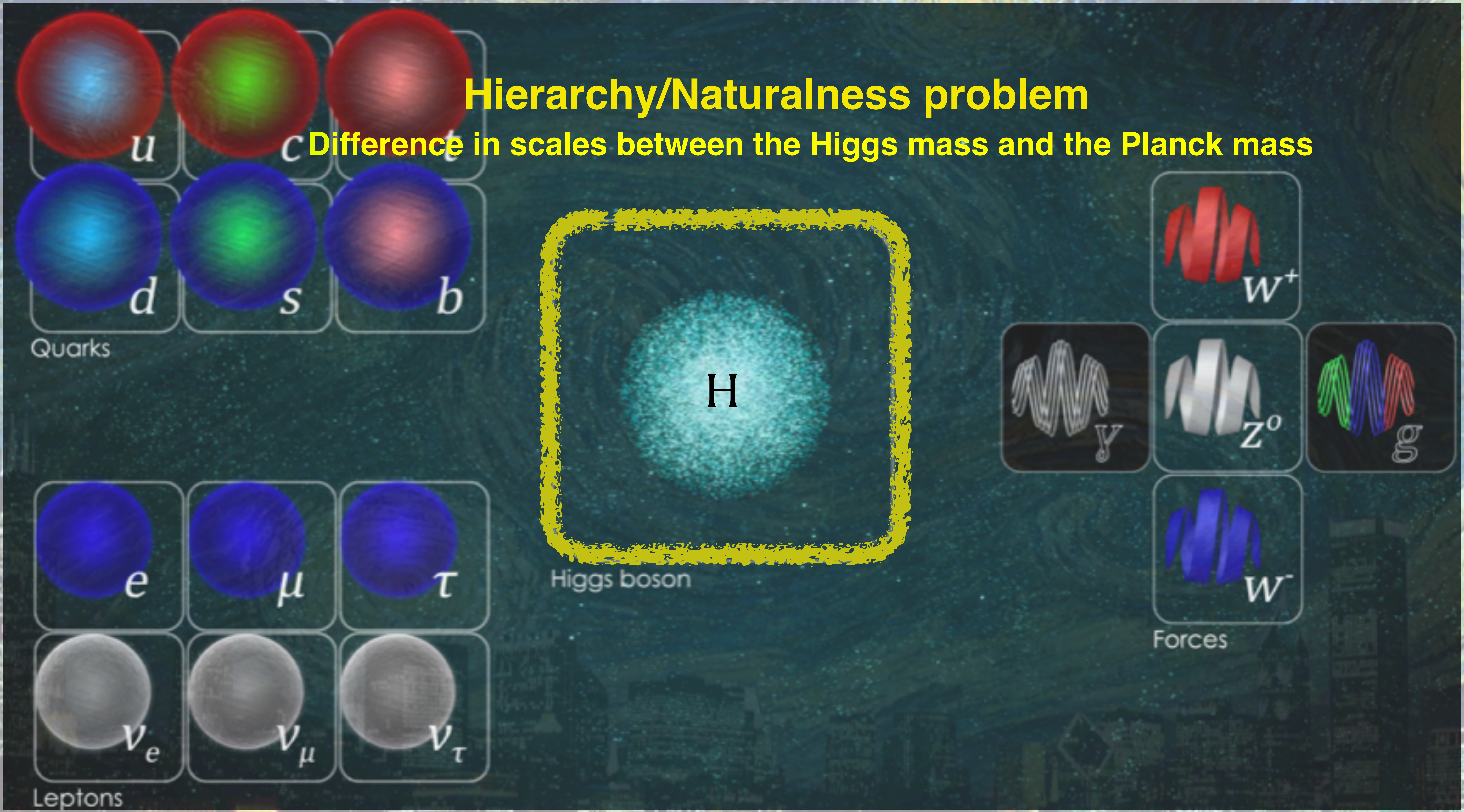
What happened to the anti-matter?

Discovery of Neutrino mass → Physics beyond Standard Model

Are neutrinos their own antiparticle?

Hierarchy/Naturalness problem

Difference in scales between the Higgs mass and the Planck mass



$M_{Higgs} \sim 125$ GeV <<< $M_{Planck} \sim 10^{19}$ GeV

Characterizes gravity

To answer the questions of missing mass/energy/antimatter

High energy

- Collide particles at high energies to try and make new ones

High Intensity

- Highly accurate/sensitive tests of SM
- Look for significant deviation
- Search for forbidden processes using high intensity muon beam

New Physics!!!

To answer the questions of missing mass/energy/antimatter

High energy

- Collide particles at high energies to try and make new ones

Muons are good candidates!

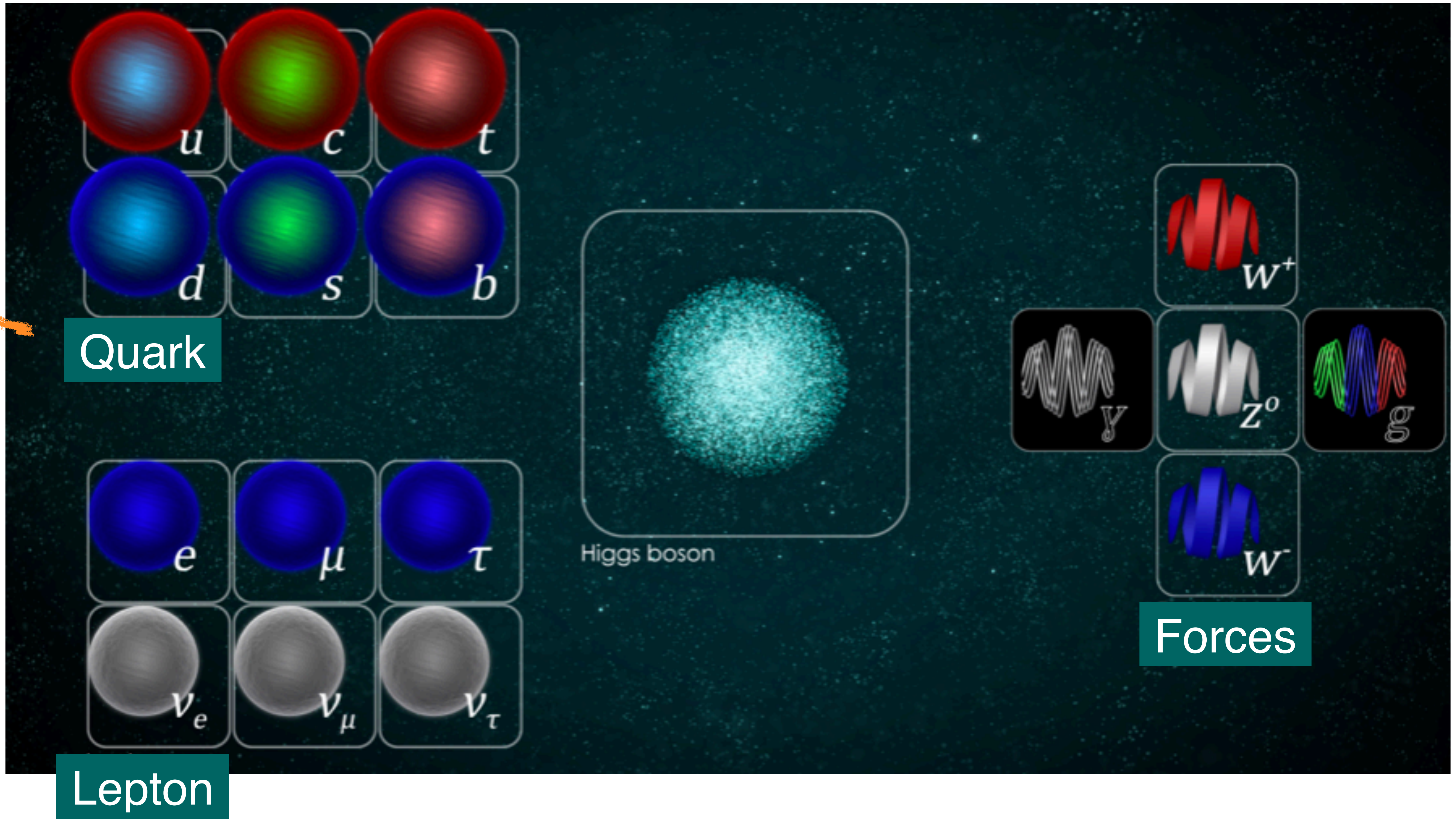
High Intensity

- Highly accurate/sensitive tests of SM
- Look for significant deviation
- Search for forbidden processes using high intensity muon beam

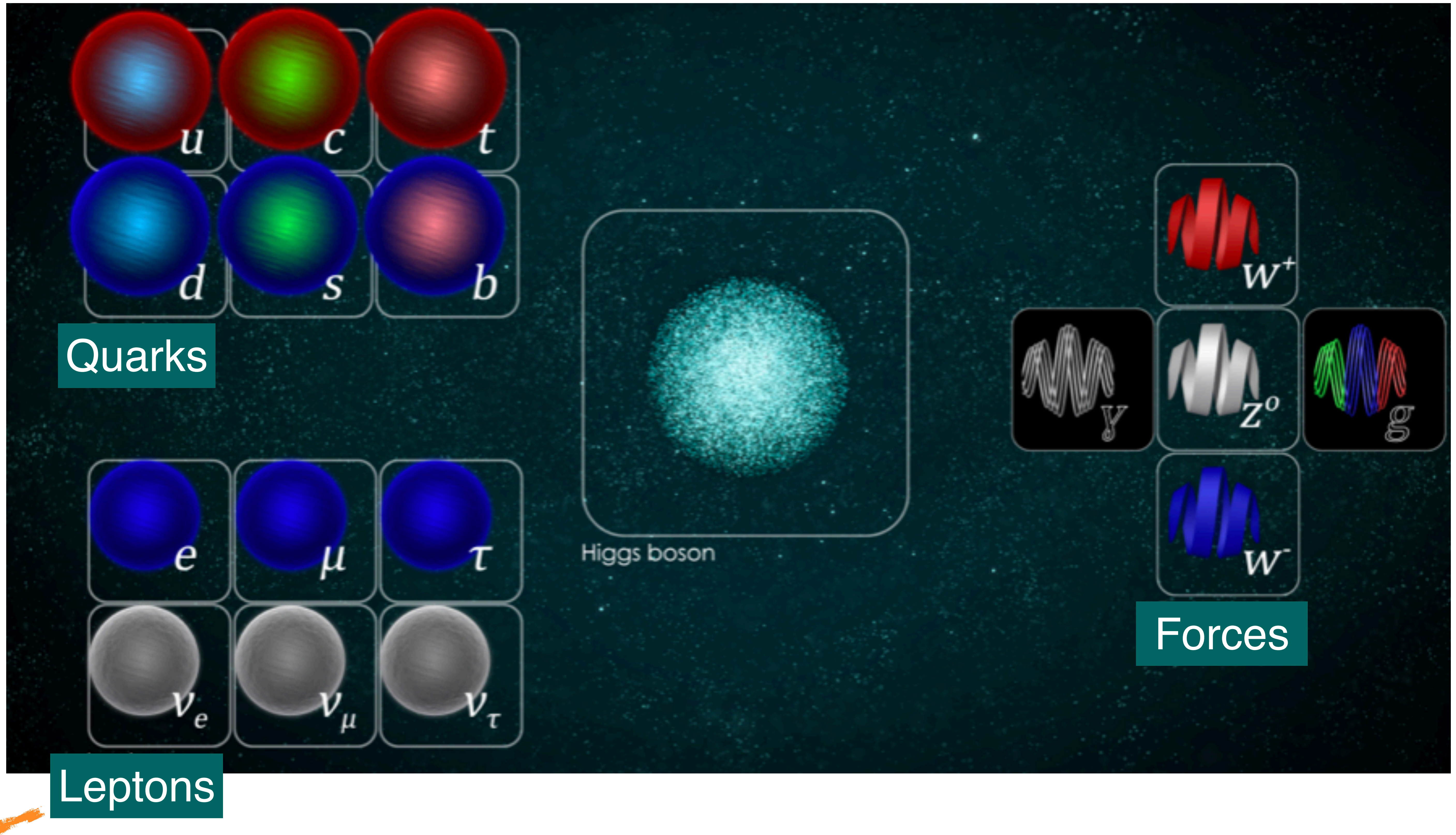
New Physics!!!

Why Muons? Why Not Other Particles?

- Quarks interact with gluons directly
- Gluons strongly interact with each other
- Very complicated to study physical processes involving quarks!

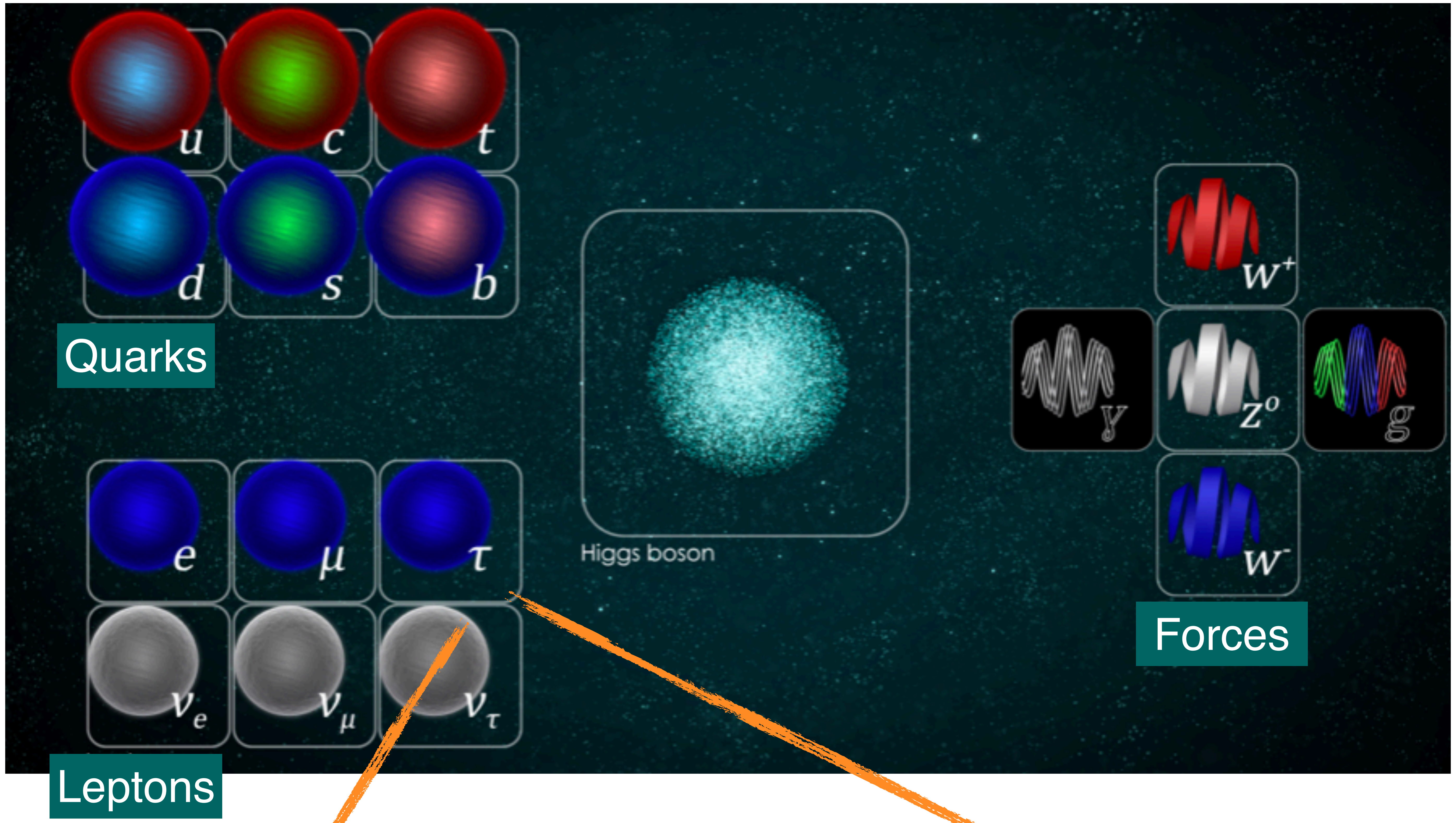


Why Muons? Why Not Other Particles?



Neutrinos weakly interact with detectors!

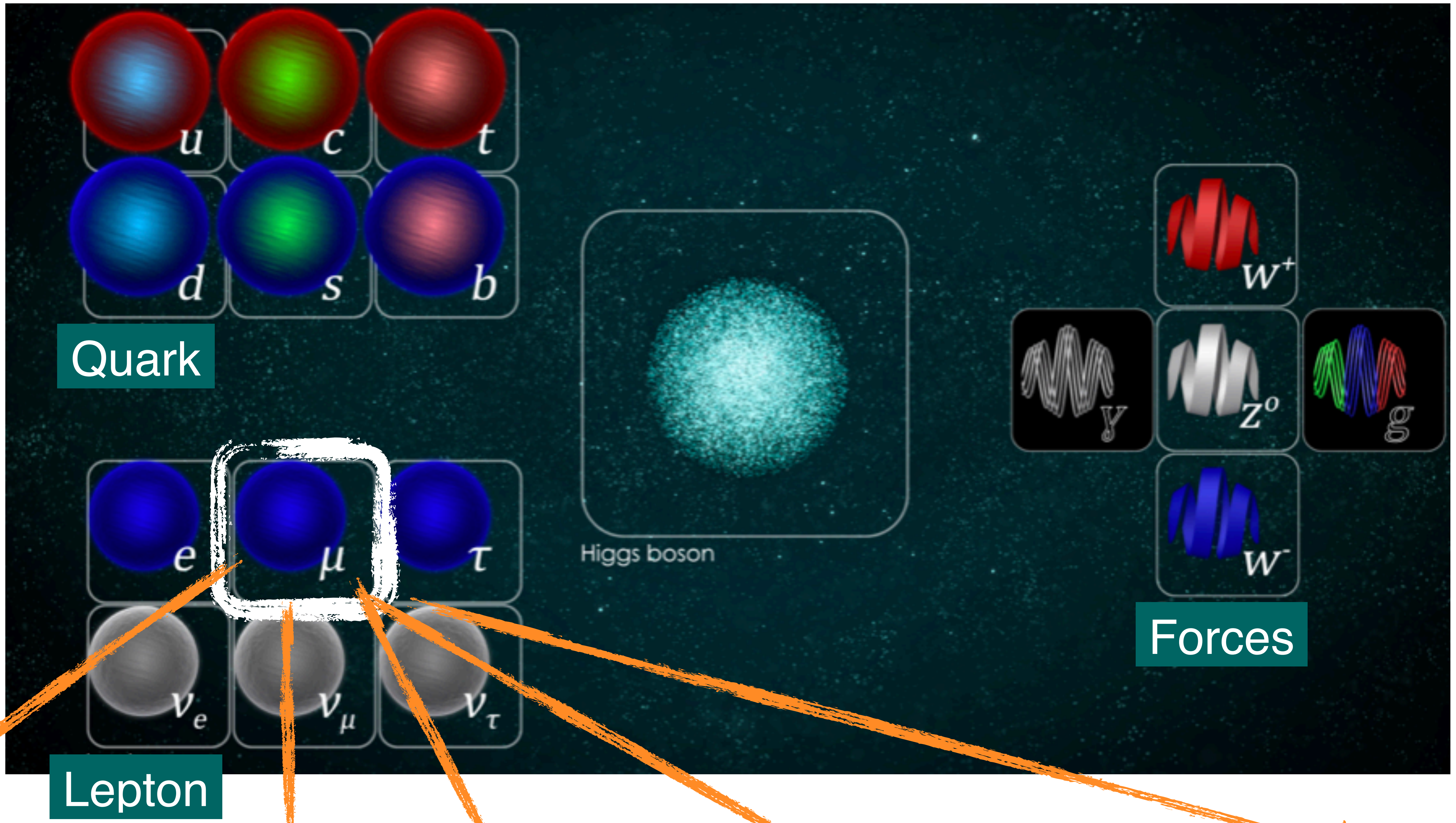
Why Muons? Why Not Other Particles?



Very short lifetime [290 x 10^{-15}s]

Difficult to make

Why Muons? Why Not Other Particles?



Easy to produce,
99.9% of pions decay to muon + neutrino

Highly polarized

Charged

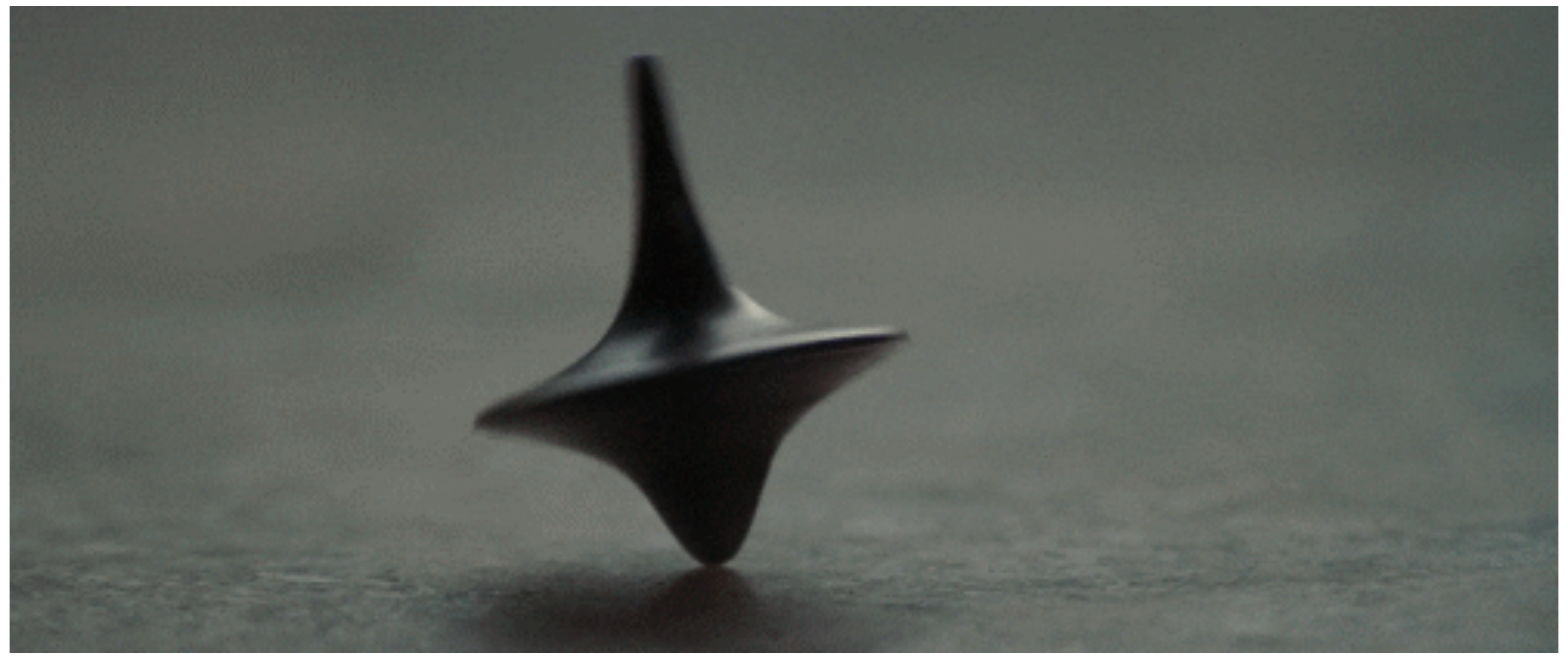
Much heavier than electron: $(m_\mu/m_e) \sim 200$

Lifetime ~ 2.2 μs (lab frame muon lifetime is >> 2.2 μs) long enough for interactions, short enough for decays

What is a polarized muon beam?

Polarized Beam → spin direction of the particles is aligned with their momentum

- Think of particles with spin just like a spinning top, rotating about an axis!
- Particles with parallel spin and momentum vectors are right-handed (RH)
- Particles with antiparallel spin and momentum vectors are left-handed (LH)
- In SM, neutrinos are always LH, and antineutrinos are always RH - a consequence of them being almost massless



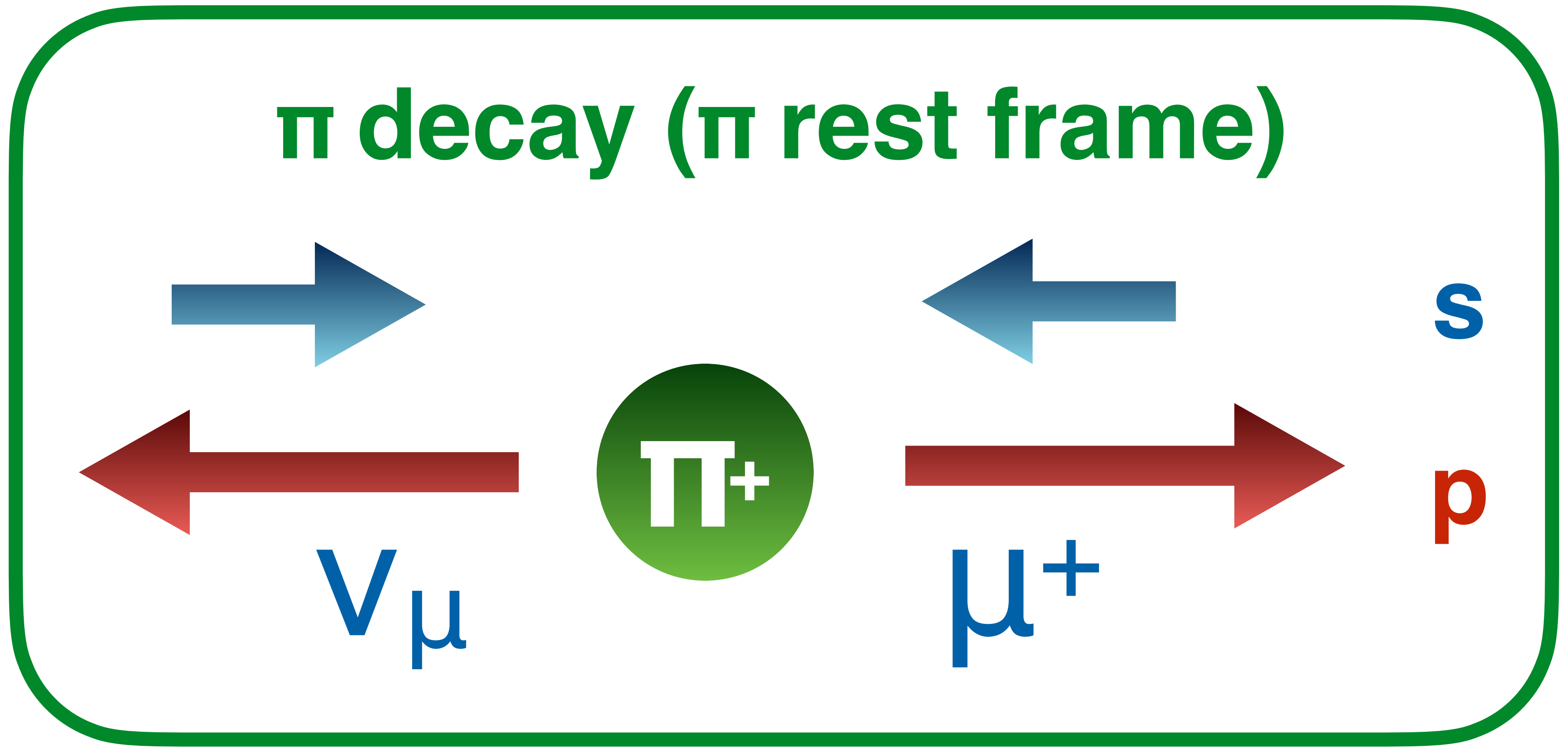
What is a polarized muon beam?

Polarized Beam → spin direction of the particles is aligned with their momentum

- Start with protons hitting a target (e.g., Ni alloys), producing pions
- Pions decay to Muons: $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Pions are spin-0, and in the pion rest frame, have momentum p=0
- To conserve momentum, neutrino and Muon must be emitted in opposite directions
- Spin (full name ‘spin angular momentum’) must also be conserved
- In the SM, neutrinos are always LH, antineutrinos are always RH

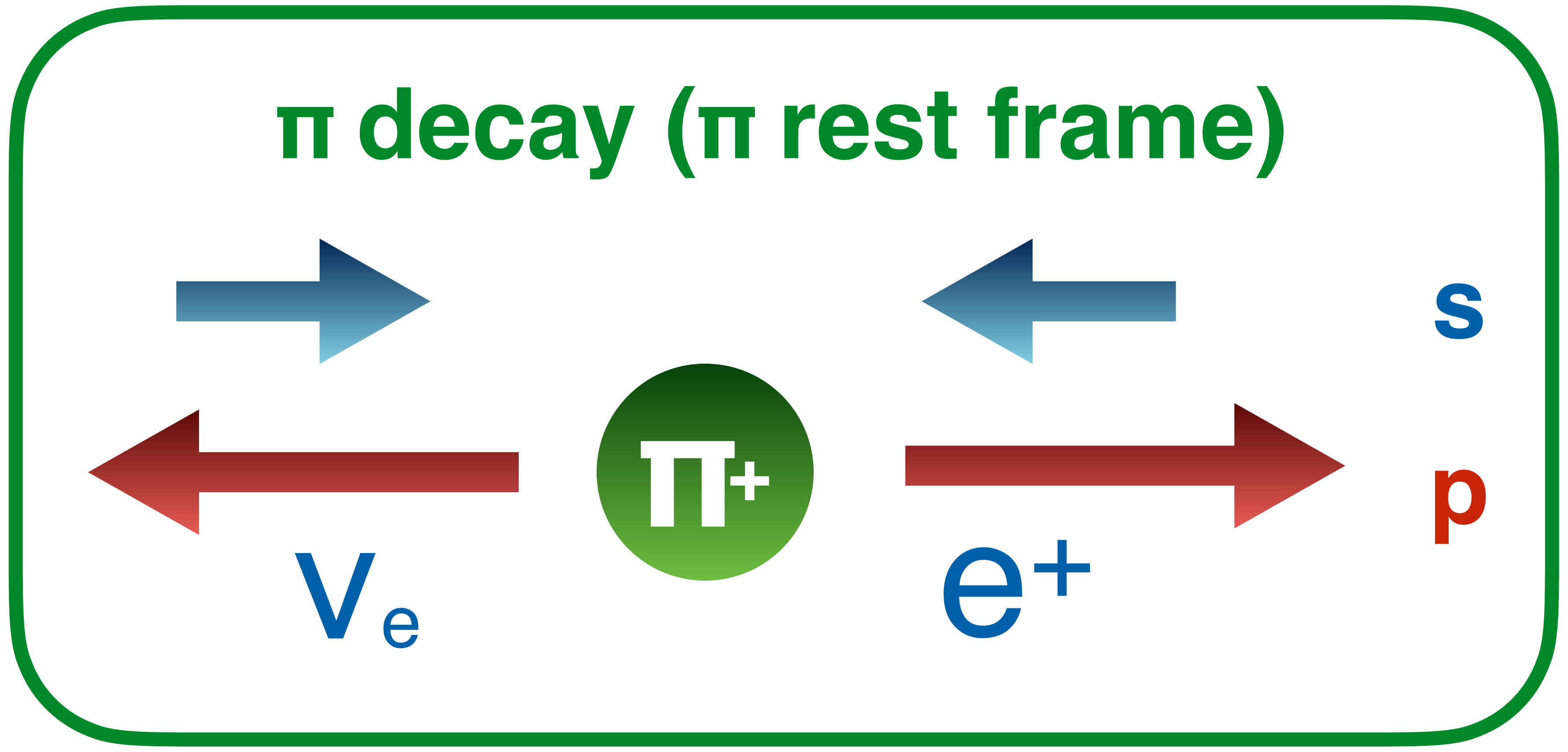
Only LH Muons must be produced!

→ 100% polarized beam!



Why Don't Pions decay to electrons?

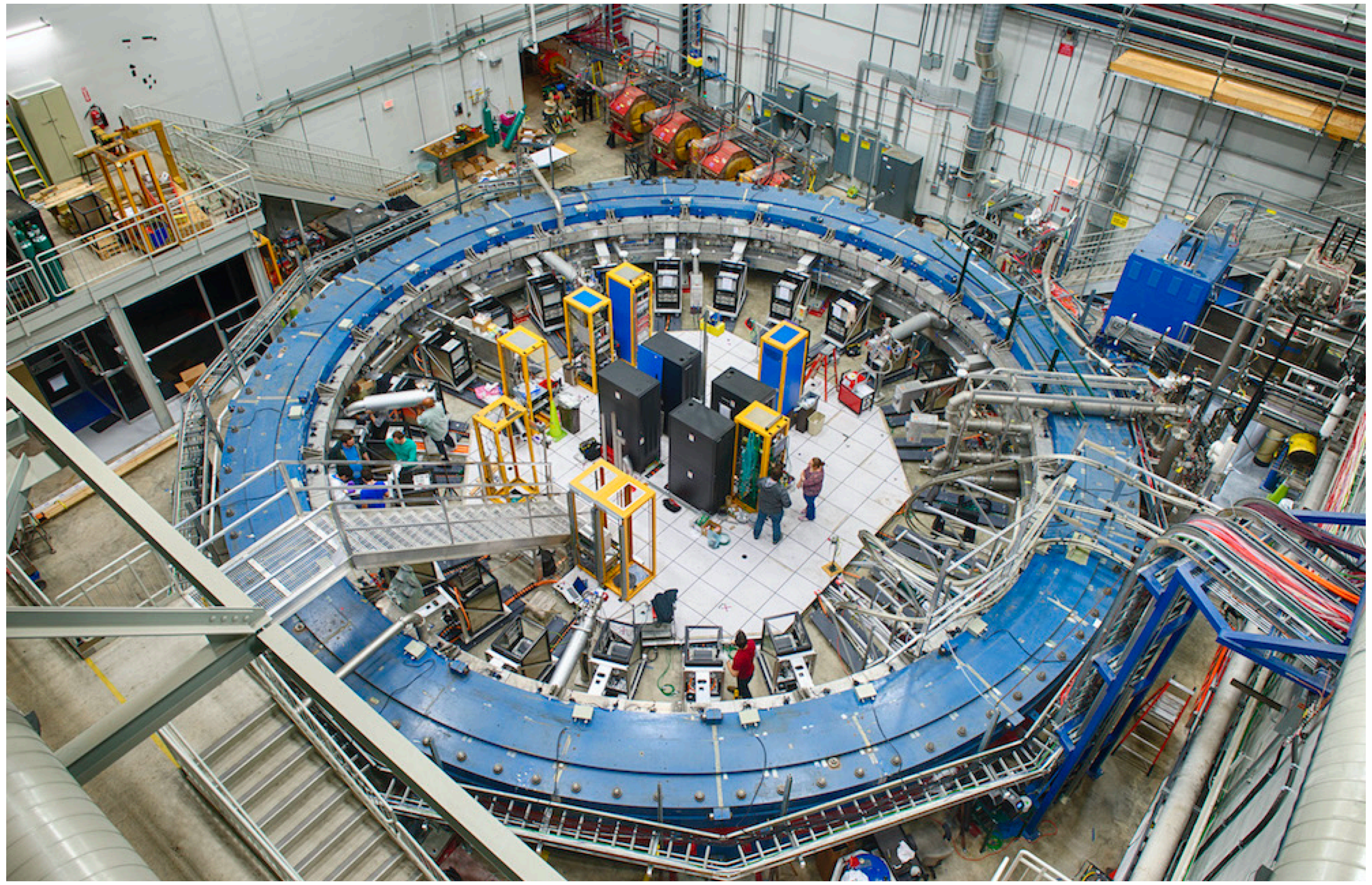
- The reason neutrinos have to be LH is because they are (nearly) massless
- Muons are heavier and don't have this constraint — they can be either LH or RH
- Electrons are nearly massless, so they want to be LH
- Positive pions produce positrons (e^+) — they want to be RH
- But conservation laws require them to be LH!
- $\pi^+ \rightarrow e^+ \nu_e$ is highly suppressed

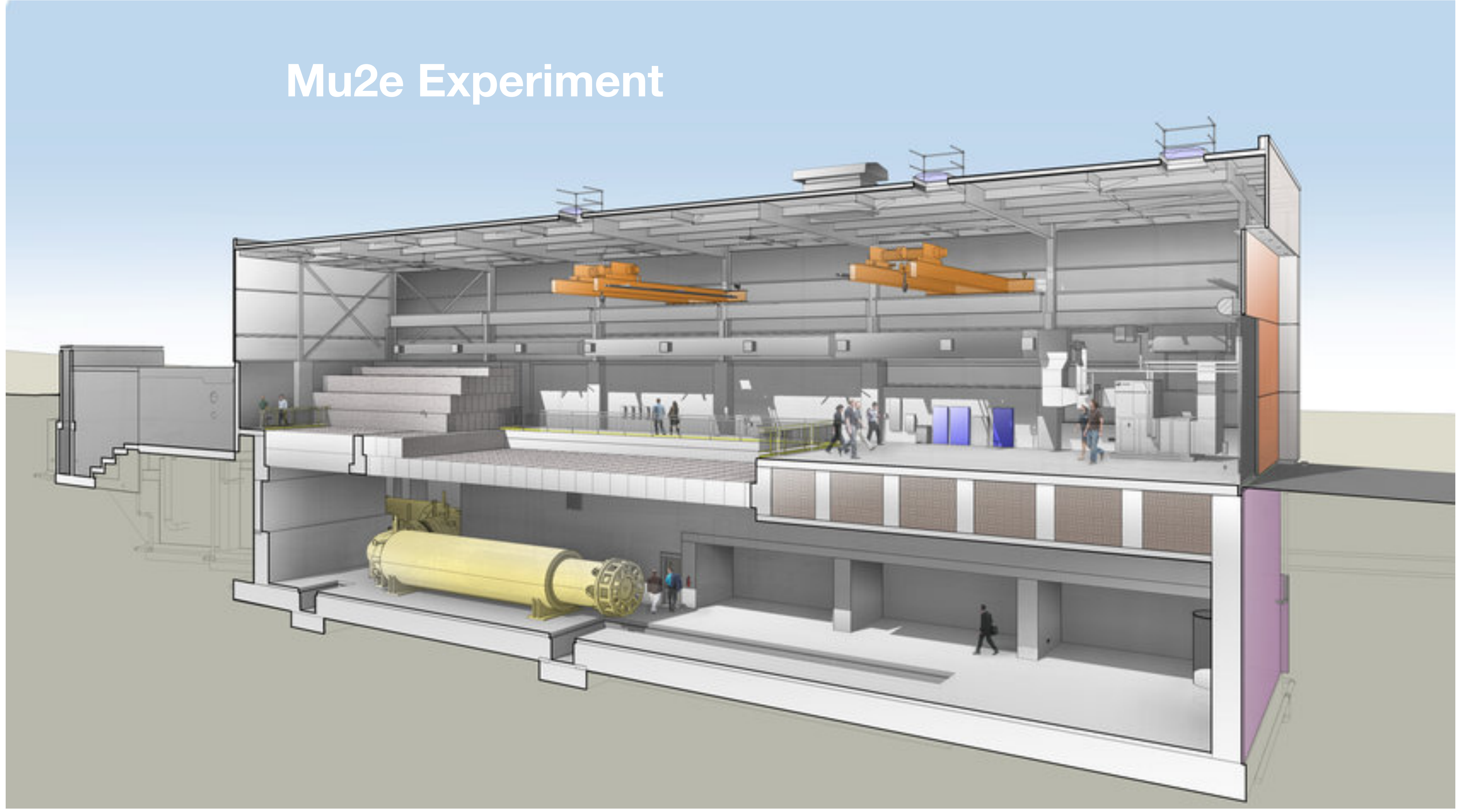


LH

Muons as a Probe for New Physics

- Two muon experiments at Fermilab





- Highly accurate tests of Standard Model
- Look for significant deviation

- Look for rare processes using high intensity muon beam

Physics of Muon g-2

Spin Precession in a Magnetic Field

- Charged particles with intrinsic spin (a quantum-mechanical property) produces a dipole magnetic field

→ has an intrinsic magnetic moment $\vec{\mu}_s = g \frac{q}{2m} \vec{S}$

g-factor : Proportionality constant b/w spin and magnetic moment. It determines the strength of the magnetic moment (gyromagnetic ratio)

Spin Precession in a Magnetic Field

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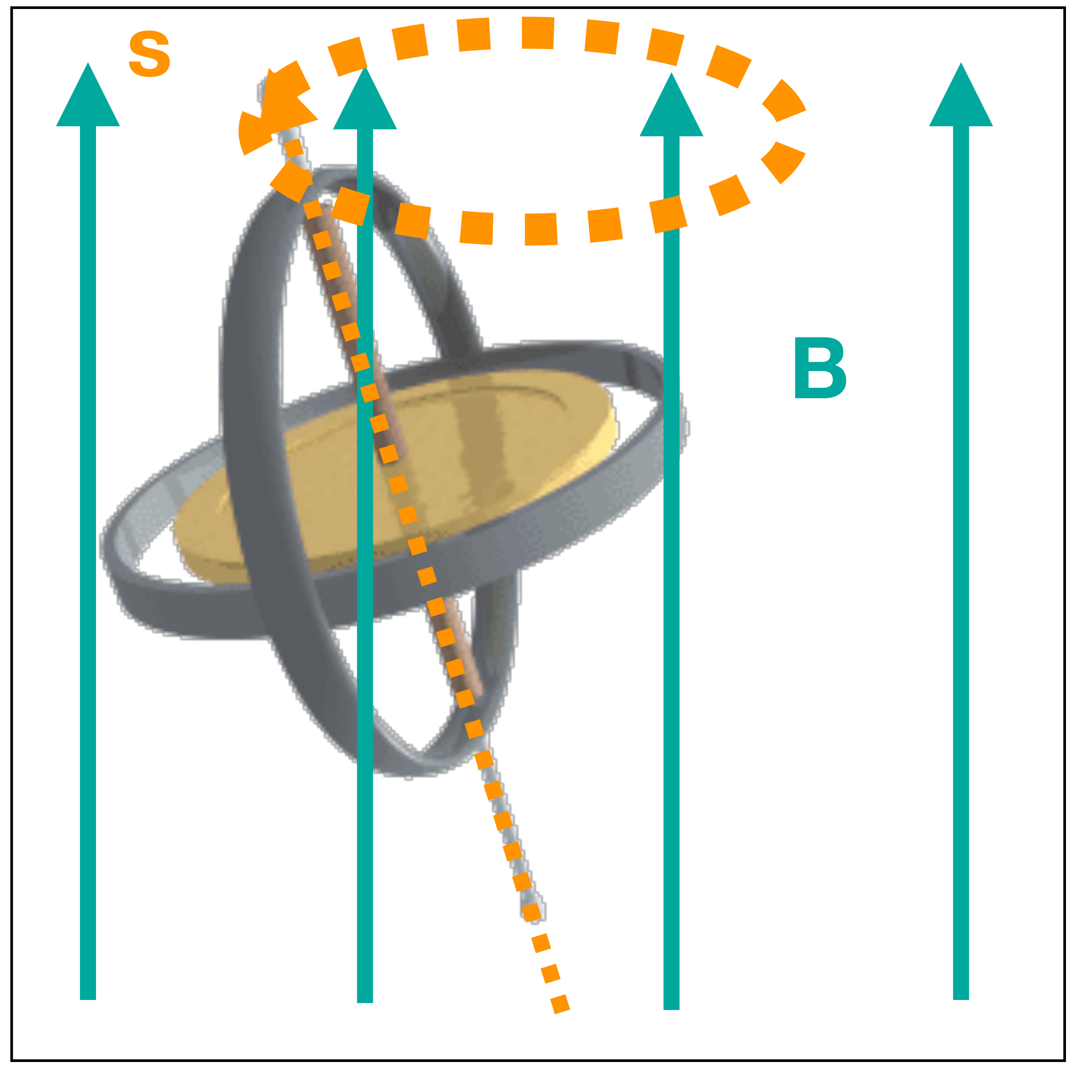
→ has an intrinsic magnetic moment $\vec{\mu}_s = g \frac{q}{2m} \vec{S}$

g-factor : Proportionality constant b/w spin and magnetic moment. It determines the strength of the magnetic moment (gyromagnetic ratio) → **tells us how fast the spin of the particle precesses when placed in a magnetic field**

- Particles with spin (e.g. leptons) will precess when placed in a magnetic field (B) - Larmor precession
- The leptons will behave like a spinning top in gravitational field with its spin vector precessing around the B-field direction



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

spin precession frequency

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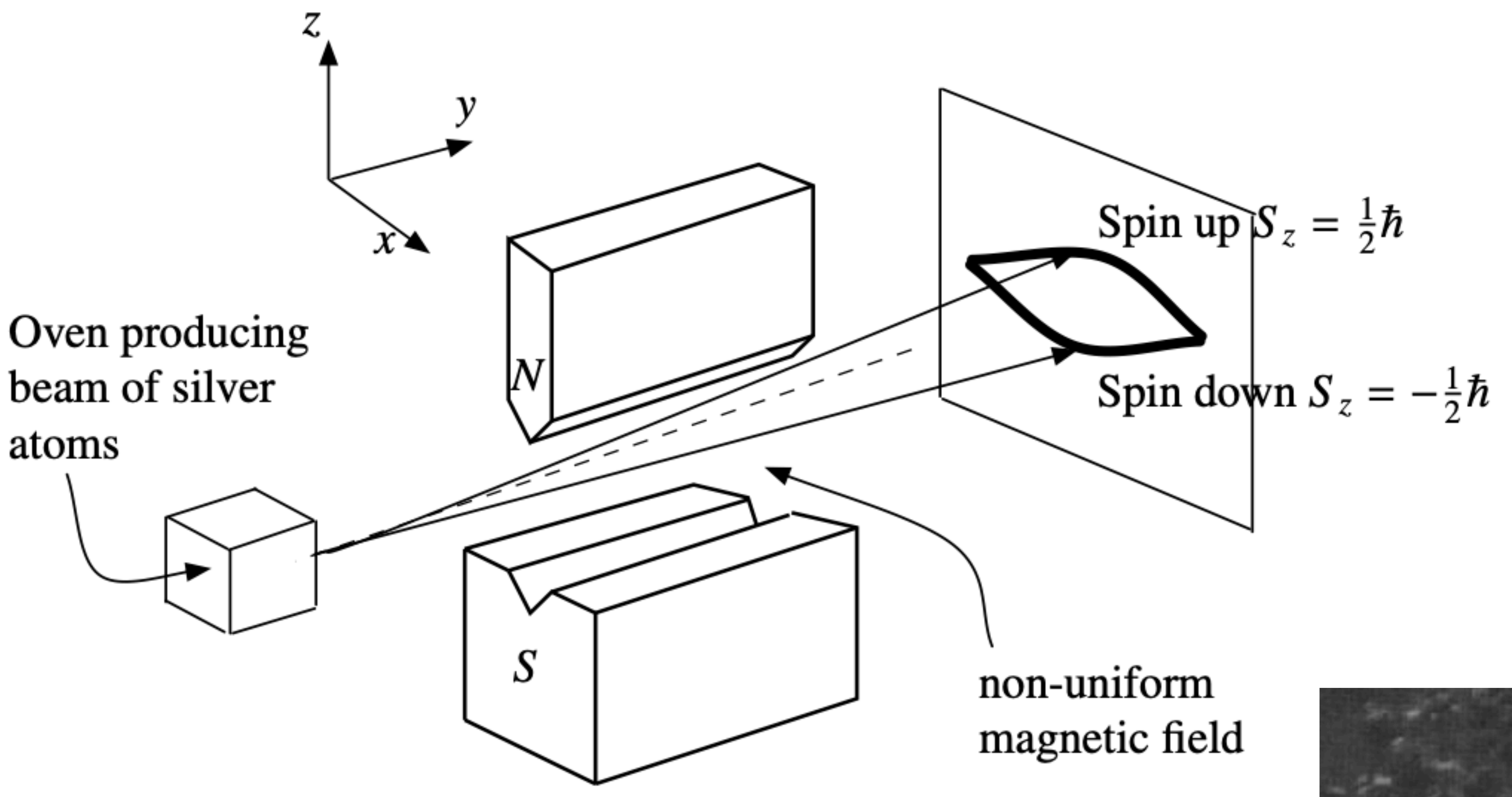
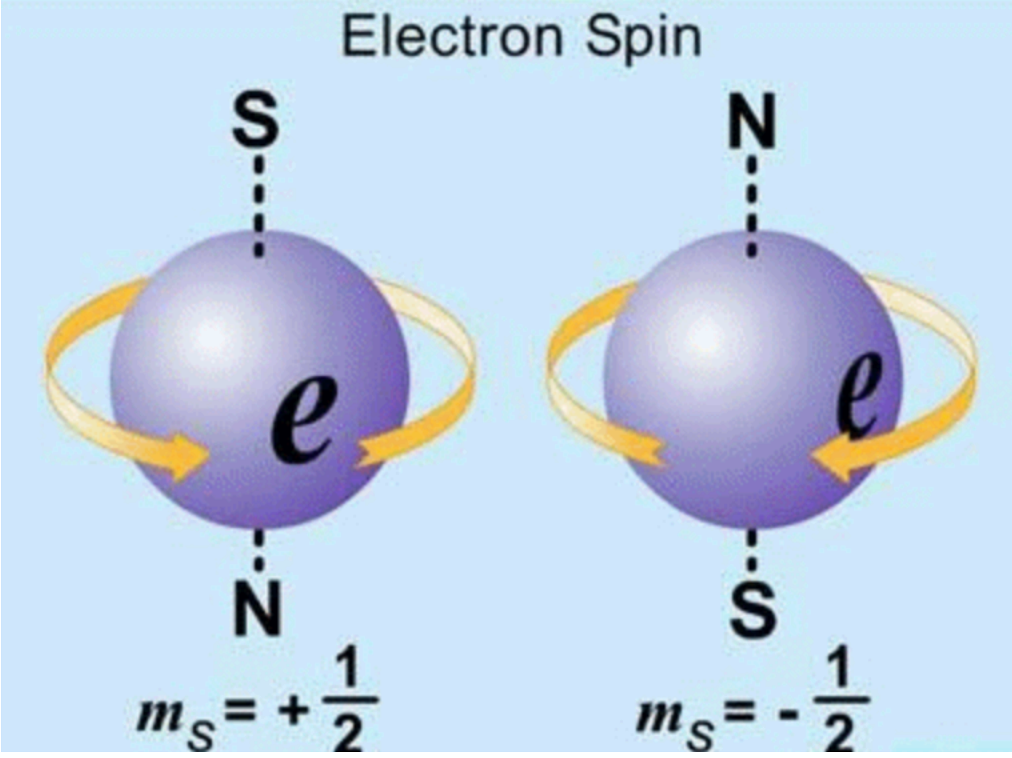
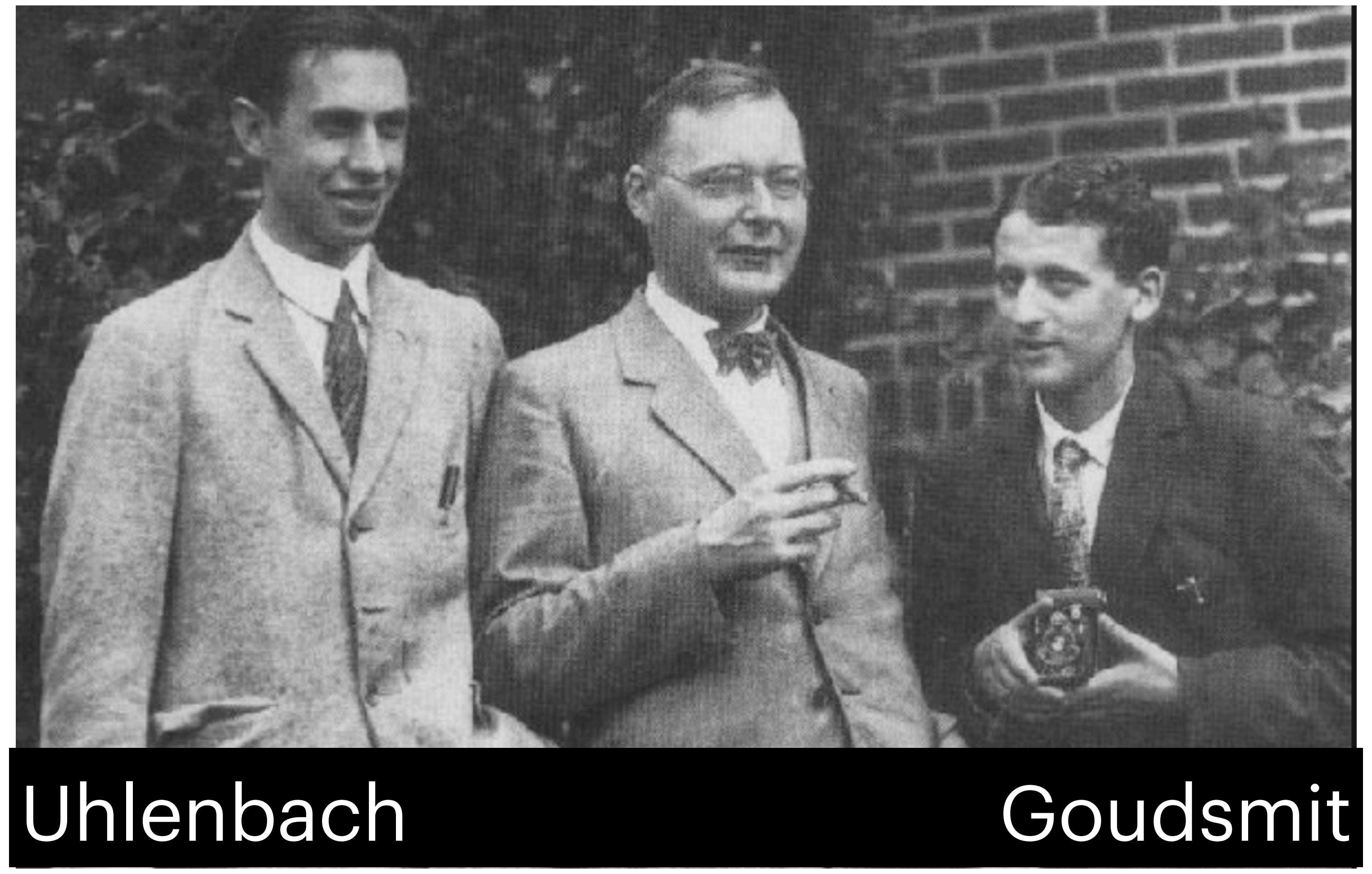
What's the value of g?

Measured in the 1920s

The Stern-Gerlach Experiment illustrated → Electrons posses spin! $g_e = 2$





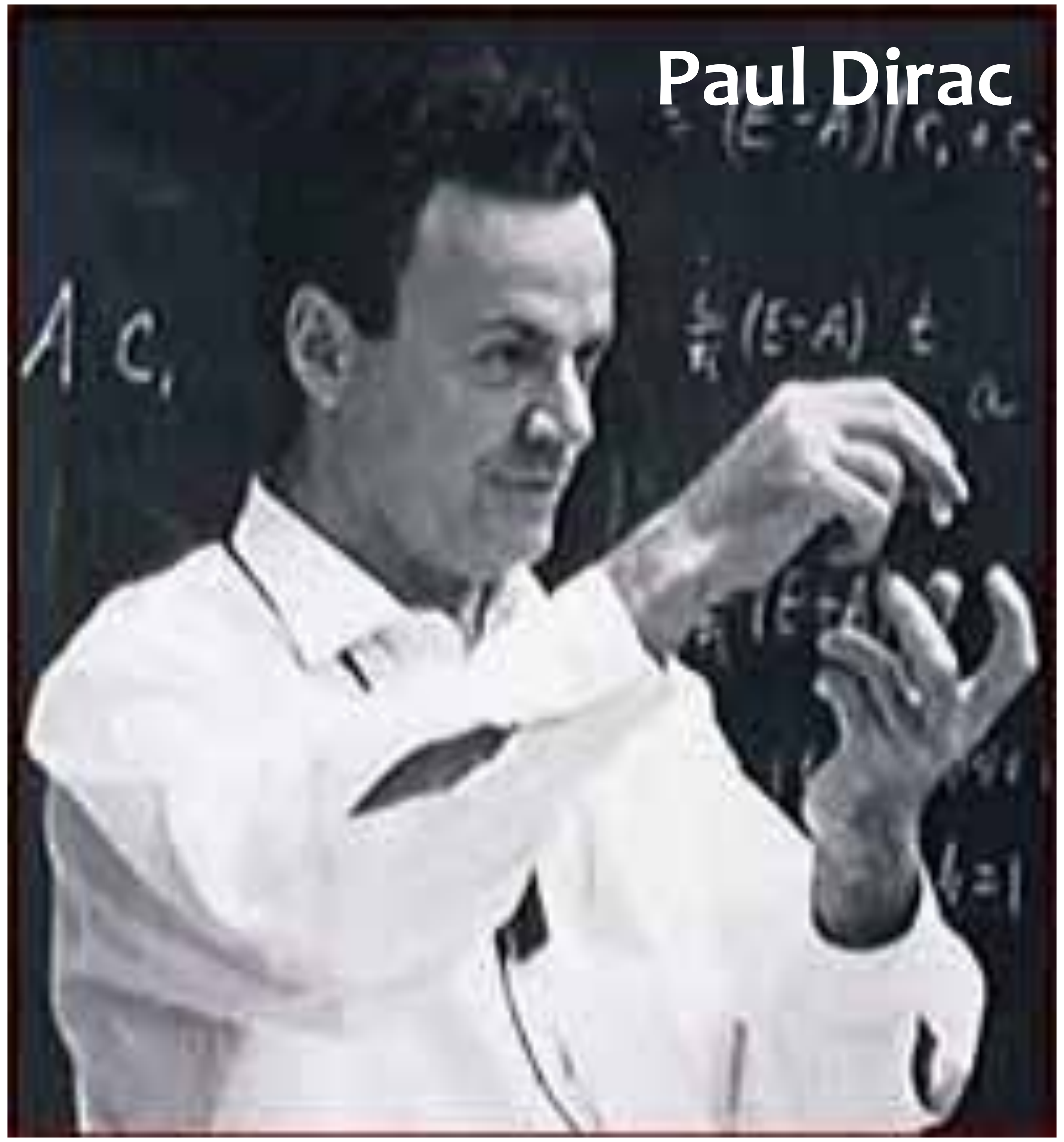


What's the value of g?

Calculated in 1928

Dirac predicted g=2 for

spin 1/2 point-like particles

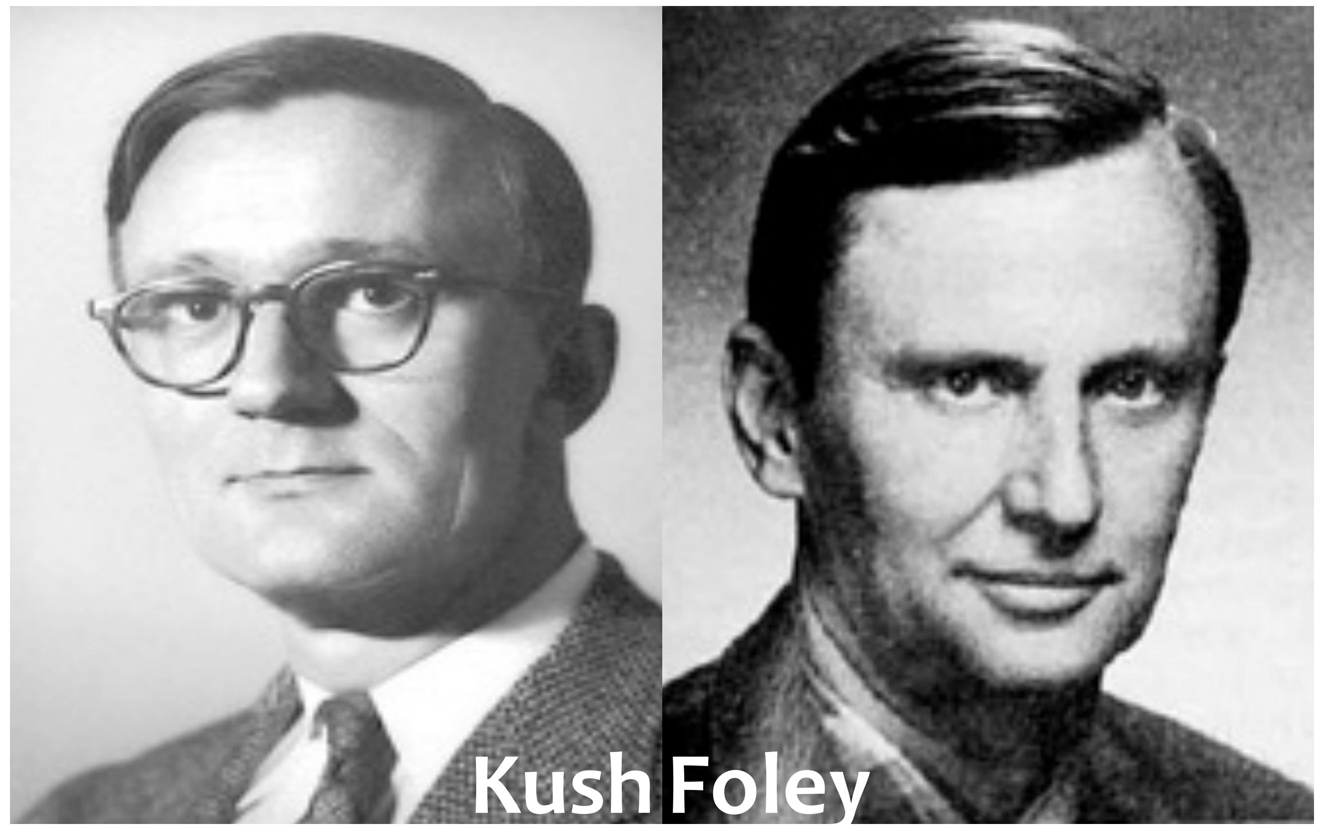


$$\omega_s = g\frac{eB}{2m}$$

- Meaning its spin would precess twice as fast
- Measure ω_s to measure size of g

What's the value of g?

Measured in 1948



PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. Kusch and H. M. Foley
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that $g_L = 1$ and $g_S = 2(1.00119 \pm 0.00005)$. The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

From spectroscopy, $g_e \neq 2$!

$$g_e = 2.00238$$

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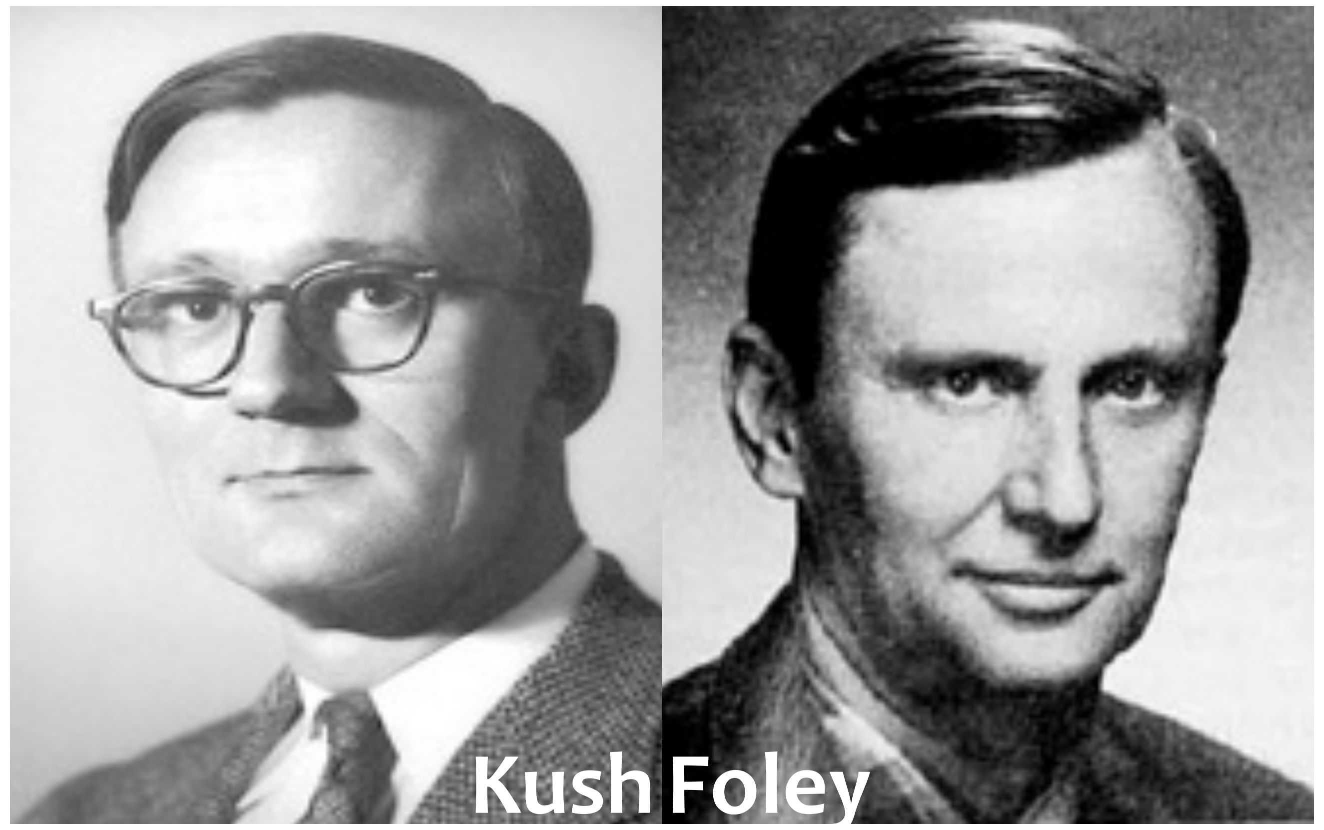
What's the value of g?

Measured in 1948



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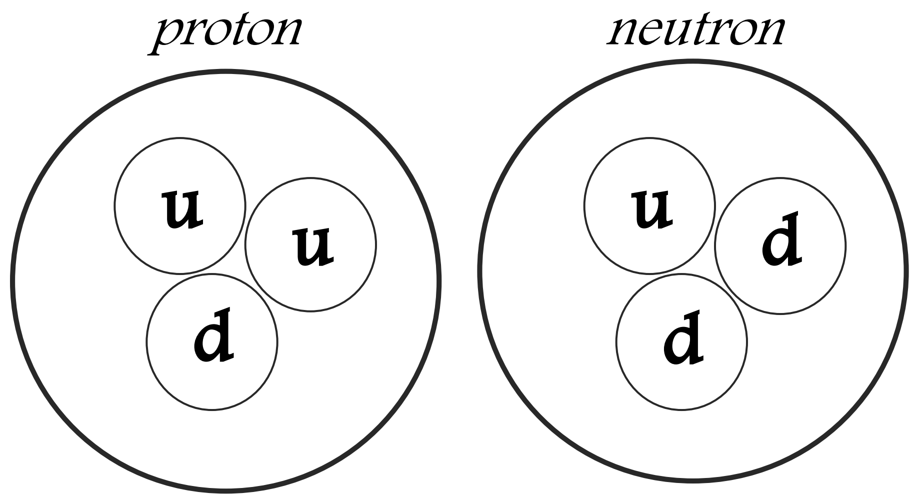
From spectroscopy, $g_e \neq 2$!

$$g_e = 2.00238$$

In 1933 & 1934 proton (g_p=5.6)& neutron (g_n = -3.8) factors were measured

Protons and neutrons are made up of quarks!



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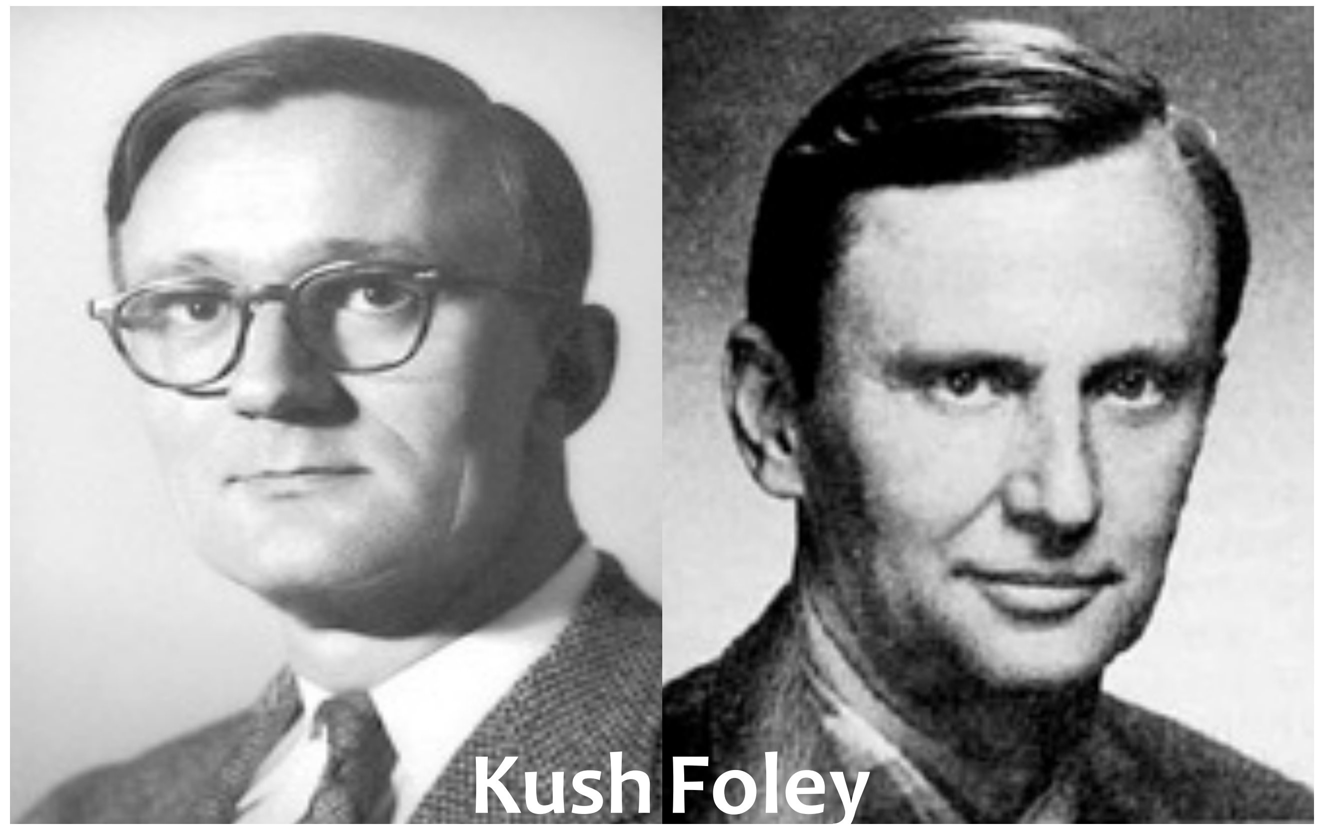

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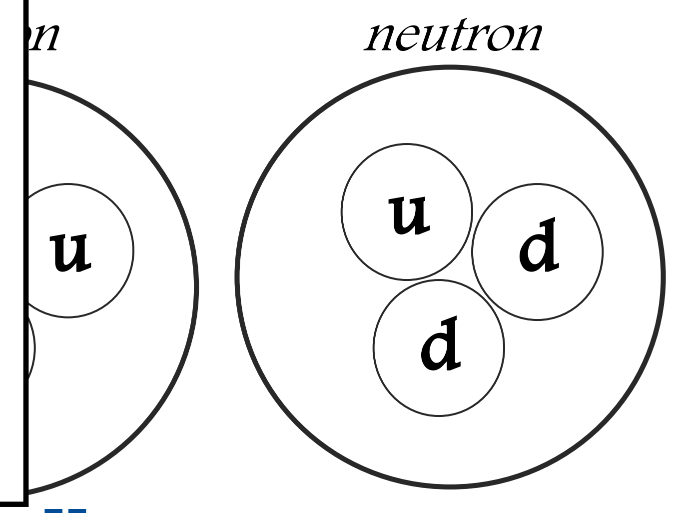
g = 2 → the particle is point-like

Is the electron NOT point-like?

OR

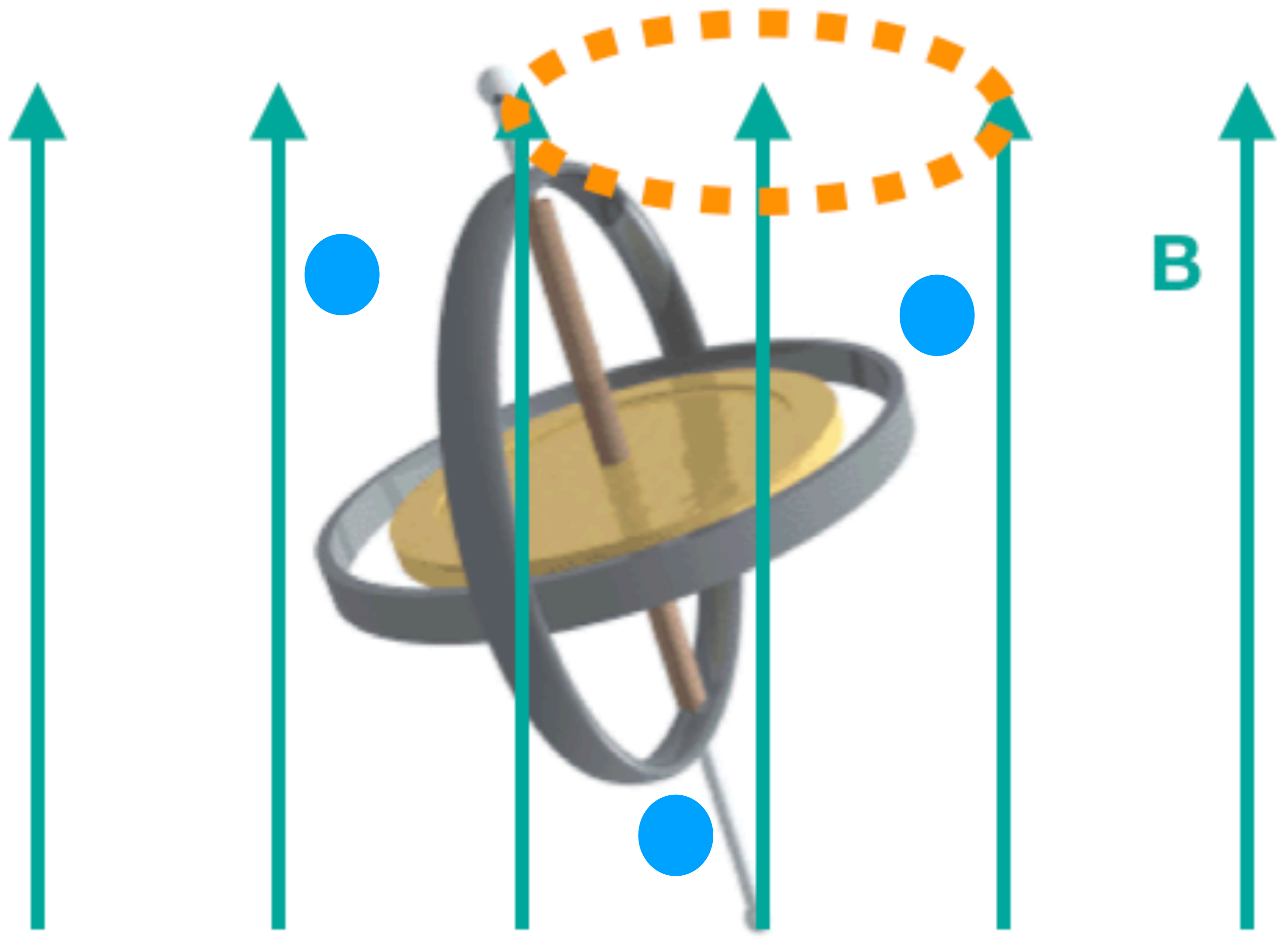
Are there other mysterious processes occurring in nature?

In 1933 &
Protons a



Is Vacuum truly an Empty Space?

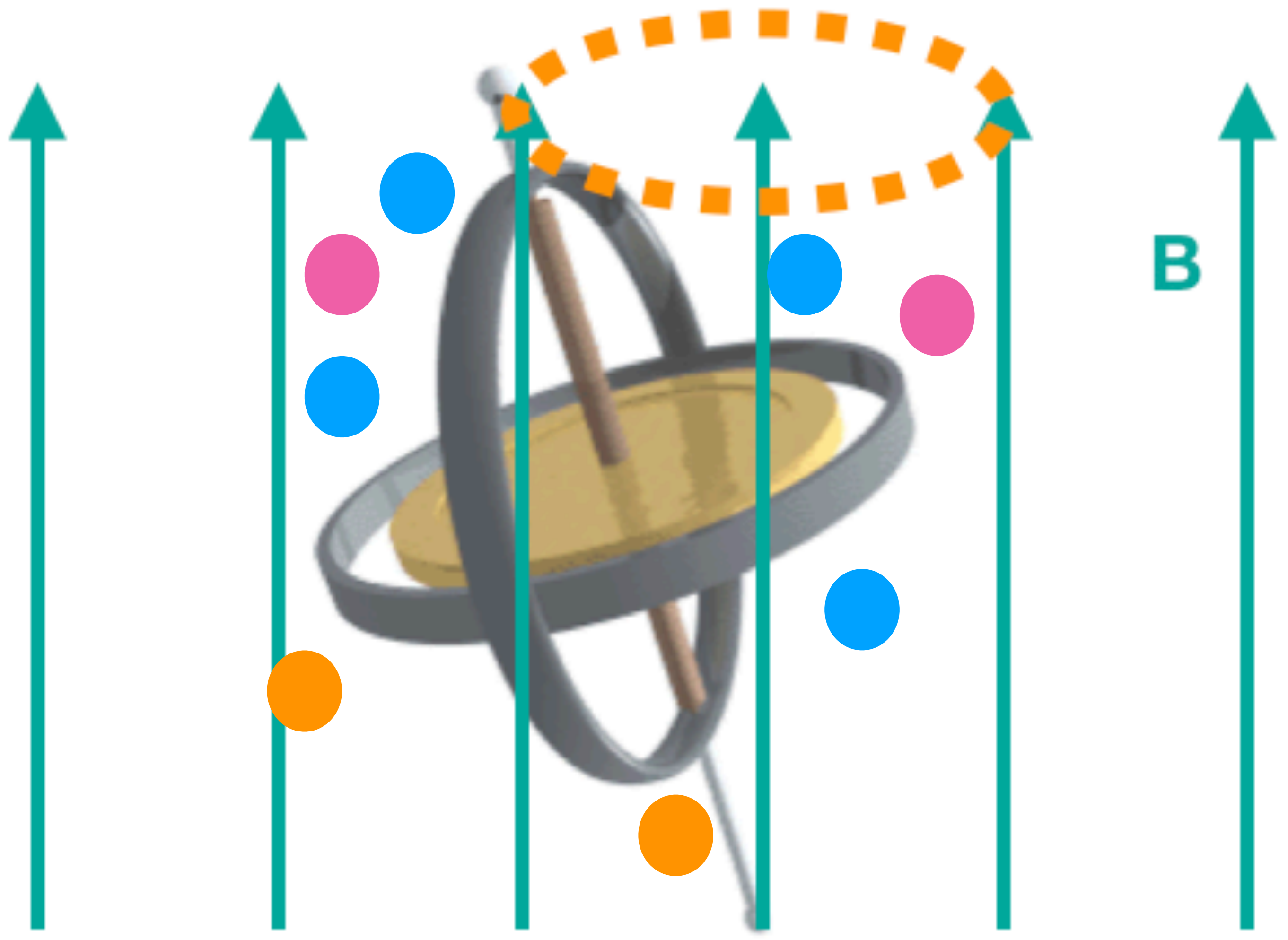
- Vacuum is filled with virtual particles
- Virtual particles continually pop in and out of existence and interact with light and other particles



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

Is Vacuum truly an Empty Space?

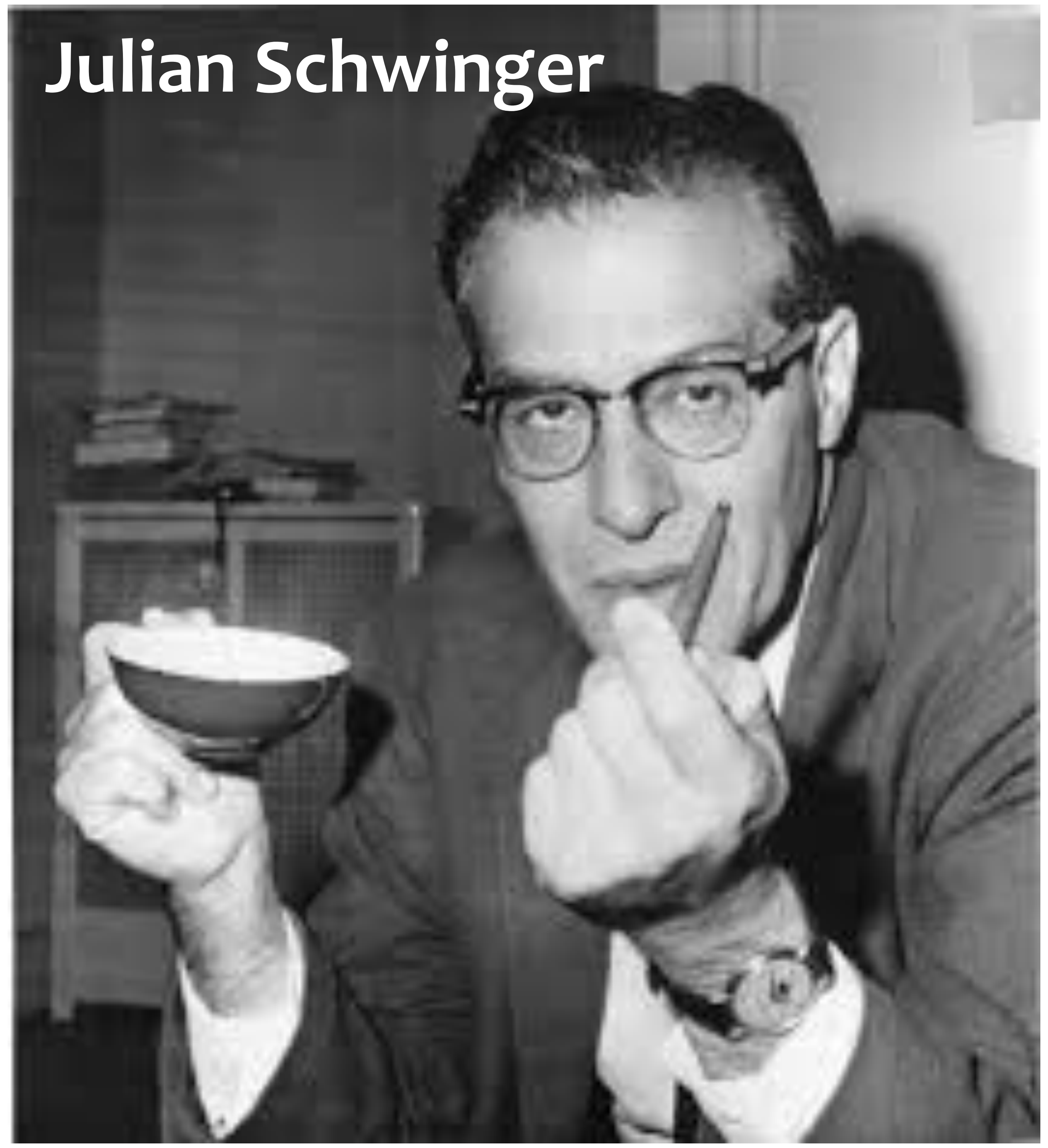
- Vacuum is filled with virtual particles
- Virtual particles continually pop in and out of existence and interact with light and other particles
- Muons, electrons and all other particles can interact with these virtual particles
- The heavier the particle, the higher the number of ways it can interact
- Effectively, the virtual particles screen the magnetic field experienced by the particle, changing the value of g



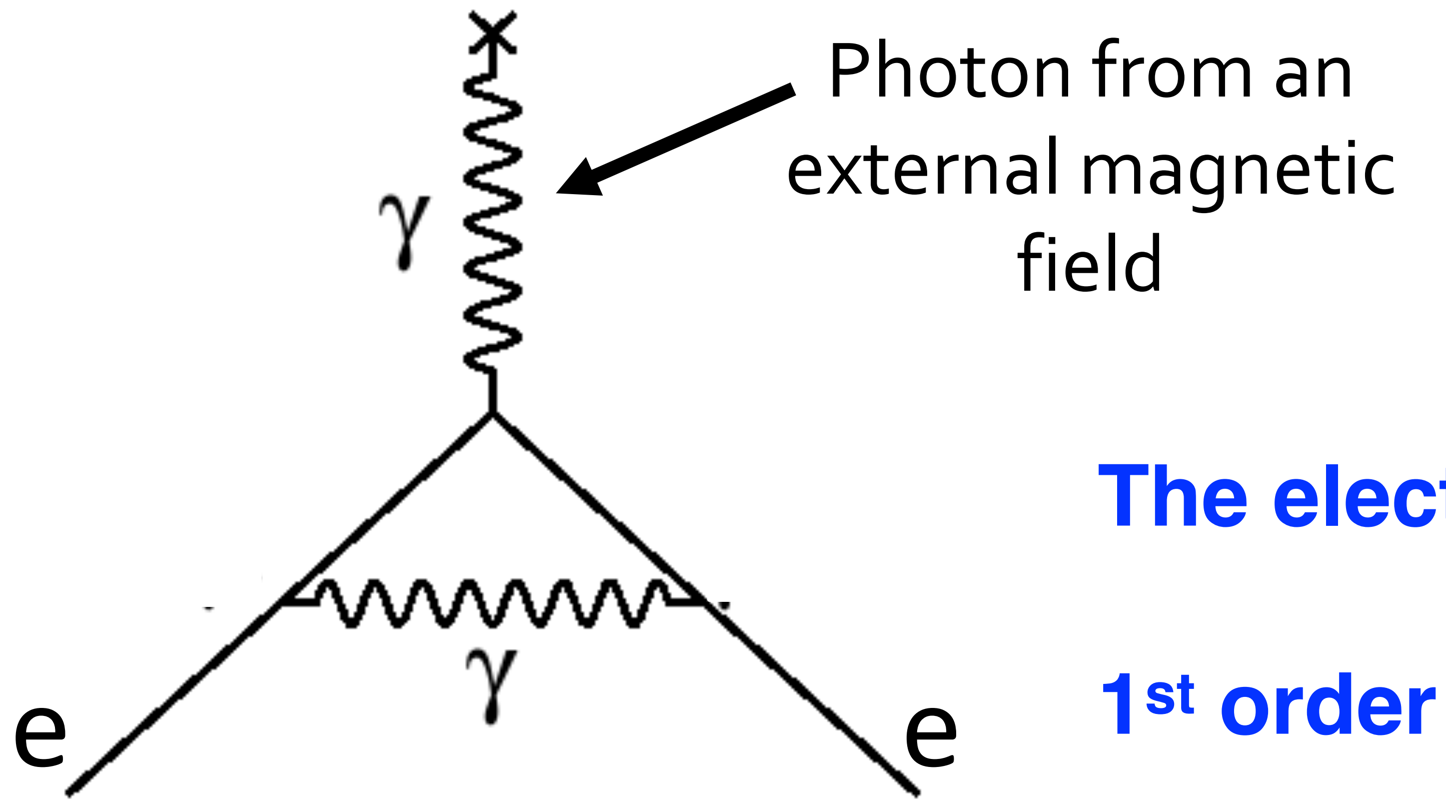
$$\omega_s = g\frac{eB}{2m}$$

How much do vacuum interactions change g?

Calculated in 1948



Quantum Electrodynamics!



The electron is interacting with itself!

1st order term of QED, the self interaction

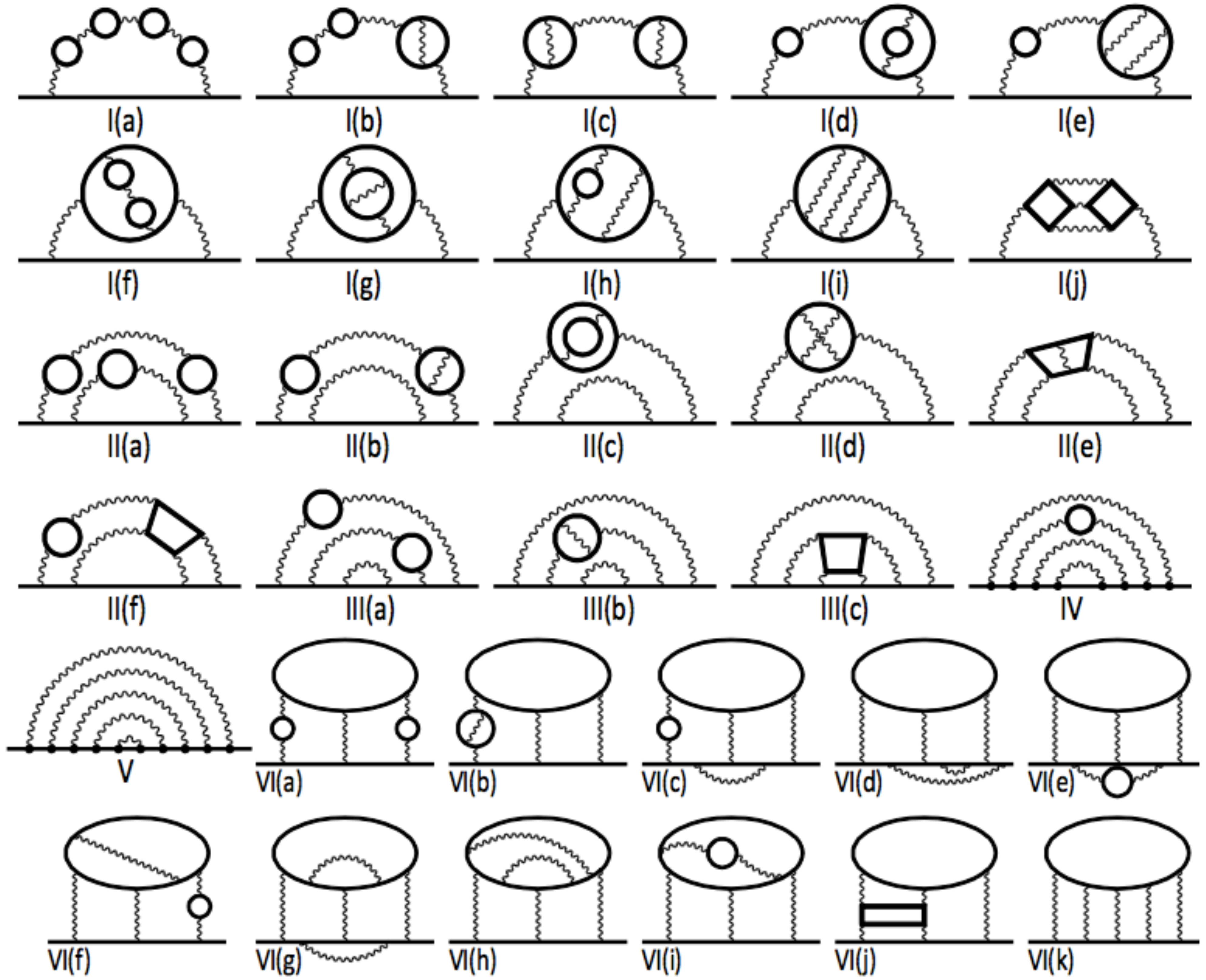
$$g \approx 2\left(1 + \frac{\alpha}{2\pi}\right)$$

$$\mathbf{g_e = 2.00232}$$

Agrees with experiment!

There are Many Corrections…

10th
12672
diagrams



Standard Model Calculation

T. Aoyama, M. Hayakawa,
T. Kinoshita, M. Nio (PRLs, 2012)

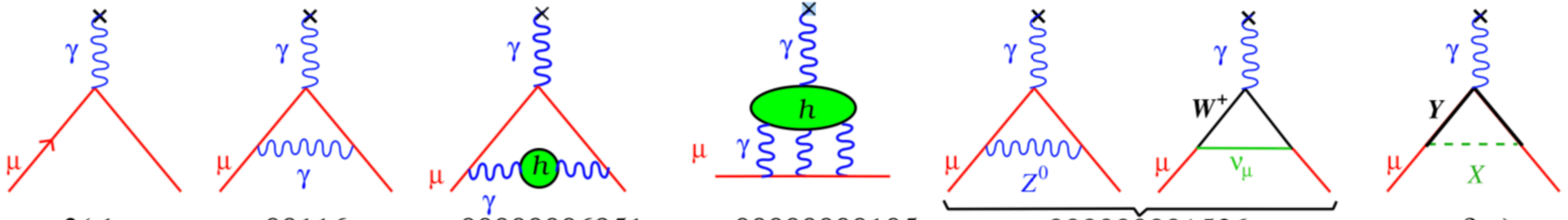
For QED, g_e is calculated up to the 10th order (12,672 diagrams).
g_e is one of the most precisely calculated and measured value.

- For electrons, QED tells the full story
- SM prediction of a_e agrees with experiment at ppt level!
- Muons are sensitive to other types of interaction, sensitivity scales as $\left(\frac{m_\mu}{m_e}\right)^2$

What's the value of g?

Hadronic

dominant uncertainty on prediction



$$g = 2(\,1 \quad + .00116\ldots \quad + .00000006951\ldots + .00000000105\ldots \quad + .000000001536 \quad +?\,)$$

Schwinger Term $\left(\frac{\alpha}{2\pi}\right)$ | **QCD** | **Electroweak** | **BSM?**

Fermilab

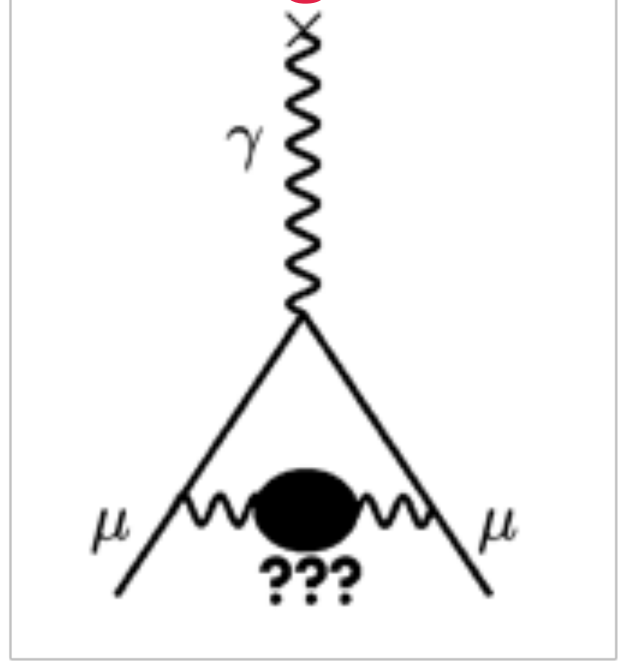
What is the Magnetic Anomaly?

From g_μ we define the magnetic anomaly : $a_\mu = \dfrac{g_\mu - 2}{2}$ → Shows how much g differs fractionally from 2!

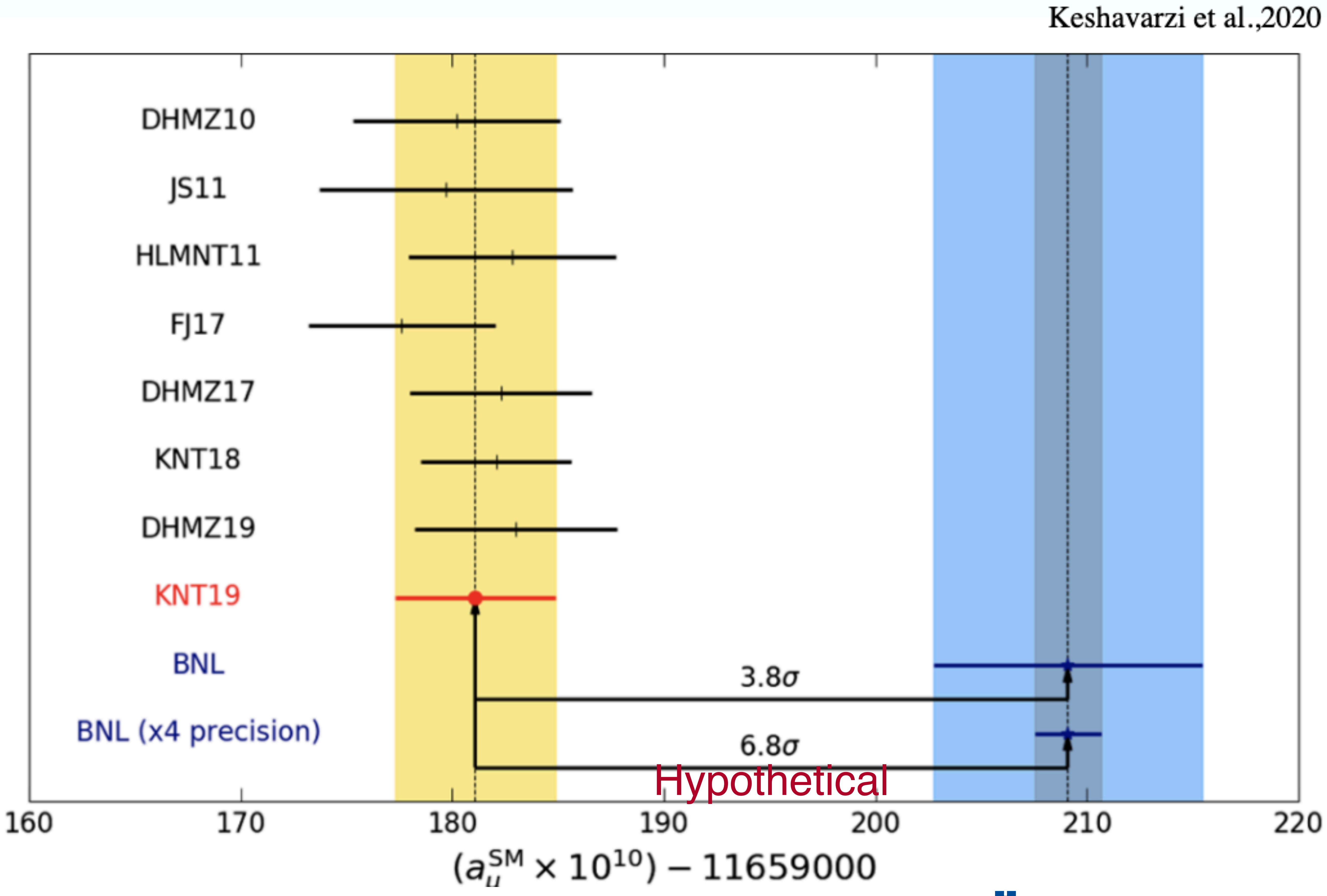
- Current best measurement of g comes from the Brookhaven (BNL) g-2 experiment
  $a_\mu^{exp} = 116\,592\,089\,(54)_{st}\,(33)_{sy}\,(63)_{tot} \times 10^{-11}$

- Disagreement between experiment and theory at $> 3\sigma$ level

How can it be different?
What's missing from the theory?



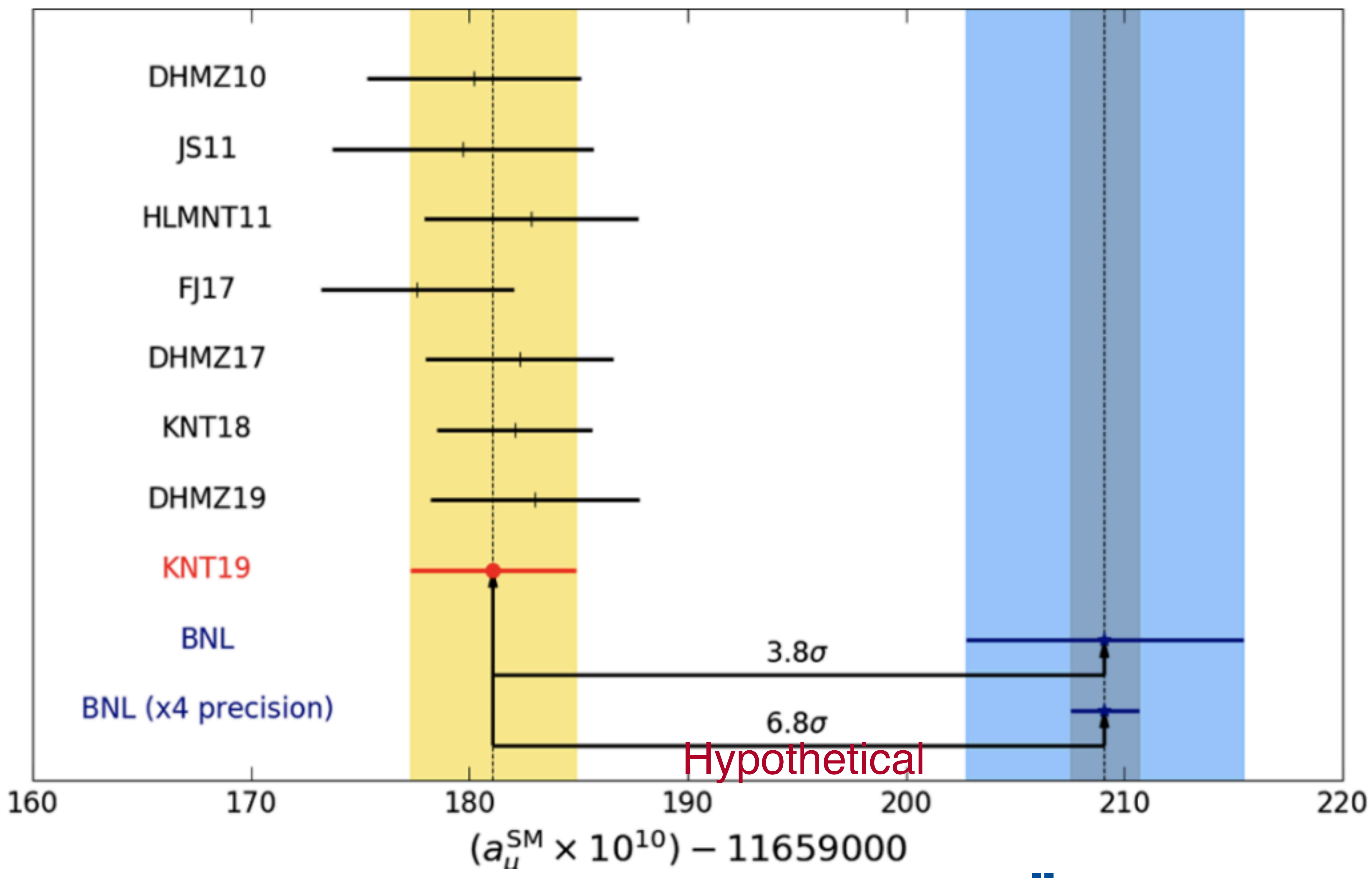
Beyond Standard Model?
Hint of new physics?



Why is the Discrepancy So Exciting?

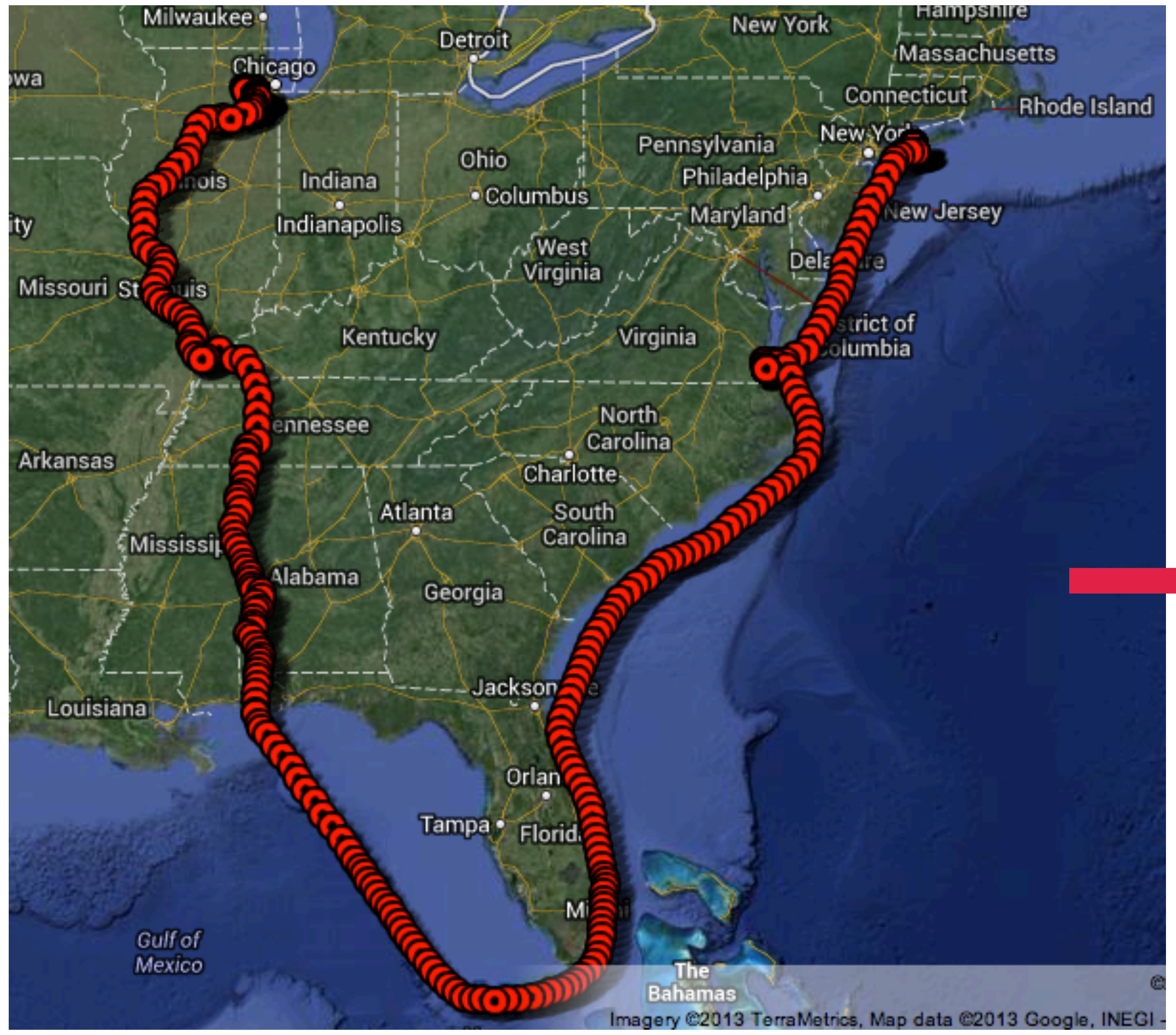
- The only way theorists think it could happen is if non-SM particles were interacting with the muon
- The size of the discrepancy could tell us about the mass range of new particles — focus the broad searches at colliders more precisely
- But can't be sure - need 5σ for discovery
- Need to reduce error bars to compare more conclusively

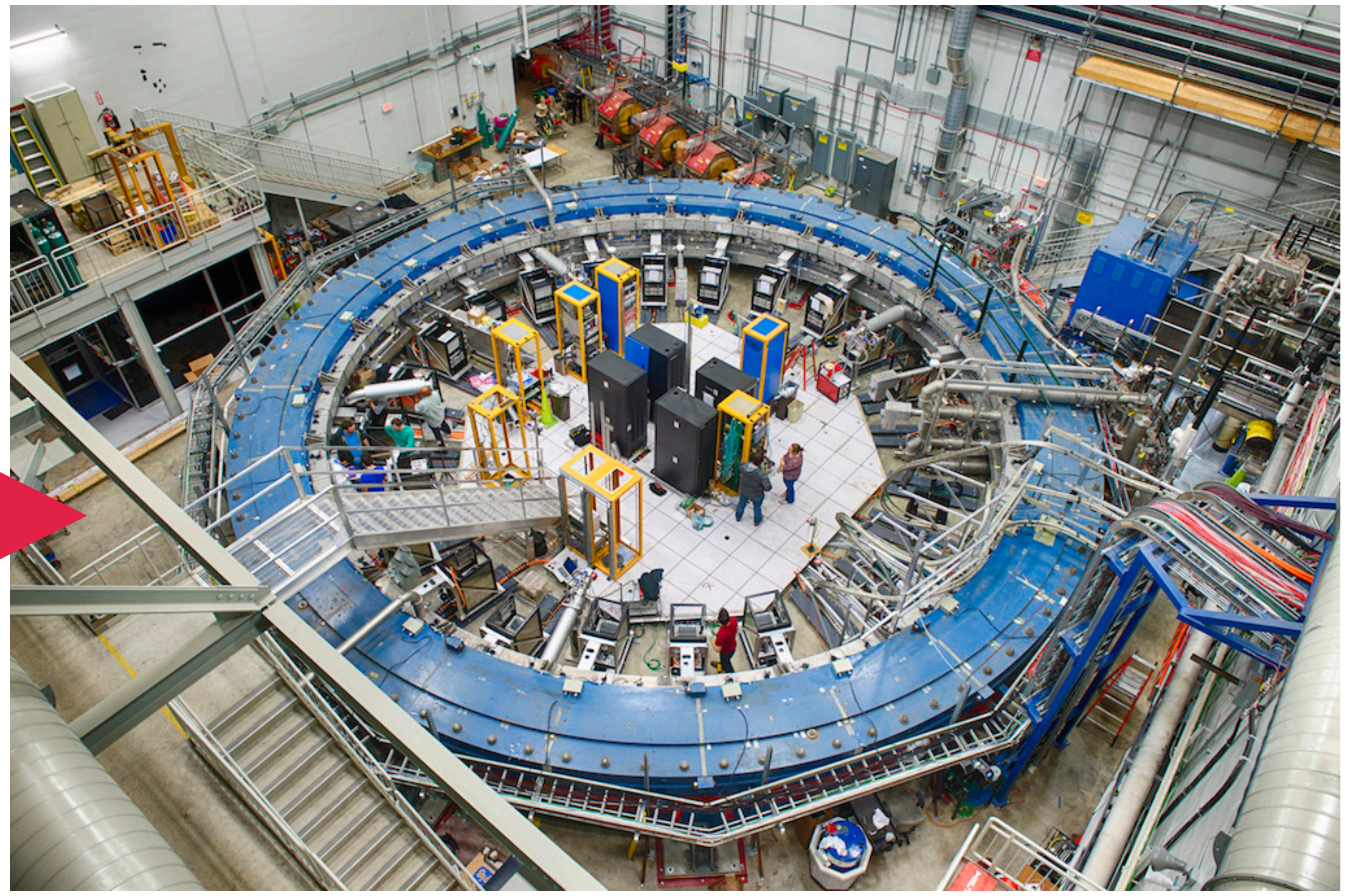
Keshavarzi et al.,2020



Measure a_μ Yet Again at Fermilab!

Move the experiment to Fermilab to use its muon beam!!!





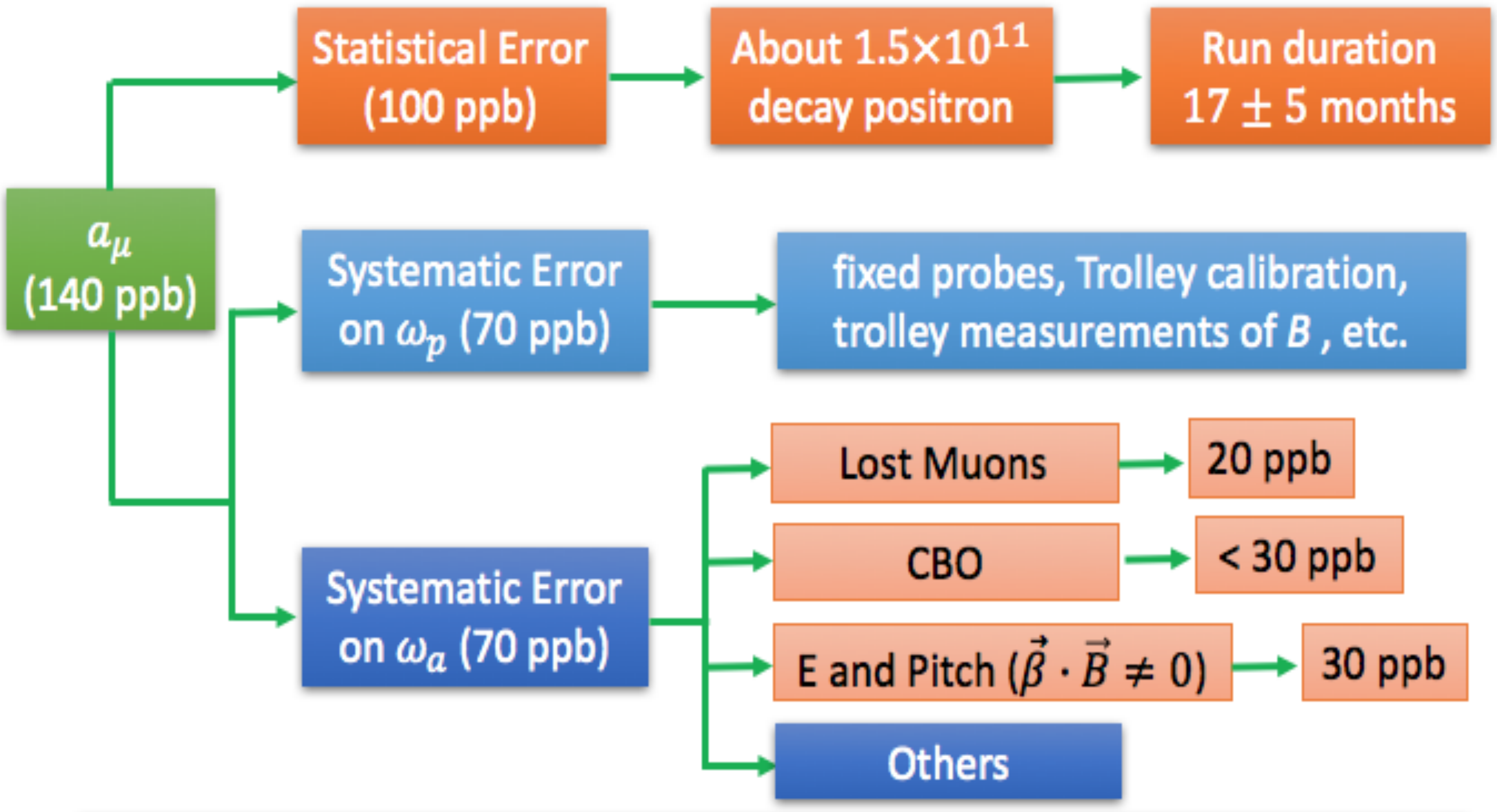
Fun experiment to work on! Intersection between different disciplines!

Fermilab

Measure a_μ Yet Again at Fermilab!

Prerequisites for a Better Measurement

Increase statistics by a factor of > 20 and reduce systematics by a factor of ~3 w.r.t BNL experiment



More beam !!!

Better Uniform Magnetic Field!!!

Better ω_a measurement !!!

How Do We Measure a_μ ?

- At injection, muon spin is aligned with its momentum (polarized beam)
- The muon circulates around the ring with frequency ω_c
- Muon takes 149 ns to go around the ring once
- The spin vector precesses around the B field with frequency ω_s
- Anomalous precession frequency:

$$\omega_a \approx \omega_s - \omega_c \approx a_\mu \frac{eB}{m_\mu c}$$

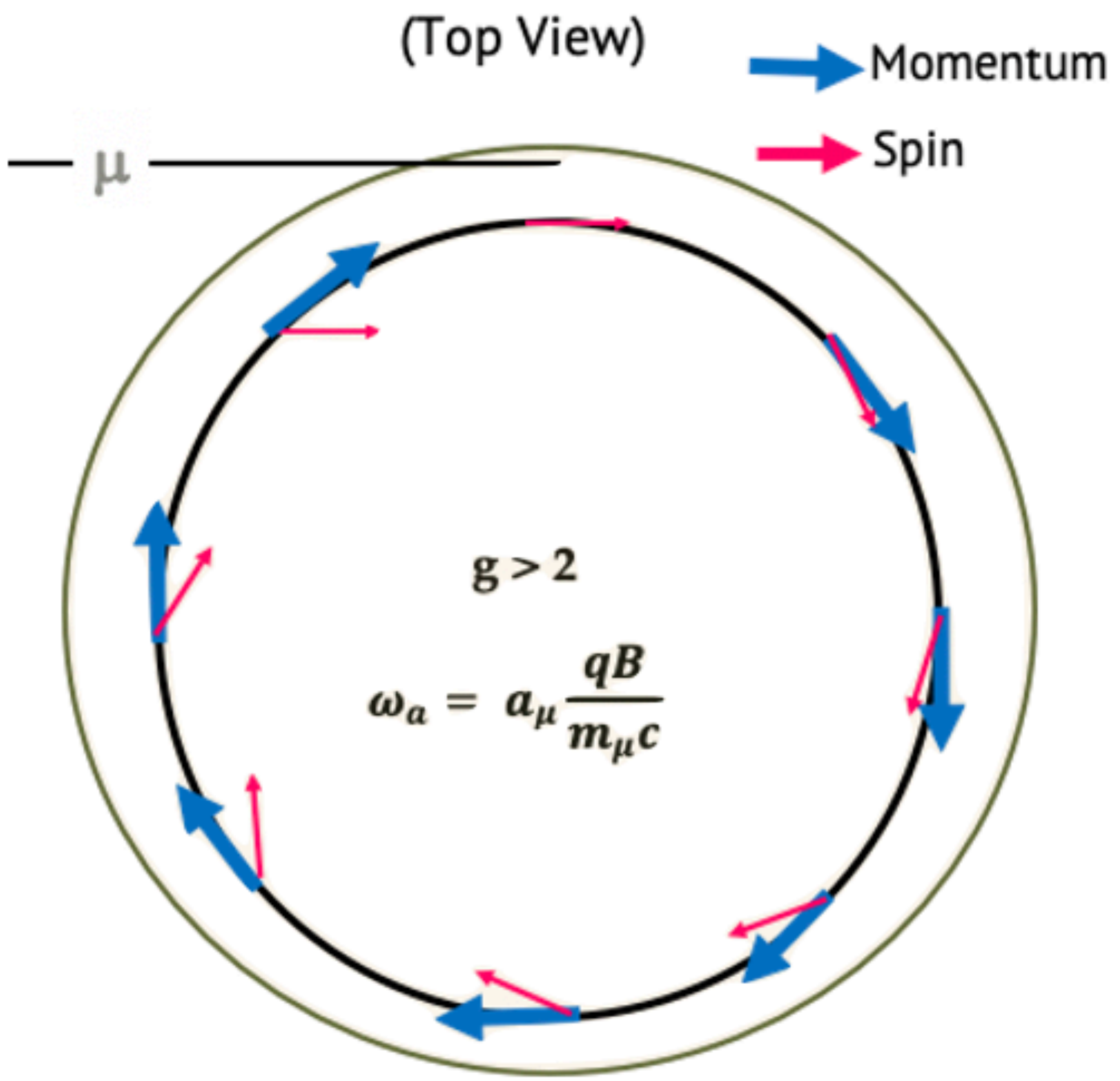
- Average magnetic field seen by the muons; measured with NMR: $\hbar\omega_p = 2\mu_p |\vec{B}|$

Cyclotron frequency

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

Larmor frequency

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



How Do We Measure a_μ ?

Measured experimentally

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

3 ppb

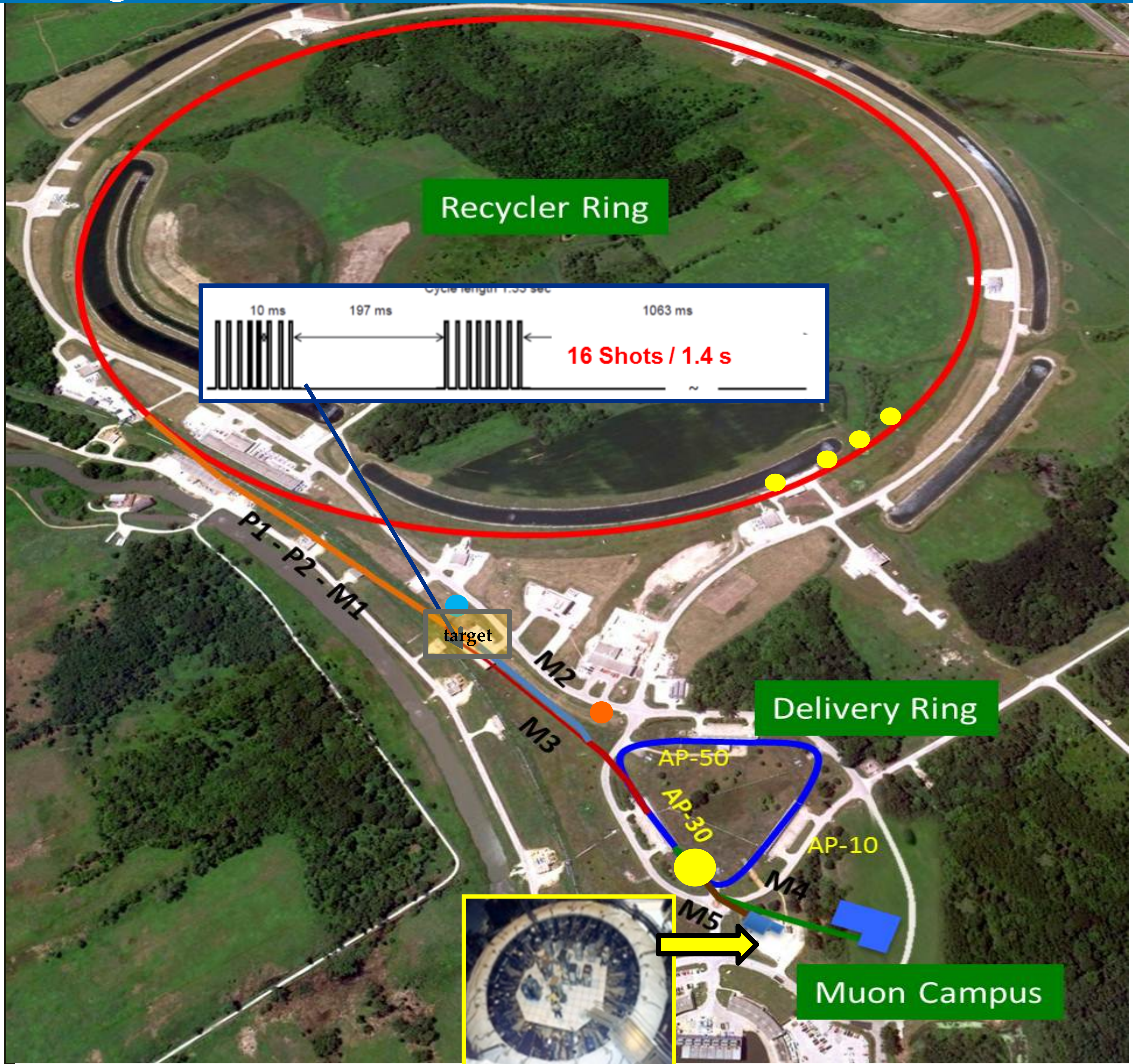
22 ppb

0.3 ppt

[1]. P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys.**88**, no. 3, 035009 (2016), doi:10.1103/RevModPhys.88.035009 [arXiv:1507.07956 [physics.atom-ph]]

Fermilab

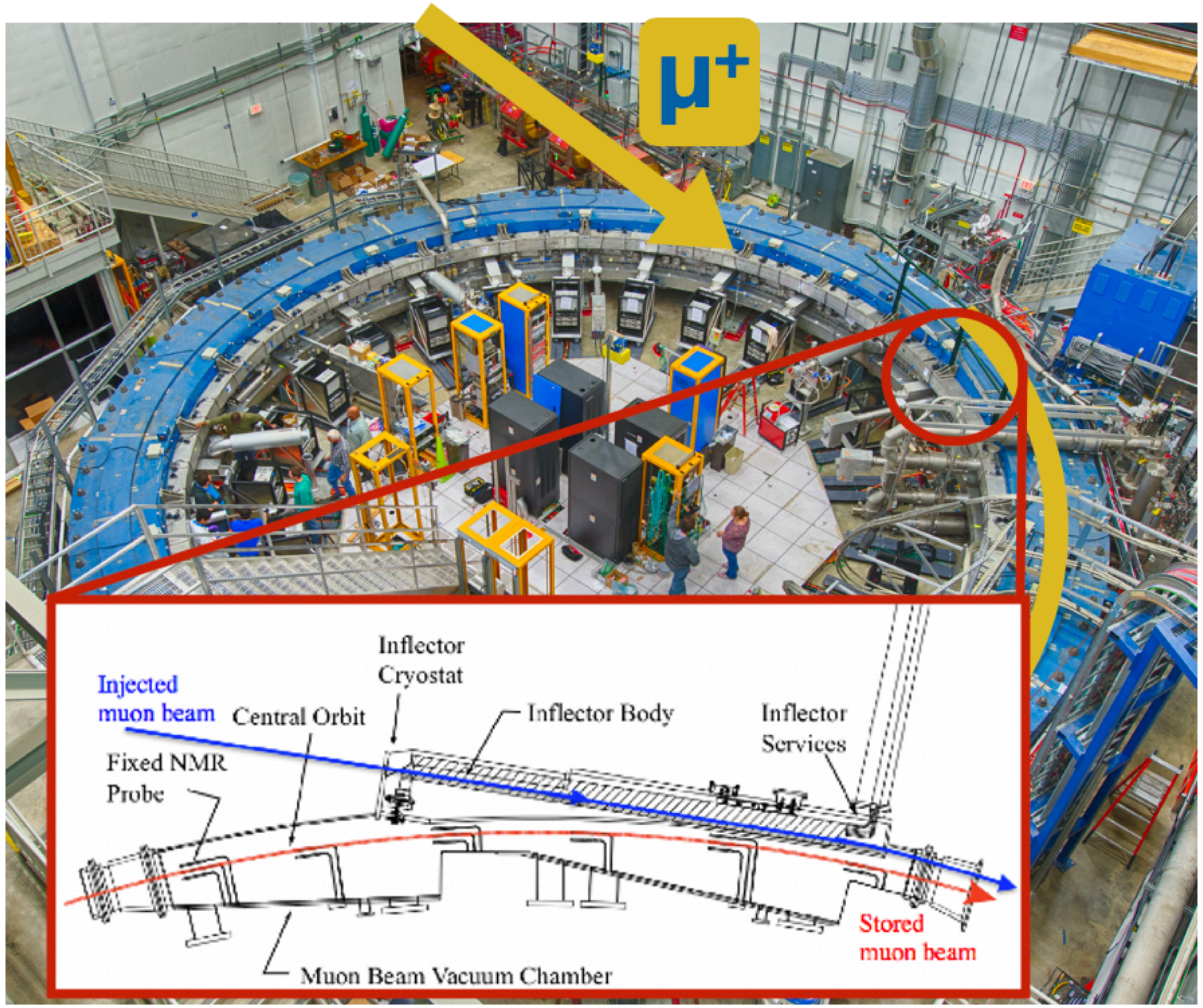
Muon g-2 Beam

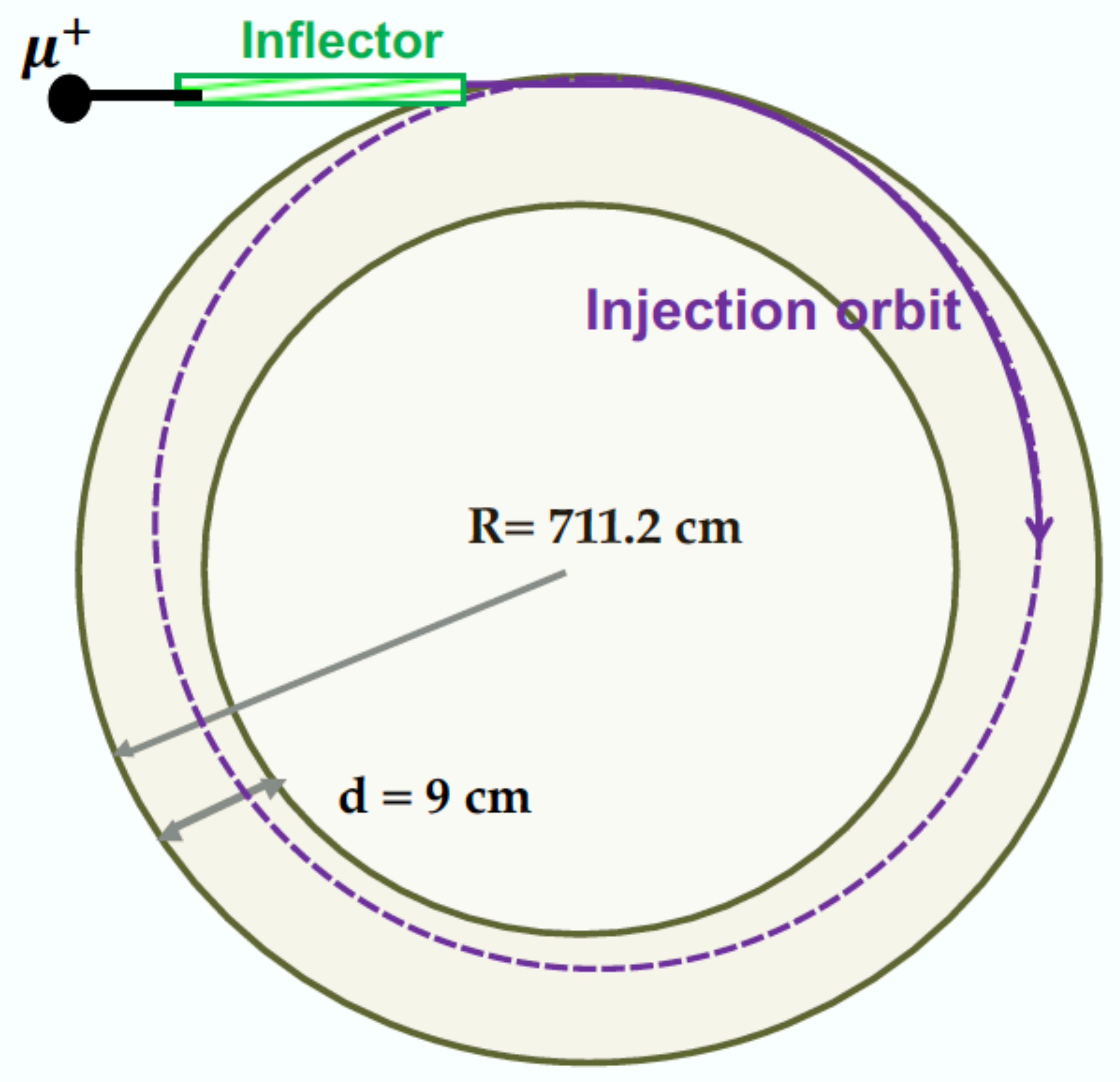


- ➢ Short batches of 8 GeV protons into Recycler
- ➢ Each batch divided into 4 bunches of 10^{12} protons each
- ➢ Extract each bunch at a time and directed to target
- ➢ Long beam line channel to collect $\pi \rightarrow \mu$
- ➢ p/π/μ beam enters DR; protons kicked out; π decay away
- ➢ ***μ* enter storage ring**

Muon Beam Injection

- Upon entering ring, all muons have spin pointing the same way (highly polarized beam)

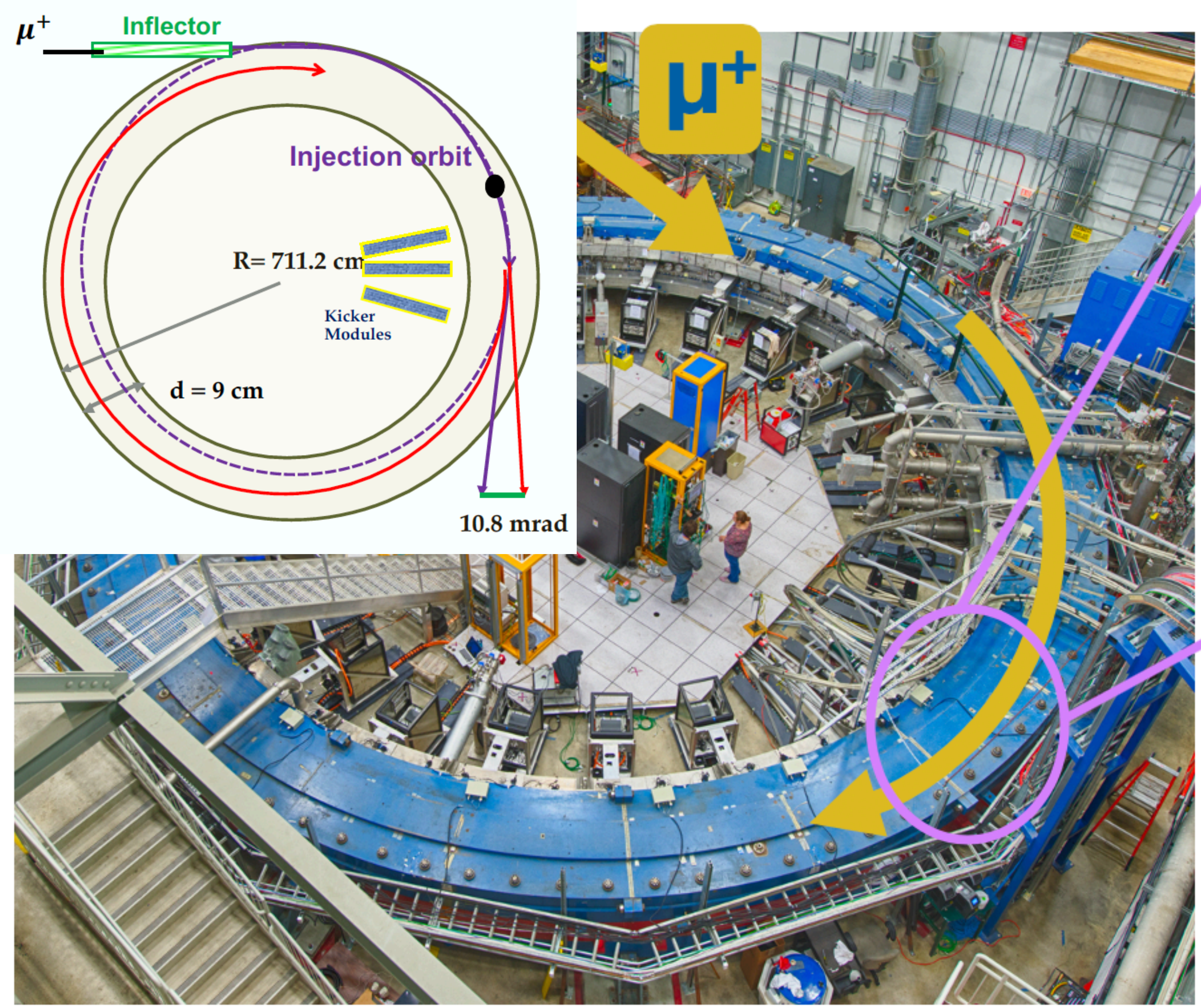


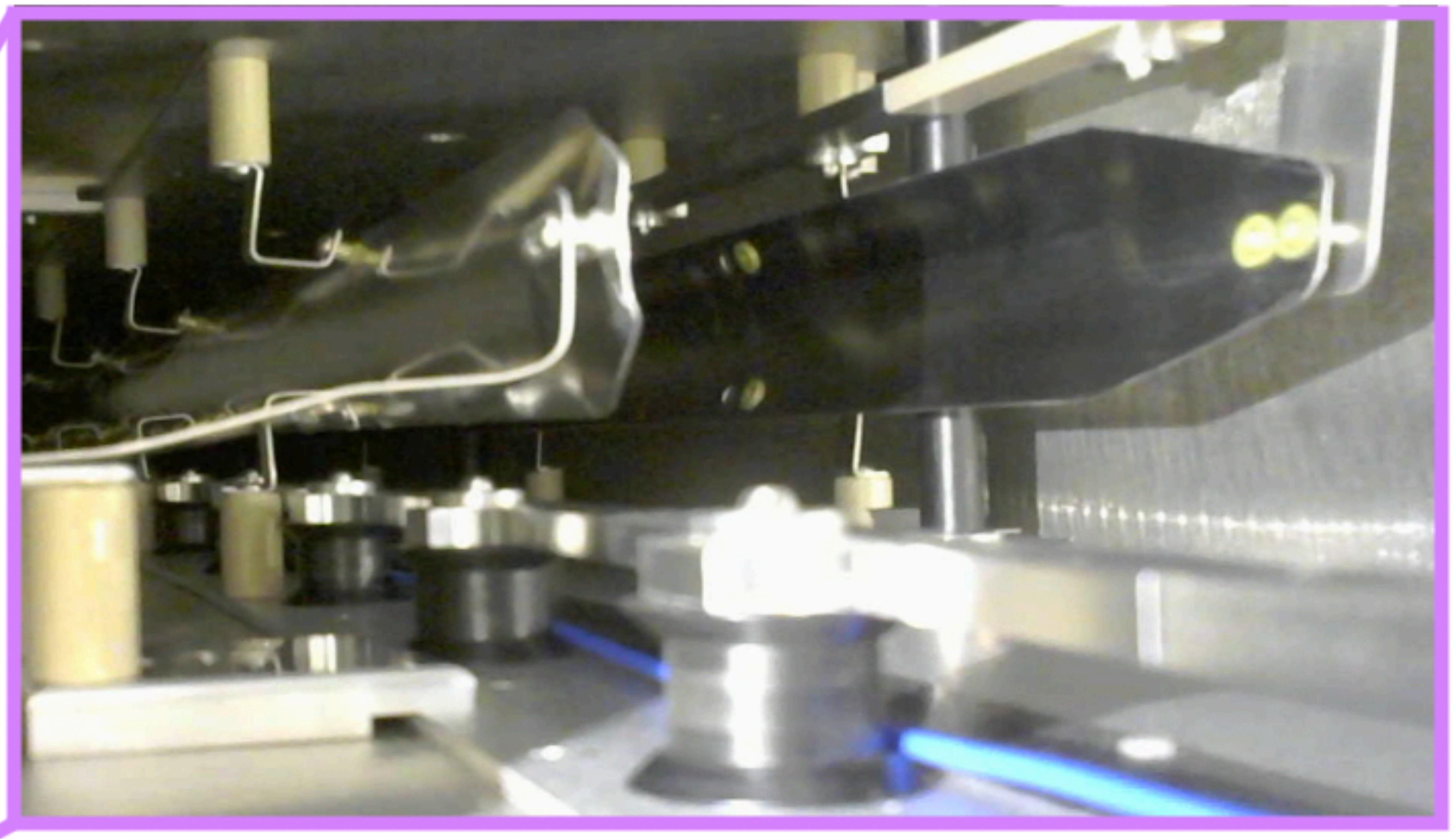


Inflector

- Cancels B field in the magnet gap & let beam enter the storage ring without being deflected
- They are at 77mm outside central closed orbit

Muon Beam Storage and Focusing





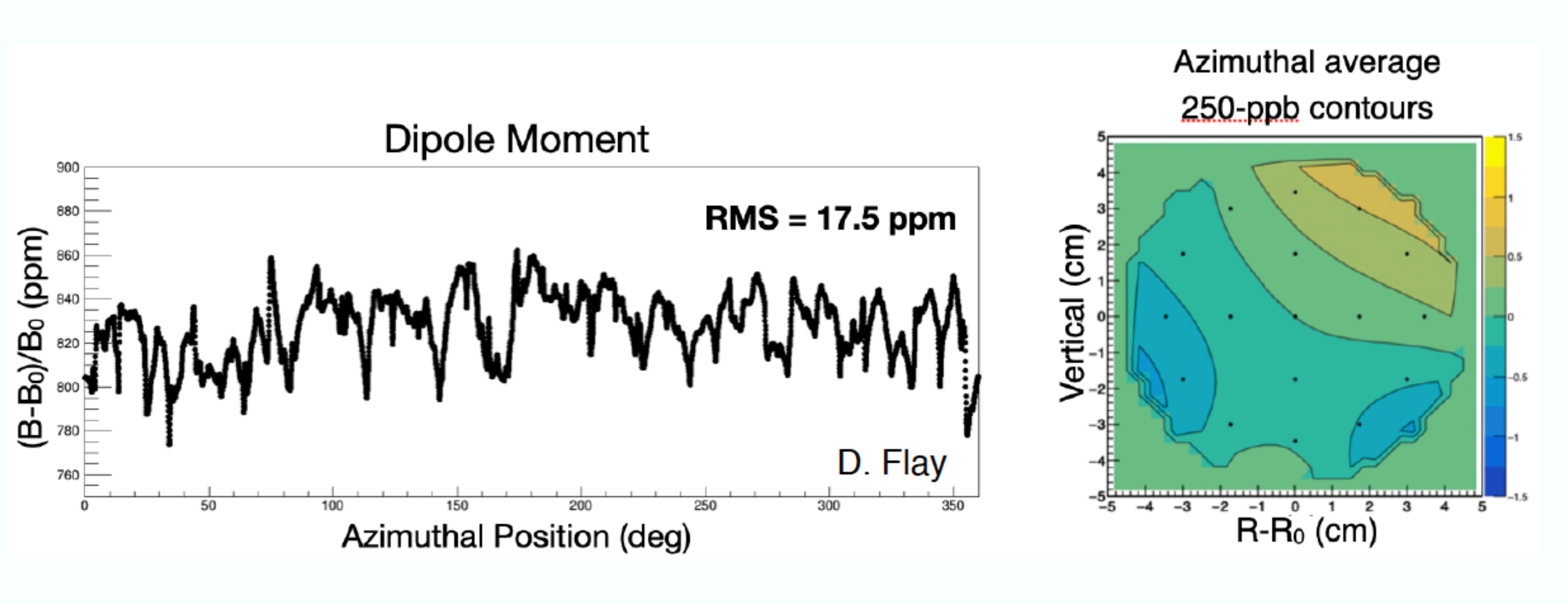
3 Magnetic Kickers

- Kick some more to direct beam into the central Orbit
- Used 10.8 mrad pulsed kick

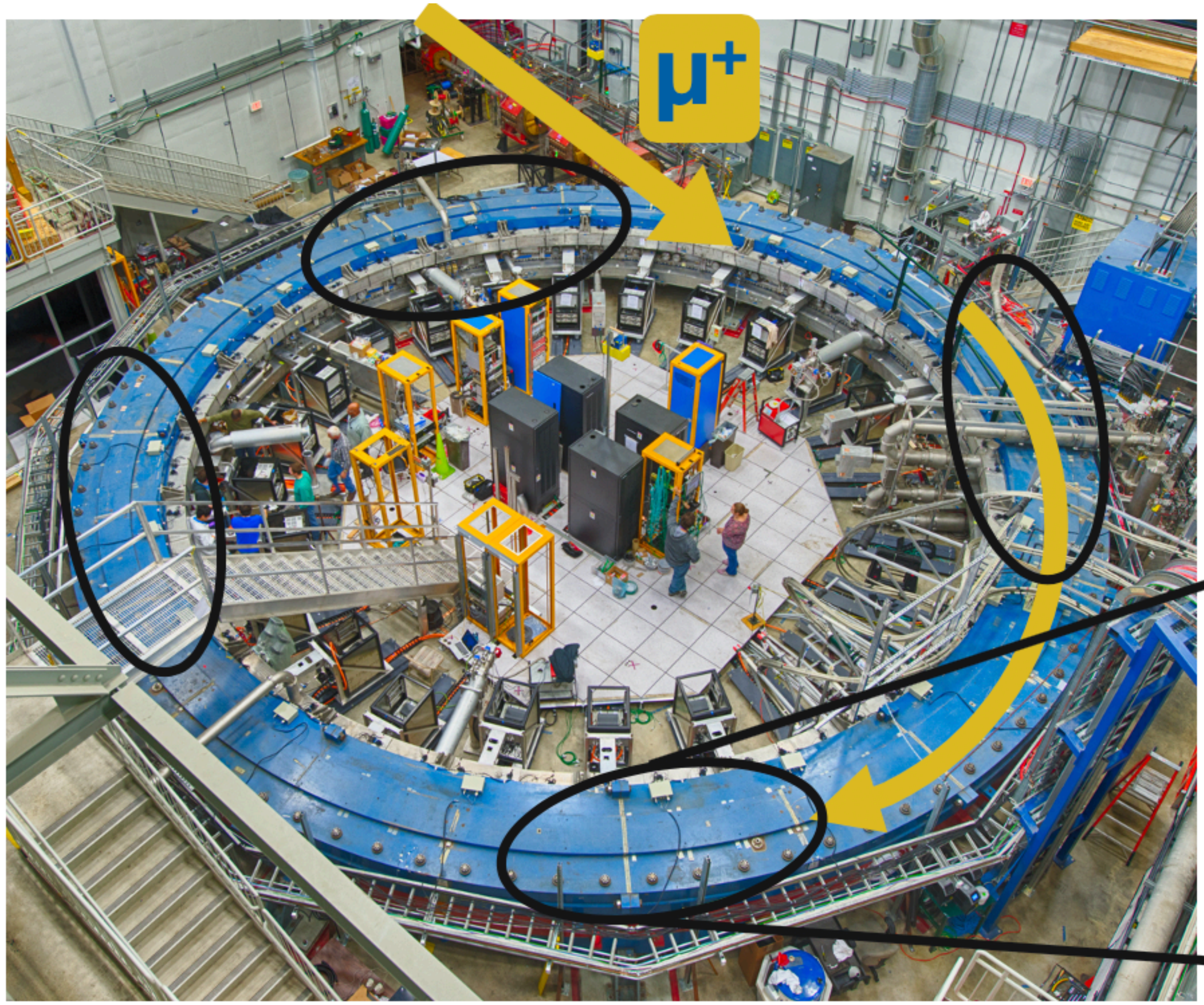
Muon Beam Storage and Focusing

Storage Ring Magnetic Field :

- Needed for physics measurement (determine ω_p at all times)
- Provides radial confinement
- Measured using a proxy: pulsed NMR of protons



Muon Beam Storage and Focusing



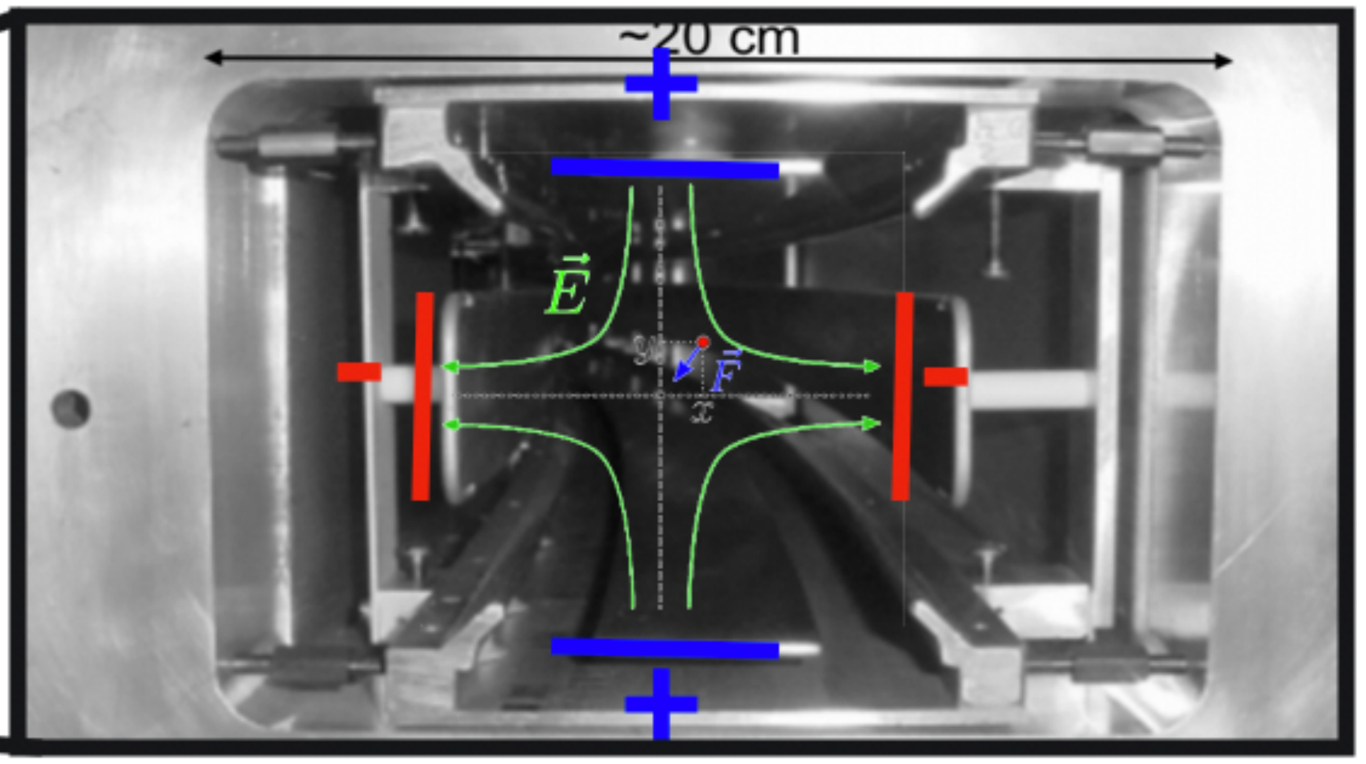
Electrostatic Quadrupoles: focuses muon beam vertically

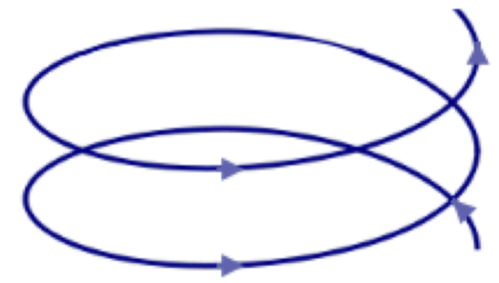
But … appears as a B field to a moving particle!

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

The magic momentum : choose γ = 29.3 (P_μ = 3.094 GeV/c)

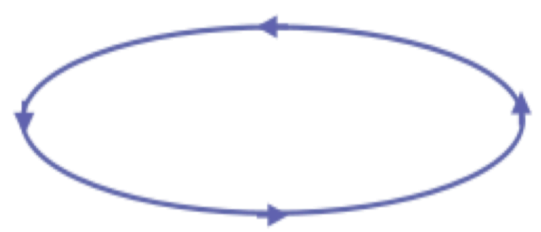
Simplifies an important correction





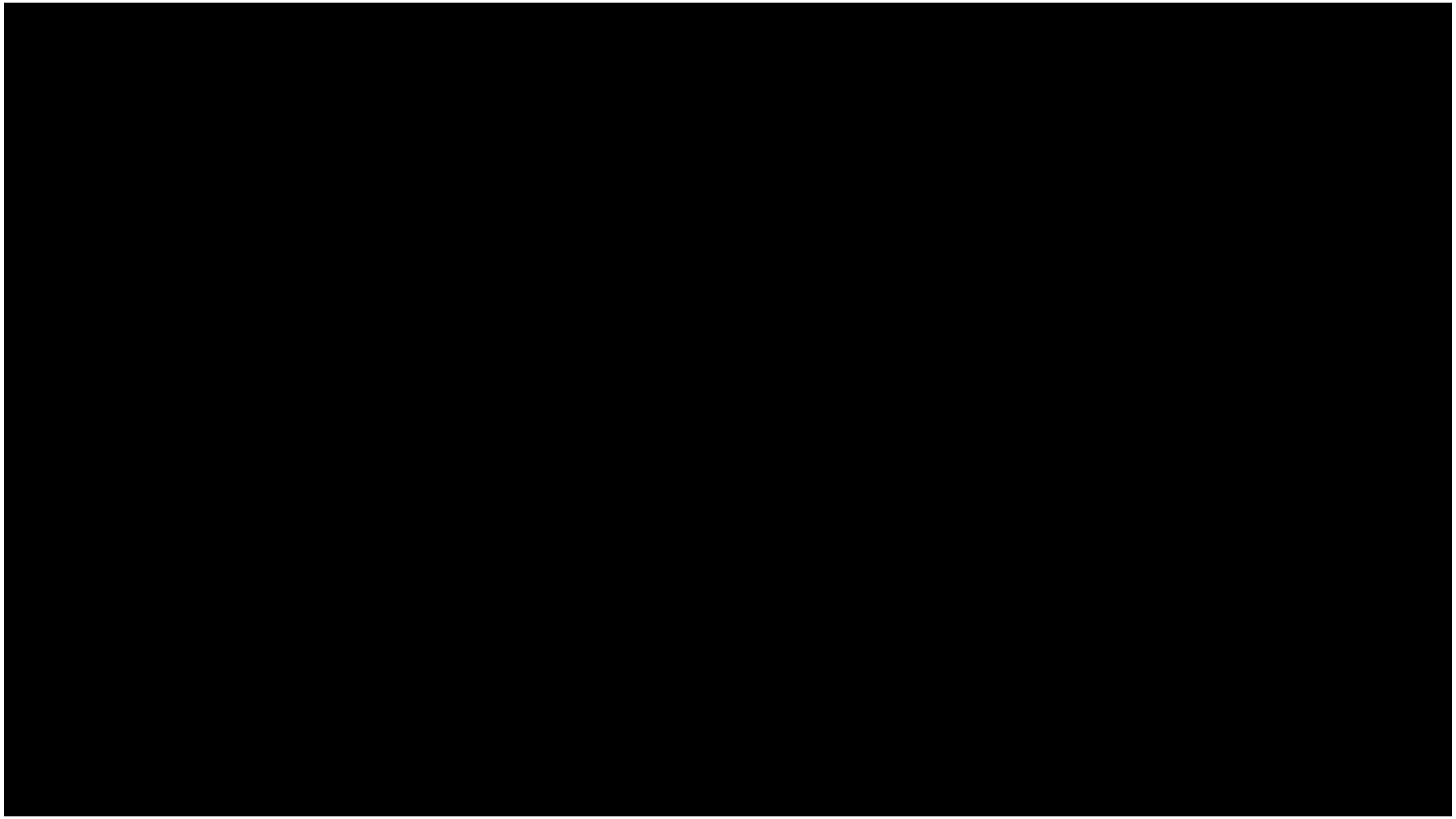
non-zero vertical momentum component without focusing

⇒



with focusing

A Muon's life inside the Storage Ring

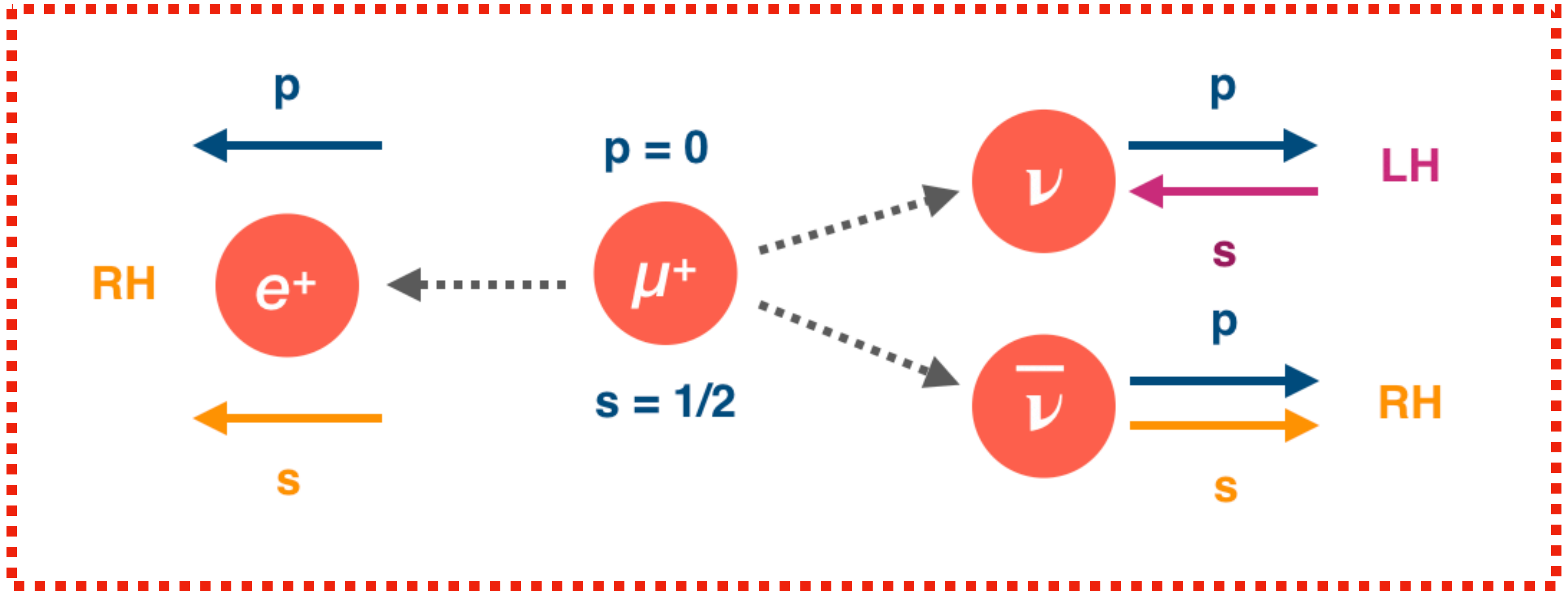


Measuring ω_a

- Upon entering ring, all muons have spin pointing the same way (highly polarized beam)
- At some random time they will spontaneously decay to e+

How do muons decay???

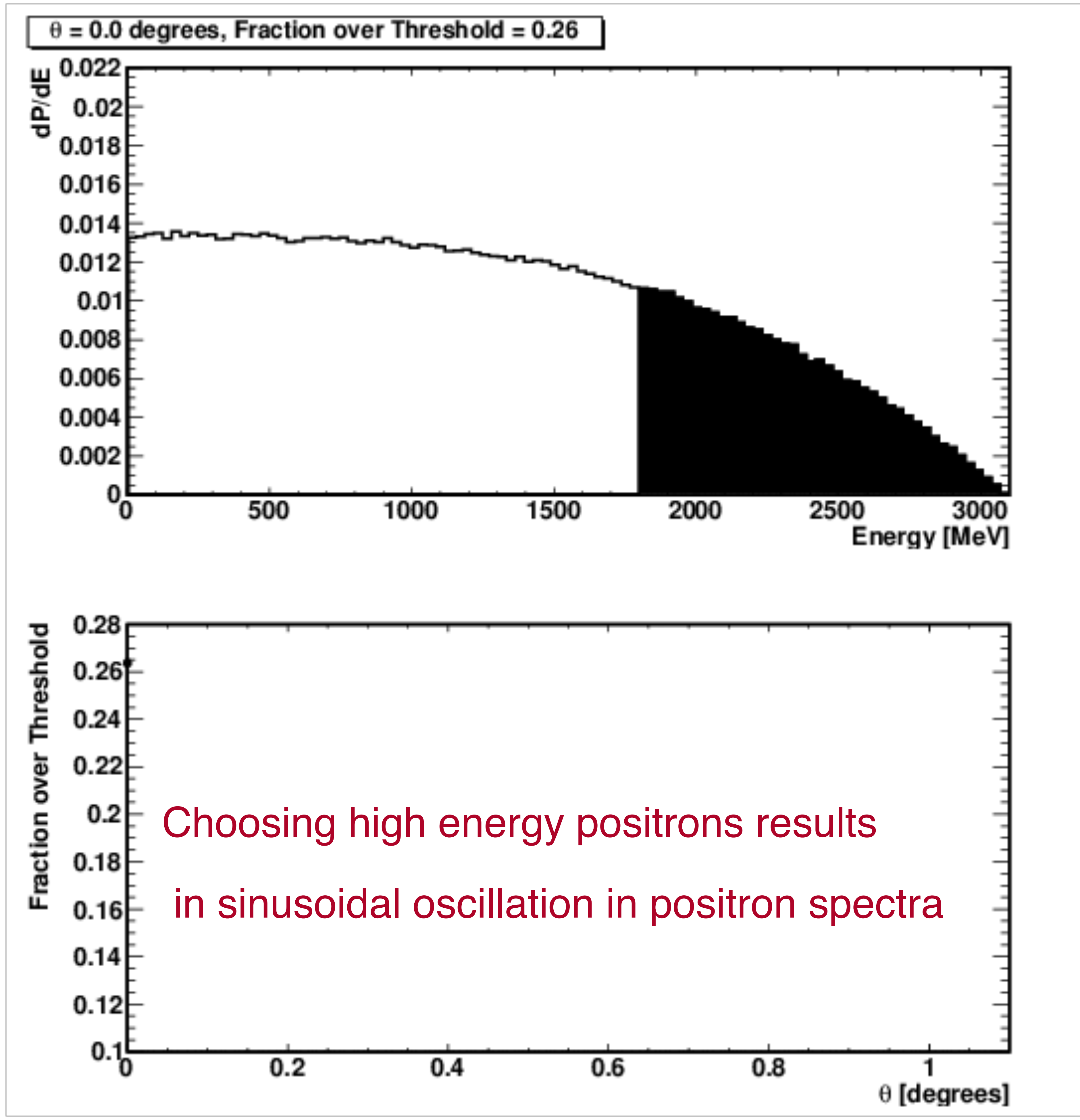
The e+ 'carries' the spin of its parent muon
We can infer the spin direction of muons by measuring the emitted positrons…



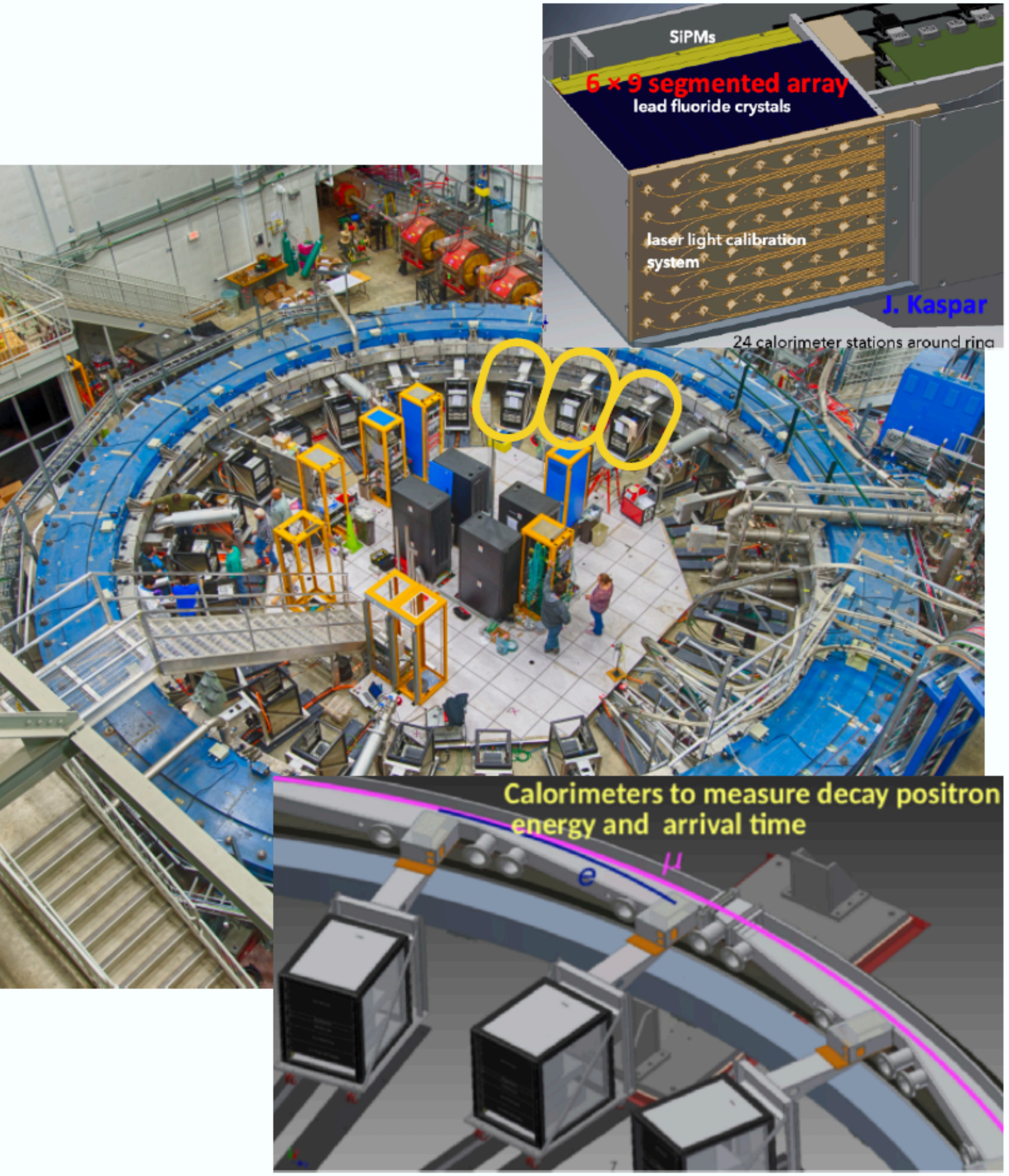
Measuring ω_a

- Two important features of muon decay allows us to measure ω_a directly

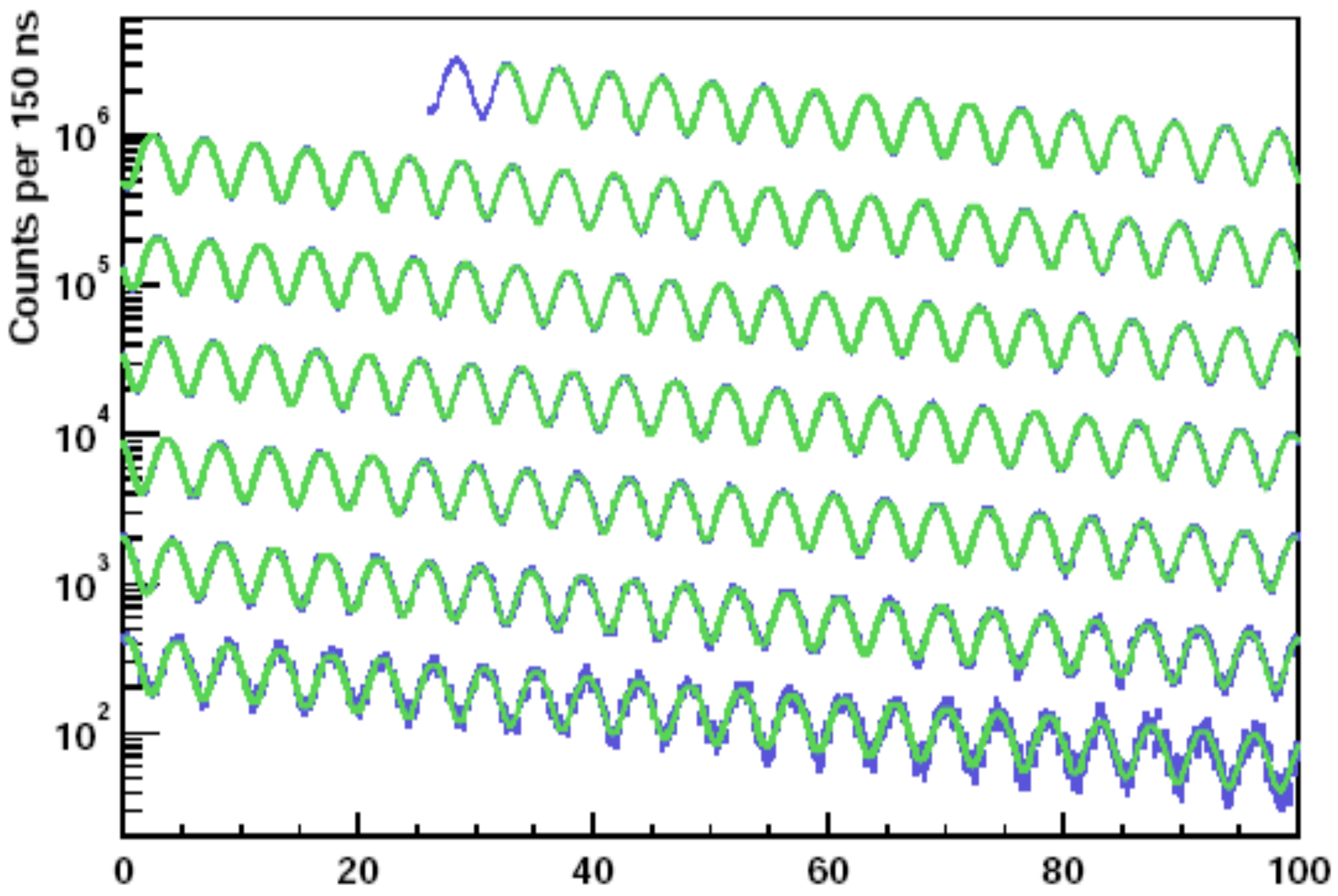
- Higher energy positrons are emitted preferentially in the direction of muon spin → Highest energy positrons have the strongest correlation b/w their momentum and spin direction



The Wiggle Plot!



- 24 calorimeters stationed around the ring
- The emitted e+ have lower momentum than the parent muons, so they curl into the center of the ring
- Signal in detectors carries information on muon spin



~1.8 GeV energy cut on decay e+ events to see a wiggle plot

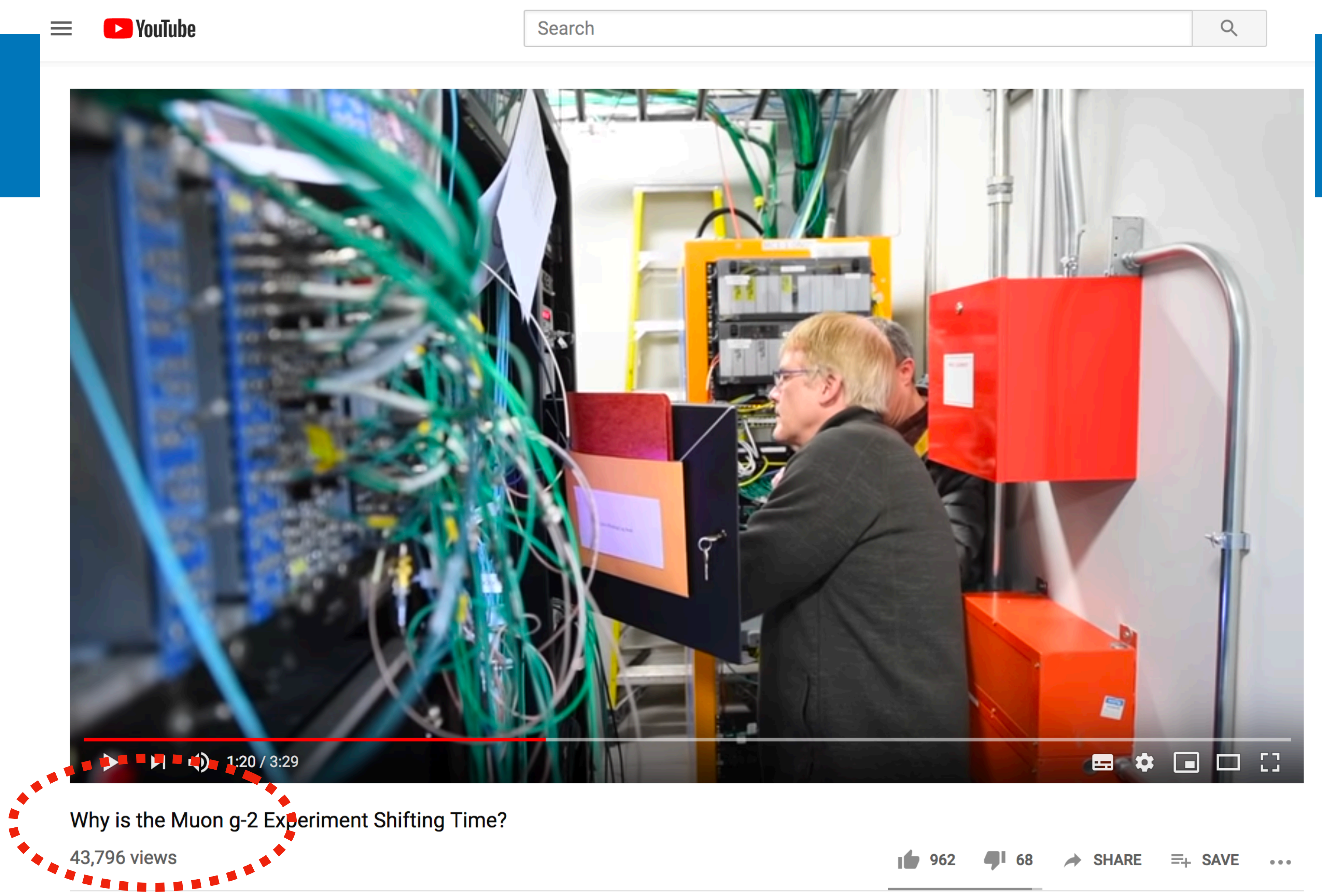
- Frequency in wiggle plot is the frequency of precession due to the anomalous magnetic moment
- Fit the wiggle and extract ω_a

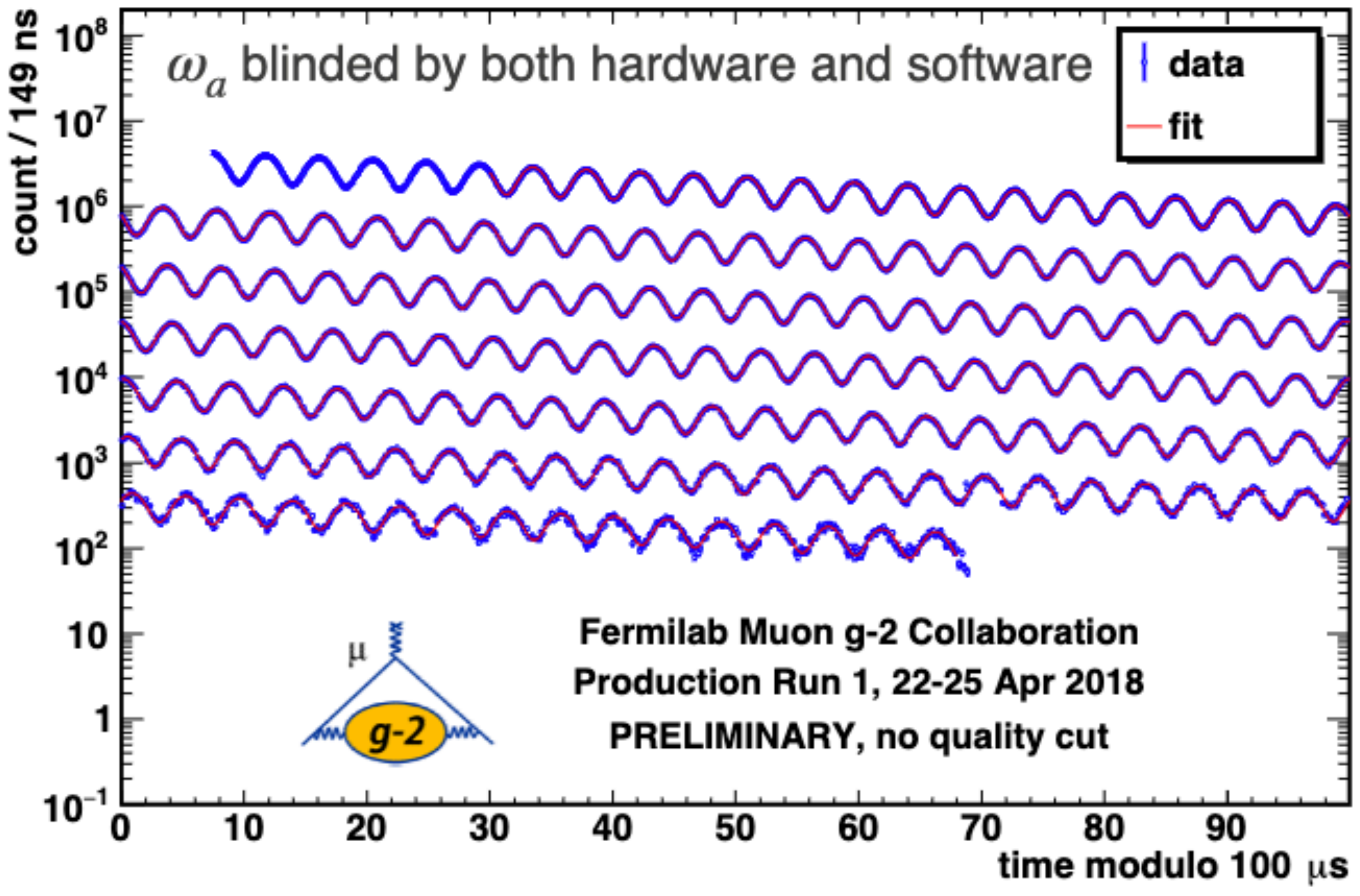
Fermilab

What's the answer?!?!

- We want to fit the wiggle and get the number!
- But this is a problem if you know what you want the number to be!
- Solution: **blind master clock system (shift nominal 40 MHz frequency by some value (±25 ppm)**
- Exact value of the shift is known by only 2 FNAL personnels!
- Additional software blinding!

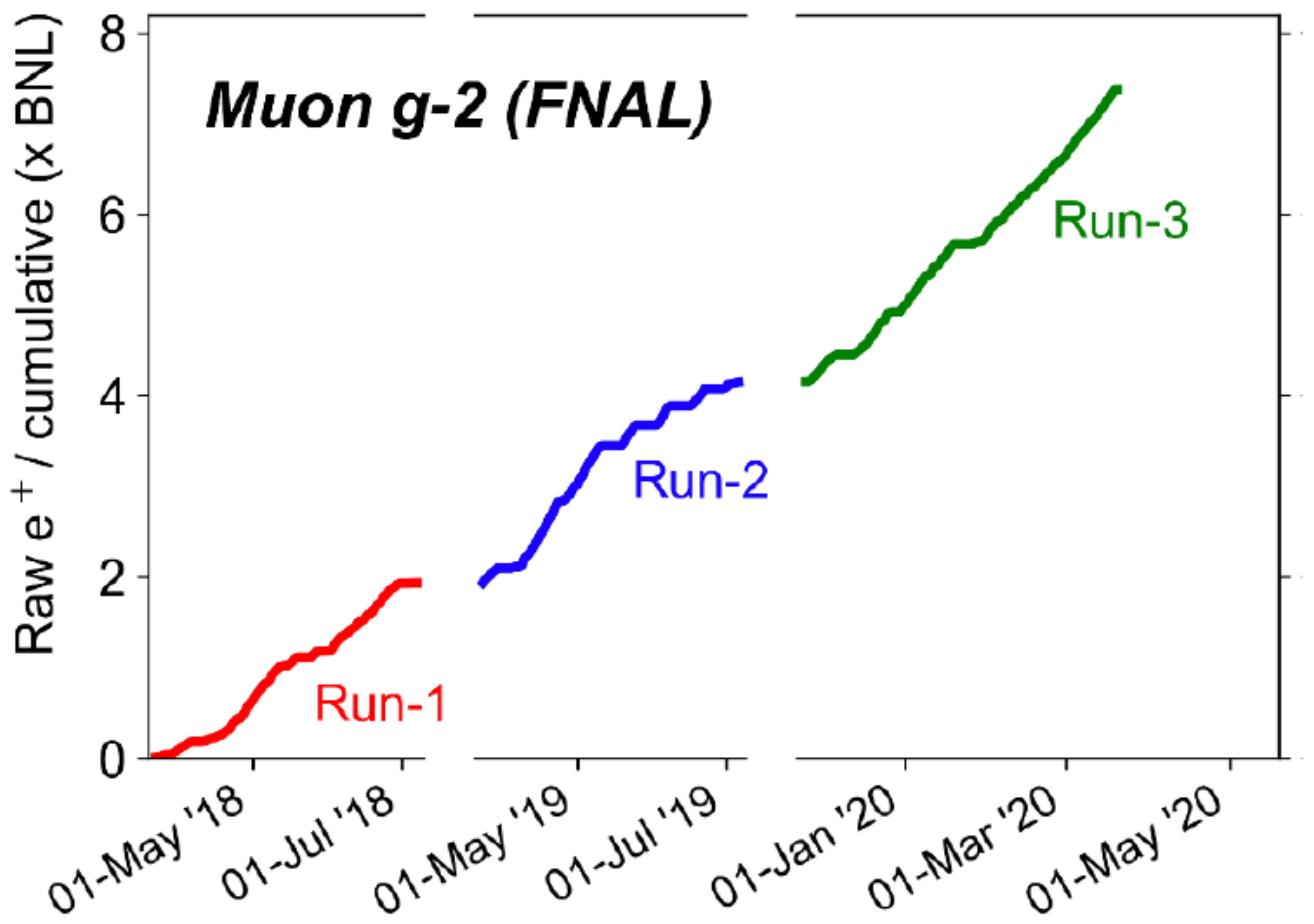
- **We won't know the answer until we 'unblind' — it will be an exciting moment!**





What's Next

- The g-2 experiment has just finished run 3 with improved kick and field stability
- Total of 6.5X BNL statistics collected
- After applying data quality cuts:
  - Run1 ~ 1 BNL
  - Run2 ~ 2.2 BNL
  - Run3 ~ 3.2 BNL
- Run2 first phase of analysis has started
- Run4 is expected to begin in Fall 2020

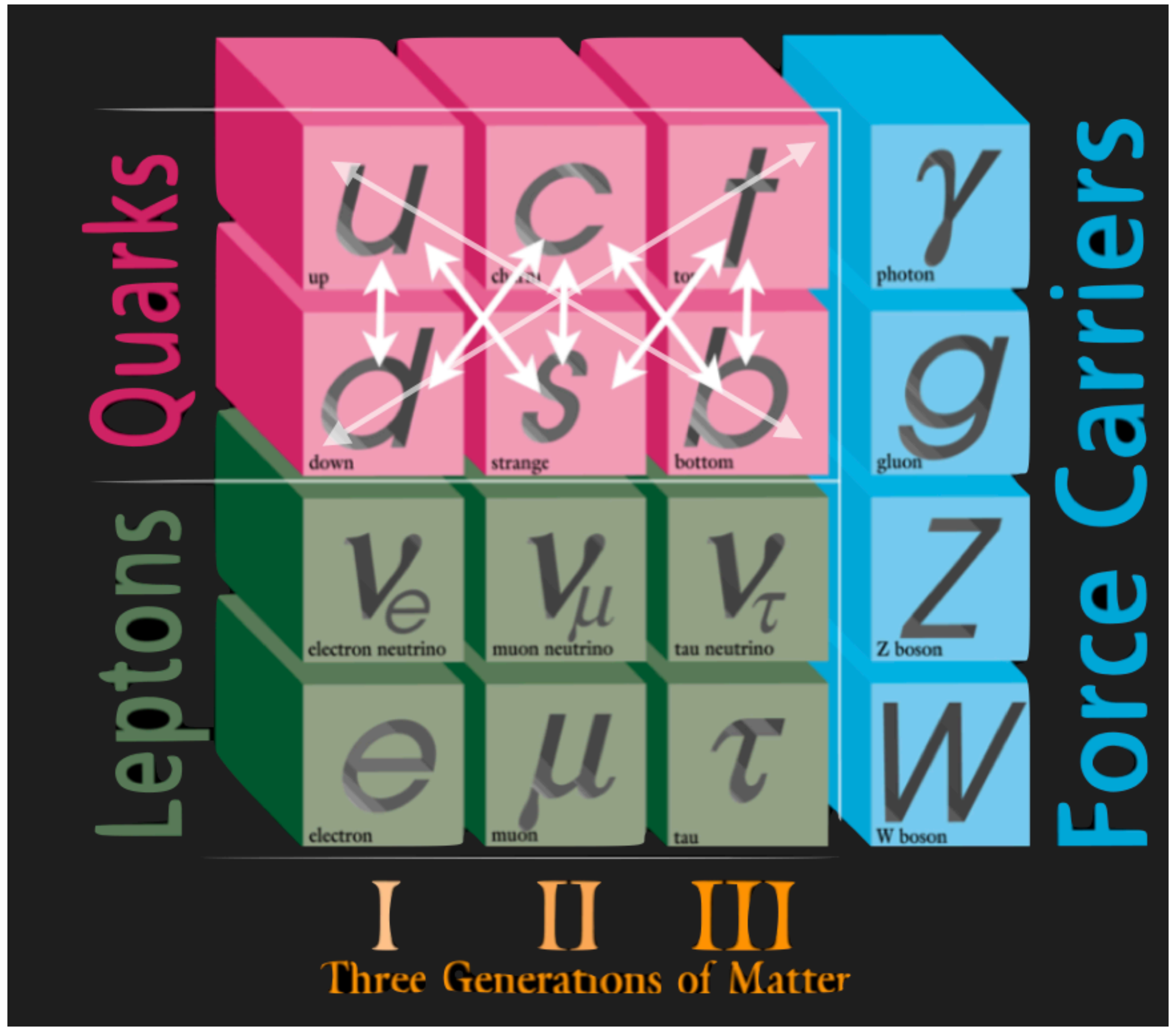


Run1 is close to being published!

Charged Lepton Flavor Violation: the Mu2e experiment

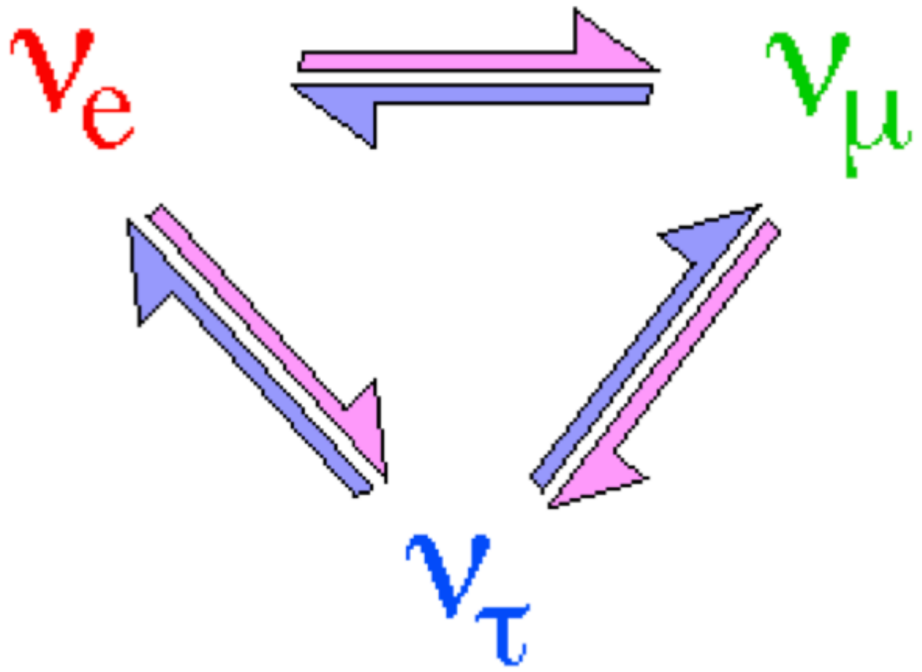
Flavor Violation in Standard Model

- Quarks display flavor violation, they mix via exchange of W



- Discovery of neutrino oscillations (Neutrinos have small mass and mix)

→ direct evidence that lepton flavor is not a conserved quantity



Is this a sign of BSM physics?

Yes it is!

Flavor Violation in Standard Model

- What about **C**harged **L**epton **F**lavor **V**iolation (**CLFV**) ?
  - A transition among charged leptons: e, μ, τ that **does not conserve lepton family number** is known as CLFV
  - Example of lepton flavor conservation is a muon decay **:** $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$
  - Example of CLFV:

$$\mu^- \rightarrow e^-\gamma \qquad h \rightarrow \mu^-\tau^+$$

$$\tau^- \rightarrow \mu^-\mu^+\mu^- \qquad \pi^0 \rightarrow e^-\mu^+$$

$$K_L^0 \rightarrow \pi^0 e^-\mu^+ \qquad \ldots$$

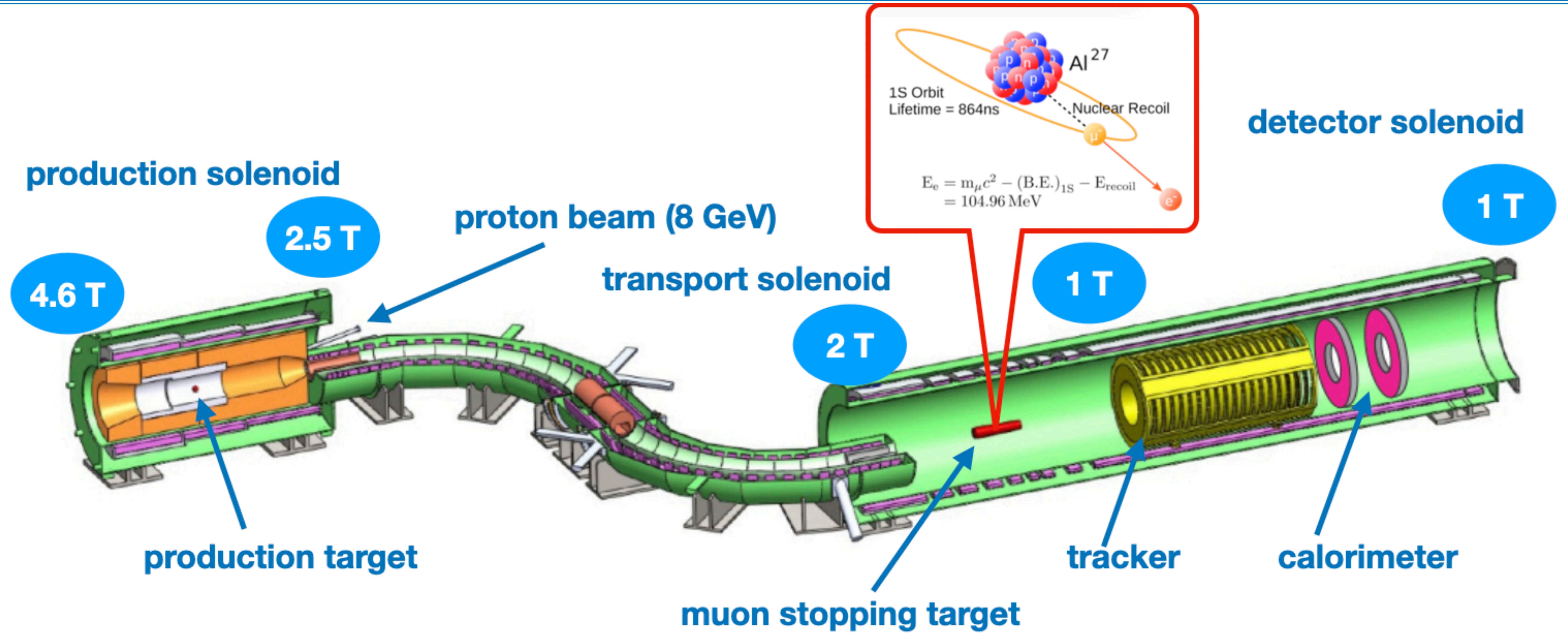
Heavily suppressed in the SM — forbidden by conservation law!

Never observed yet!

Discovery of Charged Lepton Flavor Violation is New Physics!

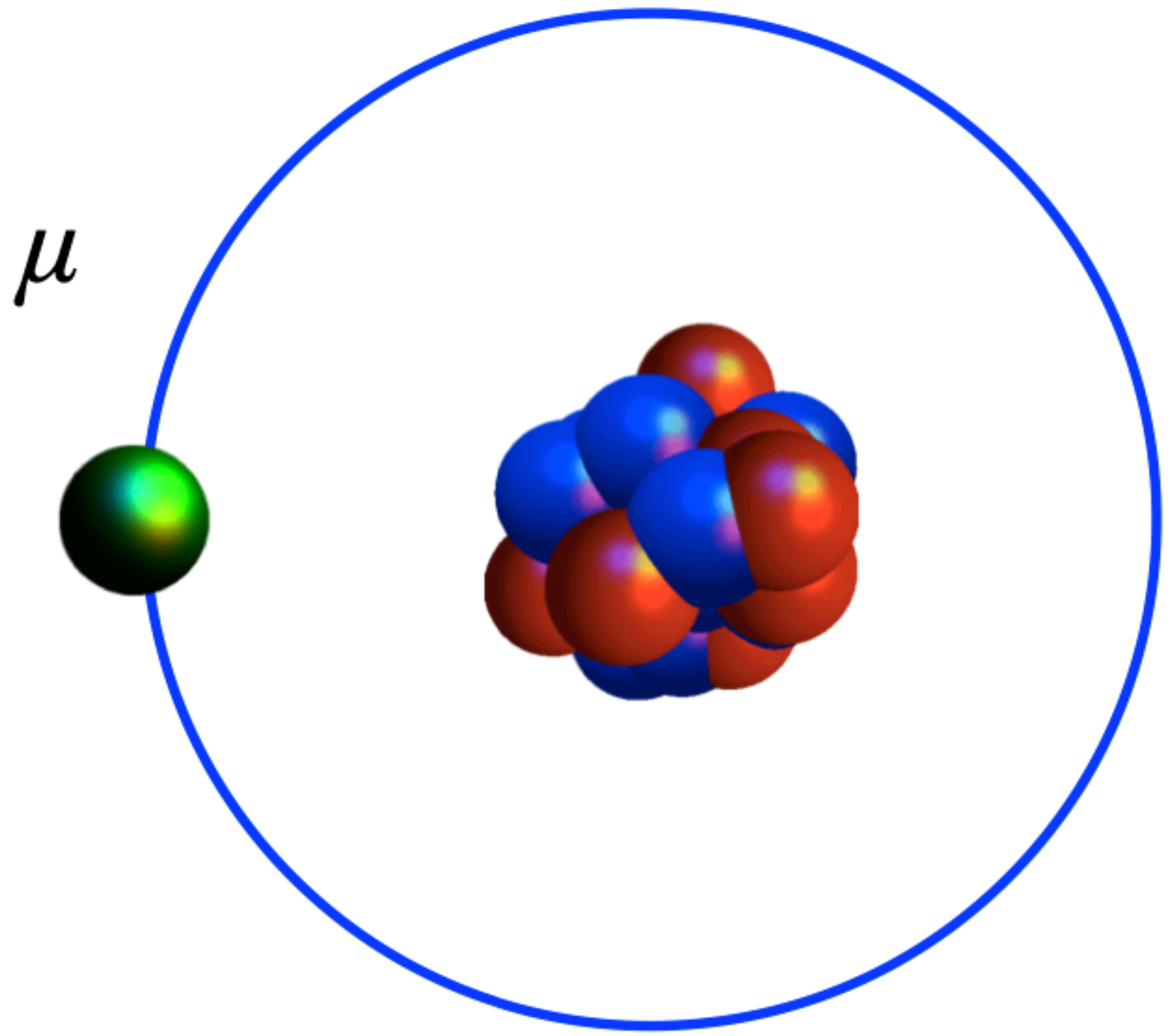
The Mu2e Experiment

Goal: search for muons that spontaneously convert to electrons in the field of a nucleus ($\mu N \rightarrow eN$)



- 8 GeV, 8 kW proton beam incident on tungsten target inside superconducting solenoid
- Capture μ^- s and guide through the S-shaped region (selects low momentum μ^- s only!) to the Al stopping target's atomic orbit
- Stop muons in orbit around an aluminum nucleus and check for outgoing e^-

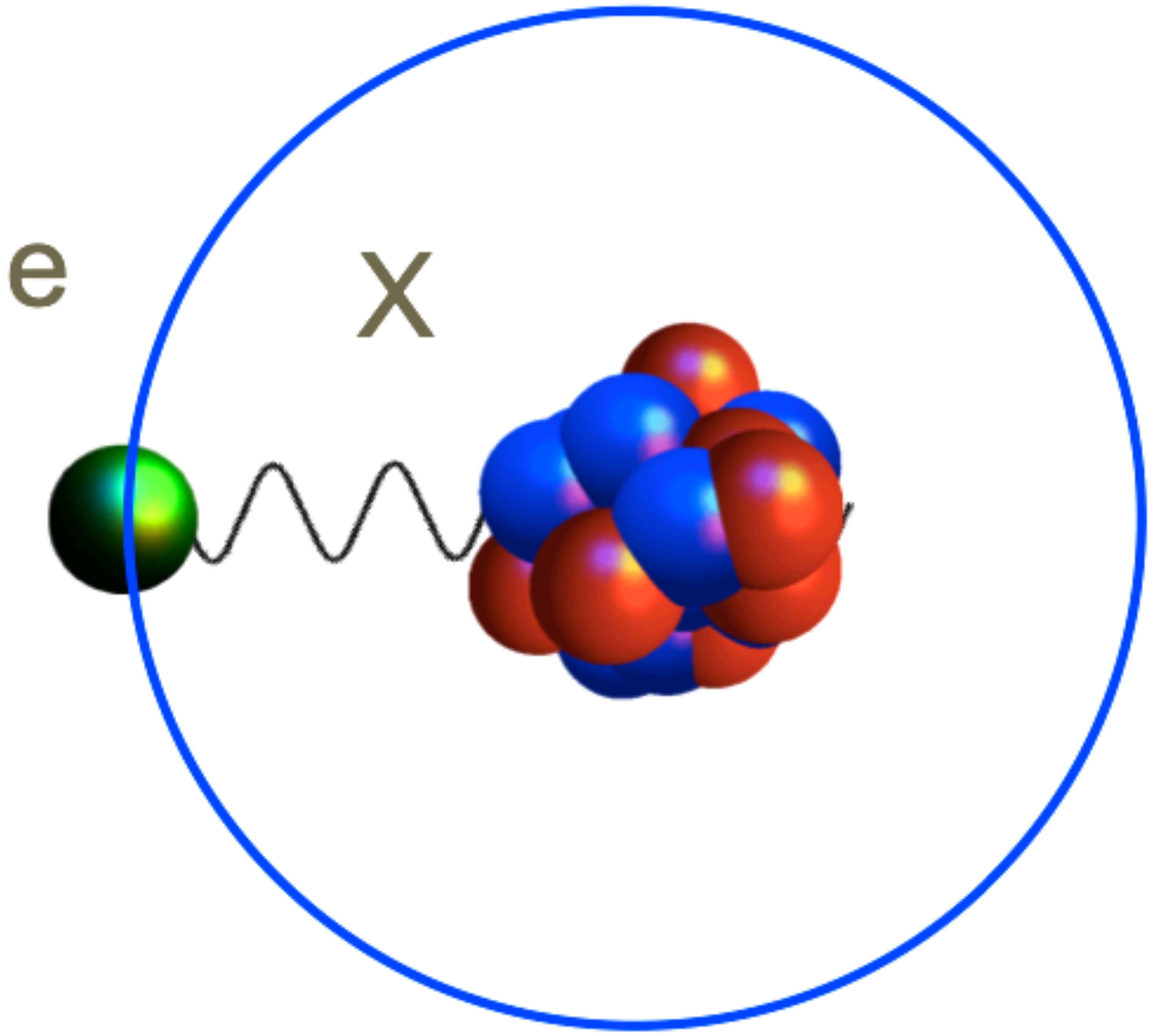
Signal



Two body conversion
μN —> eN

Nucleus delays muon from decaying → muon has more time to convert

Signal



Two body conversion
$\mu N \longrightarrow eN$

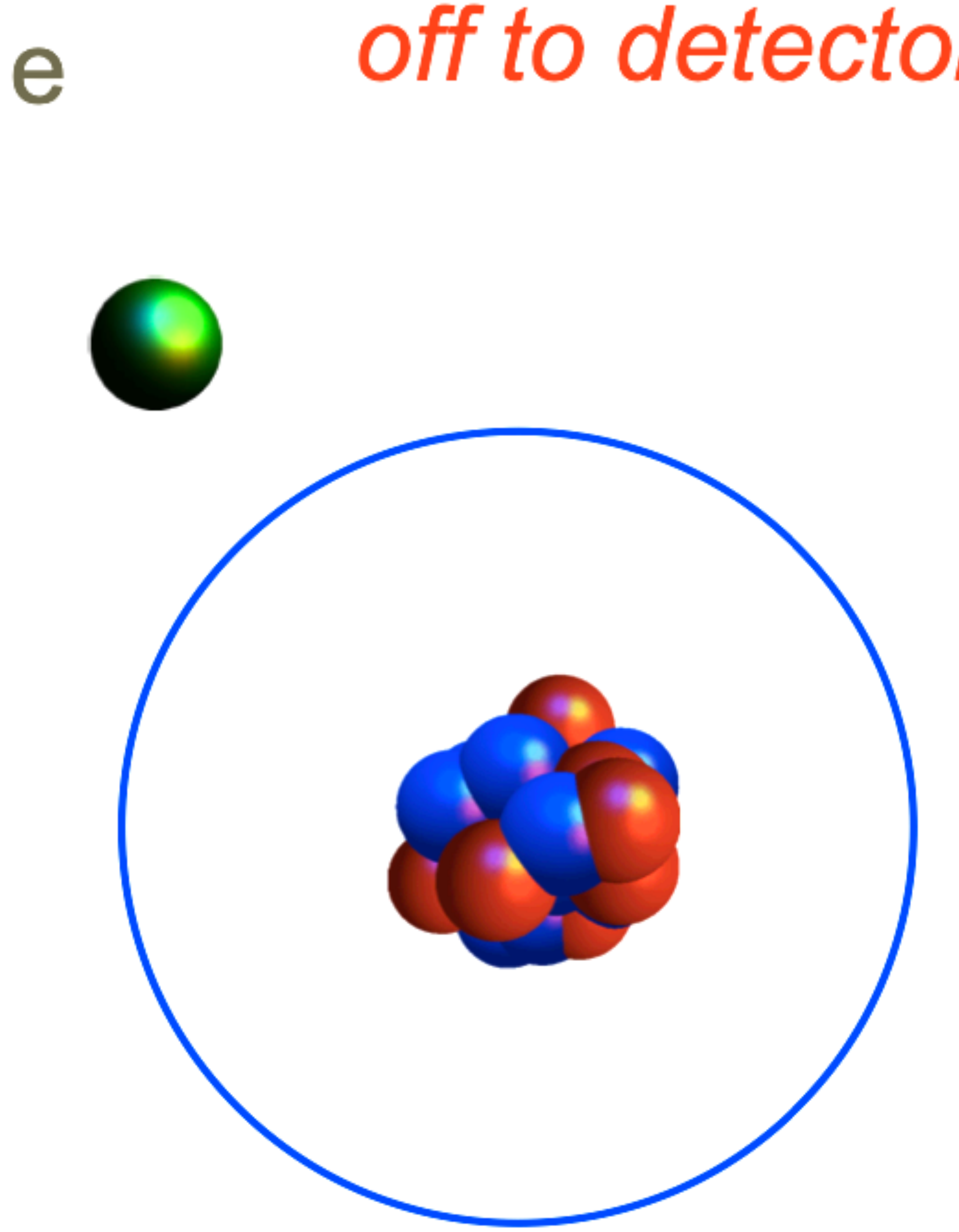
Mono-energetic e^-

- Muon converts to an electron
- Entire difference in mass between the muon and electron must be converted into kinetic energy of the resulting electron

The Mu2e Experiment

Signal

off to detector!



$$E_e = m_\mu - E_{recoil} - E_{1S,BindingEnergy}$$

for Al, E_e = 104.97 MeV

Two body conversion
μN —> eN

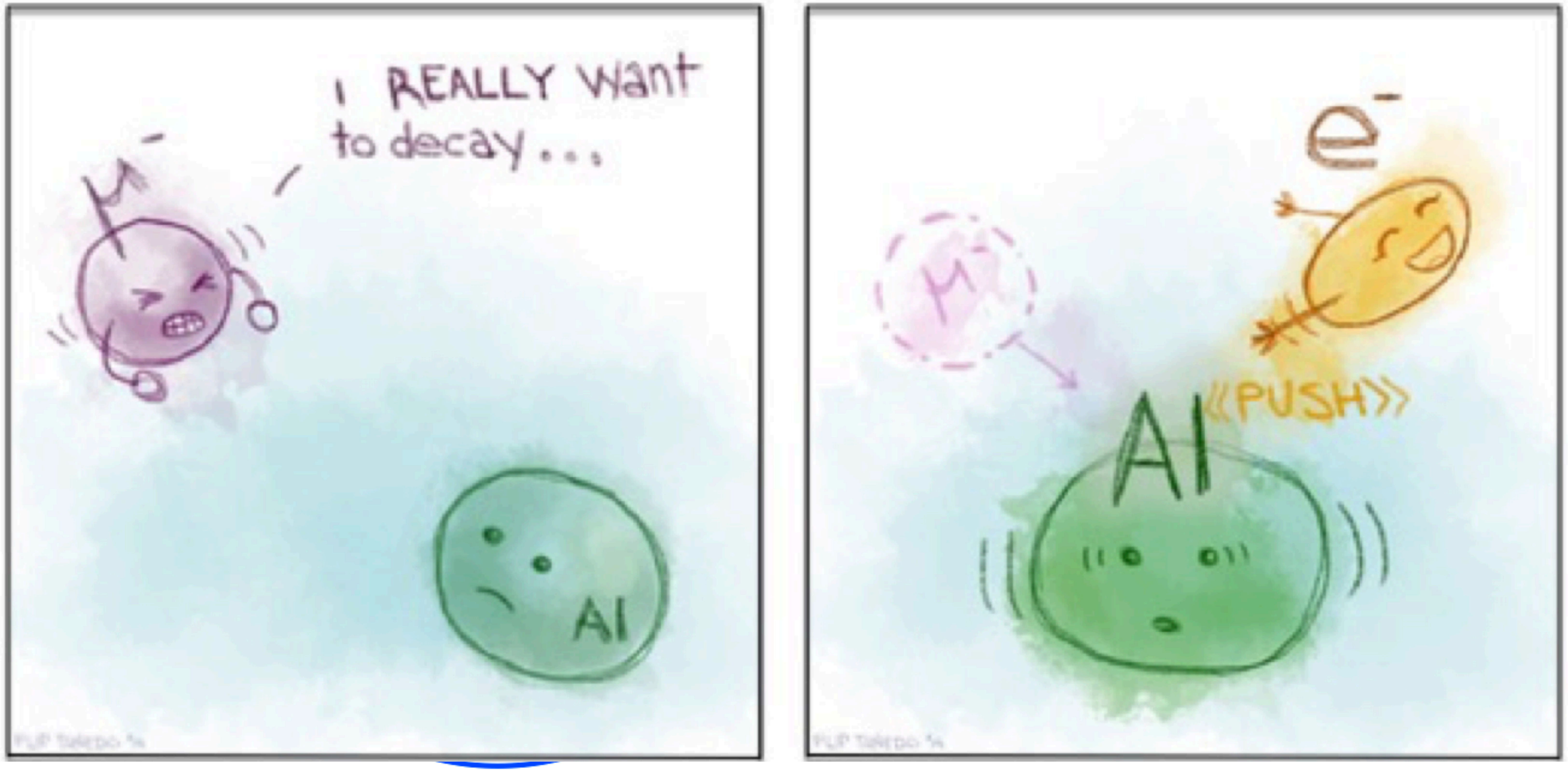
Mono-energetic e^-

- Want to detect ~105 MeV e^- using detectors: tracker (e^- momenta, trajectory), calorimeter (*E*, *t*, PID)
- **Look for one event in 10^{18} !!!!**
  (similar to looking for one grain of sand out of all the grains of sand in the world !!!!!)
- **Need 10^{10} muons stopped at Aluminum target per second**

Nucleus coherently recoils off outgoing e^-! It does not break up!

Signal

off to detector!



'nergy

Two body deca
μN —> eN

Mono-energeti

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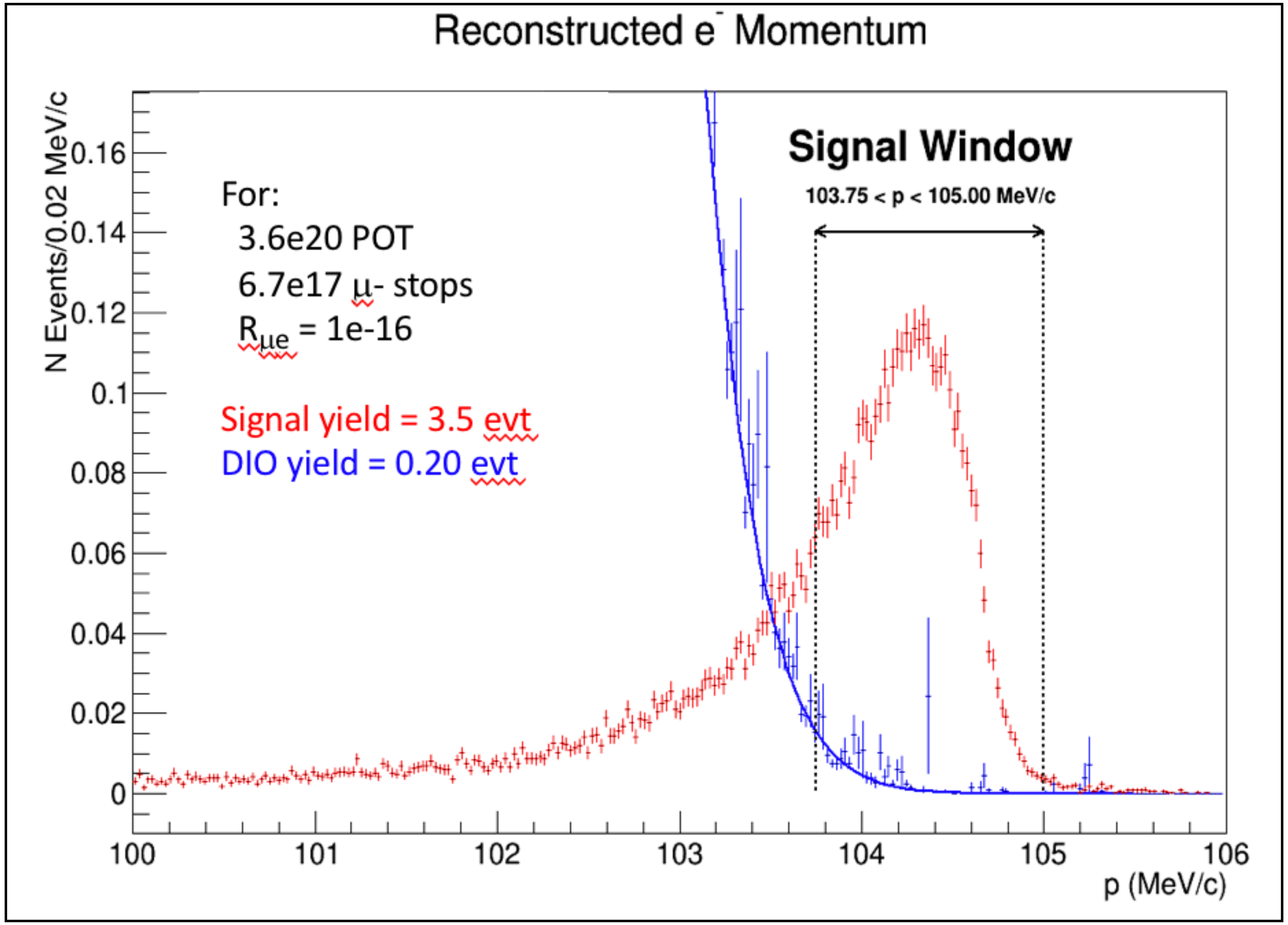
Nucleus coherently recoils off outgoing e-! It does not break up!

Signal & Background

MC simulation

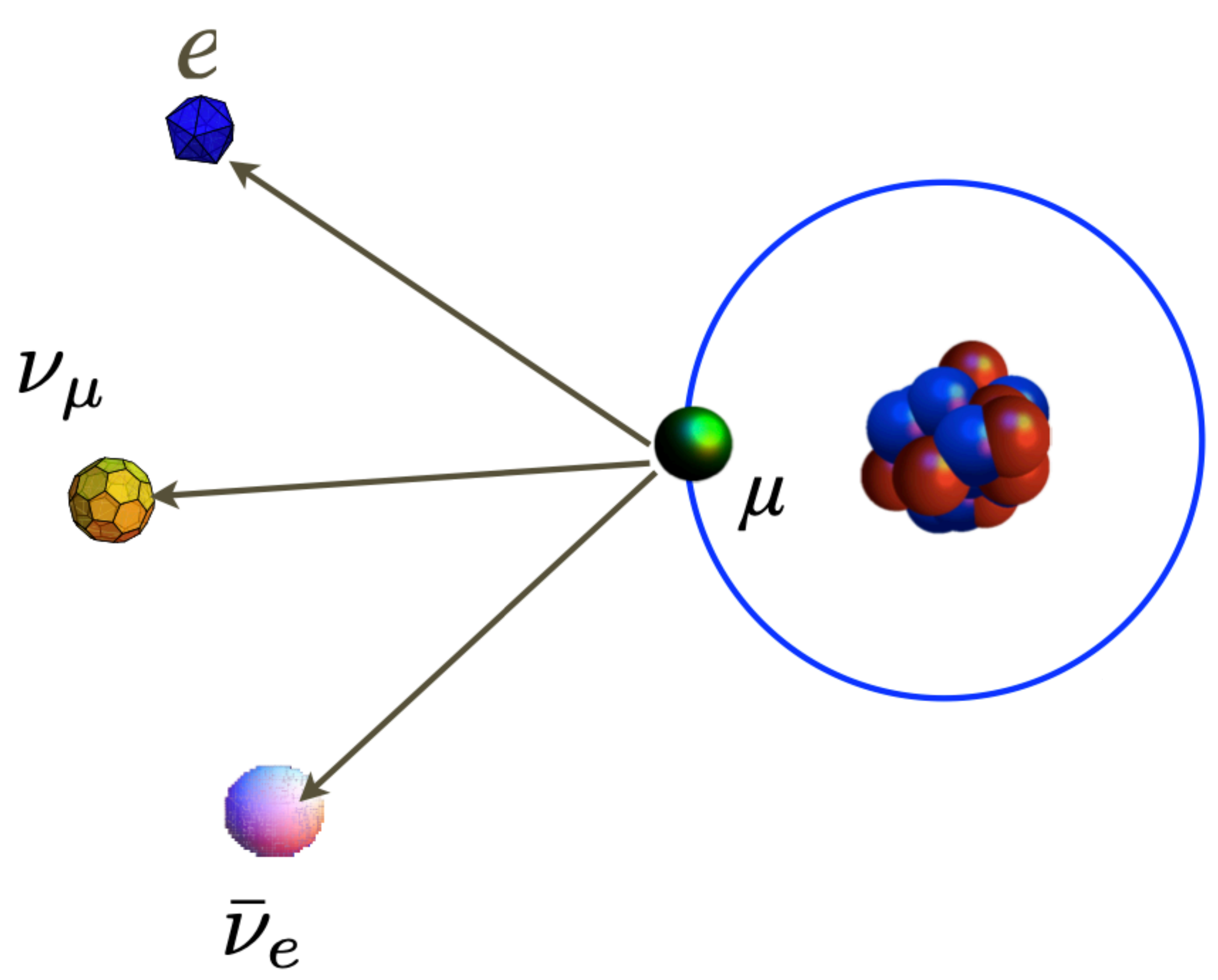


The Mu2e Experiment

What about backgrounds ("Other things" that look like a signal and challenge is to get rid of them!)?

- Once stopped, muon can decay from the 1s atomic orbit and release two neutrinos and an electron - dominant background!

- Or be captured by the nucleus — release protons, photons and neutrinos



Decay **I**n **O**rbit Background

What about cosmic ray backgrounds?

Veto cosmic rays — of the 10^9 cosmic rays a day, one per day would look like signal!

Outlook

- Muons are a versatile tool across particle physics
- This is a new exciting era at Fermilab with the construction of the muon campus
- Mu2e civil construction complete, experiment under construction, expects to start installation and commissioning in 2021, start data taking in 2023
- Muon g-2 is on the verge of publishing first result (getting to solve the puzzle of the discrepancy!)
- Both g-2 and mu2e can probe a huge variety of BSM models!

Fermilab's world class muon program is a key component of the current search for new physics

Stay tuned for publications in the near future!

Thanks for Listening!

Questions?