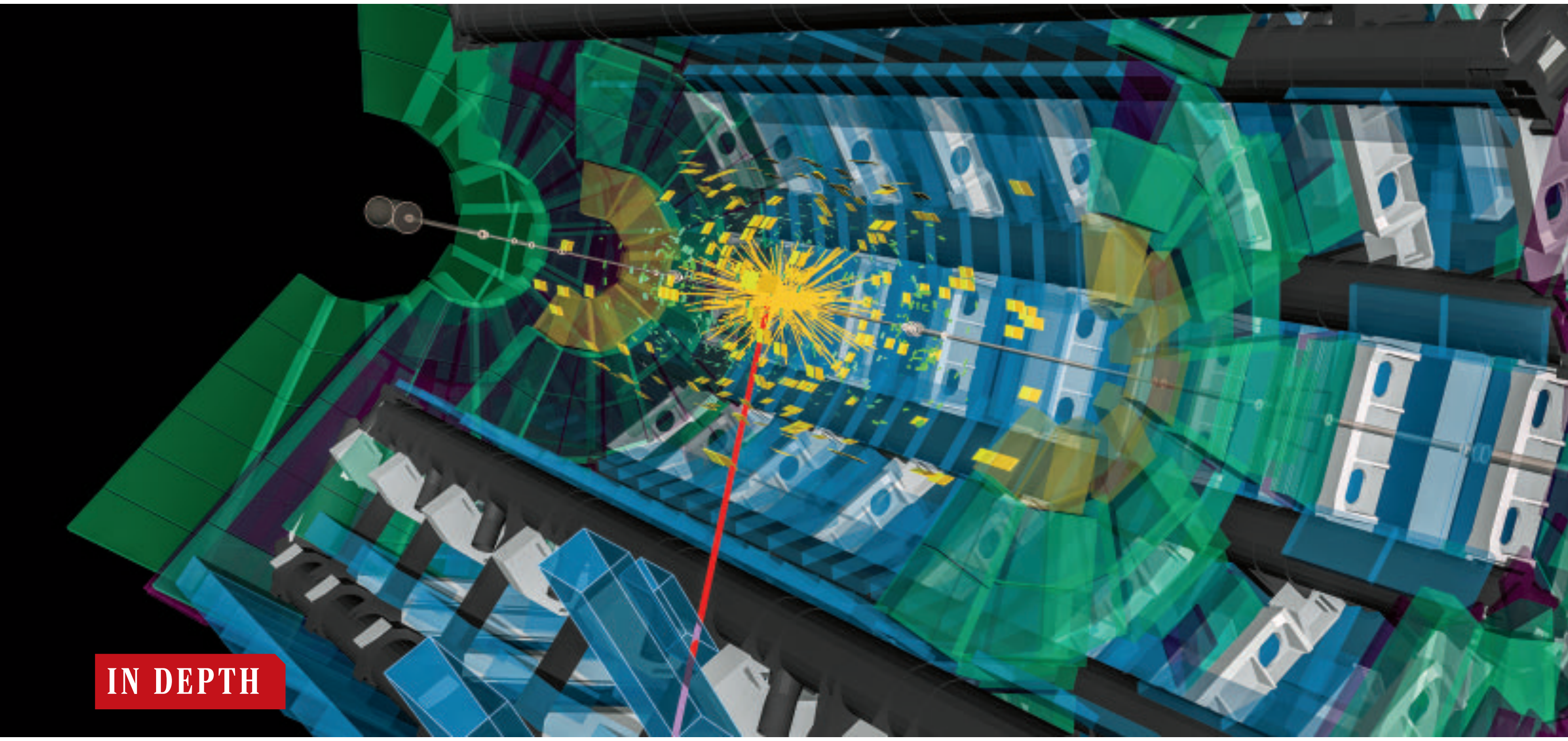

In a simulated event, the track of a decay particle called a muon (red), displaced slightly from the center of particle collisions, could be a sign of new physics.

PARTICLE PHYSICS

A hunt for long-lived particles ramps up

The Large Hadron Collider could be making new particles that are hiding in plain sight

By **Adrian Cho**

Are new particles materializing right under physicists' noses and going unnoticed? The world's great atom smasher, the Large Hadron Collider (LHC), could be making long-lived particles that slip through its detectors, some researchers say. Next week, they will gather at the LHC's home, CERN, the European particle physics laboratory near Geneva, Switzerland, to discuss how to capture them. They argue the LHC's next run should emphasize such searches, and some are calling for new detectors that could sniff out the fugitive particles.

It's a push born of anxiety. In 2012, experimenters at the $5 billion LHC discovered the Higgs boson, the last particle predicted by the standard model of particles and forces, and the key to explaining how fundamental particles get their masses. But the LHC has yet to blast out anything beyond the standard model. "We haven't found any new physics with the assumptions we started with, so maybe we need to change the assumptions," says Juliette Alimena, a physicist at Ohio State University (OSU) in Columbus who works with the Compact Muon Solenoid (CMS), one of the two main particle detectors fed by the LHC.

For decades, physicists have relied on a simple strategy to look for new particles: Smash together protons or electrons at ever-higher energies to produce heavy new particles and watch them decay instantly into lighter, familiar particles within the huge, barrel-shaped detectors. That's how CMS and its rival detector, A Toroidal LHC Apparatus (ATLAS), spotted the Higgs, which in a trillionth of a nanosecond can decay into, among other things, a pair of photons or two "jets" of lighter particles.

Long-lived particles, however, would zip through part or all of the detector before decaying. That idea is more than a shot in the dark, says Giovanna Cottin, a theorist at National Taiwan University in Taipei. "Almost all the frameworks for beyond-the-standard-model physics predict the existence of long-lived particles," she says. For example, a scheme called supersymmetry posits that every standard model particle has a heavier superpartner, some of which could be long-lived. Long-lived particles also emerge in "dark sector" theories that envision undetectable particles that interact with ordinary matter only through "porthole" particles, such as a dark photon that every so often would replace an ordinary photon in a particle interaction.

CMS and ATLAS, however, were designed to detect particles that decay instantaneously. Like an onion, each detector contains layers of subsystems—trackers that trace charged particles, calorimeters that measure particle energies, and chambers that detect penetrating and particularly handy particles called muons—all arrayed around a central point where the accelerator's proton beams collide. Particles that fly even a few millimeters before decaying would leave unusual signatures: kinked or offset tracks, or jets that emerge gradually instead of all at once.

Standard data analysis often assumes such oddities are mistakes and junk, notes Tova Holmes, an ATLAS member from the University of Chicago in Illinois who is searching for the displaced tracks of decays from long-lived supersymmetric particles. "It's a bit of a challenge because the way we've designed things, and the software people have written, basically rejects these things," she says. So Holmes and colleagues had to rewrite some of that software.

More important is ensuring that the detectors record the odd events in the first place. The LHC smashes bunches of protons together 400 million times a second. To avoid data overload, trigger systems on CMS and ATLAS sift interesting collisions from dull ones and immediately discard data about 1999 of every 2000 collisions. The culling can inadvertently toss out long-lived particles. Alimena and colleagues wanted to look for particles that live long enough to get stuck in CMS's calorimeter and decay only later. So they had to put in a special trigger that occasionally reads out the entire detector between the proton collisions.

Long-lived particle searches had been fringe efforts, says James Beacham, an ATLAS experimenter from OSU. "It's always been one guy working on this thing," he says. "Your support group was you in your office." Now, researchers are joining forces. In March, 182 of them released a 301-page white paper on how to optimize their searches.

Some want ATLAS and CMS to dedicate more triggers to long-lived particle searches in the next LHC run, from 2021 through 2023. In fact, the next run "is probably our last chance to look for unusual rare events," says Livia Soffi, a CMS member from the Sapienza University of Rome. Afterward, an upgrade will increase the intensity of the LHC's beams, requiring tighter triggers.

Others have proposed a half-dozen new detectors to search for particles so long-lived that they escape the LHC's existing detectors altogether. Jonathan Feng, a theorist at the University of California, Irvine, and colleagues have won CERN approval for the Forward Search Experiment (FASER), a small tracker to be placed in a service tunnel 480 meters down the beamline from ATLAS. Supported by $2 million from private foundations and built of borrowed parts, FASER will look for low-mass particles such as dark photons, which could spew from ATLAS, zip through the intervening rock, and decay into electron-positron pairs.

Another proposal calls for a tracking chamber in an empty hall next to the LHCb, a smaller detector fed by the LHC. The Compact Detector for Exotics at LHCb would look for long-lived particles, especially those born in Higgs decays, says Vladimir Gligorov, an LHCb member from the Laboratory for Nuclear Physics and High Energies in Paris.

Even more ambitious would be a detector called MATHUSLA, essentially a large, empty building on the surface above the subterranean CMS detector. Tracking chambers in the ceiling would detect jets spraying up from the decays of long-lived particles created 70 meters below, says David Curtin, a theorist at the University of Toronto in Canada and project co-leader. Curtin is "optimistic" MATHUSLA would cost less than €100 million. "Given that it has sensitivity to this broad range of signatures—and that we haven't seen anything else—I'd say it's a no-brainer."

Physicists have a duty to look for the odd particles, Beacham says. "The nightmare scenario is that in 20 years, Jill Theorist says, 'The reason you didn't see anything is you didn't keep the right events and do the right search.'" ■

PHOTO: IRA BLOCK

PALEOCLIMATE

Project traces 500 million years of roller-coaster climate

Sharp temperature swings pose warning for humanity

By **Paul Voosen**

When it opens next month, the revamped fossil hall of the Smithsonian Institution's National Museum of Natural History in Washington, D.C., will be more than a vault of dinosaur bones. It will show how Earth's climate has shifted over the eons, driving radical changes in life, and how, in the modern age, one form of life—humans—is in turn transforming the climate.

To tell that story, Scott Wing and Brian Huber, a paleobotanist and paleontologist, respectively, at the museum, wanted to chart swings in Earth's average surface temperature over the past 500 million years or so. The two researchers also thought a temperature curve could counter climate contrarians' claim that global warming is no concern because Earth was much hotter millions of years ago. Wing and Huber wanted to show the reality of ancient temperature extremes—and how rapid shifts between them have led to mass extinctions. Abrupt climate changes, Wing says, "have catastrophic side effects that are really hard to adapt to."

But actually making the chart was unexpectedly challenging—and triggered a major effort to reconstruct the record. Although far from complete, the research is already showing that some ancient climates were even more extreme than was thought.

Ancient glaciations are easy enough to trace, as are hothouse periods when palms grew near the poles. But otherwise little is certain, especially early in the Phanerozoic, which spans the past 541 million years. Paleoclimate scientists study their own slices of time and use their own specialized temperature proxies—leaf shape, say, or growth bands in fossilized corals—which often conflict. "We don't talk to each other all that much," says Dana Royer, a paleoclimatologist at Wesleyan University in Middletown, Connecticut. So at a meeting last year, Wing and Huber assembled a loose-knit collaboration, dubbed Phantastic, dedicated to putting together a rigorous record. "Most people came away quite inspired to do something about this," says Dan Lunt, a paleoclimate modeler at the University of Bristol in the United Kingdom.

The value of a deep-time temperature curve extends beyond the exhibit. Similar curves exist for atmospheric carbon dioxide (CO_2). Combine the two and you can see how much warming CO_2 caused in the past, says Jessica Tierney, a paleoclimatologist at the University of Arizona in Tucson. Because the latest climate models seem to forecast more warming than earlier ones (*Science*, 19 April, p. 222), "using paleoclimate to constrain the models is becoming much more important," she says. "We feel we have to step up."

But ancient global temperatures are elusive because they varied with location and season, and because the gauges drop away as you move deeper in time: Tree rings go back only thousands of years and ice cores only a million years or so. Still, oxygen isotopes in tiny fossilized shells on the ocean floor give a fairly reliable longer-term record. Because