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ELECTRON-POSITRON ANNIHILATION AND THE STRUCTURE OF HADRONS*

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I. INTRODUCTION

The last two months have been very exciting ones in elementary particle physics. They have been filled with the most rapid and unexpected discoveries that I can recall. The highlight of this period is undoubtedly the finding of very narrow boson resonances,[1-4] the ψ's at 3.1 and 3.7 GeV.

Somewhat less noticed by many, but also of great importance, is the change that has taken place in our perception of the behavior of the fundamental quantity R, the ratio of $\sigma_T(e^+e^- \rightarrow \text{hadrons})$ to $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, the point cross section for muon pair production. For we have been confused and fooled for almost a year by partial and incomplete data - a year in which perhaps the most embarrassing questions one could ask many theorists were: "What's the origin of the behavior of $\sigma_T(e^+e^- \rightarrow \text{hadrons})$? Why doesn't it scale?" Now it appears the answer is "It does," or, a little more accurately, "It did," and that perhaps still higher energy data will show that "It will" scale again. Part of the reason for the earlier confusion is that there seems to be a step or threshold near 4 GeV and a new region above it, a transition whose physics is very likely connected to that of the narrow resonances just below.

In the following I will review what we now know about $\sigma_T(e^+e^- \rightarrow \text{hadrons})$. Particular emphasis is put on scaling and the excitation of new hadronic degrees of freedom. Our present information on the ψ's is then reviewed in a phenomenological vein, from which we turn to a possible theoretical understanding of the new discoveries in terms of a new hadronic quantum number, a concrete example of which is charm.

II. THE BEHAVIOR OF R AND SCALING

Before looking at the latest data, let us recall what had been early theoretical expectations for the behavior of $R = \sigma_T(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$. On the basis of the parton model of point constituents, or of the more formal light cone algebra, one predicts that the cross section for e^+e^- annihilation into hadrons will scale, i.e., $\sigma_T(e^+e^- \to \text{hadrons}) \propto 1/Q^2$. Since the "point" cross section[5] for muon pairs,

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3Q^2} \tag{1}$$

behaves as $1/Q^2$, theoretical expectation is that R will be constant and the constant may be interpreted as the sum of the squares of the charges (in units of e) of the fundamental fields making up the produced hadrons. In the case of three Gell-Mann - Zweig quarks[6,7] this gives

$$R = \sum_i Q_i^2 = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3} \quad , \tag{2a}$$

while if these quarks each come in three colors,

$$R = 3(2/3) = 2 \quad . \tag{2b}$$

Many other schemes may be invented either by adding more quarks and/or by allowing the photon (and consequently the charge) to be a nonsinglet with respect to color. A popular version of the latter possibility is the Han-Nambu scheme[8] with integrally charged quarks and $R = 4$.

A compilation of data on R from Orsay,[9] Frascati,[10] and SLAC[11] is found in Fig. 1. One clearly sees the $\rho(770)$, $\omega(783)$, and $\phi(1020)$ resonance peaks and then a value of R between 2 and 3 up to $\sqrt{Q^2} \simeq 3.6$ GeV. Within errors, these data are entirely consistent with scaling, i.e., R = constant, once Q^2 is above a few GeV^2 (and below ≈ 13 GeV^2). Furthermore, within the experimental errors[11] a value of $R = \sum_i Q_i^2 = 2$ is allowed, quite aside from any theoretical argument that R might well be somewhat larger than 2 in this region and approaching its asymptotic value from above. It therefore appears that the naive expectations might be right after all: scaling with R given by the sum of the squares of the operative quark charges, i.e., the nine colored quarks composing the hadrons being produced, is completely consistent with the behavior of R until new physics asserts itself in the 3 to 4 GeV region.

At 3.1 GeV we get the first signal that something new is about to happen. At 3.7 GeV a second signal is immediately followed (or perhaps slightly preceded) by a rise in R. The general shape of R looks amazingly like sketches made years ago[12] to indicate what would happen due to the excitation of new hadronic degrees of freedom, whether color "thaw" or charm threshold.[13-16] The maximum in R at 4.1 GeV might be just a threshold effect or it could be a broad resonance sitting on top of a rising background, the latter being my personal feeling. In either case, a naive interpretation of the behavior of R leads to a threshold at or below 4 GeV: the broad width of the possible $\psi(4.1)$ compared to the very narrow $\psi(3.1)$ and $\psi(3.7)$ arises in the latter case precisely because one is presumably above threshold for actual decays of the resonance into new kinds of hadrons.

A look at specific channel cross sections from $\sqrt{Q^2} = 1.2$ to 1.8 GeV leads me to think that once accurate measurements are made of R in this threshold region for the "usual" quark degrees of freedom, it will appear qualitatively very much like the region from 3.8 to 4.4 GeV. The bump due to the $\rho'(1600)$, which will be less than one unit of R high, would then be the analogous structure to the larger bump in R at 4.1 GeV, even though its physics may be quite different in detail.

The presently available data[11] on R stops at $\sqrt{Q^2} = 5.0$ GeV, at which point $R \simeq 5$, i.e., double its value below the threshold. If scaling obtains and there are no further changes in R, then one has approximately doubled $\sum_i Q_i^2$ for the operative fundamental fermion fields above $\sqrt{Q^2}$ of ≈ 4 GeV.

Aside from measurements of R at higher Q^2, a better understanding of the physics above 4 GeV requires information on the final state particles. Such data would help first of all in establishing whether the structure at 4.1 GeV is a resonance - decay of such an object into a particular final state could be crucial in this regard. Present data are insufficient to draw any conclusions.

The inclusive single particle distributions are also of great interest. While not on the same level of rigor or as fundamental as the prediction of scaling of $\sigma_T(e^+e^- \to \text{hadrons})$, parton models and some extensions of light-cone ideas lead one to expect that $Q^2\, d\sigma/dx$ should scale, where $x = 2\, P \cdot Q/Q^2$ and P_μ is the four-momentum of the observed hadron. Extensive data do exist at $\sqrt{Q^2} =$ 3.0, 3.8, and 4.8 GeV on the inclusive charged particle distributions. Unfortunately, these energies are, respectively, below, in the middle of, and above the threshold or step in R. Consequently, one does not expect to see scaling of $Q^2\, d\sigma/dx$ on comparing data at these particular three energies. Testing of scaling of $Q^2\, d\sigma/dx$ awaits the accumulation of data at other energies below as well as above the threshold. Nevertheless, the data at $\sqrt{Q^2} = \sqrt{s} = 3.0$, 3.8, and 4.8 GeV shown[17] in Figure 2 are of some interest. For $x \gtrsim 0.5$, the distributions are the same! Is this an accident? If not, and the distribution at $\sqrt{Q^2} = 3.0$ GeV is already scaling and that characteristic of the component of R due to the nine colored Gell-Mann - Zweig quarks, then the new component of R is almost completely associated with particles at small x.

A look at the charged hadron multiplicity[11] in Figure 3 shows no obvious structure. Within errors it is consistent with a logarithmic rise with Q^2. Of course much is washed out in such a low moment of the data.

The proportion of π^-, K^-, and $\bar{p}$ shown[17] in Figure 4 shows that at $\sqrt{Q^2}$ = 4.8 GeV one has dominantly pions out to momenta of 600 MeV. As reported at this meeting[18,19] $K/\pi = 0.33 \pm 0.08$ or $K/\text{All} = 0.25 \pm .05$ for momenta from 1.2 to 2.4 GeV at the same value of Q^2. Furthermore there is no dramatic difference in the SLAC-LBL results[17] at $\sqrt{Q^2} = 3.0$ and 3.8 GeV from those at 4.8 GeV.

One quantity where there may be a change on crossing the threshold is in the proportion of the energy in charged hadrons in the final state. If all the final hadrons were pions, the simplest models[20] predict equal π^+, π^-, and π^o distributions, so that charged pions carry 2/3 of the energy. In practice, one expects a somewhat lower number because of η's, K's, etc. The experimental data[17] are shown in Figure 5. A biased eye sees a perfectly respectable value of ≈ 0.6 until about 4 GeV, with a decrease which makes the result look like an inverted version of R. But how is this increased proportion of energy carried by neutrals manifested? By photons? Or neutrinos? At present we do not know.

III. PHENOMENOLOGY OF THE ψ's

To establish some basis for the next section we enumerate here some of the basic facts now known about the ψ's and the consequent phenomenology. We start with the first to be discovered, which is now assigned a mass[21,22]

$$M = 3.095 \pm .005 \text{ GeV}$$

and J^{PC} is inferred to be 1^{--} from the three standard deviation interference[21,22] below the resonant energy in $e^+e^- \to \mu^+\mu^-$, the angular distribution of the muons, the lack of a $\gamma\gamma$ decay,[23,24] etc. The width into leptons is directly determined from the integrated cross section into hadrons:[25]

$$\int_{\text{Resonance}} \sigma_T(e^+e^- \to \text{hadrons})\, d\sqrt{Q^2} = \frac{6\pi^2}{M^2}\,\Gamma_{ee}\left(\frac{\Gamma_{\text{hadrons}}}{\Gamma_{\text{total}}}\right). \tag{3}$$

Using the preliminary values[21,22] for $\psi(3.1)$,

$$\int_{\text{Resonance}} \sigma_T(e^+e^- \to \text{hadrons})\, d\sqrt{Q^2} = 10{,}800 \text{ nb - MeV} \qquad (\pm 25\%)$$

and

$$\Gamma_{ee} = \Gamma_{\mu\mu} = .068\,\Gamma_{\text{total}} \quad ,$$

one finds

$$\Gamma_{ee} = \Gamma_{\mu\mu} = 5.2 \text{ keV}$$

$$\Gamma_{\text{total}} = 77 \text{ keV} \quad .$$

These values agree within errors with the quantity $\Gamma^2_{ee}/\Gamma_{\text{total}}$ extracted from Frascati[3] and DESY data.[23,26] The leptonic width may be directly converted into a vector meson-photon coupling (see Fig. 6a). Writing eM^2/f at the ψ-photon vertex and using

$$\Gamma_{ee} = \left(\frac{4\pi\alpha^2}{3}\right)\frac{M}{f^2} \quad , \tag{4}$$

gives $f^2/4\pi = 10.6$. This is to be compared with $f_\rho^2/4\pi \simeq 2.5$, $f_\omega^2/4\pi \simeq 19$, and $f_\phi^2/4\pi \simeq 11$.

For the $\psi(3.7)$ we now have

$$M = 3.684 \pm .005 \text{ GeV} .$$

The value[21,22]

$$\int_{\text{Resonance}} \sigma_T(e^+e^- \to \text{hadrons})\, d\sqrt{Q^2} = 3700 \text{ nb - MeV} \quad (\pm 25\%)$$

gives

$$\Gamma_{ee} = 2.2 \text{ keV}$$

and a corresponding coupling $f^2/4\pi = 29.8$. The branching ratio to leptons is still not completely settled and we have only the limits on the total width[21,22]

$$200 \text{ keV} < \Gamma_{total} < 800 \text{ keV} .$$

No other narrow states have been found in a scan[27] from 3.2 to 5.9 GeV. If one considers the structure at 4.1 GeV to be a single resonance, then[11]

$$\int_{\text{Resonance}} \sigma_T(e^+e^- \to \text{hadrons})\, d\sqrt{Q^2} \simeq 5500 \text{ nb - MeV}$$

leads to

$$\Gamma_{ee} = 4.0 \text{ keV}$$

and a corresponding $f^2/4\pi = 18.2$. The total width of the peak is in the 250 to 300 MeV range, making the branching ratio into a lepton pair $\approx 1.6 \times 10^{-5}$.

The data on decay modes are now beginning to pour forth from the 50,000 decays of the $\psi(3.1)$ observed by the SLAC-LBL magnetic detector. If the $\psi(3.1)$ couples to lepton pairs as in Figure 6a, it couples to hadrons as in Figure 6b with the exactly calculable rate,

$$\begin{aligned}\Gamma(\psi(3.1) \to \gamma \to \text{hadrons}) &= R(\sqrt{Q^2} = 3.1\ \text{GeV}) \times \Gamma(\psi(3.1) \to \gamma \to e^+e^-) \\ &\simeq 2.5\ (5.2\ \text{keV}) = 13\ \text{keV} = .17\ \Gamma_{\text{total}}\end{aligned} \tag{5}$$

This leaves 77 - 13 - 2(5.2) $\simeq$ 54 keV for "direct" decays of the $\psi(3.1)$ into hadrons. In particular, inasmuch as $2\pi^+ 2\pi^-$ is $\approx 1/20$ of the cross section at 3.0 GeV (just off resonance), one calculates from Eq. (5) that

$$\Gamma(\psi(3.1) \to \gamma \to 2\pi^+ 2\pi^-) \simeq \left(\frac{1}{20}\right) \Gamma(\psi(3.1) \to \gamma \to \text{hadrons}) \simeq .0085\ \Gamma_{\text{total}} \tag{6}$$

The $2\pi^+ 2\pi^-$ channel has recently been cleanly separated[21,22] from $\pi^+\pi^-K^+K^-$ and its partial width is consistent with Eq. (6), and hence with being entirely a second order electromagnetic, rather than "direct," decay mode.

A more important decay mode of $\psi(3.1)$ is five pions, including $\omega\pi\pi$ and $\rho\pi\pi\pi$. Three pion and seven pion modes are also seen.[21,22] Particularly the five pion mode occurs at a rate beyond that deduced from Eq. (5) and hence is "direct". If it occurs via strong interactions, then one concludes G = - and I = 0 or 2 for the $\psi(3.1)$, an assignment which is consistent with other observed modes[21,22] like $\pi^+\pi^-p\bar{p}$, $p\bar{p}$, $\pi^+\pi^-K^+K^-$, and $\Lambda\bar{\Lambda}$. It is also consistent with the lack of observation of $\pi\pi$ or $K\bar{K}$ modes at DESY:[26]

$$\Gamma(\psi(3.1) \to \pi\pi) < .025\ \Gamma_{ee} = .0017\ \Gamma_{\text{total}}$$

$$\Gamma(\psi(3.1) \to K\bar{K}) < .025\ \Gamma_{ee} = .0017\ \Gamma_{\text{total}} \quad ,$$

since these decays are forbidden for strong interaction "direct" decays by G parity for the $\pi\pi$ mode and by SU(3) symmetry if the $\psi(3.1)$ is an SU(3) singlet for the $K\bar{K}$ mode.[28,29]

For the $\psi(3.7)$ less detailed information on decay modes is available from the 30,000 decays observed.[21,22] The branching ratio[21]

$$\frac{\Gamma(\psi(3.7) \to \psi(3.1) + \text{any})}{\Gamma(\psi(3.7) \to \text{all})} = 0.5 \qquad (\pm 25\%)$$

includes that for the observed decay $\psi(3.7) \to \pi^+\pi^- \psi(3.1)$ and the strongly suspected $\psi(3.7) \to \pi^0\pi^0 \psi(3.1)$. Again, if this occurs due to strong interactions, then $G = C = -1$ and $I = 0$ or 2 for the $\psi(3.7)$. In the next section we shall assume that both $\psi(3.1)$ and $\psi(3.7)$ have $C = -1$, $I = 0$, and $G = -1$. Up to this point, no decay of the $\psi(3.7)$ to 4π, 5π, 6π, or 7π has been found which could not be a result of $\psi(3.7) \to \pi\pi\, \psi(3.1)$.

Since at least the first ψ has the quantum numbers of the photon it should be diffractively photoproduced at high energy with an amplitude as depicted in Fig. 7. At sufficiently high energy we assume the amplitude is pure imaginary with $d\sigma/dt \propto e^{bt}$. If we use the same ψ-photon coupling as determined at the ψ mass from $\Gamma_{ee} = 5.2$ keV, then, on integrating over t,

$$\sigma(\gamma N \to \psi N) = \frac{35 \text{ nb}}{[b \text{ GeV}^2]} \left[\frac{\sigma_T(\psi N)}{\text{mb}}\right]^2 . \tag{7}$$

An upper limit for $\sigma(\gamma N \to \psi N)$ of ≈ 0.6 nb (after correction for the branching ratio to lepton pairs) has been established by a Rochester-Cornell[30] group at 11.1 GeV. At SLAC an upper limit[31] of 29 nb at 18.2 GeV has been superseded by measurement[32] of a cross section of 2 ± 1.2 nb at 18 GeV by one group and 1 to 5 nb at 19 GeV by another.[33] At FNAL, W. Y. Lee et al.[34] have observed a peak in the muon pair spectrum at 3.1 GeV resulting from photons striking a Beryllium target. A preliminary value[34] for the $\psi(3.1)$ photoproduction cross section per nucleus times the branching ratio into $\mu^+\mu^-$ lies in the 10 to 45 nb range. Assuming a differential cross section for Beryllium with both a coherent and an incoherent part,

$$\frac{d\sigma}{dt} \propto 81\, e^{40t} + 9\, e^{4t},$$

leads on extraction of the $\gamma N \to \psi N$ cross section to values of $\sigma_T(\psi N)$ in the neighborhood of 1 mb through use of Eq. (7).

One must bear in mind that in this calculation we have assumed that the ψ-photon coupling is the same on the photon mass-shell as on the ψ mass-shell — something which could be wrong by a large factor.[35] Nevertheless, while the extracted values of $\sigma_T(\psi N)$ are considerably smaller than[36] $\sigma_T(\rho N) \simeq 28$ mb or $\sigma_T(\phi N) \simeq 13$ mb, such small cross sections are not unexpected to some,[37] and may still be taken to indicate that the $\psi(3.1)$ is a hadron with the J^{PC} quantum numbers of the photon.[38]

IV. CHARM

The existence of the narrow resonances and the rise in R have brought to the fore the question of excitation of new hadronic degrees of freedom. Such theories can be divided into those where the photon itself transforms as a non-trivial representation of a new multiplicative symmetry group of strong interactions and those where the photon is a singlet under such a group but there are additional additive strong interaction quantum numbers.[39] An example of the former is "color SU(3)", which will be discussed in detail by Professor Greenberg.[40] We concentrate on a popular example of the latter type: charm.[41,42]

At a fundamental level this involves adding a fourth quark with charge 2/3, isospin 0, and one unit of a new quantum number called charm,[43] which is conserved in strong and electromagnetic interactions. The four quarks (times three for color) are now called p, n, λ, and p' or u, d, s, and c, depending on one's geographical location, and the basic symmetry of strong interactions becomes SU(4) instead of SU(3) - the quarks falling in the fundamental four dimensional representation. An attractive aspect of this scheme is its origins in lepton-hadron symmetry and in providing an elegant way in the theory of weak interactions of keeping certain processes, which are observed or desired to be second order weak in magnitude, at that level.[43]

In such a theoretical framework, the ψ's are hadrons and interpreted as $c\bar{c}$ bound states. At least for the $\psi(3.1)$, one would like the quarks to lie in a relative s-wave ground state with net quark spin one. The resulting quantum numbers, $J^{PC} = 1^{--}$, $I = 0$ and therefore $G = -1$, are just those indicated by experiment as we have seen in the last section. The $\psi(3.1)$ would belong together with the other vector mesons, the ρ, ω, and ϕ, in the same SU(4) and quark model multiplets. In fact, the ratio of values of squared photon-vector meson couplings should then be 9 : 1 : 2 : 8 for $1/f_\rho^2 : 1/f_\omega^2 : 1/f_\phi^2 : 1/f_\psi^2$. Experimentally this is more like 9 : 1 : 2 : 2 (see the last section), but given SU(4) breaking, as evident in the large mass splittings, and the ambiguity in what quantity is to be compared with the SU(4) ratios, this is not any threat to the scheme.[44] The $\psi(3.7)$ is presumably the analogue of the $\rho'(1600)$ and its partners,[45] with J^{PC}, I, and G quantum numbers identical to the $\psi(3.1)$.

The critical tests of the charm scheme at the moment are spectroscopic. First, charmed particles with quark content $u\bar{c}$, $d\bar{c}$, $s\bar{c}$ (and $c\bar{u}$, $c\bar{d}$, $c\bar{s}$) should exist with J^P values 0^-, 1^-, etc. Most estimates[46] place the lowest mass charmed particles in the range 2.1 to 2.3 GeV, while identification of the step in R with the threshold for producing pairs of charmed particles would put the lowest such mass below 2 GeV. Second, additional $c\bar{c}$ states should exist with I = 0 and zero charm. The most obvious of these is the s-wave, quark spin zero, pseudoscalar state which is the quark model partner of the $\psi(3.1)$. Also present at somewhat higher masses if we take a clue from the observed meson states[47] composed of u, d, and s quarks are the L = 1 $c\bar{c}$ states with J^{PC} values 2^{++}, 1^{++}, 0^{++}, and 1^{+-}. Such states, as well as even more massive $c\bar{c}$ vector mesons, are also predicted by calculations using various potentials.[48]

An immediate question which arises as soon as one wants to make $\psi(3.1)$ and $\psi(3.7)$ hadrons is why are they so narrow? An answer is possibly provided by Zweig's rule,[7] which may be briefly stated for a meson decaying into two other mesons as in Figure 8: decay amplitudes corresponding to connected quark diagrams (Fig. 8a) are allowed, while those corresponding to disconnected diagrams (Fig. 8b) are forbidden. If one meson contains a quark which is not present in either of the other two, there is obviously no allowed diagram. For example, if the ϕ meson had purely $s\bar{s}$ quark content, its decay to $\pi\rho$ would thus be forbidden.

How well does this "rule" work? One way of parametrizing its empirical accuracy is to compare the observed width for a forbidden process with what the width would be for a completely allowed process with the same kinematics. For example, the decay of an "ω" meson with high enough mass into $\pi\rho$ is perfectly allowed, where the "ω" is assumed to consist entirely of nonstrange u and d quarks. The coupling of ω to $\pi\rho$ can be obtained either from a vector dominance calculation[49] of $\omega \to 3\pi$, or from the current to constituent quark transformation. The deduced couplings agree with one another,[50] and result in

$$\frac{\Gamma(\phi(1020) \to \pi\rho)}{\Gamma(\text{"}\omega\text{"}(1020) \to \pi\rho)} \simeq \frac{.0006 \text{ GeV}}{.19 \text{ GeV}} \simeq \frac{1}{300} \,. \tag{8}$$

Similarly,

$$\frac{\Gamma(\phi(1020) \to \gamma\pi)}{\Gamma(\text{"}\omega\text{"}(1020) \to \gamma\pi)} \lesssim 1/100 \tag{9}$$

from the upper limit[51,52] on $\Gamma(\phi \to \gamma\pi)$.

For the f'(1516), decay into $\pi\pi$ is forbidden if its quark content is $s\bar{s}$. Taking the f(1260) to be composed only of nonstrange quarks, the present experimental limit on $f' \to \pi\pi$ and the known width for the allowed decay $f \to \pi\pi$ gives

$$\frac{\Gamma(f'(1516) \to \pi\pi)}{\Gamma(\text{"}f\text{"}(1516) \to \pi\pi)} \lesssim 1/50 \tag{10}$$

Note that the decay $f \to K\bar{K}$ is allowed and its observed rate[51] is consistent with that calculated from SU(3) and phase space.

Thus we see that empirically in the few cases where one can test it well, Zweig's rule is accurate to one part in a few hundred in decay rate. Moreover, it is not possible to tell if the observed decays like $\phi \rightarrow \pi\rho$ are due to breaking of the "rule" or due to a small nonstrange quark ("$u\bar{u} + d\bar{d}$") component of the $\phi(1020)$. In fact, the octet-singlet mixing angle for the vector mesons which follows from a quadratic mass formula gives a $u\bar{u} + d\bar{d}$ component to the ϕ which is completely consistent with its observed decay rate to $\pi\rho$ (or $\gamma\pi$). Thus, Zweig's rule is good <u>at least</u> to $\approx 1/200$ for ϕ decays. Of course, if the "rule" is broken, one automatically is forced into mixing[53] between the $s\bar{s}$ and $u\bar{u} + d\bar{d}$ states and it is less clear quantitatively where to assign the blame for the occurrence of forbidden decays.

If the $\psi(3.1)$ and $\psi(3.7)$ are $c\bar{c}$ states below the threshold for actual decay into pairs of charmed particles (which would be allowed by Zweig's rule), then their decays to ordinary hadrons are forbidden. The decays $\psi(3.7) \rightarrow \pi\pi\psi(3.1)$ and $\psi(3.7) \rightarrow \eta\,\psi(3.1)$ are also forbidden since they too correspond to disconnected diagrams. Experimentally there is a suppression, as[51] $\Gamma(\rho'(1600) \rightarrow \pi\pi\rho) \simeq 300$ MeV and $\Gamma(N^*(1470) \rightarrow (\pi\pi)_s N) \simeq 20$ MeV correspond to allowed quark diagrams and are 100 to 1000 times larger[54] than $\psi(3.7) \rightarrow \pi\pi\psi(3.1)$. From the observed width of $\psi(3.1) \rightarrow$ hadrons one needs Zweig's rule and/or the admixture of $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ quarks in $\psi(3.1)$ to be good to $\approx 1/5000$ in the decay rate, to be compared to the $\approx 1/200$ discussed above. Calculations using asymptotically free gauge theories for strong interactions, although model dependent, indicate at least that one expects a qualitative change toward increased accuracy of Zweig's rule as the mass of the decaying particle increases.[53] The pattern of the forbidden decays discussed above is shown in Figure 9.

With the exception of the $^1P_1$ state, all the other nearby $c\bar{c}$ states ($^1S_0$, $^3P_2$, $^3P_1$, $^3P_0$) are expected to have G = C = + and are therefore reachable from the ψ's by photon transitions.[55] In particular, the pseudoscalar state associated with the $\psi(3.1)$ is likely to lie below it, as the π or K are below the ρ and K* respectively, resulting in the picture shown in Figure 10. It can't lie very much below or else the allowed magnetic dipole transition[56] $\psi(3.1) \to \gamma\eta_c$ results in too large a total width for the $\psi(3.1)$. For example, in the SU(4) limit, the amplitude relation

$$A(\psi \to \gamma\eta_c) = \frac{4}{3} A(\omega \to \gamma\pi) , \tag{11}$$

results in a 22 keV width for $\psi \to \gamma\eta_c$ if one uses simple p^3 phase space and a pseudoscalar mass of 3.0 GeV. While it is easy to obtain a smaller width by introducing mass factors in the amplitudes and/or phase space, or by making $M_\psi - M_{\eta_c}$ smaller (or negative!), this serves well to illustrate how small the $c\bar{c}$ quark content of any pseudoscalar state (including the η and η') more than a few hundred MeV below the $\psi(3.1)$ must be in order to avoid a large width for the $\psi(3.1)$. One also has the upper limit from DESY[23] for the $\psi(3.1)$:

$$\left[\frac{\Gamma(\psi \to \gamma\eta_c)}{\Gamma(\psi \to \text{all})}\right] \cdot \left[\frac{\Gamma(\eta_c \to \gamma\gamma)}{\Gamma(\eta_c \to \text{all})}\right] < .014 ,$$

but this is probably not a stringent bound since most theories would have either bracketed quantity of order a few percent or less. Much more striking is the $\approx$ 600 MeV gamma ray from the transition $\psi(3.7) \to \gamma\eta_c$. If this is even a few percent decay mode of the $\psi(3.7)$ it should be readily detectable by Professor Hofstadter's group at SPEAR in the near future.

The other even charge conjugation states, the $^3P_2$, $^3P_1$, $^3P_0$, and the $^1S_0$ state associated with the $\psi(3.7)$, would lie between 3.1 and 3.7 GeV if even a rough analogy with the ordinary L = 1 meson states is relevant. The possible transitions involving one such state between 3.1 and 3.7 GeV are given in Fig. 11. The allowed electric dipole transitions from $\psi(3.7)$ to the ^3P states are estimated[55] to collectively contribute several hundred keV to $\psi(3.7) \to$ all. Furthermore, in addition to being forbidden by Zweig's rule, the decay of the ^3P states into hadrons is further suppressed in a potential picture[55] by the vanishing of the p-wave wave function at the origin. This makes the decays of the ^3P states proceed dominantly by electric dipole radiation into $\psi(3.1)$. The main decay chain is then

$$\psi(3.7) \to \gamma\, {}^3P \to \gamma\gamma\psi(3.1) .$$

But we have heard earlier[21] that the branching ratio

$$\psi(3.7) \to \psi(3.1) + \text{anything}$$

is of order $\frac{1}{2}$. Given the bound on the total width of the $\psi(3.7)$ as well as the importance of $\psi(3.7) \to \pi^+\pi^-\psi(3.1)$ and probable existence of $\psi(3.7) \to \pi^0\pi^0\psi(3.1)$, there do not appear to be many hundreds of keV for $\psi(3.7) \to \gamma\gamma\psi(3.1)$. As better numbers come out on the $\psi(3.7)$ branching ratios and total width, this situation should be of great interest.

Another situation of interest is the question of what are the other decays of the $\psi(3.7)$ besides $\psi(3.1)$ + anything. For up to now, specific channels like $4\pi^\pm$ + one neutral or $6\pi^\pm$ + one neutral which are not due to $\pi\pi\psi(3.1)$ decays have not been identified. Furthermore, if one uses the direct decays of $\psi(3.1) \to$ hadrons to estimate those for $\psi(3.7)$ in a potential picture,[55] the combination of phase space and the wave function at the origin gives values of order 50 keV for this quantity. But about half the total width is not $\psi(3.1)$ + anything. Where are the other decays? One possibility, $\psi(3.7) \to \gamma\eta_c$, we have already discussed. Another is $\psi(3.7) \to \gamma\, {}^3P$, but that for some reason the ^3P states decay into hadrons rather than $\gamma\psi(3.1)$. But if either the η_c or the ^3P states go into hadrons, they should decay at least a few percent of the time into $4\pi^{\pm}$, $6\pi^{\pm}$, etc. In that case, if a particular transition like $\psi(3.7) \to \gamma\eta_c$ was the principal other decay mode of $\psi(3.7)$, one should have $4\pi^{\pm}\gamma$, $6\pi^{\pm}\gamma$, etc., at a detectable level in $\psi(3.7)$ decay.[57] A much more exciting possibility is that the $\psi(3.7)$ lies just above threshold for decay into charmed particles. Whatever is the case, it should be very enlightening when we know which if any of these alternatives is chosen by Nature.

The most straightforward interpretation within a charm scheme for the rise in R near 4 GeV is that this is the threshold for producing pairs of charmed particles. Meson states (like the $\psi(4.1)$?) composed of $c\bar{c}$ above such a mass find it kinematically possible to decay into pairs of charmed particles via amplitudes allowed by Zweig's rule. Hence, such meson states are no longer narrow and have more typical hadronic widths. Asymptotically one expects R to approach $3(\frac{4}{9} + \frac{1}{9} + \frac{1}{9} + \frac{4}{9}) = 10/3$ if one has four quarks, u, d, s, and c, each coming in three colors. In asymptotically free gauge theories R approaches its asymptotic value from above. The value of $R(\sqrt{Q^2} = 5.0) \simeq 5$ is thus presently regarded by charm enthusiasts[41] as compatible with their expectations.

However, in such a picture a substantial part ($\approx 1/2$) of the cross section for $e^+e^- \to$ hadrons should involve production of charmed particles in the final state once one is above the threshold. Higher mass charmed particles will decay by strong or electromagnetic interactions, both of which conserve charm, cascading eventually into the lowest mass states carrying a unit of charm. These lowest mass states may decay only weakly, and hence are very narrow. Furthermore, the most straightforward estimates[58] (as well as our experience with hyperons) indicate that nonleptonic decays dominate over semileptonic.[59] But in both cases, assuming a current-current form of the basic interaction, the origins of charm in weak interactions dictate that the charmed quark (c) is changed into a strange quark (s) by the large ($\cos\theta$) part of the Cabibbo current. As a result, states containing a charmed quark and $\bar{u}$ or $\bar{d}$ quark decay weakly dominantly into states with hadronic quantum numbers which include a unit of strangeness.[60] For meson decays, this unit of strangeness of the hadrons will manifest itself as a K meson among the decay products. Thus, following this naive argument, one expects first of all an increase in the number of K's per e^+e^- induced event once one crosses charmed particle production threshold. Secondly, from the nonleptonic decays one expects to find narrow peaks in the 2 GeV region in plots of the number of $K\pi$, $K\pi\pi$, etc., events versus invariant mass. As discussed earlier, there is no dramatic increase of kaon production between 3.0 GeV (below the threshold) and 4.8 GeV (above the threshold). Striking peaks in $K\pi$, $K\pi\pi$, etc., mass plots have not been announced - and by now everyone is aware of the importance of looking for them. One way to avoid this last difficulty would be to demand decay into $K+n\,\pi$'s where n is large (≈ 4 or 5). Then most decays involve neutral pions, which remain undetected with the present magnetic detector, and this prevents reconstruction of the invariant mass of the entire $K+n\pi$ system resulting from charmed particle decay. However, then the value of $\langle n_{ch}\rangle$ should rise once one is above threshold for charmed particle production and their subsequent decay to high multiplicity states. This doesn't seem to happen either (see Fig. 3). Another way out is to make semileptonic decays dominant, so one has an undetected neutrino in the decay products of charmed particles. Here the data[18,19] presented at this meeting on the inclusive muon spectrum

($1.0 < p_\mu < 2.4$ GeV) are an important restriction. For not only is the observed muon distribution in momentum and angle (collinearity and coplanarity) consistent with QED (including radiative corrections), but out of roughly 150 events all but a few have a total charged multiplicity of two, strongly indicating they mostly do <u>not</u> originate in multihadron events. It must be stressed that all these searches for various aspects of the charm picture are not yet conclusive, from the attempts to find evidence for the radiative transitions between $c\bar{c}$ states at the naively expected rates to the search for narrow peaks in $K\pi$ spectra and a change in the number of K's per event. Each is theoretically not crucial enough to kill the scheme, and in every case a change in the naive theoretical prediction by a factor of 2 to 5 will avoid any difficulty with present experimental results. Collectively, however, they make me, at least, somewhat uneasy.

V. CONCLUSION

In the last year many of our views on e^+e^- annihilation into hadrons have come almost full circle, except for one - its importance in understanding hadrons. As we have seen, the present data available on R are consistent with scaling, even precocious scaling, before new physics begins in the 3 to 4 GeV region. Below $\sqrt{Q^2} \simeq 3.6$ GeV, R is between 2 and 3 and consistent with, or consistent with approaching, the colored u, d, and s quark value of 2.

The new narrow resonances and the apparent threshold near $\sqrt{Q^2} = 4$ GeV are presumably related to the same physics and represent the excitation of new hadronic degrees of freedom. A possible explanation lies in the existence of a new hadronic quantum number, charm, and an associated fourth quark carrying a unit of this quantum number. The most crucial tests of this theory lie at the moment in spectroscopy - finding charmed particles and the other $c\bar{c}$ states expected to accompany the ψ's. We have examined these in some detail. Following the most naive theoretical estimates we have seen that presently there is not yet evidence for the expected spectroscopy, but that no really decisive test has been made. A scheme involving charm still seems to me the most attractive extant explanation for the totality of what has been observed.

Moreover, what has come out of all this is that the importance of quarks as the fundamental objects of hadron physics is clearer than ever. For hadron spectroscopy, current induced transitions between hadrons, deep inelastic scattering, <u>and</u> for e^+e^- annihilation, a theory based on abstraction from a field theory with fundamental fermion fields carrying quark quantum numbers again and again provides a basic understanding. When one finally writes down the complete story of strong interactions, and particularly that of hadron structure, near the beginning one will need to present the most basic hadronic measurement, that made by leptons shown in Figure 1.

ACKNOWLEDGEMENTS

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12. See, for example, J. D. Bjorken in Proceedings of the 6th International Symposium on Electron and Photon Interactions at High Energies, H. Rollnik and W. Pfeil, eds. (North-Holland, Amsterdam, 1974), p. 25.
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42. Nothing prevents one from adding more than one new quark: see R. M. Barnett, Harvard preprint, 1974 (unpublished); M. Suzuki, Berkeley

preprint, 1974 (unpublished); and many unpublished schemes.

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44. See in particular the asymptotically free gauge theory calculations of T. Appelquist and H. D. Politzer, ref. 16, and of A. De Rujula and S. L. Glashow, ref. 41.

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46. Estimates of charmed particle masses are to be found in refs. 39 and 41. A lower bound of ≈ 1.84 GeV is provided by the narrow $\psi(3.7)$ width.

47. See, for example, the review of the quark model states in F. J. Gilman, Proceedings of the Summer Institute on Particle Physics, M. Zipf, ed., SLAC Report No. SLAC-179, Vol. I, 307 (1974).

48. Such calculations are reported in the first three papers of ref. 41 and by E. Eichten et al., Cornell preprint, 1974 (unpublished); B. J. Harrington et al., Phys. Rev. Letters 34, 168 (1975); H. J. Schnitzer, Harvard preprint, 1974 (unpublished); T. P. Cheng and P. B. James, Missouri preprint, 1975 (unpublished); and J. Kogut and L. Susskind, Cornell preprint, 1975 (unpublished).

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51. N. Barash-Schmidt *et al.*, "Review of Particle Properties," Phys. Letters 50B, No. 1 (1974).

52. Using the observed rate for $\phi \to \gamma\pi$ of the Orsay experiments, ref. 9, one deduces $\approx 1/200$ for the right-hand side of Eq. (9).

53. Such mixing and a model for the violations of Zweig's rule through the three-gluon channel in asymptotically free gauge theories have been discussed in detail by A. De Rujula and S. L. Glashow, ref. 41. See also T. Appelquist and H. D. Politzer, ref. 16; and T. Appelquist *et al.*, ref. 41.

54. The phase space for $N^*(1470) \to (\pi\pi)_S N$ ($\rho'(1600) \to \pi\pi\rho$) is less (greater) than that for $\psi(3.7) \to \pi\pi\psi(3.1)$.

55. These transitions are discussed in detail by T. Appelquist *et al.*, ref. 41; E. Eichten *et al.*, ref. 48; J. Borenstein and R. Shankar, Harvard preprint, 1974 (unpublished); and S. Rudaz, Cornell preprint, 1974 (unpublished). They have also been treated with varying thoroughness in many of the papers in refs. 39 and 41.

56. We use the notation η_c for the pseudoscalar state (associated with the $\psi(3.1)$) following M. K. Gaillard, B. W. Lee, and J. L. Rosner, ref. 41.

57. Another way out of this "difficulty" is for $\eta_c \to \gamma\gamma$ to be an important decay mode. One calculates $\Gamma(\eta_c \to \gamma\gamma) \simeq 300$ keV from p^3 phase space plus SU(4) symmetry ($A(\eta_c \to \gamma\gamma) = \left(\frac{4\sqrt{2}}{3}\right) A(\pi^0 \to \gamma\gamma)$) and $\Gamma(\pi^0 \to \gamma\gamma)$ [or $\Gamma(\eta \to \gamma\gamma)$ with account of singlet-octet mixing.] However, aside from

questions of whether this overestimates the true width, even with this large a $\gamma\gamma$ width the decay of η_c into hadrons is expected to be over an order of magnitude larger according to the papers in ref. 53.

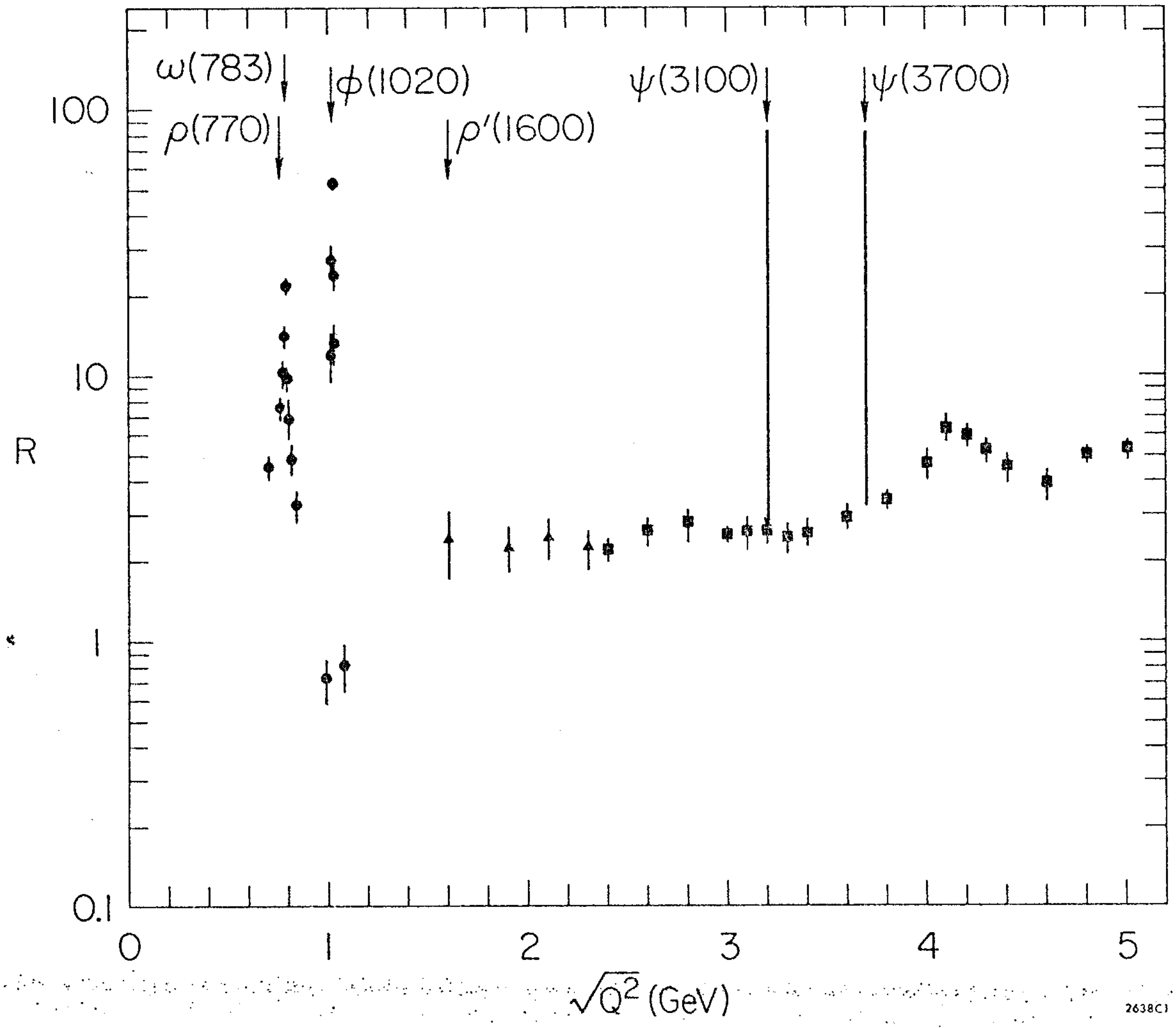
58. See for example M. K. Gaillard, B. W. Lee, and J. L. Rosner, ref. 41.

59. G. Altarelli, N. Cabibbo, and L. Maiani, Ecole Normale Superieure preprint, 1974 (unpublished). See also R. L. Kingsley et al., Princeton preprint, 1975 (unpublished).

60. If one assumes that the piece of the weak nonleptonic Hamiltonian transforming like the regular, 15-dimensional representation of SU(4) dominates, this is no longer true, as noted by J. D. Bjorken and H. Harari (private communication), and by A. Pais and V. Rittenberg, Rockefeller preprint, COO-2232B-69, 1975 (unpublished). Also H. Fritzsch (private communication).

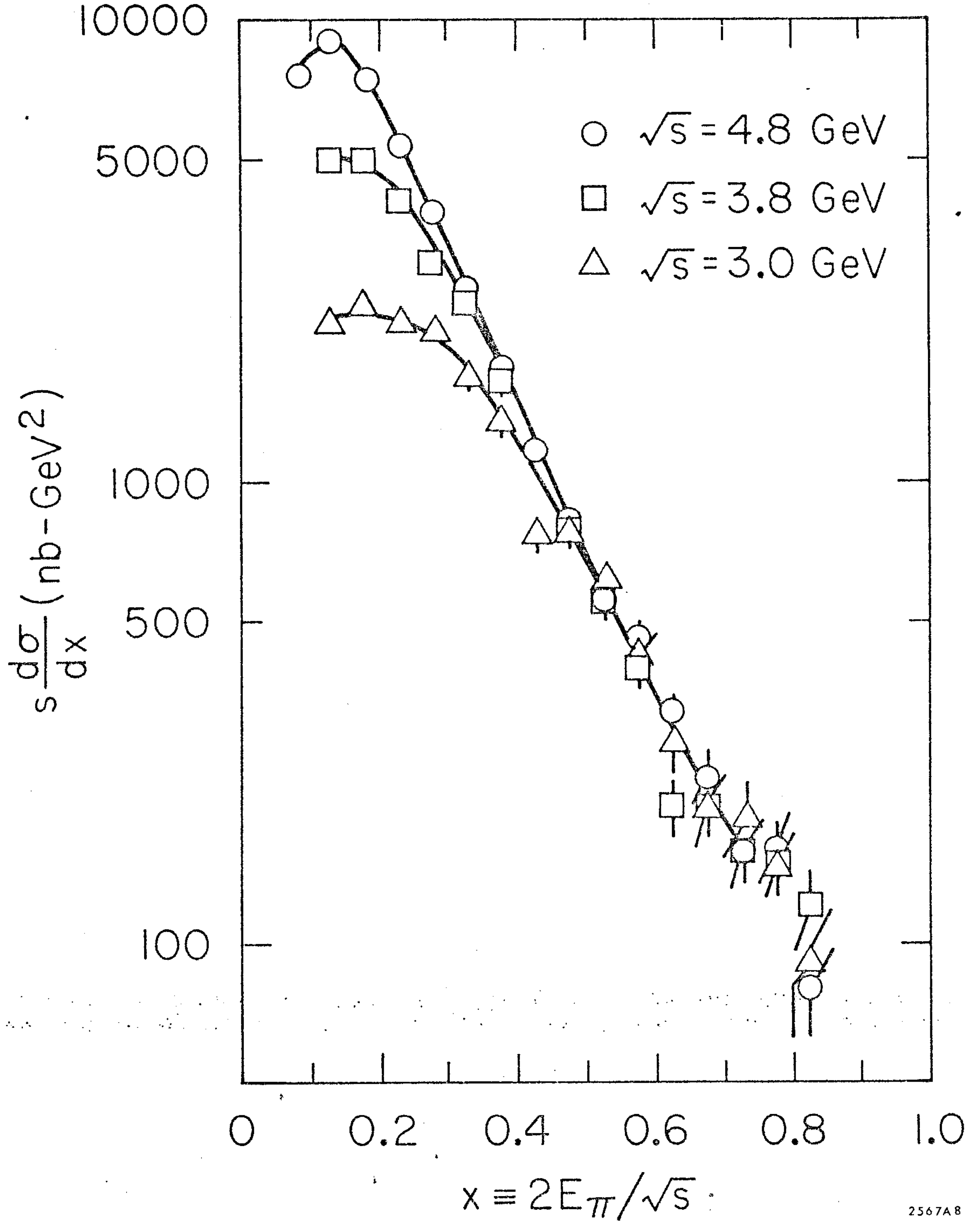
FIGURE CAPTIONS

1. $R = \sigma_T(e^+e^- \to \text{hadrons})/\sigma(e^+e^- \to \mu^+\mu^-)$ from measurements at Orsay,[9] Frascati,[10] and SLAC.[11]
2. The inclusive charged particle distribution[17] $s\, d\sigma/dx$ at $\sqrt{Q^2} = \sqrt{s} = 3.0$, 3.8, and 4.8 GeV.
3. The charged hadron multiplicity[11] versus $\sqrt{Q^2}$.
4. Fractions[17] of π^-, K^-, and $\bar{p}$ at $\sqrt{Q^2} = 4.8$ GeV.
5. Fraction of the total energy in charged hadrons.[17]
6. Decay of a ψ through a single virtual photon into (a) e^+e^- and (b) hadrons.
7. A possible mechanism for ψ photoproduction.
8. The decay of a meson to two other mesons in a quark picture which is (a) allowed or (b) forbidden by Zweig's rule.
9. The possible strong interaction transitions of the $\psi(3.1)$ and $\psi(3.7)$. Dashed lines indicate decays forbidden by Zweig's rule.
10. The possible electromagnetic and strong decays involving a $C = +$ state with $c\bar{c}$ quark content and a mass lower than 3.1 GeV. Dashed lines indicate decays forbidden by Zweig's rule.
11. The possible electromagnetic and strong decays involving a $C = +$ state with $c\bar{c}$ quark content and a mass between 3.1 and 3.7 GeV. Dashed lines indicate decays forbidden by Zweig's rule.



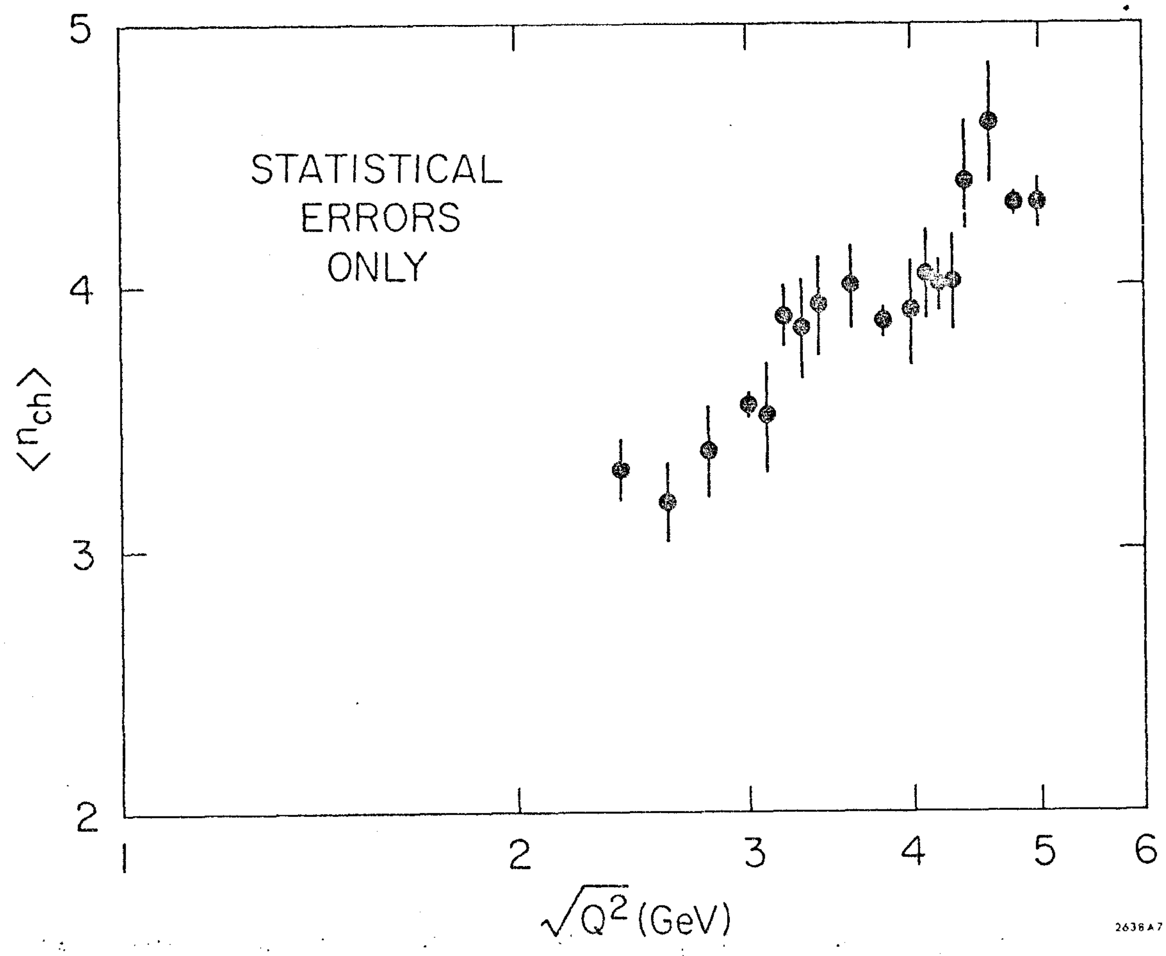
ω(783)
ρ(770)
φ(1020)
ρ′(1600)
ψ(3100)
ψ(3700)
100
10
R
1
0.1
0
1
2
3
4
5
√Q² (GeV)
2638C1

Fig. 1



10000
5000
1000
500
100
○ $\sqrt{s} = 4.8$ GeV
□ $\sqrt{s} = 3.8$ GeV
△ $\sqrt{s} = 3.0$ GeV
$s\frac{d\sigma}{dx}$ (nb-GeV^2)
0
0.2
0.4
0.6
0.8
1.0
$x \equiv 2E_\pi/\sqrt{s}$
2567A8

Fig. 2



5
4
3
2
$\langle n_{ch} \rangle$
STATISTICAL
ERRORS
ONLY
1
2
3
4
5
6
$\sqrt{Q^2}$ (GeV)
2638A7

Fig. 3

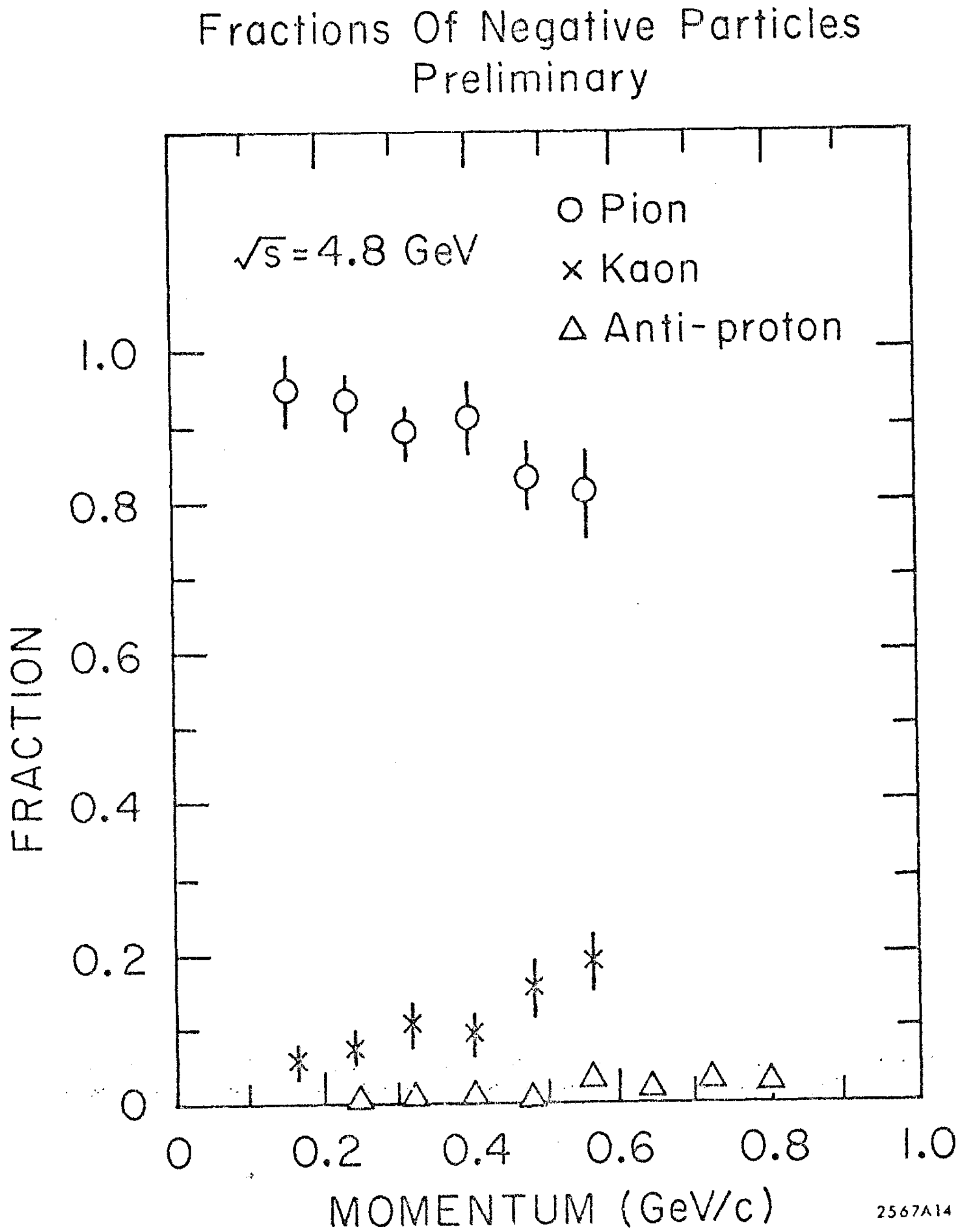
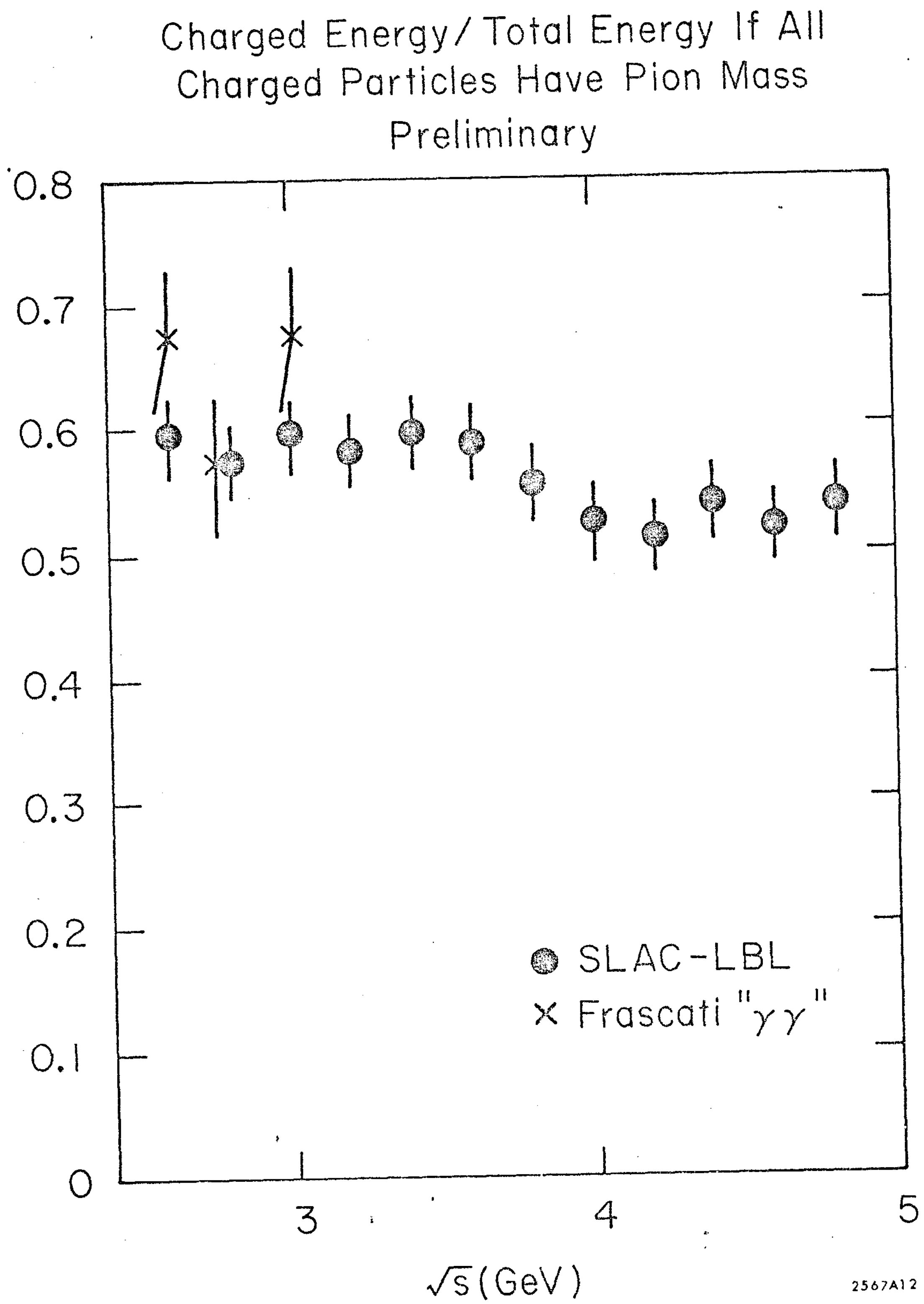
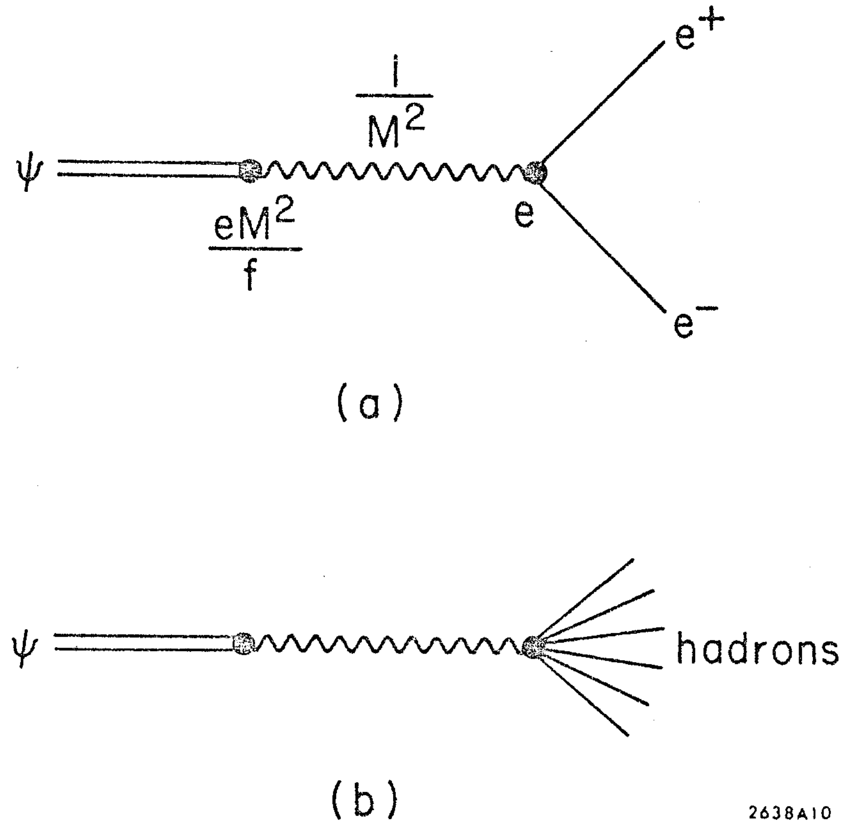

Fractions Of Negative Particles
Preliminary
$\sqrt{s}$ = 4.8 GeV
O Pion
× Kaon
Δ Anti-proton
1.0
0.8
0.6
0.4
0.2
0
FRACTION
0
0.2
0.4
0.6
0.8
1.0
MOMENTUM (GeV/c)
2567A14

Fig. 4



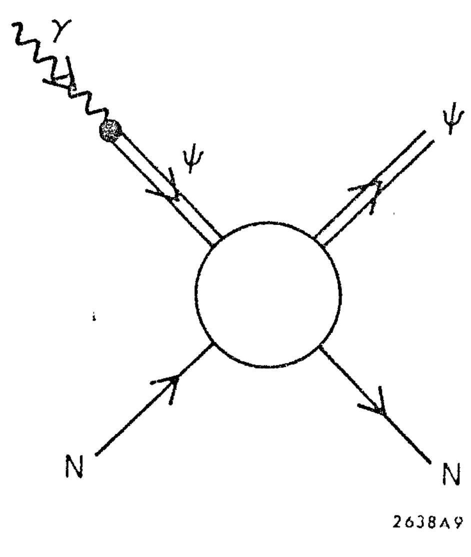
Charged Energy/ Total Energy If All
Charged Particles Have Pion Mass
Preliminary
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
3
4
5
SLAC-LBL
Frascati "$\gamma\gamma$"
$\sqrt{s}$ (GeV)
2567A12

Fig 5



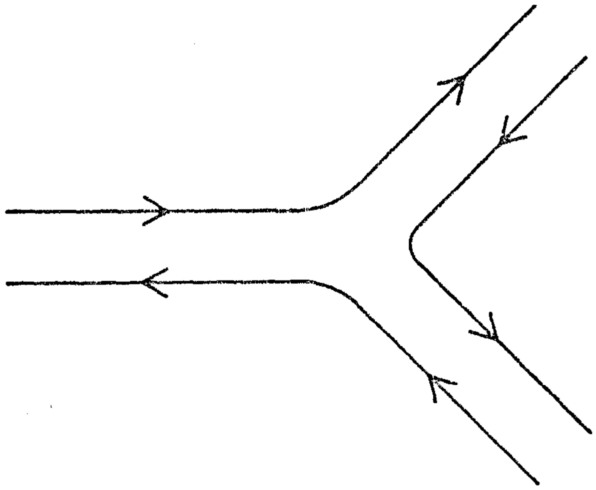
$\frac{1}{M^2}$
e^+
ψ
e
$\frac{eM^2}{f}$
e^-
(a)
ψ
hadrons
(b)
2638A10

Fig. 6

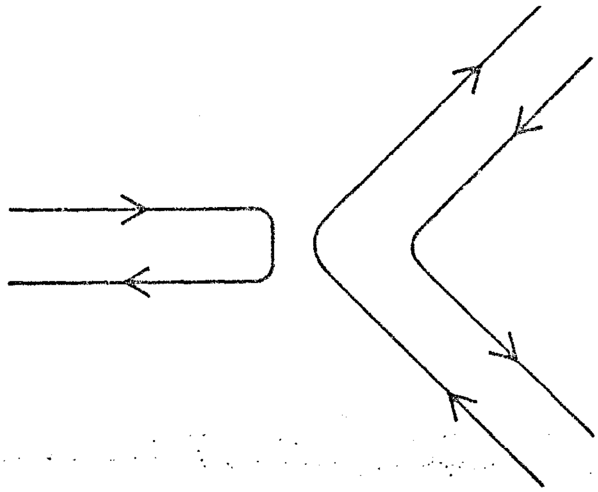


γ
ψ
ψ
N
N
2638A9

Fig. 7



ALLOWED
(a)



FORBIDDEN
(b)

2638A8

Fig. 8

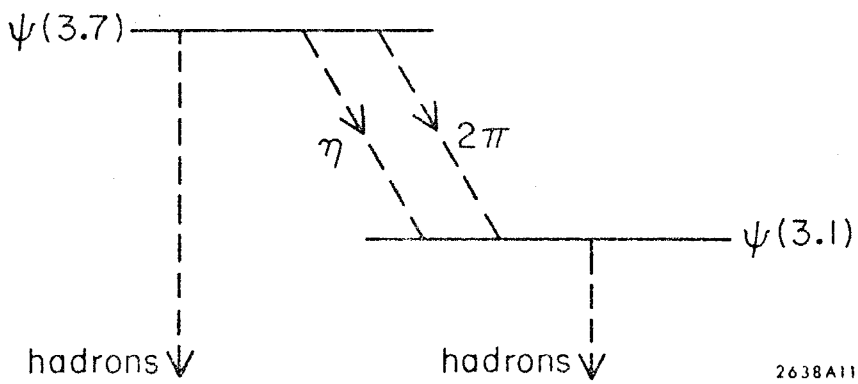


Fig. 9

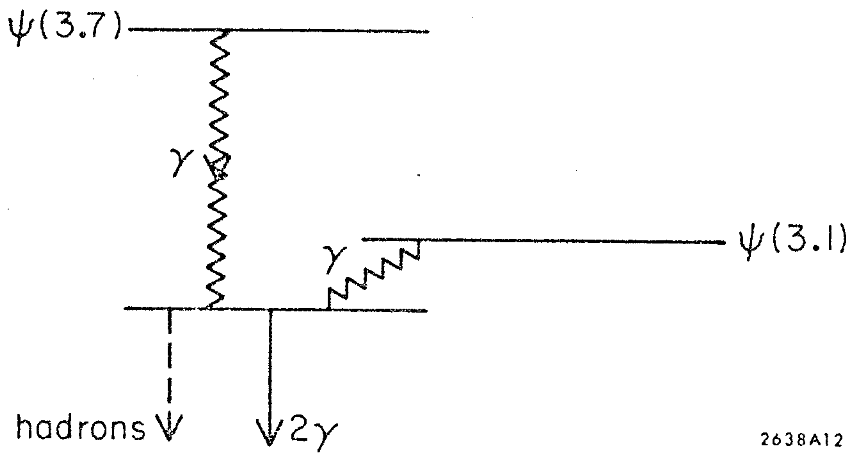


Fig. 10

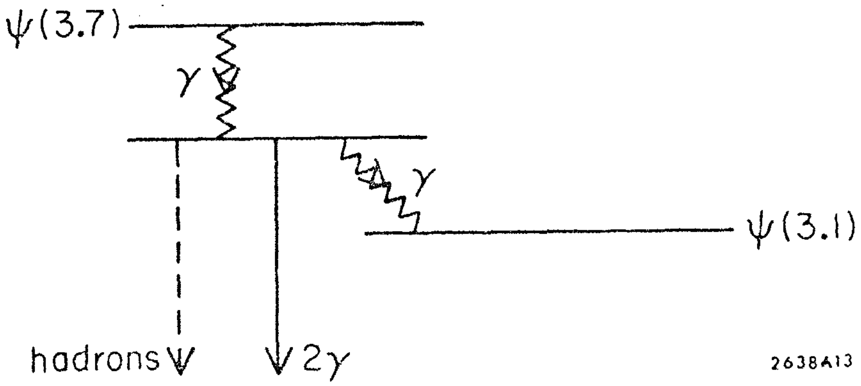


Fig. 11