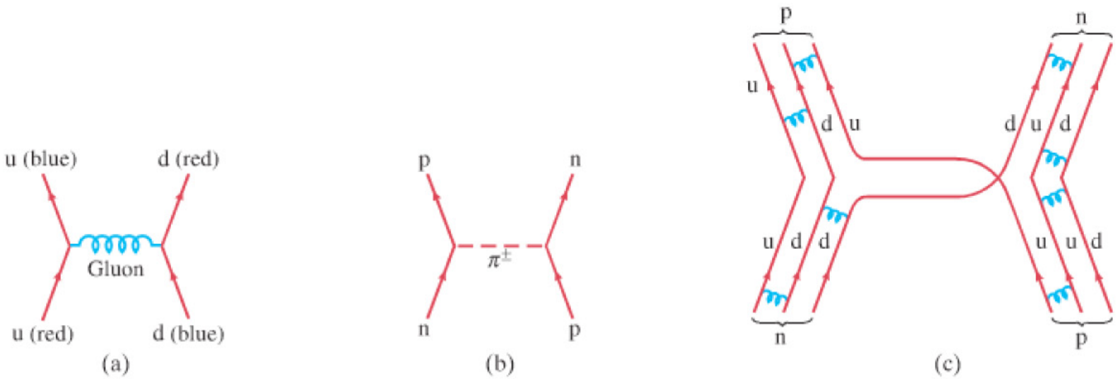

**FIGURE 32–13** (a) The force between two quarks holding them together as part of a proton, for example, is carried by a gluon, which in this case involves a change in color. (b) Strong interaction $n + p \rightarrow n + p$ with the exchange of a charged $\pi$ meson (+ or −, depending on whether it is considered moving to the left or to the right). (c) Quark representation of the same interaction $n + p \rightarrow n + p$. The blue coiled lines between quarks represent gluon exchanges holding the hadrons together.

The color force has the interesting property that, as two quarks approach each other very closely (equivalently, have high energy), the force between them becomes small. This aspect is referred to as **asymptotic freedom**.

*Leptons and the weak force*

The weak force, as we have seen, is thought to be mediated by the $W^+$, $W^-$, and $Z^0$ particles. It acts between the "weak charges" that each particle has. Each elementary particle can thus have electric charge, weak charge, color charge, and gravitational mass, although one or more of these could be zero. For example, all leptons have color charge of zero, so they do not interact via the strong force.

**CONCEPTUAL EXAMPLE 32–8** **Beta decay.** Draw a Feynman diagram, showing what happens in beta decay using quarks.

**RESPONSE** Beta decay is a result of the weak interaction, and the mediator is either a $W^{\pm}$ or $Z^0$ particle. What happens, in part, is that a neutron (udd quarks) decays into a proton (uud). Apparently a d quark (charge $-\frac{1}{3}e$) has turned into a u quark (charge $+\frac{2}{3}e$). Charge conservation means that a negatively charged particle, namely a $W^-$, was emitted by the d quark. Since an electron and an antineutrino appear in the final state, they must have come from the decay of the virtual $W^-$, as shown in Fig. 32–14.

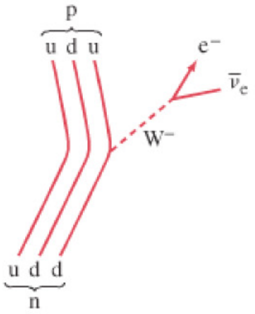

**FIGURE 32–14** Quark representation of the Feynman diagram for $\beta$ decay of a neutron into a proton.

To summarize, the standard model says that the truly elementary particles (Table 32–5) are the leptons, the quarks, and the gauge bosons (photon, W and Z, and the gluons). Some theories suggest there may be other bosons as well. The photon, leptons, $W^+$, $W^-$, and $Z^0$ have all been observed in experiments. But so far only combinations of quarks (baryons and mesons) have been observed, and it seems likely that free quarks and gluons are unobservable.

*Unification*

*Electroweak theory*

One important aspect of new theoretical work is the attempt to find a **unified** basis for the different forces in nature. This was a long-held hope of Einstein, which he was never able to fulfill. A so-called **gauge theory** that unifies the weak and electromagnetic interactions was put forward in the 1960s by S. Weinberg, S. Glashow, and A. Salam. In this **electroweak theory**, the weak and electromagnetic forces are seen as two different manifestations of a single, more fundamental, *electroweak* interaction. The electroweak theory has had many successes, including the prediction of the $W^{\pm}$ particles as carriers of the weak force, with masses of $81 \pm 2\,\text{GeV}/c^2$ in excellent agreement with the measured values of $80.41 \pm 0.10\,\text{GeV}/c^2$ (and similar accuracy for the $Z^0$).

*Standard Model*

The combination of electroweak theory plus QCD for the strong interaction is often referred to today as the **Standard Model**.