New precise particle measurement improves subatomic tool for probing mysteries of universe

September 29 2015, by Margaret Allen

Deep blue space scattered with nebulae and shining stars. Credit: NASA

Physicists at Southern Methodist University, Dallas, have achieved a new precise measurement of a key subatomic particle, opening the door to better understanding some of the deepest mysteries of our universe.

The researchers calculated the new measurement for a critical characteristic—mass—of the top quark.

Quarks make up the protons and neutrons that comprise almost all visible matter. Physicists have known the top quark's mass was large, but encountered great difficulty trying to clearly determine it.

The newly calculated measurement of the top quark will help guide physicists in formulating new theories, said Robert Kehoe, a professor in SMU's Department of Physics. Kehoe leads the SMU group that performed the measurement.

Top quark's mass matters ultimately because the particle is a highly sensitive probe and key tool to evaluate competing theories about the nature of matter and the fate of the universe.

Physicists for two decades have worked to improve measurement of the top quark's mass and narrow its value.

"Top" bears on newest fundamental particle, the Higgs boson

The new value from SMU confirms the validity of recent measurements by other physicists, said Kehoe.

But it also adds growing uncertainty about aspects of physics' Standard Model.

The Standard Model is the collection of theories physicists have derived—and continually revise—to explain the universe and how the tiniest building blocks of our universe interact with one another. Problems with the Standard Model remain to be solved. For example, gravity has not yet been successfully integrated into the framework.

The Standard Model holds that the top quark—known familiarly as "top"—is central in two of the four fundamental forces in our universe—the electroweak force, by which particles gain mass, and the strong force, which governs how quarks interact. The electroweak force governs common phenomena like light, electricity and magnetism. The strong force governs atomic nuclei and their structure, in addition to the particles that quarks comprise, like protons and neutrons in the nucleus.

The top plays a role with the newest fundamental particle in physics, the Higgs boson, in seeing if the electroweak theory holds water.

Some scientists think the top quark may be special because its mass can verify or jeopardize the electroweak theory. If jeopardized, that opens the door to what physicists refer to as "new physics"—theories about particles and our universe that go beyond the Standard Model.

Other scientists theorize the top quark might also be key to the unification of the electromagnetic and weak interactions of protons, neutrons and quarks.

In addition, as the only quark that can be observed directly, the top quark tests the Standard Model's strong force theory.

"So the top quark is really pushing both theories," Kehoe said. "The top mass is particularly interesting because its measurement is getting to the point now where we are pushing even beyond the level that the theorists understand."

He added, "Our experimental errors, or uncertainties, are so small, that it really forces theorists to try hard to understand the impact of the quark's mass. We need to observe the Higgs interacting with the top directly and we need to measure both particles more precisely."

The new measurement results were presented in August and September at the Third Annual Conference on Large Hadron Collider Physics, St. Petersburg, Russia, and at the 8th International Workshop on Top Quark Physics, Ischia, Italy.

"The public perception, with discovery of the Higgs, is 'Ok, it's done,'" Kehoe said. "But it's not done. This is really just the beginning and the top quark is a key tool for figuring out the missing pieces of the puzzle."

Their article, "Precise measurement of the top quark mass in dilepton decays with optimized neutrino weighting," is publicly available online at arxiv.org/abs/1508.03322 .

SMU measurement achieves surprising level of precision

To narrow the top quark measurement, SMU doctoral researcher Huanzhao Liu took a standard methodology for measuring the top quark and improved the accuracy of some parameters. He also improved calibration of an analysis of top quark data.

"Liu achieved a surprising level of precision," Kehoe said. "And his new method for optimizing analysis is also applicable to analyses of other particle data besides the top quark, making the methodology useful within the field of particle physics as a whole."

The SMU optimization could be used to more precisely understand the Higgs boson, which explains why matter has mass, said Liu.

The Higgs was observed for the first time in 2012, and physicists keenly want to understand its nature.

"This methodology has its advantages—including understanding Higgs interactions with other particles—and we hope that others use it," said Liu. "With it we achieved 20-percent improvement in the measurement. Here's how I think of it myself—everybody likes a $199 iPhone with contract. If someday Apple tells us they will reduce the price by 20 percent, how would we all feel to get the lower price?"

Another optimization employed by Liu improved the calibration precision by four times, Kehoe said.

Shower of Top quarks post Big Bang

Top quarks, which rarely occur now, were much more common right after the Big Bang 13.8 billion years ago. However, top is the only quark, of six different kinds, that can be observed directly. For that reason, experimental physicists focus on the characteristics of top quarks to better understand the quarks in everyday matter.

To study the top, physicists generate them in particle accelerators, such as the Tevatron, a powerful U.S. Department of Energy particle accelerator operated by Fermi National Laboratory in Illinois, or the Large Hadron Collider in Switzerland, a project of the European Organization for Nuclear Research, CERN.

SMU's measurement draws on data gathered by DZero, a collaborative experiment of more than 500 physicists from around the world. DZero's top quark data was produced from proton-antiproton collisions at the Tevatron, which Fermilab shut down in 2011.

The new measurement is the most precise of its kind from the Tevatron, and is competitive with comparable measurements from the Large Hadron Collider.

Critical question: Universe isn't necessarily stable at all energies

"The ability to measure the top quark mass precisely is fortuitous because it, together with the Higgs boson mass, tells us whether the universe is stable or not," Kehoe said. "That has emerged as one of today's most important questions."

A stable universe is one in a low energy state where particles and forces interact and behave according to theoretical predictions forever. That's in contrast to metastable, or unstable, meaning a higher energy state in which things eventually change, or change suddenly and unpredictably, and that could result in the universe collapsing. The Higgs and top quark are the two most important parameters for determining an answer to that question, Kehoe said.

Recent measurements of the Higgs and top quark indicate they describe a universe that is not necessarily stable at all energies.

"We want a theory—Standard Model or otherwise—that can predict physical processes at all energies," Kehoe said. "But the measurements now are such that it looks like we may be over the border of a stable universe. We're metastable, meaning there's a gray area, that it's stable in some energies, but not in others."

Are we facing imminent doom? Will the universe collapse?

That disparity between theory and observation indicates the Standard Model theory has been outpaced by new measurements of the Higgs and top quark.

"It's going to take some work for theorists to explain this," Kehoe said, adding it's a challenge physicists relish, as evidenced by their preoccupation with "new physics" and the possibilities the Higgs and Top quark create.

"I attended two conferences recently," Kehoe said, "and there's argument about exactly what it means, so that could be interesting."

So are we in trouble?

"Not immediately," Kehoe said. "The energies at which metastability would kick in are so high that particle interactions in our universe almost never reach that level. In any case, a metastable universe would likely not change for many billions of years."

Top quark—a window into other quarks

As the only quark that can be observed, the top quark pops in and out of existence fleetingly in protons, making it possible for physicists to test and define its properties directly.

"To me it's like fireworks," Liu said. "They shoot into the sky and explode into smaller pieces, and those smaller pieces continue exploding. That sort of describes how the top quark decays into other particles."

By measuring the particles to which the top quark decays, scientists capture a measure of the top quark, Liu explained

But study of the top is still an exotic field, Kehoe said. "For years top quarks were treated as a construct and not a real thing. Now they are real and still fairly new—and it's really important we understand their properties fully."

More information: "Precise measurement of the top quark mass in dilepton decays using optimized neutrino weighting." arxiv.org/abs/1508.03322

Provided by Southern Methodist University