# Beyond the Z

## The latest generation of high-powered particle accelerators has produced no real surprises. What's next?

By IVARS PETERSON

All seems quiet on the collider front. The first results from a new generation of powerful particle accelerators yield no startling discoveries or glimpses of novel phenomena. For the moment, the quest for the elementary particles of matter has settled into a comfortable routine of steadily accumulating large quantities of valuable but unsurprising data.

So far, those data agree extremely well with expectations based on theoretical calculations and extrapolations from observations at lower energies. The results stand as impressive testimony to how well physicists appear to understand the way fundamental particles of matter interact, as described by what theorists call the standard model of particle physics.

"It is not clear whether to rejoice or despair about this state of affairs," says James D. Bjorken of the Stanford Linear Accelerator Center (SLAC). "From one point of view, it's a fantastic success story. On the other hand, we're never satisfied with a situation when it's clear there's a next step somewhere out there to be taken."

Indeed, much remains a mystery. Despite its considerable success, today's theory remains incomplete. It fails, for example, to specify why the various elementary particles of matter have the masses they do, and why these particles fall into exactly three families.

"These are all profound questions, for which the answers may not come easily," writes Michael S. Chanowitz of the University of California, Berkeley, in the July 6 SCIENCE.

Some of the answers may emerge from detailed studies of Z particles, now being produced in copious quantities at CERN's Large Electron-Positron (LEP) collider in Geneva, Switzerland, and in far fewer numbers at SLAC. Other answers may come from renewed efforts to understand the behavior of the bottom quark. And particle physicists are pushing forward their search for the still-undiscovered top quark and a fifth force of nature required by the standard model to determine the masses of the elementary particles.

The standard model – a set of equations describing the behavior of elementary particles – seems to provide an elegant, compact answer to the question of the nature of matter. The theory holds that all matter consists of particles called fermions. These particles exert attractive or repulsive forces on each other by exchanging force-carrying particles called bosons.

Fermions themselves come in two varieties: leptons and quarks. The lepton category includes charged particles such as electrons and muons, and uncharged, virtually mass-less particles known as neutrinos. Quarks, never observed on their own, are the basic constituents of particles such as protons, neutrons and mesons.

Bosons carry the four known fundamental forces of nature. Photons carry electromagnetism; gluons carry the strong force, which holds together protons and neutrons; and presumably, as-yet-unobserved "gravitons" carry gravity. Neutral Z particles and charged W particles carry the weak force, which is responsible for radioactive decay.

One can arrange fermions into generations, each generation consisting of two quarks and two leptons. The first generation consists of the up and down quarks, which make up protons and neutrons, and the electron and the electron-neutrino. The charm and strange quarks, along with the muon and the muon-neutrino, occupy the second generation. The bottom and top quarks, and the tau particle and tau-neutrino, complete the third generation.

Last year, researchers studying the decay of Z particles produced data consistent with the existence of only three types of mass-less neutrinos, and hence, three generations of fundamental particles – in effect, limiting the capacity of the fundamental-particle zoo (SN: 10/21/89, p.260).

But a loophole still exists. The absence of a fourth, "conventional" neutrino doesn't completely rule out the possibility that other fundamental building blocks or an extremely heavy neutrino may exist.

"If we did find a fourth, massive neutrino, I think everybody would be very surprised," Chanowitz says. "Most people are assuming there's no fourth generation, but strictly speaking, it's not ruled out by any data."

"What the recent evidence indicates is that if there are more particles in our future, they are not going to be boring repetitions of what we already have in hand," Bjorken adds.

**The Family of Matter**

| Generation | Charged Leptons | Neutral Leptons | Quarks |
|---|---|---|---|
| I | electron | electron neutrino | up, down |
| II | muon | muon neutrino | charm, strange |
| III | tau | tau neutrino | top, bottom |

*The building blocks of matter — quarks and leptons — can be organized into three generations. All ordinary matter consists of various combinations of the particles listed in the first row, or generation. The top quark remains undiscovered.*

Lurking at the back of every particle physicist's mind is the recognition that the standard model really provides just a provisional theory that must break down eventually. In particular, its equations include 20 seemingly arbitrary parameters—for instance, particle masses — that the theorist must guess and fill in to get the "right" answers. Thus the standard model includes an unknown but vital element that physicists can only describe as a "black box."

"The theory contains a black box that hasn't been filled yet," Chanowitz says. "We know what has to come out of that black box, particularly the Z and W masses, and we believe that we know some of the properties of what goes into that black box, but we don't in fact know what the black box is."

Hence, the theory provides no natural answer for a variety of questions: How are the 20 parameters' values established, or at least related to one another? Why do quarks and leptons fall neatly into distinct generations? Why three generations? Do quarks and leptons contain "smaller" particles, and if so, are they composed of common constituents? Is there a higher level of organization of particles than proposed by the standard model?

Although the standard model doesn't answer these questions, its great success means that particle physicists have very little evidence on which to base a larger, more complete theory. They have to look hard for the tiny hints that will lead them to a consistent, broader picture of matter and its interactions. In effect, they're panning for the few specks of gold in a huge heap of sand.

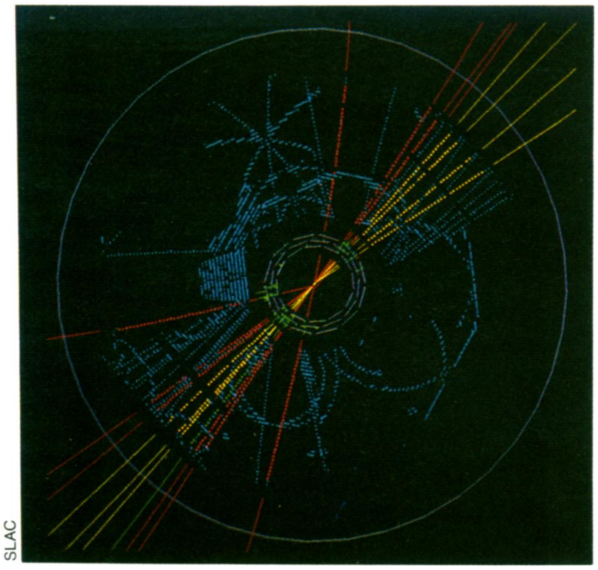
The Z boson, which occupies a strategically central position in the standard model, serves as a particularly valuable probe of the theory. Unlike photons, Z particles interact directly with all known quarks and leptons, and they cleanly decay into a variety of particle-antiparticle pairs. Each of these types of decays leaves a distinctive signature in a collider's particle detectors.

That makes CERN's "Z factory" — now well on its way toward generating and detecting more than a million Z decays per year — an important source of data. Such high-precision measurements of the properties of the Z, requiring very large numbers of events, serve as an effective means of searching for new physics and subtle deviations from standard-model predictions.

For example, recent measurements have already established important constraints on the top quark's mass (SN: 4/28/90, p.270). The results indicate that the top quark is probably heavier than the Z boson, which has a mass expressed in energy units of 91 giga-electron-volts (GeV), or nearly 100 times the proton's mass. On the other hand, theoretical arguments put the top quark's mass at less than 200 GeV, perhaps as low as 130 GeV.

Whether any of today's accelerators has sufficient energy to create a top quark remains uncertain. Fermilab's Tevatron collider probably has the best shot at finding the particle, if the top quark's mass really does fall in the 130-GeV range.

Because the top quark apparently has more mass than any known particle, theorists expect that this quark probably plays a significant role in the physics behind the origin of mass. "How much the top quark properties will teach us is hard to anticipate," Bjorken says. "The top quark could have surprises in it, but it doesn't have to surprise us. It could be a very conventional object."


SLAC

*In this computer reconstruction, a Z particle disintegrates into a pair of B-mesons (red tracks), which decay into other particles (yellow and green tracks).*

Future measurements of Z-particle decays may also provide a definitive value for a fundamental constant that characterizes the intrinsic strength of the weak force.

"This will be a major piece of business for both LEP and SLC [Stanford Linear Collider] over the next two or three years," Bjorken writes in the spring issue of the SLAC publication Beam Line. "Physicists at these machines will use different and complementary methods of determining this crucial number. Such precision measurements provide indirect indicators of what physics might (or might not) await us at energy scales not yet reached by present machines, as well as checking further that the electroweak theory really is correct."

Moreover, large samples of Z decays "afford the greatest opportunity for completely unexpected discoveries that could be more important than the phenomena we are planning to seek," Chanowitz says.

In this massive accumulation of data, researchers may catch a glimpse of new, rarely produced particles or traces of heavy particles that can't be produced in existing colliders but make their presence felt indirectly in the observations. Here, researchers may yet catch their first fleeting views of axions, squarks, sleptons, photinos, winos, zinos and other particles that populate proposed theories attempting to extend the standard model.

The bottom quark furnishes an especially promising probe for new physics. In particular, studying the behavior and properties of the several varieties of B-meson, which contain bottom quarks, could shed light on the puzzling relation between matter and antimatter. For that reason, several accelerator centers are gearing up to mass-produce B-mesons and other particles housing bottom quarks.

"As it now stands, the bottom quark is the most interesting of them all—and it may stay that way even after the top quark is found," Bjorken says.

Normally, every particle has an oppositely charged, antimatter counterpart, and the two particles of a matter-antimatter pair behave in opposite ways. Thus, a neutron decays into an electron, a proton and an antineutrino, whereas an antineutron decays into an antielectron (positron), an antiproton and a neutrino. And when particle meets antiparticle, they annihilate each other.

In the 1950s, researchers discovered exceptions to that perfect symmetry in the decay of K-mesons, or kaons (a type of meson consisting of a strange quark and a down quark). The observations showed a small but fundamental asymmetry between matter and antimatter, and theorists introduced a number of different notions about quark behavior to explain the results.

"The question that people have been asking for many, many years is whether that small deviation can be explained totally inside the framework of the standard model or whether it's evidence of some additional force that lies outside the standard model," Chanowitz says. "Either is possible."

Because B-mesons decay somewhat like kaons, detailed studies of B-meson behavior could shed light on how well the theories accounting for the asymmetry hold up. "It just so happens that [this additional] force would show up most strongly in B-meson decay, so studying B-mesons in great detail would allow you to learn a lot more about that force," Chanowitz says.

At the same time, bottom-quark behavior appears intimately linked with the question of why particles have the mass they do and the values of several arbitrary parameters in the standard model. Thus, a close scrutiny of B-meson physics could help validate important parts of the standard model and provide useful hints about the Higgs mechanism, which determines the mass of elementary particles.

"Fifty years from now, B physics will still be a hot subject, so long as the experiments can keep on improving," Bjorken predicts. But that requires getting funding – perhaps $100 million to $200 million – to build machines specially designed to generate B-mesons in sufficient quantity to collect the needed data.

Establishing the identity of the black box, so vital to the standard model and required to make the theory mathematically consistent, remains a central pursuit in particle physics. "The standard model tells us that this black box – the Higgs mechanism – has to be there," Chanowitz says. "If it's not there, then the standard model fails."

The Higgs mechanism, responsible for generating the W and Z particle masses, would manifest itself in the form of a new fundamental force (bringing to five the number of fundamental forces in nature) and at least one new particle to carry that force – perhaps a single boson, possibly a bushel load of particles. Indeed, theorists can list many possibilities that would fulfill the requirements of the Higgs mechanism. These many variants on the basic theme of introducing mass into the standard model go by such names as supersymmetry and technicolor.

"What we're looking for is a new set of particles, and we don't know exactly what they are," Chanowitz says.

"Something has to be out there," Bjorken adds. "But that something might be much more complicated than the [single] Higgs particle that's the usual object of research."

Because a Higgs particle would interact only feebly with ordinary matter and because the standard model makes no prediction about its mass, no one really knows how or at what point a Higgs particle would make its presence felt. Collider experiments, including observations of Z decays, have already ruled out certain types of proposed Higgs particles having masses of less than 25 GeV, and theory suggests an upper limit of 2 tera-electron-volts (TeV). But that still leaves a vast energy domain unexplored, much of it inaccessible to even the most powerful of today's colliders.

Pursuing this key piece of the particle puzzle requires pushing the frontier of accelerator physics and detector capabilities. This is where the proposed Superconducting Super Collider (SSC), CERN's Large Hadron Collider and the next generation of linear colliders would play their roles.

"It's possible there are clues in the present Z data, but that doesn't give us the same comprehensive look at the phenomena that the SSC would give us," Chanowitz says. "In Z decays, you're looking at just the bottom 2.5 percent of what you would be able to look at directly in the SSC, which covers the whole range within which we think this black box has to start to show up. That's why we're so eager to get on the SSC."

Meanwhile, the patient sieving of the fundamental-particle sands continues. "A lot of the progress in science comes not from spectacular discoveries but from the accumulation of a lot of little measurements or observations – the piling up of data," Bjorken says.

Indeed, good science often demands a lot of patience. Moreover, "the breakthrough could come in a completely unexpected place," Bjorken says. "One has to keep one's eyes open." ☐