What does the Standard Model predict for the magnetic moment of the muon?

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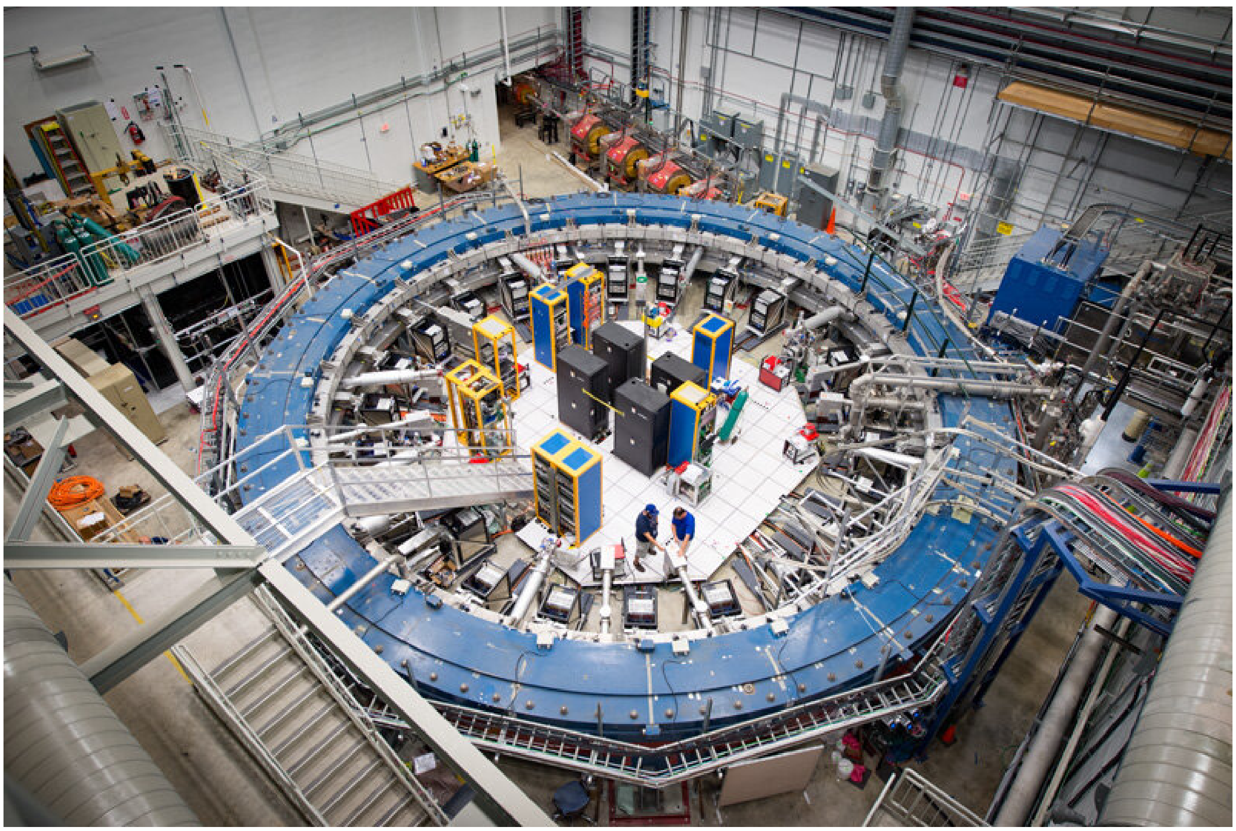

The high-energy physics community is eagerly anticipating the announcement of the world's best measurement from the Fermilab Muon g-2 experiment later this year, while the Muon g-2 Theory Initiative is working to shore up the predicted value using new data and new lattice calculations. Credit: Reidar Hahn, Fermilab

Predicting the numerical value of the magnetic moment of the muon is one of the most challenging calculations in high-energy physics. Some physicists spend the bulk of their careers improving the calculation to greater precision.

Why do physicists care about the magnetic properties of this particle? Because information from every particle and force is encoded in the numerical value of the muon's magnetic moment. If we can both measure and predict this number to ultra-high precision, we can test whether the Standard Model of Elementary Particles is complete.

Muons are identical to electrons, except they are about 200 times more massive, are not stable, and disintegrate into electrons and neutrinos after a short time. At the simplest level, theory predicts that the muon's magnetic moment, typically represented by the letter g, should equal 2. Any deviation from 2 can be attributed to quantum contributions from the muon's interaction with other—known and unknown—particles and forces. Hence scientists are focused on predicting and measuring g-2.

Several measurements of muon g-2 already exist. Scientists working on the Muon g-2 experiment at the U.S. Department of Energy's Fermi National Accelerator Laboratory expect to announce later this year the result of the most precise measurement ever made of the muon's magnetic moment.

Simultaneously, a large number of scientists are working on improving the Standard Model prediction of the value of muon g-2. Several parts feed into this calculation, related to the electromagnetic force, the weak nuclear force and the strong nuclear force.

The contribution from electromagnetic particles like photons and electrons is considered the most precise calculation in the world. The contribution from weakly interacting particles like neutrinos, W and Z bosons, and the Higgs boson is also well known. The most challenging part of the muon g-2 prediction stems from the contribution from strongly interacting particles like quarks and gluons; the equations governing their contribution are very complex.

Even though the contributions from quarks and gluons are so complex, they are calculable, in principle, and several different approaches have been developed. One of these approaches evaluates the contributions by using experimental data related to the strongly interacting nuclear force. When electrons and positrons collide, they annihilate and can produce particles made of quarks and gluons like pions. Measuring how often pions are produced in these collisions is exactly the data needed to predict the strong nuclear contribution to muon g-2.

For several decades, experiments at electron-positron colliders around the world have measured the contributions from quarks and gluons, including experiments in the US, Italy, Russia, China, and Japan. Results from all these experiments were compiled by a collaboration of experimental and theoretical physicists known as the Muon g-2 Theory Initiative. In 2020, this group announced the best Standard Model prediction for muon g-2 available at that time.

Ten months later, the Muon g-2 collaboration at Fermilab unveiled the result of their first measurement. The comparison of the two indicated a large discrepancy between the experimental result and the Standard Model prediction. In other words, the comparison of the measurement with the Standard Model provided strong evidence that the Standard Model is not complete and muons could be interacting with yet undiscovered particles or forces.

A second approach uses supercomputers to compute the complex equations for the quark and gluon interactions with a numerical approach called lattice gauge theory. While this is a well-tested method to compute the effects of the strong force, computing power has only recently become available to perform the calculations for muon g-2 to the required precision. As a result, lattice calculations published prior to 2021 were not sufficiently precise to test the Standard Model. However, a calculation published by one group of scientists in 2021, the Budapest-Marseille-Wuppertal collaboration, produced a huge surprise. Their prediction using lattice gauge theory was far from the prediction using electron-positron data.

In the last few months, the landscape of predictions for the strong force contribution to muon g-2 has only become more complex. A new round of electron-positron data has come out from the SND and CMD3 collaborations. These are two experiments taking data at the VEPP-2000 electron-positron collider in Novosibirsk, Russia. A result from the SND collaboration agrees with the previous electron-positron data, while a result from the CMD3 collaboration disagrees with the previous data.

What is going on? While there is no simple answer, there are concerted efforts by all the communities involved to better quantify the Standard Model prediction. The Lattice Gauge Theory community is working around the clock towards testing and scrutinizing the BMW collaboration's prediction in independent lattice calculations with improved precision using different methods. The electron-positron collider community is working to identify possible reasons for the differences between the CMD3 result and all previous measurements. More importantly, the community is in the process of repeating these experimental measurements using much larger data sets. Scientists are also introducing new independent techniques to understand the strong-force contribution, such as a new experiment proposed at CERN called MUonE.

What does this mean for muon g-2? The Fermilab Muon g-2 collaboration will release its next result, based on data taken in 2019 and

2020, later this year. Because of the large amount of additional data that is going into the new analysis, the Muon g-2 collaboration expects its result to be twice as precise as the first result from their experiment. But the current uncertainty in the predicted value makes it hard to use the new result to strengthen our previous indication that the Standard Model is incomplete and there are new particles and forces affecting muon g-2.

What is next? The Fermilab Muon g-2 experiment concluded data taking this spring. It will still take a couple of years to analyze the entire data set, and the experiment expects to release its final result in 2025. At the same time, the Muon g-2 Theory Initiative is working to shore up the predicted value using new data and new lattice calculations that should also be available before 2025. It will be a very exciting showdown. In the meantime, the high-energy physics community is eagerly anticipating the announcement of the world's best measurement from the Fermilab Muon g-2 experiment later this year.

Provided by Fermi National Accelerator Laboratory

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