A Shot in the Dark

Researching one of the most puzzling unsolved problems in physics.

Written by Michael Blanding

This essay is part of *[The Stories that Make Us](#)*, featuring key efforts in the Foundation's history.

Photos of FASER installation, a visit by Mark Heising and Jim Simons, and experiments, courtesy of CERN. Photos by: 1) Maximilien Brice and Julien Ordan; 2: Jacques Herve Fichet; 3) Maximilien Brice; 4) Maximilien Brice and Julien Ordan. Top banner photo by Maximilien Brice.

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> **JONATHAN FENG, THEORETICAL PHYSICIST AT UNIVERSITY OF CALIFORNIA–IRVINE**

In early 2017, theoretical physicist Jonathan Feng was working with postdoctoral scholars in his group at the University of California–Irvine, when he came to a sudden realization: the largest physics experiment in the world had a blind spot. The Large Hadron Collider (LHC) in Geneva, Switzerland, is designed to shoot beams of protons through a 27-kilometer circular tunnel buried 100 meters underground. When they smash into each other at high speeds, they create a shower of smaller particles that are measured by detectors the size of an apartment building. The collider was created to discover the secrets of the universe by finding particles that had never been seen before. In 2012, it hit pay dirt with the discovery of the Higgs boson, a super tiny particle that theorists had claimed existed for decades, but never proven.

Standing at his blackboard, however, Feng realized that the beams of protons slamming into each other at collision points might be producing even smaller particles with very weak interactions. In the energy of the collision, they wouldn't veer off at an angle within the instrumented parts of the experiments where they could be detected, but keep going forward, presumably passing through the bedrock wall of the collider and disappearing. The problem was, there was no detector there.

"The LHC, which has been the 800-pound gorilla in our field for decades now was missing this opportunity," Feng says. "All these new particles created at this multi-billion-dollar collider were just streaming down the beam pipe and being missed."

In a flash of inspiration, one of his postdocs Googled "LHC map" and came up with a schematic of the underground complex at CERN (Conseil Européen pour la Recherche Nucléaire, or European Council for Nuclear Research), which showed that detecting such particles might be possible. "We found there was an existing tunnel that just happened to be kind of in the right spot," Feng says. Excitedly, they wrote up a paper spelling out their idea, thinking someone would pick up on it. After all, as a theoretical physicist, it was Feng's job to propose theories, not carry out experiments to prove them. As the months went by without any kind of response, however, Feng realized that CERN's experimental physicists were busy with their own projects. If he was going to see his idea come to fruition, he'd need to get it built himself. "That," Feng says, "is how I became an experimentalist."

Mystery Search

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> **JOCHEN MARSCHALL, SCIENCE PROGRAM DIRECTOR, HEISING-SIMONS FOUNDATION**

Since the early 1970s, physicists have believed in a Standard Model of the universe, which posits that all matter consists of tiny atoms, made up of smaller particles such as protons and neutrons, which in turn are made up of even smaller particles such as quarks. As useful as the model has been to explain the universe, it has a major flaw: it only predicts about 5% of the mass we can observe.

"The galaxies and stars are rotating too fast to be bound by the visible mass," Feng explains. "It implies there is some new as-yet-unknown particles in nature."

The LHC was created in 2008 to not only identify the last particles predicted by the Standard Model, but also to search for so-called dark matter—these previously undetected particles that could account for some of the universe's mysterious missing mass. Feng has been a proponent of a theory known as supersymmetry, which proposes that for every particle in the Standard Model, there is a 'superpartner' with similar properties but a different spin, and some of these may be candidates for dark matter. In more than a decade of smashing protons, however, the LHC has been unable to find any evidence of such particles. That has led

Feng and others towards another theory, that dark matter isn't made up of these large particles at all, but rather, much smaller particles with weaker interactions such as dark photons—the kind of particles that would disappear down the LHC's blind spot.

Discovering them could help scientists finally explain the nature of the universe and how galaxies are formed.

"The search for dark matter is one of the two or three biggest problems in physics," says Jochen Marschall, director of the Science program at the Heising-Simons Foundation. "It's a Nobel Prize–winning discovery for whoever finds it and confirms it." For that reason, Marschall was immediately intrigued when he first heard about Feng's proposal, dubbed the FASER (Forward Search) experiment. It seemed to him to represent a completely untapped opportunity for physicists to finally catch a glimpse of the elusive dark matter that binds the universe together. Moreover, Feng's proposed detector also had the potential to study other known particles such as neutrinos that would also be carried down the beam line to the LHC's blind spot. Creating FASER and navigating CERN's bureaucracy to install it, however, would not be an easy task—and the clock was ticking.

A Race Against Time

> **"This is a really steep change from how things usually work. Suddenly, it became something that could really happen."**

JAMIE BOYD, EXPERIMENTAL PARTICLE PHYSICIST

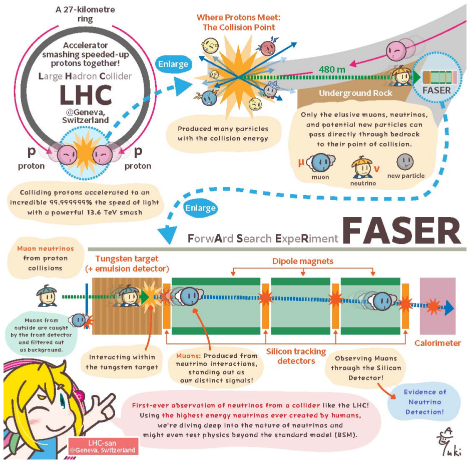

Photo: FASER collider neutrino "manga"-style poster. Poster created by Yuki Akimoto at Higgstan.com.

Feng's first opportunity to get FASER off the ground was at a prestigious conference of physicists, where CERN's senior leadership was in attendance. When he presented his idea, they were skeptical, but intrigued enough to at least refer him to a physicist who could check out the mysterious tunnel he'd seen on the online map. He sent back photos showing the tunnel could be cleaned out to accommodate a detector along the lines that Feng had proposed.

Better yet, he referred Feng to other scientists at CERN, eventually leading him to Jamie Boyd, an experimental particle physicist from the UK, who had worked at ATLAS, one of the collider's two major experiments. More recently, he had served as overall coordinator at the center, making him familiar with the ins and outs of CERN's bureaucracy. Feng's idea sounded like just the kind of promising new project he'd like to get involved in—but he had his reservations. "There are many projects like this, which sound exciting, but when you dig into the details, they are difficult to implement," Boyd said. "In particular, funding is always difficult."

At least Feng's project wouldn't require CERN to drill a new tunnel 100 meters underground. It would, however, require some excavation along the existing tunnel floor to bring it in line with the beam, and there was no way that could be done while the LHC was running. The collider was scheduled to be shut down for two years of maintenance starting in 2019, however.

If FASER could be installed then, the timing would work. That presented Feng with a frustrating chicken-and-egg dilemma. In order to convince CERN he could install FASER quickly, he needed to show he had the funding to do it; but in order to get funding, he had to have some guarantee the project would be installed. Under the most optimistic timeline, the National Science Foundation would take more than a year to approve funding—meaning they'd miss their window. The next opportunity wouldn't be for another five years.

That's when Heising-Simons' Marschall heard about the project, when Feng presented on it at a physics conference in Santa Barbara in April 2018.

Heising-Simons had a long track record of funding innovative projects in science. Mark Heising got his master's in electrical engineering and computer science, worked as a chip designer before going into finance, and never stopped believing in the capacity of science for making transformative discoveries. The Foundation made its first grants in science and climate change in 2008, and it has since provided over $250 million for scientific research.

Always on the lookout for innovative new ideas, Marschall had gone to the Santa Barbara conference to find new projects where the Foundation could make a difference.

"We can't compete with the National Science Foundation, and we don't really want to be a small part of a big thing," Marschall says. "We look for things at a scale where we can have a big impact."

What excited him about Feng's proposal was its simplicity—compared to the giant cylindrical detector of ATLAS, which is 44 meters long by 25 meters high, FASER's detector would only be about 5 meters by 1 meter, about the size of a large canoe, and most of it could be built with existing parts at CERN. Crucially, however, Feng's team would have to build powerful magnets from scratch, which would take some time.

Marschall approached Feng and after talking for over an hour, invited him to send a proposal. Feng made it clear that CERN hadn't yet approved the project, but Heising-Simons was willing to take the chance. Within just a few months, the Foundation approved $1 million for the project, with the first check cut by November—an incredibly fast timeline for a funder to approve a grant to a scientific project.

What's more, Marschall also reached out to the Simons Foundation, a sister foundation focusing on science with which it sometimes collaborates on projects.

"The fact that it was a very original experiment with a relatively low cost but potentially high reward from discoveries, made us really enthusiastic about it," says Gabadazde, senior vice president for physics and dean for arts and sciences at New York University. The Simons Foundation committed another $1 million to the project.

With those funds, Feng's team could not only start building the large cylindrical magnets, but also demonstrate to CERN that it was serious.

"This is a really steep change from how things usually work. Suddenly, it became something that could really happen," says Boyd, who was able to convince the organization to green light the project. FASER used 96 tracking detector modules built for ATLAS along with spare calorimeter modules from another big experiment, LHCb, to put together to the device, which was ready to be installed on time.

Video: FASER, or the Forward Search Experiment, recently observed the first collider neutrinos at the Large Hadron Collider at CERN. The observation had a statistical significance of roughly 16 sigma, far exceeding 5 sigma, the threshold for discovery in particle physics. Video courtesy of CERN, animations by Maximilien Brice and Piotr Traczyk, produced by Chetna Krishna

Forward to the Future

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As soon as FASER started taking measurements in 2021, it began producing results. While it has not succeeded yet in discovering dark matter, it has been able to further narrow the scope of where it potentially exists.

“We’ve put limits on dark photons and axionlike particles,” Feng explains, describing a plane with a range of masses and coupling strengths on its axes. “We’ve been able to rule out a healthy chunk of that parameter space, to focus everyone’s attention on what’s left.”

Mark Heising and Jim Simons visit FASER. Photo by Jacques Herve Fichet, courtesy of CERN.

In other words, FASER has further shown where dark matter *isn’t*—a vital step in determining where it *is*.

Just as exciting, however, FASER’s other mission of identifying neutrinos has been wildly successful. Neutrinos are incredibly small subatomic particles that are among the most abundant objects in the universe, but very difficult to detect due to their small mass and weak interactions. While scientists have observed neutrinos from cosmic radiation, they’ve never seen them in a collider before. In its first run of data, FASER found 153, most in an energy range never seen before, allowing for potentially new discoveries about their properties. Those neutrinos were all muon neutrinos. A few months later, FASER also discovered the first electron neutrinos produced at a particle collider, and the Collaboration expects to discover the first tau neutrinos once it has time to analyze the data that has already been recorded.

Neutrinos can also be used as "messengers" to better explain properties of quarks and other particles within protons.

"That's super-important, because not only are protons part of everyday life, but they're central for all kinds of scientific studies," Feng says. "This will help us better understand what protons are made of, and pin down answers to all sorts of other questions."

So dramatic were all these findings, that the FASER team proposed that CERN dig out an entirely new facility dubbed the Forward Physics Facility with a separate entrance from the surface and room for several larger and more powerful detectors for both dark matter and neutrinos—with capacity to discover as many as 1,000 particles in a single day.

Another project, proposed by Feng's UC-Irvine colleague Jianming Bian would use a different technology to detect particles. Instead of an emulsion film that has to be changed out and developed periodically to avoid overexposure, the device, called FLArE (Forward Liquid Argon Experiment), would use a chamber of liquid argon that would not only be able to measure many more interactions, but also refresh with each observation in real time. "By analyzing the timing and positions of signal electrons that reach several layers of readout planes oriented in different directions, we can create a high-resolution 3-D image of an interaction," says Bian, an Associate Professor of Physics & Astronomy. Once again, Heising-Simons has provided the initial funding, granting Bian $550,000 to hire postdocs and subcontract the technical designs.

The Forward Physics Facility is still under review by CERN, but given the success of the relatively small FASER project and the well-developed plans for the new detectors, approval is promising.

"This time it's more difficult, because it's a lot more expensive," says Boyd, pegging the price tag upwards of $30 million. "It's not guaranteed, but it's really helped that we've been getting such nice results out of FASER, so it's motivating us to push for it."

If the facility does get built, then it may represent the best chance physicists have to finally solve the mystery of dark matter, as well as other untold secrets of the universe—not to mention, an expectation beyond Feng's dreams when he stood before his blackboard seven years ago with a vision. "It's been a wild ride," he admits. "And honestly, the thrill of my scientific lifetime."