Heart of the Matter

Three hundred feet below the French-Swiss border, UW scientists are playing central roles in a massive experiment to solve the biggest mysteries in physics. What will it take to succeed?

By Jill Sakai PhD'06

Nestled among the picturesque fields between France's Jura Mountains and Switzerland's Lake Geneva lies a cluster of boxy buildings interlaced with streets bearing the names of famed physicists of the past.

This crowded campus of the European Organization for Nuclear Research, usually called CERN, is home to the largest scientific instrument ever built: a particle smasher so powerful it will condense enough energy to move a Boeing 767 at two hundred miles per hour into a proton beam thinner than a human hair.

It's not a place you would expect to spot Bucky Badger.

Yet, here he is, in a hallway of Europe's preeminent physics research institution, more than four thousand miles from home. Bucky's likeness adorns the office door of physics professor Sau Lan Wu, a Vilas Professor and one of dozens of UW-Madison professors, staff, and students working at CERN on the biggest particle physics experiment ever undertaken.

The energy and tension on the CERN campus are almost tangible as thousands of scientists and engineers work against the clock to put the finishing touches on the Large Hadron Collider, or LHC, which after nearly twenty years of planning is expected to begin operating this fall. When up and running, this massive machine will slam particles together at nearly the speed of light, bursting them open and providing an unprecedented look at the atom's innards — exotic subatomic building blocks with Seussian monikers such as lepton, meson, muon, and gluon.

UW-Madison is among a handful of institutions with large groups working on both major particle detectors at the LHC, called ATLAS and CMS. Wu's group was the first American research team invited to work on the ATLAS experiment, and physics professor Wesley Smith heads a team that has built more of the fourteen-thousand-ton CMS detector than any other university group. Together, Smith says, the UW teams top the list of American universities with leadership roles on the project.

Simply put, as the LHC gears up to start running, UW scientists are poised to make one — if not more — of the biggest discoveries of modern science.

The Frontier of Physics

It's hard to describe the LHC without superlatives. It will be the world's biggest and most powerful particle accelerator, flinging protons around its seventeen-mile, underground ring eleven thousand times per second until they barrel headlong into one another in the most energetic particle collisions ever recorded. The accelerator's massive superconducting magnets are even the coldest spot in the universe, aside from a few small lab experiments. At -456°F, the magnets are a mere three degrees above absolute zero, the theoretical deep freeze where all atomic motion stops — well, cold. Even outer space averages nearly five degrees above absolute zero.

As big as the LHC is, the ideas behind it and its experiments are even bigger.

The incredibly high energies achieved in the collider aim to mimic the conditions that existed a millionth of a billionth of a billionth of a second after the Big Bang. The energetic particles created in such an atmosphere are highly unstable, shattering almost instantly into a shower of smaller specks. Physicists use such ephemeral particles to probe the nature of the universe, hoping to improve our understanding of the physical principles underlying every aspect of the world we live in. A modern age of discovery is alive and well in high-energy physics, and this is its frontier; only by creating higher and higher energy particle collisions can physicists unlock the atom's remaining secrets.

The best explanation of the physics of the very small is called the Standard Model of particle physics. Not so long ago, the atom was believed to be the smallest unit of matter. During the twentieth century, however, physicists cracked the atom's central nucleus, and now the model is well populated with different particles that are responsible for nearly all of matter's fundamental properties.

Yet, the Standard Model has one glaring hole: the Higgs particle, sometimes referred to as the God particle. Thought to be the source of all matter's mass, the Higgs was first postulated in 1964 by British physicist Peter Higgs. People have been searching for it ever since, rewarded only by tantalizing but unconfirmed glimpses.

Does it really exist? The LHC should finally settle the question.

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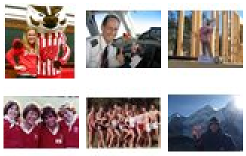

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A Needle in a Barn Full of Haystacks

Whether in his Chamberlin Hall office on the UW-Madison campus or its counterpart at CERN, Wesley Smith looks remarkably relaxed for a man whose job leaves no room for error.

As part of the senior management of the CMS project, Smith has been entrusted with the daunting task of selecting data for the entire two thousand-member team. He is in charge of designing, building, and running the CMS "trigger system," a sophisticated filter that sorts the most interesting patterns from a sea of data. It's a critical job, given the staggering scale of the LHC's particle collisions: up to 600 million each second. As protons collide and splinter almost instantly into smaller particles, physicists take the resulting debris of particle tracks, momentum, and energy to reconstruct the "whodunit" of the whole collision.

"You identify all the particles coming out, you identify all their energies, then add everything back up, and you have the complete picture of what happened in the collision," says Smith.

With a process of this scale, there aren't enough computing resources in the world to store such a huge amount of data, much less analyze it. But fortunately, Smith says, that's not necessary. Most collisions produce particles and physical interactions that are already well understood. Against this background, the trick is to find those few that reveal interesting new phenomena. Pauline Gagnon, an Indiana University physicist on the ATLAS team, describes the process as "looking for a needle in a barn full of haystacks."

Says Smith, "I'm throwing away 99.999 percent of all the data produced at the Large Hadron Collider in this detector. And if I make a mistake, that data is lost. Forever."

The Road to Discovery

Success at this numbers game comes with a twist: as the scientists search for something no one has ever seen, how do they know what to look for? And how will they know when they find it?

"If they exist, each of these new particles has a distinctive signature, due to the way they are produced and the way they decay," explains Sau Lan Wu. "We have some expectations from theories, telling us about exceptionally rare and telltale events that will indicate a discovery."

Wu has been hooked on discovery since early in her career. As a young scientist in the early 1970s, she was on one of the teams that discovered the "J particle," which confirmed the existence of a subatomic bit known as the charmed quark. Her team leader, Samuel Ting, shared the 1976 Nobel Prize in physics for the discovery. A few years later, as a newly appointed assistant professor at UW-Madison, she developed the approach that led to the discovery of the gluon, a particle that "glues" together the pieces of an atom's nucleus.

Today, she is driven by the goal of adding a third finding to her name. "Our focus is on physics discovery," she says. "We have positioned ourselves to be ready when the data come in. … We do not know where a discovery will come from, so we try to cover as many areas as possible."

Each research group within the ATLAS and CMS collaborations helps prepare for data analysis, as well as designing and building the detector. Wu's group specializes in studying particle collision simulations that mimic the data that will be produced by the LHC. Simulated collisions and the resulting decay patterns are generated based on current theories about how particles behave and interact, and they help the scientists learn what to expect and how to interpret what they might see once the machine is operating — for example, a mismatch between a simulation and an experimental outcome may signify something previously unexplained.

"By running these simulations, we gain a lot of understanding," Wu says. "We learn how to identify and reject from our data the very common events, to expose the few rare and golden events hidden in the data that could reveal new physics that lies beyond our level of current understanding."

After years of exhaustive testing, the group is ready for the unexpected, says UW assistant professor Bruce Mellado, who works closely with Wu. "The Higgs is the jewel of the collaboration," he says. "And once you understand the Higgs, you are prepared for everything else."

Rewriting the Textbooks

Though the Higgs particle has garnered much of the limelight as the LHC nears completion, it is not the only goal, nor will its absence signify a failure.

"Whether we see it or not, it will be a big discovery. … We have very good theories that tell us what we think is going to happen, but if it's something else, it'll be even more exciting," says Smith.

A Higgs discovery would fill in the last gap in the Standard Model, virtually confirming the theory. No Higgs, on the other hand, would mean the Standard Model is fundamentally flawed. "If we don't find it, we'll know it's not there, and we have to go back to the drawing board," Smith adds. "This will be a textbook rewriting experience."

Aside from the Higgs, many physicists are in search of what they call "new physics" —

particles, interactions, or phenomena beyond the reach of the Standard Model. Some hope to find evidence of alternate or extra dimensions, such as those proposed by string theory, which holds that everything in the universe is made of tiny vibrating strings of energy. Other scientists have postulated that some proton collisions may create microscopic black holes. A lawsuit filed this spring against CERN and several U.S. agencies attracted attention — and some concern — related to this idea, though physicists say any black holes created would be far too weak to cause trouble and would evaporate almost immediately. The U.S. government filed a motion in June to dismiss the lawsuit; as of press time, a ruling had not yet been issued.

In addition to the Higgs, Wu's group is searching for other exotic hypothetical particles and evidence of supersymmetry, a theory that could help explain interactions among many of the fundamental forces of nature, or even the mysterious dark matter and dark energy that make up the vast majority of our universe, says UW associate professor Yibin Pan, a member of Wu's team.

Scientists also look for new physics by focusing on what's not there. As the high-energy products of proton collisions decay into showers of smaller particles, the scientists add up the energies of all the detected particles and compare them to the starting protons. If the two values don't match, something unseen must account for the difference.

"For example, if you see a jet of particles going off in one direction but you don't see anything going off in the opposite direction, you know the momentum has to be balanced," explains CERN theoretical physicist John Ellis. "It's what I once called a Zen event. You know the little saying, 'What is the sound of one hand clapping?' Well, what is the sound of one jet of particles? It could be dark matter."

Competitive Collaboration

After decades of work, the LHC and its detectors are nearly ready for their debut. As the time approaches, the atmosphere on the CERN campus is thick with excitement and tense anticipation. While everyone is eager to start collecting data, the scientists continue to test and re-test components, connections, and computer systems up to the last moment — ensuring, if possible, that everything will work as planned. With somewhere around twenty-five hundred miles of cabling in ATLAS alone, even a task as straightforward as checking wiring connections is no small feat.

And everything has to be just right. The level of precision demanded by the project is mind-boggling; one slight miscalculation could doom the entire endeavor. Says Dick Loveless, a UW-Madison scientist in Smith's research group, "If the beam gets loose, the beam would destroy the detector — it would drill a hole right through it."

Adding to the tension is the fact that ATLAS and CMS will be looking for the same things. The two detectors are designed differently and will use slightly different analysis methods, but both have their sights set on the Higgs particle and supersymmetry, exotic particles, and dark matter. And when the data start coming in, all eyes will be watching to see which experiment reports a discovery first.

"You never want to rely on one experiment. You could make mistakes in one," explains Smith. "You want to have two independent experiments, produce two independent analyses ... and if they agree, you really know that you've got it."

The development phase for ATLAS and CMS has been marked by cooperation and frequent communication — even joint meetings. It just makes sense, Smith says, to seek feedback from others who are intimately familiar with the problems you're facing.

"No other external review, either provided by the lab or other experts, could check our work as well as we could check each other," he says. And, in the end, he acknowledges, each experiment needs the other to provide independent confirmation of any finding — and to convince the world about what they have found.

As the teams prepare to shift to data collection and analysis mode, however, the friendly rivalry may escalate. "There's a lot of competition between the [CMS and ATLAS] experiments, and it's going to heat up even more," laughs Smith.

Number Crunching

While the data are expected to start pouring out of the LHC sometime this fall, don't expect breakthrough discoveries just yet. The scientists will have a lot of number crunching to do before they can extract the physics from the raw data. The complexity of the analysis, combined with the volume of data produced, adds up to a tremendous demand for computing power. Fortunately for the groups led by Wu and Smith, UW-Madison is ready to deliver.

"Wisconsin is unique in that we have the largest regional computing facilities for both ATLAS and CMS," says Smith.

Much of the UW's computing advantage is thanks to computer science professor Miron Livny, a pioneer in the field of distributed computing, which pools the computing power of hundreds or even thousands of individual processors to efficiently crunch through large data sets. Combining Livny's computing tools and expertise with Smith and Wu's data has proven to be a boon for both disciplines. "It's a wonderful example for interdisciplinary work, where we work together in a way that advances both of our sciences — me as a computer scientist and them as physicists," Livny says.

Livny's computing prowess benefits the broader LHC community. As the principal investigator on a national initiative known as the Open Science Grid, Livny has provided distributed computing resources to the larger CMS and ATLAS collaborations, which they will use to help divide their data among many universities and institutions for local processing.

"We are really sitting on several key aspects — we have a very strong scientific activity, we have a very strong software involvement, and we have a significant infrastructure involvement at the national level," Livny says. "It's a very powerful convergence for UW."

Wu says the speed of physics success may come down to computing power. "Several years ago, what we are doing now would have been impossible without all these computing technologies. Science, in a way, is driven by the technology," she says. Compared to other institutions, she adds, "We have a lot more computing resources. … [I hope] we can detect a discovery faster."

Even so, any discovery will require time. "It may take us two or three years to make sense out of what we're seeing, because scientific discoveries do not come along and announce themselves as discoveries," Smith says. "You don't sit there and see it flash, 'Higgs! Higgs! Higgs!' First is the realization that you have something that you can't explain, and that's called a discovery. But defining what discovery you have is often more difficult."

The scientists must carefully check and re-check their work, challenging and gradually excluding every possible explanation until left with only one. Even then they must verify the explanation with further testing, always tending toward caution in their interpretations. "It is very important to have cross-checking," says UW physicist Yibin Pan. "We are talking about the discovery of potentially new particles. We don't want to have a false alarm."

Exploring the Energy Frontier

What drives these scientists to pursue a task that requires decades of work, presents major challenges, and offers unrelenting stress — with no guarantee of success? Ultimately, it may come down to basic human curiosity. People have always felt the urge to explore and expand their frontiers, and these scientists are no different.

"The potential to discover the unexpected is really one of the best parts of being an experimental physicist," says Wu.

Much like Columbus gazing at the western horizon of the Atlantic or Galileo peering through his telescope at the stars, the LHC offers a window into a new world, a previously inaccessible realm full of high-energy particles beyond what physicists call the "energy frontier." Legions of scientists around the world are eagerly awaiting what the LHC may find.

At the moment, it is largely a cerebral pursuit, with few if any planned practical applications. The LHC itself will not cure diseases, nor solve the growing world food and energy crises. But, as many scientists are quick to point out, human ingenuity will undoubtedly step in. Countless technologies — x-rays, transistors, lasers, and magnetic imaging, to name a few — can trace their roots to obscure intellectual endeavors that, at the time, had no foreseeable practical use.

CERN is well known as the birthplace of the World Wide Web, devised in 1989 by scientist Tim Berners-Lee as a way to improve data handling. His original manuscript, modestly titled "Information Management: A Proposal," is still on display in the CERN campus museum, complete with a handwritten comment from his boss: "Vague, but exciting."

While most Geneva tourists enjoy the lake, city, and mountains, University Communications science writer Jill Sakai PhD'06 spent her visit three hundred feet underground in the CERN tunnels.