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ISOLATING GLUON JETS*

Hans Peter Nilles†
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

It is shown that the identification of gluon and quark jets in the process $e^+e^- \rightarrow$ three jets is feasible if the gluon is radiated off heavy quarks. Gluon energy spectra are computed for $e^+e^- \rightarrow b\bar{b}g$ in the upper PEP-PETRA energy region and for $e^+e^- \rightarrow Z^o \rightarrow t\bar{t}g$.

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† Max Kade Fellow.

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 done. Such a distinction is of major interest in order to (i) investigate if quark and gluon jets fragment differently into hadrons as is expected due to 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.[F1] Thrust and oblateness distributions however, forced by energy momentum conservation, show only minor differences in the two cases,[3] 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,[4] which is a well defined quantity in QCD perturbation theory. A quark is 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.[4,5] It can be estimated by the average multiplicity $\langle n \rangle$ and transverse momentum $\langle p_\perp \rangle$

of the hadrons in the jets of light quarks at low energy and is expected to show only a moderate variation with the energy of the jets.[4,5] 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.[4,5] As the most promising regions[F2] to obtain a quark-gluon jet separation we propose $e^+e^- \to b\bar{b}g$ in the upper PEP-PETRA energy region and (if the t-quark exists and is not too heavy) $e^+e^- \to Z^o \to t\bar{t}g$ at the resonance of the intermediate vector boson Z^o where in the future experiments will be done with the SPC at SLAC and LEP at CERN. Especially at the Z^o 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 $Z^o \to Q\bar{Q}g$ 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^o mass. We obtain $(x_1 + x_2 + x_3 = 2)$:

$$\frac{1}{\Gamma_0}\frac{d\Gamma(Q\bar{Q}g)}{dx_1dx_2} = \frac{4\alpha_s}{3\pi\beta}\left[v^2(3-\beta^2) + 2a^2\beta^2\right]^{-1}$$

$$\times\left[\left(v^2+a^2\right)\left\{\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} - \frac{2m^2}{M^2}\left(\frac{2}{1-x_1}+\frac{2}{1-x_2}+\frac{1}{(1-x_1)^2}+\frac{1}{(1-x_2)^2}\right)\right\}\right.$$

$$+\frac{2a^2m^2}{M^2}\left\{\frac{(2-x_1-x_2)^2}{(1-x_1)(1-x_2)}+\frac{6(1-x_1-x_2)}{(1-x_1)(1-x_2)}\right\}$$

$$\left.-\frac{4m^4}{M^4}\left(v^2-2a^2\right)\frac{(2-x_1-x_2)^2}{(1-x_1)^2(1-x_2)^2}\right] \tag{1}$$

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

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

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:[7]

$$a^2 = \frac{1}{4\cos^2\theta_W} \tag{3}$$

$$v^2 = \left(1 - \frac{8}{3}\sin^2\theta_W\right)^2 \Big/ 4\cos^2\theta_W \tag{4}$$

$$\frac{g^2}{8M^2\cos^2\theta_W} = \frac{G_F}{\sqrt{2}} \approx 8.25 \times 10^{-6}\ \text{GeV}^{-2} \tag{5}$$

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 $e^+e^- \to$ "γ" $\to Q\bar{Q}g$ [8] 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

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

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[F3] the most economic cutoff in (1) to satisfy the above criteria is a restriction on the angle between the quark and antiquark direction

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

because this provides us simultaneously with $x_3 \ge \varepsilon > 0$ and a θ_{Qg}, $\theta_{\bar{Q}g}$ cutoff. The effective coupling constant[9] can be shown not to be α_s/π, but rather

$$\frac{\alpha_s}{\pi}\log^2\delta \qquad (8)$$

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 (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^o 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^o resonance.[10] 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 $\le \sqrt{s} \le$ 40 GeV and $t\bar{t}g$ at Z^o with $m_t \le 20$ GeV it is expected[F4] 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 a large mass ($\geq m_Q$), 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. 4. 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^o 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[F5] on computes $T \approx 0.83$ for events $Z^o \rightarrow Q\bar{Q}$ and events of the type $Z^o \rightarrow Q\bar{Q}g$ will be even lower in thrust, i.e., with a cut $T_{max} = 0.9$ one will not loose 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^o 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 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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FOOTNOTES

F1: 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.

F2: We should mention here that the weak semileptonic decay of c,b,t-quarks can be used to isolate gluon jets for a small percentage of the events.[6]

F3: For light quarks one has to demand a cutoff $1-x_3 \geq \varepsilon' > 0$ in addition to the one introduced in (7).

F4: 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.[1]

F5: 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.

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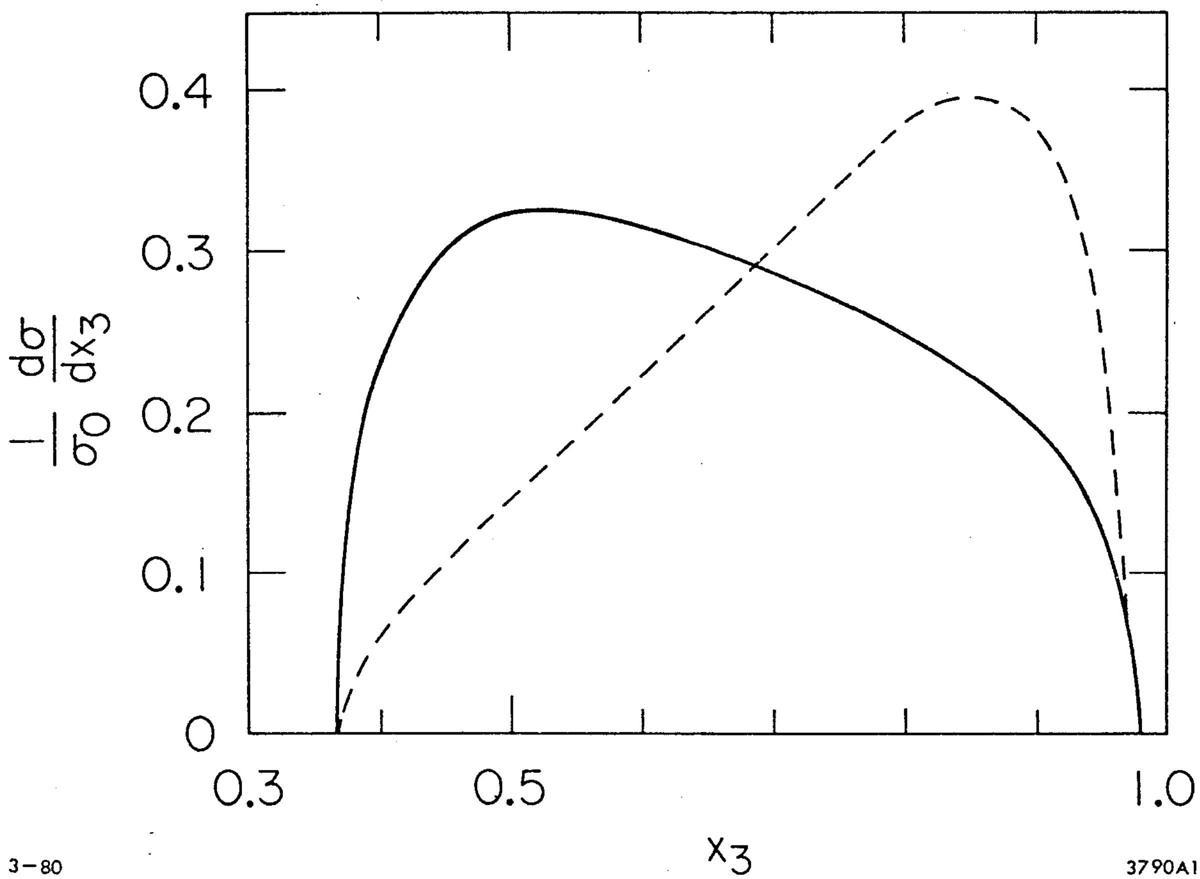
FIGURE CAPTIONS

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).

Fig. 2. Gluon energy spectra for $Z^o \to Q\bar{Q}g$ 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).



0.4
0.3
0.2
0.1
0
$\frac{1}{\sigma_0}\frac{d\sigma}{dx_3}$
0.3
0.5
1.0
x_3
3–80
3790A1

Fig. 1

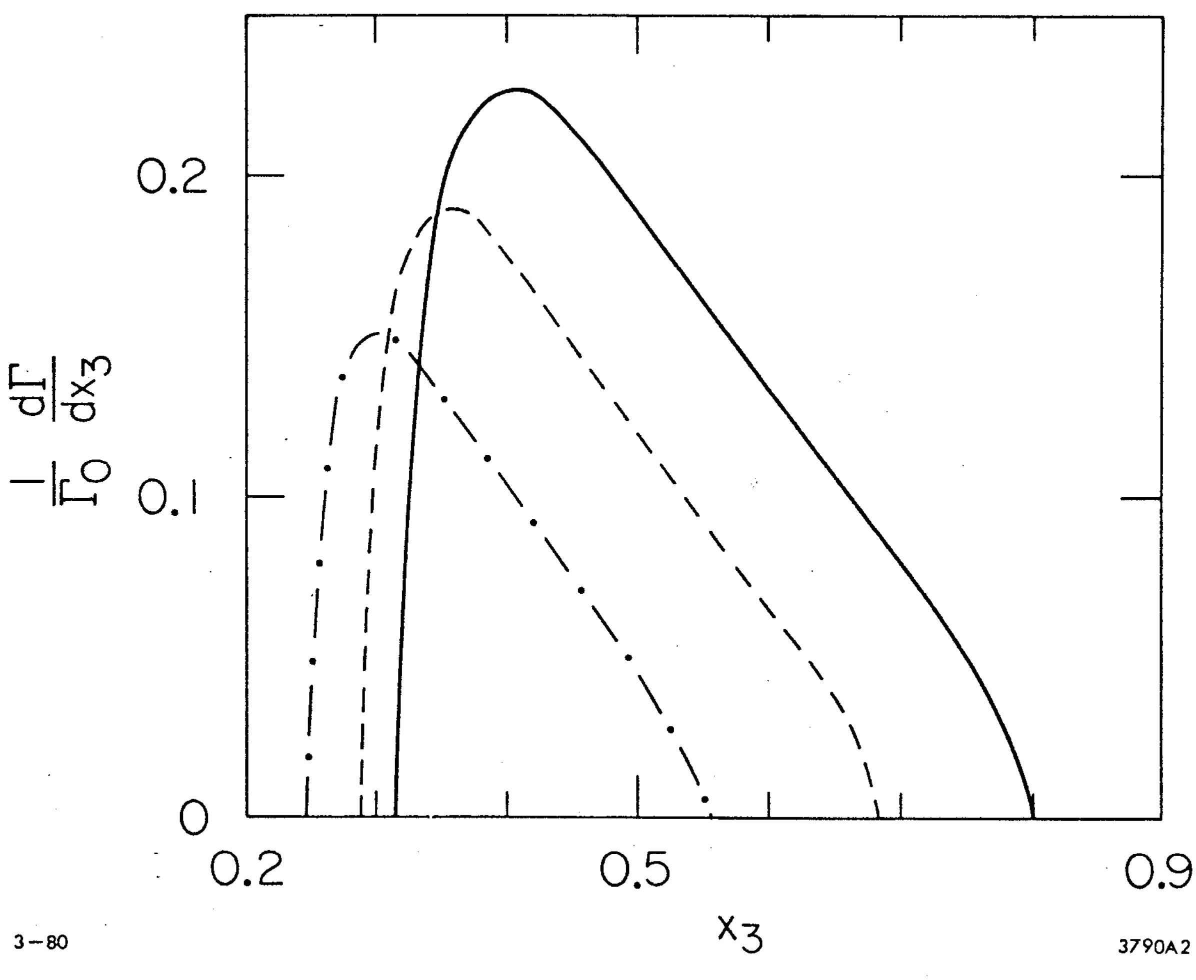


Fig. 2

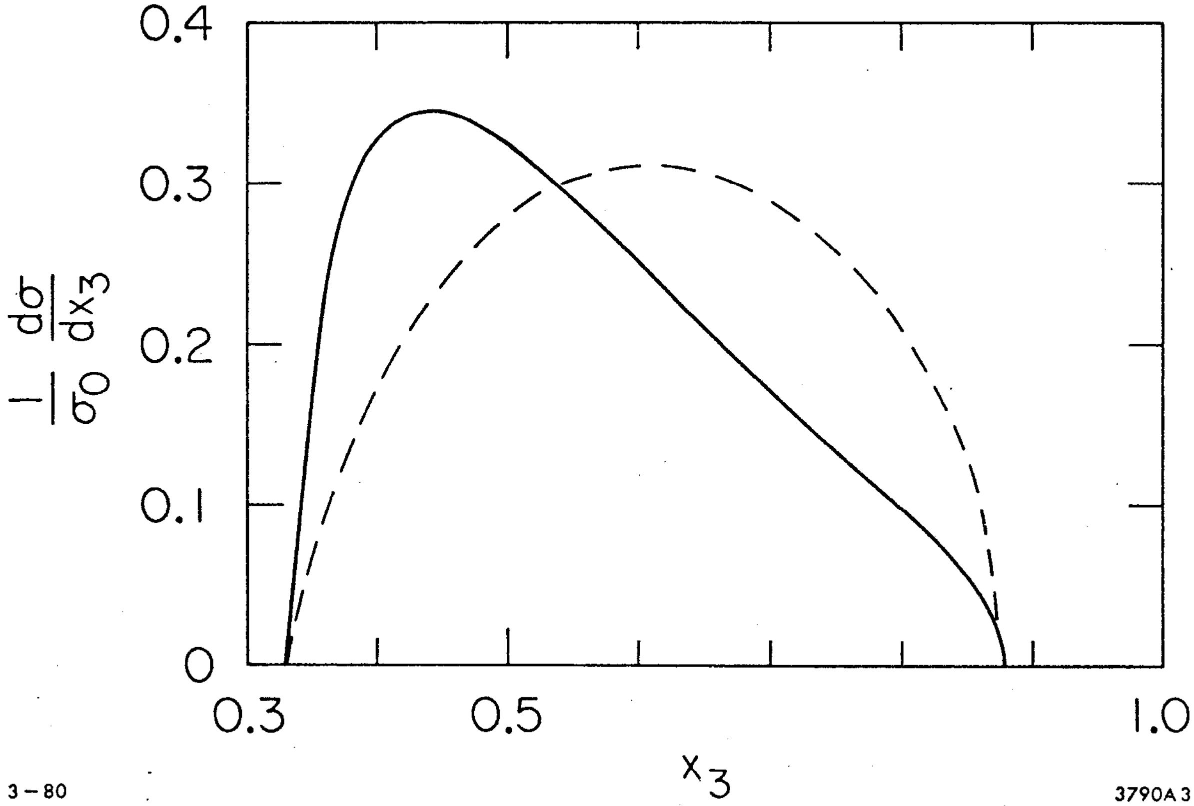


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Fig. 3