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WHAT WE CAN LEARN FROM LEPTON-QUARK INTERACTIONS

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INTRODUCTION

One of the signs of impending maturity for a high-energy physicist is that people stop asking you to talk about your own work, and ask you to talk about the work of others. This talk is an illustration of that aging phenomenon. Indeed, it represents an extension of the usual effect. I am, to be sure, not talking about my own work, but in addition I am going to be talking about a field in which I have no competence. This was not unknown to the organizers, who seem to have hoped that I would draw inspiration from a fear of public humiliation. I am afraid that this comes perilously close to experimentation on unconsenting human subjects!

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I will begin my discussion of what can be learned from lepton-quark scattering, after a brief metaphysical introduction, with a review of what has been learned from lepton-quark interactions. This will reassure us that lepton-quark scattering has been of value in the past, and will enable us to get a feeling for the range of questions addressed there. Next, I will summarize the context in which to ask future questions: the paradigm. It constitutes the set of assumptions that we believe on the basis of present experiments and which--subject always to refinement, extension, and revision--defines the way we talk about experiments done now and in the future. I will then talk very briefly about two forthcoming neutrino experiments which seem to me to be of specific interest and to go to questions of the kind that I will be framing. Finally, I will concentrate my attention upon some of the possibilities for experiments with ep colliders. The point of that discussion will be to try to understand what--in very general terms--are the things we may hope to learn from these facilities, and to begin to ask what requirements our physics questions place upon machines and experiments.

Of late I think we have all noticed that our field has taken on a greater unity. We have seen already in presentations at this meeting that people doing experiments with different beams are speaking the same language and addressing the same fundamental questions. This was not so only a decade or so ago when electron people were a strange crew who lived off in the woods somewhere and did whatever they did, and hadron people spoke only

to subsets of other hadron people, and colliding beams barely had been invented.

The unity we perceive extends beyond the traditional boundaries of high-energy physics to nearby fields such as astrophysics and cosmology, with which we are benefiting from an increasing interplay. Common interests are also developing with medium energy physics, both in the realm of fission reactors and at meson factories, where neutrino oscillations and rare decays can be investigated. In other areas, including relativistic heavy-ion physics, we find our terminology and modes of analysis being assimilated. Thus we are able to understand, at least in part, what our colleagues are doing, and we are able to begin to do science in common with them. What I hope to do in this talk is to discuss lepton-quark scattering in this wider context, and to make plain what issues we seek to illuminate.

WHAT HAS BEEN LEARNED?

Let me begin by simply making a list of things which have been learned since Antiquity in lepton-quark scattering experiments. The object of this exercise is to record the large number of commonly-held beliefs that have been invented or discovered or refined in experiments of this kind. In many cases, this information complements or is complemented by lepton-lepton and quark-quark interactions.

Measurements of the charge distribution in nuclei reveal details of nuclear structure. The observation of quasi-elastic peaks in electron-nucleus scattering verifies the existence of nucleons in nuclei. Deeper scattering of electrons from nucleons demonstrates that the "elementary" particles are composite, and that the neutron isn't all neutral. Similar form factor measurements, for the most part carried out with high-energy hadron beams incident on atomic electrons, yield values for the pion and kaon charge radii. These determinations of static properties of the hadrons provide important targets for a quantitative theory of hadron structure.

The famous SLAC-MIT experiments showed for the first time the presence of pointlike charged constituents in protons. We may interpret the results of those experiments as showing that there are three net quarks present in the proton, as well as a quark-antiquark sea. The energy-conservation sum rules also yield evidence that there are neutral constituents in nucleons. This observation provided an early hint for the existence of gluons. In addition to revealing a large cross section, these same experiments showed that to a good approximation Bjorken scaling holds in deep-inelastic scattering. More recent experiments have demonstrated, and begun to quantify, scaling violations. All of these observations have guided the development of a consistent theory of the strong interactions.

It is not often recalled, but a decade ago it was considered great theoretical sport to show that Bjorken scaling was impossible in any self-respecting interacting field theory, and that Feynman was all wet to be talking about the parton model. As theorists will, my colleagues began by showing in the simplest field theories you can calculate that scaling could not be achieved. As time passed, this program was extended to richer

field theories. It was ultimately found that **gauge theories** may be asymptotically free, and may therefore manifest approximate Bjorken scaling. Thus did the motivation of proving the impossibility of the parton model give birth to Quantum Chromodynamics.

Lepton scattering has also provided evidence of electron-muon universality, an important clue in trying to understand the spectrum of leptons. From measurements of longitudinal and transverse cross sections in deeply inelastic electron-nucleon scattering (as well as the complementary measurements in e^+e^- annihilations) we have information about the spin of charged partons. The comparison of charged lepton-nucleon and neutrino-nucleon scattering gives a measure of the mean charge of the constituents which interact weakly and electromagnetically.

Going back a bit in time, we recall the two-neutrino experiment. Weak neutral currents were discovered in neutrino-nucleon scattering. The first tangible hints of charm came in neutrino-induced dimuon events and the charmed baryon and $K_S \mu e$ events observed in bubble chambers. Over the years, neutrino-nucleon total cross section measurements have set ever more stringent lower bounds on the mass of the intermediate boson. Currently we infer $M_W \gtrsim 30$ GeV/c^2 from these data. This information has repeatedly altered theories of the weak interaction, and is now nicely consistent with the expectations of the Weinberg-Salam model. The observation of parity violation in inelastic electron-nucleon scattering was also a psychologically-important success for the Weinberg-Salam model. All in all, there is overwhelming evidence that the Weinberg-Salam model correctly describes the low-energy phenomenology.

Evidence from charm production in neutrino scattering that there is a strange sea in the nucleon supports a qualitative inference from associated production in soft collisions. First in electron scattering and subsequently in muon and neutrino scattering we have observed the jet behavior having to do with the quark "knocked out" of the target. This gave rise to the study of the quark-to-hadron fragmentation process, in which signs of jet broadening due to gluon radiation have recently been noted.

In a series of very nice experiments, the absolute lifetimes of charmed particles produced in neutrino-nucleon collisions have been determined. These are extremely important to efforts to understand the mechanism(s?) of nonleptonic enhancement, which is no doubt intimately connected with the problem of hadron structure and confinement.

Finally, and importantly, none of these experiments has produced evidence for free quarks. This is responsible for our conviction that quarks are permanently confined, or at least extremely difficult to liberate.

This brief summary gives some account of what lepton-quark scattering has done for us in the past. Before asking what we may expect in the future, let us review what we currently think we know.

THE PARADIGM

Our conceptual framework consists of two major elements: the elementary constituents and the fundamental interactions. Let us examine each of these in turn.

At the present level of experimental resolution, the quarks and leptons appear to be the basic constituents of matter. There is direct evidence for five leptons (e, ν_e, μ, ν_μ, τ) and circumstantial evidence for a sixth lepton, the ν_τ. We know of fifteen species of quarks--five flavors (up, down, charm, strange, and beauty) times three colors. Simple faith leads us to expect a sixth quark flavor as well. All of the putative elementary fermions are structureless on a scale which is now approximately on the order of 10^{-16} cm. No direct observation yet implies the existence of still smaller constituents. We entertain this possibility only by tradition, and in the hope that order may be brought to the burgeoning spectrum of elementary particles.

To the extent that we do not seek an explanation of the fermion spectrum, but accept it as given, we may claim to understand --at sort of an engineering level--the weak and electromagnetic interactions of quarks and leptons. The Weinberg-Salam theory is calculable, incorporates all observational systematics, and agrees with experiment insofar as it has been tested. It is based upon the idea that there are weak-isospin multiplets of left-handed fermions: three lepton doublets and three Cabibbo-rotated (or more properly, Kobayashi-Maskawa) quark doublets. Given the canonical multiplet assignments and the basic idea of the spontaneously broken $SU(2)_L \otimes U(1)_Y$ gauge theory, one can calculate almost everything.

Some arbitrariness remains. The theory itself does not prescribe the value of the weak mixing angle, θ_W, which therefore must be determined by experiment. So far, agreeably, the determinations of θ_W in various reactions are all compatible.

Beyond the arbitrariness, the theory is incompletely motivated. The idea that interactions may be derived from symmetry principles is beautiful and potent. But we do not have any principle to guide our choice of a symmetry to gauge. That the achromatic gauge group should be $SU(2)_L \otimes U(1)_Y$ is, for the moment at least, a purely experimental statement. It may puzzle us that the charged current is left-handed, and that parity-violation is maximal. We don't have any reason why this should be so.

Thus, if we agree for the moment not to try to explain the lepton spectrum, and if we neglect the possibility of rare, lepton-number violating processes, then we seem to have a thorough understanding of the leptons. This is so in the sense that we believe we can calculate all the weak and electromagnetic interactions among leptons. In that sense, our knowledge of leptonic interactions resembles the Ginzburg-Landau description of superconductors, which is completely adequate for many purposes. In the case of superconductivity, the Bardeen-Cooper-Schrieffer theory provides a derivation of the Ginzburg-Landau picture. It is natural to hope for a BCS analog that will explain and constrain the properties of the Higgs boson of the Weinberg-Salam

theory. This hope underlies the many ongoing investigations of dynamical symmetry breaking.

I have chosen to dwell on the conceptual incompleteness of the Weinberg-Salam theory, in order to introduce questions that ep colliders may address. However we should note that in spite of the broad phenomenological success of the theory, much remains to be verified. Details of the neutral current are yet to be explored thoroughly. Weak interactions of the heavy quarks are known schematically if at all. Finally, of course, the intermediate bosons $W^{\pm}$ and Z^0 are still to be observed.

With rather less experimental support, we have a promising theory of the strong interactions among quarks. We believe that the strong interactions among quarks have to do with the SU(3)-color charge the quarks carry. The gauge theory of interactions among SU(3) color-triplet quarks mediated by an octet of massless colored gluons is known as quantum chromodynamics, or QCD. It has the following advantages. Like the Weinberg-Salam theory for the weak and electromagnetic interactions, it incorporates observational systematics (essentially by construction). It is a gauge theory--an aesthetic plus because QED and the Weinberg-Salam theory are also gauge theories.

There are so far no experimental humiliations for QCD. In part this results from the reluctance of the theory to make definite predictions. However, for the first time in the study of the strong interactions, QCD promises that under very restrictive circumstances phenomena will be reliably calculable from first principles. This is because the strong coupling "constant" will at sufficiently short distances become small enough that perturbation theory is trustworthy. Such reliable predictions include the cross section for electron-positron annihilation into hadrons, the photon structure function, and the expectation that the interquark interaction has a limiting Coulomb-like form at short distances. The theory does not tell us how small distances must be to be small enough, so the effective value of the strong coupling constant must be measured.

With QCD and the theory of weak and electromagnetic interactions before us, it is a temptation to undertake a strategy of "grand unification." This temptation is fostered by several observations. First, it is possible that at very short distances, which is to say very high energies, all the known coupling constants become equal. A naïve extrapolation suggests that this may occur in the neighborhood of 10^{15} GeV. Second, QCD and the Weinberg-Salam theory are both gauge theories, so perhaps they may be joined. Finally, quarks and leptons are strikingly similar. The only apparent difference is that quarks have a color charge and leptons do not.

To combine these elements one may follow a straightforward, but not unique, strategy. Find a grand unifying group G that contains the individual gauge groups $SU(3)_{color} \otimes SU(2)_L \otimes U(1)_Y$ already recognized. Discern family patterns among the fermions, and assign the fermions to extended families that include both quarks and leptons. Break the symmetry down in the usual way to what is perceived at low energies.

In whatever manner this is carried out, the following consequences will result. The weak mixing angle θ_W will be fixed, if G is chosen to be a simple group. The quark and lepton charges will be related, by the act of assigning the quarks and leptons to extended families. Also necessarily, and for the same reason, there will arise new interactions that transform leptons into quarks. These might, as is well known, mediate proton decay and other exotic transitions.

Within the conceptual framework reviewed in this Section, there are three large questions that must be faced. [An overlying issue is whether the entire structure is defective. I shall assume for the rest of my talk that it is not.] The first question concerns the spectroscopy of the fundamental fermions. How many are there, and why do they have the properties they do? The second question has to do with the spectroscopy of gauge bosons or, if you like, with the identification of the gauge groups involved. As we have noted, the strategy of grand unification is not unique. Nor is it obvious that we have already recognized all the low-energy symmetries that should be gauged. These are rather basic questions at the level of field theories of the quarks and leptons. However, we don't live in a world of quarks and leptons exclusively, we live in a world populated by hadrons. There is sort of an applied science problem (the third great question) that goes along with this, which I think may be the most difficult problem of the 1980's. That is the problem of hadron structure: to understand why hadrons have the form they do, and why hadrons interact as they do. It is in the context of these three questions that I want to consider future possibilities for lepton-quark scattering.

IMMINENT NEUTRINO EXPERIMENTS

Before turning to the subject of ep colliders, I shall mention two types of neutrino experiments which I expect to yield very interesting information within the next few years. Both speak to the nature of the fermion spectrum.

The first class of experiment deals with the search for neutrino oscillations. Independent of any specific experimental motivation, our ignorance of the origin of fermion masses leaves us without any reason for neutrinos to be precisely massless. If neutrinos are massive, we have no good reason for lepton flavors not to mix as quark flavors do, since we do not understand fermion mixing in any case. The observation of neutrino oscillations would imply both nonzero neutrino mass differences and mixing of lepton flavors. Evidence for neutrino masses will shape not only our perception of the fundamental fermions but also our view of the universe at large. It makes a difference to the evolution of the universe whether or not there is a lot of mass out there hidden in neutrinos! Contrary to one's first impulse, high-energy neutrinos are well suited to a number of probing searches for oscillations.

The second topic in neutrino physics that I wish to bring up might be called a third-generation neutrino experiment both for its timing and for its subject. Two lepton generations, the electron family and the muon family, are firmly established and thoroughly studied. In addition, half of an apparent third

lepton generation is known to us: the τ-lepton.* We know the tau to be a pointlike, spin-1/2 object with a mass of 1782 MeV/c^2. If its charged current interactions are of universal strength, we expect its lifetime to be related to the muon lifetime by

$$\tau(\tau) = \tau(\mu)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{\Gamma(\tau\to e\nu\bar{\nu})}{\Gamma(\tau\to \mathrm{all})}$$

$$= 3\times10^{-13}\ \mathrm{sec.}$$

The experimental upper limit on the lifetime is currently about seven times the expected value.[1,2]

It is interesting that if the ν_τ can be shown to exist, almost everything about it is already known. We know from measurements of the electron and muon spectra in leptonic decays that the τ coupling to its neutral partner has a V-A structure, like the $e\to\nu_e$ and $\mu\to\nu_\mu$ couplings. From the same analysis, the mass of the tau-neutrino is less than about 250 MeV/c^2. With model-dependent assumptions, that limit can be reduced. It will surely be possible to improve it in future measurements of the charged lepton spectra in decays.

What is the evidence that ν_τ is distinct? First, it is easy to show that ν_τ is not identical with $\bar{\nu}_e$ or $\bar{\nu}_\mu$, because of the observed equality of leptonic decay rates, $\Gamma(\tau\to\nu_\tau e\bar{\nu}_e) = \Gamma(\tau\to\nu_\tau\mu\bar{\nu}_\mu)$. If ν_τ were identical with $\bar{\nu}_e$ or $\bar{\nu}_\mu$, these rates would differ by a factor of two. So in the absence of

*A status report on the τ, and on the search for other heavy leptons, was presented at this conference by Martin Perl, Ref. 1.

conspiratorial mixing this possibility is ruled out. The absence of any appreciable τ production in ν_μ interactions places a limit on the $\nu_\mu \to \tau$ coupling,

$$G(\nu_\mu \to \tau) \lesssim (1/40)\ G_F,$$

which is inconsistent with the bound on the τ lifetime. The remaining candidate among the previously-known neutrinos is ν_e. As statistics accumulate in neutrino beams with a finite ν_e component, that possibility too will perhaps be ruled out. For the moment, it is still a (not terribly attractive) logical alternative, I believe.

It is amusing to contemplate the possibility of a "three-neutrino experiment," an intellectual heir of the celebrated two-neutrino experiment,[3] to prove that ν_τ exists and has a separate identity. To analyze the prospects, let us assume that τ is a sequential lepton, and that ν_τ is also a sequential lepton, distinct from the known neutrino species.

The best ν_τ beam I can imagine is derived from the purely leptonic decay of the charmed-strange F-meson, $F^+ \to \tau^+\nu_\tau$. It is straightforward to estimate (by scaling from $\pi_{\mu 2}$ decay) that the leptonic decay rate is

$$\Gamma(F^+ \to \tau^+\nu_\tau) \approx 5\times10^{10}\ \mathrm{sec}^{-1}.$$

After passage through my viscera, this implies a leptonic branching ratio of perhaps 2%, give or take a factor of two.[4] The ν_τ which is a primary decay product is soft and unimportant in most geometries. However, the subsequent τ^+ decay yields a harder $\bar{\nu}_\tau$

which is the principal useful component of the exotic neutrino beam. If F^+ and F^- are produced in equal numbers, such a beam will contain equal fluxes of ν_τ and $\bar{\nu}_\tau$.

Prompt neutrino sources are favored in a beam dump mode, which is essential to enhance the ν_τ population with respect to ν_e and ν_μ. Although neither the branching ratio for $F^+ \to \tau^+\nu_\tau$ nor the F-production cross section has yet been measured, apparently conservative guesses for these parameters give rise to the expectation of a very healthy ν_τ beam at the Tevatron.[5]

Because 3×10^{-13} seconds is the expected τ-lifetime, the direct study of charged-current interactions of ν_τ becomes possible at primary energies approaching 1 TeV. That is because, as Fig. 1 will show, the taus produced in charged-current interactions live long enough in space to be identified in visible detectors. The hope is to use such detectors to verify the existence and universality of ν_τ by demonstrating that there is a distinct neutral penetrating particle which interacts weakly to produce a tau. That would complete the third generation of leptons, and would be an enormously satisfying exercise. An experiment of this kind would also be open to unexpected possibilities that the tau is coupled to a known neutrino by means of an unknown intermediate boson that produces new phenomena at the hadron vertex that have heretofore been hidden by thresholds.

To be somewhat more specific, the plan is to try to tag ν_τ interactions by observing the τ directly as a short track in a visible detector. The charge of the tau, measured from its decay products, tags the incident particle as a neutrino or antineutrino. In a plausible beam dump environment, ν_τ interactions constitute about 1% of all charged-current interactions. The event rate might even be large enough to make possible an independent measurement of the τ-lifetime.

The anticipated spectrum of outgoing taus from charged-current interactions is shown in Fig. 1 for the case of an 800 GeV primary proton beam.[6] The energy of the produced taus extends up to several hundred GeV. The typical decay path is on the order of a half centimeter or more, a distance which is child's play (more or less) for existing bubble chambers with relatively conventional optics. Evidently a modest increase in resolution--say by one order of magnitude--would be richly rewarded.

I find this type of experiment extremely attractive. It provides added incentive for the development of detectors with high spatial resolution, which I regard as one of the most important areas for innovation.

ep COLLIDER PHYSICS

With all that as prologue, I shall now turn to the subject of ep colliders. I will focus on some physics issues and refer to the talk by Mess[7] for a specific machine design. Volumes have been written on this topic: a series of CERN books,[8] the original PEP studies,[9] some POPAE documents from Fermilab,[10] the TRISTAN report,[11] and two recent proposals--CHEER from Canada,[12] and the "electron target" from Columbia.[13*] There are also some

*The University; it only seems like a country!

ISABELLE[14] and Fermilab[15] reports and a very nice but slightly dated review by Llewellyn Smith and Wiik.[16]

The principal appeal of ep colliders is their promise of extremely high energy. The total center-of-mass energy squared is simply $s = 4E_eE_p$. This relation is depicted graphically in Fig. 2 which emphasizes that for a proton energy of hundreds of GeV, a very modest investment in electron energy yields enormous (and otherwise unattainable) c.m. energies.

Some kinematical quantities are defined in Fig. 3. From the four-momenta designated there we may form the useful invariants

$$s = (\ell + p)^2,$$

$$Q^2 = -q^2 = -(\ell - \ell')^2,$$

$$\nu = q \cdot p/M_{proton},$$

$$W^2 = 2M_p\nu - Q^2,$$

and the scaling variables

$$x = Q^2/2M_p\nu,$$

$$y = \nu/\nu_{max} = Q^2/sx.$$

A collider can attain large energies; why is that interesting? The first experiment to be undertaken is evidently the measurement of total cross sections and structure functions. That is not of particular interest, in my view, if one is concerned with scaling violations and QCD tests as currently understood.

If QCD is to be the proper description of scaling violations in deep-inelastic scattering, that will have been learned from the coming generation of fixed-target experiments, long before any ep collider is operated. It is true that collider experiments have the advantage of immunity from confinement or higher twist effects, but it seems clear that with beam energies approaching 1 TeV the highly sophisticated detectors that exist at CERN and Fermilab will test QCD incisively indeed. You would not—or at least I would not—build a collider merely to measure the QCD scale parameter Λ. The point of looking at structure functions is more general; it's to look for structure.

If QCD is not only true but also the whole story, and if quarks and leptons represent the ultimate constituents of matter, structure functions may be dull and largely unchanging. If on the other hand there is something inside quarks and leptons, then structure functions may change spectacularly when the appropriate threshold or degree of resolution is reached.

A possible evolution is shown in Fig. 4. If we look at $d\sigma/dx$ with respect to an individual quark, the current situation is that the quark is pointlike so that $d\sigma/dx_1$ is proportional to $\delta(x_1-1)$. That leads to hadron structure functions of the kind we now observe. If at higher Q^2 the quark can be excited into resonant states, or shaken apart, ripples may appear in $d\sigma/dx_1$, just as they do in electron-proton cross sections in the resonance region. This causes a narrowing of the proton structure function to set in rather suddenly. Finally, far above the threshold, the quark structure functions of tomorrow will

resemble the proton structure functions of today, and the proton structure functions will be moved dramatically to smaller values of x. That would be evidence for a new level of structure, which would be a rather profound development. It seems relatively straightforward to achieve resolution of about 10^{-16} cm, which is where e^+e^- collisions can reach over the next few years. To gain an order of magnitude or more in ep colliders is challenging but by no means unthinkable.

While measuring structure functions in search of weird behavior, it is axiomatic that you do all the other conventional physics, and for the conventional reasons. This includes measuring the ratio of longitudinal to transverse cross sections in search of new phenomena, and continuing to explore the hadronic final state. The more energy carried by a jet, the richer the physics opportunities become to learn about the dressing of partons and the mechanisms for jet broadening. It is also possible that if a quark is hit harder then we have hit one before, it might be liberated. Quark confinement is at the moment an experimental, rather than theoretical, statement. [*I confess to a recurring fantasy that free quarks will be found definitively the day after one of my friends proves confinement in gauge theories. But I have a reactionary soul.*]

An electron beam is also a photon beam, as is well known, so there is the possibility of photoproducing heavy quarks and heavy leptons, and of studing photon-initiated jets. The pointlike component of the photon and the photon's relative poverty of gluons may provide important complements to the study of hadron-induced jets. Among the surprises awaiting us at larger hadron energies W may be techniquarks, technileptons, and so forth. It is foolish to presume that we can anticipate everything that will be found.

It has long been recognized that we are unable to give an explanation of baryon number conservation. Grand unified theories reëmphasize this fact by making explicit predictions for proton decay. On general grounds, then, one should be alert for leptoquark transitions in which the incident electron is transformed into a quark. This far-out possibility, as well as the more conventional ones of heavy leptons, excited electrons, and so on, argues for paying special attention to new phenomena at the lepton vertex.

Generation-changing transitions, also known as horizontal transitions, that mix the electron and tau, for example, can also be studied. If the reason such transitions have not been observed is not because they are absolutely forbidden but because they are mediated by very heavy gauge bosons, they should become relatively more prominent at high Q^2.

For both search and measurement aspects it seems to me quite important to devote some attention to polarized beams, and specifically longitudinally-polarized electron beams. I shall close by giving a few illustrations of the utility of polarized beams.

First, and just because it is there, you may combine the spin, the incoming electron direction, and the momentum of an outgoing particle to form a T-violating triple product and search

for forbidden correlations. This is again a matter of testing principles that seem sacred but lack a theoretical basis.

One may also look for evidence of right-handed charged currents in the reaction e + p → neutral lepton + anything. This complements the $p\bar{p}$ colliders. In hadron colliders, left-handed and right-handed charged W-bosons may be produced with equal efficiency. If the intermediate boson mass is sufficiently small, say less than 300 GeV/c^2, it can probably be produced and detected. It is very difficult in the $\bar{p}p$ environment to distinguish between a left-handed gauge boson and a right-handed gauge boson because both will have the same charge correlations expected[17] for the conventional case. A measurement of the ep charged-current cross section should yield no events with right-handed electrons in the standard model.[18] A right-handed gauge boson no more than four times as massive as the standard W could produce values of $\sigma_{cc}(e_R^-p)/\sigma_{cc}(e_L^-p)$ of several percent at $s \approx 10^5$ GeV^2. The total cross section is not especially sensitive to new phenomena, and greater discrimination may be obtained by measuring the energy-loss distribution $d\sigma/dy$--no easy task!

With or without polarization we may look for the effects of intermediate boson propagators more thoroughly than can be done in neutrino scattering, because of the advantages of going to higher energies, and perhaps to larger values of Q^2. Although this will presumably be done after the $W^\pm$ has been discovered in the direct channel, it would be pleasing to verify that the $W^\pm$ found in the direct channel functions as desired. One way to do so is to look for distortions of the total charged-current cross section in $e^{\pm}p$ scattering. Some expectations are shown in Fig. 5. If there were no intermediate boson, and if Bjorken scaling were perfect, the cross section would rise linearly with s. QCD scaling violations[19] modify the cross sections somewhat, but the effects are not dramatic on this scale. An intermediate boson with a mass of 85 GeV/c^2 causes a pronounced damping--by factors of two or greater at 10^5 GeV^2. Again, differential cross sections have a greater sensitivity to propagator effects than the total cross section.

As a last example, let us consider the investigation of neutral current interactions. Again, the major advantage for conventional measurements is that conferred by high energy, which also implies search possibilities. The advantage comes about because weak--electromagnetic interference effects are proportional to $Q^2/(Q^2 + M_Z^2)$. Effects that are microscopic (but measureable![20]) at SLAC become of order unity at colliders. This growth makes possible the measurement of charge asymmetries and parity violations which follow from our present understanding of the weak neutral current. One may be able to measure neutral current couplings, check by factorization the single-Z^0 hypothesis, and so on. Charge asymmetries do arise from two-photon exchange, but they are understood in principle and have a much gentler Q^2-dependence than the asymmetries due to γ-Z^0 interference.

In a theory with vector and axial vector currents, the Feynman rules for neutral current interactions are given in Fig. 6. I have written them in a helicity basis because that is

a convenience for the calculations that follow. The transcription to vector, axial vector notation is

$$L = v + a,$$
$$R = v - a.$$

In the Weinberg-Salam theory, the couplings are given by

$$L = 2I_3 - 2\, e_f\, x_W,$$
$$R = -\, 2\, e_f\, x_W,$$

where I_3 is the projection of weak isospin, e_f is the fermion charge, and $x_W = \sin^2\theta_W$ is the weak mixing parameter.

For the neutral current interactions

$$e^{\pm}p \rightarrow e^{\pm} + \text{anything},$$

mediated by the γ and Z^0 exchanges indicated in Fig. 7, all of physics (at least within the parton model) can be represented in a single formula:

$$\begin{aligned}
\frac{1}{s}\frac{d^2\sigma}{dxdy}(e^{\mp}p \rightarrow e^{\mp}X) &= \frac{4\pi\alpha^2}{Q^4}\, e_q^2(q + \bar{q})\; x\; (1-y + \frac{y^2}{2}) \\
&- \frac{2\alpha\, G_F M_Z^2\, e_q}{Q^2\, \sqrt{2}\, (Q^2 + M_Z^2)}\Big\{(L_e + R_e)\,(L_q + R_q)\,(q + \bar{q})\; x\; (1-y + \frac{y^2}{2}) \\
&\pm (L_e - R_e)\,(L_q - R_q)\,(q - \bar{q})\; x\; y(1 - \frac{y}{2})\Big\} \\
&+ \frac{1}{2\pi}\left(\frac{G_F M_Z^2}{\sqrt{2}}\right)^2 \frac{1}{(Q^2 + M_Z^2)^2}\Big\{(L_e^2 + R_e^2)\,(L_q^2 + R_q^2)\,(q + \bar{q})\; x\; (1-y + \frac{y^2}{2}) \\
&\pm (L_e^2 - R_e^2)\,(L_q^2 - R_q^2)\,(q - \bar{q})\; x\; (1 - \frac{y}{2})\Big\}.
\end{aligned}$$

The resulting parity violations and charge asymmetries are shown in Fig. 8 for representative values of the parameters: $s = 50{,}000\ \mathrm{GeV}^2$, $x_W = 0.2$, and $x = 0.3$. The ratio of $d\sigma/dxdy$ to the QED expectation shows large and characteristic deviations from unity, so observing the effects seems easily possible--given the right instrument. But before we become too euphoric at this prospect, let us notice that it will be much more difficult to understand precisely what has been observed, and to extract the coupling of the Z^0 to individual quark species. This is a challenge shared by the corresponding experiment in the timelike domain,

$$\text{hadron} + \text{hadron} \rightarrow \ell^+\ell^- + \text{anything},$$

in which important charge asymmetries are expected at high dilepton masses. In both cases, the problem is to identify the participant quark species.

I will close this discursive report by stating the obvious. Electron-proton colliders open new horizons on all three of the fundamental questions: the spectroscopy of fundamental fermions, the spectroscopy of gauge bosons, and the problem of hadron structure. In addressing these issues, the ep collider is approaching the same physics as is studied in e^+e^- and $\bar{p}p$ colliders, but in a complementary way, with emphasis on the t-channel. Each technique has its own strengths and weaknesses, which I leave you to contemplate.

In this case as for the others, physics interest is closely tied to the performance of the machine. Which of our ideas become experiments and which remain fantasies depends upon the

energy, luminosity, and degree of control over the polarization that can be attained. Both inventions and patrons would be welcome!

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CAPTIONS

Fig. 1: Secondary energy distributions for τ-leptons produced in charged-current interactions of ν_τ generated by dumping an 800 GeV proton beam.

Fig. 2: Kinematics of ep colliders. The lines are contours of the c.m. energy squared (s) corresponding to various combinations of electron and proton beam energies.

Fig. 3: Notation for ep collisions.

Fig. 4: A scenario for quark substructure and the consequences for proton structure functions. The size of the quark is denoted by r.

Fig. 5: Charged-current total cross sections for $e^{\pm}p$ scattering with "correct" helicity leptons. Predictions are shown for the parton model and QCD scaling violations in the four-fermion theory, and for the Weinberg-Salam model with scaling violations.

Fig. 6: Feynman rules for neutral current interactions.

Fig. 7: Elementary interactions governing the reactions $e^{\pm}p \rightarrow e^{\pm}$ + anything.

Fig. 8: Effects of γ-Z interference in longitudinally-polarized $e^{\pm}p$ scattering in the Weinberg-Salam model.

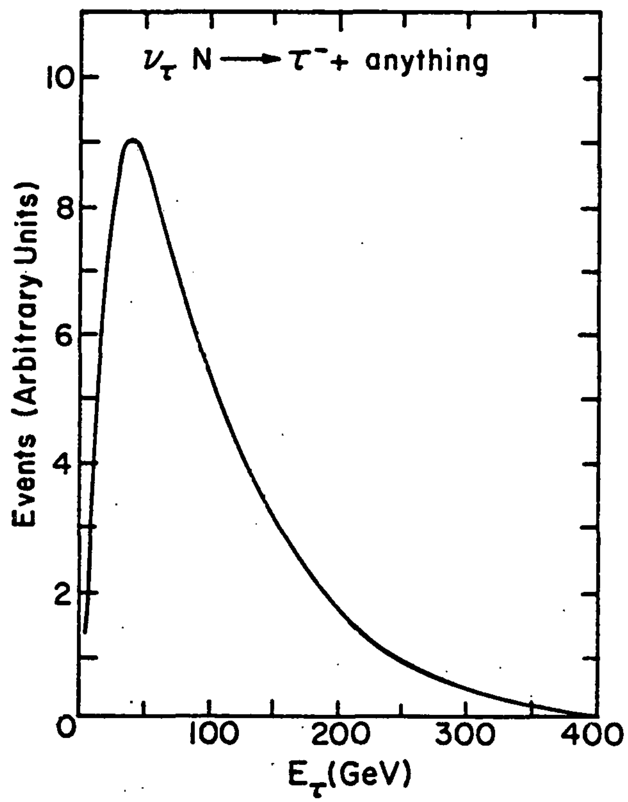
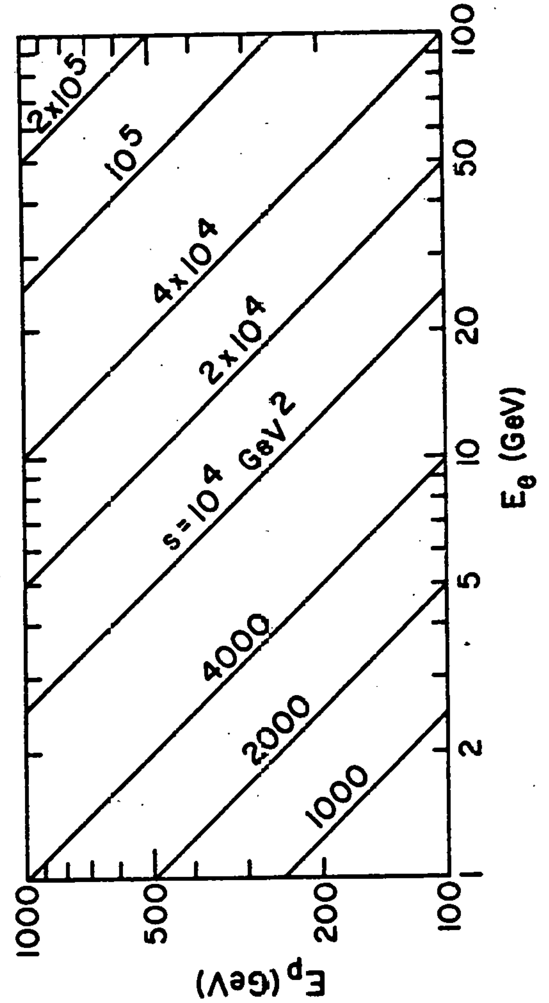
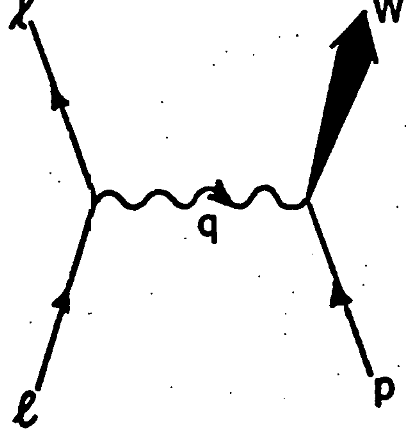


Fig. 1



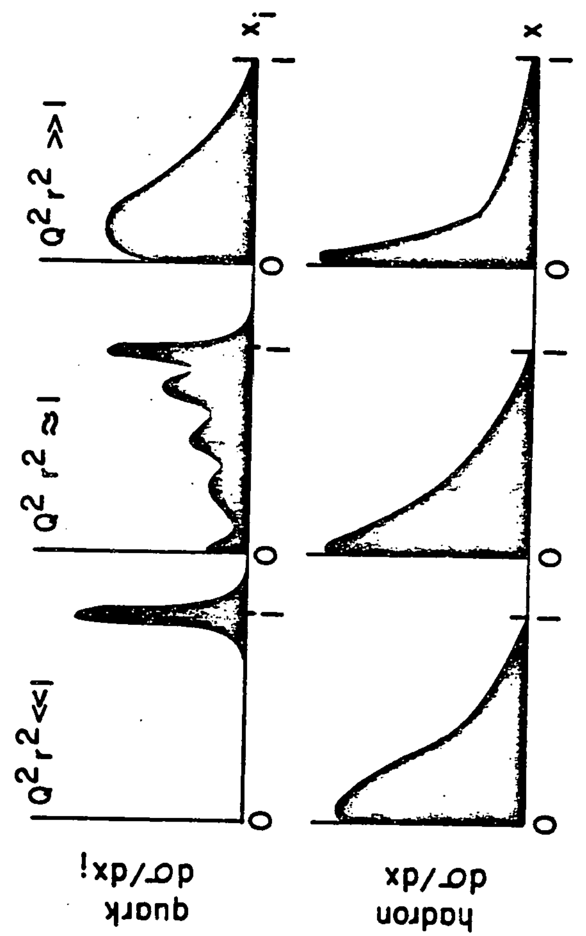
E_e (GeV)
1
2
5
10
20
50
100
E_p (GeV)
1000
500
200
100
2×10^5
10^5
4×10^4
2×10^4
$s=10^4$ GeV^2
4000
2000
1000

Fig. 2



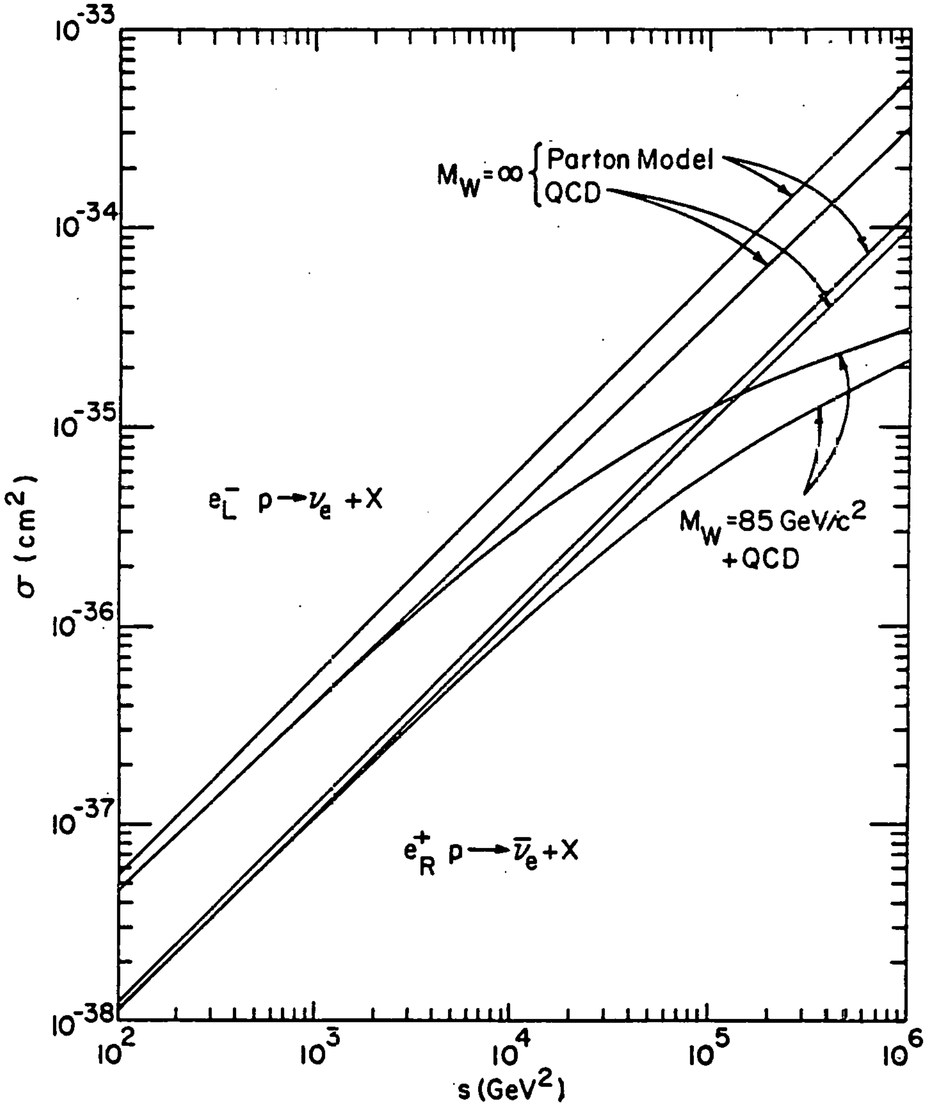
ℓ'
W
q
ℓ
p

Fig. 3



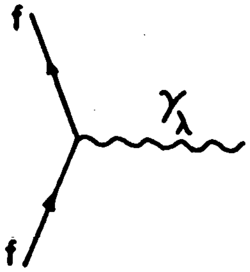
quark dσ/dx_i
hadron dσ/dx
Q²r² << 1
Q²r² ≳ 1
Q²r² >> 1
x_i
x

Fig. 4

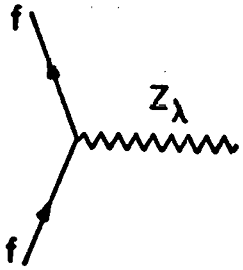


M_W = ∞ { Parton Model
QCD
M_W = 85 GeV/c²
+ QCD
e⁻_L p → ν_e + X
e⁺_R p → ν̄_e + X
σ (cm²)
s (GeV²)

Fig. 5



$$= i\, e_f\, \bar{f} \gamma_\lambda f$$



$$= \frac{-i}{\sqrt{2}} \left(\frac{G_F M_Z^2}{\sqrt{2}} \right)^{\frac{1}{2}} \bar{f} \left\{ L \gamma_\lambda (1-\gamma_5) + R \gamma_\lambda (1+\gamma_5) \right\} f$$

Fig. 6

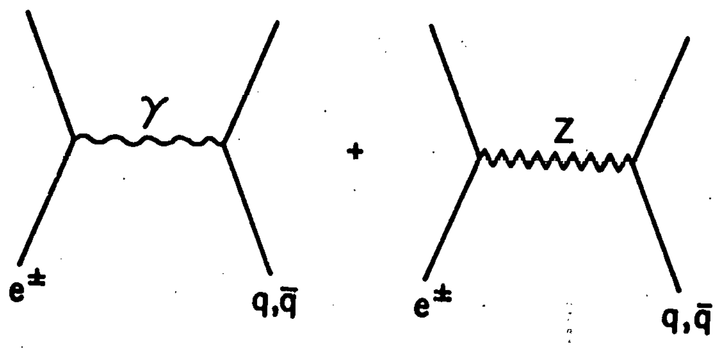
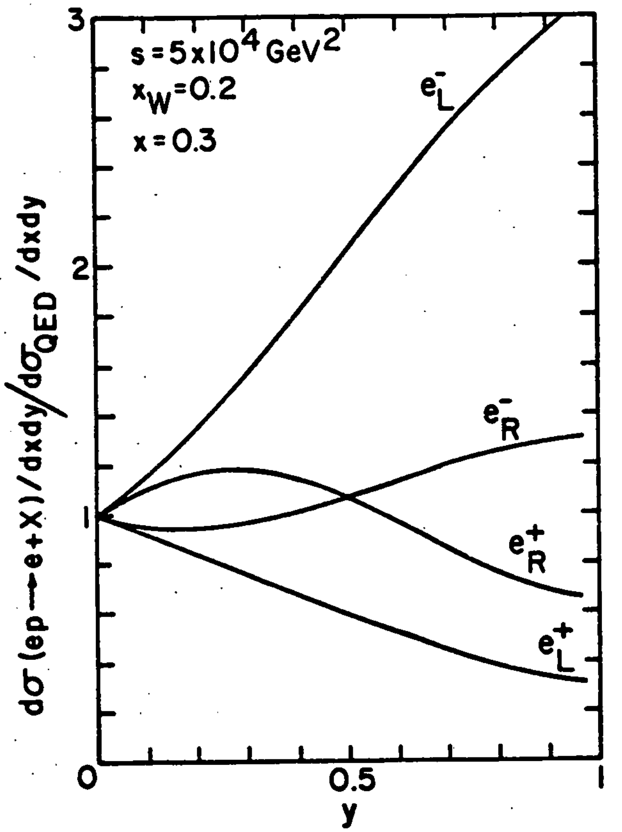


Fig. 7



s=5x10^4 GeV^2
x_W=0.2
x=0.3
e_L^-
e_R^-
e_R^+
e_L^+
dσ(ep→e+X)/dxdy/dσ_QED/dxdy
y
0
0.5
1
2
3

Fig. 8