Fermi National Accelerator Laboratory

FERMILAB-Conf-84/88-T
September 1984

THE STANDARD MODEL AND BEYOND*

C. Quigg
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

ABSTRACT

The $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge theory of interactions among quarks and leptons is briefly described, and some recent notable successes of the theory are mentioned. Some shortcomings in our ability to apply the theory are noted, and the incompleteness of the standard model is exhibited. Experimental hints that Nature may be richer in structure than the minimal theory are discussed.

THE CURRENT PARADIGM

It is popular in particle physics circles these days to speak of a grand synthesis of the laws of Nature. It seems to many among us that the unification of the strong, weak, electromagnetic, and gravitational interactions — long an aesthetic imperative — is, if not quite at hand, at least thinkable within the framework that has emerged in the last fifteen years. The convergence to this promising path has been stimulated by many important experimental results, many of which were made possible by the current generation of high-energy accelerators, and by an accompanying maturation of theoretical ideas.

Of course, scientists of many ages have felt that they stood on the threshold of a final synthesis. What are the signs that, whether or not an ultimate theory is in reach, significant progress is underway? I would cite three lines of development which support the idea that we have found a good path:

- The identification of leptons and quarks as the fundamental constituents of matter, at current limits of resolution;
- The development of gauge theories of the weak and electromagnetic interactions; and
- The notion of quark confinement by the asymptotically free gauge theory of colored quarks and gluons, quantum chromodynamics (QCD).

It will be helpful to spend a few moments explaining what we understand of the two basic elements of the standard model, the constituents and the interactions.

The elementary particles of our era are of two classes. The more familiar, because they are studied directly in the laboratory, are the leptons, which undergo weak and electromagnetic interactions. (Gravitation is normally negligible on a microscopic scale.) The known leptons form three families:

$$\begin{bmatrix} \nu_e \\ e \end{bmatrix} \quad \begin{bmatrix} \nu_\mu \\ \mu \end{bmatrix} \quad \begin{bmatrix} \nu_\tau \\ \tau \end{bmatrix} \quad . \tag{1}$$

*Talk presented at the Fermilab Accelerator School, August 1984.

inferred from the systematics of the charged-current weak interactions. The other class of elementary particles, the quarks, interact by means of the strong force as well. Unlike the leptons, they have not been studied in isolation; indeed it is conjectured that quarks are permanently confined within the strongly interacting particles common in the laboratory, such as the proton and pion. Five quark flavors are firmly established, suggesting the three families

$$\begin{bmatrix} u \\ d \end{bmatrix} \quad \begin{bmatrix} c \\ s \end{bmatrix} \quad \begin{bmatrix} [t] \\ b \end{bmatrix} \quad . \tag{2}$$

The top quark needed to complete the third family remains to be confirmed. We have indirect evidence[1] from b-quark decays that it must exist. Searches for top in the reaction

$$e^+e^- \rightarrow \text{hadrons} \tag{3}$$

lead[2] to a lower bound on the top mass,

$$M_t \geq 22.5\ \text{GeV}/c^2 \quad . \tag{4}$$

Recently, the UA-1 Collaboration has presented extremely suggestive evidence[3] for the top quark in intermediate boson decays

$$W \rightarrow t\bar{b} \quad , \tag{5}$$

from which they infer the limits

$$30\ \text{GeV}/c^2 \lesssim M_t \lesssim 60\ \text{GeV}/c^2 \quad . \tag{6}$$

Quarks and leptons have a number of attributes in common. All are spin-1/2 particles, which are pointlike and structureless on the scale of 10^{-16} cm. The weak interactions of quark and lepton families are of universal strength: the same for every family. There is a distinction between quarks and leptons, too. Each flavor of lepton comes in but a single variety, whereas the Pauli principle requires that each flavor of quark comes in three "colors."

Let us turn now to the gauge theories of the fundamental interactions. The simplest gauge theory, the most successful physical theory, and the prototype for other theories, is quantum electrodynamics (QED). QED has now been incorporated within the Weinberg-Salam theory of weak and electromagnetic interactions, which itself has accumulated many experimental successes. Among these, it is appropriate to note the successful predictions of neutral weak currents and of charm, as well as the quantitative description of a wide range of electroweak phenomena. Quantum chromodynamics, the gauge theory of the strong interactions, gives new insight into the systematics of hadrons and their interactions.

There is by now quite convincing evidence[4] for the gluon, the mediator of strong interactions, predicted by QCD, and the theory has some quantitative successes as well.

These theories of the fundamental interactions have important elements in common. They are all renormalizable field theories which are calculable (at least in perturbation theory). All are based on gauge principles, as we shall now briefly explain. Their common mathematical structure suggests a basis for further unification of forces.

The power of gauge principles is that they provide a means for deriving interactions from symmetries inferred from experimental observation. This imposes important restrictions on the form that a candidate theory may take.

Quantum electrodynamics is based on U(1) phase invariance. We can use this example to describe the strategy for constructing a gauge theory. It is a familiar truth in quantum mechanics that the absolute phase of the Schrödinger wavefunction is arbitrary and unmeasurable. Any convention we adopt for the zero of the phase angle will lead to the same predictions of observables, provided that we apply the same convention to the wavefunction everywhere in space and time. This freedom to adopt a universal arbitrary convention is known as a global invariance, or global symmetry. We may demand more, that our physical theory allow us the freedom to choose a different convention at each point in space and time. The Schrödinger equation for a free particle does not have this sort of local phase invariance. But if we modify the equations of quantum mechanics to be locally phase invariant, we find that the resulting theory is none other than electrodynamics.

Having recovered a known (and highly successful) theory by imposing a symmetry in local form, we are led to follow the same procedure for other physical symmetries. Quantum chromodynamics is based upon the family symmetry of red, blue, and green quarks described by the group $SU(3)_{color}$, with color the strong-interaction analog of electric charge. In QCD, the strong interactions among quarks are mediated by eight massless vector gluons, which themselves carry a color charge. Since the gluons are colored, they interact strongly among themselves, with two characteristic consequences. First, in contrast to the familiar screening of electric charge in a dielectric medium (or, indeed, in vacuum), the strong (color) charge is antiscreened: the effective charge becomes smaller at short distances, and longer at long distances. The increase of the effective color charge at long distances suggests that colored objects such as quarks must be permanently confined. According to this picture, it would require infinite energy to separate two opposite color charges. The second implication of QCD is a corollary, the prediction of quarkless states or glueballs made up of confined gluons.

The electroweak theory is also constructed on a gauge principle. In this case the theory is based (in part) on the family symmetry of

$$\begin{bmatrix} \nu_e \\ e \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} c \\ s \end{bmatrix} \quad \text{, etc.} \tag{7}$$

Unlike the gauge symmetries of QED or QCD, this symmetry must be spontaneously broken, or hidden, because the electron and neutrino do not have the same mass. The spontaneous breakdown of the electroweak symmetry implies that the carriers of the weak interactions, the $W^{\pm}$ and Z^0, must be massive spin-1 particles, whereas the photon and gluon are massless.

It is suggestive that we cannot make the electroweak theory mathematically self-consistent if it is restricted either to leptons or to quarks. What is required for self-consistency is three quark doublets for each lepton doublet. This is precisely the pattern experiment has revealed, and hints that there may be a deep connection between

$$\begin{bmatrix} \nu_e \\ e \end{bmatrix} \text{ and } \begin{bmatrix} u_{Red} & u_{Green} & u_{Blue} \\ d_{Red} & d_{Green} & d_{Blue} \end{bmatrix} . \qquad (8)$$

The suggestion of extended quark-lepton families may be taken as a sign of unification of all the fundamental constituents and, by implication, of all the fundamental forces.

In the simplest version[5] of a unified theory, one branch of the "first generation" ($ud\nu_e e$) family is

$$\begin{bmatrix} \bar{d}_{Red} \\ \bar{d}_{Green} \\ \bar{d}_{Blue} \\ \nu_e \\ e \end{bmatrix} . \qquad (9)$$

The symmetry hypothesized among these fundamental fermions implies that any member of the multiplet may be transformed into other by a gauge interaction. Some of these transformations are familiar. A $\bar{d}_{Red}$ changes to a $\bar{d}_{Blue}$ by emission of a blue-antired gluon. An electron changes to a neutrino by emission of a W^-. But some of the transformations,

$$\bar{d} \leftrightarrow \nu_e$$

and

$$\bar{d} \leftrightarrow e \quad ,$$

are not so familiar. They change both baryon number and lepton number, and would mediate reactions such as proton decay.

A second hint of unification is given by the calculated evolution of effective charges, or coupling constants, for the strong, weak, and electromagnetic interactions. We have already noticed that the effective electric charge grows at short distances, whereas the effective color charge decreases at short distances. This behavior is shown schematically in Fig. 1. Although it requires faith in an extrapolation over a dozen orders of magnitude, it is remarkable that the three couplings of the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ interactions appear to coincide at a distance scale corresponding to about 10^{15} GeV. We take this as an indication that at this elevated energy all the interactions are on an equal footing, and may be treated symmetrically. The program of unified theories is clearly an audacious one, with far-reaching consequences.

To conclude this brief tour[6] of the gauge theories of the fundamental interactions, what can be said of the status of these theories vis-à-vis experiment? First, that there are no observational humiliations, no pieces of data that invalidate the gauge theory program, or contradict the predictions of the current paradigm. Second, that there are many predictions that await sharpening, or detailed experimental tests. Tests of the electroweak theory have reached a very quantitative level: we are close to testing the first-order quantum corrections to the elementary predictions. Tests of QCD, while less advanced, are becoming quantitative and constrained. So far as unified theories are concerned, we are still for the most part trying to answer "yes and no" questions: does the proton decay; are quarks and leptons related, etc.

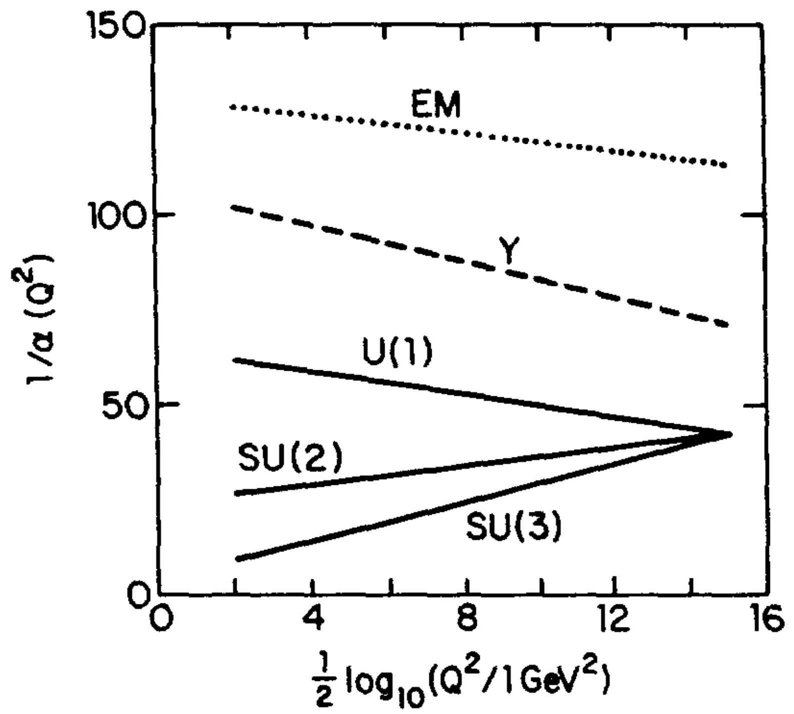

Fig. 1. Evolution of the running coupling constants in leading logarithmic approximation in the SU(5) model. Three fermion generations are assumed.

SOME RECENT SUCCESSES

The comparison of theory and experiment, and the resulting refinement of our understanding, takes place in many steps. Most of them are in the nature of the accumulation of systematics or the improvement of precision in measurements. These are highly important to the development of theory, for they tell us what we must explain, suggest how the pieces fit together, and let us know the shortcomings of our calculations. My emphasis today, however, will be on two more qualitative discoveries, both made in the study of hadron-hadron interactions at the highest energies now available, in the CERN $Sp\bar{p}S$ Collider with beams of 270 GeV.

The first of these is the discovery[7] of the intermediate bosons $W^{\pm}$ and Z^0, with properties as predicted by the Weinberg-Salam model. The elementary reactions of principal interest are

$$\begin{aligned} u\bar{d} &\to W^+ \to e^+\nu_e \text{ or } \mu^+\nu_\mu \\ \bar{u}d &\to W^- \to e^-\bar{\nu}_e \text{ or } \mu^-\bar{\nu}_\mu \\ u\bar{u} \text{ or } d\bar{d} &\to Z^0 \to e^+e^- \text{ or } \mu^+\mu^- \end{aligned} \quad . \qquad (10)$$

In the CERN experiments, the incident quarks come largely from the protons and the incident antiquarks from the antiprotons. The experimental signature is quite striking: one or two isolated charged leptons with large momentum transverse to the beam axis. An example is shown in Fig. 2, which depicts the observation of the reaction

$$p\bar{p} \to Z^0 + \text{anything} \qquad (11)$$
$$\hookrightarrow e^+e^-$$

in the UA-1 detector. Fig. 2(a) shows a computer display of all the reconstructed charged-particle tracks and calorimeter hits. Most of the tracks correspond to low transverse momentum particles. When a cut of $E_T > 2$ GeV is imposed, the event simplifies considerably to the display shown in Fig. 2(b). There we see an electron and positron, leaving the collision point essentially back to back. By combining the energies and momenta of the electron and positron, we may reconstruct the invariant mass of the Z^0. For this event, it is 91 ± 5 GeV/c^2. Three-dimensional "LEGO" displays of four $Z^0 \to e^+e^-$ events in Fig. 3 show how isolated the leptons are, and how much greater are their transverse momenta than those of the hadrons making up the "anything." The signature of the $W^{\pm}$ is equally characteristic: an isolated charged lepton whose large transverse momentum is unbalanced, having been carried off by an undetected neutrino. The masses, widths, and production rates of the intermediate bosons, insofar as they are known, agree with theoretical expectations.

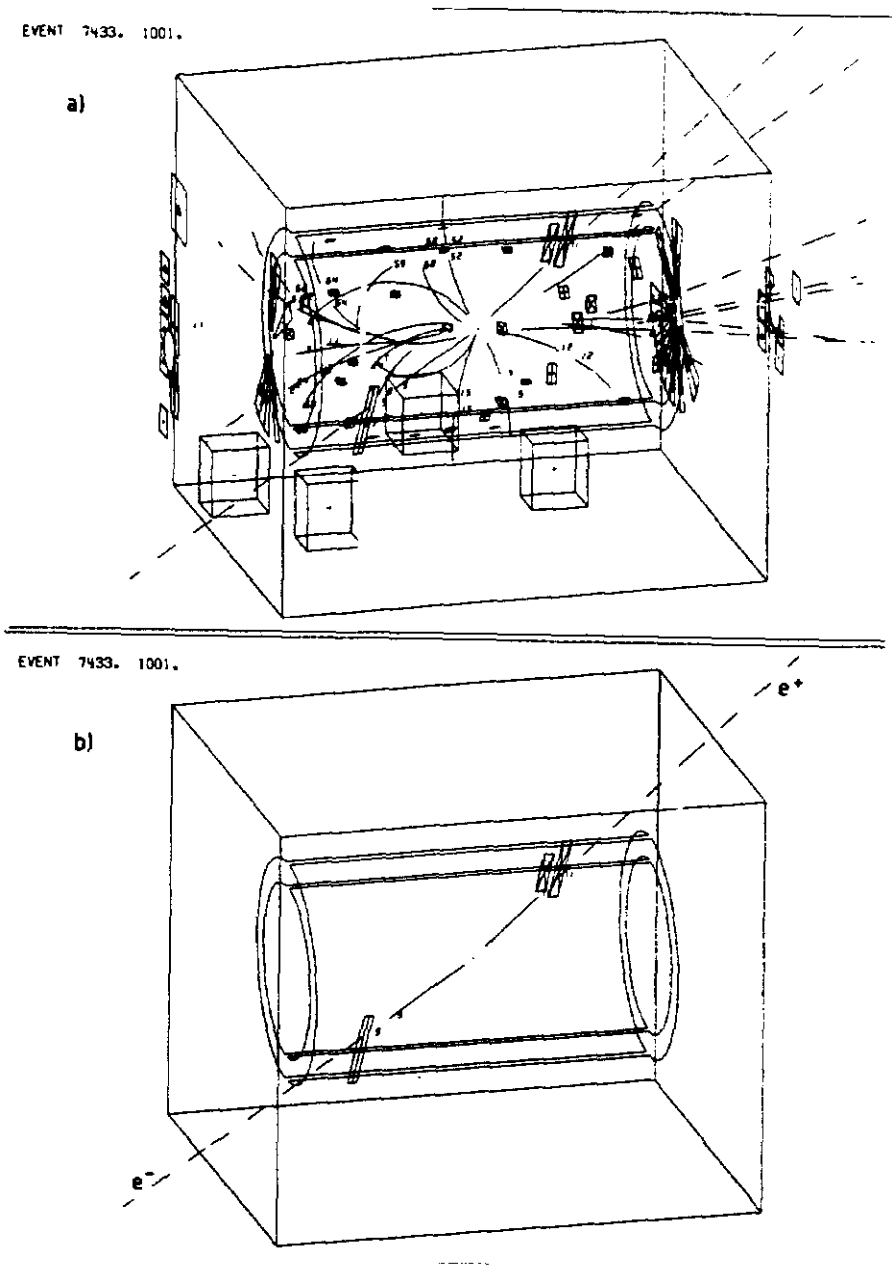

Fig. 2. Display of a dielectron event in the UA-1 detector [from G. Arnison, et al., Phys. Lett. 126B, 398 (1983)]. (a) All reconstructed vertex-associated tracks and all calorimeter hits are displayed. (b) Thresholds are raised to $p_\perp > 2$ GeV/c for charged tracks and $E_T > 2$ GeV for calorimeter hits.

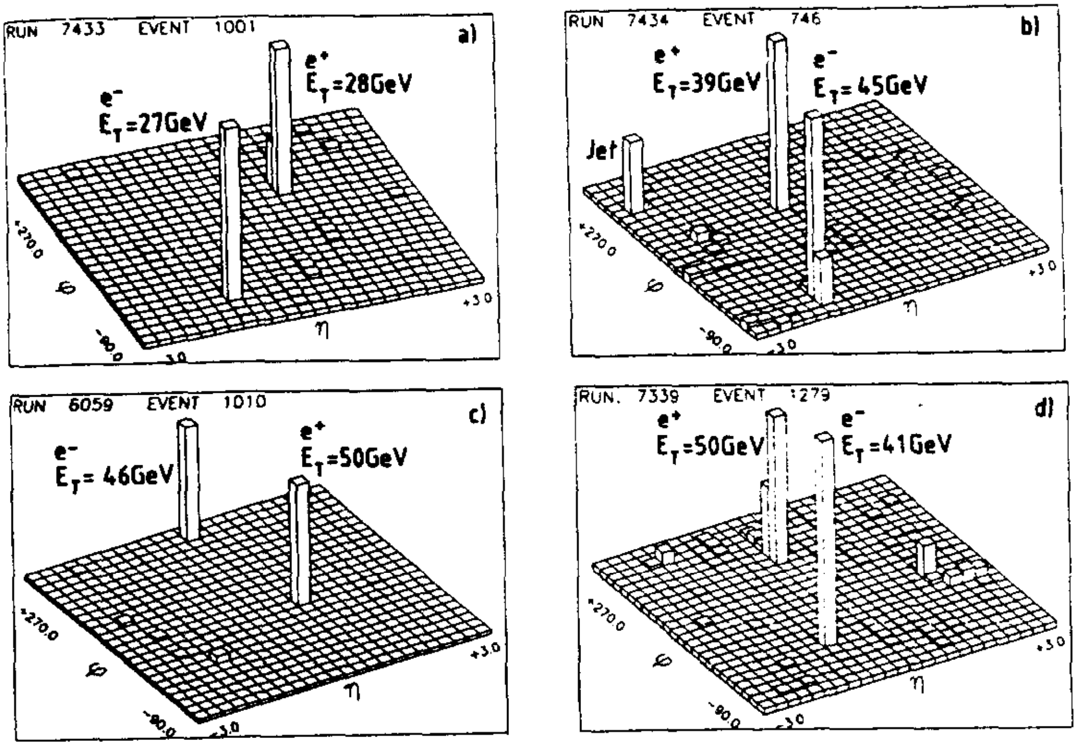

Fig. 3. Electromagnetic energy depositions at angles >5° with respect to the beam direction for four dielectron events observed in the UA-1 detector [from G. Arnison, et al., Phys. Lett. 126B, 398 (1983)].

The second important validation of the standard model in S$\bar{p}$pS experiments is the emergence of large transverse momentum jets of hadrons, as anticipated in QCD.[8] The LEGO plot of Fig. 4, from the UA-2 experiment, shows that for a class of events, two isolated, well-collimated bundles of hadrons emerge at large angles to the beam direction. At lower energies, jets did not stand out nearly so well above the background. The emergence of readily identifiable jets gives strong support to the idea that we are seeing hard two-body scattering of quarks and gluons.

Within QCD, we may calculate the rate at which two-jet events are produced in high-energy collisions. Representative predictions[9] are shown in Fig. 5, together with a compilation of measurements using the UA-1 and UA-2 detectors. The agreement in shape and magnitude is quite satisfactory. Another way of treating the data is to form the invariant mass of a two-jet system. The two-jet mass spectrum measured in the UA-2 apparatus is compared with QCD predictions in Fig. 6. Again the agreement is satisfactory. Multiparticle spectroscopy has long been a mainstay of high-energy physics. We now see the emergence of multijet spectroscopy as a significant tool.

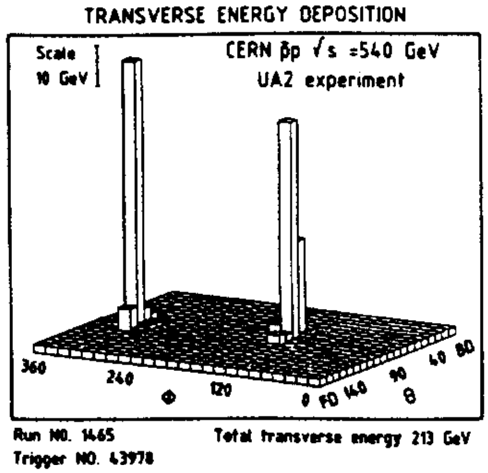

Fig. 4. Configuration of a large-E_T ($\sum E_T$=213 GeV) event observed in the UA-2 detector [from P. Bagnaia, et al., Z. Phys. C20, 117 (1983)].

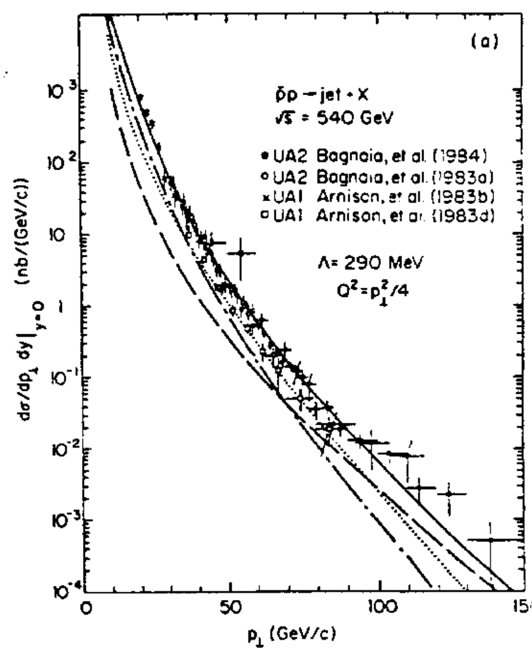

Fig. 5. Differential cross section for jet production at y=0 (90° c.m.) in $\bar{p}p$ collisions at 540 GeV [from Ref. 9].

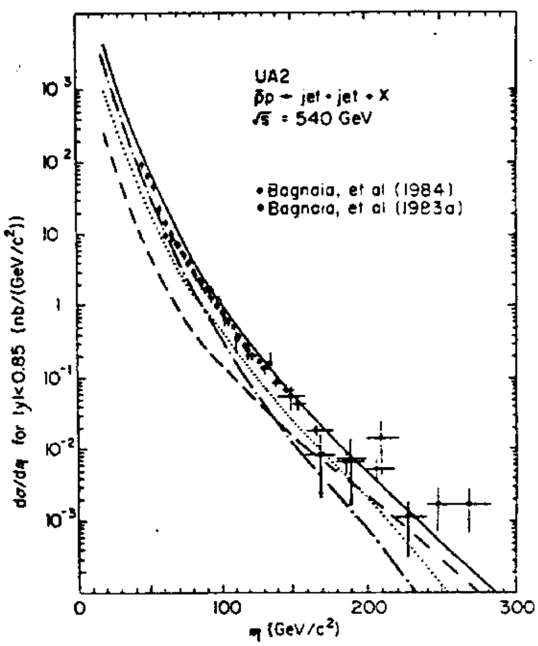

Fig. 6. Invariant mass spectrum for two-jet events produced in $\bar{p}p$ collisions at 540 GeV. Both jets must satisfy $|y| < 0.85$. [From Ref. 9].

SOME EMBARRASSMENTS

The promise of the gauge theory program is great, and the achievements of the standard model are impressive, but there are a number of areas in which we have so far failed to exploit the theory fully. There are many problems of a fundamental character before us, such as the nature of spontaneous symmetry breaking, the correct gauge symmetry of the world, etc. What I want to highlight today is more in the nature of an applied science problem, but still an issue of great significance. This is the problem of hadron structure. The standard model makes direct predictions for the interactions of free quarks and leptons, but the quarks we study in the laboratory are not free: they are confined within pions. The problem of evaluating matrix elements between hadron initial and final states, rather than free quark initial and final states, has not been solved.

Examples of special interest include the weak-interaction matrix elements for $K^0 \leftrightarrow \bar{K}^0$ transitions, and the interplay of strong- and weak-interaction effects responsible for the enhancement of nonleptonic weak decays. The fact that nonleptonic decay rates greatly exceed the rates inferred from the universality of charged weak current couplings is only partially understood, and conventional treatments typically neglect the long-range effects of the strong interactions. This is a subject for which I think the lattice QCD approach may be especially valuable. What is needed here is not so much a ±1% calculation of a rate as an insight into the mechanism of nonleptonic enhancement. Several groups are at work on this problem; I hope the results will be enlightening.

Another illustration of our inability to deal satisfactorily with hadron structure is given by recent data on nuclear effects upon inelastic lepton-nucleon scattering. The data in Fig. 7 show that the cross section per nucleon for electron or muon scattering is not the same for iron and deuterium. The Fe/d ratio is less than unity for $x \gtrsim 0.3$, and in one data set is greater than unity for small values of x. This effect was not anticipated, and is not completely understood.

Now, it is not surprising that it is hard to deal with the strong interactions in the regime in which they are strong. Our most highly developed tool, perturbation theory, is inadequate for strongly coupled systems. Nevertheless, as we learn to treat nonperturbative effects, we should be paying increasing attention to the hard problems of hadronic interactions, and not merely seeking to compute the spectrum of hadrons.

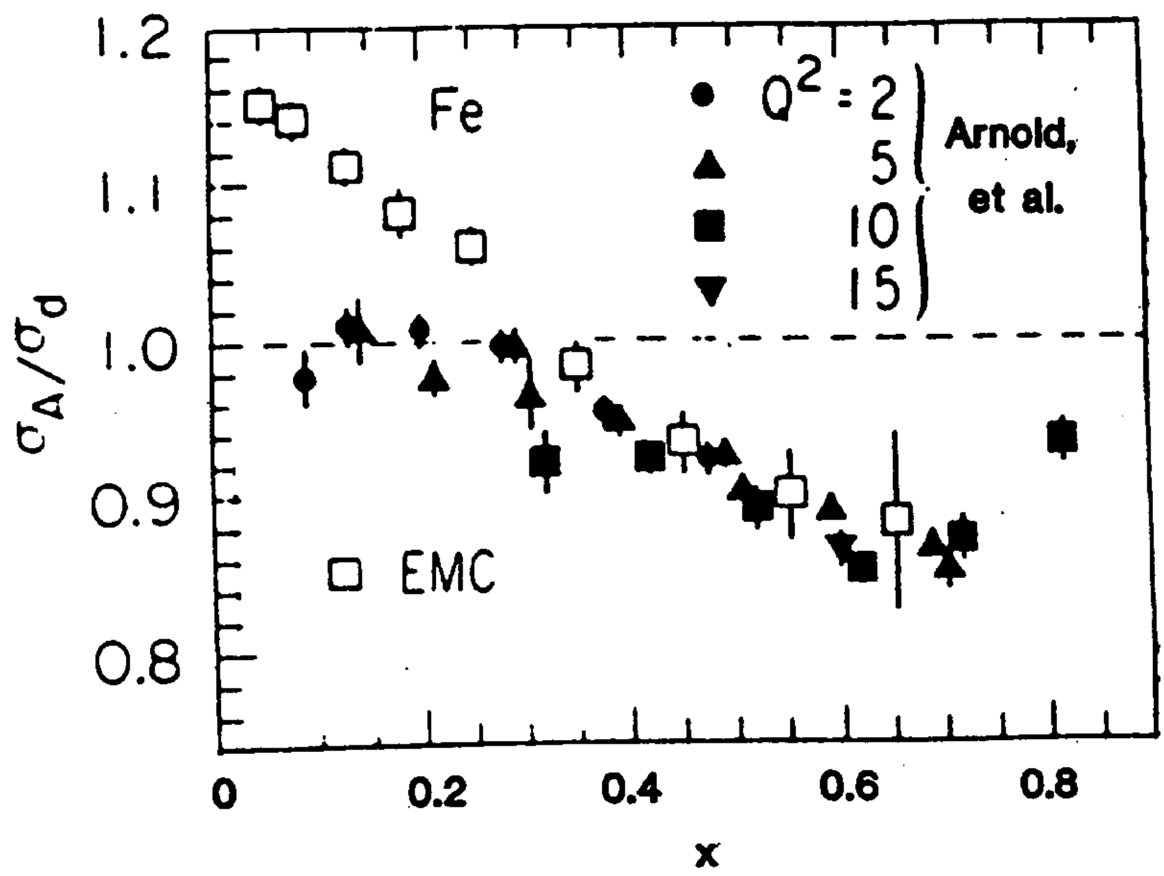

Fig. 7. The ratio of nucleon structure functions F_2^A measured on iron and deuterium as a function of x. Data are from J.J. Aubert, et al. (EMC Collaboration), Phys. Lett. 123B, 275 (1983), and from R.G. Arnold, et al., Phys. Rev. Lett. 52, 727 (1984).

INCOMPLETENESS OF THE STANDARD MODEL

While the standard model has many successes, and the promise of more to come, there are several ways in which the current paradigm is clearly incomplete or unsatisfactory. The more things are explained by the theory, the more we demand of it, and the more we are motivated to examine its foundations and its inner workings. What are some of the questions left open by the standard model?

- We lack an understanding of the pattern of quark and lepton masses and mixing angles.
- We do not understand why quark-lepton generations repeat, or how many generations there are.

- The model has a considerable degree of arbitrariness, and many apparently free parameters. In the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ model, it is necessary to specify 3 coupling constants (α_s, α_{EM}, $\sin^2\theta_W$), 6 quark masses, 3 generalized Cabibbo angles, 1 CP-violating phase, 2 parameters of the Higgs potential, 3 charged lepton masses, and 1 vacuum phase, for a total of 19 seemingly independent parameters. In unified theories, the situation is not appreciably improved.
- CP violation is not explained.
- Gravitation is omitted.
- The Higgs sector of the theory, responsible for the spontaneous breakdown of the gauge symmetry, is insufficiently constrained by general principles, and appears unstable against quantum corrections. An example of the remaining freedom is that the mass of the Higgs boson in the electroweak theory is not fixed. All we know (and even this hangs on some assumptions of simplicity) is that

$$7\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 1\ \mathrm{TeV}/c^2 \quad .$$

  In unified theories of the strong, weak, and electromagnetic interactions, we require several Higgs families.
- Does the growing number of "elementary particles" mean that quarks and leptons are in reality composite?

There is active theoretical work inspired by all these observations. The problem of spontaneous symmetry breaking has perhaps stimulated the most speculation to date. One of these speculations is worth mentioning in this brief survey, because it may bear on recent experimental results.

The usual description of electroweak symmetry breaking is akin to the Ginzburg-Landau theory of the superconducting phase transition. The Higgs boson plays the role of the Ginzburg-Landau order parameter, the wavefunction of superconducting carriers. In the microscopic BCS theory of superconductivity, the superconducting carriers are recognized as Cooper pairs of electrons, or in other words, as bound states of fundamental fermions. By analogy, we may seek a more predictive theory of electroweak symmetry breaking in which the Higgs boson is not an elementary scalar, but a composite bound state of elementary fermions. The hope of technicolor theories, as they are called, is that by understanding the dynamics of the new elementary fermions we should be able to calculate the properties of the Higgs boson.[10] This is an appealing idea, but a complete and realistic technicolor theory has not yet been found. We rely on experiment for clues to the true nature of electroweak symmetry breaking.

BEYOND THE STANDARD MODEL?

So well does the standard $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge theory reflect experimental observations, that there are only a very few pieces of data that do not fit neatly into the orthodox picture. These indicate particularly interesting areas for experimental and theoretical study because they may suggest needed revisions or extensions of the minimal theory. At the moment, the set of experimental anomalies includes:

- The production of same-sign dimuons in neutrino-nucleon collisons;[11]
- The $e^+e^-\gamma(\mu^+\mu^-\gamma)$ events observed at the $S\bar{p}pS$ Collider, which may be improbable Z^0 events, or something more unexpected;[12]
- The "Zoo events" seen in the same $S\bar{p}pS$ experiments;[13]
- The recent report[14] by the Crystal Ball Collaboration of the decay

$$\Upsilon \rightarrow \gamma + \zeta(8.3) \qquad (12)$$
$$\hookrightarrow \text{hadrons} .$$

Professor Veltman will elaborate on the first three in his talk.[15] I shall spend a few moments on the last.

The basic facts, according to the Crystal Ball experimenters, are these. The zeta is indicated by a 1.2 GeV photon line seen in decays of $\Upsilon(9.46)$. The hadronic debris is consistent with, but not established to be, a mixture of $c\bar{c}$ and $\tau^+\tau^-$ semifinal states. The recoiling system has a mass of $8322\pm8\pm24$ MeV/c^2, and a width smaller than the experimental resolution of 80 MeV. The branching ratio for the decay (12) is approximately 0.5%. The ζ is not seen in Υ' decays; the upper limit (90% C.L.) on the branching ratio is

$$B(\Upsilon'\rightarrow\gamma\zeta) < 0.22\ B(\Upsilon\rightarrow\gamma\zeta). \qquad (13)$$

The observation is interesting in the first place because the decays of heavy quarkonium had been suggested[16] as good hunting grounds for the Higgs boson in channels such as

$$^3S_1(t\bar{t}) \rightarrow \gamma + H \quad . \qquad (14)$$

There are two impediments to this interpretation of ζ, in the minimal model. First, the expected branching ratio is some two orders of magnitude smaller than what is observed. Second, the general expectation for phenomena of this kind is that

$$B(\Upsilon'\rightarrow\gamma H) \approx B(\Upsilon\rightarrow\gamma H) \quad . \qquad (15)$$

I do not know of any natural way around this second prediction, so I will focus instead on the first.

The couplings of the Higgs boson to fermion-antifermion pairs are fixed in the standard (minimal) model because the same Higgs particles give masses to the fermions and to the intermediate bosons. In a model with several (weak isospin doublets of) Higgs bosons, or with composite Higgs bosons, there is considerable freedom to adjust the couplings to fermion-antifermion pairs. Generally, these couplings remain proportional to the fermion mass, as in the minimal model. In such a model, we may adjust the rate for the decay (14) essentially at will. We may account for the observed rate of the decay (12) by enhancing the "Higgs" couplings by a factor of 15 over those of the minimal model.

Such an enhancement will have consequences elsewhere, and we must ask whether it leads to any contradictions with experiment. In this scheme, we expect the branching fractions

$$\begin{aligned} B(H\to c\bar{c}) &\approx 3/4 \\ B(H\to \tau^+\tau^-) &\approx 1/4 \\ B(H\to \mu^+\mu^-) &\approx m_\mu^2/4m_\tau^2 \approx 9\times 10^{-4} . \end{aligned} \tag{16}$$

This means that the nonminimal Higgs boson might appear as a dimuon resonance in the reaction

$$pN \to \mu^+\mu^- + \text{anything} \quad , \tag{17}$$

which has been studied extensively. Figure 8(a) shows the 95% confidence level upper limit on

$$B(X^0\to\mu^+\mu^-)\ d\sigma(pN\to X^0+\text{anything})/dy|_{y=0} \tag{18}$$

set by Fermilab experiment E-288[17] in p-Pt collisions at 400 GeV/c. Their upper limit lies well above the expected rate[18] for production of the standard Higgs boson. It is also larger than the enhanced rate anticipated at the mass of the ζ. Thus there is no immediate contradiction with the interpretation of ζ as a nonminimal Higgs boson or, equivalently for these purposes, a neutral technipion.

A sequel to E-288 known as E-605 is now in progress at Fermilab, using the 800 GeV/c proton beam provided by the Tevatron. Our expectations for standard and enhanced Higgs boson production at 800 GeV/c are indicated in Fig. 8(b). With an expected sensitivity[19] of 5×10^{-6} nb and mass resolution of 1-2%, this experiment should be well placed to see ζ, if the interpretation explored here is correct.

In any nonminimal model the neutral Higgs boson or technipion may be accompanied by charged partners of comparable mass. Are light charged scalars (or pseudoscalars) compatible with existing experiments? The contribution of charged scalar pair production to the total

$$\sigma(e^+e^-\to H^+H^-)/\sigma(e^+e^-\to\mu^+\mu^-) = \tfrac{1}{4}(1-4M_\pm^2/s)^{3/2} \quad , \tag{19}$$

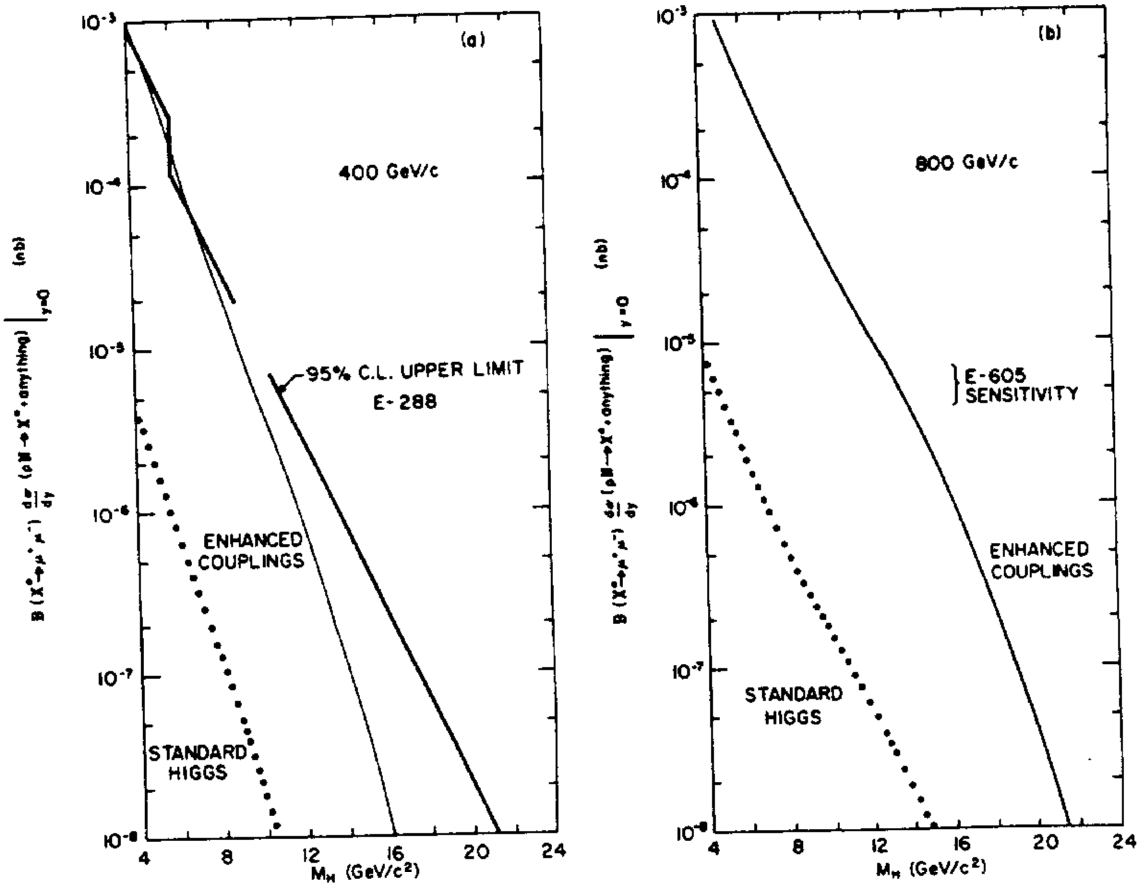

Fig. 8. (a) Upper limits (at 95% Confidence Level) on the differential cross section $d\sigma/dy$ at $y=0$ for production of a narrow resonance decaying into $\mu^+\mu^-$ in 400 GeV/c pN collisions (from Ref. 17). Theoretical curves are explained in the text. (b) Projected cross sections and experimental sensitivity for 800 GeV/c collisions.

which asymptotically yields 1/4 unit of

$$R = \sigma(e^+e^-\rightarrow\text{hadrons})/\sigma(e^+e^-\rightarrow\mu^+\mu^-) \quad . \qquad (20)$$

Representative of the total cross section measurements are those of the TASSO group[20] shown in Fig. 9. At the current normalization uncertainty, a 10 GeV/c^2 charged scalar fits comfortably with the data.

The onset of charged scalar production will change not only the event rate, but also the shape of an average event, because the dominant decays will be into heavy quarks which will subsequently decay into many-particle channels. The branching ratios for charged Higgs or technipion decays are very model-dependent. A typical range of the possibilities for $M_+ = 10$ GeV/c^2 is indicated in Table 1. Total widths are expected to be ~10-100 keV.

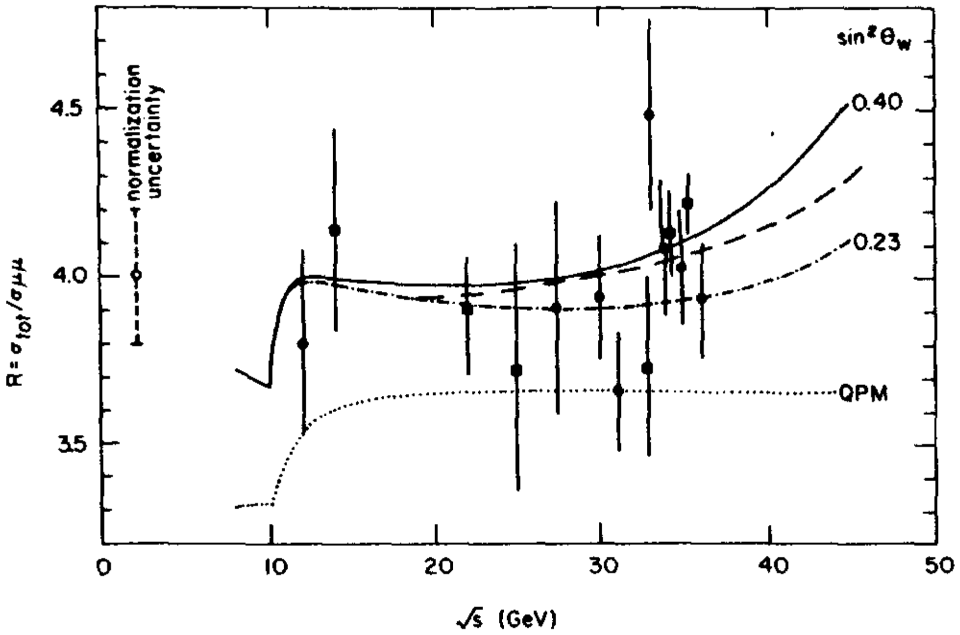

Fig. 9. TASSO results on R for the total hadronic cross section. The points marked by a circle are from the runs in 1979 and 1980, while those marked by a square are from 1981. The errors shown include the statistical and point-to-point systematic uncertainty, while the overall normalization uncertainty is indicated separately on the left. The dotted line shows the expectation from the quark parton model. The full line represents the best fit including weak contributions, while the dot-dashed line was computed with $\alpha_s(s=100\ \mathrm{GeV}^2) = 0.18$ and $\sin^2\theta_W = 0.23$. The dashed line shows the effect of adding to the standard-model expectation (dot-dashed line) the contribution of a pair of 10 GeV/c^2 charged scalars.

Table I. Branching Ratios (in per cent) for Decays of 10 GeV/c^2 Charged Electroweak Scalars (after Ref. 21).

Channel \ Model	1	2	3	4
$\tau\nu$	18	20	11	14
$c\bar{s}$	20	21	4	6
$c\bar{b}$	61	58	84	80

Some searches for light charged scalars have been conducted in experiments at PETRA. The resulting limits[22] are shown in Fig. 10. Unfortunately, the TASSO limits for hadronic decay modes only address cases in which

$$B(H^+ \to c\bar{s}) \geq B(H^+ \to c\bar{b}) \quad , \tag{21}$$

which need not arise in the simplest models. The JADE limits, based on one hadronic decay and one leptonic decay, have more force, but are not strong enough to exclude charged scalars in the range $10\ \mathrm{GeV}/c^2 \lesssim M_H \lesssim 15\ \mathrm{GeV}/c^2$. In view of the possibility that ζ may have some connection with electroweak symmetry breaking, a full-scale search for charged spin-zero particles in this region is urgently needed.[23] The implications in any specific theory of a light charged scalar for top quark decay and for the $K_L K_S$ mass difference must also be reconsidered.

Apart from confirming the ζ itself, it is important to establish whether or not $\zeta \to \tau^+\tau^-$ is an important decay mode, and to search further for evidence of ζ in Υ' decay. Good ideas are needed, too, to test the standard model against these new observations.

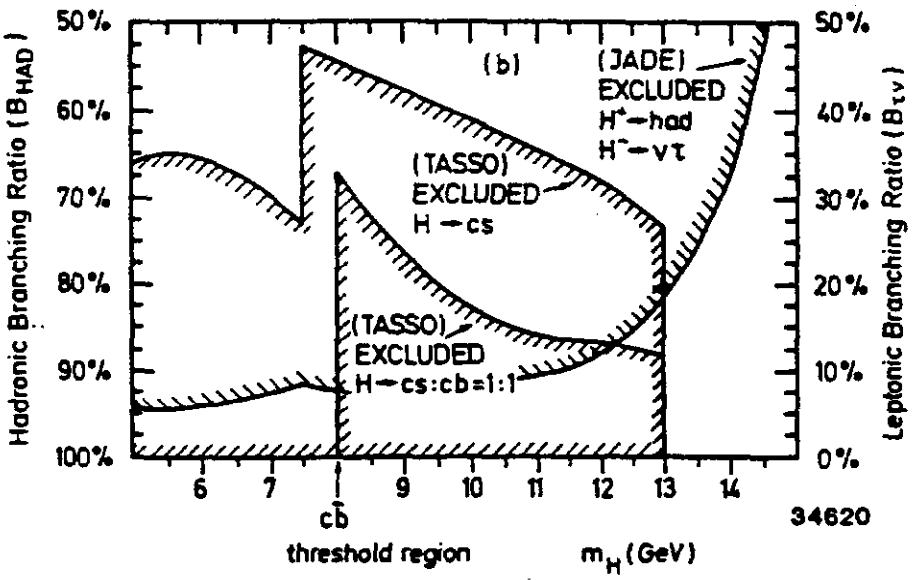

Fig. 10. Limits on the hadronic branching ratio (B_{had}) as a function of $H^\pm$ mass from TASSO for case (A) $e^+e^- \to H^+H^-$ with $H^+ \to c\bar{s}$, $H^- \to \bar{c}s$ and for case (B) $e^+e^- \to H^+H^-$ with $\Gamma(H \to c\bar{s}) = \Gamma(H \to c\bar{b})$. The shaded area is excluded at the 95% confidence level. The vertical scale on the right hand side of the figure indicates the corresponding leptonic branching ratio ($B_{\tau\nu}$) if the sum of $B_{had}+B_{\tau\nu} = 1$. Also shown are limits on the leptonic branching ratio from JADE for $H^+ \to \tau^+\nu$, $H^- \to \tau^-\bar{\nu}$ or $H^+ \to \tau^+\nu$, $H^- \to$ hadrons.

FOOTNOTES AND REFERENCES

1. For summaries, see A. Silverman, in Proceedings 1981 International Symposium on Lepton and Photon Interactions at High Energies, edited by W. Pfeil, Physikalisches Institut Universität Bonn, Bonn, 1981, p. 138; S. Stone, in Particles and Fields-1981: Testing the Standard Model, edited by C. A. Heusch and W. T. Kirk, American Institute of Physics, New York, 1982, p. 30.
2. S. Yamada, in Proceedings of the 1983 International Symposium on Lepton and Photon Interactions at High Energies, edited by D. G. Cassel and D. L. Kreinick, Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York, 1983, p. 525.
3. Reports on the UA-1 experiment given at the 1984 DPF Summer Study on the Design and Utilization of the Superconducting Super Collider, Snowmass, Colorado. See also B. Sadoulet, these proceedings, p. .
4. The first thorough discussions of the evidence for gluon radiation in $e^+e^- \to q\bar{q}g$ are to be found in the reports by H. Newman (Mark-J Collaboration), Ch. Berger (PLUTO Collaboration), G. Wolf (TASSO Collaboration), and S. Orito (JADE Collaboration), in Proceedings of the 1979 International Symposium on Lepton and Photon Interactions at High Energies, edited by T. B. W. Kirk and H. D. I. Abarbanel, Fermilab, Batavia, Illinois, 1979, p. 3, 19, 34, 52.
5. H. Georgi and S. L. Glashow, Phys. Rev. Lett. 32, 438 (1974).
6. For accessible introductions to gauge theories, see I. J. R. Aitchison and A. J. G. Hey, Gauge Theories in Particle Physics, Adam Hilger, Bristol, 1982; L. B. Okun, Leptons and Quarks, North-Holland, Amsterdam, 1981; C. Quigg, Gauge Theories of the Strong, Weak, and Electromagnetic Interactions, Benjamin/Cummings, Reading, Massachusetts, 1983.
7. The first observations of the intermediate bosons $W^\pm$ and Z^0 have been made in two experiments studying 540 GeV proton-antiproton interactions at the CERN $S\bar{p}pS$ Collider. The initial results of the UA-1 detector are reported in G. Arnison, et al., Phys. Lett. 122B, 103 (1983); ibid, 126B, 398 (1983); ibid., 129B, 273 (1983). Those of the UA-2 detector appear in M. Banner, et al., Phys. Lett. 122B, 476 (1983), and P. Bagnaia, et al., Phys. Lett. 129B, 130 (1983).
8. The production of high-$p_\perp$ jets was anticipated (before QCD) by S. M. Berman, J. D. Bjorken, and J. B. Kogut, Phys. Rev. D4, 3388 (1971).
9. E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg (EHLQ), Rev. Mod. Phys. 56, 579 (1984).
10. For a longer introduction to the technicolor approach, see Sec. VI of EHLQ, ref. 9.
11. For some of the evidence, see
M. Holder, et al., Phys. Lett. 70B, 396 (1977);
A. Benvenuti, et al., Phys. Rev. Lett. 41, 725 (1978);

J. G. H. de Groot, et al., Phys. Lett. 86B, 103 (1979);
V. V. Ammosov, et al., Phys. Lett. 106B, 151 (1981);
M. Jonker, et al., Phys. Lett. 107B, 241 (1981);
K. Nishikawa, et al., Phys. Rev. Lett. 46, 1555 (1981);
T. Trinko, et al., Phys. Rev. D19, 1889 (1981);
A. Haatuft, et al., Nucl. Phys. B222, 365 (1983).

12. G. Arnison, et al., Phys. Lett. 126B, 398 (1983); Phys. Lett. 135B, 250 (1984); P. Bagnaia, et al., Phys. Lett. 129B, 130 (1983); B. Sadoulet, these proceedings, p. .
13. P. Bagnaia, et al., Phys. Lett. 139B, 105 (1984); G. Arnison, et al., Phys. Lett. 139B, 115 (1984); B. Sadoulet, these proceedings.
14. C. Peck, et al., (Crystal Ball Collaboration), "Evidence for a Narrow Massive State in the Radiative Decays of the Upsilon," DESY 84-064, SLAC-PUB-3390.
15. M. Veltman, these proceedings, p. .
16. F. Wilczek, Phys. Rev. Lett. 39, 1304 (1977).
17. K. Ueno, et al., Phys. Rev. Lett. 42, 486 (1979).
18. The calculations reported here were done by Ian Hinchliffe and myself, using EHLQ programs.
19. R. L. McCarthy, private communication.
20. R. Brandelik, et al. (TASSO Collaboration), DESY 82-010 and Phys. Lett. 113B, 499 (1982).
21. K. Lane, in Proceedings of the 1982 DPF Summer Study on Elementary Particle Physics and Future Facilities, edited by R. Donaldson, R. Gustafson, and F. Paige, Fermilab, Batavia, Illinois, 1982, p. 222.
22. The limits shown are from W. Bartel, et al. (JADE Collaboration), Phys. Lett. 114B, 211 (1982); and M. Althoff, et al. (TASSO Collaboration), Phys. Lett. 122B, 95 (1983). See also H.J. Behrend, et al. (CELLO Collaboration), Phys. Lett. 114B, 287 (1982); B. Adeva, et al., (Mark J Collaboration), Phys. Lett. 115B, 345 (1982); C. A. Blocker, et al., (Mark II Collaboration), Phys. Rev. Lett. 49, 517 (1982).
23. A laughably crude estimate of the cross section for the reaction

$$pp \to H^+ + \text{anything}, \quad H^+ \to c\bar{b}$$

yields $\sim 10^{-5}$ nb for $M_{\pm} = 10$ GeV/c^2 and $p_{Lab} = 800$ GeV/c.