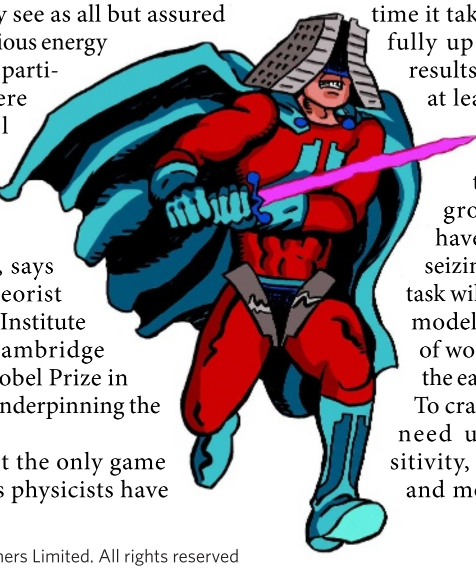
The race to break the standard model

The Large Hadron Collider is the latest attempt to move fundamental physics past the frustratingly successful 'standard model'. But it is not the only way to do it. **Geoff Brumfiel** surveys the contenders attempting to capture the prize before the collider gets up to speed.

It is powerful; it is galling; it is doomed. The incredibly successful mathematical machine that physicists call the 'standard model' is a set of equations that describes every known form of matter, from individual atoms to the farthest galaxies. It describes three of the four fundamental forces in nature: the strong, weak and electromagnetic interactions. It predicts the outcome of one experiment after another with unprecedented accuracy. And yet, as powerful as it is, the standard model is far from perfect. Its mathematical structure is arbitrary. It is littered with numerical constants that seem equally ad hoc. And perhaps most disturbingly, it has resisted every attempt to incorporate the last fundamental force: gravity.

So physicists have been trying to get beyond the standard model ever since it was put together in the 1970s. In effect, they will have to shatter the model with experimental data that contradict its near-perfect equations. And then, from its fragments, they must build a newer, better theory. The Large Hadron Collider (LHC), a giant particle accelerator at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, is the latest attempt to break the standard model — and one that many see as all but assured of success. The prodigious energy it generates will force particles into realms where the standard model cannot follow. In the race to move beyond the status quo, "the LHC is by far the favourite", says Frank Wilczek, a theorist at the Massachusetts Institute of Technology in Cambridge who won the 2004 Nobel Prize in Physics for his work underpinning the standard model.

But the LHC is not the only game in town. For decades physicists have tried to get beyond the standard model in all sorts of ways, sometimes with accelerators, sometimes with precision measurements of breathtakingly rare events, sometimes with observation of outer space. And in the time it takes for the LHC to get fully up to speed — its first results aren't expected until at least next summer (see 'The unstoppable collider') — some of those experimental groups think that they have a fighting chance of seizing the prize first. Their task will be hard: the standard model is a formidable piece of work that has resisted all the easy and obvious attacks. To crack it, experiments will need unprecedented sensitivity, a multitude of data, and more than a little luck.



ILLUSTRATIONS BY J. RIORDAN

Here's a rundown of the heroic few who feel up to the task.

TEVATRON

While the LHC gets its protons up to speed, the world's other heavyweight particle-accelerator is racing to break the standard model first. Since 2001, the Tevatron, located at Fermilab in Batavia, Illinois, has been accelerating protons and antiprotons at an energy of around 1 tera electron volt.

That's only a seventh of the eventual top energy of the LHC, but total energy isn't everything in the hunt for new physics. Collisions that would generate new particles outside the standard model are extremely rare, which means that the longer an accelerator runs and the more data it accumulates, the better its chances of finding something. So for a while, at least, the Tevatron will continue to have a data lead over the LHC. Even by the summer of 2009, the Tevatron will have several times more total data than its new competitor.

And already those data are showing some tantalizing, if tentative, hints of something beyond the standard model. One deviation comes in measurements of a particle known as the strange B (B_s) meson. The B_s is made of a strange quark and an anti-bottom quark, and it is among the heaviest of all mesons. Under a rule known as charge-parity symmetry, the standard model predicts the B_s will decay in the same way as its antiparticle (made of an anti-strange and a bottom quark). But measurements of the two are hinting at a difference in their decays. According to Dmitri Denisov, a spokesperson for the D-Zero experiment at the Tevatron, that difference could be an important clue in the quest for discoveries. It might signal the existence of new, exotic particles, or of previously unknown principles. In any case, says Denisov, "it's an exciting measurement".

The B_s anomaly is not the only oddity showing up at the accelerator, adds Robert Roser, a spokesperson for the Tevatron's other major experiment, the Collision Detector at Fermilab, or CDF. An unusual feature in the decays of pairs of top and anti-top quarks has him intrigued. Again, he admits, it's far from certain. But some of these signals may turn out to be important, Roser says. "As you add data, one of [these anomalies] may become real."

Perhaps not surprisingly, a more sceptical view comes from John Ellis, a theorist at CERN. Yes, the Tevatron could provide some tantalizing hints, says Ellis, but it is unlikely to make a definitive find before the LHC comes on strong. In the world of particle physics, he points out, nothing constitutes a discovery until it is measured to five σ (five standard deviations from the mean), the equivalent of 99.99994267% accuracy. Much more data than the Tevatron has accumulated so far will be needed to reach that exacting standard, and the detector is unlikely to make those big gains before it is overtaken by its new rival. "I think its going to be very, very tough for the Tevatron," Ellis says. "I just don't see them getting it before the LHC starts going gangbusters."

COSMOS

While the high-energy physicists gather in their machine's control rooms, another group of physicists is looking to the heavens. There they hope to find something that shatters the standard model — if the Universe cooperates.

The main thing that their spacecraft will look for are indications of dark matter, the ghostly substance that could make up as much as 85% of the matter in the Universe. Astronomers know that dark matter exists only because of its gravitational pull on galaxies and its influence on the Universe's shape; it seems to pass right through the kind of ordinary matter found in stars, planets and people. Presumably, dark matter is a haze of particles that rarely, if ever, react with the ordinary variety. But nobody is quite sure what those particles might be — except that they are not accounted for in the standard model.

One candidate comes from the 'supersymmetry' theory, which predicts that every particle in the standard model has another, heavier partner lying outside the model. The lightest of these supersymmetric partners is called the neutralino, and is predicted to have just the right properties to be dark matter.

Neutralinos themselves wouldn't be seen by telescopes, orbiting or otherwise. But periodically, two neutralinos could collide and annihilate — creating a shower of more mundane particles that orbiting detectors might pick up. The PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) experiment has already seen an intriguing clue. The satellite-borne instrument has unofficially reported a surplus of anti-electrons that may have been generated by dark-matter annihilations (see *Nature* **454,** 808; 2008). "It's a beautiful result," says Graciela Gelmini, a physicist at the University of California, Los Angeles, who has seen PAMELA's data. Still, she adds, the complexities of the measurement require caution.

A second, recently launched satellite may also be able to spot the untimely demise of the neutralino. The Fermi Gamma-ray Space Telescope is a US$690-million space instrument designed to scan the entire sky for ultra-high-energy photons. It is possible that such γ-rays could be created by neutralino collisions, in which case they would show up as a ubiquitous haze in the orbiting detector's sky-map. "That would be a stunning, stunning signature," says Steven Ritz, the telescope's project scientist at NASA's Goddard Space Flight Centre in Greenbelt, Maryland.

Such signatures, if they're spotted and confirmed in time, definitely have a chance to beat the LHC in the quest to break the standard model, says Michael Turner, a cosmologist at the University of Chicago in Illinois. But Ritz points out that although astrophysics could technically be the first to make such a discovery, they can't do much more than that. Anti-electrons, γ-rays and other such signatures could provide physicists with only a rough mass range for the new particles, and would say nothing about how supersymmetry might work. For those reasons "there would still be a large number of essential question marks", says Ritz — questions that would have to be resolved at the LHC.

M. BRICE/CERN

A welder makes the first connection between two cryomagnets for the Large Hadron Collider.

The unstoppable collider

As *Nature* went to press, the Large Hadron Collider (LHC) at CERN, Europe's particle-physics laboratory near Geneva, was on the verge of circulating its first protons. But there is much to be done before the machine produces publishable scientific findings. In the coming months, even as operators fine-tune the collider itself, other physicists will be trying to get the experiments spaced around the ring up and running.

Switching on a detector the size of a building is no small task. Each instrument is made of hundreds of thousands of smaller detectors, which must be synchronized to track the particles generated by collisions. The detectors are currently being brought into alignment using cosmic rays from outer space, says Peter Jenni, the spokesperson for the ATLAS (Toroidal LHC Apparatus) experiment. But watching particles from real collisions will be a different matter entirely. The colliding proton beams will produce hundreds of millions of distinct 'events' every second, each event comprising hundreds or thousands of debris particles flying outward from the collision point. As the detectors are designed to track most or all of these particles individually, the result will be far more data than the experimentalists can handle. Fortunately, the vast majority of the collisions will produce nothing out of the ordinary. So the experimenters have equipped their detectors with electronic 'triggers' that separate the interesting collisions from the rest. For example, one simple trigger will tag collisions that produce 'muons' — particles that can be created by the decay of more massive particles. Each trigger will be designed to save the evidence of a certain kind of interesting event, and each must be carefully tuned, according to Jenni.

After the data are filtered, they must be analysed. To that end, data from the experiments will be sent to thousands of physicists via a massive computing grid that can shuttle petabytes of data to university labs around the globe. Initial trials have gone well, says Jim Virdee, the spokesperson for the Compact Muon Solenoid (CMS) experiment at CERN, another major experiment, and teams at ATLAS and the CMS are now drilling with computer-generated practice data.

Assuming everything goes smoothly, Jenni and Virdee both say that results could come as early as summer of 2009. By then, the accelerator should have been running for a few months at its full 7-tera-electron-volt strength, and there will have been time to sort out any technical issues.

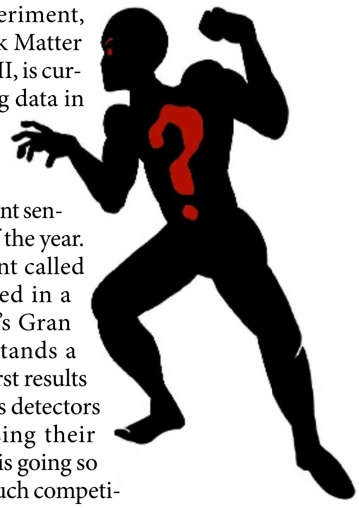
Will the LHC find some new physics in that first run? Possibly. The machine will collide particles at roughly seven times the energy of the world's current leading accelerator, the Tevatron, located at Fermilab in Batavia, Illinois. That's a big jump, and it will, in principle, be possible to see new particles almost immediately, says Virdee. "You don't need that much data to probe beyond what Fermilab has done," he says.

Fermilab physicists are understandably sceptical of that assessment. It took two full years for physicists working at the Tevatron to fully grasp the idiosyncrasies of their experiments, says Robert Roser, a spokesperson for the Collision Detector at Fermilab. And even with the higher energies, it will take a significant number of collisions to find something new, adds Dmitri Denisov, a spokesperson at Fermilab's D-Zero experiment. "Colliding one proton with one proton at the centre of a detector will not be enough," he says. **G.B**

THE DARK

Other physicists have chosen darkness over light. From their lairs inside disused mines and traffic tunnels, they are watching a number of highly sensitive detectors that could find direct signatures of dark matter, including supersymmetric neutralinos (see *Nature* **448,** 240; 2007).

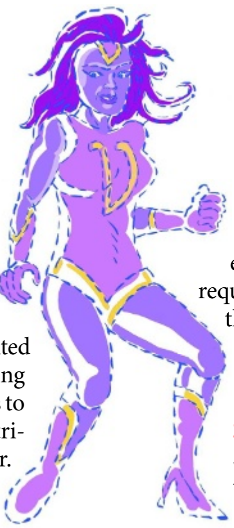
There are around half-a-dozen different schemes for such detectors, but they all follow the same basic concept. Take some stuff you think could respond to dark matter, place it deep underground to protect it from cosmic rays and other disruptive influences, and wait for something to happen. "It's like watching grass grow," says Wilczek.



Although they are perhaps not the most exciting way to beat the LHC, these detectors are making impressive progress. One experiment, the Cryogenic Dark Matter Search II, or CDMS II, is currently accumulating data in the Soudan Mine deep beneath Minnesota. Its operators aim to treble its current sensitivity by the end of the year. Another experiment called XENON100, located in a tunnel under Italy's Gran Sasso Mountain, stands a chance to have its first results out before the LHC's detectors can finish processing their findings. "The field is going so fast and there's so much competition, that it's not easy to survive at the moment," says Elena Aprile, the principal investigator for XENON100 at Columbia University in New York. "It's an amazing time."

And on top of these prospects, one group claims that it has already seen dark matter in its detector. Earlier this year, the DAMA/LIBRA (Dark Matter Large Sodium Iodide Bulk for Rare Processes) experiment, also at the Gran Sasso National Laboratory, announced that it had seen a signal in its latest generation of detector (see *Nature* **452,** 918; 2008). But their finding has the other groups stumped, says Aprile, whose experiment sits in a vault next to that of DAMA/LIBRA. No one else has yet been able to confirm the signal, and in fact, the findings from other teams seem contradictory, she says. "We are definitely not consistent."

Although these detectors seem to be improving in leaps and bounds, they have an Achilles heel: they only work if the so-far unseen dark-matter particles interact, at least occasionally, with regular matter. There's no guarantee that that is the case, says Ellis. And



as far as he's concerned, that makes these experiments "shots in the dark".

Still, Ellis concedes that there is a chance that these esoteric searches might manage to see something before the LHC can. "I think the dark-matter guys are the jokers in the pack," he says.

NEUTRINO

The next few months will be a caffeine-fuelled blur for most of those scientists racing to beat the LHC. But neutrino physicists can take it easy: they've already broken new ground, and they did it a decade ago.

Neutrinos are the neutral members of the 'lepton' family of particles, the group that includes the electron. The original version of the standard model predicted that neutrinos should be completely massless, but experimentalists suspected otherwise. For years they saw fewer neutrinos from the Sun than theorists predicted. One possible explanation for the deficit was that solar neutrinos could be switching from one type to another. But that switching would be possible only if neutrinos had mass. In 1998, a Japanese experiment in Hida called Super-Kamiokande saw the neutrino switch in action, and that result is the first — and to date the only — firm finding that defies the standard model.

Unfortunately, says Ellis, the neutrino's mass can be accommodated within the standard model by making just a few simple modifications to the equations. "It's possible to add something in relatively easily," he says. And consequently, although neutrino physicists can arguably claim the prize, their discovery hasn't helped theorists in their search for new models of physics.

But neutrinos may not be finished just yet. Experiments in the United States, Europe and Japan are now firing beams of neutrinos at their detectors to try to learn more about how the neutrinos switch from one kind to another. The precise details of this switching may help narrow the field of possible new theoretical models, says Lisa Randall, a theorist at Harvard University in Cambridge, Massachusetts.

And two new detectors could go further still. A European collaboration is now running the Astronomy with a Neutrino Telescope and Abyss Environmental Research (ANTARES) detector under the Mediterranean Sea off the coast of Toulon, France, and a team of Americans is installing IceCube beneath the ice of Antarctica. Both use strings of detectors to see high-energy neutrinos from cosmic sources striking water or ice. ANTARES was completed earlier this summer, whereas IceCube has about half of its 70 strings of detectors installed. But already IceCube is five times more sensitive than Super-Kamiokande, according to Francis Halzen, IceCube's principal investigator at the University of Wisconsin, Madison. "It's not inconceivable we'll find something," he says.

Just what that something might be is up for debate. One possibility would be neutrinos produced by dark-matter particles trapped in the Sun's core. But again, Halzen says, anything seen by the neutrino experiments would almost certainly require follow-up by the LHC. "I think these experiments are complementary," he says. "But if you give me a choice, I'd rather see it first."

SUCCESS?

So can any of these projects best the standard model? Wilczek is sceptical. "I'm not on the edge of my seat," he says. Looking the track record, it seems that, "the standard model always wins". He believes that only the LHC stands a real chance of breaking the existing paradigm.

And there's no guarantee that even the giant collider will find something new. "Super symmetry could show up anytime between mid-2009 and never," says Ellis. If never is the date, he says, physicists will face "the maximum conceivable horror scenario". "What will we do next?" he asks.

But Turner takes a different view. Ultimately, these experiments and the LHC are fighting the battle together. He is confident that by combining their data with the LHC's, the standard model can be bested, and that new physics will be discovered. "We're on the verge of a major revolution," he says. ■

Geoff Brumfiel is a senior reporter for *Nature* based in London.

To read more about the LHC start-up, visit the *Nature News* special at http://tinyurl.com/5usrfl.