Fermilab g-2 Experimental Result

- You may have seen recent articles talking about an unexpected experimental result from Fermilab regarding muons and its property called its "g factor".
- Theory predicted that a certain numerical value for the g factor would be found by experiments.
- But the experiments showed a significantly different value.
- What can explain the discrepancy?
- Let's explore the issues involved.

The Standard Model of Physics

- Our current best understanding of how the universe works. And in particular includes Quantum Mechanics.
- It basically consists all the equations that represent how forces and particles (e.g., protons, electrons, atoms, photons, etc., etc., etc.) interact.
- Ideally, we would like it to be able to explain *everything* in the universe (a so-called Theory of Everything).
- But can't (currently) explain various things such as gravity (i.e., General Relativity is known to be incompatible with Quantum Mechanics), dark matter, and dark energy.
- From a different point of view, it also can't explain why particles have the masses they have. Yes, we can measure the mass of particles, but the Standard Model doesn't *predict* the values we find.
- So the Standard Model is a work-in-progress.
  - https://en.wikipedia.org/wiki/Physics_beyond_the_Standard_Model

Muons (and Tau Particles)

- We're all familiar with electrons. But did you know that electrons have two "cousins" – the muon and the tau particles?
- Muons and tauons seem to be exactly the same as electrons (e.g., have the same electric charge, the same quantum-mechanical spin, etc.), but have different masses and are unstable (decay into less massive particles) whereas the electron (as far as we know) does not decay.
  - Muons are almost 207 times more massive than electrons and decay in 2.2 milliseconds.
  - Tau particles are over 3,477 times more massive than electrons and decay in less than a trillionth of a second.
- The Standard Model doesn't explain why there seem to be three "generations" of the same particle.
  - These three particles seem to be, perhaps, "3 sides of the same coin" so to speak.
  - Speculation: Is there possibly just one type of electron and some not understood process that blows it up??? Dunno…
  - Side note: We also have three generations of quarks with the same type of issues and the same questions.
- So is the Standard Model incomplete, wrong, is an approximation to a more fundamental theory, or what? We don't know… yet!

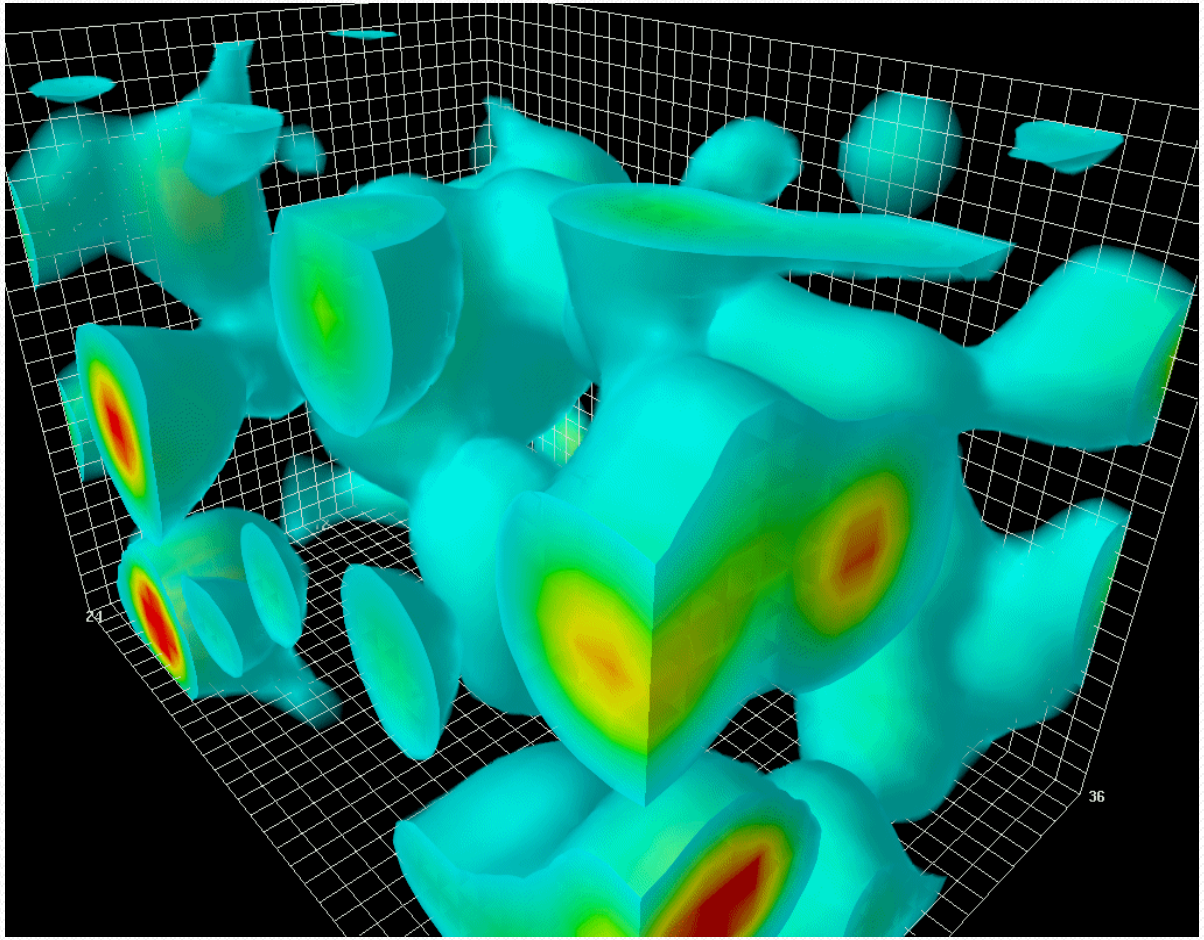
Muon g-2

- From https://en.wikipedia.org/wiki/Muon_g-2
- The “g factor” (https://en.wikipedia.org/wiki/G-factor_(physics)) of a particle is a number that represents how strong the magnetic field of the particle is and how much it interacts with an external magnetic field.
- A first-cut application of the equations of the Standard Model would predict that the value of *g* should be exactly equal 2.0.
- But a more sophisticated analysis (involving virtual particles (see next slide)) predicts that the g factor is slightly greater that 2. So g-2 would have a small positive value.
- And indeed, experiments show that this is the case. So we need a more sophisticated analysis.

Heisenberg’s Uncertainly Principle to the Rescue

- Consider a very special volume of space.
  - It’s not any particular place in space. We’ll choose it so it’s very isolated (e.g., it’s out in intergalactic space)
  - It’s extremely small (subatomic size or even smaller).
  - And we’ll consider it for an extremely short period of time (e.g., a trillionth (10^{-12}th) of a second or even much less!)
  - We’re simply trying to get a volume with a perfect vacuum.
- Suppose I were to tell you that this volume, for that very short time interval, was entirely empty of any form of matter or energy (e.g., no photons passing through).
  - Would you believe me?
  - You shouldn’t!
- One way to state Heisenberg’s Uncertainty Principle (https://en.wikipedia.org/wiki/Uncertainty_principle) says that the uncertainty of the amount of energy in a volume of space must be greater than zero.
- And the amount of energy depends on how short a period we’re considering. For our very special volume, there could be enough energy ($E = mc^2$) to create new “virtual particles” (e.g., another muon, two photons, neutrinos, pions, whatever).
- And in that very short period of time, these new particles can interact with the muon, which leads to an updated value of g-2, larger than zero.

Virtual Particles



- The black background with the white grid lines represents a volume of supposedly empty space.
- But according to Heisenberg we know it can't be totally empty and that vacuum fluctuations occur leading to the creation and quick annihilation of particles.
- The pulsating blobs represent the new particles being created, based on supercomputer calculations of the Quantum Mechanical implications of Heisenberg's equations.
- And as should be obvious, this is actually a very short video played back in a continuous loop.
- These new particles are called *virtual* particles (https://en.wikipedia.org/wiki/Virtual_particle). And other experiments show that they do exist: https://en.wikipedia.org/wiki/Casimir_effect and https://en.wikipedia.org/wiki/Vacuum_energy).
- This video from https://upload.wikimedia.org/wikipedia/commons/2/2a/Quantum_Fluctuations.gif

Disconnect Between Theory and Experiments

- So even when you take into account the muon’s interactions with these virtual particles, the value predicted for g-2 still doesn’t match the experimental results!
- Why is this? There are a number of possible reasons.
  - Experimental error – possible but unlikely. Fermilab is arguably the second-best particle physics lab after the LHC and is extremely reliable.
  - Quantum Mechanics is inherently random and maybe the experimental results are just somewhat random values.
    - But Fermilab has done these experiments multiple times and keeps getting consistent results.
  - And so on.

But Maybe…

- Another possibility is that among the virtual particles are new particles that the Standard Model knows nothing about (e.g., dark matter, supersymmetric particles from String Theory, etc.) and interact with the muon’s g factor to give the observed experimental results
- So we might require a new force of nature that tells us how these new particles interact with themselves and with known particles.
- Should Fermilab announce the discovery of new physics?

What Qualifies as a Discovery

- Statistics makes it possible to quantify this.
- For example, the LHC couldn't announce the discovery of the Higgs boson with only one piece of data. It took many experimental observations to get enough data points such that it the odds of these being just random Quantum Mechanical events passed the 5-sigma limit (roughly 1 chance in 1.7 million) .
- In general, particle physicists require enough experimental evidence to show that the odds of getting the observed results must be better than the gold standard 5-sigma level compared to merely random results.
  - See https://en.wikipedia.org/wiki/68%E2%80%9395%E2%80%9399.7_rule

So Has Fermilab Discovered Something New?

- No. Not really. Well, not quite. Maybe…
- Fermilab started collecting muon g-2 data in 2017. It took years to both collect the data then meticulously analyze the data. And in April 2021, the evidence from the first year's experimental data was only at the 4.2-sigma level (roughly 1 chance in 40,000). So we couldn't pop the champagne corks yet!
- But in July 2023, the evidence from the first 3 year's data (2017..2019) was at the 5.1-sigma level. But this still didn't quite match the results from supercomputer models of what the result should be. So we still don't understand what's going on with the muon in particular and the Standard Model in general. And there are still 3 additional years of data to analyze, which won't be analyzed and announced until 2025.

Summary

- The discrepancy between theory and experiment is provocative. It seems that we're missing something, but we don't know what…
- Announcing the existence of a new set of particles and their associated forces is not something physicists take lightly. And there are enough questions (e.g., just what are these hypothetical new particles and how do they interact with themselves and with more conventional particles?) to make them queasy about announcing something they understand so little .
- So at the moment,
  - Either hang on until 2025 when the new analysis is available .
  - Or wait until a theorist comes up with a reasonable theoretical explanation for the new particles (which must in turn lead to matching the experimental data).
- Until then we're in a sort of limbo. Sigh…
- But it looks like Nature is trying to tell us something, and we're not quite bright enough (yet!) to understand what's going on.
- But brilliant scientists are working hard to figure this out and it may well wind up with one of the century's most exciting announcements.
- As a perhaps should have said several slides back, "watch this space!"

Fermilab (and other) Links

- https://muon-g-2.fnal.gov/
- https://www.youtube.com/watch?v=hkHd_wxMfrs
- https://muon-g-2.fnal.gov/news.html
- https://en.wikipedia.org/wiki/Muon_g-2

Where to Find This Talk

- http://lrs5.net/science/HintsOfAFifthForceOfNature.pptx
- http://lrs5.net/science/HintsOfAFifthForceOfNature.pdf