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Sonia Fernandez

Physicists extend the search for quantum black holes at the LHC

Physicists at UC Santa Barbara have extended the search for evidence of microscopic black holes produced at the Large Hadron Collider (LHC) at the European Center for Nuclear Research (CERN). The formation of these tiny, fleeting objects at the LHC represents one way in which theorists have sought to resolve anomalies in our understanding of the basic structure of spacetime, while the method that was used to look for them demonstrates a whole new way of searching for new particles.

“Had we found evidence, we could have begun to directly study quantum gravity,” said Tamas Vami, a researcher in the Compact Muon Solenoid (CMS) experiment who is conducting his postdoctoral work under the guidance of UCSB physics professor Joe Incandela. “It’s a step toward unifying all of the known fundamental forces, which has been a goal of physicists for more than a century.”

But a null result does not a fruitless search make, said Incandela Lab graduate student researcher Danyi Zhang. Quite the opposite, actually.

“It’s not a dead-end,” she said. “The result is an exclusion limit, which is a real, publishable statement: ‘If this thing existed with these properties, we’d have seen it. We didn’t, so we can rule it out here.’ That’s genuine knowledge about how the universe works.”

One of the mysteries of our universe is that we exist at a scale that is much lower than the one fundamental energy scale that we know, the Planck scale. This could be explained by new physics or a symmetry we have yet to detect, and theorists have determined that this new physics could appear at the energy scales accessible to the LHC. Many new theoretical possibilities and experimental searches have excluded a large space of possibilities; the fact that no new physics has been seen at the LHC has created a real conundrum for fundamental physics. However, analogous situations have occurred before and have led to completely new paradigms, such as Einstein’s relativity. In this context, the researchers said, null results are an important part of the record and serve to guide future ideas and experimental searches.

Vami’s and Zhang’s results are published in the journal Progress in High Energy Physics (PHEP).

Black holes at the LHC

The notion of black holes at the LHC began a couple decades ago when it was suggested that with high enough energies, and the possibility of extra spatial dimensions (which are already required in string theory), quantum black holes could potentially be formed among the trillions of proton-proton collisions generated by the LHC particle accelerator.

“They wouldn’t stick around very long — if you made one, it would disintegrate immediately,” said UCSB physics theorist Steven Giddings, an expert in the paradoxical implications of combining quantum mechanics with gravity, and one of a few scientists at the time who proposed that under certain conditions these tiny voids in spacetime could exist.

The fact that these microscopic quantum black holes would evaporate instantly was then misunderstood in the popular imagination, which latched onto news of potential stable black holes at the LHC and ran with it.

“People were more focused on the classical behavior of black holes,” said Giddings, referring to those massive voids in spacetime, areas of extreme gravity that can eat whole stars, grow, merge. These LHC black holes would be the result of proton-proton collisions and as yet undiscovered extra dimensions.

“So what do you need to make a black hole? Well, you have to compress some energy into a really small volume,” Giddings explained. This “really small volume” could be within two or more hypothetical extra spatial dimensions too small for us to register in our 3 + 1 dimension reality. Their existence has been proposed as a solution for longstanding fundamental physics puzzles such as the hierarchy problem, which asks why, for instance, gravity is so much weaker than the other fundamental forces of our universe. This question is part of the larger difficulty that physicists have in explaining why everything we see exists at a mass and energy scale as low as it is.

With regard to gravity, the idea is that there might actually be much stronger gravity, but it could be “leaking” into these extra dimensions, something that would imply that the Planck scale could be much closer to our energy scale than we think. Its effect would grow to be much stronger in those smaller dimensions, according to Giddings.

“Basically, the gravitational force gets stronger, faster, as you go to shorter distances,” he said.

Enter the Large Hadron Collider and the incredible energies generated by those proton-proton collisions.

“At the LHC, we’re colliding particles at extremely high energy, which corresponds to tiny distance scales,” Incandela said. “As with microscopy, higher energies mean smaller wavelengths, allowing one to probe smaller distances.” They’re probing as low as 10^{-20} meters at the LHC — a distance that is to an atom, what an atom is to a human. “The extra dimensions wouldn’t have to be that small,” Incandela continued, “meaning that the LHC proton-proton collisions could be affected by them.” This combination of extremely dense energy in a strong gravity environment would theoretically have been enough to make spacetime fold upon itself and create a quantum black hole.

The controversy surrounding black holes at the LHC was ultimately resolved after safety reports and comparisons with bombardments by ultra-high-energy cosmic rays interacting in the upper atmosphere or with other astronomical objects confirmed that these high energy collisions must not be a threat, and any quantum black holes would evaporate instantly. In spite of their extremely short lifetimes, LHC physicists realized that they could potentially detect them via the ways in which they decay. Early searches were conducted by ATLAS and CMS that did not turn up any evidence for them, but these were carried out with relatively small datasets.

With much more data available it was possible for a new search that could push to higher energy regions. Because quantum black holes would be an exceedingly rare event, more data would increase the probability they could be found, if they existed.

“We have two big theories that describe nature,” Tamas Vami said. “If you want to describe things that are small, you go to quantum field theory. We have the Standard Model to describe all the particles, and it performs exceptionally well in practice. And when you go to the very, very big you have general relativity that would describe how big and massive objects behave.” The goal is to somehow merge the two theories into a single, unified theory, he said, “and that’s really hard to do because you don’t often have a situation which is really tiny but also extremely heavy.”

Black holes address the need for the intersection of classical and quantum physics, in particular microscopic black holes, for which quantum effects would become more significant.

In their paper the researchers outline two methods for determining the presence of black holes from data taken between 2016 and 2018 with the CMS detector.

One involves a property called sphericity, Incandela explained.

“You form a black hole, and it immediately disintegrates. But it has a very spherical decay signature, lots of things going in all directions.”

The other is very high energy.

“We know that black holes are very high energy,” Danyi Zhang said. “So we basically just take the energy of these particles that are decay products of whatever was created in the collision and sum them together. And if the sum is large enough, we can say that this is the region where we are likely to find the signal.”

That kind of event structure also lends itself well to a new “phase-space distance” method developed by UCSB particle theorist Nathaniel Craig and collaborators. The method enabled them to use a machine learning tool called a Support Vector

Machine for particle searches. It helps users distinguish the structure of the desired signal events from the background of other high-energy events occurring as a result of already established processes. “Phase space” refers to a mathematical, multidimensional map in which every dimension of space and time, as well as energy and momentum of a system of particles is incorporated into a single position.

“We developed the idea of the phase space between events, which can be combined with SVM to help the search,” Craig said. The distances between all events are converted into a single variable called an SVM score. The larger the score, the more likely the researchers were looking at the signal. This is the first time the method was applied to a particle physics data analysis.

“We compared phase space distance with the sphericity variable and our conclusion is that phase space distance outperforms sphericity,” Zhang said. Additionally, unlike the “black box” types of machine learning, this method is supervised, so the researchers can peek under the hood at the math that underlies the results.

The researchers did not find the telltale signs of quantum black hole production in their search, meaning that up to about 12 TeV (Tera-electron volts) quantum black holes are unlikely, as are extra dimensions, as they are described in certain theories.

This restriction is valuable, as it puts concrete limits on these theoretical models of the universe. For instance, Vami said, string theory assumes a total of 10 dimensions, “but these measurements say that, assuming the parameters of the theories we considered, you cannot have more than two.”

“Theories don’t predict one exact answer,” Zhang added. “They predict a whole range of places a particle could be hiding. Each

search clears out part of that range and says ‘not here,’ and over time the map of where new physics could still be, shrinks.” That’s how the particles such as the Higgs boson were eventually found, she continued — in 2012, after decades of excluding one energy region after another in a rigorous process of elimination. This process both forces better ideas and affects the development of new models, and the design of new experiments and detectors.

So for now the mystery of the hierarchy problem remains intact, and according to Giddings’ estimates, in the absence of extra dimensions, it would take particle collisions a million billion times the energy of the ones currently produced at the LHC to create the smallest, microgram-sized black holes.

“Theorists will continue to generate ideas and maybe we will do better in figuring things out without experimental data, but it will be difficult,” Giddings said. “The best guide is experimental data, and that’s what we’d really like to have,” he said, to study quantum gravity, which he calls “the most profound problem in theoretical physics.”

For experimentalists Vami and Zhang, their work at the highest energies the collider can currently muster has allowed them to test the Standard Model to the extreme. Their work not only provides direction for future quantum black hole searches as possible solutions to the hierarchy problem, it has also demonstrated that a generalizable new method, the phase-space distance tool, can boost searches for other exotic and heretofore unknown particles, and uncommon interactions and conditions.

In fact, in the same paper the researchers document their search for sphalerons, which are not particles; rather they are a theoretical unstable configurations of particle fields that would — similar to quantum black holes — have fairly spherical energy signatures. They could also explain another fundamental mystery of physics — the matter-antimatter asymmetry problem, or why our universe has matter when the

Big Bang is thought to have created matter and antimatter in equal amounts, which ought to have annihilated one another, leaving only energy behind. The researchers did not find these hypothetical processes in their search, thereby setting limits on the fraction of interactions that could possibly be producing sphaleron transitions.

“We will be putting constraints on what theories can be true,” said Zhang, who is looking forward to new data with upgraded obtained in the future at the LHC, which is currently shut down for the installation of an ambitious set of upgrades. The future High Luminosity Large Hadron Collider (HL-LHC) will allow researchers “to study fundamental components of matter in more detail,” including processes that may reveal how the early universe evolved.

Media Contact

Sonia Fernandez
Senior Science Writer
(805) 893-4765
sonia.fernandez@ucsb.edu

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