Light gluinos in four-jet events at CERN LEP

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The light gluino hypothesis can explain the apparent incompatibility between the measurements of α_s at low and high energies. Such gluinos are produced directly in four-jet events, for which we perform a detailed analysis. Because the jet energies are not large, the effect of the nonzero gluino mass is important. We take the gluino mass into account in the computation of the cross sections and shape variables. As expected, we find that mass effects tend to reduce the impact of the gluinos in the cross section, weakening the bounds from obtaining massless gluinos.

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In recent years, many precision tests of quantum chromodynamics (QCD) have been carried out at the CERN e^+e^- collider LEP and, in particular, much attention has been devoted to the measurement of the strong coupling constant at the M_Z scale, $\alpha_s mz$. These measurements can be compared with the values extracted from deep inelastic experiments, at lower energies, and evolved using the standard QCD renormalization group equation. It has already been noted that there is a slight discrepancy between the results obtained in this way. The LEP measurements yield an average of $\alpha_s(M_Z) = 0.122 \pm 0.006$, while the deep inelastic values suggest $\alpha_s(M_Z) = 0.112 \pm 0.005$ [1]. Of course the statistical significance of this discrepancy is very small, but nonetheless it has led to speculation that the evolution of coupling is being slowed down by a contribution to the β function of a new light, neutral, colored fermion, the so-called "light gluino" hypothesis [2]. Although it is theoretically difficult to reconcile such an object with a realistic supersymmetric standard model, there is in fact an experimental window open precisely in the few GeV region [3]. However, there is no unanimous consensus concerning the extent of this window. For example, from data on quarkonia states a gluino mass of less than one GeV is suggested in the second reference of [2]. Our analysis, therefore, will cover a range of possible gluino masses down to zero. A gluino, in the adjoint representation, would slow the evolution between the deep inelastic and LEP scales by just the correct amount to reconcile the $\alpha_s(M_Z)$ measurements. In simple terms,

$$\frac{d\alpha_s(\mu)}{d\ln\mu} = \beta_0 \alpha_s^2(\mu)$$

$$\beta_0 = \frac{1}{2\pi}\left[11 - \frac{2}{3}n_f - 2\theta(\mu - m_{\tilde{g}})\right] . \qquad (1)$$

Note that, above the threshold, the effect is the same as increasing the number of quark flavors, $n_f \to n_f + 3$. Of course the presence of a light gluino also modifies the values extracted for α_s. The effects are fairly small as compared to the experimental uncertainties for α_s extracted from the total Z hadronic width , but larger for the coupling extracted from shape variables [4].

It is certainly worth looking for evidence of the light gluino in other processes. At LEP, gluino pairs can be produced directly at $O(\alpha_s^2)$, i.e., as a contribution to the four-jet cross section [5]. One can, at least in principle, extract from the data the number of light hadronic fermion pairs contributing to $e^+e^- \to q\bar{q}f\bar{f}$. Naively, a light gluino would increase n_f by three, just as for the evolution of the coupling constant. The main purpose of this note is to analyze the four-jet event rate at LEP energies, in order to quantify as the effect due to gluino production. In particular, we are primarily interested in the effect of the nonzero mass $m_{\tilde{g}}$ on the cross section. Previous analyses [5–8] have assumed massless quarks, gluons and gluinos, but since the energies of the gluino jets are not large, mass effects will presumably be important.

In Figs. 1(a)–1(d) we show the lowest order Feynman graphs for four-jet production in QCD. The gluino contributes through gluon splitting processes of the type (d), shown in Fig. 2. To study the effect of a nonzero gluino mass, we have computed the matrix element for $e^+e^- \to q\bar{q}\tilde{g}\bar{\tilde{g}}$ with $m_{\tilde{g}} \neq 0$, using the spinor techniques of Ref. [9]. In Fig. 3 we show (solid line) the total cross section $\sigma(Z \to \sum_q q\bar{q}\tilde{g}\bar{\tilde{g}})$, normalized to the leading order (two-jet) cross section $\sigma_0 \equiv \sigma(Z \to \sum_q q\bar{q})$, as a function of $m_{\tilde{g}}$. Note that this cross section is infrared finite for $m_{\tilde{g}} > 0$. For $m_{\tilde{g}} \gtrsim 5$ GeV, the cross section falls exponentially with the gluino mass. In order to define the part of this that corresponds to the four-jet cross section we need to introduce a jet algorithm. In what follows we

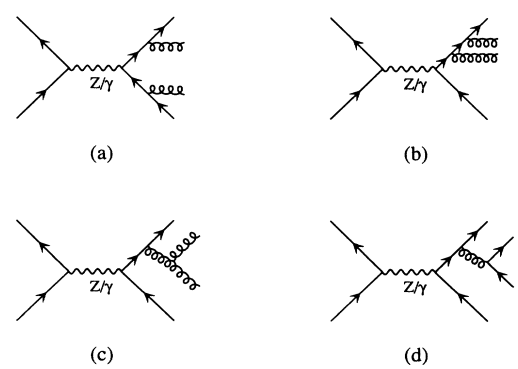

FIG. 1. Feynman diagrams contributing to the four-jet cross section. Other permutations are not shown.

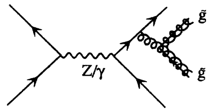

FIG. 2. Feynman diagram corresponding to the production of a pair of gluinos in four-jet events. The other permutation is not shown.

will adopt the widely used JADE algorithm; i.e., we introduce a dimensionless parameter y_{cut} and require that jets i and j be separated in phase space according to

$$\tilde{y}_{ij} = \frac{2E_iE_j(1-\cos\theta_{ij})}{s} > y_{\text{cut}}, \tag{2}$$

where θ_{ij} is the angle between the jets with energies E_i and E_j, respectively. In our calculation, the indices $1 \le i,j \le 4$ run over the four final-state partons. Figure 3 shows the gluino pair contribution to the four-jet cross section defined in this way, for three y_{cut} values, again as a function of $m_{\tilde{g}}$. Notice that for $y_{\text{cut}} = 0.01$, the cross section decreases by a factor of 2 going from $m_{\tilde{g}} = 0$ to $m_{\tilde{g}} = 5$ GeV.

In Fig. 4 the various contributions to the total four-jet cross section (i.e., summed over the processes shown in Figs. 1 and 2) are presented, as a function of y_{cut}. As can be seen, by far the most important contribution is from the $q\bar{q}gg$ final state. The four-quark contribution $q\bar{q}q\bar{q}$ is one order of magnitude smaller. Note that in computing this contribution, the b quark mass has been taken into account. The gluino contribution is shown for different masses. For $m_{\tilde{g}} = 0$ it is of the same order as the quark contribution — the number of flavors is compensated by the enhanced color factor of the gluino. A nonzero mass

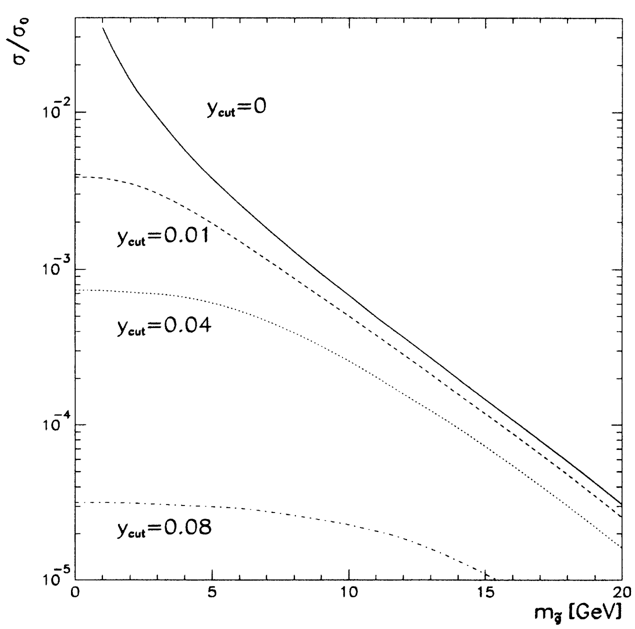

FIG. 3. Mass dependence of the four-jet total cross section for different y_{cut}. The values are normalized to the lowest order cross section.

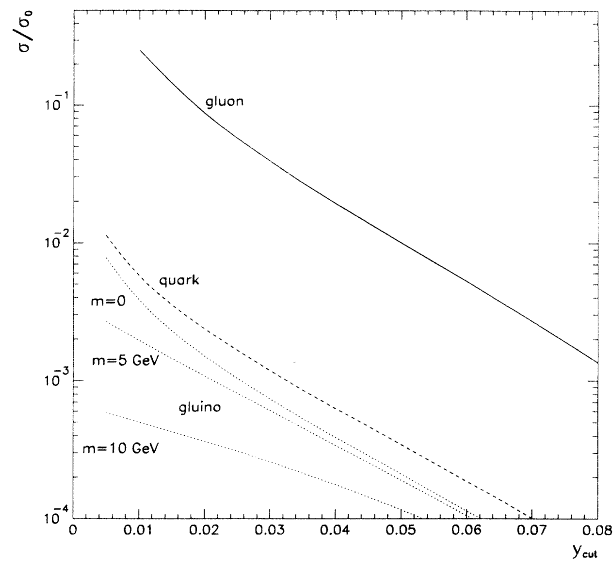

FIG. 4. y_{cut} dependence of the total cross section for the gluon, quark, and gluino contributions to the four-jet final state. In the quark line, the mass effect of the b quark is taken into account.

has, however, an important effect in suppressing the cross section: the value for $m_{\tilde{g}} = 10$ GeV is four times lower than that for $m_{\tilde{g}} = 5$ GeV at $y_{\text{cut}} = 0.01$. The conclusion from this Fig. 4 is that a heavier gluino would be very hard to detect, even if one could separate the fermion from the vector boson jets.

Reference [6] describes an attempt by the ALEPH Collaboration to measure the QCD color factors from a sample of four-jet events. The idea is to fit the theoretical predictions to the data, leaving the color factors to be determined by the fit. The theoretical expression for the $Z \to q\bar{q}gg$ contribution, Figs. 1(a)–1(c), is

$$\frac{1}{\sigma_0}d\sigma^{(4)} = \left(\frac{\alpha_s C_F}{\pi}\right)^2 \left[F_A(y_{ij}) + \left(1 - \frac{1}{2}\frac{N_C}{C_F}\right)F_B(y_{ij}) + \frac{N_C}{C_F}F_C(y_{ij})\right] \tag{3}$$

and, for $Z \to q\bar{q}q\bar{q}$ [Fig. 1(d)],

$$\frac{1}{\sigma_0}d\sigma^{(4)} = \left(\frac{\alpha_s C_F}{\pi}\right)^2 n_f \left[\frac{T_F}{C_F}F_D(y_{ij}) + \left(1 - \frac{1}{2}\frac{N_C}{C_F}\right)F_E(y_{ij})\right], \tag{4}$$

where $y_{ij} = m_{ij}^2/s$ denotes the scaled invariant mass squared between a pair of partons and n_f is the number of active flavors. The color factors are determined from the SU(3) generators $(T^a)_{ij}$ and structure constants f^{abc}:

$$\sum_a \left(T^a T^{\dagger a}\right)_{ij} = \delta_{ij} C_F, \tag{5}$$

$$\sum_{a,b} f^{abc} f^{abd*} = \delta^{cd} N_C, \tag{6}$$

$$\text{Tr}\left[T^a T^{b\dagger}\right] = \delta^{ab} T_F. \tag{7}$$

The analytical form of the functions $F_A, \ldots, F_E$ can be found in Ref. [10]. In the ALEPH analysis [6], a fit with $y_{\rm cut} = 0.03$ gives

$$T_F/C_F = 0.58 \pm 0.17_{\rm stat} \pm 0.23_{\rm syst}, \quad (8)$$

$$N_C/C_F = 2.24 \pm 0.32_{\rm stat} \pm 0.24_{\rm syst}, \quad (9)$$

which is in good agreement with the theoretical expectation, for $n_f = 5$:

$$(T_F/C_F)_{\rm QCD} = 0.375, \quad (10)$$

$$(N_C/C_F)_{\rm QCD} = 2.25. \quad (11)$$

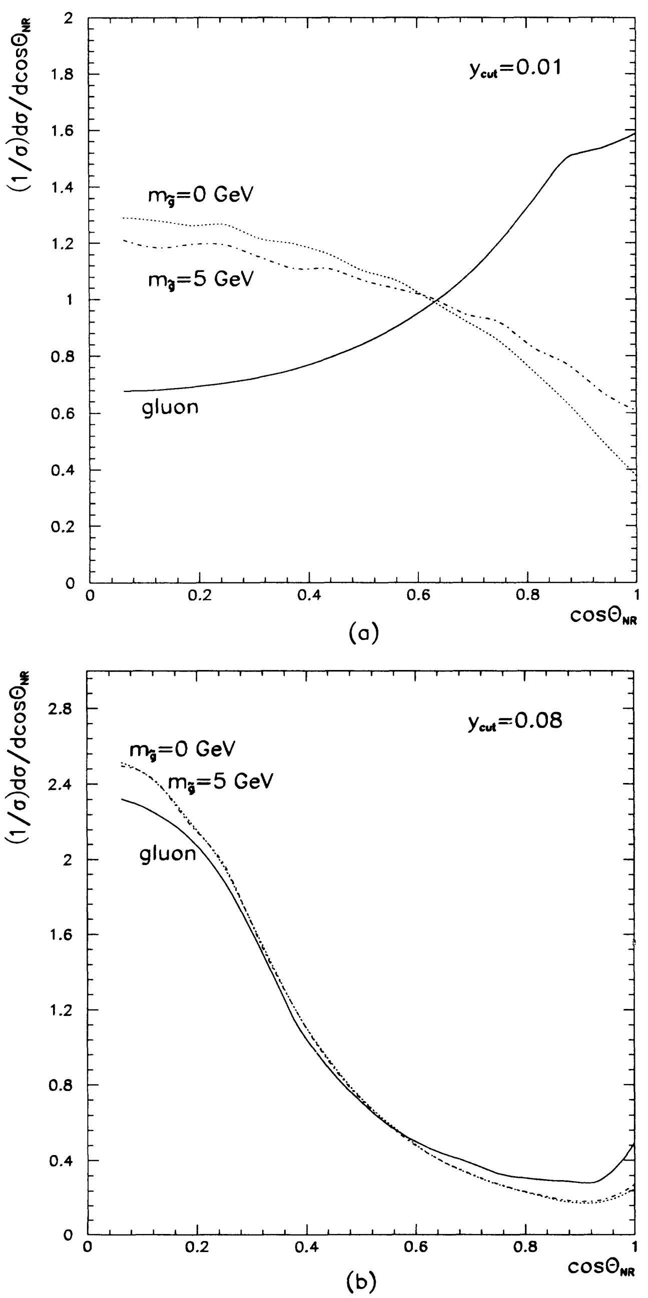

FIG. 5. Shape distribution in $\cos\theta^*_{\rm NR}$ of the four-jet cross section for (a) $y_{\rm cut} = 0.01$ and (b) $y_{\rm cut} = 0.08$. The difference in the shape of the gluon distribution is due to the influence of the hard cuts on the phase space.

However, it is important to note that the theoretical expressions in (3) and (4) above are only valid for *massless* quarks and should be corrected for massive fermions. For example, for $y_{\rm cut} = 0.03$ and $m_Q = 5$ GeV a $Q\bar{Q}$ pair effectively contributes 0.8 relative to a massless pair. When the mass of the b quark is taken into account and the contribution of a light gluino of 5 GeV is included, the value of N_C/C_F does not change but (10) becomes

$$(T_F/C_F)_{\rm QCD\,+\,gluino} = 0.568. \quad (12)$$

This result is surprisingly close to the experimental value (8) and (9). A calculation using massless quarks and gluinos would yield $0.375 \times 8/5 = 0.6$ for this quantity. Obviously, the size of the experimental errors precludes any definitive conclusion at present. All we can say is that the four-jet measurements are consistent with the gluino hypothesis.

Since we have seen in Fig. 4 that the gluino contribution to the total four-jet cross is quite small, it is worth investigating whether shape variables can provide a further discrimination [5]. If we order the jets in the final state according to their energy, it is very likely that the two least energetic jets come from the splitting of the gluon radiated off the quark pair which couple to the Z, Figs. 1 and 2. The angular correlation between the plane of this soft jet pair and the more energetic primary $q\bar{q}$ pair is different for the $q\bar{q}gg$ and $q\bar{q}q\bar{q}$ final states [11]. This can be quantified by using a modified Nachtmann-Reiter angle $\theta^*_{\rm NR}$ [11, 12], defined as the angle between the vectors $(\mathbf{p_1} - \mathbf{p_3})$ and $(\mathbf{p_2} - \mathbf{p_4})$, where the three-momenta are ordered according to the energy of the jet.

The distribution in $\theta^*_{\rm NR}$ for *massive* fermion jets with $E_j \sim m_j$ is in fact rather different from the massless dis-

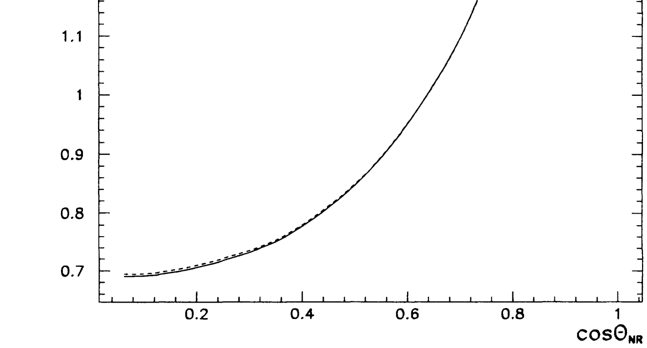

FIG. 6. Four-jet cross section differential in $\cos\theta^*_{\rm NR}$. The solid line corresponds to QCD (gluon+quarks), while the dashed line corresponds to QCD+gluino.

tribution. The difference is due to the different helicity structure of the matrix element when masses are included [9]. These new helicity structures have the opposite behavior in $\theta^*_{\rm NR}$ to the massless contributions, and the net effect is that the shape of the distribution resembles more that of the vector boson jets. However, these effects are mainly confined to very small $y_{\rm cut}$, and are not important for the region of experimental interest, i.e., $y_{\rm cut} \gtrsim 0.01$. Figure 5 shows the $\cos\theta^*_{\rm NR}$ distribution for the various contributions to the four-jet cross section. The two figures correspond to (a) $y_{\rm cut} = 0.01$ and (b) $y_{\rm cut} = 0.08$. At the lower $y_{\rm cut}$ value, a distinctively different behavior is observed for the quark-gluino and gluon distributions. On the other hand, the harder cut of $y_{\rm cut} = 0.08$ in Fig. 5(b) distorts the phase space so much that the shape of the distributions is virtually indistinguishable, and the differences due to the gluino mass are negligible. Note that in this figure the different contributions are normalized separately. The crossover between the two types of behavior shown in Fig. 5 occurs at $y_{\rm cut} \sim 0.04$. A $y_{\rm cut}$ value smaller than this is therefore needed to distinguish the fermion and vector boson contributions.

Using angular distributions of this type, the OPAL Collaboration has recently put bounds on the production rate of four-quark jet events [7]. They find an upper limit of 4.7% at 68% confidence level (C.L.) and of 9.1% at 95% C.L. on the fraction of four-jet events of fermion type. The theoretical prediction of QCD is 4.7%, so that the inclusion of a light gluino would naively enhance this value to $4.7 \times 8/5 = 7.5\%$. However, at $y_{\rm cut} = 0.01$ (the value used by OPAL) a 5 GeV fermion contributes only 0.51 relative to a massless one. Therefore the production rate with a 5 GeV gluino included is only enhanced to a value of 5.25% (73% C.L.). This weakens considerably the strength of the bounds coming from this approach.

Finally, we show in Fig. 6 the theoretical predictions for the $\cos\theta^*_{\rm NR}$ distributions for QCD (quark+gluons) and for QCD+gluino, with $y_{\rm cut} = 0.01$ and $m_{\tilde g} = 5$ GeV. Due to the order of magnitude difference between the quark and gluon contributions (Fig. 4) the differences are rather small. Even with improved statistics, the procedure of Ref. [7] will have difficulty in putting stringent bounds on the existence of light gluinos.

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