CERN Finds Evidence for Top Quark

An international collaboration of 151 mainly European physicists working at the European Laboratory for Particle Physics (CERN) near Geneva presented on 3 July to a critical CERN audience its evidence for the top quark, a particle whose existence has been surmised on theoretical grounds for some time but which has escaped detection.

Last year the same physicists, whose chief spokesman is Carlo Rubbia of CERN and Harvard University, were the first to uncover signs of the long-sought and exceptionally massive W and and Z vector bosons. The group has only to find the enigmatic Higgs particle, which like the W and Z is required by the unified field theory of the weak and electromagnetic forces, to almost single-handedly close the electro-weak chapter in high energy physics.

The simplest version of the unified field theory requires quarks, which are constituents of more familiar elementary particles (hadrons), such as the proton and the numerous mesons, to come in pairs. Since five quarks had been known, physicists presumed (and anxiously hoped) that a sixth would eventually be found. The fifth and six quarks, which make up the third pair, are called bottom and top or sometimes simply b and t.

The evidence for the top quark comprises six events recorded in the spring of 1983, when CERN's proton-synchrotron (the SPS) last operated in its colliding-beam mode. Packets of protons and antiprotons race around the accelerator ring in opposite directions at nearly the speed of light, passing through one another at certain points. Occasionally a quark from a proton and an antiquark from an antiproton will collide head on and annihilate, releasing the exceptionally large amount of energy needed for the creation of heavy elementary particles.

CERN's SPS was modified to run as a colliding-beam machine primarily to find the W and Z. However, the top quark has turned out to be more massive than theorists initially guessed (the theory does not provide a prediction of the mass). Hence, lower-energy accelerators have been unable to produce the particle, which now seems to have a mass somewhere between 30 and 50 billion electron volts (GeV) and is well within the range of the SPS in its collider mode.

As Rubbia explained to *Science*, unearthing the top quark is considerably more difficult than finding the W and Z. The problem is to find a distinctive signature for these short-lived particles that stands out against a background of scores of more ordinary entities produced each time protons and antiprotons collide.

The W itself provides a way to see the top quark. More often than not, the W decays into a quark and an antiquark, which then fly apart. One possibility involves top and bottom quarks. There are two W's, one positively charged and one negatively charged. The positively charged W^+ decays into a top-antibottom pair, while the negatively charged W^- decays into an antitop-bottom pair because the top quark has an electrical charge of $+2/3$, while the bottom charge is $-1/3$.

Because it is so massive, the top quark itself quickly decays. It disintegrates by a process analogous to the beta decay of a neutron into a proton; that is, the top transforms into a bottom quark (mass 5 GeV) plus an electron (or muon) plus a neutrino. Free quarks are not permitted, so the bottom and antibottom quarks ultimately end up as "jets" comprising several hadrons and an energetic electron or muon traveling as a tightly bunched group.

In sum, the top quark signature is two jets, an energetic electron (or muon), and a neutrino. In addition, the energies and momenta of these entities must satisfy certain restrictions imposed by the kinematics of W decay.

As compared to the W signature, this one is much less clear-cut. The W decays part of the time into an electron (or muon) and a neutrino, which fly apart, each carrying about half of the W's 81-GeV energy. The analogous decay of the 91-GeV Z is into an electron-positron (or muon-antimuon) pair. Relatively speaking, these decay products stick out like sore thumbs because of their abnormally high transverse (perpendicular to the beam) energies and momenta.

However, for a top quark of mass 40 GeV, say, the most probable electron (or muon) transverse energy is less than 9 GeV. But in the violent proton-antiproton collisions of CERN's SPS, such particles, while energetic by most standards, are rather common. Moreover, jets can mimic electrons sometimes, or jets and electrons may overlap and thus be hard to disentangle. The CERN physicists winnowed a sample of 152 candidate events that looked like an electron with transverse energy of 12 GeV or greater plus jets, and 40 that looked like muons plus jets to six that passed all the tests and looked like top quarks.

Says Rubbia, "we believe that we have succeeded in cleaning up the background and that we are seeing a genuine signal." Among the encouraging signs, the six events are equally divided between electrons and muons, as theory requires.

To be certain that the top quark has been found, the physicists will need a much larger number of events. Having this, they will be able to verify that the cross section for producing top quarks is what theory predicts and that the electrical charge is in fact $+2/3$. They will also be able to deduce the particle mass. Finally, a second group at CERN with a different detector should also see the top quark, but it has reported nothing as yet.

So far, there is only a hint as to the mass. The sums of the energies of the jets, the electron (or muon), and the neutrino cluster just below the mass of the W, almost as they should. At the same time, the sums of the energies of the lower-energy jet, the electron (or muon), and the neutrino cluster near 40 GeV.

The temptation is to conclude that the top quark mass is in fact 40 GeV or thereabouts. However, Rubbia warns this is the first time that this "invariant mass" technique has ever been tried with jet events, and there could be systematic errors that could cause the mass to vary by quite a bit. For example, the energy of a jet that the detector records depends on the composition of the jet, but this is an unknown quantity. For the moment, the mass is set at between 30 and 50 GeV.

A new SPS collider run will begin in September. With numerous improvements in the accelerator and in the detector, the CERN group hopes to collect ten times as many events as in the last run. This would go a long way toward verifying the top quark.—**ARTHUR L. ROBINSON**