Neutralization of a color charge and electric charge of a quark in jets

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A method of determining the size of the region of space in which the color charge and electric charge of a quark are neutralized in e^+e^- annihilation is proposed. These charges are neutralized through the emission of hard photons at large angles.

1. The creation of a quark and an antiquark in e^+e^- annihilation processes may be classically viewed as an instantaneous acceleration of two color and electric charges at the point of the e^+e^- collision. This event should naturally be accompanied by the emission of gluons and photons. The properties of gluon emission are affected by the process by which a quark loses color[1-3]: photon emission should also depend on the particular way in which a quark transforms into a hadronic jet.

The process by which a quark that produces a hadron jet loses color involves principally the restriction of the spatial range over which the color quark current is active by screening the current during the pair production from the vacuum (the breaking of a string).

A decrease in the active range of the current increases the emission angle of the corresponding field quantum. This situation was demonstrated in Refs. 2 and 4 and examples were given of qualitatively new effects in hadron-hadron interactions, which are the consequence of such a restriction (the appearance of so-called ring events in which a substantial group of hadrons has the same polar angle).

In e^+e^- annihilation, there is also an increase in the emission angle of a gluon by a quark due to the restriction of the active range of the color current, but at relatively low energies, $Q \lesssim 10$ GeV, the three-jet events unfortunately cannot be distinguished from the two-jet events and at high energies, where the three-jet events can be singled out, the effect is small[5] and can be observed theoretically only when the values in Fig. 1 are approximately equal to unity, when the three-jet events again cannot be distinguished experimentally from the two-jet events.

As was pointed out in Ref. 6, the problem of identifying three-jet events can be circumvented by studying the photon emission instead of gluon emission. Such an approach makes it possible to use the experimental data at lower energies. Furthermore, by singling out the events in which the total electric charge of each hadronic jet is zero, we can determine the distance at which the electric charge of a quark is neutralized. We can assume that in such events the color charge and electric charge are neutralized at the same distance from the annihilation point; i.e., the neutralization region of the color charge is also determined at this time.[1])

We will explain this situation by using a special example in which the "jet" consists of a single neutral hadron, say, π^0; i.e., let us examine the process

$$e^+ + e^- \to \pi^0 + \pi^0 + \gamma. \tag{1}$$

In the inital stage, a $u\bar{u}$ pair is created in 80% of the cases and a $d\bar{d}$ pair is created in 20% of the cases. Flying apart in different directions, u and $\bar{u}$ quarks, for example, may emit a photon before being neutralized by the corresponding partners, $\bar{u}$ and u, which are produced from the vacuum. As we can see, the color charge and the electric charge are neutralized at the same time.

A similar situation seems to occur in the more general case in which a hadronic jet, instead of π^0, is produced without an electric charge. We propose a study of such processes involving the production of neutral jets.

2. To quantitatively analyze the creation of two neutral jets with an extra photon, we must assume, as in the case of Ref. 5, that in the c.m. frame the screening of the charge of a quark or an antiquark leads to the following modification of their propagators by the exponential factor (which characterizes the "start" of interaction):

$$\tilde{G}(x-y) \sim \frac{\hat{x}-\hat{y}}{(x-y)^4} \exp[-|\vec{x}-\vec{y}|/R] , \tag{2}$$

which in the momentum space gives, to accuracy within terms $\sim R^{-1}$,

$$\tilde{G}(p) \sim \hat{p}/(p^2 + 2ip_0R^{-1}) \tag{3}$$

(where p_0 is the time component of the vector p), i.e., a propagator typical of decay processes.

Using the standard method (see Ref. 7, for example), we find the doubly differential cross section of the process under consideration^2)

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{dx_1dx_2} = \frac{e_u^4 + e_d^4}{e_u^2 + e_d^2}\frac{\alpha}{2\pi}\frac{(1-x_1)(1-x_2)(x_1^2+x_2^2)}{[(1-x_1)^2+(QR)^{-2}][(1-x_2)^2+(QR)^{-2}]}, \tag{4}$$

where e_u and e_d are electric charges of the u and d quarks in units of electron charge, $x_{1,2,3} = 2E_{q,\bar{q}\gamma}/Q$, Q is the total energy in the c.m. frame, and σ_0 is the cross section of the two-jet process in which no γ rays are released. Using cross section (4), we find for the distribution for $T = \max\{x_1,x_2\}$

$$\frac{1}{\sigma_0}\frac{d\sigma}{dT} = \frac{e_u^4 + e_d^4}{e_u^2 + e_d^2}\frac{\alpha}{4\pi}\left\{\frac{(1-T)(1+T^2)}{(1-T)^2+(QR)^{-2}}\,\frac{1}{2}\ln\frac{(1-\delta)^2+(QR)^{-2}}{(1-T)^2+(QR)^{-2}} + \frac{(1-T)(\delta-T)(2+\delta-T)}{(1-T)^2+(QR)^{-2}}\right\}, \tag{5}$$

where $\delta \cong 4/Q$ is the minimum energy necessary to form a hadronic jet of lower energy. Figure 1 shows the cross-section ratio (5) at energies $Q = 6$ GeV and 8 GeV, with screening and without it, for model-based functions $R(Q)$: $R = Q$, $R = \ln Q$, and

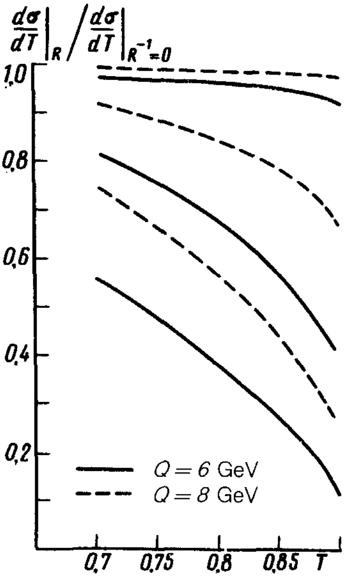

FIG. 1. Distribution ratio.

$R = 1$ (in units of 1 GeV). Figure 1 shows that there is the hope that for $R = \ln Q$, and especially $R = 1$, the effect can be observed experimentally.

The expression for a double differential cross section is

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{du\,dT} = \frac{e_u^4 + e_d^4}{e_u^2 + e_d^2}\,\frac{16\alpha}{\pi}\,\frac{(1-T)^3}{(1-T)^2 + (QR)^{-2}}$$

$$\times\, u(1-u)\,\frac{[T^2(1-u)^2 + (1-u(2-T))^2]}{u^2(1-T)^2 + (1-u)^2(QR)^{-2}}\,, \qquad (6)$$

where $u = (T/2)(1 - \cos\theta)$, and θ is the angle between the T axis and the direction of photon emission. The typical kinematic structure of the event is: photon energies $E \sim 2$–4 GeV and angles of emission over the range of angle $120° < \theta < 140°$.

Allowance for screening eliminated in (4)–(6) the characteristic infrared discrepancies in perturbation theory in the limit $T \to 1$.

3. The photon background can apparently be ignored in the other processes. In reaction (1), for example, the background photons are attributed to the decay and emission of the original e^+e^- beams. In the first case, the background can be singled out on the basis of energy considerations and in the second case it can be singled out on the basis of the phase space, because the photon in question must lie in the same plane as the π^0 mesons. In the case of a jet, the radiation of charged decay products is directed along the jet axis. This comparatively soft radiation falls off rapidly with the distance from the jet axis, whereas radiation (6) is very hard.

We thus see that a search for sufficiently hard photons emitted at a large angle with respect to the T axis in the processes involving the production of two neutral jets in e^+e^- annihilation at energies from 5 to 10 GeV is important in determining the size of the region of neutralization of the color charge and electric charge of a quark.

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1) *We assume that at the moment of hadronization the quark virtualities are small* (~ 1 GeV).

2) Only the photons that are emitted by the quarks are taken into account.

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