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WHAT IS GLUE GOOD FOR? or GLUONS COME OUT OF THE CLOSET

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Introduction

The most dramatic and encouraging development in Strong Interaction physics in the past few years has been the emergence of a candidate field theory to describe these interactions. This situation is in sharp contrast to that which obtained ten years ago when, at least at one well known institution of higher learning, it was "taught" that field theory was irrelevant to Strong Interactions$^{1)}$. It is important to keep in mind this rapid rate of recent developments when assessing the value of the physics discussed below. In particular, while quarks have now become well established as important (and valid) phenomenological and theoretical entities (albeit after a rather checkered early history), it is only with the recent emergence of a possibly correct theory of interacting quarks and vector gluons, Quantum Chromo-Dynamics (QCD), that a similar role has been thrust upon gluons. Crudely stated, if the gluons are present inside hadrons, then it is important to consider in what fashion the gluons make their presence explicitly felt in the interaction of hadrons. Skepticism about the role of gluons should be considered in the light of earlier skepticism about the role of quarks, a skepticism which has now largely vanished in the face of repeated successes.

This talk is intended as a partial review$^{2)}$ of recent progress in the study of the role of gluons in hadronic interactions. The general outline is to proceed from highly phenomenological (i.e., conjectural) topics to more rigorous applications of gluon physics which are explicitly related to the basic field theory. In particular, the last section of the talk is devoted to one attempt to define experimental tests of the basic properties of QCD and gluons which can be unambiguously calculated in perturbation theory.

Quarks and Gluons in QCD

Within the context of QCD the gluons (which form an octet under "color" transformations) serve to mediate the interactions between the quarks and among the gluons themselves. These interactions exhibit strong infrared divergences and it is presumed that the long distance interactions are sufficiently strong to insure the "confinement" of all color nonsinglet states. At the other end of the spectrum the non-Abelian character of the theory (and the gluons) insures that the effective "runnning" coupling is small at short distances and vanishes in the limit of zero separation$^{3)}$. This feature of the theory is generally accepted as the explanation of the apparent success (or more precisely, near success) of the naive quark-parton model as applied to processes involving interactions at "short distances". Within the naive model the quarks are treated as free at short distances while the distributions of quarks within a hadron (which involve long distance, confinement physics) are assumed to depend only on the fraction of the total momentum carried by the quark (scaling). A similar assumption is made concerning the distribution of final state hadrons which arise from the evolution of the scattered quark. In this case the scaling is in terms of the fraction of the quark's momentum carried by the hadron and the distribution is referred to as the distribution of hadrons in a jet. In situations where some rigor is possible, e.g., $e^+e^- \rightarrow$ hadrons and $ep \rightarrow eX$ (see fig. 1a and 1b), the corrections to this naive picture which result

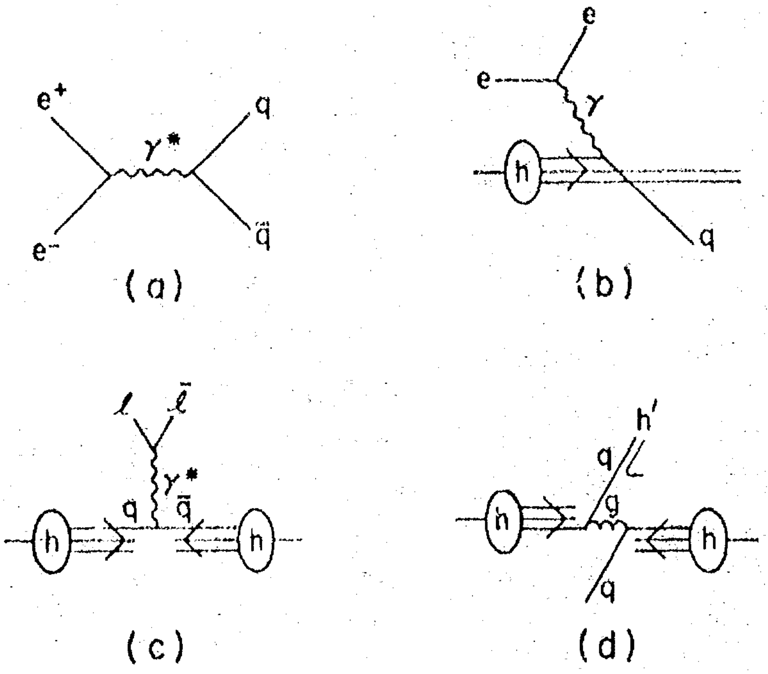


Fig. 1 Simple quark processes:
a) $e^+e^- \rightarrow$ hadrons;
b) $ep \rightarrow eX$;
c) Drell-Yan;
d) large p_T.

from the interactions inherent in QCD are found to be rather small[3]. Cross sections do not scale precisely but rather moments of the cross sections vary as prescribed powers of the logarithm of the relevant large kinematic variable, a behavior in good agreement with the data. The application of the naive quark model to more complex processes involving two initial hadrons, e.g., the Drell-Yan process[4] consisting of quark-antiquark annihilation into a massive virtual photon (see fig. 1c), or large p_T hadronic production[5] involving large angle quark-quark scattering (see fig. 1d), was accomplished by the assumption that these processes can be described by the incoherent convolution of up to three components as suggested in fig. 1. For the large p_T example the three components are: 1) the distributions of quarks in the initial hadrons, taken, for example, from single hadron processes like $ep \to eX$; 2) the quark-quark scattering process in lowest order; 3) the hadron distribution in the produced large p_T jet, taken, for example, from $e^+e^- \to hX$. More explicitly this structure, for the process $A + B \to C + X$, can be expressed as

$$E\frac{d^3\sigma}{d^3p}\bigg|_{A+B\to C+X} = \int dx_a d^2k_a F_{a/A}(x_a,k_a)\int dx_b d^2k_b F_{b/B}(x_b,k_b)$$

$$\int \frac{dz_C}{z_C^2} d^2k_C D_{C/c}(z_C,k_C)\ \frac{\hat{s}}{\pi}\ \delta(\hat{s}+\hat{t}+\hat{u}) \qquad (1)$$

where $F_{a/A}$ is the distribution of quark a in hadron A ($x_a = p_a/p_A$ and k_a is a transverse momentum variable), $D_{C/c}$ is the distribution of hadron C in the jet initiated by quark c ($z_{C/c} = p_C/p_c$), and $d\sigma/d\hat{t}$ is the quark-quark scattering cross section (^ refers to quark-quark variables). That this naive extension to more complex processes is appropriate in the context of QCD has yet to be fully demonstrated but early indications[6] are that the naive model is, in fact, the correct starting point.

Hadronic Production of Heavy Hadrons

Having set the stage with the phenomenological applications of quarks, as illustrated in fig. 1, the phenomenological applications of gluons arise simply by replacing quarks with gluons in these figures. Perhaps the first direct discussion of the possible role of gluons was in the hadronic production of hadrons containing charmed quarks[7,8]. The idea was to replace the $q\bar{q}$ pair in fig. 1c by gluons and the massive photon by the η_c, the pseudoscalar partner of the ψ/J particle, as shown in fig. 2a. To calculate one

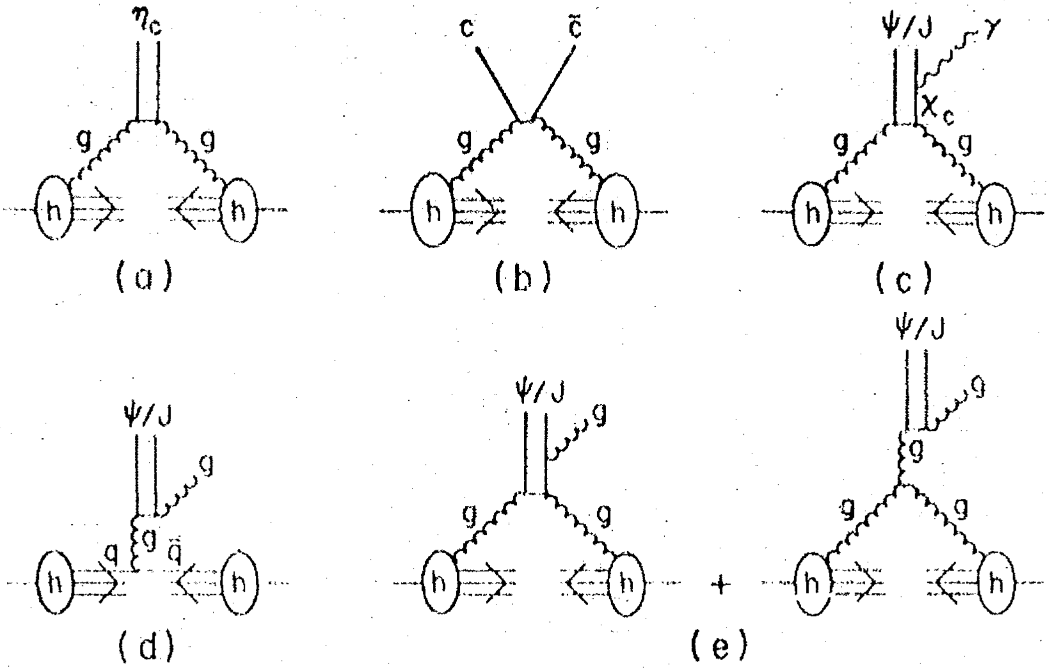


Fig. 2 Simple gluon processes: a) η_c production;
b) $c\bar{c}$ production;
c) ψ/J + γ production;
d) and e) ψ/J + gluon production.

need only make an assumption as to the form of the gluon distribution in protons (the total momentum in glue is known to be about 50%), about which there are various theoretical biases (e.g., $f_g \sim (1 - x)^5$, $x = p_g/p_h$) and an assumption as to the $\eta_c \to gg$ coupling. One can also estimate in this model total hadronic production of charm via the gluonic production of an unconstrained $c\bar{c}$ pair as in the diagrams of fig. 2b. Such estimates can easily account for the 10-100μb charm production cross section suggested by the recent "beam dump" experiments discussed in this meeting[9]. The best measured cross section involving the production of the new heavy particles is for ψ/J production. It was suggested[7] that production might occur via the gluonic production of the χ_c states which would then electromagnetically decay to yield a ψ/J and a γ as in fig. 2c. Recent data on ψ/J-γ coincidences suggest that this process may indeed account for part of the observed ψ/J signal[10]. Note that this mechanism allows a simple explanation of the suppression of ψ' production (but not Υ' production) since the $\chi_c{}'$ states are above the threshold for hadronic decays (while the corresponding states for the Υ' are presumably not).

More recent theoretical studies[8] have included consideration of the gluonic or $q\bar{q}$ production of color octet states which then decay into the ψ/J via gluon emission as in fig. 2d and 2e (we are explicitly ignoring the small 3 gluon coupling of ψ/J to $q\bar{q}$ and the role of charmed quarks in the hadronic sea). Analyses[8] involving a mix of these processes seem to allow a good explanation of the existing data including the sizeable ratio of $\bar{p}p \to \psi/J + X$ / $pp \to \psi/J + X$ which would be unity in a gluon dominated model. However, as $x = M_{\psi/J}/\sqrt{s}$ becomes small in larger s data one does expect gluon dominance for most model gluon distributions and it will be interesting to see if this ratio approaches one.

Another important test is to compare the excitation curves ($\sigma(s)$) for the ψ/J ($M^2 \approx 10$ GeV^2) with that for the Υ ($M^2 \approx 100$ GeV^2) to look for the predicted differences due to QCD scaling violation effects in the gluon distributions. Overall hadronic production of heavy particles appears to be a good place to test our phenomenological ideas about the role of gluons. At present the data are certainly consistent with expectations, including gluon distributions behaving essentially as $(1 - x)^5$.

Gluons in Large p_T Physics

The most promising arena for the observation of the characteristics of individual hadronic constituents in purely hadronic processes is the inclusive production of hadrons at large p_T[5]. As illustrated in fig. 1d this is conjectured to occur via the large angle scattering of two constituents[11]. In order to calculate this process within the context of QCD, even *assuming* the simple factorized form of fig. 1d and eq. (1), one must discuss not only the standard quark-quark scattering term (fig. 3a) but also include the possibility of gluon-quark scattering (fig. 3b), and the possibility of 2 gluons in (fig. 3c) or out (i.e., $q\bar{q} \to gg$, fig. 3d) or both[12,13] (fig. 3e). As in the previous section the

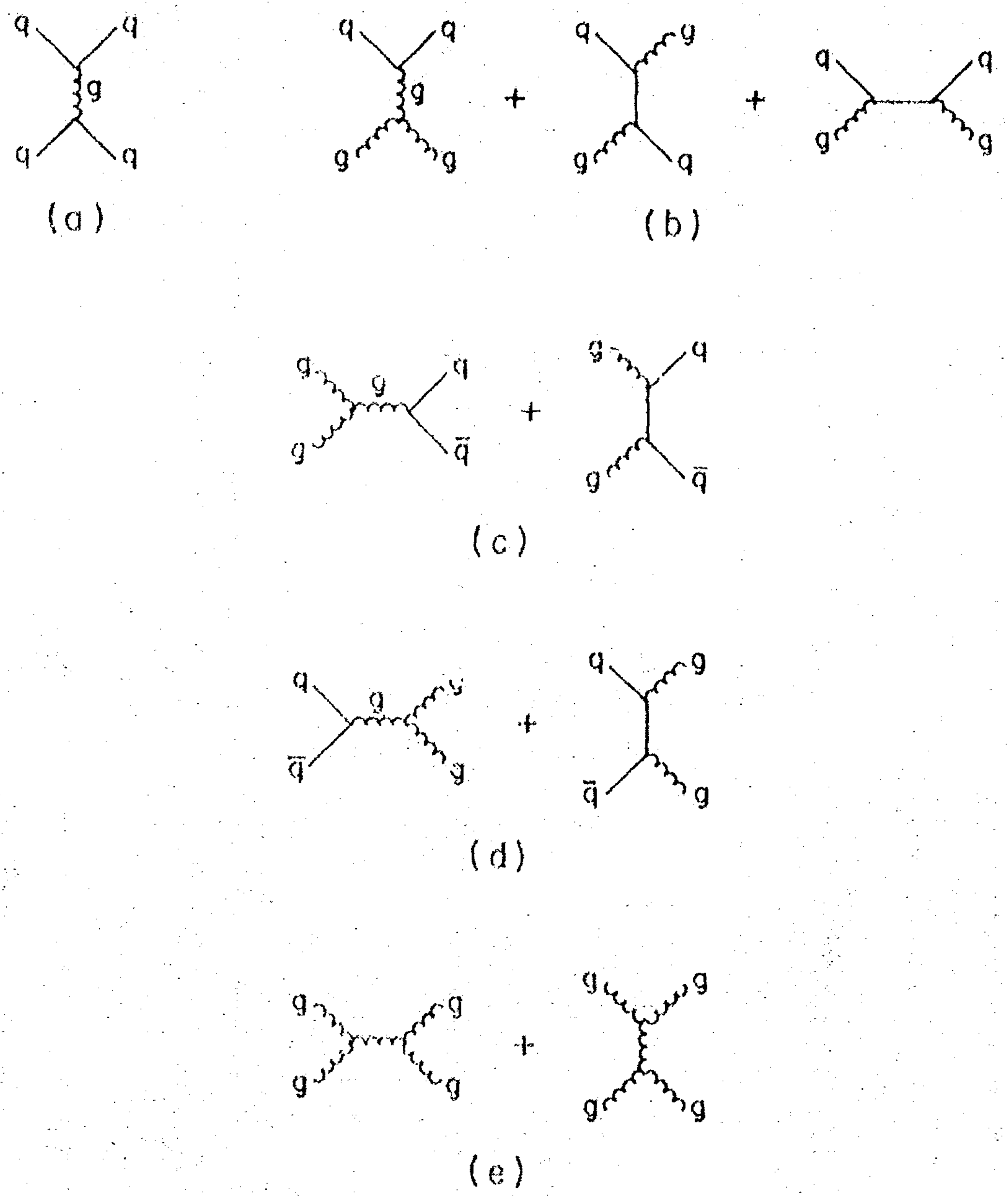


Fig. 3 Simple scattering: a) qq; d) q$\bar{q}$ → gg;
b) qg; e) gg → gg.
c) gg → q$\bar{q}$;

gluon distributions are presumed to be sharply peaked at small $x = p_g/p_h$. Furthermore, since a gluon must first fragment into quarks before it can start to produce hadrons, a jet initiated by a gluon is presumed to produce more hadrons with smaller average $z = p_h/p_g$ than a corresponding quark initiated jet. Thus the dominant effect of the inclusion of gluons in large p_T physics is to increase the cross section at small $x_T = 2p_T/\sqrt{s}$ which is particularly useful in fitting the higher s data from the ISR 12,13).

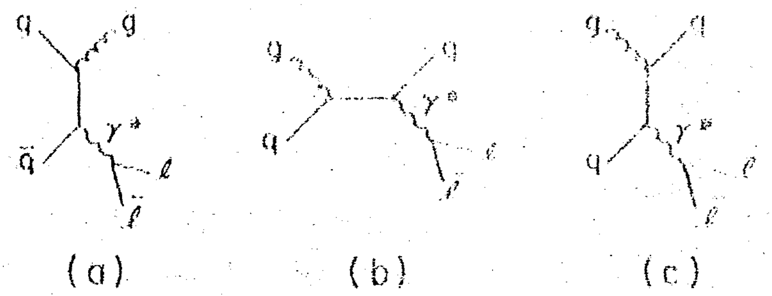
Of course one must also include the effects of gluons as they are realized in the nonscaling behavior of the quark, gluon and jet distributions. Several parameterizations of this momentum dependence are available 14,15) which are fairly similar for the experimentally relatively "well" determined quark distributions but differ considerably in the less well specified gluon distributions as noted below. These differences appear to arise from differing assumptions about the input shape of the gluon distribution [e.g., $(a + bx)(1 - x)^4$ instead of $(1 - x)^5$]. Finally, even for lowest order scattering, account must be taken of the feature of QCD that the effective coupling is a decreasing function of p_T^2. The result of the convolution of all these effects is to produce an inclusive cross section $Ed^3\sigma/d^3p$ which, at large p_T and *fixed* x_T, exhibits a behavior much more like the observed p_T^{-8} behavior than the naively expected p_T^{-4} form 12,13). In fact, with the inclusion of some internal transverse momentum for the constituents within the initial hadrons, one can achieve a quite acceptable fit to the observed data over a wide energy range 12,13). Unfortunately detailed fits within the presently accessible p_T range depend strongly on the *assumed* shape of the constituents' internal p_T distributions. At best one can only argue for the consistency of QCD and the simple factorizing picture with the data. To actually test the *predictions* of QCD will require data at considerably larger p_T's ($p_T >> 4$ GeV/c) where the cross section should exhibit a slower fall off at fixed x_T. There is actually some evidence that this is the case 16).

Returning to the explicit role of gluons in large p_T physics, the results of ref. 13 (the reader is referred also to the talk of A. P. Contogouris elsewhere in these proceedings) suggest a sizable role indeed. For example in the process $pp \to \pi^0 + X$ at 90° with $\sqrt{s} = 19.4$ GeV and at $p_T = 1.94$ GeV/c 46% of the triggers are found to arise from glue jets while at $p_T = 6$ GeV/c the fraction is only 3%. At $\sqrt{s} = 53$ GeV and p_T's of 2 and 9 the corresponding fractions are 43% and 7%. However the reader is warned that these results presumably are sensitive to using the gluon distributions of ref. 15 which have a larger density of intermediate x gluons than is generally assumed [i.e., an input shape like $(a + bx)(1 - x)^4$ rather than $(1 - x)^5$]. It would be informative to test this distribution in the hadronic production calculations of the previous section. As noted above the large gluon induced contribution at small x_T is very helpful in explaining the shape and magnitude of the existing data on single particle inclusive production.

A perhaps more striking result is the role of gluon induced jets for the particles produced opposite the large p_T trigger particle. Since gluon induced jets are assumed to be less efficient than quark jets at giving a large fraction of momentum to a single hadron, their role is relatively suppressed on the trigger side. However, in the calculations of ref. 13, the quark-gluon scattering term (fig. 3b) leads to a dominant contribution of gluon jets opposite the trigger. The fraction of opposite jets which are one gluon induced for the process $pp \to \pi^0 + h^{\pm}_{\text{opposite}} + X$ are 76% and 43% at $p_{\text{Trigger}} \approx 1.94$ GeV/c and 6 GeV/c at $\sqrt{s} = 19.4$ GeV and 69% and 51% at $p_{\text{Trigger}} = 2$ GeV/c and 9 GeV/c at $\sqrt{s} = 53$ GeV. This large gluon jet contribution tends to reduce the number of large p_T (i.e., large $x_E = p_h/p_{\text{Trigger}}$) hadrons opposite the trigger relative to a pure quark-quark model, an effect useful in order to understand the data[13]. Also the inclusion of even a small fraction of gluon induced jets on the trigger side will lead to a smaller average hadron momentum within an average jet. This means that for calorimeter (i.e., jet) triggers[17], the ratio prediction for the rate of jet versus single hadron triggers at a fixed p_T will increase as a result of the inclusion of gluons, an apparently desirable effect although the experimental situation is far from clear. In summary the gluons appear to play an essential role if one is to understand large p_T physics in terms of elementary constituent scattering[18]. At the same time the results of this area of study are not of sufficient rigor to actually be able to test QCD here.

Glue as a Source of Large p_T in the Drell-Yan Process

Since this question is discussed in detail elsewhere in these proceedings[19], the present discussion will be brief. The Drell-Yan process[4], fig. 1c, is viewed as the source of the large mass lepton pairs observed in pp collisions[20]. Since these pairs are seen to exhibit sizable average p_T ($\langle p_T\rangle \sim 800$ MeV/c) with respect to the beam direction, gluon emission, as illustrated in fig. 4a,



(a) (b) (c)

Fig. 4 Large p_T Drell-Yan: a) g emission;
b) and c) g incident and q emission.

has been discussed[21] as a possible source. Of course it was also noted[21] that gluons can participate as one of the incident constituents as illustrated in fig. 4b and 4c. The central difficulty in exploring the gluon emission contribution is that the diagram involved behaves as

$$d^2\sigma/d^2p_T \sim 1/p_T^2 \tag{[illegible]}$$

i.e., it exhibits an infrared divergence. Various methods have been proposed to handle this question including putting in an explicit quark mass or simply cutting off the distribution at small p_T. While it is likely that gluon physics plays an important role in the Drell-Yan process, it seems clear that simple gluon emission cannot explain all of the observed p_T of the lepton pair. Thus, at present energies, nonperturbative (i.e., noncalculable) sources of p_T are still important. Hence this is not the process to precisely test out understanding of gluons and QCD. Thus while gluons are certainly an important part of the phenomenological understanding of various hadronic processes, this connection cannot yet be inverted to actually check whether QCD is the correct theory of Strong Interactions. One attempt to define processes which can provide precise tests is discussed in the next section.

Gluons in Precise Calculations

From the discussions of the previous sections it should be apparent that at least part of the difficulty of defining experimental tests of whether QCD is the correct theory arises from the presence of hadrons in the initial state with their attendant constituent distribution functions. Essentially the only reliable tool available for calculation is perturbation theory. Even when augmented by the simultaneous application of renormalization group techniques, one can, at present, only calculate the large momentum transfer behavior of these distribution functions, taking the low momentum behavior from the (presently rather incomplete) data. To attack the full hadron-hadron problem starting from first principles, i.e., the QCD Lagrangian, is at present impossible. A natural response to this situation is to study e^+e^- annihilation into hadrons which removes the problem of initial state hadronic wave functions. Furthermore, one must avoid introducing noncalculable quantities via the specification of the final state. For example, the single pion inclusive cross section is not calculable in perturbation theory alone. However, it does appear possible to calculate the total e^+e^- annihilation cross section in perturbation theory. The procedure is to calculate the cross section for the production of massless quarks and gluons in renormalized perturbation theory and then, using the renormalization group, replace the fixed renormalized coupling with the effective running coupling constant which behaves at large total energy W as

$$\tilde{g}_W^{\,2} \simeq \frac{8\pi^2}{(11-2/3N_f)\ln(W/\mu)} \qquad (3)$$

where N_f is the number of quark "flavors" and μ defines the renormalization point. The parameter μ is generally chosen[22] to have a value around 500 MeV in order to minimize the $(\ln W/\mu)^{-2}$ corrections to the leading behavior of eq. (3). The result of this perturbative calculation of σ_{tot} is in exact agreement with the results of the more rigorous scheme of studying the absorptive part of the photon propagator. The success of this asymptotically free perturbation calculation for σ_{tot} suggests[23] the possibility of the existence of an heriarchy of partial cross sections for the e^+e^- annihilation process which are both precisely calculable and accessible experimentally. Furthermore, since the validity of the perturbation calculation rests on the existence of a massless limit so that the renormalization group can be employed to put all non-trivial W dependence into the running coupling of eq. (3), one can interrogate the theory itself as to which quantities are appropriate to calculate in this fashion. In particular, within this scheme those quantities which exhibit explicit infrared singularities cannot be reliably calculated. For example, if a mass m is introduced for the gluon (or quark) to provide an infrared cutoff, some cross sections will be calculated as a power series in the quantity (g^2 lnW/m) which is not well behaved in the $W \to \infty$ or $m \to 0$ limit. This situation is interpreted as an indication that such cross sections cannot be reliably calculated in perturbation theory and therefore it is not possible to obtain intuition about these processes by considering simple perturbation diagrams. However, other quantities, like the total cross section, are free of such divergences and can be precisely calculated in perturbation theory[24] and should be directly comparable to experiment. This discussion is, of course, only relevant far from any explicit quark thresholds.

Cross sections of the nature discussed above are presently being studied[25] at the University of Washington. The basic idea is to consider inclusive processes which measure energy deposition in a fixed angular region. Such quantities should be insensitive to soft gluon emission or the branching of quarks into quarks and gluons, the usual sources of infrared divergences. Also it should be feasible to compare energy deposition calculated as if it occurs via quarks and gluons to experiment where it occurs in the form of hadrons. As demonstrated by low order calculations[25,26] these cross sections have a well defined perturbation expansion in the limit of zero quark and gluon mass. Thus the renormalization group can be used to replace g^2 by $\bar{g}_W^{\,2}$ where all the nontrivial W dependence is in $\bar{g}_W^{\,2}$. Hence for large enough W, the series expansion is always rapidly convergent. The simplest such cross section is the "antenna pattern" $d\Sigma/d\Omega$ defined to be the hadronic power radiated into solid angle $d\Omega$ divided by the energy flux in the e^+e^- beams. Considering the case of e^+e^- beams polarized transverse to the beam direction and defining a polar angle ψ measured from the polarization direction, the order g^2 result is[25)]

$$\frac{d\Sigma}{d\Omega} = \frac{\alpha^2}{2W^2} \sum_f 3Q_f{}^2 \left[\sin^2\psi + \frac{\bar{g}_W{}^2}{2\pi^2} \cos^2\psi \right] \qquad (4)$$

where α is the fine structure constant ($\sim 1/137$) and Q_f are the electric charges of the various quark flavors in units of the electron charge. The relevant perturbation diagrams are displayed in fig. 5.

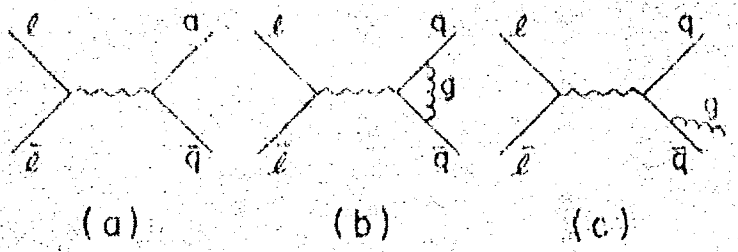


Fig. 5 $e^+e^- \to$ hadrons: a) $q\bar{q}$;
b) virtual gluon;
c) gluon emission (+ crossed case).

This calculation does not include corrections due to the fragmentation of the quarks and gluons into hadrons which are of order m/W compared to the logarithmic terms calculated above. These power corrections can be estimated[25)] by assuming that the hadronic distribution within a jet is a function of the longitudinal momentum fraction times a rapidly cutoff transverse momentum distribution. This quark fragmentation effect modifies the basic order $(g^2)^0$ cross section to read

$$\frac{d\Sigma}{d\Omega}\ (\text{frag.}) = \frac{\alpha^2}{2W^2} \sum_f 3Q_f{}^2 \left[\sin^2\psi + \frac{1}{2} \langle \sin^2\eta \rangle (3\cos^2\psi - 1) \right] \quad . \qquad (5)$$

The quantity $\langle \sin^2\eta \rangle$ is essentially the energy weighted average (over the hadrons in the jet) opening angle of the jet induced by the fragmentation process (i.e., it is not a perturbative effect). With the above assumptions it has the form

$$\langle \sin^2\eta \rangle = \frac{\pi C \langle h_T \rangle}{2W} \qquad (6)$$

where $\langle h_T \rangle$ is the average transverse momentum in a jet ($\langle h_T \rangle \sim 300$ MeV in the data) and C is the coefficient of the lnW dependence of the total multiplicity in e^+e^- annihilation ($\langle n \rangle \sim C \ln W$ + constant).

Comparison of eqs. (4) and (5) suggests the definition of a total jet opening angle

$$\langle \sin^2\eta \rangle_{\mathrm{TOTAL}} = \frac{\bar{g}_W^{\,2}}{2\pi^2} + \frac{\pi C \langle h_T \rangle}{2W} \qquad (7)$$

where both the perturbative (precise) and nonperturbative (phenomenological-confinement) contributions are explicitly displayed. While this simple additive approach is certainly overly naive it probably does afford a reasonable estimate of the relative sizes of the two effects. With $N_f = 4$, $C = 2$, $\langle h_T \rangle = 300$ MeV, and μ (eq. 3) = 500 MeV, the perturbation contribution already dominates by a factor 3 at W = 30 GeV. The "full" cross section to order g^2 and additively corrected for quark fragmentation is

$$\frac{d\Sigma}{d\Omega} = \frac{\alpha^2}{2W^2} \sum_f 3Q_f^{\,2} \left[1 + \frac{\bar{g}_W^{\,2}}{4\pi^2}\right] \left[\sin^2\theta + \frac{1}{2} \langle \sin^2\eta \rangle_{\mathrm{TOTAL}} (3\cos^2\theta - 1)\right]. \qquad (8)$$

The relative shape and size of this quantity with the parameter values given above is plotted for various energies in fig. 6.

While the prediction of eq. (8) is most directly tested with a calorimeter experiment (assuming that correction is made for heavy lepton production), making the assumption that the energy in neutral hadrons has the same angular distribution as that in charged hadrons and ignoring the caveat that one is to be far from thresholds, allows a comparison with existing charged hadron data. The resulting agreement is remarkably good[25].

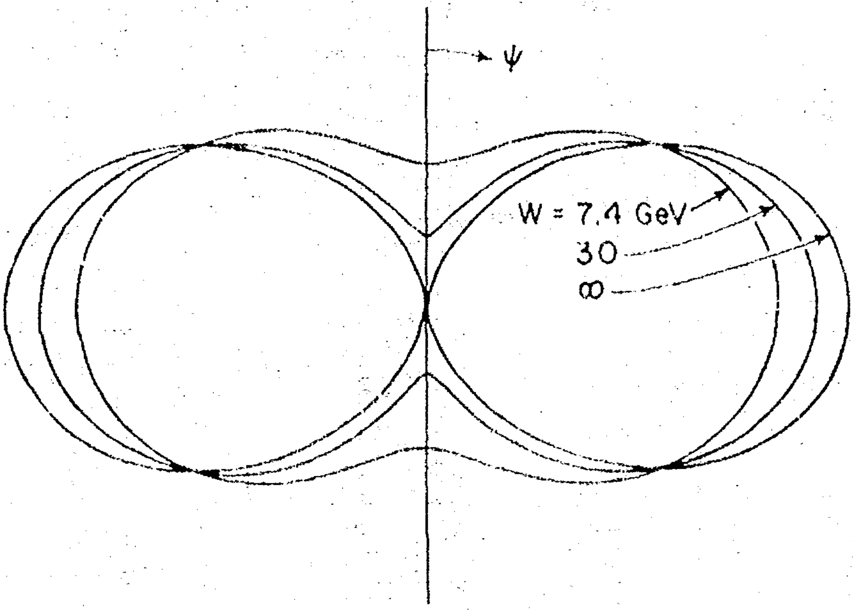


Fig. 6 Antenna pattern.

It is important to note that the individual contributions to eq. (4) arising from the energy in quarks and the energy in gluons separately exhibit infrared divergences. It is only the total energy cross section which is a meaningful quantity to study perturbatively. This point also applies to the question of looking at the energy and electric charge weighted cross section in order to see whether, on average, fractional charge resides near the edge of phase space as an indication of "quarkiness". Since the glue does not contribute to this cross section, it will exhibit infrared singularities and not be calculable perturbatively. Hence one should not anticipate that the expectations which arise from consideration of the simple perturbative diagrams of fig. 5 will be relevant. Also, while at order g^2 the quark production cross section (i.e., with no energy factor) is not divergent, it is found$^{26)}$ to be divergent at order g^4 in keeping with the philosophy that the theory should not give sensible perturbative results for nonsensible quantities. Work is continuing$^{26)}$ to study the form of higher order contributions to $d\Sigma/d\Omega$ and to illuminate the structure of more complicated correlations in the heirarchy of perturbatively calculable cross sections.

Summary

Progress in the understanding of the role of glue in Strong Interactions is progressing on several fronts. Phenomenological studies of large p_T, Drell-Yan, and heavy particle production physics give strong, if somewhat peripheral, indications that gluons are indeed present in hadrons and with distributions consistent with naive expectations. At the same time more rigorous studies of the implications of gluons and QCD give every indication that confirmation that this is the correct theory is near at hand.

Acknowledgements

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18) Again the reader is reminded of the alternative approach of the ClModel. See. ref. 11.

19) See the contributions of C. T. Sachrajda, R. Petronzio and G. Altarelli elsewhere in these Proceedings.

20) See the contribution of L. Lederman to these Proceedings and S. W. Herb et al., Phys. Rev. Lett. 40, 435 (1978).

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