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[1]M. Banner *et al.*, Nucl. Phys. B126, 61 (1977); M.G. Albrow *et al.*, Nucl. Phys. B114, 365 (1976).

[2]A. S. Carroll *et al.*, Phys. Rev. Lett. 32, 247 (1974); V. Chaloupka *et al.*, Phys. Lett. 61B, 487 (1976); W. Brückner *et al.*, Phys. Lett. 67B, 222 (1977); P. Benkheiri *et al.*, Phys. Lett. 68B, 483 (1977); B. G. Gibbard *et al.*, Phys. Rev. Lett. 42, 1593 (1979).

[3]R. P. Hamilton *et al.*, Phys. Rev. Lett. 44, 1182 (1980).

[4]M. Fukugita, K. Konishi, and T. H. Hansson, Phys. Lett. 74B, 261 (1978).

[5]H. Hogaasen and P. Sorba, Nucl. Phys. B145, 119 (1978).

[6]J. Amirzadeh *et al.*, Phys. Lett. 89B, 125 (1979).

[7]A. J. Pawlicki *et al.*, Phys. Rev. D 15, 3196 (1977); D. S. Ayres, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Frascati, Italy, 1973,* edited by S. Stipcich (Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare Servizio Documentazione, Frascati, Italy, 1973), p. 665.

[8]I. Ambats *et al.*, ANL Report No. ANL-HEP-PR-80-13 (to be published).

[9]From the observed e^t behavior, we can estimate the cross-section suppression caused by $t_{\min}$ effects. For example, at $M_{p\bar{p}}=3.1$ GeV/c^2, where $|t_{\min}|=0.25$ GeV^2, our recoil detector cutoff at $1.16t_{\min}$ causes a $\approx 4\%$ loss of events; in addition, the kinematic cutoff at $t_{\min}$ would reduce the cross section by $\approx 21\%$, as compared with the case $t_{\min}=0$.

[10]The nongeometric corrections included attenuation of primary and secondary particles (8%), interactions in the trigger hodoscope causing extra hodoscope hits (7%), Čerenkov veto of protons due to interactions (5%), reconstruction losses (3%), and recoil-detector inefficiency (4%).

[11]The 5-s.d. upper limits were obtained from a crude fit to the observed mass distributions, with use of a smooth background plus a Gaussian with half width ≈ 5 MeV/c^2. For example, for the case of zero background, the 5-s.d. limit would correspond to 25 events in the central 10-MeV/c^2 bin and an integrated total of ≈ 37 resonance events.

[12]C. Evangelista *et al.*, Phys. Lett. 72B, 139 (1977).

[13]T. A. Armstrong *et al.*, Phys. Lett. 85B, 304 (1979).

Isolating Gluon Jets

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It is shown that the identification of gluon and quark jets in the process $e^+e^-\to$ three jets is feasible if the gluon is radiated off heavy quarks. Gluon energy spectra are computed for $e^+e^-\to b\bar{b}g$ in the 30–40-GeV energy region and for $e^+e^-\to Z^0\to t\bar{t}g$.

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The properties of three-jet events in e^+e^- annihilation[1] have become one of the most important tests of perturbative quantum chromodynamics (QCD), but unfortunately up to now there has been no distinction between jets that have originated from either quarks or gluons. In this Letter we show that in the case of gluons emitted from *heavy* quarks a separate identification of quark and gluon jets can be made. Such a distinction is of major interest in order to (i) investigate if quark and gluon jets fragment differently into hadrons as is expected because of their different color charge,[2] (ii) decide whether the gluon spectrum coincides with that predicted by QCD. The first question could be answered as well in different reactions such as quarkonium decay to three gluons, whereas the second should be checked in e^+e^- annihilation to quarks and gluons as well. To illustrate (ii) let us consider Fig. 1, which shows a large difference in the gluon spectra as predicted by QCD and a model with scalar gluons.[3] Thrust and oblateness distributions, however, forced by energy-momentum conservation, show only minor differences in the two cases,[4] and if quark and gluon jets are not distinguished rather complicated angular correlations have to be considered in order to obtain results that are not just a reflection of kinematic restrictions.

We propose a separation of gluon jets and jets of heavy quarks by the measurement of the *invariant masses* of jets,[5] which is a well-defined quantity in QCD perturbation theory. A quark is

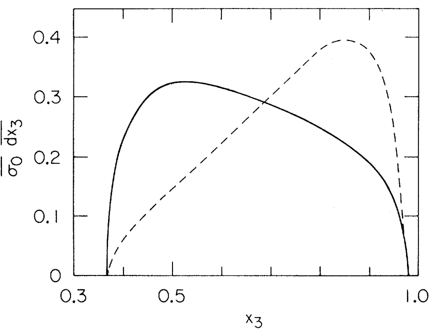

FIG. 1. Gluon energy spectra for $e^+e^- \to Q\bar{Q}g$ at $\sqrt{s} = 90$ GeV and $m_Q = 5$ GeV as given by QCD (solid line) and a model with scalar gluons (dashed line).

called heavy as long as its mass is considerably larger than the effective mass originated by the fragmentation of the quarks into hadrons. This effective mass corresponds to the invariant masses of the jets of massless quarks.[5,6] It can be estimated by the average multiplicity $\langle n\rangle$ and transverse momentum $\langle p_\perp\rangle$ of the hadrons in the jet of light quarks at low energy and is expected to show only a moderate variation with the energy of the jets.[5,6] For our purpose, we will consider the charmed quark as a light quark, but the b quark and certainly the hypothetical t quark can be regarded as heavy.[5,6] As the most promising regions[7] to obtain a quark-gluon jet separation we propose $e^+e^- \to b\bar{b}g$ in the 30–40 GeV energy region, and (if the t quark exists and is not too heavy) $e^+e^- \to Z^0 \to t\bar{t}g$ at the resonance of the intermediate vector boson Z^0 where experiments will be done in the future with the Single-Pass Collider at Stanford Linear Accelerator Center and the Large Electron Project at CERN. Especially at the Z^0 resonance one will have high statistics and the mass of the t quark is expected to be so high that just a rough experimental estimate of the jet masses will allow a separation.

In the following we will compute three-jet cross sections and gluon energy spectra for the process $Z^0 \to Q\bar{Q}g$ where Q denotes a quark of mass m and g a gluon, and show how this specializes to the spectra in the process $e^+e^- \to$ "γ" $\to Q\bar{Q}g$. Let us introduce the energy fractions $x_i = 2E_i/M$, where $i = 1, 2, 3$ corresponds to Q, $\bar{Q}$, g, and M is the Z^0 mass. We obtain ($x_1 + x_2 + x_3 = 2$)

$$\frac{1}{\Gamma_0}\frac{d\Gamma(Q\bar{Q}g)}{dx_1dx_2} = \frac{4\alpha_s}{3\pi\beta}[v^2(3-\beta^2)+2a^2\beta^2]^{-1} \times\left[(v^2+a^2)\left\{\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} - \frac{2m^2}{M^2}\left(\frac{2}{1-x_1}+\frac{2}{1-x_2}+\frac{1}{(1-x_1)^2}+\frac{1}{(1-x_2)^2}\right)\right\} + \frac{2a^2m^2}{M^2}\left\{\frac{(2-x_1-x_2)^2}{(1-x_1)(1-x_2)}+\frac{6(1-x_1-x_2)}{(1-x_1)(1-x_2)}\right\} - \frac{4m^4}{M^4}(v^2-2a^2)\frac{(2-x_1-x_2)^2}{(1-x_1)^2(1-x_2)^2}\right], \tag{1}$$

where α_s is the strong coupling constant and Γ_0 is the cross section for $Z^0 \to Q\bar{Q}$ to lowest order:

$$\Gamma_0 = (g^2M/32\pi)\beta[v^2(3-\beta^2)+2a^2\beta^2] \tag{2}$$

with $\beta = 1-(4m^2/M^2)$. gv (ga) are the vector (axial vector) coupling constants which have the following values for u, c, t quarks in the standard model[8]:

$$a^2 = 1(4\cos^2\theta_W)^{-1}, \tag{3}$$

$$v^2 = (1-\tfrac{8}{3}\sin^2\theta_W)^2/4\cos^2\theta_W, \tag{4}$$

$$\frac{g^2}{8M^2\cos^2\theta_W} = \frac{G_F}{\sqrt{2}} \approx 8.25\times10^{-6}\ \mathrm{GeV}^{-2}. \tag{5}$$

In our calculation we use $\sin^2\theta_W = 0.23$ and $M = 90$ GeV. The cross section $(1/\sigma_0)(d\sigma/dx_1dx_2)$ for the process[9] $e^+e^- \to$ "γ" $\to Q\bar{Q}g$ is obtained from (1) by replacing M by $\sqrt{s}$ (c.m. energy), $a^2 = 0$, and $v^2 = 4e_Q^2$ where e_Q is the charge of the quark and

$$\sigma_0 = (2\pi\alpha^2/3s)3e_Q^2\beta(3-\beta^2). \tag{6}$$

Expression (1) shows the usual infrared and collinear singularities as x_1 and/or x_2 approach 1. We are specifically interested in the gluon spectra that appear in three-jet events and will therefore define a quantity that satisfies the following two criteria: (i) the three jets are separated; (ii) the defined quantity can be reliably computed in a first-order α_s approximation.

For heavy quarks[10] the most economic cutoff in (1) to satisfy the above criteria is a restriction on the angle between the quark and antiquark direction:

$$-(1-\delta) \leq \cos\theta_{Q\bar{Q}} = \frac{2-2(x_1+x_2)+x_1x_2+4m^2/M^2}{[(x_1^2-4m^2/M^2)(x_2^2-4m^2/M^2)]^{1/2}} \leq (1-\delta) \tag{7}$$

because this provides us simultaneously with $x_3 \geq \epsilon > 0$ and a θ_{Qg}, $\theta_{\bar{Q}g}$ cutoff. The effective coupling constant[11] can be shown not to be α_s/π, but rather

$$(\alpha_s/\pi)\ln^2\delta \qquad (8)$$

in the region of small x_3. δ should be chosen that the quantity (8) is small and thus a summation of large logarithms is not necessary. We took $\alpha_s = 0.17$ at 90 GeV and chose $\delta = 0.1$ which assures the validity of a calculation in first order in α_s, but we are aware of the fact that in certain regions of m and $\sqrt{s}$ criterion (i) (the experimental separation of the three individual jets) may force us to use a larger value of δ up to 0.2.

Using $x_1 + x_2 + x_3 = 2$ and integrating over $y \equiv x_1 - x_2$ in expression (1) gives us the gluon energy spectra. These spectra scale in m^2/s except for a logarithmic variation of $\alpha_s(s)$. Figure 2 shows the result for various t-quark masses at the Z^0 resonance ($M = \sqrt{s} = 90$ GeV) and Fig. 3 the gluon spectrum for the process $e^+e^- \to$ "γ" $\to \bar{b}bg$ at $\sqrt{s} = 30$ GeV. The total cross section Γ/Γ_0 is 7% for $\delta = 0.1$ and $m = 20$ GeV, which would correspond to as much as 10^2–10^3 events a day at the Z^0 resonance.[12] The mean energy of the gluon jet in these events is $\langle E_3\rangle = 22$ GeV ($\langle x_3\rangle \approx 0.5$).

For $b\bar{b}g$ production at 30 GeV $\leq \sqrt{s} \leq$ 40 GeV and $t\bar{t}g$ at Z^0 with $m_t \leq 20$ GeV it is expected[13] that a three-jet structure will be observable. In this case one has to select experimentally from the sample of all three-jet events those which contain jets of high invariant masses. (In the case of $t\bar{t}$ even a rough estimate would be sufficient.) Since in the $Q\bar{Q}g$ events *two* of the jets have large masses ($\geq m_Q$), uncertainties due to statistical fluctuations and even jet broadening due to additional hard gluon bremsstrahlung can be regarded as negligible backgrounds as explained in great detail in Ref. 5. Moreover, the invariant mass has the nice property that it is completely independent of the structure of the weak interaction that is responsible for the decay of the heavy quarks. The specific QCD predictions such as quark and gluon energy spectra as well as angular distributions based on (1) can then be checked. As far as we have seen in our calculation, the angular distribution in $\theta_{Q\bar{Q}}$ for fixed x_3 is very sensitive to the spin of the gluon.

If $m_t > 20$ GeV the heavy quarks will presumably not appear as collimated jets which could be disentangled from each other at $\sqrt{s} = 90$ GeV. The high-statistics experiments expected at the Z^0 resonance, however, make it worthwhile to think more about that situation, since there will still be the signal of a narrow gluon jet with large energy. These events could be selected experimentally by imposing thrust and acoplanarity cuts, which in the case of light quarks can only be survived by events which show an explicit multijet structure. Let us illustrate that for $m = 25$ GeV. Assuming that the quark fragments symmetrically in its rest frame[14] one computes $T \approx 0.83$ for events $Z^0 \to Q\bar{Q}$, and events of the type $Z^0 \to Q\bar{Q}g$ will be even lower in thrust; i.e., with a cut $T_{max} = 0.9$, one will not lose events in which heavy quarks are produced. For $q\bar{q}g$ events with light quarks $T \leq 0.9$ implies that the smallest angle between any two of the three partons is larger than 70° and at this high energy one will have clearly separated jets. (A similar argument can be applied to four-jet events with a combined thrust and acoplanarity cutoff.) By this procedure one can select a clean sample of events containing

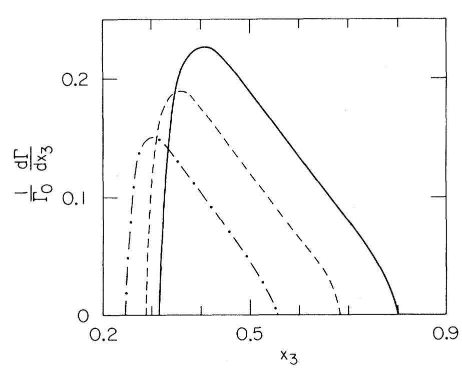

FIG. 2. Gluon energy spectra for $Z^0 \to Q\bar{Q}g$ for $\delta = 0.1$ and $m_Q = 20$ GeV (solid line), 25 GeV (dashed line), and 30 GeV (dashed dotted line).

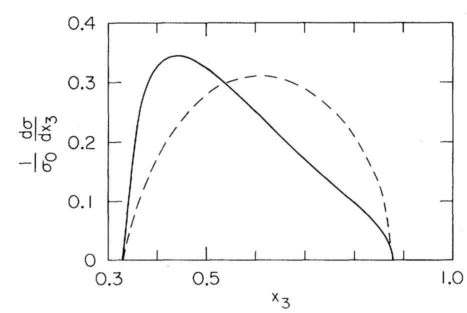

FIG. 3. Gluon energy spectra for $e^+e^- \to$ "γ" $\to b\bar{b}g$ at $\sqrt{s} = 30$ GeV, $\delta = 0.1$ and $\alpha_s = 0.23$. The solid line corresponds to the prediction of QCD whereas the dashed line gives the result of a scalar gluon model (normalized to the QCD result).

heavy quarks and should then scan for a narrow gluon jet of high energy.

Let us conclude with the remark that the concept of invariant masses of jets will not only allow a separate identification of gluon and heavy-quark jets, but will also be a powerful tool in the procedure of detecting the hadrons that carry the new quantum number of the heavy quark.

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[1]For a recent review see B. H. Wiik, DESY Report No. 79/84, 1979 (unpublished), and references contained therein.

[2]S. J. Brodsky and J. F. Gunion, Phys. Rev. Lett. 37, 402 (1976); K. Konishi, A. Ukawa, and G. Veneziano, Nucl. Phys. B157, 45 (1979).

[3]A model with scalar gluons should not be regarded as a serious alternative to QCD, but should rather illustrate that in some cases the results are mainly reflecting phase space restrictions.

[4]K. Koller, H. G. Sander, T. F. Walsh, and P. M. Zerwas, DESY Report No. 79/87, 1979 (unpublished).

[5]L. C. Clavelli and H. P. Nilles, Phys. Rev. D 21, 1242 (1980).

[6]M. Suzuki, University of California Report No. LBL-10094, 1979 (unpublished).

[7]We should mention here that the weak semileptonic decay of c, b, and t quarks can be used to isolate gluon jets for a small percentage of the events (G. Feldman, private communication).

[8]S. Weinberg, Phys. Rev. Lett. 19, 1264 (1967); A. Salam and J. C. Ward, Phys. Lett. 13, 168 (1964); S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D 2, 1285 (1970).

[9]This special case $a=0$ has been computed previously by B. L. Ioffee, Phys. Lett. 78B, 277 (1978), and including polarization effects by E. Learmann and P. M. Zerwas, Phys. Lett. 89B, 225 (1980); G. Grunberg, Y. J. Ng, and S.-H. H. Tye, Phys. Rev. D 21, 62 (1980); G. Kramer, G. Schierholz, and J. Willrodt, DESY Report No. 79/69, 1979 (unpublished).

[10]For light quarks one has to demand a cutoff $1-x_3 \geq \epsilon' > 0$ in addition to the one introduced in (7).

[11]G. C. Branco, H. P. Nilles, and K. H. Streng, Phys. Lett. 85B, 269 (1979), and references contained therein.

[12]See, e.g., J. Ellis, in *Proceedings of the Summer Institute on Particle Physics, 1978*, edited by M. C. Zipf (Stanford Univ. Press, Stanford, Cal., 1978), p. 69.

[13]This expectation is based on general estimates of multiplicity and transverse momentum of hadrons inside jets, which are deduced from results in the PETRA experiments (Ref. 1).

[14]One has to be aware of the fact that the weak decay of the heavy quark may lead to a jet structure, but this would only slightly modify our estimates of the thrust value.

Diffractive Dissociation Processes and Quark-Antiquark Jets

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A model for pion diffractive dissociation as a two-stage process is examined, where first the pion breaks up to $q\bar{q}$ system, followed by the hadronization of this quark-antiquark system. This model appears to be consistent with the present experimental data. Implications of this hypothesis for a study of quark-antiquark jets is suggested.

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We note here that hadronization of quark-antiquark pairs is an important theoretical, as well as an experimental, problem. We observe this process, e.g., in e^+e^- annihilation to two jets of hadrons.[1] These jets, however, will be the result of hadronization of many types of quark-antiquark pairs: $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $c\bar{c}$, or $b\bar{b}$. We thus have here very mixed information regarding the hadronization of quarks and antiquarks which cannot be easily deciphered since the signals from heavy-quark-antiquark pairs will differ from that of light ones. E.g., a strong SU(3) nonconservation is derived on phenomenological grounds[2] regarding "fragmentation" of the u and d quarks producing π and K mesons. Further, the decay modes of the D and F mesons are not yet well established.

We would like to propose here, however, that there is most likely an alternative source of hadronization of quark-antiquark pairs which is

