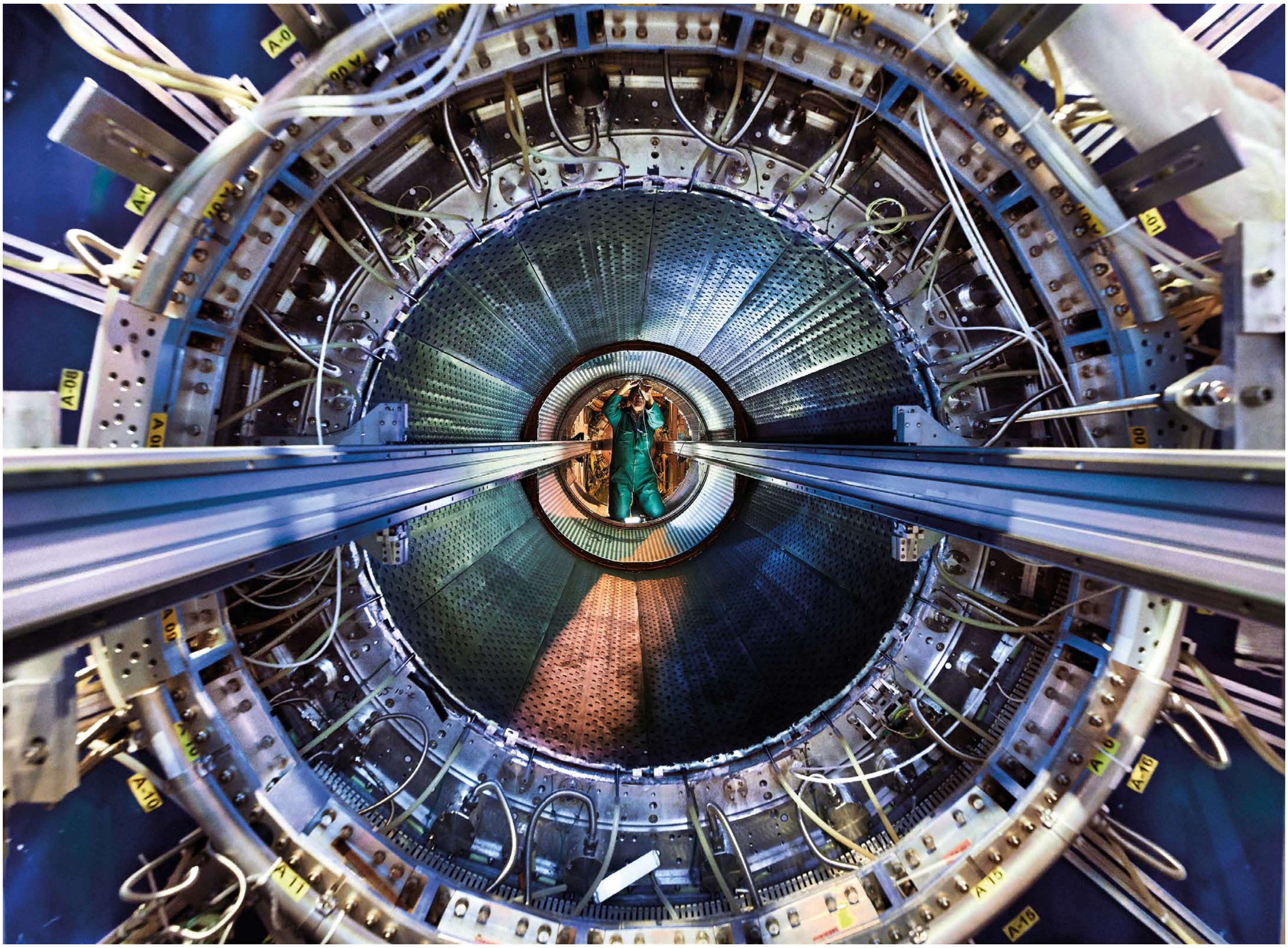

Detectors at the ALICE experiment were revamped during the Large Hadron Collider's 2018–22 shutdown.

LHC: THIRD TIME LUCKY?

The Large Hadron Collider restarts this year — sparking fresh hope it can lead to a revolution in physics. **By Elizabeth Gibney**

The hunt for new physics is back on. The world's most powerful machine for smashing high-energy particles together, the Large Hadron Collider (LHC), has fired up after a shutdown of more than three years. Beams of protons are once again whizzing around its 27-kilometre loop at CERN, Europe's particle-physics laboratory near Geneva. By July, physicists will be able to switch on their experiments and watch bunches of particles collide.

In its first two stints, in 2009–13 and 2015–18, the LHC explored the known physics world. All of that work — including the triumphant 2012 discovery of the Higgs boson — reaffirmed physicists' current best description of the particles and forces that make up the Universe: the standard model. But scientists sifting through the detritus of quadrillions of high-energy collisions have yet to find proof of any surprising new particles or anything else completely unknown.

This time could be different. The LHC has so far cost US$9.2 billion to build, including the latest upgrades: version three comes with more data, better detectors and innovative ways to search for new physics. What's more, scientists start with a tantalizing shopping list of anomalous results — many more than at the start of the last run — that hint at where to look for particles outside the standard model.

"We're really starting with adrenaline up," says Isabel Pedraza, a particle physicist at the Meritorious Autonomous University of Puebla (BUAP) in Mexico. "I'm sure we will see something in run 3."

Higher energy and more data

After renovations to its particle accelerators, the third version of the LHC will collide protons at 13.6 trillion electron volts (TeV) — slightly higher than in run 2, which reached

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13 TeV. The more-energetic smashes should increase the chances that collisions will create particles in high-energy regions where some theories suggest new physics could lie, says Rende Steerenberg, who leads beam operations at CERN. The machine's beams will also deliver more-compact bunches of particles, increasing the probability of collisions. This will allow the LHC to maintain its peak rate of collisions for longer, ultimately allowing experiments to record as many data as in the first two runs combined.

To deal with the flood, the machine's detectors – layers of sensors that capture particles that spray from collisions and measure their energy, momentum and other properties – have been upgraded to make them more efficient and precise (see 'Data boost').

A major challenge for LHC researchers has always been that so little of the collision data can be stored. The machine collides bunches 40 million times per second, and each proton–proton collision, or 'event', can spew out hundreds of particles. 'Trigger' systems must weed out the most interesting of these events and throw the bulk of the data away. For example, at CMS – one of the LHC's four main experiments – a trigger built into the hardware makes a rough cut of around 100,000 events per second on the basis of assessments of properties such as the particles' energies, before software picks out around 1,000 to reconstruct in full for analysis.

With more data, the trigger systems must triage even more events. One improvement comes from a trial of chips originally designed for video games, called GPUs (graphics processing units). These can reconstruct particle histories more quickly than conventional processors can, so the software will be able to scan faster and across more criteria each second. That will allow it to potentially spot strange collisions that might previously have been missed.

In particular, the LHCb experiment has revamped its detector electronics so that it will use only software to scan events for interesting physics. Improvements across the experiment mean that it should collect four times more data in run 3 than it did in run 2. It is "almost like a brand new detector", says Yasmine Amhis, a physicist at the Laboratory of the Irène-Joliot Curie Physics of the Two Infinities Lab in Orsay, France, and member of the LHCb collaboration.

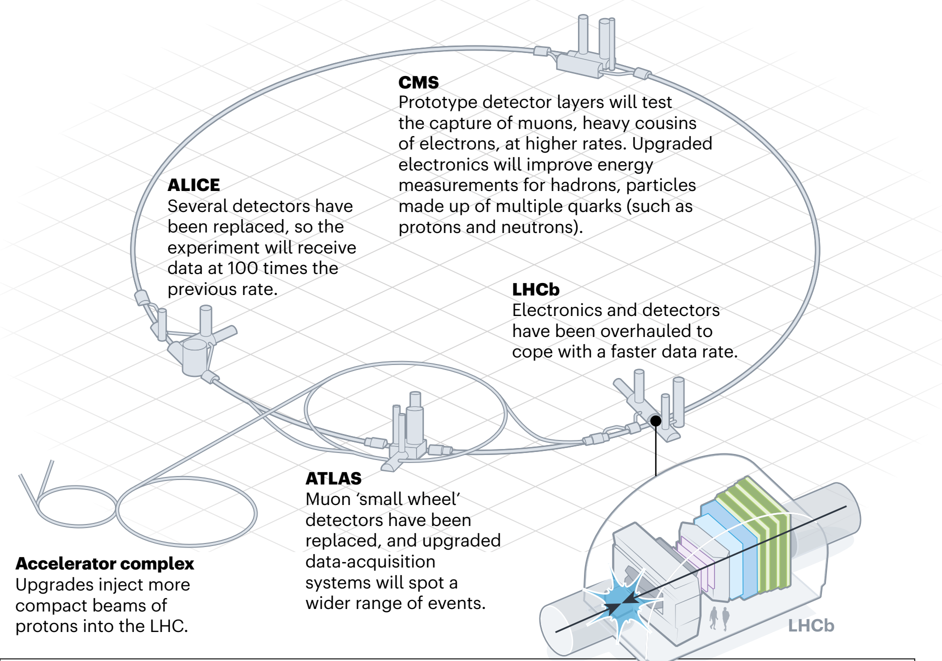
Spotting anomalies

Run 3 will also give physicists more precision in their measurements of known particles, such as the Higgs boson, says Ludovico Pontecorvo, a physicist with the ATLAS experiment. This alone could produce results that conflict with known physics – for instance, when measuring it more precisely shrinks the error bars enough to put it outside the standard model's predictions.

NIK SPENCER/*NATURE*; SOURCE: CERN

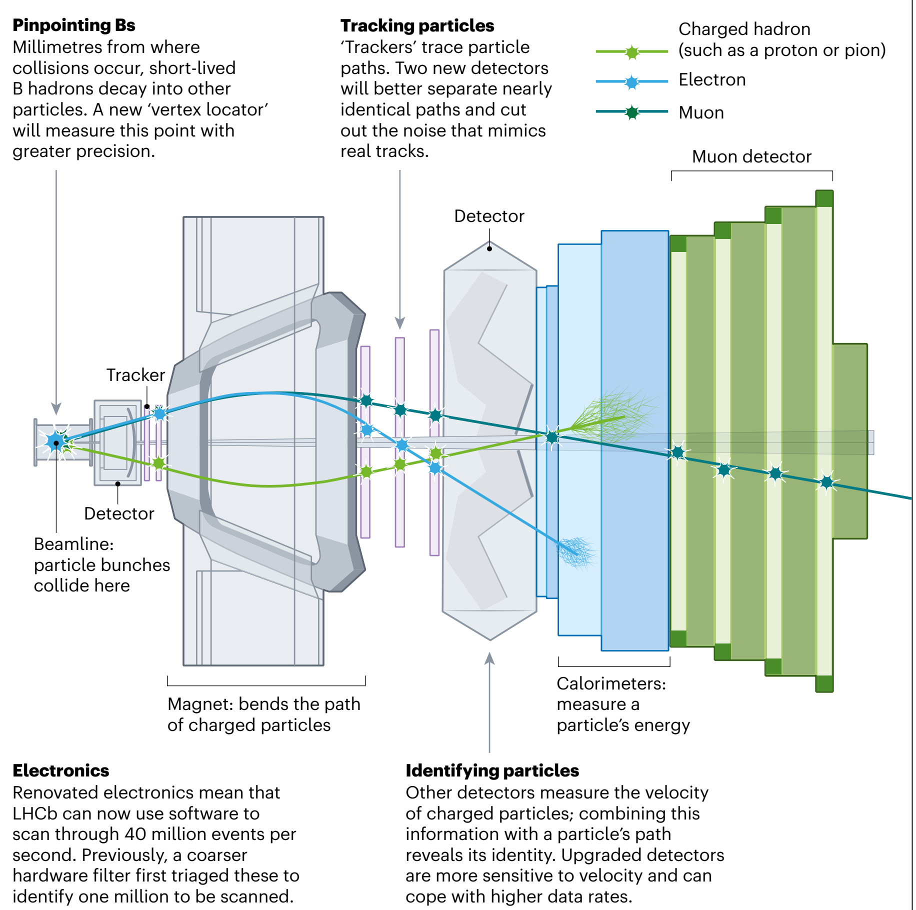
DATA BOOST

In the third run of the Large Hadron Collider (LHC), researchers expect to record as many data on particle collisions as in the machine's first two runs combined. That's in part owing to more collisions, produced by stabler, more tightly packed streams of particles circulating around the ring. It is also because of upgrades to the machine's four main detectors: CMS, ATLAS, ALICE and LHCb. The LHCb has been completely revamped.



Better detectors

The LHCb experiment has been comprehensively upgraded for the LHC's third run. This top-down view shows how it detects particles spraying out of collisions, and how its electronics and detectors have been improved.



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But physicists also want to know whether a host of odd recent results are genuine anomalies, which might help to fill some gaps in understanding about the Universe. The standard model is incomplete: it cannot account for phenomena such as dark matter, for instance. And findings that jar with the model — but are not firm enough to claim as a definite discrepancy — have popped up many times in the past two years (see 'Hints of new physics?').

The most recent is from the Tevatron collider at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, which shut down in 2011. Researchers have spent the past decade poring through data from the Tevatron's CDF experiment. In April, they reported[1] that the mass of the *W* boson, a fundamental particle that carries the weak nuclear force involved in radioactive decay, is significantly higher than the standard model predicts.

That doesn't chime with LHC data: measurements at ATLAS and LHCb disagree with the CDF data, although they are less precise. Physicists at CMS are now working on their own measurement, using data from the machine's second run. Data from run 3 could provide a definitive answer, although not immediately, because the mass of the *W* boson is notoriously difficult to measure.

MAXIMILIEN BRICE, JULIEN MARIUS ORDAN/CERN

The LHCb's 'vertex locator', placed close to the LHC's beamline to see short-lived particles.

B-meson confusion

The LHC's data have hinted at other anomalies. In particular, evidence has been building for almost a decade of odd behaviour in particles called B mesons. These transient particles, which quickly decay into others, are so named because they contain pairs of fundamental particles that include a 'bottom' or 'beauty' quark. LHCb analyses suggest that B-meson decays tend to produce electrons more often than they produce their heavier cousins, muons[2]. The standard model predicts that nature should not prefer one over the other, says Tara Shears, a particle physicist at the University of Liverpool, UK, and a member of the LHCb collaboration. "Muons are being produced about 15% less often than electrons, and it's utterly bizarre," she says.

The result differs from the predictions of the standard model with a significance of around 3 sigma, or 3 standard deviations from what's expected — which translates to a 3 in 1,000 chance that random noise could have produced the apparent bias. Only more data can confirm whether the effect is real or a statistical fluke. Experimentalists might have misunderstood something in their data or machine, but now that many of the relevant LHCb detectors have been replaced, the next phase of data-gathering should provide a cross-check, Shears says. "We will be crushed if [the anomaly] goes away. But that's life as a scientist, that can happen."

The anomaly is backed up by similar subtle discrepancies that LHCb has seen in other decays involving bottom quarks; experiments at colliders in Japan and the United States have also seen hints of this odd result. This kind of work is LHCb's métier: its detectors were designed to study in detail the decays of particles that contain heavy quarks, allowing the experiment to gather indirect hints of phenomena that might influence these particles' behaviour. CMS and ATLAS are more general-purpose experiments, but experimenters there are now checking to see whether they can spot more of the events that are sensitive to the anomalies, says Florencia Canelli, an experimental particle physicist at the University of Zurich in Switzerland and member of the CMS collaboration.

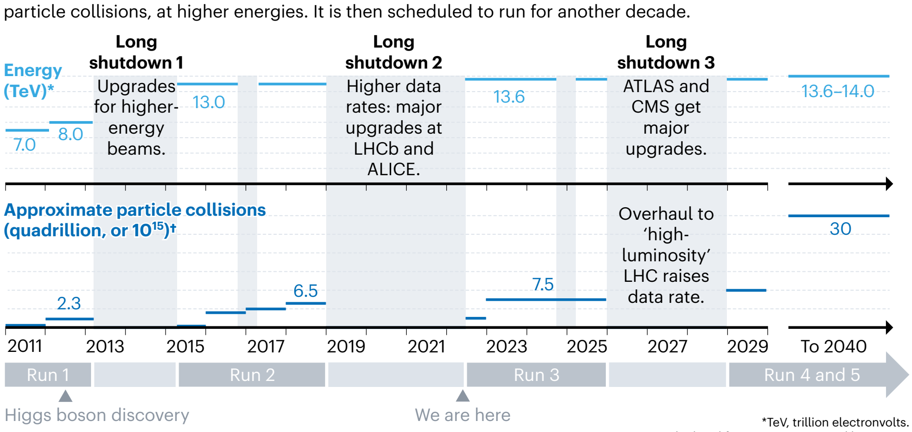
Hunt for the leptoquark

CMS and ATLAS will also do what LHCb cannot: comb collision data to look directly for the exotic particles that theorists suggest could be causing the still-unconfirmed anomalies. One such hypothetical particle has been dubbed the leptoquark, because it would, at high energies, take on properties of two otherwise distinct families of particles — leptons, such as electrons and muons, and quarks. This hybrid particle comes from theories that seek to unite the electromagnetic, weak and strong fundamental forces as aspects of the same force, and could explain the LHCb results. The leptoquark — or a complex version of it — also fits with another tantalizing anomaly; a measurement last year[3], from the Muon $g-2$ experiment at Fermilab, that muons are more magnetic than expected.

At the Moriond particle-physics conference in La Thuile, Italy, in March, CMS researchers presented results of a search that found intriguing hints of a beyond-standard-model lepton. This particle would interact with leptoquarks and is predicted by some leptoquark theories. Physicists saw a slight excess of the particles that the proposed lepton could decay into, bottom quarks and taus (heavier cousins of the muon), but the finding's significance is only 2.8 sigma. "Those are very exciting results, as LHCb is also seeing something similar," says Pedraza. CMS physicists presented hints of other new phenomena at the conference:

LHC TIMELINE

The Large Hadron Collider (LHC) will be further upgraded from 2026 to 2029 to conduct even more particle collisions, at higher energies. It is then scheduled to run for another decade.



*TeV, trillion electronvolts.
†Calculated from LHC's integrated luminosity (one inverse femtobarn ~100 trillion proton–proton collisions). 2023 onwards: design expectations.

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two possible particles that might decay into two taus (see go.nature.com/3kutxsh), and a potential high-energy particle that, through a theorized but unproven decay route, would turn into distinctive particle cascades termed jets (see go.nature.com/3wweejx).

Another intriguing result comes from ATLAS, where Ismet Siral at the University of Oregon in Eugene and his colleagues looked for hypothetical heavy, long-lived charged particles. In trillions of collisions from 3 years of data they found 7 candidates at around 1.4 TeV, around 8 times the energy of the heaviest known particle[4]. Those results are 3.3 sigma, and the identity of the candidate particles remains a mystery. “We don’t know if this is real, we need more data. That’s where run 3 comes in,” says Siral.

Another LHC experiment, ALICE, will explore its own surprising finding: that the extreme conditions created in collisions between lead ions (which the LHC smashes together when not working with protons) might crop up elsewhere. ALICE is designed to study quark–gluon plasma, a hot, dense soup of fundamental particles created in collisions of heavy ions that is thought to have existed just after the Big Bang. Analyses of the first two runs found that particles in proton–proton and proton–lead ion collisions show some traits of this state of matter, such as paths that are correlated rather than random. “It’s an extremely interesting, unexpected phenomenon,” says Barbara Erazmus, deputy spokesperson for ALICE at CERN.

Like LHCb, ALICE has had a major upgrade, including updated electronics to provide it with a faster software-only trigger system. The experiment, which will probe the temperature of the plasma as well as precisely measuring particles that contain charm and beauty quarks, will be able to collect 100 times more events this time than in its previous two runs, thanks to improvements across its detectors.

Machine learning aids the search

The ATLAS and CMS experiments now have improved detectors but will not receive major hardware upgrades until the next long shutdown, in 2026. At this point, the LHC will be overhauled to create more focused ‘high-luminosity’ beams, which will start up in 2029 (see ‘LHC timeline’). This will allow scientists in the following runs to collect 10 times more collision data than in runs 1 to 3 combined. For now, CMS and ATLAS have got prototype technology to help them prepare.

As well as collecting more events, physicists such as Siral are keen to change the way in which LHC experiments hunt for particles. So far, much of the LHC’s research has involved testing specific predictions (such as searching for the Higgs where physicists expected to see it) or hunting for particular hypotheses of new physics.

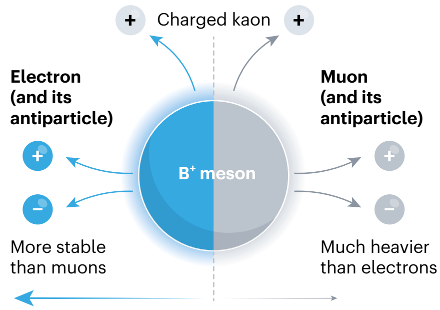
NIK SPENCER/*NATURE*; SOURCE: CERN

HINTS OF NEW PHYSICS?

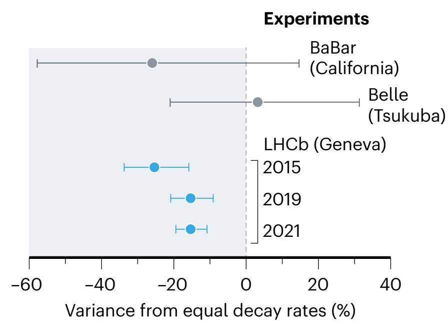
Some recent anomalies clash with physics’ standard model — but they are not yet firm enough to claim as discoveries.

The B-meson anomaly

The B^+ meson — a transient particle — can decay in two ways that should be equally rare.

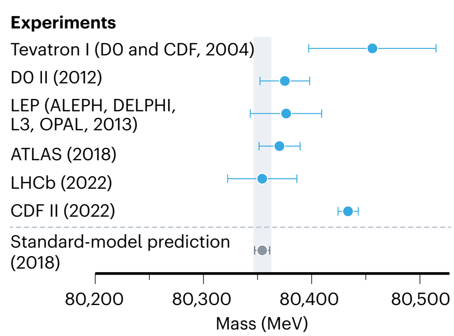


The LHCb detector has seen the electron decay pathway 15% more often than the muon one. That suggests the influence of particles beyond the standard model. Here’s how the LHCb results compare with those from other experiments.



The *W* boson puzzle

The latest analysis of data from the CDF detector at the Tevatron — a US collider — suggests that the mass of the *W* boson is higher than the standard model predicts. Most other experiments disagree.



Scientists thought this would be a fruitful strategy, because they had a good steer on where to look. Many expected to find new heavy particles, such as those predicted by a group of theories known as supersymmetry, soon after the LHC started. That they have seen none rules out all but the most convoluted versions of supersymmetry. Today, few theoretical extensions of the standard model seem any more likely to be true than others.

Experimentalists are now shifting to search strategies that are less constrained by expectations. Both ATLAS and CMS are going to search for long-lived particles that could linger across two collisions, for instance. New search strategies often mean writing analysis software that rejects the usual assumptions, says Siral.

Machine learning is likely to help, too. Many LHC experiments already use this technique to distinguish particular sought-for collisions from the background noise. This is ‘supervised’ learning: the algorithm is given a pattern to hunt for. But researchers are increasingly using ‘unsupervised’ machine-learning algorithms that can scan widely for anomalies, without expectations. For example, a neural network can compare events against a learned simulation of the standard model. If the simulation can’t recreate the event, that’s an anomaly. Although this kind of approach is not yet used systematically, “I do think this is the direction people will go in,” says Sascha Caron of Radboud University Nijmegen in the Netherlands, who works on applying these techniques to ATLAS data.

In making searches less biased, the triggers that decide which events are interesting to look at are crucial, so it helps that the new GPUs will be able to scour candidate events with wider criteria. CMS will also use an approach called ‘scouting’: analysing rough reconstructions of all the 100,000 or so events initially selected but not saved in full detail. “It’s the equivalent of 10 years more of running your detector, but in one year,” says Andrea Massironi, a physicist with the CMS experiment.

The triggers themselves could also soon rely on machine learning to make their choices. Katya Govorkova, a particle physicist at CERN, and her colleagues have come up with a high-speed proof-of-principle algorithm that uses machine learning to select which of the collider’s 40 million events per second to save, according to their fit with the standard model[5]. In run 3, researchers plan to train and test the algorithm on CMS collisions, alongside the experiment’s conventional trigger. A challenge will be knowing how to analyse events that the algorithm labels as anomalous, because it cannot yet point to exactly why an event is anomalous, says Govorkova.

Physicists must keep an open mind about where they might find the thread that will lead them to a theory beyond the standard model, says Amhis. Although the current crop of anomalies is exciting, even previous oddities seen by multiple experiments turned out to be statistical flukes that faded away when more data were gathered. “It’s important that we continue to push all of the physics programme,” she says. “It’s a matter of not putting all your eggs in one basket.”

Elizabeth Gibney is a senior reporter at *Nature*.

1. CDF Collaboration. *Science* **376**, 170–176 (2022).
2. LHCb collaboration. *Nature Phys.* 18, 277–282 (2022).
3. Abi, B. *et al. Phys. Rev. Lett.* **126**, 141801 (2021).
4. ATLAS Collaboration. Preprint at arXiv https://doi.org/10.48550/arXiv.2205.06013 (2022).
5. Govorkova, E. *et al. Nature Mach. Int.* **4**, 154–161 (2022).

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