another—is precisely what gives rise to the interquark force. The gluons, then, are the bearers of this property. Eight neutral, massless, spin-1 gluons are responsible for conveying the force between quarks, actually *carrying color* from one quark to another. In analogy with quantum electrodynamics, Gell-Mann dubbed this new gauge theory *quantum chromodynamics,* or *QCD* for short.

Experimental tests of QCD, however, were hard to come by. Like quarks, gluons should be trapped inside hadrons and be thus unobservable in particle detectors. Any proofs therefore had to be indirect. If gluons did exist, there would be slight deviations from free quark behavior inside a hadron; quarks would not act *exactly* like free marbles inside bags. Traces of that slackened "rubber band" ought to be detectable, for example, in deep inelastic scattering of leptons from nucleons. Such deviations were indeed reported in 1975 by sensitive experiments at SLAC and Fermilab. Detailed confirmation of this behavior came later from CERN.

Another proof of QCD occurred at a new storage ring in Germany, in which electrons and positrons collided at combined energies of 30 GeV or more. Experimenters at this facility noticed trios of jets emerging from some collisions. Two of these were clearly the visible footprints of a quark and its antiquark, but the third jet was interpreted as the track of a gluon emitted by one of them. Similar three-jet events soon turned up at other storage rings. By the following year, the evidence was conclusive that the object responsible for the third jet was a spin-1 particle, as expected in QCD. The gluon had been discovered.

In 1980 another storage ring called Positron-Electron Project (PEP) began operations at SLAC. More than 2 kilometers in circumference, this ring circulated electrons and positrons at energies up to 18 GeV. Collisions occurred at six points around the ring, where large particle detectors sampled the debris. From the frequency of the three-jet events, scientists working at PEP were able to measure, for the first time, the *strength* of the QCD force carried by gluons.

Thanks to all this work, stretching over an entire decade, physicists now have a working description of the force binding quarks within hadrons. Though weak at close quarters, it becomes tremendous at large distances. To pull two quarks a foot apart (if that were possible) would require the same energy as needed to lift an automobile a foot off the ground. The "strong" force between

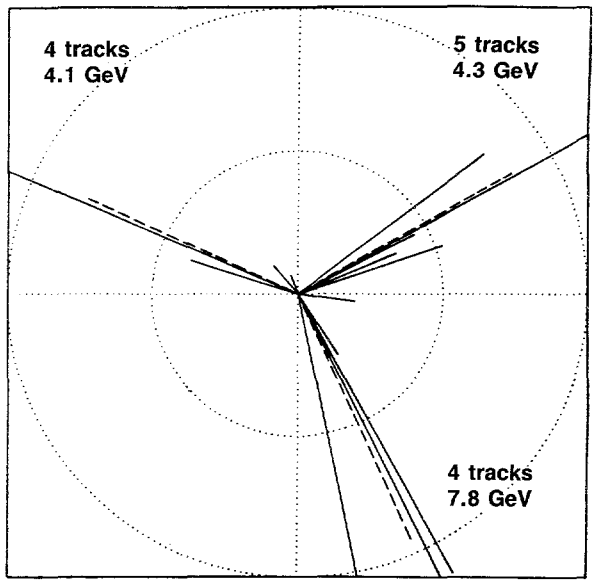

Figure 20. One of the first three-jet events witnessed at electron-positron storage rings.

hadrons is just the residual force remaining after the quarks inside have essentially neutralized their immense attraction for one another.

By the late 1970's particle physicists were also reaching consensus on a theory of the electroweak force. After the experiments at CERN and Fermilab had proved the existence of neutral currents (see Chapter 6), there followed a period of confusion over which particular gauge theory was most appropriate. The one proposed by Glashow, Salam, and Weinberg—known as the GSW theory—was but the simplest of many possibilities. Experimental anomalies that cropped up in the mid-1970's seemed to require more complex theories to explain them.

If the GSW theory were indeed true, electrons had to violate parity occasionally. Because left-handed electrons could sometimes feel the force carried by a Z boson, they would interact a little more often than right-handed electrons, which could not. It was a tiny effect, however, only about 1 part in 10,000. Until 1978 nobody had been able to find evidence for it.

That year a team of SLAC and Yale physicists shot beams of *polarized* electrons—those with their spin vectors aligned either along or opposite the beam direction—at a target of liquid deuterium, a heavy form of hydrogen. It was a difficult experiment requiring extreme precision all along the two-mile accelerator. But the SLAC-Yale team finally