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THEORY OF ELECTRON-POSITRON ANNIHILATION INTO HADRONS*

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I. INTRODUCTION

In the incredible year that has just passed a new world of physics has come into being with electron-positron annihilation its principal gateway. Part way through, I thought that between the searches for monoenergetic gamma rays, measurements of the total cross section and final states, and searches for charmed particles, everything would break in the Spring.

Nature was more subtle and is probably richer than many of us thought. But since May and June, when the spectroscopy started to fill in, I've been optimistic again. Major developments have been coming so fast since then that this is the first time I remember some of my experimentalist friends telling me several weeks before a conference that they had analyzed some particular aspect of recently acquired data and luckily had found nothing surprising.

Maybe we are beginning to see some of the pieces fall together. Rather remarkably, the emerging picture still fits well into the general framework of theoretical proposals made a number of years ago involving ideas such as quarks, scaling and the parton model, charm, heavy leptons, ... What is so amazing is that it's all there in a comparatively narrow energy interval and has all burst upon us in a short time span.

We shall first consider the total cross section for $e^+e^- \to$ hadrons and R, its ratio to the muon pair cross section. After some general considerations we examine the physics found below, and then above, the "threshold" near 4 GeV in center-of-mass energy. We shall pay particular attention to what is changing there and exactly where it happens. Then we shall turn to inclusive distributions and jets of final state hadrons. As we know, there have been major developments in every one of these areas – changes such that the experimental situation and the concomitant theoretical outlook are opposite to what was held to be the case only one year ago.

II. THE TOTAL CROSS SECTION AND SCALING: GENERAL CONSIDERATIONS

We shall be considering electron-positron annihilation through a single timelike photon[1] with four-momentum squared, $Q^2 > 0$. The total cross section for electron-positron annihilation into hadrons is proportional to the vacuum expectation value of the product of two electromagnetic currents:

$$(q^2\delta_{\mu\nu} - q_\mu q_\nu)\sigma_{total}(e^+e^- \to \text{hadrons}) \propto \int d^4x e^{-iq\cdot x} < 0|J_\mu(x)J_\nu(0)|0> . \tag{1}$$

As $Q^2 = -q^2 \to \infty$, the behavior of σ_{total} is controlled by the leading light cone ($x^2 = 0$) singularity[2] in the operator product $J_\mu(x)J_\nu(0)$. If this singularity is characterized by having no anomalous dimension, then as $Q^2 \to \infty$ we have the scaling law:

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† Dedicated to the memory of my grandmother, Becky Furstencel Goldberg (February 1, 1885 - August 28, 1975).

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$$\sigma_{\text{total}} \propto \sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3Q^2} \;. \tag{2}$$

The constant of proportionality, called

$$R \equiv \sigma_{\text{total}}(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$$

is calculable in certain cases. In a parton model, i.e., free field theory for calculating R, one has asymptotically[3]

$$R = \sum_i Q_i^2 \tag{3}$$

where i runs over the fundamental fermions in the theory and Q_i is their charge in units of e. If one is dealing with an asymptotically free gauge theory,[4] then the next leading term as $Q^2 \to \infty$ is determined as well:[5]

$$R = \sum_i Q_i^2 \,[1 + b/\ln(Q^2/\mu^2) + \ldots] \;, \tag{4}$$

where the constant b is positive and known in a particular theory, but the parameter μ is a priori free.

Technically, the predictions in asymptotically free gauge theories (or, more generally, predictions using field theoretic arguments involving the renormalization group) are made on the hadronic vacuum polarization tensor, $\Pi(Q^2)$ in the spacelike region ($Q^2 < 0$). These are then related to the timelike region using analyticity properties, which are succinctly expressed in terms of the dispersion relation,

$$\Pi(Q^2) = \frac{Q^2}{\pi} \int_{4m_\pi^2}^{\infty} \frac{dQ'^2}{Q'^2} \, \frac{\text{Im}\,\Pi(Q'^2)}{Q'^2 - Q^2 - i\epsilon} \;, \tag{5}$$

where

$$\text{Im}\,\Pi(Q^2) = \frac{Q^2}{32\pi\alpha^2}\, \sigma_{\text{total}}(e^+e^- \to \text{hadrons}) \,. \tag{6}$$

Work in the past year[6,7,8] has served to tighten up considerably the mathematics of the constraints imposed on the timelike region by particular behaviors favored theoretically on the spacelike side. Still, one outcome of these careful mathematical investigations is that smooth behavior on the spacelike side, such as that which one wishes to relate to the timelike behavior found in Eq. (3) or (4), does not prevent infinitely many oscillations in the timelike region about the desired smooth behavior.

A number of more practical calculations have also been carried out.[9,10,11] In particular, by noting[9] that ($Q^2 > 0$)

$$\Pi'(-Q^2) = \frac{1}{\pi} \int_{4m_\pi^2}^{\infty} \frac{dQ'^2 \, \mathrm{Im}\, \Pi(Q'^2)}{(Q'^2 + Q^2)^2} \quad , \tag{7}$$

it is seen that using data for the positive quantity $\mathrm{Im}\,\Pi(Q'^2)$ up to Q'^2_{max} gives a lower bound on $\Pi'(-Q^2)$ evaluated at the spacelike point, $-Q^2 < 0$. Although the dispersion relation prevents[12] the onset of scaling behavior from occurring in the spacelike and timelike regions at radically different values of $|Q^2|$, one possibility[11] which emerges from such calculations is that $\Pi'(-Q^2)$ can be smaller at the spacelike point, $-Q^2$, than is the analogous quantity, which is proportional to σ_{total}, at $+Q^2$ on the timelike side. Therefore, if your gauge theory predicts a value of R or equivalently σ_{total} which is smaller than the present data at $Q^2 = +|Q^2|$, take heart – perhaps in the spacelike region where your prediction is really made $\Pi'(Q^2)$ at $Q^2 = -|Q^2|$ is smaller and nearer to your theoretical value. On the other hand, if your favorite theory gives a value of R which is larger than is given by present data, just remember experiment – aside from the high energy side of some well-known resonances, R has never gone down as Q^2 has increased.

III. R AND THE THRESHOLD NEAR 4 GeV

Before taking up the exciting discoveries at higher energy, it is very much worth recalling, if only for comparison of the pattern,[13] what happens below $\sqrt{Q^2} \simeq 3.5$ GeV. First, one has the ρ, ω, and ϕ resonance bumps. Some beautiful new work on the ϕ decay modes from Orsay has been reported to this conference.[14] A scan for narrow resonances from 770 to 1340 MeV finds no other states.[15]

Somewhere between 0.9 and 1.0 GeV, nonresonant multihadron production starts. There is the possibility of another bump in the 1.2 GeV - 1.3 GeV region,[16] but further work needs to be done on this potential ρ'. In addition, if we have learned something from the success of the quark model in spectroscopy either this year or in past years, one can not have just a ρ': its quark model relatives ω', ϕ', $K^{*\prime}$, π', etc., should be there as well. If they are not yet observed, then one must have a good excuse for their temporary absence from the roster of experimentally established states.

On much solider footing is the $\rho'(1600)$, although even here the present measurements of $\sigma_{total}(e^+e^- \to \text{hadrons})$ show much less convincing evidence[17] of a bump than does the channel cross section for $e^+e^- \to 2\pi^+2\pi^-$. Again, it is imperative that ω' and ϕ' states exist nearby in mass. The $\omega(1675)$, which is sometimes used as a candidate for the ω', should not be – its spin-parity is established[18] as 3^- and it is therefore an SU(3) partner of the g meson.

Somewhere in this region also is the effective strange particle threshold. Especially in light of what we will discuss later regarding charmed particle threshold, it would be extremely interesting to know something about the energy dependence of inclusive K meson production and its relation to the ϕ, ϕ', etc. Unfortunately, detailed information of this kind is presently lacking, as are limits on any thresholds in R in this energy range. We do know from a scan at Frascati[14] that there are no narrow resonances between 1910 and 2545 MeV and between 2970 and 3090 MeV. Searches[19] involving photoproduction of lepton pairs also put rather tight limits on narrow vector states below the ψ.

For $2.4 \leq \sqrt{Q^2} \leq 3.4$ GeV, measurements[20] from SPEAR give $R \simeq 2.5$. This is certainly consistent,[21] given experimental error bars and the theoretical possibility of an approach to a constant value of R from above,[5] with the value

$$R = \sum_i Q_i^2 = 3\left(\frac{4}{9} + \frac{1}{9} + \frac{1}{9}\right) = 2 \qquad (8)$$

predicted from the usual Gell-Mann and Zweig quarks, u, d, and s, each coming in three colors.

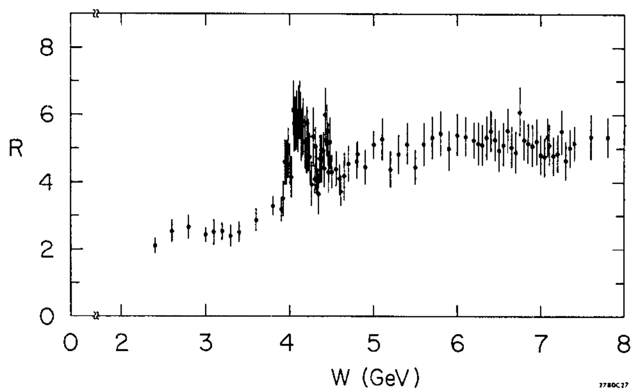

Fig. 1--$R = \sigma_{total}(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ from measurements at SPEAR.[22] $W = \sqrt{Q^2}$.

These measurements are included in Figure 1, which shows[22] R from $\sqrt{Q^2}$ = 2.4 to 7.8 GeV, i.e., $Q^2 \simeq 6$ to 60 GeV^2. After the two narrow resonances, $\psi(3.1)$ and $\psi'(3.7)$ (which are not shown), there are broad structures, $\psi''(4.1)$ and $\psi'''(4.4)$, sitting on a rising value of R. Given the ψ'' and ψ''', it would be surprising if there were not broader structures yet to be established above them in energy. My eye, and a secret theoretical formula, say that 4.7 to 4.8 GeV and 5.0 to 5.1 GeV are likely places to investigate. No narrow resonances other than the ψ and ψ' are found in a scan up to the highest SPEAR energies.[22]

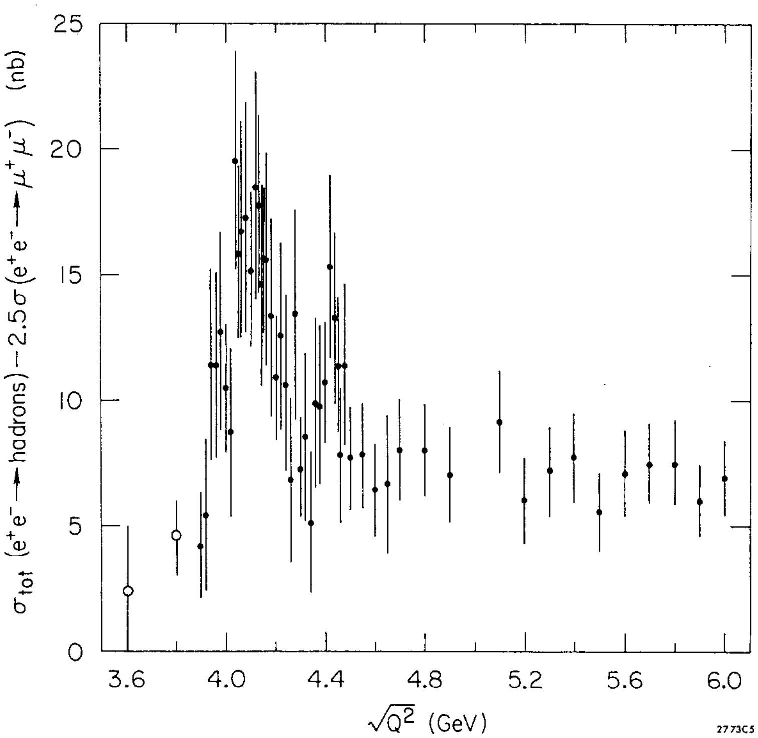

Fig. 2--The cross section for new physics, $\sigma_{total}(e^+e^- \rightarrow \text{hadrons}) - 2.5\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ from SPEAR I (open circles)[20] and SPEAR II (closed circles) data.[22]

The situation is shown in a little more detail in Fig. 2, where $\sigma_{total}(e^+e^- \rightarrow \text{hadrons}) - 2.5\ \sigma(e^+e^- \rightarrow \mu^+\mu^-)$, i.e., the cross section for new physics is shown from SPEAR data.[20,22] The relative narrowness of the ψ''' by itself raises the question of why the lower mass bump at 4.1 GeV is wider. Depending on the amount of imagination which one shows in looking at the present data, one can envisage many different possibilities. While I think it is likely that the $\psi''(4.1)$ is not a single simple object, only further experiments will settle this question.

R is still rising somewhat through the 5 GeV region. However it seems to have leveled off at another constant value of five, or perhaps slightly higher, at the maximum SPEAR energies.

We shall assume in the remainder of this talk that the observation of approximate constancy of R both below ≈ 3.5 GeV and above ≈ 5 GeV is not an accident, but a consequence of the theory discussed in Section II being applicable at nonasymptotic values of Q^2. Then the value of $R(Q^2)$ reflects the sum of the squares of the charges of the operative fundamental fermions in the world, and $R(Q^2)$ becomes the basic measurement of hadron physics by revealing the number and the charges of their quark constituents.

At present, a charged heavy lepton, i.e., its decay products, would be counted in what we have taken as $\sigma_{total}(e^+e^- \rightarrow \text{hadrons})$ from SPEAR. If such a lepton exists, it would be directly pair-produced with a known cross section,

$$\sigma(e^+e^- \rightarrow L^+L^-) = \left(\frac{4\pi\alpha^2}{3Q^2}\right)\left(1 + \frac{2M_L^2}{Q^2}\right)\left(1 - \frac{4M_L^2}{Q^2}\right)^{\frac{1}{2}} . \tag{9}$$

If we restrict quarks to have charges $-1/3$ or $2/3$ and to come in three colors, and leptons to have charges 0 or ± 1, then the SPEAR data at the largest Q^2 values demands[23] that more than one new fundamental fermion becomes operative above $\sqrt{Q^2} \simeq 3.5$ GeV. Examining Fig. 2 again, the apparent "threshold" for at least one such fermion lies below $\sqrt{Q^2} = 4.0$ GeV. The existence and hadronic nature of the ψ, ψ', ψ'', ψ''', ..., together with their apparent association with the threshold immediately leads one to require at least one of the fermions to be a new quark. We now explicitly restrict our attention to the case where the new quark or quarks carry a new additive quantum number.[24] We shall use charm[25] as a generic name for this quantum number without commitment to the specific scheme which grew out of curing certain difficulties in the theory of weak interactions of hadrons.[26] When we are dealing with one or more new quarks, unlike a heavy lepton they would be indirectly pair-produced, appearing in the final state in combination with the u, d, and s quarks (and antiquarks) as hadrons carrying the new quantum number.

Let us then examine in more detail what is known about the behavior of other characteristics of the final state near the threshold in R, with an eye as to what is the mechanism causing it.

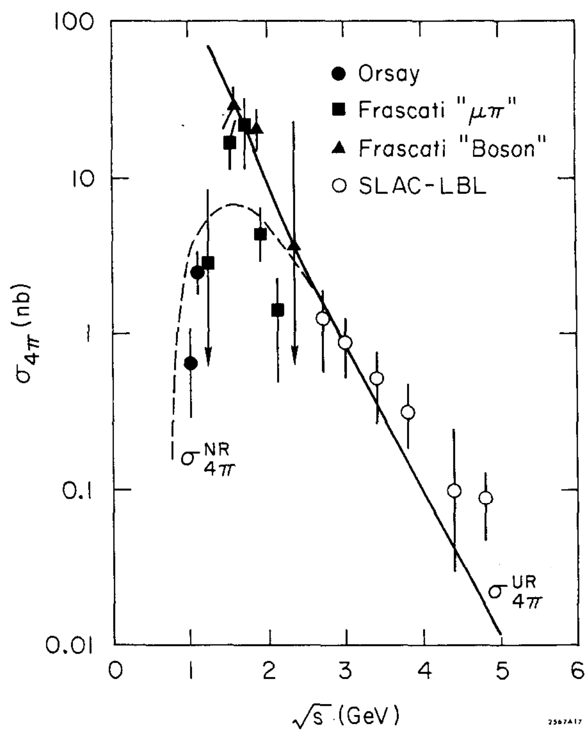

Fig. 3--The cross section[27] for the exclusive channel $e^+e^- \rightarrow 4\pi^\pm$ as a function of $\sqrt{s} = \sqrt{Q^2}$.

A. Exclusive Channels

First consider channels like $4\pi^\pm$ and $6\pi^\pm$, presumably composed of u, $\bar{u}$, d, and $\bar{d}$ quarks, which occur both above and below the rise in R. Figures 3 and 4, from the

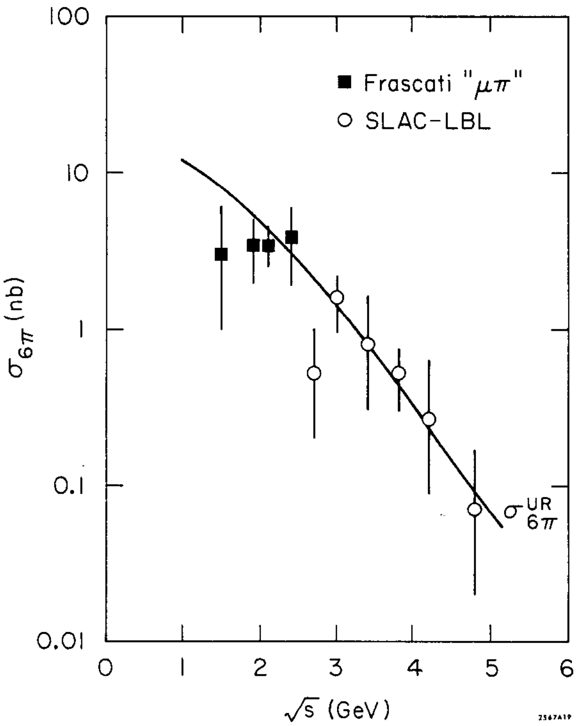

Fig. 4--The cross section[27] for the exclusive channel $e^+e^- \rightarrow 6\pi^\pm$ as a function of $\sqrt{s} = \sqrt{Q^2}$.

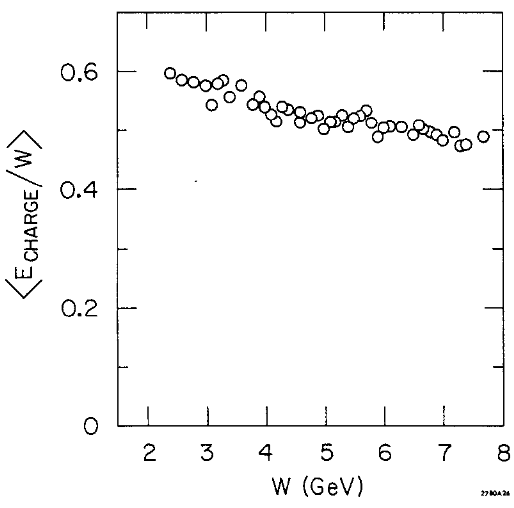

Fig. 5--The proportion of center-of-mass energy $W = \sqrt{Q^2}$ which is carried by charged particles (assumed to be pions).[22]

London Conference,[27] show that there is no apparent disturbance in these cross sections in passing through the 4 GeV region. With the much better data now available, much more accurate statements can be made on these and other exclusive channels in the near future.

B. Inclusive ψ Production

It is natural to ask if the rise in R is caused by production of states whose decay products include ψ's. While it is clear that ψ's are not common[28] in the final state at SPEAR II, detailed limits have not yet been given. Nevertheless, the possibility that a new quark and its antiquark occur in the final state mostly when bound together in a ψ or states which decay into ψ's is ruled out.

C. Particle Ratios

Another aspect of the data that fails to change dramatically on passing through the 4 GeV region is the ratio of π's to K's to p's or the number of each type of particle per event.[29] This is reaffirmed by the measurements at 4.1 GeV presented to this conference from DORIS.[30]

D. Energy in Charged Particles

Somewhat more problematical is the proportion of the center-of-mass energy found in charged particles, as shown[22] in Fig. 5. While a change in character is possible just below 4 GeV, it is not required. Independent of whether an abrupt change occurs, there is definitely a drop in the proportion of energy carried by charged particles as one moves from 3 to 5 GeV.

E. Energy per Charged Track

More definite evidence of structure is seen in Fig. 6, showing the mean energy per charged track.[22] This quantity does seem to flatten out just below 4 GeV and then rise again. If one assumes that both neutral and charged particles have the same mean energy, then $\sqrt{Q^2}/\langle E_{track} \rangle$ gives the total multiplicity. The structure in $\langle E_{track} \rangle$ then has the consequence that the total multiplicity makes a step upward in this region.

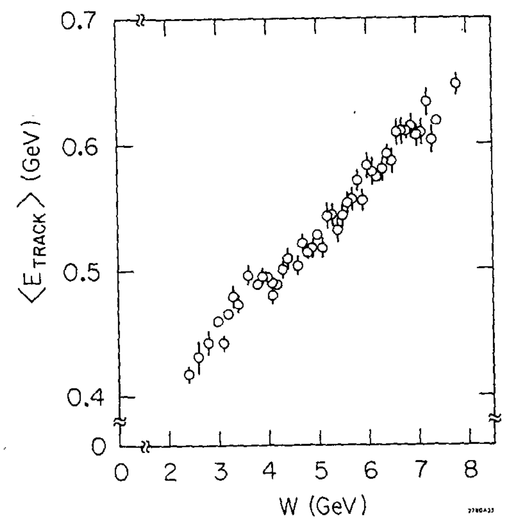

Fig. 6--Observed average energy per charged track[22] (not corrected for acceptance) as a function of $W = \sqrt{Q^2}$.

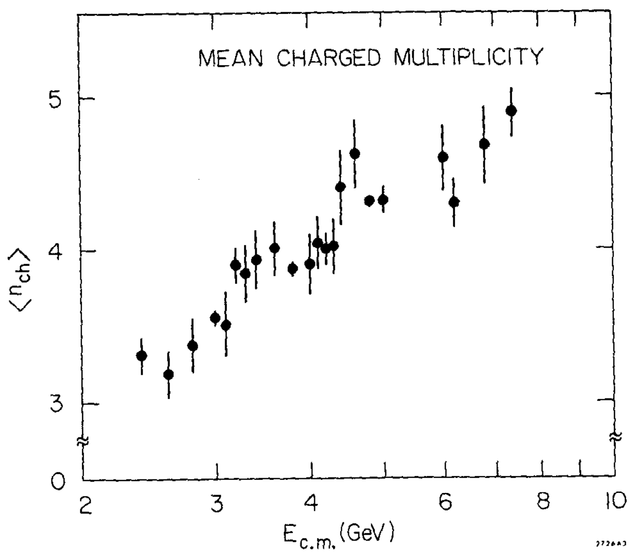

Fig. 7--Charged particle multiplicity[22] as a function of $E_{c.m.} = \sqrt{Q^2}$.

F. Charged Particle Multiplicity

On the other hand, the charged multiplicity, shown in Figure 7, indicates no corresponding jump. If anything, there is a flat region around 4 GeV, which is both preceded and followed by a rise with increasing Q^2. Consequently, if the assumption about charged and neutral particles having the same average energy is correct, it is the neutral particles that exhibit a step upward near the threshold in R.

G. Inclusive Distributions

One thing which does change, and in a very interesting manner, in passing through the threshold in R is the inclusive distribution for charged particles. Defining the dimensionless variable $\bar{\omega} = E_{hadron}/E_{beam} = 2E_{hadron}/\sqrt{Q^2}$, which lies between 0 and 1, we consider[31] $(d\sigma/d\bar{\omega})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) \propto Q^2 d\sigma/d\bar{\omega}$. This distribution for charged particles[22] at $\sqrt{Q^2} = 3.0$, 3.8, 4.0 - 4.4, and 4.8 GeV is shown in Figure 8. We note that the data immediately above the threshold, around the 4.1 GeV bump, look very much like those at the still higher energy of 4.8 GeV, and both are substantially different from the data at 3.0 GeV, which is where R is still ≈ 2.5. On closer examination there is some evidence of a "bulge" in the 4.0 - 4.4 GeV distribution compared to the

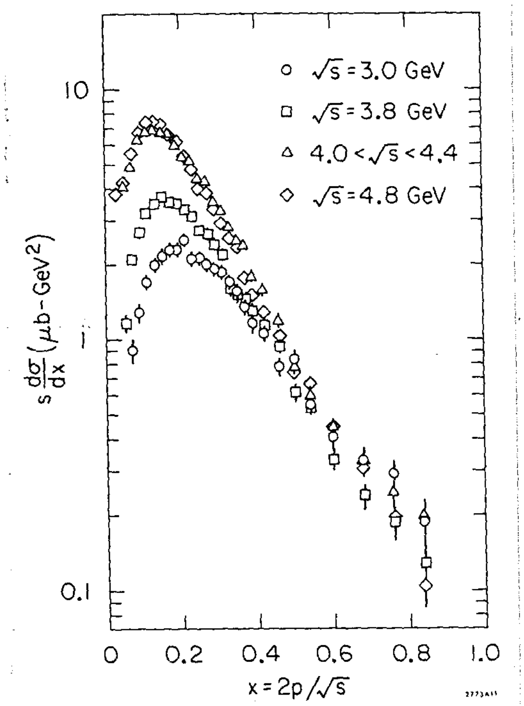

Fig. 8--Inclusive distributions[22] of charged hadrons for $\sqrt{s} = \sqrt{Q^2} = 3.0$, 3.8, 4.0 - 4.4, and 4.8 GeV. The variable $x = 2p/\sqrt{s} \rightarrow \bar{\omega} = E_{hadron}/E_{beam}$ for relativistic particles, and correspondingly $s\, d\sigma/dx \rightarrow Q^2 d\sigma/d\bar{\omega}$.

4.8 GeV distribution, something which deserves further experimental investigation. Note that almost all the change in the inclusive distribution on crossing the threshold occurs below $\bar{\omega} \simeq 0.5$. As pointed out previously,[13] if the inclusive distribution associated with a given value of R scales,[31] then the physics resulting in the new addition to R is associated with an inclusive distribution which lies almost completely below $\bar{\omega} = 0.5$. A natural explanation of such a phenomenon, as emphasized by Harari,[32] is that at the threshold pairs of equal mass particles are being produced at rest, the decay products of which can at most (for two-body decay) have an energy of $E_{beam}/2$, i.e., $\bar{\omega} = 0.5$.

H. The μe Events

The most obviously new and unexpected physics which comes in at or near the threshold are the $\mu^{\pm}e^{\mp}$ events.[33] From the observed cross section,[33,34] shown in Figure 9, these events begin to appear at or below $\simeq$ 4 GeV. Inasmuch as no conventional explanation is consistent with the data, we are led to consider whether the decays of charmed particles, in particular charmed mesons which we call generically D's, or the decays of pair-produced heavy leptons are responsible for these events.

The data, together with some theoretical considerations, favor the heavy lepton hypothesis for the following reasons:

(i) If these events, which contain two charged tracks and no observed neutrals, are to be explained as purely leptonic decays[35] of pair-produced charmed particles, i.e., $e^+e^- \to D^+D^-$, $D^- \to \ell^-\bar{\nu}_\ell$, $D^+ \to \ell^+\nu_\ell$, then the lowest mass such particle must be a vector meson (D^*) rather than the expected pseudoscalar (D). This is because $D \to e\nu$ and $D \to \mu\nu$ are suppressed by m_e^2 and m_μ^2, respectively, if the D has spin zero. Given that $m_\pi < m_\rho$, $m_K < m_{K^*}$, and from what we learned at this conference,[30] probably $m_{\eta_c} < m_\psi$, it seems very likely $m_D < m_{D^*}$. But it is still possible to argue the opposite,[36] and it will probably continue to be so until charmed particles are found.

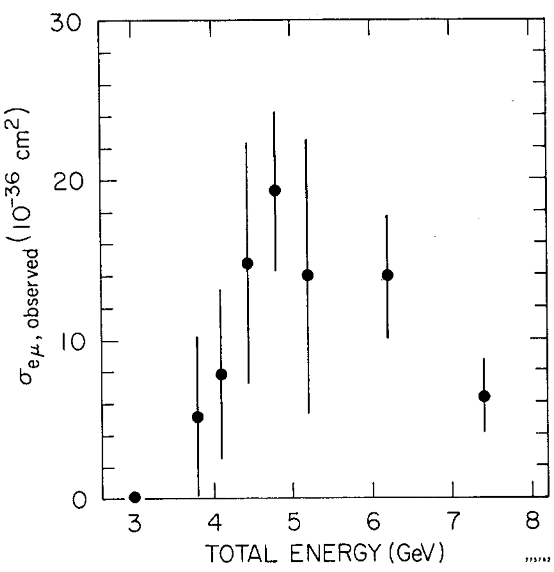

Fig. 9--The observed cross section[33] for $\mu^{\pm}e^{\mp}$ events (with momentum and acceptance cuts) as a function of $\sqrt{Q^2} \equiv$ Total Energy.

(ii) One expects naively that the rate for purely leptonic and semileptonic decays of charmed particles would only be a small fraction of the nonleptonic decay rate.[37] It is only the decays involving leptons from <u>both</u> charmed particles that would be candidates for explaining the μe events (assuming the associated hadrons in semileptonic decays sometimes escape detection) - something which is proportional to the square of the presumably small branching ratio for decays involving leptons. In this view, there would be too many μe events seen! But, it is possible to argue on a reasonable basis[38] that leptonic and semileptonic decays of charmed particles are a good fraction of the total decays, basically because nonleptonic decays may not be enhanced in the same way as for strange particle decays.

(iii) An important restriction comes from the strong experimental favoring[34] of pairs of three-body decays (such as $L \to \ell\bar{\nu}_\ell \nu_L$) over pairs of two-body decays (such as $D^* \to \ell\bar{\nu}_\ell$) in producing the μe events. This, together with point (i) would seem to eliminate the possibility that $e^+e^- \to D\bar{D}$ or $e^+e^- \to D^*\bar{D}^*$, followed by purely leptonic decays, provides a satisfactory explanation.

(iv) The energy dependence of the observed cross section in Fig. 9 at large Q^2 is consistent with falling as $1/Q^2$, as $e^+e^- \to L^+L^-$ should. It is difficult to see why the exclusive hadronic channel $e^+e^- \to D\bar{D}$ would not fall off much faster. The inclusive process $e^+e^- \to D\bar{D} + \pi$'s + K's probably should fall as $1/Q^2$, but we recall that the μe events in question have no observed accompanying charged or neutral particles. But it is still possible to argue that[34] production of the exclusive channel $D\bar{D}$, with an energy dependence like $\beta^3/(Q^2)^3$ is not a very poor fit to the data, and that the statistics are limited. However, one still needs a sizable semileptonic branching ratio of the D, and then inclusive D production faces the stringent limits placed by the muon tower[34] on the process $e^+e^- \to \mu$ + anything.[39] Only if the lepton spectrum from $D \to \ell\bar{\nu}_\ell$ + hadrons is rather "soft" might one avoid this by the μ falling below the 0.9 GeV/c momentum cut for the muon tower.

(v) A comparison of the peaks in the cross section for "new physics" in Fig. 2 with the observed μe cross section in Figure 9 shows clear disagreement.[40] Since the width of the ψ'' and ψ''' is understood precisely because of the possibility of decay into charmed particles, this is another piece of evidence against charmed particles being the source of μe events. But here one can object on grounds of binning (the values of $\sigma_{\mu,e,\text{observed}}$ at 4.1 and 4.4 GeV are actually over the range 3.9 - 4.3 and 4.3 - 4.8 GeV), limited statistics, and reduced acceptance near the threshold compared to higher Q^2 (unless one insists on two-body decays, which were ruled out in points (i) and (iii)).

Even taken together, I still would not say that the evidence is completely decisive. However if the choice is only between heavy lepton or charmed particle decays causing the μe events, then at each turn we are pushed toward a heavy lepton as the source. Furthermore, all the data at the present time are consistent[34] with a heavy lepton with a mass between 1.6 and 2.0 GeV.

What is so incredible to me is that before I was born a search was launched for another theoretically predicted meson, the pion. Instead, in the predicted mass range a heavy lepton, the muon, was found and caused considerable confusion with the pion over many years. Finally, the pion itself was found at a somewhat higher mass, so that it decayed into the muon. In spite of what logic and the data tell me, it is difficult to believe that we might be privileged to be living through an analogous period in the history of physics.

* * *

We are now ready to examine the question of exactly where is the threshold. Connected with this is the question of what the first threshold is for, particularly if we have both a heavy lepton, with the threshold being that for $e^+e^- \to L^+L^-$, and a new quark, with the associated threshold being that for $e^+e^- \to D\bar{D}$. Connecting the broad $\psi''(4.1)$ with the existence of decays into charmed particles already forces $M_D \lesssim 2$ GeV and the "charm" threshold below about 4 GeV.

It is convenient to use the narrow $\psi'(3.7)$ as a division between two major possibilities. If the threshold in R occurs more than a few MeV below $M_{\psi'}$, then the first threshold must be that for producing heavy leptons; for if it was charm threshold we would expect $\psi' \to D\bar{D}$ and a width of the ψ' at least an order of magnitude larger than observed. Ignoring error bars, the combined SPEAR data[20,22,41] shown in Figure 10 suggest that R may begin to rise between 3.4 and 3.6 GeV. If we assume R = 2.5 below the threshold and add the contribution to R coming from a heavy lepton with a mass of 1.75 GeV, we obtain the curve shown in Figure 10. It is quite consistent with the data up to $\sqrt{Q^2} \simeq 3.9$ GeV, at which point one needs to have $D\bar{D}$ threshold in order to get the further increase in R and the wide resonance or resonances in the 4 GeV region.[42] While the mass of the lepton could be pushed somewhat higher with no loss in fitting the data, everything presently known about the μe events and about R is consistent with a heavy lepton threshold as low as 3.5 GeV. The importance of further experimental work in this region is obvious.

On the other hand, given the error bars on the R data, the threshold might well lie above $M_{\psi'}$. In this case the $D\bar{D}$ ("charm") threshold could come first, but then the source of the μe events, whatever it is, must have a threshold quite close by.

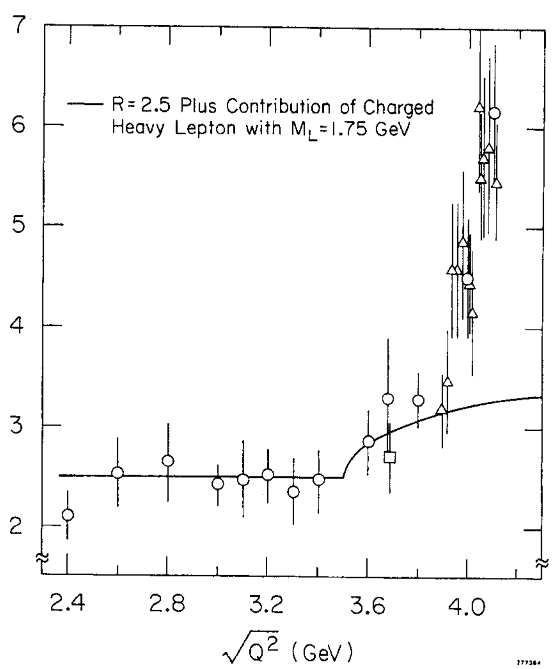

Fig. 10--Measurements of R near the threshold from SPEAR I[20] (open circles), SPEAR II[22] (triangles), and data[41] just below (open circle) and at (square) the ψ'.

If both charmed particles and a heavy lepton have thresholds nearby to one another, then all the conventional tests for, or constraints on, the presence of charmed particles decaying weakly, like changes in the K to π ratio, charged multiplicity, or energy in neutrals, are made much less discerning since the heavy lepton and charmed particles can have compensating effects on these quantities.[43] For example, in a recent paper[44] a detailed calculation of heavy lepton decays is made ($L \to \mu\bar{\nu}_\mu \nu_L$, $L \to e\bar{\nu}_e \nu_L$, $L \to$ hadrons + ν_L) with the result that $E_{charged}/E_{total} \simeq 0.38$ for heavy lepton decays. This is to be compared to ≈ 0.6 for the corresponding quantity for $e^+e^- \to$ hadrons below the threshold, so that the pair production of such leptons would result in a drop in $\langle E_{charged} \rangle/\sqrt{Q^2}$ similar[44] to that observed experimentally.

Even excluding the possible existence of $e^+e^- \to L^+L^-$, the structure in R in the 3.5 to 6 GeV region looks like it will keep both experimentalists and theorists busy for years. The general structure of this region - narrow spikes followed by broad enhancements - was anticipated before the experiments by the theoretical work of Appelquist and Politzer.[45]

However, except for some heady days in November, the possibility that the physics in this region is governed by the coulomb potential due to single colored gluon exchange (between a charmed quark and antiquark at short distances where, à la asymptotic freedom,[4] the coupling is weak) has been discarded. It was quickly realized by many people that the long range forces, which presumably bind quarks and correspond to the infrared region ("infrared slavery") in asymptotically free gauge theories, play a very important role near the threshold.

Moving a step back from trying to do a fundamental gauge theory calculation, a number of authors[46] have tried more phenomenological calculations employing a quark confining linear potential, possibly with an additional Coulomb piece, to calculate the ψ spectrum and leptonic decay rates. These calculations are at least self-consistent in that the charmed quarks turn out to have a high mass (1.5 - 2 GeV) and move non-relativistically, with the most important aspects of the results being governed by the quark-confining (linear) part of the potential.

Above $D\bar{D}$ threshold, the resonances are no longer narrow and they pick up a continuum component in their wave function. One may still do a sort of perturbative calculation about the previous (narrow resonance) results, assuming that the heavy, charmed quark part of the wave function remains at shorter distances and is still nonrelativistic, while the much lighter $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ pairs may be pulled from the vacuum at larger distances to form the $D\bar{D}$ part of the wave function.[47] Several more recent papers[48,49] do variants of such a calculation, with the resulting prediction for R from one of them[48] shown in Figure 11. All predict a rather broad enhancement near 4.1 GeV, followed by even broader, less prominent, bumps at higher energies.

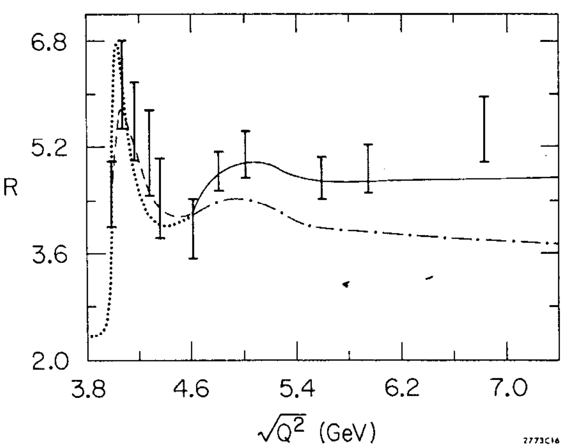

Fig. 11--Predicted values[48] of R in the continuum region above the threshold assuming a charmed quark and antiquark bound in two different potentials (dotted and dashed lines). The dot-dash line is the continuation of the four-quark potential model prediction, while the solid line adds the contribution of a heavy lepton with $M_L = 2.3$ GeV. The data points are from Ref. 20.

In fact, all the calculations I have seen look much like the data published in January[20] and not like Fig. 1, which was presented to this conference. Particularly the $\psi'''(4.4)$ would seem to be a source of trouble for many of these calculations. By integrating the cross section for $e^+e^- \to$ hadrons over the resonance peaks, one finds values for the leptonic widths:[50]

$$\Gamma_{e^+e^-}(\psi) = 4.8 \pm 0.6 \text{ keV} \tag{10a}$$

$$\Gamma_{e^+e^-}(\psi') = 2.1 \pm 0.3 \text{ keV} \tag{10b}$$

$$\Gamma_{e^+e^-}(\psi'') = 1.8 \text{ to } 3.3 \text{ keV} \tag{10c}$$

$$\Gamma_{e^+e^-}(\psi''') = 0.4 \text{ to } 0.8 \text{ keV} , \tag{10d}$$

where the ψ'' and ψ''' are assumed to be single objects. However, in the potential calculations,[45,46]

$$\Gamma_{e^+e^-} = \frac{16\pi Q_c^2 \alpha^2 |\phi(0)|^2}{M^2} , \tag{11}$$

where Q_c is the charge of the charmed quark, $\phi(0)$ is the wave function at the origin for the resonance, and M its mass. It is a peculiarity of the linear potential that the wave functions of the s-wave states at the origin, $\phi_s^{(n)}(0)$, are independent of n, the principal quantum number. Therefore, viewing the ψ's as successive s-wave radial excitations, one expects $\Gamma_{e^+e^-}$ to drop like $1/M_n^2$, or about a factor of 2 from the ψ to ψ''', instead of the approximate order of magnitude fall observed.

If the assignment of the ψ, ψ', ψ'', and ψ''' to the principal s-wave series is correct, only a large drop in the charmed quark-antiquark part of the wave function, and hence $|\phi_s(0)|$ would save the leptonic widths. But then the continuum corrections change the wave function at short distances by a very large amount. Another way out is to invoke a d-state, whose wave function vanishes at the origin, slightly mixed with a nearby s-wave state to be the ψ'''. Wilder options include postulating another kind of excitation entirely[51] or utilizing a new combination of quarks already found in the ψ and ψ', if more than one new quark is involved there.

Altogether, the rise in R to a value of ≈ 5, or perhaps a little larger, at the highest SPEAR energies, plus the information we have deduced about the threshold leaves us with two main possibilities:

A. There is a new charged heavy lepton and a new quark (c) with charge + 2/3 (coming in three colors) as in the charm scheme.[25,26] R is 2 from the u, d, and s quarks, plus 1.0 from the heavy lepton, plus 4/3 from the c quark for a total of 4 1/3. Adding 20% to the hadronic part of R, to account for the approach to the constant limiting value as $Q^2 \to \infty$ from above, gives $R \approx 5$. Given the dilution of the various tests for charmed particles by the heavy lepton,[43] the present situation is even consistent with charm in the specific sense of Glashow et al.[26]

B. There are two or more new quarks, as proposed by a number of authors.[52] In the specific scheme of Harari,[32,52] there are three new quarks (9 including color) with charges 2/3, 2/3, and -1/3. Hence R is 2 from u, d, and s quarks plus 3 from the new quarks, for a total of 5.

However, if we want to have lepton-quark symmetry and have no Adler anomaly,[53] then in scheme A we need more quarks, and in B more leptons. A popular example[54] at the moment is to have 6 quarks and 6 (or more) leptons. The quarks are u, d, s, and three new ones which are essentially those of Harari in B, while the leptons include e, ν_e, μ, ν_μ, and two new ones, L, ν_L as in A. While this is often connected theoretically with the existence of both V-A and V+A currents in a theory which becomes asymptotically a pure vector theory at super high energies, and which also involves several new heavy neutral leptons, it remains to be seen what will be the ultimate form such a theory will take.[55] In any case, <u>at present energies all these quarks and leptons cannot be present</u> or R would be larger than observed. If we accept the evidence pointing to a heavy lepton at SPEAR,[56] then at the largest present values of Q^2 we have alternative A, and some of the 6(?) quarks are inoperative, or, to use this year's jargon, "postponed" until yet higher energies are reached. But before that we have a good deal to understand in the present energy range, and the first order of business is to find the rest of the spectroscopy, particularly that of the charmed particles, associated with <u>just</u> a fourth quark.

IV. INCLUSIVE DISTRIBUTIONS AND JETS

We have already touched on the inclusive production of hadrons in electron-positron annihilation in connection with examining the character of the threshold in R. The production of a particular hadron generally depends on Q^2, the energy E_h of the hadron, and the angle its momentum vector makes with the incoming beams. Using rotational invariance in the case of annihilation through a single photon, it can be shown[57] that the inclusive distribution $e^+e^- \to h + \ldots$ has the form[58]

$$\left(\frac{\sqrt{Q^2}}{2}\right)\frac{d^2\sigma}{d\Omega\, dE_h} = \frac{1}{2}\left(\sigma_T + \sigma_L\right)\left\{1 + \frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L}\cos^2\theta + P^2\,\frac{\sigma_T - \sigma_L}{\sigma_T + \sigma_L}\sin^2\theta\cos 2\phi\right\}. \quad (12)$$

Here P is the polarization (transverse to the plane of the storage ring) of each beam; θ, ϕ are polar and azimuthal angles of the hadron three-momentum defined relative to the beam direction and the plane of the storage ring; and $\sigma_T(Q^2, E_h)$ and $\sigma_L(Q^2, E_h)$ are independent, positive quantities which depend on both Q^2 and E_h in general. While one could define structure functions[59] $\overline{W}_1$ and $\overline{W}_2$, as in deep inelastic scattering, they are not both positive in general. Instead, $\sigma_T(Q^2, E_h)$ or $\sigma_L(Q^2, E_h)$ is positive, easy to work with, and has the simple interpretation of being proportional to the square of the amplitude for producing the hadron via a virtual photon polarized perpendicular or parallel, respectively, to $\vec{P}_h$.

An unbelievably useful mnemonic for the present data and a reference point for the theory of such inclusive distributions is the quark parton model.[60] However we need more than the assumptions needed to derive $R = \sum_i Q_i^2$ or Bjorken scaling in deep inelastic scattering. A condensed version of these assumptions might be:

(i) The current couples, in an appropriate limit, to point, spin 1/2, partons - the quarks. The current-quark interaction is treatable in impulse approximation, as if the quarks were free particles (but the quarks do not appear in the final state).

(ii) The struck or pair produced quark-parton fragments into hadrons independently of its origin in deep inelastic scattering or electron-positron annihilation.

(iii) The hadrons fragmented from a given quark of type i have a distribution which, in a frame where the quark has a very large momentum, is only a function of $z = p_{\parallel,\text{hadron}}/p_{\text{quark}}$ and $p_{\perp,\text{hadron}}$. The parallel and perpendicular components of the hadron momentum are defined relative to the parton momentum. As $|p_{\perp,\text{hadron}}|$ is limited, at sufficiently high energies one will necessarily have jets.

Note that assumption (i) is the usual one necessary to derive Bjorken scaling and $R(Q^2) = \sum_i Q_i^2$. It involves a "hard" process of a current interacting with a point quark. Assumptions (ii) and (iii) are new and involve the "soft" process of quarks fragmenting to hadrons, with (ii) allowing us to relate different deep inelastic processes. However, (ii) and (iii) must occur without quarks themselves appearing in the final state, so the physical process cannot be too "soft". This is a very delicate balance to achieve and, while intuitive pictures of how this might come about have been developed,[60,61] no real theory or model in four dimensions has been forthcoming which exhibits simultaneously all these assumptions.

In the following we shall use functions[60] $D_i^h(z, p_{\perp,\text{hadron}})$ to be the probability that a quark of type i fragments into a hadron h as in assumption (iii). In electron-positron annihilation, as $Q^2 \to \infty$

$$z \to \frac{E_h}{\left(\sqrt{Q^2/2}\right)} = \frac{2Q\cdot P_h}{Q^2} \equiv \bar{\omega}\ , \quad (13)$$

the inclusive variable for e^+e^- we introduced before. Considering finite values of $\bar{\omega}$

as $Q^2 \to \infty$ (so that $E_h \to \infty$), and integrating over $p_{\perp,\text{hadron}}$ relative to the quark direction, we find[62]

$$\frac{d^2\sigma}{d\Omega\, d\bar{\omega}}\,(e^+e^- \to h + \ldots) = \frac{3}{16\pi}\,(1 + \cos^2\theta + P^2\sin^2\theta\,\cos 2\phi)\,\sigma(e^+e^- \to \mu^+\mu^-)$$

$$\times \sum_i Q_i^2\,[D_i^h(\bar{\omega}) + D_{\bar{i}}^h(\bar{\omega})]\ , \tag{14}$$

where the two terms in brackets arise from the quark-antiquark pair produced by the virtual photon. Eq. (14) exhibits inclusive scaling: after dividing out $\sigma(e^+e^- \to \mu^+\mu^-)$, the right-hand side depends not on E_h and q^2 separately, but on $\bar{\omega}$. In other words, for the cross sections defined in Eq. (12)

$$\sigma(Q^2, E_h) = \sigma(e^+e^- \to \mu^+\mu^-)\,F(\bar{\omega} = 2E_h/\sqrt{Q^2})\ . \tag{15}$$

In addition, because of the spin 1/2 assumption for the parent quark-partons, Eq. (14) corresponds to $\sigma_L = 0$.

The result analogous to Eq. (14) for deep inelastic electroproduction of hadrons, $ep \to e + h + \ldots$ involves "hybrid" scaling in z and the Bjorken[63] scaling variable ω of the form:[64]

$$\frac{1}{\sigma_T}\frac{d\sigma_T}{dz} = \sum_i Q_i^2 f_i(1/\omega) D_i^h(z) \Big/ \sum_i Q_i^2 f_i(1/\omega)\ , \tag{16}$$

where the $f_i(1/\omega)$ give the probability of finding quark type i in the proton with momentum fraction $1/\omega$, and z at large ν and q^2 is E_h^{lab}/ν.

Neither Eq. (14) nor Eq. (16) follows from the light cone behavior of the operator product of two currents. Additional, very strong, assumptions are needed on a fourfold product of currents and hadronic sources. Whether we work within the parton model or light cone approach, we have gone well beyond the relatively solid theoretical ground needed to derive scaling of R or νW_2.

In spite of this, and in spite of the limited values of Q^2 available, the data look very much like they are approaching Eq. (14) at the highest SPEAR energies. Since we have a threshold in R, it only makes sense to test for scaling of the inclusive distributions either below $\sqrt{Q^2} \approx 3.5$ GeV or above ≈ 4.5 GeV. The data[22,65] are shown in Figure 12. For the region where $R \simeq 2.5$ we have only a single value of $\sqrt{Q^2} = 3.0$, so no test is possible. But the data at $\sqrt{Q^2} = 4.8$, 6.2, and 7.4 GeV do indicate approximate scaling for $\bar{\omega} \gtrsim 0.2$, and it appears that successively higher energies show the scaling behavior moving to ever smaller values of $\bar{\omega}$. The climb in $(d\sigma/d\bar{\omega})/\sigma(e^+e^- \to \mu^+\mu^-)$ at small $\bar{\omega}$ is expected: It is just what yields a rising charged particle multiplicity since

$$\frac{1}{\sigma(e^+e^- \to \mu^+\mu^-)}\int_{2M_h/\sqrt{Q^2}}^{1} d\bar{\omega}\,\frac{d\sigma}{d\bar{\omega}}\,(e^+e^- \to h + \ldots) = \mathbf{R} < n_h >\ , \tag{17}$$

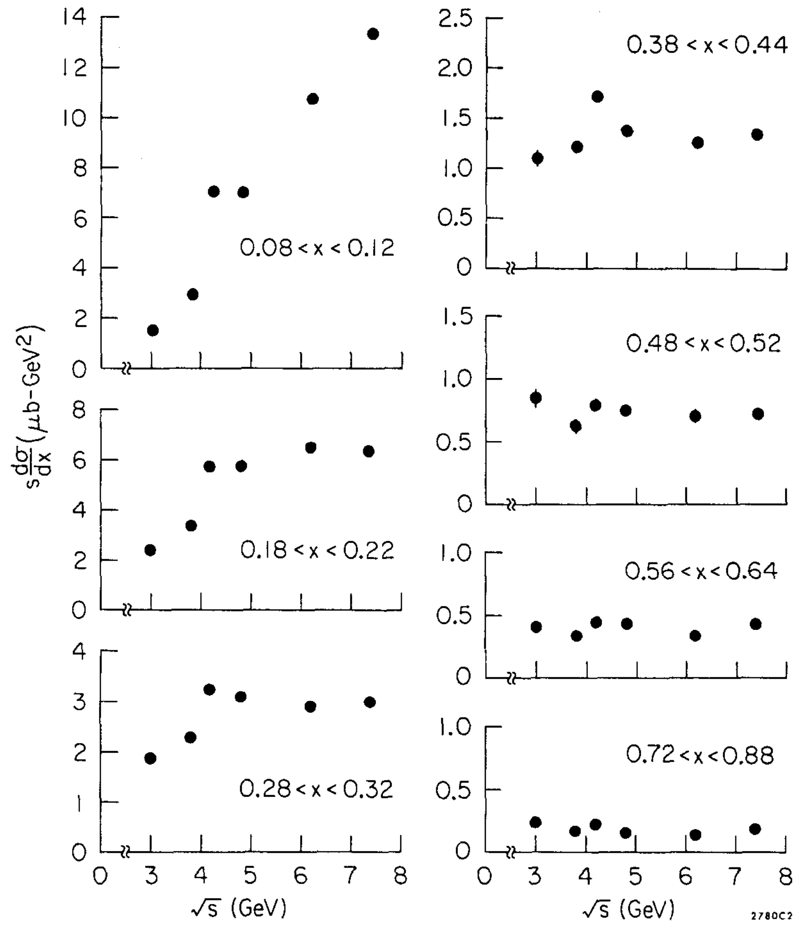

Fig. 12--Values[22] of the inclusive charged hadron distribution, s $d\sigma/dx$, for various x intervals as a function of $\sqrt{s} = \sqrt{Q^2}$. The variable[65] $x = 2p/\sqrt{s} \rightarrow \bar{\omega} = E_{hadron}/E_{beam}$ for relativistic particles, and correspondingly s $d\sigma/dx \rightarrow Q^2\, d\sigma/d\bar{\omega}$.

and R is roughly constant above 4.8 GeV. The small value of σ_L/σ_T beyond $\bar{\omega} \approx 0.2$ and its consistency with zero for $\bar{\omega} \rightarrow 1$, as shown[65] in Figure 13, is also just that predicted by Eq. (14).

What is still needed is a separation of different types of charged particles to test for scaling of individual hadron species, as is actually predicted by the theory. As seen in data at the resonances,[30] when considered as a function of E_h (or $\bar{\omega}$), π's, K's, and p's are comparable in yield, so the true shape of the inclusive distribution and any really quantitative test of their scaling must await a separation of particle types. Even so, it is already clear that if we are discussing scaling now, by the next conference we will be examining scaling breakdown. The formalism, including the analogs of anomalous dimensions, has already been set up and is waiting.[67] For the moment, I must add one note of caution on some phenomenology done in the past: Since we presumably have charmed particles and a possible heavy lepton decaying weakly into π's and K's above $\sqrt{Q^2} \simeq 4$ GeV, their respective inclusive distributions are "contaminated," and extraction of say $D_u^K(z)$ from such data is, to say the least, very suspect.

This brings us to another exciting subject, jets. I shall use the definition that a jet is a particular kind of multiparticle correlation where an axis exists about which $p_\perp$ is limited. The evidence for jets from a study of "sphericity" of the multihadron events has been presented in some detail.[22,68] This is briefly summarized by Fig. 14, where the drop in the sphericity with increasing $\sqrt{Q^2}$ and the deviation from the results

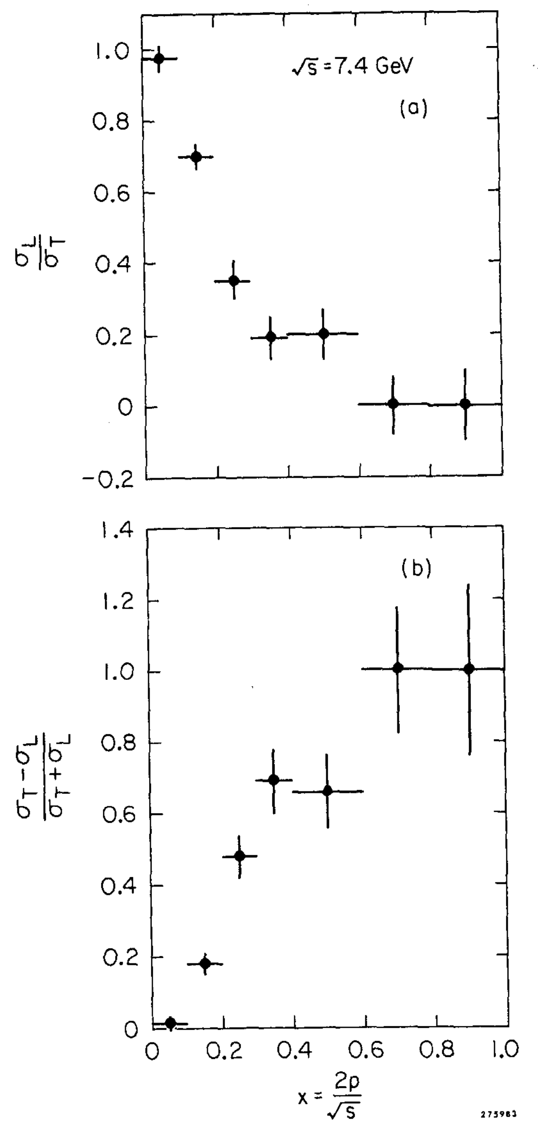

Fig. 13--Values[66] of (a) σ_L/σ_T and (b) $(\sigma_T - \sigma_L)/\sigma_T + \sigma_L)$ for the inclusive charged hadron distribution as a function of $x = 2p/\sqrt{s}$ at $\sqrt{s} = \sqrt{Q^2} = 7.4$ GeV.

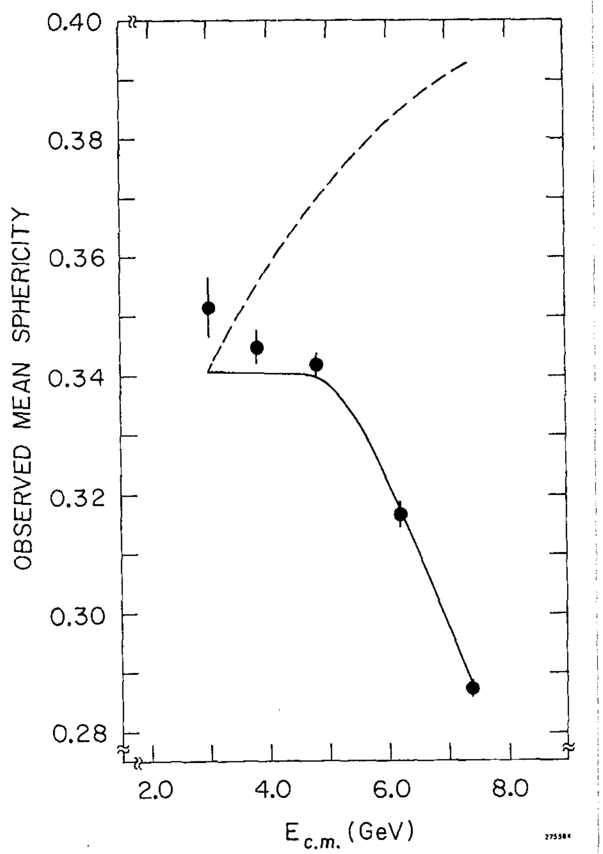

Fig. 14--The observed mean sphericity[22,68] of hadronic events with three or more prongs observed as a function of $E_{c.m.} = \sqrt{Q^2}$.

expected from phase space are seen. Another important aspect of the jets is that σ_L/σ_T for the jets at 7.4 GeV is 0.10 ± 0.08, i.e., almost zero. In other words, the jets act like they have the same angular distribution as muon pairs. Somehow it takes a while for the meaning of "sphericity" to be quantitatively appreciated by many people. It may be of some help to know that at $\sqrt{Q^2} = 7.4$ GeV the "sphericity" in momentum space of events containing a charged particle with $\bar{\omega} > 0.6$ is about the same as the "sphericity" of the present speaker in configuration space. I will not discuss an analogy with phase space.

While all this fits beautifully with preconceptions based on the quark-parton model, it by no means "proves" it.[69] There is also a possible concern that what is being observed is not "real" jets, but only an artifact of some other physics together with the comparison with phase space distributions. One possibility, that heavy lepton production and decay gives the observed effect, is easily disposed of on a quantitative basis, although at sufficiently high energy a heavy lepton certainly contributes to inclusive "hadron" distributions exactly in the form of a jet originating from a spin 1/2 particle.

A more serious worry is that the jets just result from the scaling (for $\bar{\omega} \gtrsim 0.2$) of the single-particle inclusive distributions and are not a true multiparticle effect. This is because scaling of the single-particle distribution implies that at high values of $\sqrt{Q^2}$ there will be more particles with high momentum than phase space would predict. Conservation of energy and momentum then demands that there be particles going in the opposite direction, with limited energy and hence limited transverse momentum relative to the direction of the high momentum particle, i.e., there be jets. In fact, it is clear that some part of what is being called jets when comparison is made to phase space is accreditable to scaling of the single-particle distributions together with energy-momentum conservation and the slow rise in multiplicity.

But this does not appear to be the whole effect. One piece of evidence comes from the distribution in the angle between any two charged particle momenta.[70] Not only does one observe too many particles going back to back compared to phase space (as expected from having more high momentum prongs), but there is also an excess of particles going in the same direction. This is a true multiparticle effect (two-particle in this case) and is what one expects with real jets.

More quantitative evidence[70] comes from considering exactly those events with a high momentum prong, say $0.4 \lesssim \omega \leq 0.6$ at $\sqrt{Q^2} = 7.4$ GeV. While phase space would predict less events with such a high momentum, we can renormalize to the same number of events and ask if the other characteristics of the events are the same. The answer is a definite no. The data have a much lower sphericity than phase space, but a higher multiplicity. In contrast, larger sphericities and multiplicities usually go together (both for the data and for phase space), as one would naively expect. In other words, the real events with a high momentum prong exhibit a larger multiplicity than phase space but still manage to have a very significantly lower sphericity. While much remains to be done concerning correlations in the data, this certainly is nontrivial, is more than a single particle effect, and fits the definition of jets as a true multiparticle effect.

Even then, there is still another out: Perhaps the jets are all due to two-body or quasi-two-body resonance production, like $e^+e^- \to \pi\rho$, $\pi\omega$, πA_2, ρA_2, ωA_3, etc. A look at the data,[70] and particularly the invariant mass distribution of (charged particles in) the jets, reveals that a small set of low mass resonances does not dominate what is taking place. Any picture involving resonances must involve many of them and include very high mass ones. Furthermore, one must incorporate the fact that σ_L/σ_T for the jets is almost zero. While σ_L is zero for channels like $\pi\rho$ and πA_2, σ_L/σ_T is arbitrary for ρA_2, πA_3, ωA_3, etc., and only a tremendous conspiracy will yield the desired result. In short, while always possible in principle, any description of the observations in terms of a sum of quasi-two-body channels must be not only extremely complicated, but also highly conspiratorial. When one is all done with such a construction, it is impossible not to ask "so what?"

One of the things that makes it so difficult to separate single particle inclusive scaling from the question of whether nontrivial jets exist is that a simple jet model[71] gives a good fit to the entire data on final state hadrons.[68,70] Taking $\sigma_L/\sigma_T = 0.10$ for the jet and limiting the transverse momentum about the jet axis so that $\langle p_\perp \rangle = 315$ MeV/c yields a good description of the inclusive single particle distributions above $\sqrt{Q^2} = 4.8$ GeV. An example[68,70] of this fit is shown in Fig. 15, where the $\bar{\omega}$ dependence of $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ at $\sqrt{Q^2} = 7.4$ GeV is shown to be well described in this way. The drop in the asymmetry at small x arises because $p_\perp$ and $p_\parallel$ of the hadron relative to the jet axis are comparable there, and the particles no longer follow the jet axis, as they do when $p_\parallel \gg p_\perp$. Again, it is not that there is no other conclusion except that spin 1/2 partons are giving rise to jets, but what we observe is certainly consistent with such a naive picture. Also, the success of such a fit to the data is circumstantial evidence that not only is the physics associated with the u, d, and s quarks jetlike, but also that arising from the "new" physics; for the model fits all the inclusive distributions and the value of σ_L/σ_T, not just that half of R which comes from the "old" physics.

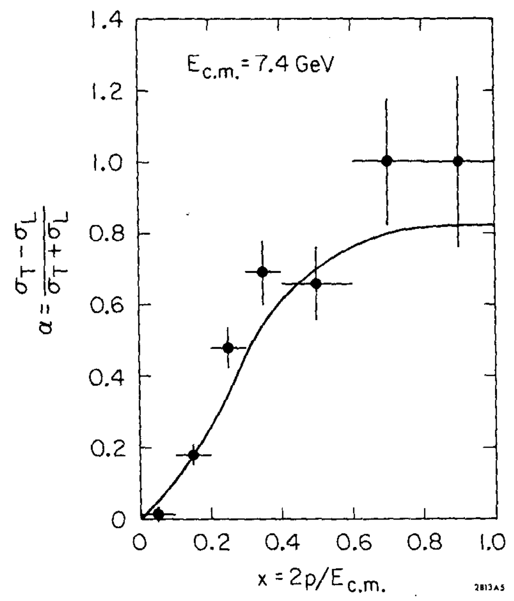

Fig. 15--The values of $(\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ for the charged hadron inclusive distribution at $E_{c.m.} = \sqrt{Q^2} = 7.4$ GeV and the fit (solid line) from a simple jet model with $(\sigma_L/\sigma_T)_{jet} = 0.10$.

With the quark parton picture for final state hadrons appearing to be in surprisingly good shape, it is worth looking at the comparison with hadron production in deep inelastic scattering, and in particular at the hadrons found in the photon fragmentation region. We choose to consider the reaction $ep \to e + h + \ldots$ simply because the most high energy data has been collected in this case.

For deep inelastic scattering on protons at moderate values of ω, it is the u quark which contributes dominantly to the structure functions. Making the approximation that only the u quark is important, we see that all the dependence of $\frac{1}{\sigma_T}\frac{d\sigma_T}{dz}$ on parton distributions in the proton drops out of Eq. (16). Summing over both positive and negative produced hadrons of all types, we have

$$\frac{1}{\sigma_T}\left[\frac{d\sigma_T}{dz}(ep \to e + h^+ + \ldots) + \frac{d\sigma_T}{dz}(ep \to e + h^- + \ldots)\right] \simeq D_u^{h^+}(z) + D_u^{h^-}(z) . \tag{18}$$

For electron-positron annihilation we want to stay below $\sqrt{Q^2} \approx 3.5$ GeV, in which case presumably only u, d, and s quarks are being produced. Again, taking the contribution[72] from $u\bar{u}$ as the largest part of R, and remembering that hadrons fragment from both the quark and antiquark, we have that

$$\frac{1}{2\sigma_{total}}\left[\frac{d\sigma}{d\bar{\omega}}(e^+e^- \to h^+ + \ldots) + \frac{d\sigma}{d\bar{\omega}}(e^+e^- \to h^- + \ldots)\right] \simeq$$
$$\simeq \frac{1}{2}\left[D_u^{h^+}(\bar{\omega}) + D_u^{h^-}(\bar{\omega}) + D_{\bar{u}}^{h^+}(\bar{\omega}) + D_{\bar{u}}^{h^-}(\bar{\omega})\right] = D_u^{h^+}(\bar{\omega}) + D_u^{h^-}(\bar{\omega}) . \tag{19}$$

A beginning at making a comparison of Eq. (18), using $ep \to e + h^\pm + \ldots$ data[73] from SLAC, with Eq. (19), using $e^+e^- \to h^\pm + \ldots$ data[27] at $\sqrt{Q^2} = 3.0$ GeV, is made in

Fig. 16. Particularly at larger $\bar{\omega}$ or z ($\gtrsim 0.5$), where the relatively low values of the kinematical invariants make less of a difference in exactly what variable is used to make the comparison,[74] the two distributions agree roughly in both shape and magnitude.[75]

I am sure you will see more comparisons of this type at this conference, and even more so at future conferences. Many things remain to be done to make it really quantitative. In particular, one should separate π, K, and p production and see if each individually is the same in electron-positron annihilation and deep inelastic scattering. It also is possible using data from both neutrino and electron-induced reactions to separate out the contribution coming from each type of quark, and to do so at much higher values of q^2 than used above.

Nevertheless, pending such further investigation, it seems that the quark parton model for electron-positron annihilation has recovered from its seemingly incurable difficulties of only a year ago[27] and is healthier than ever. Not only do we have scaling of R and of the single particle inclusive distributions, but jets characterized by a very small value of σ_L/σ_T and perhaps even agreement between the photon fragmentation into hadrons found in deep inelastic scattering and in electron-positron annihilation. We only leave the "details" to be cleaned up by future experiments and the construction of a solid theoretical foundation for the present models and intuition.

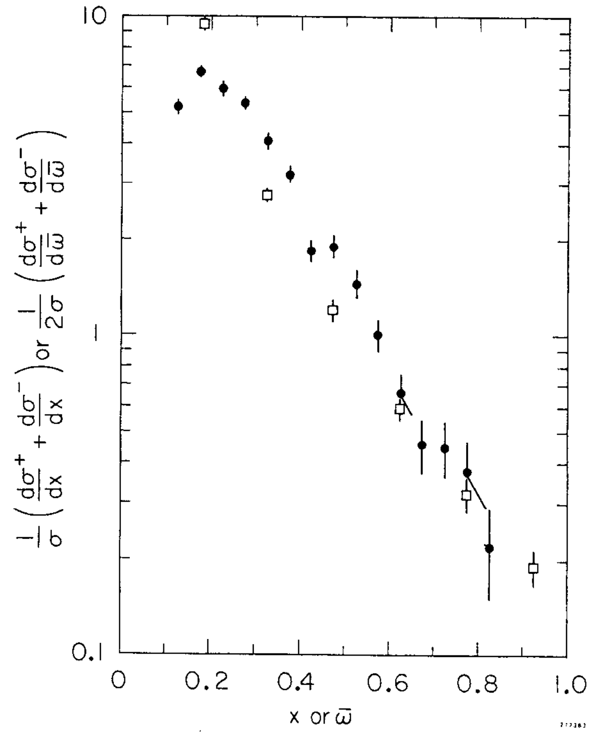

Fig. 16--Comparison of the measured charged hadron inclusive distribution[27] at $\sqrt{Q^2} = 3.0$ GeV (solid points) with the measured inclusive hadron distribution[73] (open squares) along the virtual photon direction in inelastic electron-proton scattering with $0.5\ \mathrm{GeV}^2 \leq q^2 \leq 1.0\ \mathrm{GeV}^2$, $12\ \mathrm{GeV}^2 \leq s \leq 30\ \mathrm{GeV}^2$ and where $x = (p_\parallel/p_{max})_{c.m.}$. See text.[74]

V. CONCLUSION

A rather concise way to summarize what we have been discussing is to extend the presently observed physics to the energies that will be explored by the next generation of machines: PEP, PETRA, and EPIC. First, R will remain constant until we encounter the quarks "postponed" in Section III, when it will rise by $\Delta(\Sigma Q_i^2)$. Before the rise there will be more narrow resonances. But since the strong interaction coupling (of the colored gluons) will be so small at such high Q^2, the resonances will have almost no direct decays into hadrons, going instead through a virtual photon into e^+e^-, $\mu^+\mu^-$, L^+L^-, and hadrons (with a width $R\Gamma_{e^+e^-}$).

At the same energies, inclusive distributions will scale down to $\bar{\omega} \approx 0.05$. The average charged particle momentum will be ≈ 3 GeV.

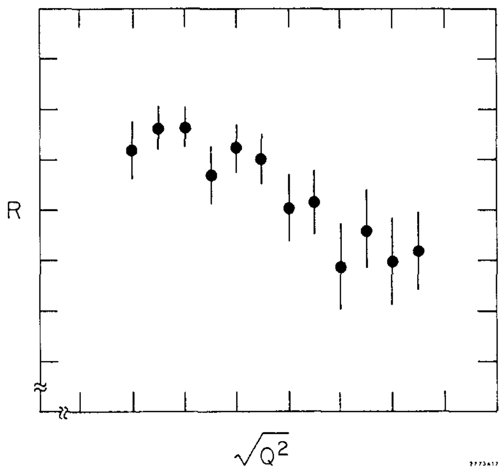

Fig. 17--Values of R from the next generation of storage rings to be presented at the 1981 Symposium.

There will be no need for extensive discussions of whether jets exist using sphericity. One will only need to look at the first (or any) dozen multihadron events detected - each event will look like a pencil.

And then, six years from now in the 1981 conference, we will get the first experimental results from these new colliding beam machines. The first data analyzed will be that for σ_{total}, and hence $R(Q^2)$. Luckily, we don't have to wait, for Roy Schwitters gave me this morning a somewhat familiar looking graph that he didn't use in his talk which shows the preliminary R values to be presented at the 1981 Symposium. They are given in Fig. 17.

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1. We use Q^2 inasmuch as all the experimental talks employ W^2, $E^2_{c.m.}$ and s instead. When discussing the space-like region, we revert to $q^2 = q_\mu q_u = |\vec{q}|^2 - |q_0|^2 = -Q^2$. $\alpha = e^2/4\pi \approx 1/137$.

2. The light-cone and operator product approach is extensively reviewed and referenced by Y. Frishman in Proc. XVI Int. Conf. on High Energy Physics, J. D. Jackson and A. Roberts, eds. (National Accelerator Laboratory, Batavia, Ill., 1972), p. 119.

3. For spin-zero fundamental fields, a possibility we discard, there is an extra factor of 1/4 on the right-hand side of Eq. (3).

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11. A. De Rújula, unpublished. I thank Professor H. J. Schnitzer for informing me of this work.

12. We ignore the possibility of oscillations.

13. The similarity in the pattern was emphasized previously; see F. J. Gilman, in Theories and Experiments in High-Energy Physics, A. Perlmutter and S. M.

Widmayer, eds. (Plenum Press, New York, 1975), p. 29.

14. C. Bemporad, invited talk at this conference and references therein.

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16. M. Conversi et al., paper submitted to the 4th Int. Conf. on Experimental Meson Spectroscopy, Boston, April 26-27, 1974. See also Fig. 7 of W. Chinowsky, in Experimental Meson Spectroscopy - 1974, D. A. Garelick, ed. (American Institute of Physics, New York, 1974), AIP Conference Series No. 21, Particles and Fields Subseries No. 8, p. 124.

17. There is of course other evidence for the $\rho'(1600)$ from $\pi\pi$ partial wave analysis and from photoproduction - see A. Silverman, invited talk at this conference and references therein.

18. F. Wagner, M. Tabak, and D. M. Chew, Berkeley preprint LBL-3395, 1975 (unpublished).

19. See R. Prepost, invited talk at this conference and references therein.

20. J.-E. Augustin et al., Phys. Rev. Letters 34, 764 (1975).

21. It is also consistent with $R = 2\frac{1}{3}$ which follows from u, d, and s quarks plus a new quark with charge - 1/3, all in three colors. However, since the corresponding threshold is below ≈ 2.6 GeV, one expects an associated family of relatively narrow vector resonances well below the ψ. These do not seem to be there; see Refs. 14 and 19.

22. R. Schwitters, invited talk presented at this conference.

23. Quarks with charges other than - 1/3, $-\frac{1}{3} \pm 1$, $-\frac{1}{3} \pm 2$, ..., yield fractionally charged mesons. A colored charge - 4/3 quark alone makes a contribution of $5\frac{1}{3}$ to R and is discarded as a possibility.

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33. M. L. Perl et al., SLAC preprint SLAC-PUB-1626, 1975 (unpublished).

34. G. J. Feldman, invited talk at this conference.

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40. This has been stressed to me by H. Harari; see his talk at this conference, Ref. 43.

41. The values for R near the ψ' come from a measurement 13 MeV below $M_{\psi'}$; see V. Lüth et al., SLAC preprint SLAC-PUB-1617, 1975 (unpublished); and from a fit to all the data near 3.684 GeV to a resonance plus background, A. Boyarski, private communication.

42. If charm threshold is near $\sqrt{Q^2} = 3.9$ GeV, then the region from 3.7 to 3.9 GeV could contain narrow d and possibly f-wave charmed quark-antiquark bound states, which it will be very difficult to discover.

43. See, also, H. Harari, invited talk at this conference.

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57. See, for example, F. Gilman, lectures at the SLAC Summer Institute on Particle Physics, July 21-31, 1975 (unpublished). The same formula is applicable to two-body channels or to axes of many-body systems where E_h is fixed or averaged over, respectively.

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62. The functions $D_i^h(\bar{\omega})$ result from integrating the $D_i^h(\bar{\omega}, p_\perp, \text{hadron})$ over the transverse momentum. In the limit of Q^2 and $E_h \to \infty$, the hadrons follow the quark-parton or jet direction.

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65. There is no separation of particle types, so the distributions in $x = 2p/\sqrt{s}$ are not the same as they would be in $\bar{\omega}$. However, at large x all the particles are relativistic for $\sqrt{Q^2} \geq 3.0$ GeV, so that $p_h \to E_h$, and $x \to \bar{\omega}$ for each type.

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71. The model consists of imposing a transverse momentum cutoff of the form $e^{-p_\perp^2/b^2}$ about an axis on a phase space distribution, and giving the resulting jet a value of σ_L/σ_T.

72. The u quark contributes $3\left(\frac{4}{9}\right)/3\left(\frac{4}{9}+\frac{1}{9}+\frac{1}{9}\right) = 2/3$ of R. Alternately, if each type of quark fragments into hadrons in the same way, then Eq. (19) also follows.

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75. A similar rough comparison was made by J. D. Bjorken in lectures at the SLAC Summer Institute in Particle Physics, July 21-31, 1975 (unpublished).