proved that left-handed electrons scattered a bit more often, in complete accord with predictions of the GSW theory. The very next year Glashow, Salam, and Weinberg shared the Nobel prize in physics for their pivotal contributions to the unified theory of electromagnetic and weak interactions—an epochal feat.

The SLAC-Yale experiment also provided an accurate measurement of a key quantity in the GSW theory, from which one could deduce the masses of the W and Z particles. The W mass had to be about 80 GeV and the Z mass about 90 GeV. These particles finally turned up in an experiment performed by a large collaboration of European and American physicists. Led by Carlo Rubbia of CERN and Harvard and Simon Van der Meer of CERN, this team found several W and Z particles in the debris of proton-antiproton collisions. Their masses came in at about what was expected, and the rate of their production was close to what had been predicted by QCD. Rubbia and Van der Meer shared the 1984 Nobel prize for this discovery.

All known features of the subatomic world, down to distances a thousandth the size of a proton, can now be explained in terms of the Standard Model. According to this picture, matter is subdivided into quarks and leptons, and forces are described by gauge theories. Matter particles come in three families of four spin-1/2 members each—a pair of quarks and a pair of leptons. Forces are carried by spin-1 particles: the electromagnetic force by the photon, the weak force by the W and Z bosons, and the QCD force by gluons.

One more piece is needed to complete this Standard Model. Accepting the Higgs mechanism, which gives the W and Z particles their tremendous masses, means there should exist at least one massive, spin-0 particle called the *Higgs boson*. This particle is also thought to endow the various quarks and leptons with their different masses. The simplest theory, the Standard Model, calls for only one Higgs boson, but more complex theories allow for more.

Finding a Higgs boson would be a major step forward in explaining why there are so many different quark and lepton masses; now these are just externally determined properties one must plug into equations of the Standard Model. Low-energy searches at existing accelerators have not yet turned up any convincing candidates for a Higgs boson, so experimenters have begun to focus attention on the very highest energies.

During the late 1980's, a pair of powerful colliders began operations—the Stanford Linear Collider (SLC) at SLAC and the Tevatron at Fermilab—able to create particles with masses of 100 GeV or more. The SLC brings 50 GeV electrons and positrons into collision after a single trip down the SLAC accelerator. The Tevatron boosts protons and antiprotons inside the Fermilab ring to energies of almost 1,000 GeV, or 1 TeV, and smashes them together inside a huge particle detector four stories high. Using these two colliders, American physicists made the first precision measurements of the massive W and Z particles, thereby providing key tests of the Standard Model.

Designed to create the Z particle in quantity, the SLC produced about 500 by the end of 1989, enabling physicists at SLAC to establish its mass to be 91.1 GeV. From the apparent yield of Z particles when the electron and positron beams were tuned to a total energy close to this value, the same scientists also concluded that there are no more conventional families of quarks and leptons beyond the three families already known to exist. Meanwhile, physicists working on the Tevatron at

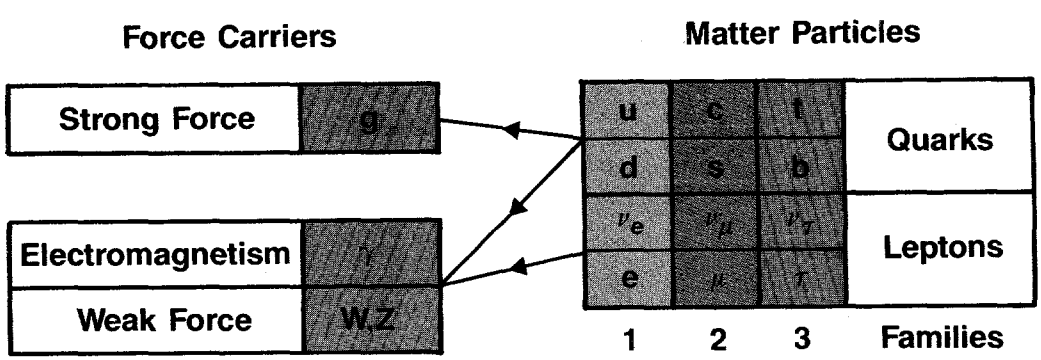

Figure 21. The elementary particles of the Standard Model. Quarks exert both strong and electroweak forces, but leptons feel only the latter.