

## **What is happening in Particle Physics Theory: A Review Talk for Non-particle Physicists**

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### *Abstract*

This talk presents a review of the current status of particle physics theory. It is intended for the physicist working in other areas of physics and hence describes the particle content of an  $SU(3) \otimes SU(2) \otimes U(1)$  gauge theory with very few technical details. Attempts to find a 'grand-unified' version of the theory are also briefly discussed.

I want to begin with two apologies: the first to the particle physicists in this audience, for I will say little in this talk that they do not already know; and the second to particle physicists in general, for this review will be too short to allow a proper assignment of credit to all those who contributed to the development of the picture I shall describe.

Particle physics today is at a very different place than it was 10 years ago. Today we have a theory which we believe explains (or would explain if we knew how to do the relevant calculations) all particle phenomena with energies up to tens of GeV. Work is proceeding in two directions: the first is one of consolidation—trying to learn how to calculate with this theory so we can test that it does indeed describe the physics we see (here we become more like solid state or atomic physicists—they too have a theory, QED, but there are still phenomena which we all believe must result from that theory which have in fact never been derived; for example, the existence of a crystal). The second more speculative direction of research at present has to do with the region beyond present data—it makes suggestions about new phenomena on the TeV or higher scale. The reason for this is that our present theory of strong, electromagnetic and weak interactions, which I shall describe to you, really begs for unification into a single theory. Different approaches to this problem lead to different TeV range physics. Towards the end of this talk I will tell you more about this, but first I must describe what we now see as the structure of the 'low' energy world.

I will be talking about one class of field theory throughout, namely field theories known as 'non-Abelian gauge theories'—gauge theories because, like QED, they have a local gauge invariance; non-Abelian because, unlike QED, they contain more than one vector (spin 1) particle and the algebra of the currents to which these particles couple, or of the generators of the gauge transformations, is a non-Abelian one. I will not try to explain to you the technical details of how these theories work. Following the pioneering work of 't Hooft in 1971 (see also 't Hooft and Veltman 1972) we have developed a considerable understanding, at least of the perturbative and even some non-perturbative aspects, of these theories. I will abstract some of

this understanding as 'rules of the game' which I will state without proof, though sometimes I can give at least a partial intuitive argument for a rule.

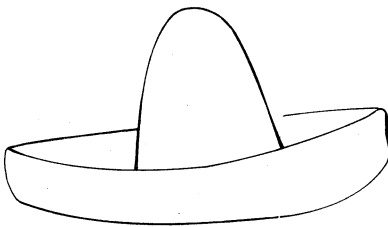
Now let us begin the picture.

The minimal content of a non-Abelian gauge theory which is to describe a world which contains fermions is:

- (1) A set of fundamental vector particles, one for each generator of the gauge group; these are the gauge bosons.
- (2) A set (or sets) of fundamental fermions which couple to one another through the emission of gauge bosons. We call these fermions 'quarks' if they are strongly interacting, and leptons otherwise.

For example, the electron and neutrino are leptons. They interact only with the weak vector bosons  $W^+$ ,  $W^-$  and  $Z$  and with the photon. The proton and neutron, on the other hand (and in fact all strongly interacting particles) are composites: they are made from quarks, held together by the strong gauge bosons, which are therefore referred to as the gluons. There are two types of composite: baryons are made from three quarks  $qqq$ , and mesons from the binding of a quark with an antiquark  $q\bar{q}$ .

Here the big difference between the strong and the weak gauge theories becomes evident. We see physically only the particles carrying weak gauge quantum numbers, and the gauge particles themselves. (At least we see the photon and we are fairly sure that when we get to the right energy we will produce the  $W$  and  $Z$  bosons—if not, all I am saying is probably wrong.) The  $W$  and  $Z$  bosons are massive; but we cannot write a gauge theory which has both masses for them and non-Abelian gauge invariance. The answer to this conundrum is that the symmetry is spontaneously broken: it is a symmetry of the Lagrangian but not of the states of nature. Only the Abelian subgroup corresponding to the photon remains as the manifest symmetry of charge conservation.



**Fig. 1.** A potential well shaped like a Mexican hat has rotational invariance.

(To understand the idea of a spontaneously broken symmetry, consider the problem of a potential well shaped like a Mexican hat (Fig. 1). This clearly has a rotational invariance. However, a ball placed on the top of the hat will come to rest somewhere around the rim. There exists a degenerate infinity of possible choices for its position but any one of them breaks the symmetry. The states of the system are not manifestly rotationally symmetric even though the Hamiltonian itself is so.)

There is another option for a gauge theory, which we believe is chosen by the strong or colour gauge theory. The symmetry is manifest, which requires that all physical states must be singlets; that is, objects which transform into themselves under the action of the gauge group, and which are thus neutral with respect to the gauge bosons. The quarks and gluons, being nonsinglet objects, are confined, and can never be observed alone. The magical combinations  $qqq$  or  $q\bar{q}$  are thus explained

if we say the other gauge group is SU(3) and the quarks belong to the fundamental of triplet representation. Then an antiquark must belong to the conjugate representation. We can thus form a singlet from three quarks or from a quark and an antiquark as shown in the Young tableaux of Fig. 2. This suggests that there must also be another type of physical particle, a colour singlet object made from gluons alone, called a glueball (for the group theorists, the gluons are in an octet and there is a singlet in the product  $8 \otimes 8$ ). Such a particle has never been observed; to find one would be a victory for this theory. Present mass predictions suggest that they should occur somewhere in the few GeV range. They come in a number of spin-parity combinations, some of which cannot be duplicated by  $q\bar{q}$  states. While on the subject of experiment: it is unfair to present this viewpoint without a warning that there is one experiment (La Rue *et al.* 1977, 1979) that appears to have seen a quark, or at least a particle carrying 1/3 proton charge, which is one of the peculiar properties of quarks. I have no criticism to make of this experiment, but if it is right then the theory I am describing needs at least a minor modification (for example, the addition of a charge 1/3 lepton), if not a very major one.

	q	Triplet of SU(3)
	$\bar{q}$	Antitriplet of SU(3)
	$\epsilon_{\alpha\beta\gamma} q^\alpha q^\beta q^\gamma$ or $\sum_\alpha q^\alpha \bar{q}_\alpha$	Singlets of SU(3)
	Gluon	
		Octet of SU(3)

Fig. 2. SU(3) representation content.

So now we have: leptons, for example,  $e$  and  $\nu_e$ ; the electroweak gauge bosons  $W^+$ ,  $W^-$  and  $Z$ ; and composite hadrons made from quarks and glue. Let us start with the everyday quarks. These are of two 'flavours', distinguished by their electrical charge. There are three 'up' quarks  $u^\alpha$ , where  $\alpha$  is the strong or colour quantum number which runs over the values 1–3 (sometimes called the colours red, white and blue), and these have charge 2/3 (in units where the proton has charge 1), and similarly three colours of 'down' quark  $d^\alpha$  which have charge  $-1/3$ . The proton is the combination  $\epsilon_{\alpha\beta\gamma} u^\alpha u^\beta d^\gamma$  and the neutron is  $\epsilon_{\alpha\beta\gamma} u^\alpha d^\beta d^\gamma$ . Thus colour solves an old problem of the quark model. To make a spin 1/2, isotopic spin 1/2 object out of spin 1/2 quarks gives a wavefunction which is symmetric in both spin and isospin, whereas Fermi statistics says that it must be antisymmetric under fermion interchange. The answer is in the  $\epsilon$  symbol above. The colour singlet state made from these quarks is antisymmetric in the hidden (or confined) colour degree of freedom.

The quarks also have weak interactions. The  $\beta$ -decay process  $n \rightarrow p + e + \bar{\nu}_e$  is understood in this language as a two-stage process,

$$d \rightarrow u + W^-$$

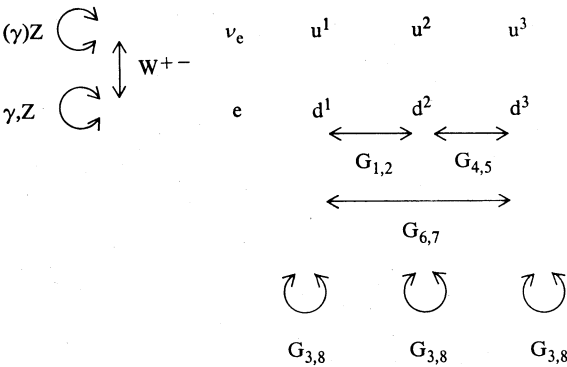
$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad \rightarrow e + \bar{\nu}_e,$$

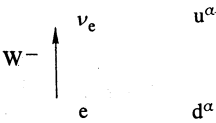
where in the first stage the constituent quark decays and hence turns udd into uud, plus a virtual W boson, which then decays into an electron and an anti-electron neutrino.

Now this completes the first generation of particles, so let me draw it out for you and make some remarks on the pattern, as it is shown in Fig. 3a. Here a line indicates a possible transition (for example, Fig. 3b is the process  $e \rightarrow \nu_e + W^-$ ). The parentheses around the photon in the top line of Fig. 3a are simply a reminder that, since the  $\nu_e$  has zero charge, the process  $\nu_e \rightarrow \nu_e + \gamma$  does not occur: however, the process

(a)



(b)



Represents

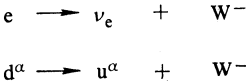


Fig. 3. Showing (a) the first generation of particles and (b) the decoding of the connections in this scheme.

$\nu_e \rightarrow \nu_e + Z$  is now well documented. One sends a high energy neutrino beam into a detector and looks for events where a neutrino emits a Z. The Z is absorbed by a proton or a neutron, giving rise to a shower of hadrons, which is all one sees in the detector. This neutral current process provided the first piece of evidence (Hasert *et al.* 1973; Benvenuti *et al.* 1974) for the now standard non-Abelian gauge theory of electroweak interactions (Weinberg 1967; Salam 1968). The neutral currents are an essential part of the Weinberg-Salam version of that theory because one of the rules of the non-Abelian gauge theories is that the full algebra must be included in the theory, which translates in my diagram (Fig. 3) to the full set of connections for every pair of points connected by a given interaction. (It is possible to construct a

theory where the only neutral current is that coupled to the photon, by adding additional leptons (Georgi and Glashow 1972a). However, experiments have made that an academic exercise at this point).

A remarkable fact about the picture in Fig. 3a and a property which turns out to be necessary in order for the weak interaction theory to make finite predictions (that is, to be renormalizable) is the fact that the sum of the electric charges of all the particles in the picture is zero (Bouchiat *et al.* 1972; Gross and Jackiw 1972; Georgi and Glashow 1972b):

$$\sum q_i = \underbrace{0 + -1}_{\text{leptons}} + \underbrace{3(2/3)}_{\text{up quarks}} + \underbrace{3(-1/3)}_{\text{down quarks}} = 0. \quad (1)$$

If you ever wondered why the electron and the proton have exactly equal and opposite charge, this equation provides an explanation: it must be so if this is the right theory. (In the grand-unified theories which I shall talk about later, this property is related also to the existence of a type of monopole in the theory and hence to the old Dirac argument for the quantization of charge ('t Hooft 1974; Polyakov 1974; for a review of this subject see Goddard and Olive 1978).)

As far as everything in this room is concerned the particle story could end here, but we have long since known that it does not. The picture is duplicated: we not only have electrons and  $\nu_e$ , but we also have a heavy lepton called the muon and its related neutrino  $\nu_\mu$ . The muon differs from the electron (as far as we know) only in its mass. Furthermore, even in 1964 when the quark model was first proposed (Gell-Mann 1964; Zweig 1964) there were three 'flavours' of quark: up, down and strange. The strange quark is just like the down quark but heavier. Strong interactions, being horizontal in my picture (Fig. 3a), never change the flavour. Thus the down and strange quarks are distinguished by a quantum number, called strangeness, which is conserved in the strong interactions. However, there is a slight lie in my picture: in weak interactions the u quark does not become a d quark, it becomes the linear combination

$$d_c = (\cos \theta_c d + \sin \theta_c s),$$

where the mixing angle is called the Cabibbo angle (the lie is slight because  $\sin \theta_c$  is small). The eigenstates of the mass matrix are the objects we call d and s, but the weak interaction eigenstates are linear combinations of these objects; the weak interactions do not respect the 'flavour' quantum number, strangeness. The d's in Fig. 3 should have been  $d_c$ 's. In addition, we have the particles shown in Fig. 4a where

$$s_c = -\sin \theta_c d + \cos \theta_c s$$

is the orthogonal combination to  $d_c$ . Two facts forced us to complete this picture by predicting a fourth quark flavour, a heavier charge 2/3 quark carrying a flavour label we call 'charm'. One fact has to do with the rule  $\sum q_i = 0$  (equation 1). Clearly a replication of the original picture is needed for that to still apply. The other and even more compelling reason is that without the charmed quarks the first generation picture contains another lie: it predicts the process

$$d \rightarrow s + Z, \quad (2)$$

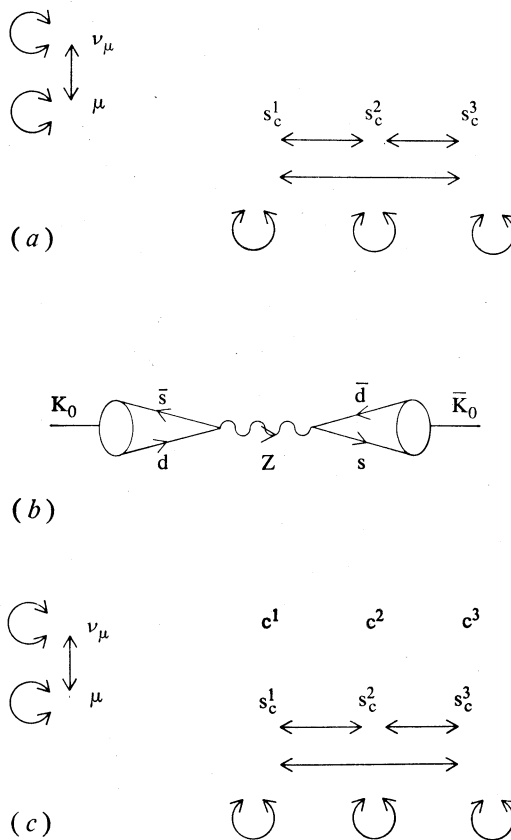


Fig. 4. Showing (a) the pre-1974 second generation of particles, (b) mixing of  $K_0$  and  $\bar{K}_0$  mesons via a neutral vector boson, and (c) the completed second generation.

with strength proportional to  $\sin \theta_c \cos \theta_c$ . However, this would be a disaster. There exist mesons called  $K_0$  and  $\bar{K}_0$  which are respectively  $d\bar{s}$  and  $s\bar{d}$ . Such an interaction would provide a mechanism for a  $K_0 \rightarrow \bar{K}_0$  transition as shown in Fig. 4b. Experimentally the  $K_0$  mass eigenstates are  $(K_0 \pm \bar{K}_0)/\sqrt{2}$  (almost) and they are very nearly degenerate. The mechanism of Fig. 4b would produce considerable splitting between them, and hence cannot exist. By completing the second picture as in Fig. 4c, we get an additional contribution to the process (2) above that is proportional to  $-\sin \theta_c \cos \theta_c$ , which exactly cancels the one from the first picture. This is called the GIM mechanism, after Glashow *et al.* (1970) since these were the people who first realized the necessity of charm in the electroweak gauge theory.

The fact that charm indeed exists is by now an old story. In November 1974, the first particles containing charm quarks, the  $J/\psi$  meson which is a  $c\bar{c}$  state, were found (Aubert *et al.* 1974; Augustin *et al.* 1974). Since then, D mesons, which are  $c\bar{d}$ ,  $c\bar{u}$ ,  $u\bar{c}$  or  $d\bar{c}$ , have been discovered (Goldhaber *et al.* 1976; Peruzzi *et al.* 1976). The evidence for states containing  $c$  and  $s$  quarks or for baryons with charm quarks is still fairly limited, though there exist bubble chamber pictures interpreted as a sequence of decays involving some of these particles (Cazzoli *et al.* 1975; see also Knapp *et al.* 1976).

However, nature was not content to let us discover charm and think we now had the whole story. The same SPEAR experiments that convinced us that  $c\bar{c}$  was indeed a good interpretation of the  $\psi$  and  $\psi'$  system provided evidence for yet other new particles (Perl *et al.* 1975), namely a lepton of mass  $1.8 \text{ GeV}$ , called the  $\tau$ , and its accompanying neutrino  $\nu_\tau$  (which may or may not be massless). The rule of  $\sum q = 0$  suggested we should assume that an entire third generation exists. The search continued, and at Fermilab a new particle, the  $Y$  (upsilon), was found (Herb *et al.* 1977; Innes *et al.* 1977; Kephart *et al.* 1977). The interpretation was: states  $b\bar{b}$ , the third generation bottom quark member (the form of the picture in Fig. 5 explains the unimaginative name). The top quark 't' still eludes us; searches at PETRA say that it must be heavier than about  $15 \text{ GeV}$  (Barber *et al.* 1979; Berger *et al.* 1979; Wolf *et al.* 1979). We have no good way to predict its mass, but it is widely assumed that the picture simply replicates once more, and that such a quark exists somewhere.

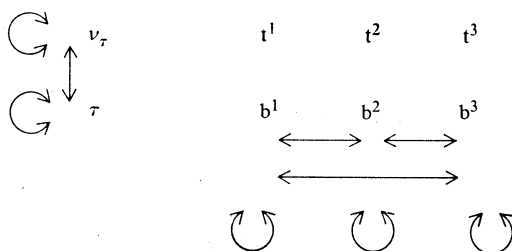


Fig. 5. Third generation of particles.

One feature of these pictures may have struck you as curious, namely the division into the lepton and hadron worlds. The picture would be much more uniform if, instead of disjoint worlds with two unrelated gauge theories, we could somehow tie it all together in one big gauge theory which contains both of these as disjoint subgroups. In more technical language we want:

Group	$G$	$\supset$	$SU(3)$	$\otimes$	$SU(2) \otimes U(1)$
Content	Unified		Colour		Electroweak
Coupling	$g_{un}$		$g_s$		$g \quad g'$

Preferably we want a simple group  $G$  so that instead of three coupling constants there is only one ( $g_{un}$ ). Such a theory is referred to as a grand unified theory. The construction of such theories is a very lively subject at present. The simplest theory is that where  $G = SU(5)$ , first discussed by Georgi and Glashow (1974). In the  $SU(5)$  theory more connections in the picture are made, as shown in Fig. 6. The new connections must, like the weak part of the theory, correspond to a spontaneously broken symmetry, so that the associated gauge bosons are heavy—very heavy. We can in fact calculate how heavy they are in an  $SU(5)$  theory and the answer comes out around  $10^{14}$ – $10^{15} \text{ GeV}$  (Georgi *et al.* 1974; for a more recent and refined version of this calculation see e.g. Goldman and Ross 1979; Marciano 1980). This is a relief and an exciting prediction at the same time. These gauge bosons turn quarks into leptons, and hence mediate exotic new processes such as proton decay. A mass of  $10^{14}$ – $10^{15} \text{ GeV}$  gives a prediction of a proton lifetime of the order of  $10^{30}$ – $10^{32} \text{ yr}$ , where the present experimental limits are  $10^{28}$ – $10^{30} \text{ yr}$  (Reines and Crouch 1974).

A great deal of interest has been generated by this prediction and several experiments are now being set up to try to push this bound further, or, better yet, to observe proton decay.

Lest I fool you into thinking that such a grand unified theory is a one-parameter theory of the world, I must discuss one more piece of the picture before I stop. I have mentioned the breaking of some symmetries: this gives masses to some vector bosons and also to the quarks and leptons. At the level of manipulating Lagrangian field theories, we know one sure way to achieve this effect: we add to the theory

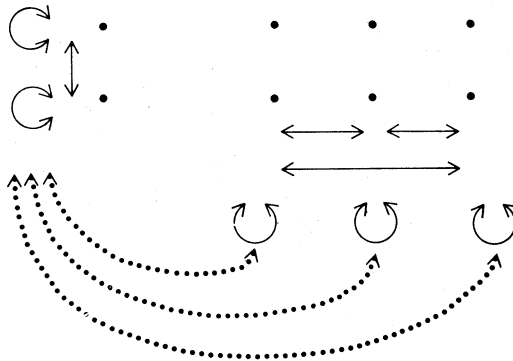


Fig. 6. Some of the extra gauge bosons in the SU(5) theory.

a set of as yet unseen particles, which are fundamental scalars. By playing with the gauge-group representation content and the parameters of the scalar world, including Yukawa couplings of these scalars directly to the fermions, we can achieve all the desired symmetry-breaking effects. The price we pay is to turn our one-parameter theory into a many-parameter theory. Aside from the proliferation of parameters and the fact that no such particles have been observed, many of us have a strong theoretical prejudice against these fundamental scalar particles. This is because in order to achieve the desired result it is necessary to assume incredibly fine tuning of the parameters of the scalar world (for a discussion of this see Farhi and Susskind 1979; Weinberg 1980*a*). The rest of the theory is much more 'natural' in the sense that the physics is insensitive to small changes of parameters. The grand unified theory with fundamental scalars also has a peculiar 'desert', aside from a few scalar particles in the 10 GeV region and the W and Z bosons in the 100 GeV region: nothing new awaits us until  $10^{15}$  GeV! It takes considerable hubris to believe such an extrapolation of our present knowledge. An alternative exists, namely grand unified theories much bigger than SU(5) where new types of quarks and gauge symmetries are introduced with strong coupling at the very high energy scales (see e.g. Dimopoulos and Raby 1980; Eichten and Lane 1980). Then the confinement of these quarks provides composite scalars which do the job of driving the spontaneous symmetry breaking of the less strongly coupled parts of the theory. This picture has the advantage of avoiding the light (i.e. 10 GeV or so) fundamental scalars, but it has the disadvantage of being much more speculative. Various stages of the analysis are based on the assumption that any strongly coupled, unbroken, gauge theory will behave just as we observe QCD to do (that is, as we assume QCD does because we assume that QCD describes the world we see around us). The distinction between



the two classes of grand unified theory experimentally is also quite out of the presently available energy range—the theories without fundamental scalars *do* have new processes appearing which occur between 100 and  $10^{14}$  GeV, but at ‘low’ energies the two look quite the same (for a discussion of possible experimental tests of these ideas see Dimopoulos 1980).

Some versions of grand unified theories also attempt to answer the question why there should be three generations of particles. Many introduce gauge interactions which connect the generations, turning my three pictures into one three-dimensional

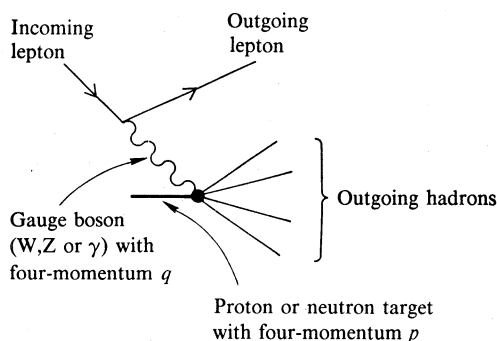


Fig. 7. Deep inelastic lepton scattering.

picture three layers deep. Some insight on the question of how many generations might exist is provided by looking at higher order corrections to weak processes coming from possible further generations. Veltman (1980) has calculated these corrections as they affect the measured ratio of weak vector boson masses  $m_W/m_Z$ , which in the standard electroweak theory can be predicted on the basis of other measurements. His conclusion is that the ratio is close to the expected value without further generations; at the present level of experimental accuracy he says there is room for at most one further generation in the standard theory.

I have presented up to now the standard particle physics view of what is, and a little discussion of the questions currently being asked about what lies beyond our present energy ranges. Clearly there is much going on in particle physics that I have not mentioned, or just barely referred to in passing. The theory I have described is being studied and tested in many ways. For example, my own work in recent years has focused on trying to develop some non-perturbative calculational methods to address problems such as the hadron spectrum in this theory. A recent paper on this work is Svetitsky *et al.* (1980). However, I do not have time here to discuss this work, nor to consider all the details of what has or has not been established for the picture I have described. A few brief remarks on this subject are needed, however.

For the electroweak theory many tests have been made and we are almost certain we have the right theory, or at least the right low energy part of the theory, as was affirmed by the award of the Nobel Prize last year (Glashow 1980; Weinberg 1980b; Salam 1980). For the strong theory, the situation is less conclusive. In my opinion, the basic reason for believing that QCD is the right theory is that *only* non-Abelian gauge field theories can explain a property of highly inelastic lepton–hadron scattering which we call scaling. In the process shown in Fig. 7, it is found that, apart from some trivial kinematic factors, the cross section depends only on the ratio  $x = q^2/q \cdot p$

and not on  $q^2$  and  $q \cdot p$  separately (see for electrons the experiments of Bloom *et al.* 1969; Bodek *et al.* 1969; for neutrinos see e.g. Bosetti *et al.* 1978; deGroot *et al.* 1979a, 1979b). This is the zeroth order prediction of QCD; higher order corrections give  $\ln(q^2)$  corrections as well (for a review of this subject see Buras 1980) but these corrections are very small and slowly varying, and despite much experimental effort I do not believe that they have been convincingly detected (see the analysis of Abbott and Barnett 1980). Much effort, both theoretical and experimental, is going into the question of devising and carrying out more refined tests of QCD, or at least of perturbative calculations from QCD plus certain models for how high energy quarks and gluons become high energy hadrons.

I have tried to give you a flavour of where we are now in particle physics. I have described to you a viewpoint which has become widely accepted as the theory of particles. Like any theory, it is probably not the whole story, and much work remains to demonstrate and define its region of validity. I have made some comments about a few presently active research areas; clearly I have made no attempt to give an exhaustive survey of what is going on. I hope that for at least some of you this talk has been informative—I apologize again to the particle physicists among you for telling you only what you know already.

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