A new kind of experiment at the LHC could unravel quantum reality

The Large Hadron Collider is testing entanglement in a whole new energy range, probing the meaning of quantum theory – and the possibility that an even stranger reality lies beneath

For Alan Barr, it started during the covid-19 lockdowns. "I had a bit more time. I could sit and think," he says.

He had enjoyed being part of the success at CERN's Large Hadron Collider (LHC) near Geneva, Switzerland — the particle collider that discovered the Higgs boson. But now, he wondered, were they missing a trick? "I had spent long hours screwing bits of it together. And I thought, 'Well, we've built this beautiful piece of apparatus, but maybe we could be doing more with it,' " he says.

The LHC is typically seen as a machine for finding new particles. But now Barr and a slew of other physicists are asking if it can also be used to probe the underlying meaning of quantum theory and why it paints reality as being so deeply weird.

That's exactly what Barr and his colleagues are now investigating in earnest. Last year, they published the results of an experiment in which they showed that pairs of fundamental particles called top quarks could be put into the quantum state known as entanglement.

This was just the first of many entanglement experiments at particle colliders that could open up a whole new way of studying the nature of the universe. We can now ask why reality in quantum mechanics is so hard to pin down and what this has to do with experimenters — or even particles — having free will. Doing so could reveal whether space-time is fundamental or perhaps unveil a deeper reality that is even stranger than quantum mechanics. “We can do really different things with this collider,” says Barr.

Rethinking reality: Is the entire universe a single quantum object?

In the face of new evidence, physicists are starting to view the cosmos not as made up of disparate layers, but as a quantum whole linked by entanglement

If you want to unlock the quantum world, entanglement provides the key. According to Erwin Schrödinger, one of the founders of quantum theory, entanglement is the field’s “characteristic trait”. It is, essentially, a link between quantum particles, however widely separated they might be in space, that defies common sense. That is why Albert Einstein dismissed it as “spooky action at a distance” and assumed — incorrectly — that its existence would be disproved once the theory matured.

Entanglement works like this. First, get two quantum particles, such as photons of light, to interact in some way. It might be as simple as them colliding, or both being products of the same quantum event, such as the spontaneous decay of a Higgs boson.

The spookiness becomes apparent when you perform a measurement on one and then do the same on the other. In the right circumstances, this reveals that the properties of the two particles are correlated: action on one has an instantaneous, corresponding effect on the other.

Think of that correlation as like flipping two coins multiple times and finding that they always land as two heads or two tails. After a while, you would suspect that something suspicious was going on — maybe some hidden magnet was causing them to unfailingly land in the same orientation. If you can’t find a hidden magnet, you might just throw up your hands and declare that someone will eventually come up with a reasonable explanation.

The ATLAS detector at CERN, where high-energy particles decay

ATLAS Collaboration/CERN

That was certainly Einstein's hope, as it was for CERN physicist John Bell, who, in the 1960s, proposed an experiment to check up on correlations between entangled particles that were distantly separated. Typically, in these Bell tests, two entangled photons are generated by the same source and then sent to two hypothetical experimenters named Alice and Bob. Alice and Bob each randomly choose to measure the orientation of their photon — measuring a quantum property known as spin — along one of three directions. Afterwards, they compare observations to assess the correlation. Because quantum theory deals only in probabilities about the results of measurements, not fixed outcomes, the set-up and the measurement have to be done many times. But if there really is spooky action at a distance, more properly termed non-locality, there should be more correlation than Einstein would have expected. Bell quantified this in a mathematical "inequality" that would only be violated if Einstein had been wrong about non-locality.

Their hope that common sense would prevail was in vain. Bell inequalities have since been violated in countless laboratory experiments, proving that in the quantum world, distant points in space can be instantly connected. Physicists have even demonstrated entanglement between a variety of entities, from chilled atoms to diamonds.

However, for all our experimental success, entanglement remains an uncomfortably blunt fact about reality. We are yet to uncover deeper insights about the meaning of quantum theory or to understand whether the quantum rules we have tested in well-controlled lab conditions still apply at the wild frontier found in particle colliders.

The quantum world: A concise guide to the particles that make reality

Now that might be about to change because we are doing Bell tests inside the messy, high-energy environments of particle colliders. Last year's observation of entanglement between pairs of top quarks at the LHC showed that we can investigate the phenomenon in an entirely new sphere — and gain a different perspective on the quantum world. “We’re doing this at a trillion times higher energy than typical Bell tests,” says Barr, who is based at the University of Oxford. “In such a totally different regime, nature might surprise us.”

The top quark entanglement wasn’t a direct observation. Researchers learned about the entanglement by looking at the properties of the cascade of particles that hit the collider’s ATLAS detectors after the quarks decayed naturally. “You infer what happened from the debris,” says Juan Ramón Muñoz de Nova at the Complutense University of Madrid, Spain. That inference is hard though: it depends on studying the angles at which the cascading particles travel while knowing the exact energy of the proton collisions that formed the quarks in the first place and the trajectories they followed.

But this also means that the many petabytes of data on particle decays gathered by CERN over the past few years, and the data to be gathered in its future experiments, should be a similarly rich source of information. “This paves the way for many future quantum experiments at colliders,” says Muñoz de Nova.

Emergent space-time

One intriguing possibility is that these collider experiments could overturn our assumptions about the nature of space, says Vlatko Vedral, a theorist at the University of Oxford. Traditional Bell tests examine entanglement over large distances, but correlations over tiny distances are equally interesting, he says. These collider-based tests look at links that span just quadrillionths of a metre and might tell us whether there is no such thing as space — and thus locality — on that scale. Maybe, he suggests, spooky action at a distance is the norm and the world of particles is non-local by default. In which case, perhaps space isn't fundamental but arises out of entanglement as an emergent phenomenon. "Could it be that we are making a mistake by assuming that things should be local there?" he asks.

What's more, the high energies bring a new world of "virtual" particles into play, says Barr. When particles are accelerated close to the speed of light inside a collider like the LHC, some of the beam energy is turned into additional particles. These aren't real, as such: they are fleeting disturbances in the high-energy fields inside the collider. But they are involved in a range of fascinating and contentious phenomena, including the paradoxical way that black holes seem to emit radiation, and possibly the dark energy that is accelerating the expansion of our universe. "There's a whole realm of quantum phenomena that you'd like to be able to check" using particle-collider Bell tests, says Barr.

The Large Hadron Collider blips that could herald a new era of physics

Colliders could even help us uncover more about the nuances and limits of quantum theory itself. After all, despite the theory being wonderfully successful at predicting the likely outcome of a series of experiments involving quantum-scale particles, we don't understand why it works. Observing entanglement in colliders might assist in finding the parts of a "post-quantum" theory that tell us where quantum phenomena come from.

It might also help us to dissect subtle variations of entanglement. An often-overlooked detail of the quantum realm is that entanglement isn't just one thing. Two fully, or "maximally", entangled particles share all their information — you can't describe one without describing the other. But jolts from their environment might cause some of the information in two entangled particles to be lost, for instance, leaving them less entangled, but not fully disconnected. "There are different levels," says Martina Javurkova at the University of Massachusetts, Amherst.

Then there is "steering", an asymmetric form of quantum entanglement in which the influence of one particle, or set of particles, dominates over the other. And there's discord, which involves a network of weaker links so that one particle can still affect the other, but in a much less dramatic way.

“They are separable states, but they can provide extra information about each other,” says Javurkova.

Entanglement between quantum bits is the core of quantum computing, so understanding these nuances of entanglement helps us to build more sophisticated quantum computers. On top of this is the possibility of entanglement involving three, four or perhaps more particles. These states are incredibly difficult to study in traditional laboratories, but occur naturally during particle collisions. This could have big implications for quantum computing. “We know how to make it work,” says Barr.

Grasping the nuances of entanglement lets us build better quantum computers

Sven Hoppe/dpa picture alliance/Alamy

If all that isn’t enough, what about digging into the very depths of what it means to be a human doing a science experiment? At the LHC, human action has been completely removed from the Bell test. Usually, an experimenter chooses a particular orientation for the detectors or uses a random number generator to determine the choice. This is part of the process of showing that the correlations between the particles don’t come from some pre-existing property in the particles themselves that is hidden from us.

But in a collider Bell test, the measurement of a particle’s quantum state occurs when it spontaneously decays into other, less massive particles. So these collider-based Bell tests just “happen”, with no human involvement, and before the particles interact with the collider’s detection apparatus, says Christopher Timpson, a philosopher also based at the University of Oxford. All of which brings into question what a measurement actually is, he says, and whether particles have something akin to free will. “Does the particle get to choose the nature of the measurement that’s done to it?” he asks. “And if the choice of measurement direction is being selected by the particle, not by an independent process, is that the same as a random number generator?”

In other words, this all might have something to contribute to the long-standing “measurement problem”, the source of all the weird ideas in quantum theory about what reality is really like. A quantum particle can be set up so that it is in what looks like multiple different states at once. This "superposition", famously exemplified by Schrödinger's dead-and-alive cat, lasts until a measurement is made on it. But no one has ever been able to agree on what actually constitutes a measurement, resulting in myriad interpretations of what happens when a measurement occurs.

Quantum interpretations

Famous examples include the many-worlds interpretation, which says that quantum events unfold in a succession of separated universes; the Copenhagen interpretation, which says that a measurement on a quantum particle induces a fundamental change in the system that we observe as the normal, "classical" world; and the hidden variables interpretation, which suggests that the bizarre course of quantum events is caused by certain factors that we can't access. In this view, if we just had knowledge about the hidden variables, then nothing would look strange.

Some of these ideas, such as the Copenhagen interpretation, require a classical context. In others, like the many-worlds picture, everything is quantum mechanical. If anything gets ruled out by the colliders, it is likely to be the idea that the classical world is in any way relevant in making sense of things, says Vedral. That is partly because there is no human-scale — that is, classical — action involved when quantum measurements are made inside particle colliders. But Vedral admits that this is also his instinctive bias. “If and when quantum mechanics fails, if experiments start to really contradict it, it’s unlikely that we will see some kind of return to classical physics,” he says. Rather, it is much more likely that it will expose an even more perplexing reality that, in certain scenarios, looks like quantum mechanics.

Eminent physicists, including Marie Curie and Albert Einstein, discussed interpretations of quantum mechanics at the famous Solvay conference in 1927

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Barr is also interested in what the LHC might teach us about the validity of certain quantum interpretations. “I’m not going to say it will definitely favour one thing over another, but it does seem to bring the element of subjectivity into question," he says. "That does tend to favour certain interpretations of quantum mechanics." He is already working with philosophers of physics to dig into what collider experiments might reveal about how we interface with quantum matter. Timpson is one of them, and he believes there is a huge amount to explore. "These experiments are a playground for bringing together concerns about quantum measurements, quantum interpretations, the nature of entanglement and the nature of non-locality," he says.

Schrödinger's kittens: New thought experiment breaks quantum theory

In a collider experiment, however, the researchers can't take anything for granted: there are a lot of unknowns in quantum experiments that involve such extreme conditions as well as hard-to-access particles like top quarks and W bosons. "The kinds of interactions we see in the LHC would certainly be exotic in the lab," says Yoav Afik at CERN, one of the researchers behind the entangled top quarks result. That work has already thrown out a surprise, he says: the degree of entanglement observed was stronger than what you would expect according to the standard model of particle physics, hinting at the existence of new particles and forces. "It could be that we can use these techniques to measure something interesting about the standard model itself," says Afik.

In fact, there is so much excitement that Barr is keen to avoid hype about what will come out of doing quantum physics at colliders. "I'd be lying if I said I've got all the answers," he says. "But regardless of the results, it poses lots of questions that will make us think."

Michael Brooks is a New Scientist consultant. His latest book is The Maths That Made Us