PETER GINTER/CERN

The Large Hadron Collider's LHCb detector, pictured, reported anomalies in the behaviour of muons.

MUON RESULTS THROW PHYSICS THEORIES INTO CONFUSION

Surprising particle behaviour has physicists trying to concoct new explanations.

By Davide Castelvecchi

Physicists should be ecstatic right now. Taken at face value, the surprisingly strong magnetism of elementary particles called muons, revealed by an experiment last month, suggests that the established theory of fundamental particles is incomplete. If the discrepancy pans out, it would be the first time that the theory has failed to account for observations since its inception five decades ago — and there is nothing physicists love more than proving a theory wrong.

But the result — announced on 7 April[1] by the Muon *g* – 2 experiment near Chicago, Illinois — poses a riddle. It seems maddeningly hard to explain it in a way that is compatible with everything else physicists know about elementary particles. And further anomalies in the muon's behaviour, reported in March[2] by a collider experiment, only make that task harder.

Take supersymmetry, or SUSY, a theory that many physicists once thought was the most promising for extending the current paradigm, the standard model of particle physics. Supersymmetry comes in many variants, but, in general, it posits that every particle in the standard model has a yet-to-be-discovered heavier counterpart, called a superpartner. Superpartners could be among the 'virtual particles' that constantly pop in and out of the empty space surrounding the muon, a quantum effect that would help to explain why this particle's magnetic field is stronger than expected.

These particles could solve two mysteries at once: muon magnetism and dark matter, the unseen stuff that, through its gravitational pull, seems to keep galaxies from flying apart.

Until ten years ago, various lines of evidence had suggested that a superpartner weighing as much as a few hundred protons could constitute dark matter. Many expected that the collisions at the Large Hadron Collider (LHC) outside Geneva, Switzerland, would produce a plethora of these new particles, but so far none have materialized. The data that the LHC has produced so far suggest that typical superpartners, if they exist, cannot weigh less than 1,000 protons.

"Many people would say supersymmetry is almost dead," says Dominik Stöckinger, a theoretical physicist at the Dresden University of Technology in Germany, who is a member of the Muon *g* – 2 collaboration. But he still sees it as a plausible way to explain the experiment's findings. "If you look at it in comparison to any other ideas, it's not worse," he says.

There is one way in which Muon *g* – 2 could resurrect supersymmetry and also provide evidence for dark matter, Stöckinger says. There could be not one superpartner, but two appearing in LHC collisions, both of roughly similar masses — say, around 550 and 500 protons. Collisions would create the more massive one, which would then rapidly decay into two particles: the lighter superpartner plus a run-of-the-mill, standard-model particle carrying away the 50 protons' worth of mass difference.

The LHC detectors are well-equipped to reveal this kind of decay as long as the ordinary particle — the one that carries away the mass difference between the two superpartners — is large enough. But a very light particle could escape unobserved.

The trouble is that models that include two superpartners with similar masses also tend to predict that the Universe should contain a much larger amount of dark matter than astronomers observe. So an extra mechanism would be needed — one that can reduce the amount of predicted dark matter. This adds complexity to the theory.

Meanwhile, physicists have uncovered more hints that muons behave oddly. An experiment at the LHC, called LHCb, has found tentative evidence that muons occur significantly less often than electrons as the breakdown products of certain heavier particles called B mesons[2]. According to the standard model, muons are supposed to be identical to electrons in every way except for their mass, which is 207 times larger. As a consequence, B mesons should produce electrons and muons at nearly equal rates.

Other options

The task of explaining Muon $g-2$'s results becomes even harder when researchers try to concoct a theory that fits both those findings and the LHCb results. In particular, the supersymmetry model that explains Muon $g-2$ and dark matter would do nothing for LHCb.

Some solutions that could fit both do exist. One is the leptoquark — a hypothetical particle that could have the ability to transform a quark into either a muon or an electron (which are both examples of a lepton). Leptoquarks could resurrect an attempt made by physicists in the 1970s to achieve a 'grand unification' of particle physics, showing that its three fundamental forces — strong, weak and electromagnetic — are all aspects of the same force.

Most of the grand-unification schemes of that era failed experimental tests, and the surviving leptoquark models have become more complicated — but they still have their fans. "Leptoquarks could solve another big mystery: why different families of particles have such different masses," says Gino Isidori, a theoretician at the University of Zurich in Switzerland.

There is one other major contender that might reconcile both the LHCb and Muon $g-2$ discrepancies. It is a particle called the Z′ boson, because of its similarity to the Z boson, which carries the 'weak force' responsible for nuclear decay. Both leptoquarks and the Z′ boson have an advantage, says Ben Allanach, a theorist at the University of Cambridge, UK: they have not been completely ruled out by the LHC.

The LHC is currently undergoing an upgrade, but it will start to smash protons together again in April 2022. The coming data could strengthen the muon anomalies and perhaps provide hints of long-sought new particles. Meanwhile, beginning next year, Muon $g-2$ will release further measurements. Once it's known more precisely, the size of the discrepancy between muon magnetism and theory could itself rule out some explanations and point to others.

Unless, that is, the discrepancies disappear and the standard model wins again. A recent recalculation of the standard model's prediction for muon magnetism[3] gave a value much closer to the experimental result. So far, those who have bet against the standard model have always lost, which makes physicists cautious. "We are — maybe — at the beginning of a new era," Stöckinger says.

1. Abi, B. *et al. Phys. Rev. Lett.* **126**, 141801 (2021).
2. LHCb Collaboration *et al.* Preprint at https://arxiv.org/abs/2103.11769 (2021).
3. Borsanyi, Sz. *et al. Nature* **593**, 51–55 (2021).

US NATIONAL SCIENCE FOUNDATION SET FOR A FUNDING BOOM

But some worry the proposed budget boost will change the agency's scientific mission.

By Ariana Remmel

US officials are discussing whether the National Science Foundation (NSF) — which funds about 25% of all basic academic research in the country — should get a historic budget boost, potentially changing the US science landscape. During congressional hearings last month, legislators evaluated proposals that would increase the agency's funding by as much as US$100 billion over about five years. Any of these, if passed, would represent one of the largest increases for the NSF since it launched nearly 70 years ago.

A big cash influx for the NSF, which supports basic research and development in the science, technology, engineering and mathematics (STEM) workforce, could help to fortify the country's status as a global leader in innovation — at a time when US officials are worried that it's losing ground to other nations. In particular, China has invested aggressively in research and development at a rate that might soon surpass the United States' own research and development funding levels. In 2019, China's patent office received more than twice as many applications as its US counterpart did.

> **"I've never been as optimistic that, finally, the National Science budget will be significantly increased."**

"It is not an overstatement to say that we are already losing leadership," says Rita Colwell, a microbiologist at the University of Maryland, College Park, who led the NSF from 1998 to 2004. "If we don't invest significantly in basic research and technology-transfer capabilities, we will find ourselves far below leadership in the years ahead."

The administration of President Joe Biden, the US Senate and the US House of Representatives have each put forward a slightly different vision for expanding the NSF, although each of their proposals agrees that the agency should invest in emerging technologies and assist in their commercialization. That suggestion has made some researchers nervous about losing funding for basic research — a core priority for the NSF since its inception. As US legislators debate the merits of the proposals and converge on a final plan, one thing is certain: big changes are on the horizon for the NSF.

A boost for basic science

"The National Science Foundation budget should have been substantially increased long before now," says Colwell. Since its launch in 1950, the agency has seen its budget steadily plod towards its current level of $8.5 billion. By comparison, the National Institutes of Health (NIH) — the country's top science funding agency for biomedical research — received $42.9 billion this year.

The NIH's budget more than doubled between 1990 and 2003, and during this time it was able to fund roughly 30% of the grant proposals it received (that proportion has since dropped to around 20%). Members of the scientific community say that boost was responsible for significant achievements in US science. "The mRNA vaccines are a product of doubling our investment in the NIH," said Sudip Parikh, chief executive of the American Association for the Advancement of Science, at a presentation to the National Press Club last month. The NIH