

THEORETICAL IDEAS ABOUT $e^-e^+ \rightarrow$ HADRONS AT HIGH ENERGIES

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1. INTRODUCTION

The subject does not really need much introduction: theorists were almost unanimous in predicting that

$$R(q^2) \equiv \frac{\sigma(e^-e^+ \rightarrow \gamma \rightarrow \text{hadrons})}{\sigma(e^-e^+ \rightarrow \gamma \rightarrow \mu^-\mu^+)}$$

would $\rightarrow$ constant as $q^2 \rightarrow \infty$, but these predictions have not been borne out in the range $9 \lesssim q^2 \lesssim 25$ as seen by experiments at CEA¹⁾ and SPEAR²⁾. Because of the gravity of this theoretical debacle, and the intensity of interest mirrored by the number of recent theoretical papers on $e^-e^+ \rightarrow$ hadrons, in this talk I allow myself to be deflected into mainly discussing this process in energy ranges presently (CEA and SPEAR) and soon to be (SPEAR II, DORIS) available. Tests of QED, implications of gauge theories of weak interactions,⁽³⁾

and purely theoretical problems such as quark confinement will be unjustifiably ignored. Other topics - such as the implications of the hadronic data for QED, and two-photon processes⁽⁴⁾ - will be treated slightly.

We start by summarizing the main features of the high ($q^2 \gtrsim 9$) energy data from CEA and SPEAR which theoreticians must confront.

1) The ratio R of the "hadronic" cross-section (derived from events with ≥ 3 , or ≥ 2 coplanar, charged tracks) to $\sigma(e^-e^+ \rightarrow \mu^-\mu^+)$ is large and rising from about 2 or 3 at $q^2 \approx 9$ to about 4 to 7 at $q^2 \approx 25$.

2) For $x \equiv 2E/\sqrt{q^2} \gtrsim 0.5$, the inclusive hadronic distribution is small, and consistent with $q^2 d\sigma/dx$ scaling. For $x \lesssim 0.5$ distribution is large and $q^2 d\sigma/dx$ increases rapidly with q^2 . The average charged particle momentum is almost constant at ~ 500 MeV.

3) The angular distribution of charged tracks is consistent with isotropy for $9 \lesssim q^2 \lesssim 25$, and

$$|\cos \theta| \lesssim 0.6.$$

4) The mean charged particle multiplicity seems to rise only slowly, with $\langle n_{ch} \rangle \approx 4$.

5) As a result of 2) and 4) the fraction of the total available energy which is carried by charged particles seems small, falling from around 0.6 at $q^2 \approx 9$ to about 0.5 at $q^2 \approx 25$.

6) At least at lower momenta where they can be reliably separated $\langle n_{\pi^\pm} \rangle : \langle n_K^\pm \rangle : \langle n_p \rangle \approx 100:10:1$.

2. Possible Mechanisms

It is possible to classify possible explanations of the data as follows:

1. The "hadronic" events may not in fact be due to the production of hadrons alone.
2. Hadrons may be produced by two-photon collisions.
3. Hadrons may be produced by one photon exchange.
4. Hadrons may be produced by some "no-photon" mechanism.

In the remainder of this section we will give arguments against the first two of these possibilities. Much of the rest of the talk will discuss the one-photon exchange mechanism, thereby reflecting my prejudice.

Are the "hadronic" events really hadronic?

The most likely non-hadronic explanation of the data seems to be production via a single photon (see Fig. 1) of a heavy lepton pair. These would then decay weakly, emitting a $(\nu, \bar{\nu})$ pair and some other particles. These might either be leptons (μ, e) or hadrons $(\pi, K, \rho, A, \dots)$. Thus there are some obvious experimental signatures such as (μe) coincidences, and deviations from the QED predictions for the distributions of $(\mu^+ \mu^-)$ pairs.

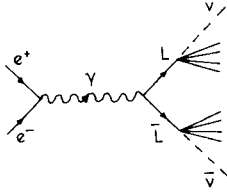


Fig. 1 $e^+e^- \rightarrow \gamma \rightarrow L\bar{L} \rightarrow \nu\bar{\nu} + \text{anything}$.

The model has the advantage that it discards neutral energy in the form of neutrinos. However the model has problems - if it is to explain the apparent rise in R then at least two leptons with masses in the range 1.5 to 2 GeV are needed. While fashionable gauge models often require heavy leptons⁽⁵⁾, these masses are surprisingly small, and well below experimental limits on heavy muon masses. Also all the (μe) coincidences are consistent with other mechanisms, and the observed charged multiplicity is larger than expected from heavy leptons. Hence we discard them provisionally, while waiting for the definitive answer from heavy lepton searches at SPEAR II and DORIS.

The Two-photon Process

The dominant higher order electromagnetic graph at CEA-SPEAR-DORIS energies is expected to be the two-photon graph of Fig. 2. This process also has an answer to the energy problem, losing energy via $e^\pm$ passing unseen out of the ends of the apparatus. However the SPEAR experimenters have reasons to believe that $\sigma_{2\gamma}/\sigma_{1\gamma} \leq 10\%$. This is in accord with the 2γ cross section observed at Frascati, which agrees with theoretical expectations of a small value. The SPEAR experimenters are improving their understanding of the 2γ events, but for now we discard them as a possible explanation of the large value of R .

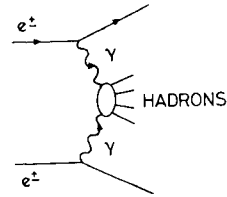


Fig. 2 The two photon process $e^\pm e^\pm \rightarrow e^\pm e^\pm + \text{hadrons}$.

Before leaving 2γ processes, there are some interesting theoretical observations to be made. The bugbear of parton models for this reaction has always been that their predictions have been most clear cut when both photons were highly space-like $(|q_1^2|, |q_2^2|, (q_1+q_2)^2 \rightarrow \infty)$ in which limit the disconnected box diagrams of Fig.3 would dominate.

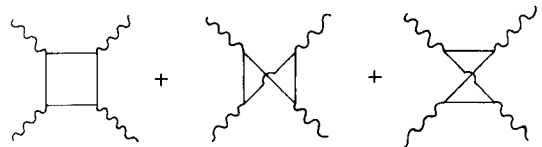


Fig. 3 The parton model box diagrams for $\gamma\gamma$ scattering.

However the cross-section in this case would be murderously small. Various authors including Walsh and Zerwas, Kingsley, Worden and Zerwas⁽⁶⁾ have however given good arguments that the box diagrams should also show up, and in fact dominate, in the singly deep inelastic limit ($|q_1^2| \rightarrow \infty$, q_2^2 fixed, $(q_1+q_2)^2 \rightarrow \infty$). They find - this is also true in generalized vector meson dominance approaches - that

$$\sigma_T \rightarrow f(x) \log q_1^2$$

$$\sigma_L \rightarrow g(x)$$

where $x \approx q_1^2/2q_1 \cdot q_2$. Hence there is an anomalous scaling law, and the Callan-Gross relation is violated for scattering off photons. Worden⁷⁾ has gone further, and argued that analogously to the conventional parton-model polynomial fixed pole in deep inelastic eN scattering, the box diagrams give a polynomial fixed pole in $\gamma\gamma$ scattering, which yields a sum rule valid at $q_1^2 = q_2^2 = 0$ for the amplitude T_{++--} . In the parton model it gives the sum of the quark (charge)⁴:

$$\frac{2}{\pi} \int_{\text{Thresh}}^{\infty} \frac{d\nu}{\nu} \text{Im } T_{++--} = - \frac{1}{2\pi^2} \sum Q_i^4$$

Hence we at last have a parton model result valid for small q^2 where the bulk of the 2γ cross-section lies. It may help us to discover whether the parton model failures in single-photon annihilation are connected with having time-like photons, or with trying to use disconnected parton loops.

3. The One-Photon Mechanism - General Results

Before discussing models based on the one-photon mechanism we review general results applicable to all such models.

QED and a large $R(q^2)$

Hadronic vacuum polarization effects clearly affect standard QED calculations: we should ask

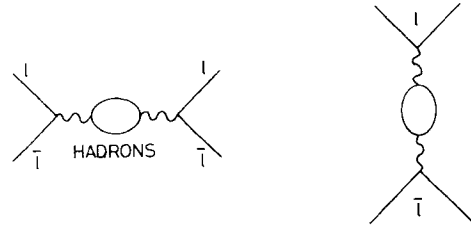


Fig. 4 Lowest order hadronic insertion corrections to leptonic processes.

what modifications occur in processes such as $e^-e^+ \rightarrow e^-e^+, \mu^-\mu^+$ from such insertions (see Fig. 4), and also whether any disasters would befall QED were $R(q^2)$ to increase indefinitely. Calculations of Bjorken, Brodsky and Frishman⁽⁸⁾ suggest that if $R(q^2)$ were to increase linearly up to $\sqrt{q^2} \approx 35$ GeV, where it would be $O(100)$ so that perturbation theory in α would break down, then effects on Bhabha scattering and $e^-e^+ \rightarrow \mu^-\mu^+$ would be $\leq O(10\%)$ at SPEAR II/DORIS energies. The possibility exists that precision QED tests at these energies could start revealing deviations from lowest order QED, and even give us information about the behaviour of $R(q^2)$ at higher energies. Could $R(q^2)$ increase indefinitely? If the increase were linear the vacuum polarization would need an extra subtraction, introducing an extra parameter into QED. Sensible choices of this parameter would not unduly disturb the muon (g-2) calculations. In any case it would be necessary to sum all orders in the hadronic vacuum polarization $\pi(q^2)$ getting a photon propagator $D(q^2) = \frac{1}{q^2(1-\pi(q^2))}$

$$\text{with } \pi(q^2) \sim \begin{cases} (q^2)^\beta (\beta < 1) & \text{when } R(q^2) \sim (q^2)^\beta \\ (q^2) \log q^2 & \end{cases}$$

Such theory would be very bizarre: Cabibbo

and Karl⁽⁹⁾ have pointed out that it would have Lee-Wick complex poles, and the photon propagator would be so self-damped that $\sigma(e^-e^+ \rightarrow \mu^-\mu^+)$ would fall relative

to the conventional point-like cross-section by a power $(q^2)^{-2\beta}$ (10). This is how $R \sim (q^2)^\beta$ remains consistent with the new improved unitarity bound of Cabibbo, Karl and Wolfenstein¹¹⁾.

$$\sigma(e^-e^+ \rightarrow \text{hadrons}) \lesssim \frac{12\pi}{q^2(R+4/R)}$$

derived assuming photon-like quantum numbers in the direct channel and other reasonable-seeming approximations. This is a great improvement on the old unitarity bound of Cabibbo and Gatto¹²⁾:

$$\sigma(e^-e^+ \rightarrow \text{hadrons}) + \sigma(e^-e^+ \rightarrow \mu^-\mu^+) \leq \frac{3\pi}{2} q^2$$

In a theory with $R(q^2)$ indefinitely increasing QED apparently remains renormalizable, at least if photon-photon scattering does not behave too strangely. Time will tell whether Nature chooses this course.

Energy crisis or energy problem?

The small fraction of observed charged energy has caused much comment. Most simple dynamical models - conventional partons or light-cone ideas, thermodynamical models, etc - predict

$$d\sigma(\pi^+) = d\sigma(\pi^0) = d\sigma(\pi^-)$$

and it seems that $\langle n_\pi \rangle \gg \langle n_K \rangle, \langle n_p \rangle$ at least at low momenta. Hence one would have expected $\frac{\langle E_\pi \rangle}{\langle E_{ch} \rangle} \sim \frac{1}{2}$

instead of 2/3 to 1 as apparently observed.

(Though it is possible that an anomalously large fraction of the energy passes unseen out of the ends of the apparatus, as in the two-photon mechanism).

If not, the ratio $\langle E_\pi \rangle / \langle E_{ch} \rangle$ is higher than in most purely hadronic reactions, though at $q^2 \approx 9$ not much different from that in $p\bar{p} \rightarrow$ pions. There are some other processes with $\langle E_\pi \rangle / \langle E_{ch} \rangle$ large - for example in both charged and neutral current neutrino-production events at low energies $\langle E_\pi \rangle / \langle E_{ch} \rangle$ is large and indications are that essentially all the neutral energy is in the form of γ 's correlated into π^0 's.

Also, stringent rigorous bounds on $\langle E_\pi \rangle / \langle E_{ch} \rangle$ are hard to come by. The optimal isospin bound for

the π^0 energy as a fraction of the total energy is found by Bell, Karl and Llewellyn Smith³⁾ to be:

$$\langle E_\pi \rangle / \langle E_{tot} \rangle < 0.77$$

Even with a reasonable admixture of $I=0$ final states of pions, for which $\langle E_\pi \rangle / \langle E_{ch} \rangle = 1$ rigorously this bound is not yet threatened by the data. Because if this, the possibility of "creeping 20%ism" modifying the experimental data, and the possibility of non-pion contamination, we are tempted to demote the energy crisis to an energy problem. Also, mechanisms have been proposed, for example by Devenish et al¹⁴⁾, whereby the average π^0 energy is greater than that for $\pi^\pm$.

4. The Naive parton model

Everyone knows the predictions of the naive parton model

$$R(q^2) \rightarrow \sum_{\text{spin } \frac{1}{2}} Q_i^2 + \frac{1}{4} \sum_{\text{spin } 0} Q_i^2$$

summing over the (charge)² of the partons, with $q^2 \frac{d\sigma}{dx} \rightarrow f(x)$

These predictions are common to canonical light-cone and short distance approaches: even agnostic followers of Wilson at short distances would agree on $R \rightarrow$ constant. In the most popular coloured quark model $R \rightarrow 2$. In view of the experimental rise in R for $9 < q^2 < 25$, two viewpoints are possible.

(i) R scaled in the range $2 \leq q^2 \leq 9$ (data in this shows an apparent plateau with $R \sim 1.5$ to 2.5) and the CEA and SPEAR data reflect a modification or supplement to the parton model result, which was correct.

(ii) R has not yet scaled, but may do for $q^2 \geq 25$.

and late scaling was anyway to be expected for time like photons.

Hence we should examine theoretically the

Approach to scaling in $\sigma_{\text{tot}}(q^2)$

Reasons for not being worried by a slow approach to scaling in annihilation include¹⁵⁾:

a) there are strong direct channel resonances with $q^2 > \rho, \omega, \phi, \rho', \dots$ and presumably these must be well past before scaling sets in. (But should the required $|q^2|$ be an order of magnitude greater than the $1/2$ of electroproduction?);

b) only one partial wave contributes to e^-e^+ annihilation via 1γ exchange. Hence the density of states is far less than in electroproduction where all partial waves are excited. Since scaling is presumably a co-operative phenomenon with contributions from a statistically large number of hadronic states, scaling should be slower in annihilation than in electroproduction;

c) there may be threshold effects, such as that for producing $N\bar{N}$ pairs, which may delay the onset of scaling;

d) there may be a connection with the confinement problem - perhaps it requires much q^2 to create a "bag" - "anti-bag" pair out of the vacuum.

The first two of these arguments may well be correct, but a counter-example does exist¹⁶⁾. It is a simple dual model-inspired ratio of Γ - functions model which has just generalized vector meson poles, the same rate of approach to scaling for $q^2 \geq 0$, and

$$R(q^2)/R(\infty) = 1 + \frac{o(1)}{\alpha' q^2} + \dots$$

where α' is the usual Regge trajectory slope. The small ratios of $\langle n_p \rangle : \langle n_{K^\pm} \rangle : \langle n_{\pi^\pm} \rangle$ at CEA and SPEAR suggest that the production of real $N\bar{N}$ pairs cannot be blamed. However, di Giacomo and Konishi¹⁷⁾

point out that there could be virtual pairs which annihilate to yield pions predominately. In connection with viewpoint (i) above we should perhaps remember that at $q^2 \approx 9$, SPEAR found $\langle E_o \rangle / \langle E_{ch} \rangle \approx 0.6$, not too different from the naive parton prediction of $1/2$.

To further confuse the issue, recall that as emphasized by Fritzsche and Minowski and by Choudhury⁽¹⁸⁾, if the canonical quark-parton picture is taken seriously, then

$$\frac{R(q^2)}{R(\infty)} = 1 + O(1/q^4)$$

Approach to scaling in $d\sigma/dx$

Many authors¹⁹⁾ have pointed out that scaling in $d\sigma/dx$ is not to be expected in the naive parton model at present values of q^2 . In a large class of canonical parton or light-cone models large corrections are expected at small centre of mass energies, so that

$$q^2 x \frac{d\sigma}{dx} \rightarrow f(x) + \frac{1}{x^2 q^2} g(x) + \dots$$

where f and g are finite as $x \rightarrow 0$. To see simply how this effect arises, consider for example the simple Bjorken-Feynman parton model in which the virtual photon forms a parton-anti-parton pair, which then transmogrify into a "cigar" or double jet of hadrons, aligned in momentum space along the jet axis except for a transverse momentum of $O(400)$ MeV (see Fig.5). Calculating the contribution of such a cigar to the one particle inclusive hadronic

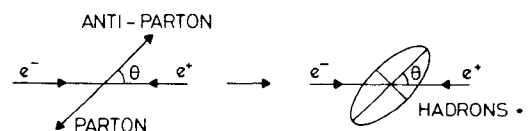


Fig. 5 Conversion of parton-antiparton pair into a cigar of hadrons in momentum space.

distribution the finite $\langle p_T \rangle$ gives $\frac{1}{x^2 q^2}$

corrections to scaling as exhibited above, and also changes the hadronic angular distribution from the canonical spin $\frac{1}{2}$ parton prediction $(1 + \cos^2\theta)$. It is easy to get a complete break down of scaling and near isotropy for $x \lesssim 0.4$, with an angular distribution $\propto (1 + O(\frac{1}{2}) \cos^2\theta)$ at $x \sim 0.6$ even at CEA-SPEAR energies. The situation is reminiscent of that in purely hadronic processes at comparable energies, where apart from transparent leading particle effects, pion distributions looked rather isotropic in the centre-of-mass.

²⁰
Gatto and Preparata have recently emphasized these low centre-of-mass momentum corrections to parton scaling, using the massive quark model to connect $e^+e^- \rightarrow \pi + x$ and $pp \rightarrow \pi + x$. But it is not necessary that a slow approach to scaling in the inclusive cross-section need imply a slow approach to scaling in σ_{tot} : recall the different rates at which $\sigma(\pi^- p \rightarrow \pi^+ + x)$ and $\sigma_{\text{tot}}(\pi^- p)$ approach asymptotically. In the naive parton model the approach to scaling in σ_{tot} is just related to the rate at which parton-anti-parton pairs are produced, which is independent of the hadronic P_T cut-off and the real $1/x^2 q^2$ corrections in $q^2 \times d\sigma/dx$.

5 - Modifications to the Naive Parton Model

In this section we discuss approaches which modify the conventional quark-parton model, either by changing the spectrum of partons, or by giving the partons structure, or by drawing new parton diagrams. First we discuss some constraints which should apply in all models where $\sigma(e^+e^- \rightarrow \gamma \rightarrow \text{hadrons}) \sim 1/q^2$ asymptotically.

Anomalies

Wilson²¹⁾ showed how (assuming PCAC) short distance effects determine the $\pi^0 \rightarrow 2\gamma$ decay rate. Crewther²²⁾ showed that this amplitude was proportional to the product of a parameter K (proportional via a sum rule of Bjorken²³⁾ to the polarization asymmetry in deep inelastic electroproduction), and R_8 (the portion of R due to the usual SU_3 octet part of the electromagnetic current). The experimental $\pi^0 \rightarrow 2\gamma$ decay rate agrees well with the usual three-colour quark model, so if we accept the Wilson-Crewther analysis, three possibilities occur - either
i) R eventually falls to 2, as predicted by the quark-parton model;
ii) R tends to some other limit, and the difference is due to an SU_3 singlet part of the electromagnetic current, as generated by charmed quarks for example
iii) R approaches a limit $\neq 2$, there is no SU_3 singlet current contribution, and K differs from the quark parton prediction.

This last possibility is very interesting - perhaps the CEA and SPEAR data are telling us to expect surprises in polarized electroproduction? An experiment at SLAC is underway which, while unable to test rigorously the sum rule of Bjorken, should give us some indication whether K is much smaller than quark-partons would suggest.

There is another anomaly^{22,24)} which relates R directly to the vertex of the trace of the energy momentum tensor θ_μ^μ and two electromagnetic currents all at zero momentum. This result has been used in two ways. The first^{22,24)} was to extrapolate in the e_μ^μ channel to the $\epsilon(700)$ meson pole, getting a relation between R and the $\epsilon \rightarrow 2\gamma$ decay rate. If the two recently observed $e^+e^- \rightarrow e^+e^- \pi^+ \pi^-$ events with $M(\pi^+ \pi^-) \sim 600-700$ MeV are interpreted

as proceeding via the ϵ , the experimental rate yields $R_{\gamma}^{25)} 5.8^{+3.2}_{-2.5}$. Eliezer²⁶⁾ has taken a slightly different approach, dominating θ_{μ}^{ν} with two scalar mesons, and estimating independently their $\gamma\gamma$ decay rates, and hence estimating $R \approx 8^{+2}$. Terazawa²⁷⁾ has used the anomaly differently, extrapolating in the current channels to the vector meson poles and getting

$$R \approx \frac{16\pi^2}{f_{\rho}^2}, \text{ where } \frac{f_{\rho}^2}{4\pi} \approx 2.2 \text{ implying } R \approx 5.7^{+0.9}$$

However there are theoretical problems with this application of vector meson dominance²⁸⁾. Using a specific lagrangian model, O'Donnell²⁹⁾ gets $R \approx \frac{12\pi^2}{f_{\rho}^2}$, and Greco's generalized vector dominance³⁰⁾ has $R \approx \frac{8\pi^2}{f_{\rho}^2}$.

New partons

One attractive possibility is to retain the parton idea, but change the spectrum of partons. The charmed quark of Glashow, Iliopoulos and Maiani³¹⁾ gives, in its three-colour form, $R = 3^{1/3}$ (rather lower than present data) whose attainment need not be accompanied by copious production of charmed particles. Another attractive model is that of Han and Nambu³²⁾ which replaced each fractionally charged quark by an integrally charged triplet of coloured quarks. Low-mass hadrons are supposed to be colour symmetric quark combinations and as long as just they are being produced, R is 2. Then there are unsymmetric quark combinations (coloured hadrons), with higher masses: above the colour threshold their production increases R to 4. This is not inconsistent with the Frascati observations of $R = 1.5$ to 2.5, and the highest energy SPEAR estimate 4.9 ± 0.8 . It could be that the hadronic Hamiltonian is colour symmetric, in which case coloured hadrons could only decay electromagnetically, and the rise in R would be accompanied by a rise in the fraction of neutral energy.

Han and Nambu reproduce standard quark model results below the colour threshold; afterwards cross-sections rise in general. If this effect does not show up in deep inelastic experiments at NAL, then the model is probably irrelevant to present annihilation data.

Recently more drastic additions to the parton spectrum have been proposed. For example Cleymans and Komen³³⁾ have discussed spin-1 partons, getting

$$\sigma(e^{-}e^{+} \rightarrow \text{hadrons}) \rightarrow \frac{\pi\alpha^2}{3m_v^2}$$

A motivation for such beasts has recently been found by Fritzsch and Minkowski³⁴⁾ amongst others, while constructing unified gauge theories of the weak, electromagnetic and strong interactions. They give examples of theories based on $SU_{12} \times SU_{12}$ and $SU_{16} \times SU_{16}$ which have $R \rightarrow 18$ and $35^{1/3}$ respectively. Renormalizability means that $R \not\rightarrow \infty$ in their models.

Most radically of all, Cabibbo and Karl⁹⁾, Matveev and Tolkachev³⁵⁾ and Rozenblit³⁶⁾ have considered the possibility of an infinity of partons, in which case $R \rightarrow \infty$ asymptotically.

Renormalization Group Approaches

One of the first deductions³⁷⁾ in asymptotically free gauge theories was that for them the asymptotic limit $R \rightarrow \Sigma Q^2$ should be approached logarithmically

$$R \rightarrow 2 \left(1 + \frac{4}{9} \frac{1}{\log(q^2/q_0^2)} + \dots \right)$$

for example in the three colour quark model, with q_0 some unknown scale. This cannot be compared with present data, as it predicts an asymptotic fall to a constant value of R . The present rise would have to be ascribed to mass corrections not

calculable using renormalization group techniques.

Kogut³⁸⁾ has suggested an alternative, one in which for $q^2 \lesssim 15$ the effective coupling constant is small, but in the CEA-SPEAR range it increases, implying non-negligible corrections to the simple parton diagrams from the gluonic radiative correction graphs of Fig. 6, and an increasing R . Still another approach has been taken by Nachtmann³⁹⁾, who postulates a non-trivial fixed point in the coupling constant, and compares the data with the leading and first non-leading terms expected from broken scale invariance arguments.

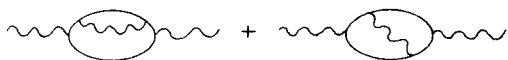


Fig. 6 Gluonic "radiative corrections" to the naive parton model.

Possibly the most radical suggestion comes from Parisi⁴⁰⁾, who postulates that at distances comparable with the gravitational cut-off, strong, weak and electromagnetic forces all have the same strength. From the observed strengths of these interactions, he then deduces a value for the Weinberg angle of weak interactions and $R \approx 9$.

Partons with Structure

An alternative to having many partons is to endow the conventional ones with structure, either charge radii⁴¹⁾ or magnetic moments⁴²⁾. Then for q^2 small compared with the mass scales in the parton form factors, $R \approx (\text{const}) + (\text{const})' q^2 + \dots$ and the inclusive angular distribution in annihilation which is $\alpha(1 - \cos^2\theta)$ at larger q^2 , can well be essentially isotropic at present energies. A judicious choice⁴²⁾ of charge radius and magnetic

moment can leave electroproduction near scaling in the NAL range of q^2 , though σ_L/σ_T should be $\propto q^2$ for $|q^2| \gg 10$. It has been pointed out that models with a magnetic moment give large violations of scaling in polarized electroproduction. These authors are generally agnostic about the asymptotic behaviour of R , but agree that q^2 one or two orders of magnitude greater than those presently available will be necessary to see it. At intermediate energies, gluons may show up as direct channel resonances⁴¹⁾.

Another approach to endowing quarks with structure has been taken by Raitio⁴³⁾, who makes quarks out of spin $\frac{1}{2}$ and spin 0 fields, the latter ultimately to be $q\bar{q}$ systems themselves. He has R increasing to about 7, and then falling within the SPEAR II - DORIS range, reaching about 1 asymptotically.

New Parton Diagrams

Some people have suggested we were too naive in just drawing the simple quark-parton loop diagrams. One example is Kogut³⁸⁾ above. Fritzsche and Minkowski⁴⁴⁾ have argued that the quark-gluon coupling may be small so that one sees at SLAC just the Born term, while radiative corrections become significant at higher energies. Cheng and Mandula⁴⁵⁾ argue that graphs like those of Fig. 7 should be considered. Summing these they get $R \sim (q^2)^a$ with $a \sim \log q^2$. The maximum possible size of corrections to the naive parton model diagrams has been estimated by Muta et al⁴⁶⁾ using unitarity for partons.

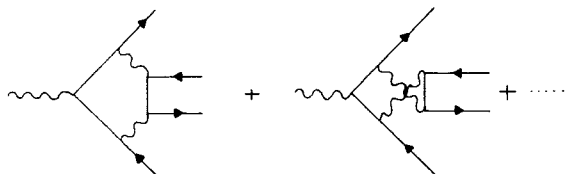


Fig. 7 Possible higher order corrections to the naive parton model.

6. Models not Based on Partons

These models can be put into two categories - those that make macroscopic hypotheses about the dynamics (statistical, hydrodynamical, thermodynamical), and those that do not. Among the latter are

Generalized Vector Meson Dominance Models

The first of these models^{30,46)} postulated vector meson couplings chosen so as to get a point-like $1/q^2$ cross-section. Low-lying vector mesons then suggested $R \rightarrow 2.5-3$. Other authors⁴⁷⁾ using the "duality" sum rule

$$\int_{4m_\pi^2}^{\infty} dq^2 q^2 (\sigma(q^2) - \tilde{\sigma}(q^2)) = 0$$

(where $\tilde{\sigma}$ is some comparison cross-section) and saturating with low-lying vector meson states found $R \approx 2-5$. Greco has retained²⁸⁾ his estimate in the face of the new data, and suggests that something not dual to the usual vector mesons is responsible for the experimental rise in R with q^2 . Sato⁴⁸⁾ has used an alternative finite energy sum rule to suggest that the vector mesons may be dual to a $1/q^2$ component in the cross-section, with a constant piece dual to non-resonant contributions. Renard⁴⁹⁾ has proposed a model in which R rises linearly with q^2 for a while, and then interference effects between overlapping resonances cause R to flatten out and become asymptotically constant. Schlereth⁵⁰⁾ however goes all the way, and fixes his vector mesons to give a constant $\sigma(e^-e^+ \rightarrow \gamma \rightarrow \text{Hadrons})$, at least until unitarity effects set in.

Dual Models

Most dual models for annihilation have been for the one and two particle inclusive distributions, rather than for the total cross-section directly. The one particle distributions scale in the same way as in electroproduction in general⁵¹⁾, though it is

possible⁵²⁾ for them to yield an extra component⁵³⁾ in the centre of mass, scaling as $E \frac{d\sigma}{d^3p} \sim (\frac{1}{q^2})^d f(E)$ with $d < 1$. At least one of these models has no jets - the two particle distribution is not limited in relative transverse momentum. Schierholz and Schmidt⁵³⁾ have proposed a dual model which apparently gives good results for the approach to scaling in annihilation - unfortunately they do not give full details of the model.

Other Resonance Models

We should remember that the dominant contributions to hadronic cross-sections at high energies comes not from direct channel resonances, but from multi-quasi-particle states. This point is taken up by Ferro Fontan and Rubinstein⁵⁵⁾ who stress that many multi-resonant channels are opening up at CEA-SPEAR energies. If their form-factors are at all point-like near threshold, then they can give a substantial cross-section which is approximately constant over the CEA-SPEAR energy range.

Craigie and Walsh, and Craigie and Rothe⁵⁶⁾, have discussed chain emission models, in which the virtual photon decays into a pion and an off-shell vector meson, which latter decays into a pion and an off-shell vector meson, and so on. Two encouraging features of the model are its ability to give a large neutral to charged energy ratio, and a violation of scaling at low centre of mass energies.

Finally, Moffat, Savaria and Wright⁵⁷⁾ have applied their global model of current-hadron interactions to annihilation, finding large scale-breaking in the inclusive pion distribution and $R \sim \sqrt{q^2}$ over a range in energy. Orfanides and Rittenberg⁵⁸⁾ get a sensible inclusive hadronic distribution from a branching process model.

Phase Space or Statistical Model

In this picture^{59,60)} final state hadrons are supposed to populate uniformly all kinematically allowed phase space for N particles. The multiplicity $\langle n \rangle \propto (q^2)^{1/3}$, and the normalized inclusive distribution $\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{d^3p}$ rises at small x and falls at large x, in agreement with experiment. However the energy dependence of the total cross-section is unspecified.

Thermodynamical or Statistical Bootstrap Model

According to this picture^{59,60)}, the spectrum of hadronic states is bootstrapped by requiring the level density of each system to be the same as that of its constituents, and all exclusive states are supposed to contribute to the inclusive process with equal statistical weight. Again, the model cannot calculate the total cross-section, and the inclusive distribution is large at small centre of mass energies:

$$\frac{1}{\sigma_{\text{tot}}} \frac{d\sigma}{d^3p} \text{ and } \bar{n} \sim \sqrt{q^2} \text{ are predicted.}$$

Hydrodynamical Model

According to this picture⁶²⁾, a blob of very dense matter is supposed to be formed in a small volume, then expand and cool according to some hydrodynamical equation of state, and then condense out into normal hadrons when the density falls to typical hadronic values. Opinions differ as to what initial volume should be assumed (this is directly related to the total cross-section behaviour) and on the appropriate equation of state. However, unless one takes the initial volume $\sim (q^2)^{-3/2}$, the multiplicity grows like some power of q^2 : $\bar{n} \propto (q^2)^p$, $0 < p < 1/2$ and the hadrons again congregate near the centre of mass, as favoured by experiment.

7. Hadron Production without Photons

In the previous sections no really swasivious model for the CEA-SPEAR data has emerged based on the one photon mechanism. This and other more philosophical considerations, led various people to propose some new semileptonic interaction as an explanation.

General Formulation

One can imagine direct current-current interactions resembling the Fermi weak interaction model, or models in which a particle is exchanged which is so massive that its propagator is structureless at present momenta. In either of these cases one gets an effective langrangian of the form

$$L_{\text{eff}} = \sum_i g_i (\bar{L} \Gamma_i L) (\bar{q} \Gamma_i q)$$

where the Γ_i run over the usual S,P,V,A,T, possibilities, and the $\bar{q} \Gamma_i q$ are to be interpreted as hadronic currents isomorphic to, for example, quark bilinears. A useful aspect^{63,64)} of such a scheme is that the non-vector contributions depend in general on the transverse polarization of the beams

$$\sigma_{\text{pol}}^{S,P} = (1 \pm p^2) \sigma_{\text{unpol}}^{S,P}$$

As the transverse polarization of the beams is expected to increase during their storage, the annihilation cross-section might be time-dependent!

The freedom of action in this framework enables one to violate scaling drastically in annihilation while respecting scaling approximately in deep inelastic leptonproduction at present q^2 .

s-channel Models

Several authors have proposed^{64,65,66)} models with s-channel exchanges (see Fig. 8) - either vector bosons (Z's) or scalar bosons (ϕ 's). Llewellyn Smith and Nanopoulos⁶⁵⁾ conclude that present data on leptonic neutral current events and deep inelastic

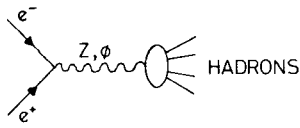


Fig. 8 Non photonic s-channel contributions to $e^+e^- \rightarrow$ hadrons.

scattering rule out a Z . It is not yet so easy to rule out a ϕ ^(64,66): studies of the polarization dependence of the cross-section may help.

t-channel Models

Pati and Salam⁽⁶⁷⁾ have emphasized that in a class of gauge theories of strong electromagnetic and weak interactions, gauge bosons (X 's) carrying both lepton and hadron quantum numbers occur naturally, giving rise to the diagram of Fig. 9. The original such models gave effects too small to explain CEA and SPEAR, but the general principle can be abstracted. Upper limits on $\pi^0, \eta \rightarrow e^+e^-, \mu^+\mu^-$ force m_X to be $O(100\text{GeV})$, so that the above general formulation is applicable. Models of this type generally violate μ - e universality and give differences in e^+N and μ^+N scattering - however they can be made compatible with present lepton production data.

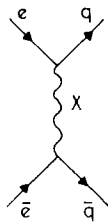


Fig. 9 A contribution to $e^+e^- \rightarrow$ hadrons in the Pati-Salam model.

Other Models

Budini and Furlan have argued that, starting from a Fermi lagrangian, the exchange of lepton pairs can generate an asymptotically constant $\sigma(e^+e^- \rightarrow$

hadrons) $\approx 2\pi G_F$ in good agreement with experiment. Greenberg and Yodh⁽⁶⁹⁾, and Nanopoulos and Vlassopoulos⁽⁷⁰⁾ also obtain this value, postulating a dynamical structure for leptons analogous to that for hadrons, with reggeized W -bosons and a leptonic Pomeron. Unfortunately the angular distribution of charged particles disagrees with the strong peaking originally expected in these models, and it is unclear why the asymptotic behaviour should set in at energies $\ll G_F^{-1} \approx 10^5 \text{ GeV}^2$, where the composite nature of leptons might be expected to become apparent. Greenberg and Yodh now disbelieve their original claim of a strong angular dependence in the angular distribution, on the grounds that at present energies scattering should be predominantly in the s-wave. Schlereth⁽⁵⁰⁾ also makes some speculations about possible contact lepton-hadron interactions.

8. Conclusions

It is clear that there is no consensus among theoreticians working on e^+e^- annihilation - not even about such basic questions as whether or not it proceeds predominately by one photon exchange, or whether or not to use parton ideas. At the moment developments in two directions seem necessary - the experimental exclusion of some of the theoretical alternatives, and finding good theoretical reasons for believing one model rather than another. Here are a list of questions to be answered.

Experimental

For the e^+e^- experimentalist

Can heavy leptons be found? (e.g by (μe) coincidences, $(\mu^+\mu^-)$ anomalies and so on). Is the 2γ cross-section really small?

Does anything odd happen in e^+e^- collisions? (as expected if the 2γ cross-section is large, or in some no-photon mechanisms).

Does R decrease at higher energies? (cf conventional quarks) remain constant at about 4? (Han-Nambu) or go up? for ever?

Is there a bump in the cross section? (gluon, Z, ϕ)

Is the e^+e^- cross-section polarization dependent? (as in some no-photon mechanisms).

Does the hadron distribution become anisotropic at small angles? or at higher energies? Does the structure in phase space expected in the parton model ever show up?

Will high precision high energy QED tests at SPEAR II and DORIS indicate what happens to R above these energies?

Is the energy crisis real? is the missing energy in π^0 's or η 's? or in loose single photons (Han-Nambu)?

For the deep inelastic lepton-production experimentalist

Does the electroproduction cross-section go up? (charm, Han-Nambu) scale? (does anyone remember scaling?) go down? (asymptotic freedom).

Do the e^+N , μ^+N cross-section differ at higher q^2 ? (Several no photon mechanisms expect this).

Is deep inelastic electroproduction polarization small? (a possibility suggested by the anomaly analysis).

Is scaling in the polarization structure function badly violated? (as expected if partons have magnetic moments).

Theoretical

For the parton theorist:

If you make a phenomenological jet model, with a rising plateau, a transverse momentum cut-off and a suppression in the parton fragmentation regions, can it fit the present data?

Does this apparent failure of the quark-parton model have anything to do with other problems of the model, such as confinement, the $pp \rightarrow \mu^+\mu^- + X$ process^{64,71)} or the ninth axial current⁷²⁾?

For the statistician or thermodynamicist:

What is the total cross-section, or the initial hadronic volume? What is the equation of state of the hadronic fluid?

Why should the idea of equilibrium statistical physics be relevant?

For the proposers of no-photon mechanisms:

Why is your cross-section so big at such low energies?

We finish with a table of the theoretical confusion on the value of R as $q^2 \rightarrow \infty$.

Table of Values of R

<u>Value</u>	<u>Model</u>	<u>Source</u>
0.36	Bethe-Salpeter bound quarks	Bohm et al, ref 42
2/3	Gell-Mann-Zweig quarks	
0.69	Generalized vector meson dominance	Renard, ref 49
~ 1	Composite quarks	Raitio, ref 43
10/9	Gell-Mann-Zweig with charm	Glashow et al, ref 31
2	Coloured quarks	
2.5 to 3	Generalized vector meson dominance	Greco, ref 30
2 to 5	" " " "	Sakurai, Gounaris, ref 47
$3^{1/3}$	Coloured charmed quarks	Glashow et al, ref 31
4	Han-Nambu quarks	Han and Nambu, ref 32
5.7 ± 0.9	Trace anomaly and ρ dominance	Terazawa, ref 27
$5.8^{+3.2}_{-3.5}$	Trace anomaly and ϵ dominance	Orito et al, ref 25
6	Han-Nambu with charm	Han and Nambu, ref 32
6.69 to 7.77	Broken scale invariance	Choudhury, ref 18
8	Tati quarks	Han and Nambu, ref 32
8 ± 2	Trace anomaly and ϵ dominance	Eliezer, ref 26
9	Gravitational cut-off, universality	Parisi, ref 40
9	Broken scale invariance	Nachtmann, ref 39
16	$SU_{12} \times SU_{12}$)	Fritzsch & Minkowski, ref 34
$35^{1/3}$	$SU_{16} \times SU_{16}$) gauge models	
~ 5000	High Z quarks)	Yock, ref 73
70,383	Schwinger's quarks)	
∞	∞ of partons	Cabibbo and Karl, ref 9
		Matveev and Tolkachev, ref 35
		Rozenblit, ref 36

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