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A THEORIST'S VIEW OF e^+e^- ANNIHILATION*

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I. INTRODUCTION

I shall not attempt a complete review of the field, both from lack of space and lack of competence. Excellent reviews¹ emphasizing various sides of the subject have appeared recently, and I shall try to emphasize topics either new, especially relevant, or which are represented by contributions to this Conference. I have chosen the following subjects:

1. Total cross-section behavior

2. Weak-interaction effects

3. Exclusive channels

4. Only a few words on two-photon processes

5. Multihadron final states.

II. TOTAL CROSS-SECTION BEHAVIOR

The first-generation experiments at high energy are now essentially complete. To me the major result is the large cross-section for multihadron production observed at Frascati and the remarkably high total hadron cross-section reported by CEA. These results, especially the latter, are a bonanza for the experimentalist and therefore, in the long run, a bonanza for everybody. However, not all theorists (myself included) expected so much, and some of my colleagues prefer to take a "wait and see" attitude, and not worry about data until the returns from the second-generation experiments at SPEAR, DORIS, as well as Frascati come in, and error bars get smaller. I think that is a mistake. The results so far do present more questions than answers. But no matter how things eventually turn out, there is value in taking the present data as it is and using it as an imagination-stretcher. [There's never enough of that commodity.] We should force ourselves to think in directions we would perhaps otherwise not think. That cannot help but be a beneficial thing to do, as long as we keep our sense of perspective.

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In this spirit, what are the questions which the present data invite? We shall phrase them in terms of the behavior of the quantity

$$R = \frac{\sigma_{tot}(e^+e^- \to hadrons)_{1\gamma}}{\sigma_{tot}(e^+e^- \to \mu^+\mu^-)}$$
(2.1)

1. Is R a smooth or irregular function of Q^2 ?

For example, if R is built predominantly from vector-meson resonances, 2^{-5} perhaps <u>a la</u> Veneziano, we might allow appreciable irregularity, despite the smooth systematic behavior on the spacelike side.

To check for such irregularity demands higher precision at many neighboring energies. That in turn demands patience.

Another possibility,⁶ which will be discussed by Drell, is that the partons have a form-factor (history repeats itself) which is an enhancement effect for timelike Q^2 and a suppression factor for spacelike Q^2 .

2. Is the observed R of hadronic origin?

My understanding of the observations is that, while an appreciable fraction of the observed tracks are hadronic, an appreciable fraction could be leptons. Among the non-hadronic possibilities are:

(a) <u>Charged heavy leptons</u>. If so we might need quite a few, inasmuch as R increases by ≤ 1 unit per heavy-lepton pair. (Fig. 1.) Observation of the rather sharp steps with energy in σ_{tot} appears to be a good way to establish (or kill) this hypothesis.

(b) <u>A charged J=1 intermediate boson $(W')^{\pm}$ </u>. This is not the usual one, but one which decays (semiweakly?) into hadrons, but <u>not</u> leptons. Then,⁷ if the g-factor of the W' is unity (Proca equations), $R \sim q^2$, while if $g \neq 1$ (e.g.,

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equal to 2, as in a Yang-Mills theory),⁸ $R \sim q^4$. A mass $M_{W'} \sim 1$ GeV, with g = 1, is the kind of number needed to account for the observations. (Fig. 2).

A test of such a hypothesis is that the mean multiplicity \overline{n} should evidently be independent of Q^2 .

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No doubt some of the more extravagant gauge theories with many W's could eventually accommodate such a beast.

3. If R is of hadronic origin and a smooth function of Q^2 , can it increase indefinitely with Q^2 ?

For example, we could take that J=1 charged vector meson and make it a parton (Han-Nambu colored gluon??). But before getting so extravagant, it is necessary to stop and look⁹ at the general implications of an R which increases indefinitely with Q^2 . They are serious. In particular, look at the photon propagator and the hadron vacuum-polarization corrections thereto.¹⁰ Write

$$e^{2}D(q^{2}) = \frac{e^{2}}{q^{2}} \left[1 - \frac{\alpha}{3\pi} q^{2} \int \frac{dm^{2}R(m^{2})}{m^{2}(m^{2}-q^{2})} + \cdots \right]$$
(2.2)

Let

$$R = (const)(Q^2)^n \qquad 0 < n < 1 \qquad (2.3)$$

Then, for Q^2 spacelike

$$e^{2}D = \frac{e^{2}}{Q^{2}} \left[1 + \frac{\alpha}{3\sin\pi n} R(Q^{2}) + \cdots \right]$$
 (2.4)

We conclude;

(a) If R >> 137, perturbative quantum electrodynamics breaks down because the propagator modifications are O(1) and out of control. For $n \sim 1$ and a linear extrapolation of the present trend of data, disaster is

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reached for

$$\sqrt{Q^2} \sim 50 \text{ GeV} \qquad (2.5)$$

(b) A big R at high energies modifies the photon propagator at low energies. Therefore <u>precision</u> tests of quantum electrodynamics (1% accuracy or better in the cross-sections) for $e^+e^- \rightarrow e^+e^-$ and $e^+e^- \rightarrow \mu^+\mu^-$ can tell us something about R at energies higher than we can directly reach.

Thus there is value to pushing yet another order of magnitude of accuracy beyond that attained in the very beautiful experiment reported by the Adone group¹¹ on Bhabha scattering.

(c) For timelike Q^2 (relevant to $e^+e^- \rightarrow \mu^+\mu^-$), the vacuum polarization gets a phase $e^{i\pi n}$. Only the real part interferes with the lowest order. The effect is proportional to $\cot \pi n$ (a function sensitive to n). Thus comparison of the modifications to $e^+e^- \rightarrow e^+e^-$ (spacelike dominated) and $e^+e^- \rightarrow \mu^+\mu^-$ are especially interesting in determining the energy dependence of R.

4. <u>Can R be a decreasing function of Q²?</u> Remember field-algebra?¹² It predicts¹³

$$R < \frac{const}{Q^2 \log Q^2}$$
(2.6)

"Asymptotic freedom" (discussed below) also eventually requires R to approach its limit from above.

5. If R is a constant, what is the constant?

Most theorists like R to be a constant. The reasons include:

(a) The trend of the data.

(b) Canonical structure of the Schwinger-term in the equal-time commutator of electromagnetic current with itself.^{14,15}

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(c) Wilson operator product expansion plus scale-invariance at short distances.^{16, 17, 18} (Almost the same thing, but much more persuasive.)

(d) Parton model. 19, 20, 21

(e) Automodelity (translated out of the Russian, that means dimensional analysis).²²

(f) Asymptotic freedom. $^{23-25}$

Some combination of the above arguments gives the result 26

$$R = \sum_{\substack{\text{spin } 1/2 \\ \text{partons}}} e_i^2 + \frac{1}{4} \sum_{\substack{\text{spin } 0 \\ \text{partons}}} e_i^2 \qquad (2.7)$$

In particular this formula emerges from the recent work on nonabelian gauge theories of strong interactions which have the property of becoming a free-field theory at short distances (asymptotic freedom). This will be discussed by others, and I only sketch the idea and quote a result of Appelquist and Georgi.²⁷ For a theory of red, white and blue quarks of fractional charge coupled to an octet of neutral colored gluons,

$$R = \sum_{i} e_{i}^{2} \left[1 + \frac{4}{9 \log \frac{Q^{2}}{M^{2}}} + 0 \left(\frac{\log \log}{\log^{2}} \right) \right]$$
(2.8)

The idea behind asymptotic freedom can be seen by a nonrigorous argument taken from the behavior of vacuum polarization in quantum electrodynamics

$$\frac{e^2}{4\pi} D = \frac{\frac{e^2}{4\pi}}{Q^2 \left[1 - \frac{N\alpha}{3\pi} \log \frac{Q^2}{M^2}\right]} = \frac{\alpha_{\text{eff}}}{Q^2}$$
(2.9)

Here N is the number of interger-charge fermion loops included. As Q^2 gets large, α_{eff} grows. But if the sign of the vacuum polarization could be turned around (it can't), then we'd get

$$\alpha_{\text{eff}} \rightarrow \frac{3\pi}{N\log\frac{Q^2}{M^2}} \rightarrow 0 \qquad \text{as } Q^2 \rightarrow \infty \qquad (2.10)$$

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The sign does come out opposite in the nonabelian gauge theories. Also the coefficient of $(1/\log)$ gets smaller as the group gets bigger, i.e., as the number of degrees of freedom proliferate.

Formulae for R can be attained in other ways, in particular using a generalized vector dominance idea. For example, Bramon, Etim and $\operatorname{Greco}^{2,3}$ take a Veneziano-like spectrum of vector mesons, with properties

$$m_n^2 = m_\rho^2 (1 + 2n) \qquad \frac{\Gamma_n}{\Gamma_\rho} = \frac{m_n}{m_\rho} \qquad \frac{f_n}{f_\rho} = \frac{m_n}{m_\rho} \qquad (2.11)$$

and adds up all their contributions. On the average R is a constant (locally, it is evidently spiky), and the constant can be computed in terms of f_o

$$R = \frac{8\pi^2}{f_{\rho}^2} \approx 2.5 - 3 \tag{2.12}$$

Griffith²⁸ has also arrived at a similar estimate (somewhat larger) from a related line of reasoning, but not tied to the dual models. The choices (2.11) are tailored to the wish to obtain a constant R. Dominguez and Zepeda²⁹ have made a different choice, which produces a R growing with increasing Q^2 . It has to be admitted that the results in this vector-dominant approach to the subject can be largely shaped by the choice of assumptions. However, it is generally the case that once assumptions are made to obtain the behavior of e^+e^- annihilation,

there is little freedom left in describing the nature of large- ω vector-dominant electroproduction final states.

Sakurai^{4,30} looks at this from a different perspective, called "new duality." He suggests, with some plausibility, a superconvergence relation for the vacuum polarization:

$$\int_{0}^{\infty} ds \ s \left[\sigma(s)_{had} - \sigma(s)_{comparison} \right] = 0$$
 (2.13)

where (except near threshold)

$$\sigma_{\rm comparison} \approx {\rm R}\,\sigma({\rm s})_{\mu} + \mu^{-}$$
 (2.14)

Then infinity in Eq. (2.13) is replaced by 1.2 GeV^2 (above the ϕ , below the continuum). He gets

$$R \sim 3-5$$
 (2.15)

If this is right, the Frascati points, which indicate $R \sim (1-2)$, should be an increasing function of time.

Let us return to the more field-theoretic or parton-like ideas about R. Favorite hadron models give the following values for Σe_i^2 :

R = 2/3	Standard 3 quarks
R = 2	3 triplets of fractionally charged quarks (red, white, blue). 31
R = 31/3	3 quartets of fractionally charged quarks 32
	u, u' $Q = 2/3$
	d, s $Q = -1/3$
	[They are good for gauge theories of weak and electro-
	magnetic interactions.]
R = 4	Han-Nambu model of 3 triplets of integrally charged quarks. ^{33,34}

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6. Can R be not one, but two constants?

This idea is relevant to the Han-Nambu model, and can be called the color thaw.³⁵The natural symmetry group of the Han-Nambu model is $SU(3) \times SU(3)'$, where SU(3) transforms members of a triplet among each other (it is the ordinary SU(3) of the eight-fold way) and SU(3)', the color group, transforms the triplets among each other. Observed hadrons are color singlets. But the electromagnetic current has two pieces $(\underline{8}, 1) + (1, \underline{8})$. The first piece of the current is identical to the fractionally-charged current of the red, white and blue quark model. The second, a color octet, must be thrown away at present energies because observed hadron states are color singlets. The colored degrees of freedom are frozen out at present energies, thus R = 2. However after the thaw, the integer charge of the parton is probed and R increases to 4 (Fig. 3).

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A challenge to this idea, and any similar one invoking charmed, colored, or nonhadronic final states is to find specific signatures in the final states (such as the famous μ -e coincidence for heavy lepton production). In the present case of color thaw, the (1, 8) produced state (e.g., a vector dominant colored $\tilde{\rho}$) may decay electromagnetically into ordinary hadrons. This could lead (because of the big cross-section) to a substantial excess of single γ rays in the final states.

Also interesting is the impact of color thaw on electroproduction and neutrino-production. Because the effective parton charge is integer instead of fractional, we expect an increase in the structure function (Fig. 4) by a factor ~ 2 well above color threshold. Notice this effect is opposite in sign to a parton form-factor effect, such as discussed by Chanowitz and Drell.⁶ It is probable that this enhancement only occurs for Q^2 greater than the (mass)² of colored states in order to protect the $Q^2 \sim 0$ (photoproduction) limit from an

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enhancement ~ a factor 2. [Were that present, we'd expect it in $\sigma (\rho^{0}p)$. Therefore it also should appear in $\sigma(\pi p)$, where it is not seen, even at NAL energies.] A similar enhancement may or may not exist for neutrinos, depending upon whether the weak current contains a (1, 8) piece. If so, color asymptopia for $\sigma_{tot}^{\nu N}$ is very far away because, according to Fig. 4, the effect is most pronounced for ω small, where the structure function is small. For $\omega > 4$, we need $W^{2} > 60 \text{ GeV}^{2}$ just to enter the enhanced region. Even for 150 GeV monoenergetic neutrinos, asymptopia is not reached in the total crosssection behavior.

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I find it impressive that the phenomena in e^+e^- annihilation with 2.5 GeV per beam competes favorably in sensitivity with lepton-hadron or hadron-hadron processes at a value of s at least an order of magnitude higher. e^+e^- annihilation is unique in converting every scrap of cms energy into very interesting phenomena. If you think this is meant to be propaganda for higher energy $e^+e^$ facilities, you're right: e^+e^- colliding beams are great!

III. WEAK INTERACTION EFFECTS

Weak-interaction cross-sections tend to rise linearly with $s(\sigma \sim G^2 s)$, while the lowest-order electromagnetic cross-section fall $(\sigma \sim \alpha^2/s)$. The crossover occurs at cms energies of a few hundred GeV. The physics at such energies is very interesting and has been studied by Soviet physicists in particular. ³⁶⁻³⁸ It has been reviewed by Zakharov in the Chicago meeting last year. ³⁹

At low energy all that is left are subtle effects, or effects associated with a major breakdown in the low energy structure of the weak interactions. The most promising subtle effect occurs in the process $e^+e^- \rightarrow \mu^+\mu^-$ with transversely polarized incident leptons.⁴⁰⁻⁴³ [A transverse polarization of up to 93%

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is expected theoretically.] The cross-section is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \sim \left[1 + \cos^2\theta - \mathrm{P}_{+}\mathrm{P}_{-}\sin^2\theta \,\cos 2\psi\right]$$
(3.1)

A. A. B. W.

where P_{\pm} are the transverse polarizations of the incoming leptons. For $\theta = 90^{\circ}$, $\phi = 0$, and $P_{+}P_{-} \sim 1$ there is a hole in the angular distribution. Weak and higher order electromagnetic effects fill it up. With neutral currents⁴⁴ such as exist in the Weinberg model, weak interaction effects exist at the few percent level at $E_{cm} = 5$ GeV.

The same idea has been entertained for hadrons.⁴⁵⁻⁴⁶ One looks for a chargeasymmetry (i.e., $\cos \theta$ term in the inclusive distribution of energetic hadrons). In typical gauge theories the expected effects are at the 1% level, even for $E_{\rm cm} \sim 10$ GeV. Also 2-photon exchange contributions compete. Their angular and especially energy dependence differ so that there is hope of separating them.

Life may be easier if one can create longitudinally polarized beams, for then asymmetries could exist even for σ_{tot} . A similar comment applies to detection of longitudinal polarization in the final state⁴⁷(e.g., decaying Λ 's or μ 's).

In addition to the search for asymmetries, there may be other manifestations of weak interactions. Many gauge theories predict new heavy leptons.⁴⁸ They may be produced via the classical pair-production mechanism. Alternatively a "heavy neutrino" might be produced singly, e.g., $e^+e^- \rightarrow \overline{E}^0 \nu_e$ via W^{\pm} -exchange, with a cross-section $10^{-36} - 10^{-37}$ cm² at attainable energies.⁴⁸

Scalar Higgs particles Φ abound in these models and perhaps they can manifest themselves.⁴⁹ s-channel Φ exchange can interfere with the t-channel photon exchange in Bhabha scattering (Fig. 5). A search for possible resonant production of Φ is an especially sensitive probe.⁵⁰ One performs a continuous

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scan in E_{cm} and looks for a resonant signal. That experiment is a good one, independent of Higgs particles and gauge theories.

IV. EXCLUSIVE CHANNELS

The energy range $E_{cm} \sim 1-3$ GeV should be especially rich territory for clean study of the meson resonances in the 1-2 GeV range of masses. This may require quite exhaustive analysis of 3,4,5-body final states. A fair amount of exploratory theoretical work exists, but I think it is fair to say that this is an area where experiments will guide the theory as much as vice versa. I do not qualify as any kind of expert in this area, and I limit myself to a potpourri of miscellaneous comments.

1. <u>SU(3)</u>

Lipkin⁵¹ has recently reminded us of the value of the electromagnetic form factors of K and π as good SU(3) tests. In unbroken SU(3)

$$\mathbf{F}_{\pi^+} = \mathbf{F}_{K^+}$$
$$\mathbf{F}_{K^0} = 0$$

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The magnitude of F_{K^0} is therefore sensitive to the assumed SU(3) breaking pattern, which is catalogued by Lipkin.

2. "Inclusive" ρ and ϕ production

Renard⁵² has pointed out that

 $e^+e^- \rightarrow \begin{cases} \rho + resonance \\ \phi + resonance \end{cases}$ or $e^+e^- \rightarrow \begin{cases} f + resonance \\ f' + resonance \end{cases}$

are of special interest.

The first is a splendid way to study C = +1 resonant systems. Rosner⁵³ also would like to see whether the strange analogue of the $D(I^G J^P = 0^+ 1^+)$ is produced in association with the ϕ . From SU(6) it seems plausible that at least

for P/P_{max} large, the production of ρ and ϕ should be about as large as π and K. And, from the experimental side, perhaps the trigger of two charged particles is an advantage.

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3. Shape of π and K form factors in the timelike region.

The measurements of F_{π} for timelike Q^2 lie above the Gounaris-Sakurai⁵⁴ predictions based on extrapolating the relativistic Breit-Wigner tail of the ρ . Renard⁵⁵uses a matrix N/D formalism to estimate corrections from higher mass vector states (e.g., $\pi\omega$, $\rho\epsilon$). An interesting possibility is the presence of cusp-like wiggles in the form factor in the neighborhood of the threshold for strongly produced inelastic channels (Fig. 6). It will take quite precise measurements at close spacings in energy to find such effects.

Roos⁵⁶ has taken the $\pi\pi$ p-wave phase-shifts as determined from the CERN-Munich analysis⁵⁷ $\pi N \rightarrow \pi\pi N$, and a generalized Omnes method to compute the pion form factor. He finds a bump at the ρ ' mass and some enhancement relative to the Gounaris-Sakurai formula (Fig. 7).

4. The $\rho \pi \pi$ Channel.

Hirshfeld and Kramer⁵⁸ have made a detailed spin-parity analysis of this channel, and then considered a model based on the diagrams in Fig. 8 (π and ϵ exchange). Their result for the s-dependence of the cross-section is shown in Fig. 9. This has, of course, no direct s-channel resonance enhancement. I leave it to the reader to decide whether the data requires it.

Fujikawa and O'Donnell⁵⁹ approach the subject from another direction. They consider an effective Lagrangian inspired by the spontaneously broken gauge theories and to some extent, also their possible connection as a zero slope limit of dual models, as discussed by Gervais and Neveu.⁶⁰ With relatively few parameters they interpret ρ' production in terms of $\rho'\rho\epsilon$ and $\rho\rho\epsilon$ couplings and

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a direct $\rho\rho'$ mixing. The agreement with the ρ' data as well as pion formfactor data is good. They also obtain $\Gamma(\rho' \rightarrow \rho \epsilon) / \Gamma(\rho' \rightarrow \pi \pi) \sim 13\%$.

5. Formation of Higher Vector States.

The question of $\rho \pi \pi$ as resonance or no resonance also invites the general question: is the continuum built of J=1 resonances? Can we find $\omega' \rightarrow \omega \epsilon$ or $\phi' \rightarrow \phi \epsilon$? And what about ρ'' , ω'' , ϵ'' etc.? Good territory to explore⁵³ is

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 $s \sim 1.1 L + 0.6$ $\rho', \omega', etc.$ $s \sim 1.1 L + 1.0$ ϕ

(L even)

If a sequence were to be found, how do they decay? If they cascade, with no high p_{\perp} , then $\overline{n} \sim Q$ as in the thermodynamic picture (to be discussed below). The alternative is high-momentum decay products, which is rather unprecedented.

V. TWO-PHOTON PROCESSES

Inasmuch as there is to be a whole conference⁶¹ on two-photon processes, as there exist excellent reviews already,¹ and as there is almost no data, I will omit a review of this subject. I shall mention briefly two items. The first item is a contribution of Gatto and Preparata⁶² to this conference. They have shown that while the two-photon process has a big cross-section, it is so dominated by configurations of low p_{\perp} particles traveling along the beam axis that a cut in the p_{\perp} of secondaries of order 0.5-1 GeV sufficies to separate the two-photon process from the smaller single-photon annihilation. This assumes what is called in the next section "orthodoxy" for the final hadron distributions in the one-photon annihilation. But I believe it could survive various generalizations of that as well. It appears that we need not fear, at any energy, that the two-photon processes will obscure the one-photon

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annihilation. This conclusion has also been reached by others in various ways.

A related point has been made by Matinian, Pirogov, Ter-Isaakian, and Shakhnazarian.⁶³ They show that the process $e^+e^- \rightarrow hadrons + \gamma$, which proceeds via electron exchange at low t, dominates $e^+e^- \rightarrow hadrons$ in the low t region. The reason is easily seen: the former cross-section is (by ρ -dominance) $\geq 1/250$ of the 2γ yield which in turn is comparable to the $\mu^+\mu^-$ yield. However the emitted hadrons are concentrated in a cone $\Delta\Omega \sim const./Q^2$. The number of hadrons from the single-photon annihilation in that cone is of order $\sigma_{\mu\mu}\Delta\Omega \ll 1/250$ for large enough Q^2 . The moral in this, as well as the previous case, is clear: for single- γ processes, stay out of the beam direction.

VI. MULTIHADRON PRODUCTION

Just as for strong interactions, it can be expected that the bulk of σ_{tot} is contributed by complicated multiparticle final states, and that some generalization of the inclusive phenomenology used there is appropriate. A considerable amount of work has been done on this since Cornell⁶⁴ and the theoretical issues have come into sharper focus. Some issues are phenomenological in nature, others quite fundamental and central to the problem of understanding deepinelastic dynamics.

I shall first discuss what I call heretical models: thermodynamic and hydrodynamic. Then I will turn to what is almost an orthodoxy (although quite a few may disagree with that).

1. The thermodynamic model ^{65,66}

This is in the spirit of Fermi's statistical model or, better, Hagedorn's.⁶⁷ The main features are:

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(a) Particle production proceeds according to invariant phase space with a cutoff at high momentum.

(b)
$$\bar{n} \sim (Q^2)^{1/2}$$

(c) $\langle p \rangle$ = constant, independent of Q^2 .

Brodsky and I entertained this idea some time ago.⁶⁵ Engels, Satz, and Schilling⁶⁶ have criticized (properly) what we did, and extended it considerably. They argue that we made implicit assumptions, justifiable only in the context of the Hagedorn statistical bootstrap.^{67,68} However, no matter how nice the formulation, the idea has to cope with the following difficulties:

(1) If the inclusive spectrum falls off rapidly with p, it does not join smoothly onto the exclusive channels at the endpoint, which falls off as a power of p. A smooth join keeping the distribution absolute in p, can be obtained from the form⁶⁹

$$\frac{\mathrm{dN}}{\mathrm{dp}} \sim \mathrm{p}^{-3} \tag{6.1}$$

But that doesn't look very thermodynamic. But it shouldn't be ruled out; such low-multiplicity models with small or no angular correlation in the hadron distributions have been proposed and are not in conflict with any data.^{66,70,71} The best test lies in the behavior of the two-body correlation function, as we discuss later on.

(2) The CEA data, $\overline{n}~=~4.3$ (implying $\overline{n}_{tot} \lesssim$ 7?) at Q = 5 GeV, implies

$$\langle p \rangle \sim \frac{Q}{\overline{n}} \gtrsim 700 \text{ MeV}$$
 (6.2)

The model is most comfortable⁶⁶ with $\sim 400-500$ MeV, and constant.

2. Hydrodynamic Model.

Carruthers and Minh Duong-Van⁷² have taken up the Landau hydrodynamic model⁷³ and view the e^+e^- reaction as follows. First, the photon materializes into a hot gas or fluid of partons satisfying a relativistic equation of state

$$p = \frac{1}{3} \epsilon \tag{6.3}$$

This leads (by dimensional analysis) to

entropy
$$S \sim VT^3$$
 $V = volume$
energy $Q = VT^4$ $T = temperature$ (6.4)

The gas expands, conserving entropy. When S/V becomes small, the partons materialize into hadrons with $\overline{n}/V \propto S/V$. Thus

$$\overline{n} \sim S = Q^{3/4} V^{1/4}$$
 (6.5)

What is V? They guess a constant. This yields

$$\overline{n} \sim (Q^2)^{3/8}$$
 (6.6)

The difficulties here are:

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(a) There is no connection with electroproduction; no generalized vector dominance.

(b) The choice V = constant seems a weak point. Why not $V \sim Q^{-3}$, leading to \overline{n} = constant?

3. Orthodoxy

The main elements of the orthodoxy are

(a) $\sigma_{tot} \sim (Q^2)^{-1}$

(b) Inclusive scaling: $p \frac{dN}{dp} = f \left(\frac{2p}{\sqrt{Q^2}}\right)$.

(c) Two-jet structure.

(d) $\overline{n} \sim C_{e^+e^-} \log Q^2$ [with $C_{e^+e^-}$ the same as the coefficient for the current plateau in electroproduction]. This element is the most controversial and uncertain component of the orthodoxy.

The total cross-section behavior has already been discussed. The remaining elements we take up in turn.

A. <u>Inclusive Scaling</u>

This can be motivated by

(a) Crossing the structure functions and scaling variable from the scattering to annihilation channel.^{19,74}

- (b) Use of Gribov-Lipatov reciprocity $f_i(\omega) \propto \nu W_2\left(\frac{1}{\omega}\right)$.
- (c) Parton model.^{19, 20, 21, 76, 77}
- (d) Light-cone plus some auxiliary assumptions. 78, 79

Here I will not try to justify the hypothesis, but briefly describe how things look in the simple parton picture. First the e^+e^- annihilates into a $q\bar{q}$

$$e^+e^- \rightarrow \begin{pmatrix} u\overline{u} & 67\% \\ d\overline{d} & 17\% \\ s\overline{s} & 16\% \end{pmatrix} \rightarrow hadrons \qquad (6.7)$$

The q and \overline{q} eventually evolve into a hadron system (the inner workings of that we return to later), and the leading hadrons remember only their parton of origin. The inclusive distribution of hadrons is determined by scaling functions D(x), where x is the fraction of parton momentum carried by the observed hadron. For example

$$\frac{dN_{\pi}}{dx} \propto \frac{4}{9} \left[D_{u}^{\pi}(x) + D_{\overline{u}}^{\pi}(x) \right] + \frac{1}{9} \left[D_{d}^{\pi}(x) + D_{\overline{d}}^{\pi}(x) \right] + \cdots \quad (6.8)$$

The D_i can be estimated from electroproduction data, 80 (Fig. 10). Various

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isospin relations can be worked out; e.g.,^{78,81}

$$\frac{\mathrm{dN}_{\pi^+}}{\mathrm{dx}} = \frac{\mathrm{dN}_{\pi^0}}{\mathrm{dx}} = \frac{\mathrm{dN}_{\pi^-}}{\mathrm{dx}}$$
(6.9)

With exact SU(3) (probably it's broken) one would have

$$\frac{dN_{\pi^+}}{dx} = \frac{dN_{K^+}}{dx} = \frac{dN_{K^-}}{dx}$$

and

$$\frac{dN_{K^+}}{dx} + 2 \quad \frac{dN_{K^0}}{dx} = 3 \quad \frac{dN_{\eta}}{dx}$$
(6.10)

Even allowing SU(3) breaking, there are duality and/or positivity bounds which considerably constrain the fragmentation functions. There is a bountiful literature on this. $^{19,21,77,78,81-88}$

There may also be a connection with high-p phenomena in hadron physics. Evidence is growing that the inclusive distribution in pp \rightarrow pion + x obeys approximately the scaling law (at $\theta_{\rm cm} = 90^{\circ}$)⁸⁹

$$E\frac{d\sigma}{d^{3}p} = \frac{1}{p^{8}} f\left(\frac{2p_{\perp}}{\sqrt{s}}\right)$$
(6.11)

Let us assume that the observed high-p_hadrons are progeny of a parton (such as a u quark), which "fragments" into hadrons again according to the $D_u^{\pi}(x)$ function as in Eq. (6.8). Easy calculation then shows that the form (6.11) of the distribution is unchanged in going from parent parton to hadron child. For $f \sim constant (2p_{\perp} \ll \sqrt{s})$

$$\frac{\pi^{+}}{q} = \int_{0}^{1} dx x^{7} D_{q}^{\pi^{+}}(x) , \text{ etc.}$$
 (6.12)

$$\overline{\overline{p}}_{\pi^{-}} = \frac{\langle \int_{0}^{1} dx x^{7} D_{q}^{\overline{p}}(x) \rangle}{\langle \int_{0}^{1} dx x^{7} D_{q}^{\pi^{-}}(x) \rangle}$$
(6.13)

where the average is over quark types in the spectrum. With a D of shape shown in Fig. 10, the important x is ~0.7. We see that in that x region the ratio $D_q^{\overline{p}}/D_q^{\pi^-}$ should be comparable to the high $-p_{\perp} \overline{p}/\pi^-$ ratio measured in pp collisions. It should be as large as observed at the ISR, which is <u>large</u>:⁹⁰ ~0.3 at $p_{\perp} \sim 3$ GeV. It may be necessary that the center-of-mass energy of the parton pair be comparable in the two cases; if so this would imply E_{cm} ~8 GeV in the e⁺e⁻ annihilation to get that big a number.

Is this thinkable? Kogut and I⁶⁹tried to estimate that ratio; our guess is shown in Fig. 11. We miss by an order of magnitude. From the shape of D_u^{π} (Fig. 10), we may have overestimated the pion yield by at least a factor of 2. Upon re-examination of the \overline{p} estimate, we may have been overconservative by a factor ~3, and the gap begins to be closed. However, the \overline{p} prediction cannot be increased too much without encountering trouble with the upper bound quoted by the UCLA group. (Fig. 12)

Another argument for a large \overline{p} yield comes from the Feynman conjecture⁹¹ of quantum number retention in the parton fragmentation region, e.g.,

$$\sum_{B=p,n} \int dx \left[D_u^B(x) - D_u^{\overline{B}}(x) \right] = \frac{1}{3} \quad (baryon-no.)$$

to be compared with

$$\sum_{h=\pi^+, K^+, p} \int dx \left[D_u^h(x) - D_u^{\overline{h}} \right] = \frac{2}{3}$$
 (charge)

suggesting again the possibility of a large ratio of baryons to mesons.

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or

Thus to me such a big \overline{p}/π ratio in colliding beams, along with a parton interpretation of the two processes, remains thinkable. But there remains a lot of thinking to be done.

B. Jet Structure

A double-jet structure for the emerging hadrons is natural in a parton picture; the hadrons remember the direction of the parent parton.^{19,20,66} It is, in fact, a necessary consequence of the "parton fragmentation" hypothesis used above. Tests of the idea include: in the set

(a) The angular distribution of leading (high p) hadrons should be $\approx (1 + \cos^2 \theta)$ if they are progeny of spin 1/2 partons.

(b) The two-particle correlation function should be positive if both hadrons are leading particles and have low relative p_1 . The distribution in the relative transverse momentum should fall steeply. Gatto and Preparata,⁶² and Walsh and Zerwas⁸⁸ have studied this problem in some detail. It is likely that cms energies considerably in excess of 5 GeV will be needed for a clear test.

C. <u>Central Region: Is There a Plateau ?</u>

Given a jet structure and the parton fragmentation hypothesis, the inclusive distribution can be described in terms of a rapidity variable, chosen with z-axis along the jet axis. In addition to the two fragmentation regions, there will be at sufficiently high energies (I estimate $Q^2 \ge 400 \text{ GeV}^2$ is needed), a central region separating the fragmentation regions. What goes into that region, if anything, comprises the greatest difficulty (indeed it is the central problem) facing the orthodox picture. The simplest calculations^{76, 92} state that the central region should remain empty. A similar result first occurred also for those following a light-cone approach,⁹³ although a loophole was found.⁷⁹ But if the central region remains empty, then $\overline{n} \rightarrow \text{constant}$ as $Q^2 \rightarrow \infty$, and scaling exists for some exclusive channel.

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There are various theoretical reactions submitted to this conference. Stack,⁹⁴ arguing from a light-cone point of view, expresses despair, preferring a violation of scaling in order to solve the problem. Kingsley, Landshoff, Nash and Polkinghorne⁹⁵ use an analogue of the fragmentation model for strong interactions. Event by event the rapidity distributions appear as shown in Fig. 13, sometimes two fireballs widely spaced, other times high-multiplicity overlapping fireballs. The summed inclusive distribution is almost unconstrained. There are difficulties:

(a) As in the strong interaction analogue $\sigma_{excl}/\sigma_{tot}$ tends to a constant at high Q^2 ; some exclusive channel scales.⁹⁶

(b) If the low multiplicity clusters are progeny of their parent partons, they would appear to contain fractional charge. The mechanism of getting the fractional charge from one cluster to the other is not explicitly addressed. Perhaps if one understood that, it would also solve the first difficulty.

Why can't a ladder exchange, as in Fig. 14, solve the problem? I once advocated that, but was wrong.⁹⁷ Kogut, Sinclair, and Susskind⁹⁸ studied the question in some detail and traced the problem to the space-time development of the final state: the $q\bar{q}$ are outgoing, not incoming waves. It turns out to be of considerable value to watch carefully what happens to the evolution of the final state in space-time. The basic problem is that one finds in simple cases that the natural time-scale for a parton to do something (such as emit a hadron or break into two partons) to be proportional to its momentum. That is in accord with the time-dilation ideas of special relativity. But a time $\sim Q$ is too long, because by then the two partons have separated by a distance $\sim 2Q$. They are by then out of sight of each other: why don't they escape? Although rather exotic alternatives can be entertained (such as the analogues of rubber-bands or

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lightning bolts), it seems to be most satisfactory to imitate the space-time evolution of an ordinary collision. After all, orthodoxy assumes the final hadron configurations to be very similar to what occurs in ordinary processes. Perhaps its microscopic evolution in space-time is also similar.

The evolution of an ordinary collision according to the short-rangecorrelation picture is depicted⁹⁹ in Fig. 15. Just after the collision, we partons have been heated (excited) and no hadrons have been emitted. As time goes on, the wee partons rapidly cool by emitting wee hadrons and by heating the neighboring non-wee partons. These in turn cool by emitting non-wee hadrons and again heating their neighbor partons in rapidity-space. Thus the hadron plateau grows from the center outward. The time at which partons of momentum p are heated is proportional to p (because of time dilation) so that the total duration of the collision is $\Delta t - E_{CM}$.

In the colliding-beam process we have only a parton-antiparton pair immediately after the collision. If we wish to imitate the previous example, we must a short time later have some wee partons emitting wee hadrons and creating more hot not-so-wee partons. Later on the hot partons form polarization clouds which pursue the leading partons, all the time emitting hadrons and building a plateau from the center outward (Fig. 16). Simple calculation shows that the lag Δz , i.e., the longitudinal distance separating the polarization cloud from the leading parton, should decrease with time as t⁻¹. At a time t ~ Q, the cloud captures the parton, neutralizing any fractional charge or peculiar quantum number it may have carried.⁹⁹

What is the price that has been paid? It is that <u>there exists an interaction</u> possessing long range correlation in rapidity whenever fractional charge begins to separate in space-time. How should that price be paid? A very natural choice

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is a gauge theory containing J=1 bosons, spontaneously broken in such a way as to screen fractional charge. The important diagrams should look something like Fig. 17 for production of hadrons and like Fig. 18 (the trampoline-diagram) for the vacuum polarization itself. The many wee gluon exchanges between developing plateau and leading partons are a necessary element for this inside-outside cascade. They will put an eikonal phase on the leading-parton wave function. [The physics of that is simply that energy is pumped from the leading partons into the developing hadron plateau; hence the leading parton is decelerated.] That eikonal phase should not in itself wreck the deep-inelastic scaling behavior or light-cone dominance.

An important step in removing the above speculations from the domain of handwaving was taken by Casher, Kogut, and Susskind,¹⁰⁰ who showed that two dimensional quantum electrodynamics (solved by Schwinger¹⁰¹ long ago) works this way. In that theory the vacuum polarization is so infrared-singular that there is total screening of charges and of the Coulomb field: the photon gets a mass. They study an analogue of e^+e^- annihilation, which they find to possess the above features: (i) it scales according to parton-model expectations, (ii) an inside-outside cascade develops, and (iii) no partons escape, only massive photons. There exist questions of whether the model is too trivial to really tell us about the real world,¹⁰² but at the very least it does provide encouragement that the picture of the inside-outside cascade has some relevance.

A detailed dynamics of the above pictures does not exist for the real-life four-dimensional case. But a phenomenology which seems to incorporate all elements of the orthodoxy has been pursued by Preparata^{103-105, 62} recently. This is the model of infinitely massive massless quarks. I hope he describes it in his talk. The basic rules for calculation go, according to the diagram in

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Fig. 19, as follows:

(a) p for the propagators (no propagation!)

(b) γ_{μ} for the photon vertices

(c) strong (exponential?) damping at the vertices in all masses (about m = 0!) and in t.

(d) Reggeon exchange, with flat trajectory at $\alpha(t) = 1$.

The result scales (R=const) and the model is evidently capable of providing a Mueller-Regge phenomenology for inclusive spectra and correlation functions. This model may in fact be interpretable in terms of the hand-waving picture given above. If an energetic parton is always accompanied by a polarization cloud in its neighborhood, with which it interacts by exchange of wee gluons, its four-momentum will fluctuate. Suppose the parton momentum P_{μ} is

$$\mathbf{P}_{\mu} = \mathbf{p}_{\mu} + \Delta \mathbf{p}_{\mu}$$

where p_{μ} is null and Δp_{μ} is a fluctuating piece (~ 300 MeV). Then although $p^2=0$,

$$\mathbf{P}^2 \cong \mathbf{p}^2 + 2\mathbf{p} \cdot \Delta \mathbf{p} \sim \mathbf{E} < \Delta \mathbf{p} > \rightarrow \infty$$

as the energy E of the parton tends to infinity. For deep-inelastic parton kinematics the small fluctuating piece is safely ignored and the standard results can be recovered.

Thus I feel that since the Cornell conference a great deal has come into better focus. If the orthodoxy, including $R \approx \text{constant}$, turns out successfully, we may be on the way to a better understanding of quite basic elements of hadron dynamics. If on the other hand, R continues to rise, we will clearly be entering into a very new and unprecedented kind of physics. Either alternative can only lead to extremely interesting and fruitful results.

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ACKNOWLEDGMENTS

1 Ale and

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FIGURE CAPTIONS

a for the

1.	Interpretation of observations on R in terms of heavy lepton production.
2.	Interpretation of observations on R in terms of production of J=1 boson $W^{t^{\pm}}$.
3.	Interpretation of observations on R in terms of color thaw and the Han-
	Nambu model of hadrons.
4.	Region of $Q^2 - W^2$ space affected by color thaw.
5.	Exchange of scalar Higgs mesons in Bhabha scattering.
6.	Estimates by Renard ⁵⁵ of $ F_{\pi} $ under varying assumptions.
7.	Estimate by Roos ⁵⁶ of $ \mathbf{F}_{\pi} ^2$ using CERN-Munich $\pi\pi$ phase shifts.
8.	Diagrams used by Hirshfeld and Kramer ⁵⁸ to estimate production of ρ '.
9.	Fit of Hirshfeld and Kramer 58 to $ ho'$ production cross-section.
10.	My own crude estimates of the parton-fragmentation functions $D_u^{\pi\pm}$.
	They lie slightly higher than those of Cleymens and Rodenburg. ⁸⁰
11.	Estimate 70 of \overline{p} and π^- production in e ⁺ e ⁻ annihilation using "corres-
	pondence." Notice the π^- estimate (dashed line) has already been divided
	by 10 before plotting it.
12.	Fraction of events containing a \overline{p} in the final state, 70 using the distributions
	presented in Fig. 11. The UCLA upper bound, as reported here by Strauch,
	is also shown.
13.	Schematic hadron final-state distributions for individual events expected
	in the covariant parton model. ⁹⁶
14.	Ladder exchange contribution to e^+e^- annihilation into hadrons.
15.	Space-time development of an ordinary collision. The rapidity distribution
	of constituents and emitted hadrons is also shown.
16.	Conjectured space-time development of e^+e^- annihilations into hadrons.

17. Structure of diagrams needed to obtain the space-time picture in Fig. 16. The wiggly lines are J=1 gluons.

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18. The analogous diagram (trampoline diagram) for the total cross-section.

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19. Diagram for Coleman-Preparata model of e^+e^- annihilation.



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Fig. 10



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Fig. 11



Fig. 12

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Fig.14

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