A moment for muons

The recent measurement of the muon's anomalous magnetic moment increases the tension with predictions from theory. Or does it?

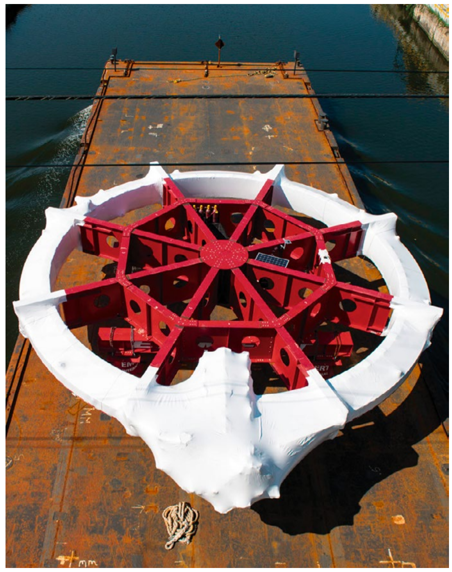
The muon can be seen as a heavier and unstable carbon copy of the electron — so far, so unremarkable. But whereas measurements of the anomalous magnetic moment of the electron conform to our theoretical predictions[1], those of the muon tell a different story. And as the comparison between measurement and prediction directly tests the standard model of particle physics at the level of quantum loop effects, probing this deviation may reveal as yet unknown particles. The key to doing so, as so often, lies with increasing precision.

The Dirac equation predicts that the muon's magnetic moment has a gyromagnetic ratio, g, of exactly two. But quantum loop effects induce corrections to this prediction — a deviation that the anomalous magnetic moment captures directly. Recent results released by the aptly titled Muon $g-2$ experiment at the Fermi National Accelerator Laboratory give muons a moment to shine.

The first measurements of the muon's anomalous magnetic moment date back to the 1960s at CERN, and over the course of three experimental campaigns, their precision improved from 4,300 ppm to 10 ppm (ref. [2]) — all results were in agreement with the standard model. However, this picture changed when the E821 experiment at Brookhaven National Laboratory reported a slight tension with predictions — a result now confirmed by the Muon $g-2$ experiment.

The two experiments rely on a technique pioneered at CERN: in a storage ring with a highly uniform — and very precisely known — magnetic field, the muon's spin precesses around the magnetic field, and a measurement of the precession frequency gives access to the muon's anomalous magnetic moment. The final value of the Brookhaven result with a combined statistical and systematic uncertainty of 0.54 ppm (ref. [2]) lay more than two standard deviations higher than what was expected from the standard model. To quote the white paper from the Muon $g-2$ Theory Initiative: "The situation was interesting, but by no means convincing."[3]

With refined theory calculations, the discrepancy grew to something between three and four standard deviations, thus motivating the design and construction of the Muon $g-2$ experiment to determine how anomalous the muon's anomalous magnetic moment truly was.



Credit: Reidar Hahn, Fermilab

Building such an experiment is certainly not an easy feat. The Muon $g-2$ experiment re-uses the 1.45 T superconducting storage ring magnet from the Brookhaven experiment, which was shipped to Batavia, Illinois (pictured), and benefits from numerous improvements, such as a purer and more intense muon beam. These efforts paid off, yielding a measurement with a precision of 0.46 ppm (ref. [4]). Combined with the Brookhaven result, the average shows a tension with respect to the latest standard model predictions[3] of 4.2 standard deviations. The wait was finally over — or so we thought.

On the day of the announcement of these results, another theoretical calculation using lattice quantum chromodynamics (QCD) was published[5], weakening the long-standing tension with respect to the Brookhaven result. The reason for these different conclusions on the size of the tension between experiment and theory lies in the computation of the quantum loop corrections to the muon's anomalous magnetic moment in the standard model.

The corrections include contributions from quantum electrodynamics involving loops with photons and leptons, from the weak interaction comprising loops with Z, W or Higgs bosons, and from quark and gluon loops, the hadronic contribution, — the latter being the dominant theory uncertainty. The hadronic contribution, subdivided into vacuum polarization and light-by-light scattering, are difficult to calculate. They can be computed either by a combination of cross-section data with dispersion relations or by lattice QCD. Although the precision of lattice QCD calculations is catching up[5,6] with those of the dispersion approach, the calculation of the vacuum polarization[5] is awaiting confirmation from other lattice QCD groups.

The comparison between experimental measurements and theoretical predictions of the muon's anomalous magnetic moment remains somewhat inconclusive, but the prospects for further insight are looking good. A reduction of the hadronic uncertainties by a factor of two is considered a realistic outcome by the end of the experiment's operation. Moreover, an independent method for measuring the muon's anomalous magnetic moment will be possible at the Japan Proton Accelerator Research Complex (J-PARC) in Japan[7].

Expected to start operations in 2025, the experiment will make use of an ultracold muon beam injected into a compact storage ring with a magnetic field of unprecedented quality. With the targeted precisions of below 0.07 ppm at J-PARC and of 0.14 ppm at the Muon $g-2$ experiment, we will finally learn to what extent the muon's anomalous magnetic moment is anomalous. ❐

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