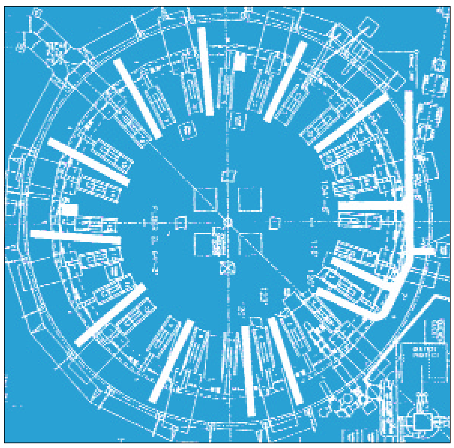
Measurements of the anomalous magnetic moment of the muon provide strong hints that the Standard Model of particle physics might be incomplete

Muons: particles of the moment

David W Hertzog



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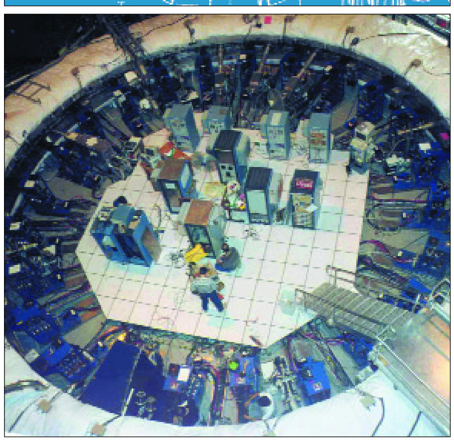


Ripp Bowman

Blueprint for new physics – muons orbiting the $g-2$ storage ring at the Brookhaven National Laboratory do not behave as theory predicts they should.

WHEN asked what the most important issue in particle physics is today, my colleagues offer three burning questions: What is the origin of mass? Why is the universe made of matter and not equal parts of matter and antimatter? And is there any physics beyond the Standard Model?

The first question is being addressed by a feverish quest to find the Higgs boson, which is believed to be responsible for the mass of fundamental particles. The Tevatron at Fermilab, which is currently running, or the Large Hadron Collider at CERN, which is due to start experiments in 2007, should eventually provide the answer to this question by detecting the Higgs and measuring its properties – or showing that it does not exist.

The fact that the universe is dominated by matter is also a mystery. It is thought that equal amounts of matter and antimatter were produced in the Big Bang, so there must be some fundamental process that led to the virtual disappearance of antimatter. A violation of charge conjugation and parity (CP) symmetry is thought to be part of the answer to this question, and is being investigated in detail at the BABAR experiment at Stanford in the US and the BELLE experiment at the KEK laboratory in Japan (see *Physics World* July 2003 pp27–31).

But it is the third question – is there new physics beyond the Standard Model? – that could rock the very foundations of modern physics.

Playing cat and mouse

The Standard Model represents our current understanding of the fundamental building blocks of the universe. It identifies a basic set of 12 particles: six quarks called up, down, charm, strange, bottom and top; and six leptons, namely the electron, muon and tau-lepton plus their associated neutrinos.

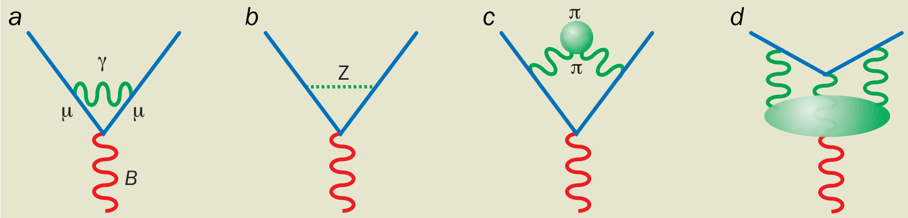
A different set of particles is responsible for the interactions between these matter particles in the model. The electromagnetic interaction that binds electrons to nuclei results from the exchange of photons, whereas the strong force that binds quarks together inside neutrons, protons and other hadrons is carried by particles called gluons. The third force in the Standard Model – the weak nuclear interaction, which is responsible for radioactive decay – is carried by the W and Z bosons.

Physicists love the Standard Model, but they do not like it. Although just about every conceivable prediction of the model has turned out to be correct, it seems unnatural and messy. Many physical parameters, such as the masses of the particles, cannot be predicted by any rules in the model and must, instead, be put in "by hand". The top quark, for example, is 35 000 times heavier than the up quark, and the other quarks have masses that lie somewhere in between these values with no discernable pattern.

Researchers call the model "robust" and wonder if it will ever really fail. If physics beyond the Standard Model is discovered, exploring it will be like tapping a rich new vein in an otherwise well explored mine. This will require new particle accelerators and armies of physicists, and the cost will be significant. How can we test the Standard Model in such a way that these veins are revealed? One technique is to identify predictions of the model that can be tested with extremely high precision. If the experimental results differ from those predicted by the theory, it may be because the theory is incomplete.

The muon $g-2$ experiment at the Brookhaven National

Feynman diagrams



Quantum fluctuations give rise to a change in the magnetic moment of the muon, and they are usually represented by "Feynman diagrams". Time flows horizontally and space is represented vertically in these diagrams; the muon path is shown in blue and the "fluctuation" particles are shown in green. (*a*) A muon emits a photon before interacting with a photon of the magnetic field (red), after which the muon re-absorbs the photon. The contribution of this "photon exchange" diagram can be calculated exactly using QED, and is the dominant contribution to the muon anomaly. However, QED permits hundreds of additional diagrams involving photon and electron–positron loops, which must all be computed to obtain the full QED effect. This enormous task has been completed, and we now know the QED part of the muon anomaly to a far greater precision than our experimental measurement. (*b*) A muon can exchange a Z boson in the same way as (*a*), although this Z exchange process is very rare because the Z is extremely massive (whereas the photon is massless). This process reduces the muon anomaly by about 1.6 parts per million. Other weak-interaction diagrams are important too, such as the creation of a virtual W boson. (*c*) Things start to get messy when the exchanged photon momentarily produces a pair of strongly interacting pions. This process is called hadronic vacuum polarization, and it cannot be calculated using trustworthy QED. It contributes about 60 parts per million to the muon anomaly, so we need to know its value with a precision of more than 1% to stay below the experimental uncertainty. Fortunately, this diagram is related to reliable data from independent experiments. (*d*) The hadronic light-by-light scattering process is even more complicated than the hadronic vacuum polarization, and can only be described by models. Although the contribution of this diagram to the muon anomaly is believed to be quite small, its uncertainty is about half that of the measurement uncertainty. It is therefore important to improve this calculation. These hadronic diagrams have recently been the subject of intense debate.

Laboratory in Upton, New York, is an example of this approach. The experiment measures the motion of the spin angular momentum of a muon in a magnetic field with great precision. Meanwhile, theorists have calculated the expected motion of this spin within the context of the Standard Model, and also from creative extensions to the model.

In January this year the final result from the $g-2$ experiment was announced, and it is tantalizingly different from theory. It seems that the Standard Model might just be starting to crack – a conclusion that has taken four years of playing cat and mouse with theory and experiment to reach.

A sensitive magnet

The muon is a close cousin of the electron. Both particles have the same electric charge and both are governed by the laws of electromagnetism and the weak force. The muon is about 200 times heavier than the electron but otherwise it behaves identically. When a muon – or an electron – moves in a uniform magnetic field that is perpendicular to its direction of motion, it follows a precise circular orbit. Quantum mechanics, however, complicates this picture because the intrinsic angular momentum or "spin" of the muon comes into play.

If the spin axis of the muon initially points in the same direction as the direction of motion, you might think that it will continue to point in the direction of motion as the muon completes a circular orbit in a magnetic field. This is precisely what the Dirac equation predicts. In Dirac's theory the ratio of the angular momentum of a particle to its magnetic moment – which is called the gyromagnetic ratio, or "*g*-factor" – is exactly equal to two. However, experiments in the 1940s revealed that *g* is slightly greater than two for electrons. Julian Schwinger explained such deviations with an elegant theory now known as quantum electrodynamics (QED), which is widely considered to be the most precise theory in all of physics.

QED permits particles to emit and re-absorb "virtual photons" as they move. This process – which is allowed by the uncertainty principle – temporarily violates the conservation of energy and momentum (see box). Moreover, it affects how the spin of the muon changes direction, and causes the *g*-factor to increase by about 1 part in 800 above its semiclassical value. The results of muon experiments tend to be given in terms of the anomalous magnetic moment of the muon, which is defined as $a_\mu = (g-2)/2$.

But this is only part of the story. The full extent of the muon anomaly depends on all the different ways that a muon can emit and re-absorb a photon. These more complex quantum fluctuations correspond to higher-order "Feynman diagrams". Fortunately, QED is a rigorous theory, and with formidable effort these contributions to the magnetic moment of the muon can be calculated. Indeed, the anomalous magnetic moment of the *electron* is believed to be one of the most precisely known quantities in physics, with theory and experiment agreeing to eight decimal places.

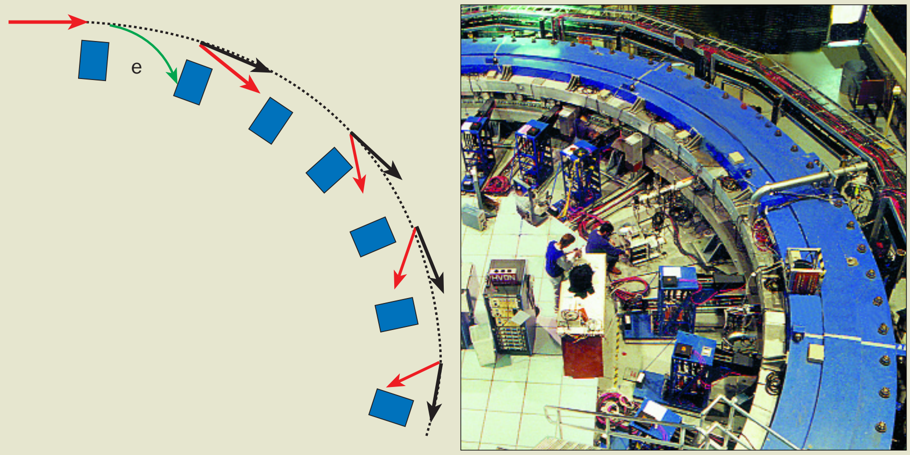
The fact that muons are so much heavier than electrons means that they are far more likely to emit a heavy particle in one of their quantum fluctuations. The Feynman diagram in which a muon emits and re-absorbs a Z boson, for example, reduces a_μ by about 1.6 parts per million, which is some 40 000 times greater than the effect of the same process for an electron. This is because the contribution to the anomaly depends on the square of the mass ratio between a muon and an electron.

This brings us to the discovery potential for a high-precision muon experiment. If there exists some undiscovered family of massive fundamental particles that interact with muons, a Feynman-like diagram can be devised to account for their influence on the *g*-factor. This means that the Standard Model prediction will be wrong unless it includes the effects of this family of particles on the *g*-factor.

From an experimental perspective, the anomalous magnetic moment of the muon causes the spin of a moving muon to rotate faster than the particle itself when in a magnetic field. Therefore, if we measure the difference in the spin-rotation frequency and the orbital-rotation frequency, we can learn something about the value of a_μ. Apart from small corrections, the anomalous magnetic moment can be written as $a_\mu = mc\omega/eB$, where m is the mass of the muon, c is the speed of light, ω is the difference frequency, e is the charge of the muon and B is the magnetic field. For the experiment to work it is therefore essential for the magnetic field to remain constant, and for its value to be known to high precision.

Any difference between the measured value of a_μ and the theoretical prediction could provide evidence for physics beyond the Standard Model. It would not tell us what kind of new physics is required, only that something is missing in the existing theory. This is the strategy of the muon $g-2$ experiment: if the measurement agrees with the Standard Model, the speculations of theorists will be constrained; if it differs, however, champagne will flow to mark the beginning of a new era in particle physics.

1 Experimenting with spin



Brookhaven National Laboratory

The muon $g-2$ experiment can detect the difference between the orbital and the spin directions of muons as they are guided round a large circular storage ring by a magnetic field. The diagram and photograph show one quarter of the muon storage ring, which is 14.2 m in diameter. When positive muons are injected into the ring, their spin direction (red) points in the same direction as their momentum direction (black). However, the anomalous magnetic moment of the muon causes the spin direction to rotate faster than the momentum direction. This effect is greatly exaggerated in the diagram, and in practice the spin "laps" the momentum after about 29 turns round the ring. To gain information about the magnetic moment of the muons, researchers study the positrons that the muons decay into (green). These positrons curl to the inside of the ring, where they are detected by one of 24 electromagnetic calorimeters (blue).

In February 2001 the corks started to pop. Our experimental result from data taken in 1999 differed from the Standard Model by 2.6 standard deviations, which meant there was only a 1% chance that it was due to statistical fluctuation (see *Physics World* March 2001 p5). Three explanations were possible: it was either a statistical fluke, a mistake in the theory or in the experiment, or the onset of new physics.

A lot has happened since then. In particular, we know that mistakes were made related to certain Feynman diagrams that contain hadrons. These processes are much more complicated than those that contain only, say, photons because they involve the strong interaction (see box on page opposite). When the mistakes in the theory were corrected, the Standard Model prediction of a_μ shifted closer to the experimental value, which was bad news for new physics. Meanwhile, researchers on the $g-2$ experiment collected and analysed about seven times more data, and therefore nailed down the measurement to ever tighter precision.

The *g*-factor

In 1984 the late Vernon Hughes of Yale University organized a workshop at Brookhaven to discuss a new muon $g-2$ experiment. His dream was to use a uniform superconducting storage ring, together with the intense beams of particles that were available at the Brookhaven AGS accelerator, to create 400 times more muons than were available at previous $g-2$ experiments. Statistically, this would improve on the earlier measurements – which were made at the CERN I, II and III experiments between the 1950s and 1970s – by a factor of 20.

Hughes' dream was finally realized in 1997 when the first data-taking began. To generate the muons a pulse of high-energy protons is first smashed into a nickel target. Part of the debris from these collisions is an intense burst of charged pions, which is then channelled magnetically through a 122 m long beamline towards the storage ring. Along the way, about one pion in two decays into a muon and a neutrino. When positive muons are used, they are polarized such that their spins are aligned with their direction of motion. Finally, they are injected into the storage ring, which has a diameter of 14.2 m.

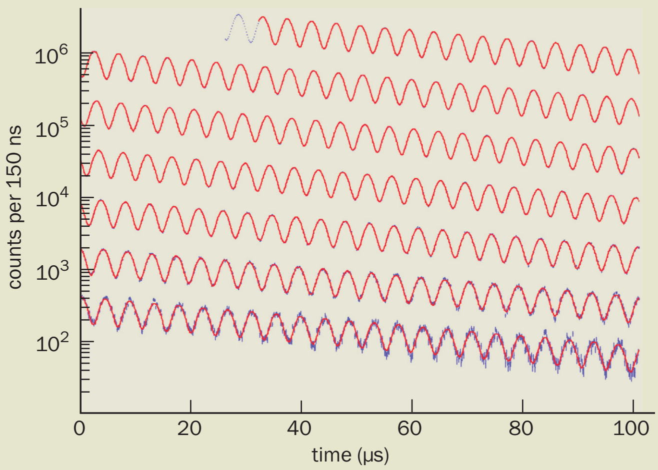
Once inside the ring the muons are kicked into a circular orbit, which is maintained by a highly uniform magnetic field. The particles travel round the ring at relativistic speeds until they decay with a typical lifetime of about 64 μs. Thanks to time dilation this brief existence is roughly 30 times longer than it would have been if the particles had remained at rest, which allows the muons to make many hundreds of revolutions. As the muons orbit round the storage ring, their spins precess, and after about 29 revolutions the spin direction "laps" the momentum direction (figure 1).

To determine the spin direction, and hence determine a_μ, we study events in which a muon decays into an electron (or positron) and two neutrinos. This interaction has what is called mirror asymmetry due to parity violation, and this leads to an asymmetry in the energy of the emitted electrons. The highest energy electrons are emitted in the direction of the muon spin, while the lower-energy electrons are emitted in the opposite direction.

Detectors in our experiment catch the electron and measure its energy and its time of arrival. The number of electrons detected falls exponentially with time, and is modulated by a sine wave due to the difference between the spin and momentum directions of the muons as they travel round the storage ring (figure 2). All we have to do to determine the anomalous magnetic moment of the muon is to find the oscillation frequency of this curve and divide it by the value of the magnetic field. In practice, of course, the process turns out to be more complicated than this.

One problem is background contamination. In the previous CERN experiments, for example, pions were injected directly into the storage ring. However, only about 1 in 50 000 of them had the good fortune to produce a muon in a stable

2 Spin and orbit frequencies



The anomalous magnetic moment of the muon is directly proportional to the difference between the spin-rotation frequency and the orbital-rotation frequency of muons as they orbit the $g-2$ storage ring. This diagram shows a sample of the $g-2$ data (blue) and a fit to this data (red) in which the number of electrons from muon decays is plotted against the electron arrival times. The oscillation of this signal, which has a period of about 4.3 µs, yields the difference frequency between the spin and the momentum of the muon. The curve is wrapped around every 100 µs and its intensity drops with a lifetime of 64 µs, which is precisely the lifetime of the muons in the ring.

orbit. The rest either crashed, sending background particles into the detectors, or they launched muons in directions that did not correspond to stored orbits. In short, it was messy.

The $g-2$ experiment avoids this problem by using three fast "kicker" magnets, which are timed precisely to fire on the first turn of a muon beam after it has been injected into the ring. Left unkicked, the muons would crash into the very aperture through which they arrived, but the sideways kick deflects them just enough to land in a stable orbit. The result is that significantly more muons are stored, and the background rate is greatly reduced.

Furthermore, the muon beam is gently focused using electric quadrupoles located round the ring to prevent the particles from drifting into the top or bottom of the magnets. However, this electric field looks like an additional magnetic field to a relativistic muon because of the symmetry of electromagnetism: a stationary charged particle produces an electric field, while a moving charged particle creates an electric and a magnetic field. At relativistic speeds, a moving charged particle in a static electric field therefore sees the electric field as an equivalent magnetic field.

This "motional" magnetic field acts on the spin of the muon, and poses a big problem for the $g-2$ measurement because it cannot be measured with high enough precision. However, the CERN III experiment made a remarkable observation: the effect of the motional field on the spin vanishes when the muon has a momentum of 3.094 GeV/c, which corresponds to a velocity of about 99.94% of the speed of light. At this "magic momentum" the electric field from the quadrupoles has the same effect on both the muon's magnetic moment precession rate and its rate of momentum rotation, and therefore does not affect the frequency difference between them.

The average value of the magnetic field appears in the denominator of the final anomaly computation, and it is therefore crucial to know the value of the field to an accuracy of better than one part in a million. To this end, we use a network of NMR probes located in the vicinity of the storage ring, including some that are mounted on a non-magnetic trolley. This trolley periodically rides through the storage ring exactly where the muons travel, thus determining the field *in situ*. The $g-2$ measuring system, combined with a heroic effort to make the magnetic field uniform, is a significant advance compared with the CERN III experiment.

Going blind

The final measurement of the muon anomalous magnetic moment is a single number that will either agree or disagree with the Standard Model. We therefore have to use a data-analysis method that is blind to bias. For instance, each analysis of the precession frequency (i.e. the wiggles in figure 2) is reported to the rest of the $g-2$ collaboration with a secret frequency offset. This offset is known only to the handful of people analysing this part of the data – usually four or five graduate students or postdocs. Similarly, the magnetic-field measurements are made by different groups, who also report their intermediate findings with a secret offset. As a result, no one can compute $g-2$ during the year-long process of analysing the data.

To further build confidence in the final result, the raw spin-precession data are processed at two different institutions using unrelated software tools. At least two independent researchers then analyse the data from each institution and work out a precession frequency.

After all the different analysis groups agree, and reports are written, and a review committee is satisfied, then the $g-2$ collaboration votes to accept the results. If the results are accepted, the secret offsets are revealed and we assign three people with steady hands to do the long division necessary to obtain a measurement of $g-2$. While this is happening the rest of us leave the room to ponder – and take bets on – the fate of the Standard Model. Once the result is revealed, no further fitting or checking takes place. We then write a paper for *Physical Review Letters* and organize an announcement to be made when the paper is submitted.

This rather complex procedure has been performed five times since 1997, and can be seen together with the running world average in figure 3. The Standard Model prediction, on the other hand, has followed a bumpier, and sometimes forked, road.

Champagne on ice

The bubble of excitement of early 2001, when theory and experiment disagreed by 2.6 standard deviations, burst in November that year. Marc Knecht and Andreas Nyffeler at the Centre for Theoretical Physics in Marseille, France, had used a new technique to estimate one of the contributing Feynman diagrams known as hadronic light-by-light scattering (see figure d in box on page 30). This diagram is so complex that only a theoretical model, rather than a rigorous theory, can suggest a value for its amplitude (see Knecht and Nyffeler in further reading). Worse still, it cannot be determined directly from measurements.

The hadronic light-by-light scattering diagram had last been evaluated in the mid-1990s, when two independent groups arrived at similar results. This result reduced the value of the muon anomaly by about 0.8 parts per million. But Knecht and Nyffeler disagreed. While they found the same magnitude for the effect, they concluded that the sign was wrong, which meant that the diagram actually increases the muon anomaly. Their result was later confirmed by many other groups, and the errors in the original calculations were found. This 200% swing reduced the gap between theory and experiment to a paltry 1.6 standard deviations, which meant that there was an altogether more likely 13% chance that the disagreement between theory and experiment was a statistical fluke. The champagne bottles, alas, were laid back down.

In the summer of 2002 we published a new experimental result based on data taken in 2000. This measurement had a precision of 0.7 parts per million – twice as good as our previous work – and took the difference between theory and experiment back to 2.6 standard deviations. But before anyone started to celebrate, another major theoretical controversy began to unfold.

As before, the uncertainty involved the hadronic contribution to the muon anomaly, but this time it was related to the main hadronic Feynman diagram: the hadronic vacuum polarization (see figure *c* in box on page 30). In this process a photon emitted by a muon fluctuates for an instant into a pair of strongly interacting pions before being re-absorbed by the muon. The contribution of this diagram to the muon's magnetic moment is therefore governed by the strong interaction and cannot be calculated using trustworthy QED.

Ironically, the hadronic vacuum polarization is evaluated using data, which have been extracted from two different types of experiments. In the first method, the probability of creating hadrons is measured as a function of energy from electron–positron collisions. In the second, the probability that the very heavy tau-lepton decays into hadrons is measured. The tau method is not direct, and it therefore requires some corrections to mimic the electron–positron collision data. But if these corrections are applied properly, both approaches should give exactly the same value for the hadronic vacuum polarization.

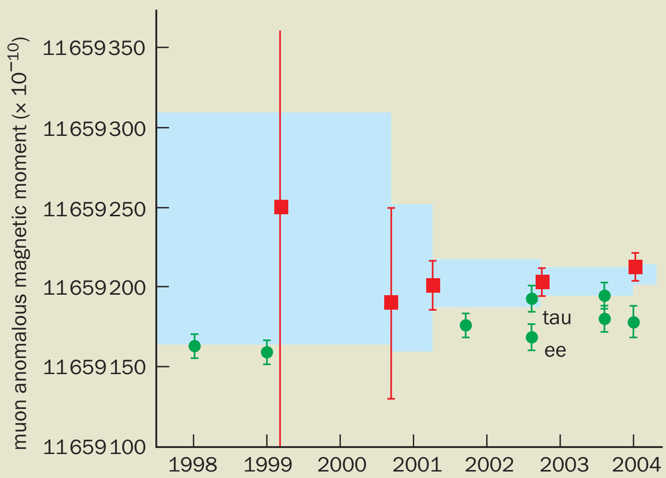
However, in August 2002 Michael Davier, Andreas Hocker and Zhiqing Zhang of the Université de Paris-Sud in Orsay, France, and Simon Eidelman of the Budker Institute in Novosibirsk, Russia, discovered that the latest, most precise data from both types of experiments gave different results. So they published a paper with two different theoretical predictions. The electron–positron collision data implied that the difference between theory and experiment for the muon anomaly was significant, but the tau-decay data did not (see Davier *et al.* in further reading).

Close chase

In the spring of 2003, however, theorists at Novosibirsk discovered that they had left out an important and straightforward correction to the normalization of their precision electron–positron data. Once included, the theoretical result moved closer to the experimental one, but it did not close the gap completely: the difference was still 1.9 standard deviations. The theory based on tau decays, on the other hand, agreed with the $g-2$ experimental value (figure 3).

However, to really understand the crucial electron–positron and the tau predictions we need to look further than their magnitudes: the raw data from which the hadronic prediction is derived also need to be consistent. Unfortunately they are not, which has prompted several theorists to speculate about what might be wrong.

3 Theory versus experiment



Measurements of the anomalous magnetic moment of the muon at the Brookhaven $g-2$ experiment are now more precise than theoretical predictions. Red squares show the experimental values with their error bars, while the blue band represents the uncertainty in the world average experimental value. The centre of this band is therefore the most accurate measured value. The Standard Model prediction for the muon anomaly (green circles) has followed a somewhat bumpier path. Since the combined electron–positron (ee) collision and tau-decay results in 1998, various corrections to the theory have been made. In particular, the sign of the hadronic light-by-light contribution to the muon anomaly flipped in 2001, bringing the theory closer to experiment. The latest theory point is a recently suggested value in which the tau-decay results are not included (see text). Dates refer to the year in which the data or theory results were published. Earlier measurements of the muon anomaly from the CERN I, II and III experiments are not shown because their uncertainties are so large that the results no longer affect the world average.

Recently, Stephane Ghozzi and Fred Jegerlehner at the DESY laboratory in Germany proposed that the corrections necessary to make the tau-decay data match the collision data are incomplete. The corrections seem to neglect a subtle difference in the way that a photon that is emitted and re-absorbed by a muon forms an intermediate state called a rho-meson. The charged rho-mesons that are created in the tau-decay data have a slightly different mass and lifetime compared with the neutral rho that is produced in the collision data. As it is the neutral rho-meson that counts for the muon anomaly, the tau data require an additional correction to make them consistent. Once applied, according to Ghozzi and Jegerlehner, the tau data will give a closer result to the electron–positron data. Davier, however, recently checked this suggestion and disagrees.

Final anomaly

In January 2004 the $g-2$ collaboration announced the result from an analysis of its final data set. Once again, the measurement of the anomalous magnetic moment of the muon is consistent with earlier measurements, and once again it continues to deviate from the Standard Model. Furthermore, the new data were obtained using negative muons, whereas the previous data sets were for positive muons.

Combining all our previous measurements, the world average experimental measurement of a_μ is 11 659 208 ± 6, while the Standard Model prediction based on electron–positron collision data is 11 659 181 ± 8 (both these values must be multiplied by 10^{-10}). The difference between experiment and theory is therefore 27 ± 10, or 2.7 standard deviations, which means that statistically there is less than a 1% chance that the disagreement is a fluke. However, the tau-based Standard Model calculation is higher than the electron–positron calculation by 15 in these units, which makes the difference between experiment and theory just 1.4 standard deviations.

The fact that that the measured value is higher than the Standard Model prediction (it could just as likely have been lower if the result is a fluke) agrees with the expectations of the most popular extensions to the Standard Model, namely supersymmetry. In supersymmetric extensions of the Standard Model all particles have a "superpartner", although these particles have never been detected. The fermionic matter particles in the Standard Model – the quarks and leptons – have bosonic superpartners, while the bosons that are responsible for carrying forces, such as the W and Z bosons, have fermionic superpartners.

Clearly it is too early to judge whether the disagreement between theory and experiment will stand the test of time, and whether it points to supersymmetry or to some other extension of the Standard Model. However, we expect that many people will view the $g-2$ result as a harbinger of good things to come for particle physics. A difference between experiment and theory implies that new particles should start to appear in the highest energy collisions, perhaps at the Tevatron and most certainly at the LHC. These particles will then open the chapters of the next Standard Model.

Meanwhile, the muon $g-2$ collaboration dreams of continuing its magnetic-moment measurements. Funding constraints have currently stopped the $g-2$ experiment, but with a modest upgrade – which would represent a tiny fraction of the cost of any proposed colliders – we could do even better. The uncertainty in the muon measurement could then be knocked down by another factor of 2 to 3, thus sharpening the resolution of our crystal ball into the world of physics yet to come.

Further reading

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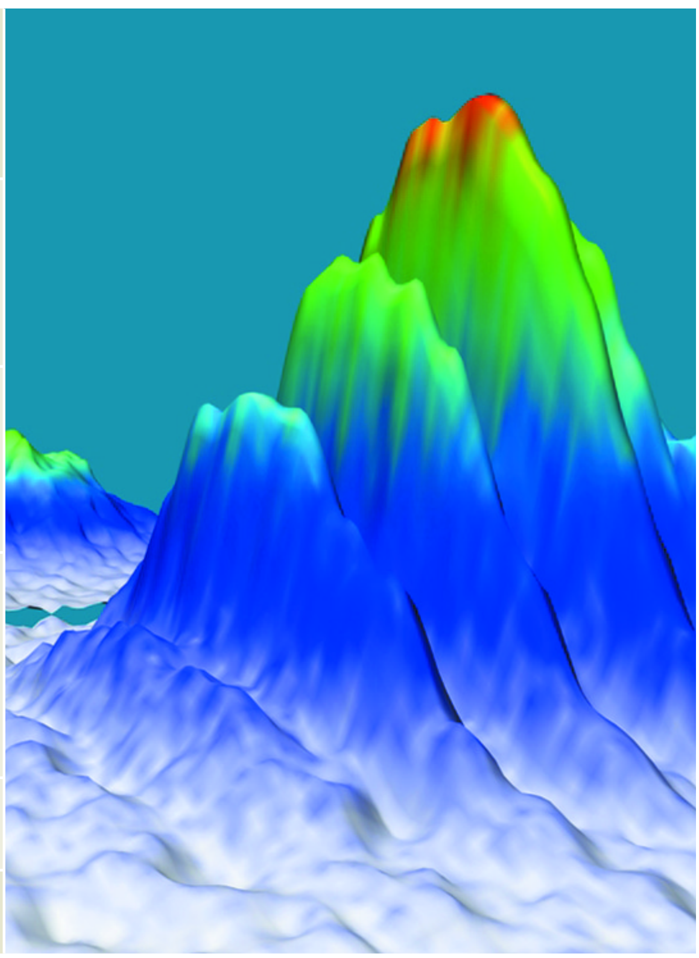

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