PARTICLE PHYSICS

Strong case for weak bosons

Dieter Zeppenfeld

A DOZEN years after the discovery of the intermediate vector bosons W^+, W^- and Z at CERN, the CDF and D0 collaborations at Fermilab in the United States have observed the production of pairs of vector bosons. Various combinations have been searched for, and the two collaborations now report, in a cluster of papers in *Physical Review Letters*, that they have observed the production of weak bosons associated with photons, γ ($W\gamma$ production[1,2] and $Z\gamma$ production[3,4]) and a probable W^+W^- pair production event[5], together with much improved upper bounds on the production rate of WW and WZ pairs[6]. How do these findings fit into the overall picture of forces between elementary particles?

In the proton–antiproton collisions which are being studied at Fermilab, single weak bosons as well as vector boson pairs are generated in the annihilation of quarks and antiquarks, the constituents of the colliding protons. There are two different ways in which a quark and an antiquark may annihilate to produce two vector bosons (see box). One possibility is that the vector bosons are radiated directly from the incident particles. This process, which is depicted in the first part of the figure, is also responsible for the annihilation of an electron and a positron into two photons. A second possibility, which is forbidden for two photons, is the annihilation of the quark and antiquark into a virtual boson which then splits into the pair of vector bosons which is observed in the experiment.

This second contribution depends on the way in which the vector bosons interact with each other. Via the pair production process, it now becomes possible to study the simultaneous interactions of three vector bosons in a systematic way. It is the direct measurement of these three-boson vertices, as they are known, which is at the heart of the present excitement. It allows a first direct test of whether the W, the Z and the photon are indeed the gauge bosons of a non-abelian gauge symmetry, as stipulated in the standard model of particle physics.

Within the gauge theory framework the $WW\gamma$ and WWZ vertices are fixed precisely. For example, the magnetic moment of the W, g_W, is predicted to be two 'W magnetons', in complete analogy to Dirac's famous result for the electron. Similarly, quantities like the electric dipole and quadrupole moments of the W and analogous quantities for the WWZ vertex are uniquely fixed by the gauge symmetry of the standard model. Exactly for these gauge theory values the two contributions in the figure show strong destructive interference: there are 'gauge theory cancellations' between the two contributions and these cancellations lead to cross-sections which decrease as the available energy is increased. At very high energies these cancellations are absolutely necessary. Without them the sacred principle of conservation of probability would eventually be violated.

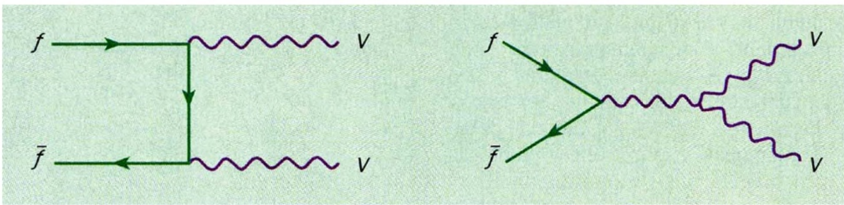
For the Fermilab experiments, a confirmation of the gauge theory structure thus corresponds to showing that the production rates for the vector boson pairs are the smallest possible for any choice of the vector boson vertices. Any rate enhancement at high energies would show the standard model to be faulty. Because of the probability conservation problems, this would imply that Ws and Zs cease to be pointlike particles at this high energy scale E or, using Heisenberg's uncertainty relation, at the equivalent short distances of order $\hbar cE$.

In their analysis of WW and WZ production[3], the CDF Collaboration has searched for one vector boson decaying into two quarks (which would be seen as two jets of particles in the detector) and the other one decaying into electrons or muons. In an energy range around 500 GeV one such event was found where, in the absence of a WWZ vertex, 15 would have been expected. Thus, the existence of non-vanishing interactions between Ws and Zs has been established. Similarly, the D0 Collaboration has seen one event where a W^+W^- pair is produced and subsequently each of these Ws decays into an electron (or positron, depending on sign) and a neutrino, ν.

In the W plus photon channel both collaborations have seen about 25 events, at relatively low energies and thus probing correspondingly larger distance scales. Many of these events are probably due to W radiative decay, for example $W \to e\nu\gamma$, but at least ten clearly correspond to $W\gamma$ production. These observations are, again, completely consistent with the gauge theory expectation. The determination of the $W\gamma$ production cross-section corresponds to a measurement of the non-abelian couplings of three vector bosons with an error of about 30 per cent for at least some of the W multipole moments. Thus, we now have a direct confirmation that the intermediate vector bosons are indeed gauge bosons.

How do these measurements compare to the much more precise results which have been collected in electron–positron collisions at CERN over the past six years? At CERN well over ten million Z-decays have been analysed so far. They confirm the gauge theory predictions for the interactions of the Z-boson with quarks and leptons at the few parts in a thousand level. This stunning agreement has convinced nearly everybody that Ws and Zs are indeed gauge bosons. Thus any report of a significant discrepancy in these

Measuring the vertices



THE weak interactions between nuclei are caused by the exchange of the so-called weak bosons W (W^+ and W^-) and Z. W-exchange is responsible for the beta-decay of nuclei. Ws and Zs carry spin 1 (in units of the reduced Planck constant $\hbar=1.05\times10^{-34}$ J s) and are therefore also called vector bosons. Within the standard model of particle physics they arise as gauge bosons of an underlying gauge symmetry group, SU(2)×U(1). The fourth partner in this quartet is the photon, the gauge boson of electromagnetism. The symmetry group SU(2) is non-commutative, or non-abelian, so the gauge bosons are said to have non-abelian character: they can directly couple to one another.

Two contributions determine the annihilation rate of a fermion and an anti-fermion into two vector bosons V, in other words the cross-section for the process $f\bar{f}\to VV$. The first graph describes radiation of the vector bosons off the incident particles and is solely responsible for processes like $e^-e^+\to\gamma\gamma$. In processes such as W^+Z production via annihilation between an 'up' (u) and an 'anti-down' ($\bar{d}$) quark, the second contribution corresponds to the decay of a virtual W^+ into a real W^+ and a Z boson. This contribution depends on the coupling of two Ws and a Z. The process $u\bar{d}$ to W^+Z therefore allows for a direct measurement of this WWZ 'vertex'.

D. Z.