Three Jet Events and New Strong Couplings at LEP and NLC

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We study the effects of new dimension–6 operators, resulting from a general $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ invariant effective Lagrangian, on three jet production at LEP and at the Next Linear Collider. Contributions to the total event rate and to some event shape variables are analysed in order to establish bounds on these operators.

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Quantum Chromodynamics (QCD), an important part of the Standard Model (SM), has been tested in the perturbative regime to a high degree of precision [1]. However, the possible existence of new physics beyond the Standard Model, involving heavy colored particles, may give rise to small effects in QCD phenomenology at present and future colliders. Certainly, one of the main goals of the future generation of colliders will be to scrutinize the several competitive models describing the physics at high energies.

On the phenomenological side, instead of concentrating on a specific model, it is in general quite instructive to make a model independent analysis of the indirect effects that an unknown high–energy theory can have at the present energy scale. This can be accomplished by the effective Lagrangian approach [2]. After the heavy fields of the high–energy theory have been integrated out, their low–energy consequences can be represented by a series of local $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ invariant operators built from the light Standard Model fields:

$$\mathcal{L}_{\rm eff} = \mathcal{L}_0 + \sum_{n=1\cdots} \frac{f_{(n+4)}}{\Lambda^n} O_{(n+4)} \tag{1}$$

where $\mathcal{L}_{\rm SM}$ is the Standard Model Lagrangian, Λ is the characteristic scale of the new physics and $O_{(n+4)}$ are the local operators of dimension $(n+4)$. Different scenarios can generate the same kind of operator but with distinct effective couplings f_{n+4} making possible, at least in principle, to point out a specific model for the new physics.

The classification of the operators $O_{(n+4)}$ have been first done in Ref. [3] and since then the phenomenological implications have been studied in the bosonic sector of the SM [4], and for the third–family quarks [5]. There have also been many studies of the so–called purely gluonic operators [6] where the high dimension operators $O_{(n+4)}$ involves only the gluon field and modify the non–abelian three and four vertex.

Nevertheless, effective operators involving gluons and light quarks (and possibly the Higgs fields) can also give rise to some measurable effects in QCD processes at the present colliders. These new couplings can be generated via loops of colored objects belonging to the underlying theory [7]. In this letter we search for possible signals of the existence of these new couplings in three jet events at e^+e^- colliders. We analyze the total event rate for different values of the jet resolution variable ($y_{\rm cut}$). Event shape observables in e^+e^- colliders are important to test QCD and have been studied at PETRA [8], LEP1 [9] and LEP2 [10] energies. Therefore, we also explore the differences in the event shape distributions due to the anomalous contribution in order to establish bounds on the coefficient of the dimension 6 operators that alter the qqg interaction.

In order to study the possible deviation from the Standard Model predictions for the couplings involving quarks and gluons, we start by writing the most general dimension–6 effective Lagrangian requiring the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ invariance of the new operators. We assume that there are no additional new fields and we construct these operators taking into account only the usual light particles, *i.e.* gauge bosons and quarks. Furthermore, we do not consider here the operators that modify the couplings of the gauge bosons with fermions since they are strongly constrained by the LEP1 measurements at the Z^0 pole. Therefore the new Lagrangian can be written as [3],

$$\mathcal{L}_2 = \frac{1}{\Lambda^2} \sum_i A_i \, \mathcal{O}_i \; , \tag{2}$$

where A_i are constants and the dimension–6 operators $\mathcal{O}_i$ can either involve just quarks and vector bosons or may contain also the Higgs field. In the first case, we have,

$$\mathcal{O}_{Qg} = i \left(\bar{Q} \lambda^a \gamma^\mu \mathcal{D}^\nu Q \right) \, G^a_{\mu\nu} + \text{h.c.} \; , \tag{3a}$$

$$\mathcal{O}_{Ug} = i \left(\bar{U} \lambda^a \gamma^\mu \mathcal{D}^\nu U \right) \, G^a_{\mu\nu} + \text{h.c.} \; , \tag{3b}$$

$$\mathcal{O}_{Dg} = i \left(\bar{D} \lambda^a \gamma^\mu \mathcal{D}^\nu D \right) \, G^a_{\mu\nu} + \text{h.c.} \; , \tag{3c}$$

where Q are the left–handed quark doublets while U and D are the right–handed quark singlets. $G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f^{abc} G^b_\mu G^c_\nu$ is the usual $SU(3)_C$ strength tensors and $\mathcal{D}_\mu = \partial_\mu - i g_s (\lambda^a/2) G^a_\mu - i g (\tau^i/2) W^i_\mu - i g' Y B_\mu$ is the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ covariant derivative of the quarks. The operator (3a) gives rise to a new qqg vertex involving left–handed up and down quarks while (3b) and (3c) operators involve right–handed up and down quarks respectively. Therefore, if we assume that the quark–gluon coupling is blind to the quark flavors, *i.e.* universal, and that the new physics affects left and right–handed quarks in the same way, we should require that $A_{Qg} = A_{Ug} = A_{Dg} \equiv A_{qg}$. We should point out that the new interactions (3) also generate new couplings involving weak–vector bosons (V), like $qqgV$ and $qqggV$, and also vertex with quarks and two and three gluons.

The operators that involves also the Higgs field doublet (ϕ) can be written as,

$$\mathcal{O}_{Ug\phi} = \left(\bar{Q}\sigma^{\mu\nu}\lambda^a U\right)\tilde{\phi}\, G^a_{\mu\nu} + \text{h.c.}\ , \tag{4a}$$

$$\mathcal{O}_{Dg\phi} = \left(\bar{Q}\sigma^{\mu\nu}\lambda^a D\right)\phi\, G^a_{\mu\nu} + \text{h.c.}\ , \tag{4b}$$

where $\sigma^{\mu\nu} = (i/2)[\gamma^\mu, \gamma^\nu]$. When ϕ is replaced by its vacuum expectation value, the operators (4) generate new qqg, and $qqgg$ interactions, for $q = u,\ d$ quarks. In order to guarantee the universality also in the magnetic type qqg coupling, we should assume that $A_{Ug\phi} = A_{Dg\phi} \equiv A_{qg\phi}$.

Therefore, we end up with the following new Lagrangians,

$$\begin{aligned}\mathcal{L}_{qg} = \frac{2A_{qg}}{\Lambda^2}\Bigg\{ & \frac{i}{2}\sum_q \left[\bar{q}\lambda^a\gamma^\mu(\partial^\nu q) - (\partial^\nu\bar{q})\lambda^a\gamma^\mu q\right] \\ & + \frac{g_s}{2}\sum_q \left(\bar{q}\{\lambda^a,\lambda^b\}\gamma^\mu q\right) G^b_\nu \\ & + e\sum_q Q_q\left(\bar{q}\lambda^a\gamma^\mu q\right) A^\nu \\ & + \frac{e}{s_W c_W}\sum_q \left[\bar{q}\lambda^a\gamma^\mu(g^q_V + g^q_A\gamma_5)q\right] Z^\nu \\ & + \frac{e}{2\sqrt{2}s_W}\sum_{u,d}\Big[\bar{u}\lambda^a\gamma^\mu(1-\gamma_5)d\, W^{+\,\nu} \\ & + \bar{d}\lambda^a\gamma^\mu(1-\gamma_5)u\, W^{-\,\nu}\Big]\Bigg\} G^a_{\mu\nu}\ ,\end{aligned} \tag{5}$$

where the summation is made over all the quark flavors q and over up and down quarks (u, d). $g^q_V = T^q_3/2 - Q_q s^2_W$ and $g^q_A = -T^q_3/2$ with s_W being the sine of the Weinberg angle, T^q_3 and Q_q being the quark weak isospin and electric charge respectively, and

$$\mathcal{L}_{qg\phi} = \frac{A_{qg\phi}}{\Lambda^2}\frac{(v+H)}{\sqrt{2}}\sum_q \left(\bar{q}\,\sigma^{\mu\nu}\,\lambda^a\, q\right) G^a_{\mu\nu}\ , \tag{6}$$

We shall start by studying the sensitivity to these new higher dimensional operators at LEP1, which has accumulated a large data sample of three jet events. This analysis was performed by including the new couplings generated by the higher dimensional operators into the package CompHEP [11]. We found that there is no contribution of the operators $\mathcal{O}_{qg}$ when the gluon is on–shell, like in the process $e^+e^- \to q\bar{q}g$. Furthermore, for the contributions generated by the $\mathcal{L}_{qg\phi}$ Lagrangian there is no interference with the SM amplitudes.

In order to compare with LEP1 data, we used the OPAL Collaboration [12] best fit values for the relevant energy scale ($Q^2 = (6.4\ \text{GeV})^2$) and for the QCD scale ($\Lambda_{\text{QCD}} = 147$ MeV). In this way we effectively minimize the uncertainty due to next–to–leading order corrections. We employed the JADE jet algorithm [13] by requiring that the three final state partons obey:

$$y_{ij} \equiv \frac{M^2_{ij}}{s} > y_{\text{cut}} \tag{7}$$

for any pair of final state partons, where M_{ij} is the invariant mass of the (i,j) pair and y_{cut} is a parameter that determines the jet separation criteria used experimentally. We have checked that our result do not change in a significant way if we consider the Durham [14] or Cambridge [15] jet algorithms where $M_{ij} = 2\,\min(E^2_i, E^2_j)(1 - \cos\theta_{ij})$.

In our analysis, we assumed $y^{\min}_{\text{cut}} = 0.05$ and we analyzed, besides the relative production rate of three jet events as a function of y_{cut}, different event shape distributions, like thrust (T) [16]

$$T = \max_n \frac{\sum_i |p_i \cdot n|}{\sum_i |p_i|}\ , \tag{8}$$

spherocity (S) [17],

$$S = \left(\frac{4}{\pi}\right)^2 \min_n \left(\frac{\sum_i |p_i \times n|}{\sum_i |p_i|}\right)^2\ , \tag{9}$$

and the C–variable [18],

$$C = \frac{3}{2}\frac{\sum_{i,j}\left[|p_i||p_j| - (p_i\cdot p_j)^2/|p_i||p_j|\right]}{(\sum_i |p_i|)^2}\ . \tag{10}$$

In order to illustrate the shape of these distributions, we present in Fig. 1, our results for y_{cut}, S, T and C normalized distributions for the Standard Model and for the pure anomalous case.

We performed a χ^2 analysis for the various distributions to estimate the sensitivity of the three jet events to the anomalous parameter. We have taken into account the statistical errors and the overall normalization uncertainty of the QCD prediction. We consider,

$$\chi^2 = \sum_i \frac{[N_i - f N^{\text{SM}}_i]^2}{f N^{\text{SM}}_i} = \sum_i \frac{[N^{\text{ANO}}_i + (1-f)N^{SM}_i]^2}{f N^{\text{SM}}_i}$$

where, N_i and $N_i^{\rm SM}$ are the numbers of events in the ith histogram bin in the presence of anomalous coupling and for the pure standard case, while $N_i^{\rm ANO} = N_i - N_i^{\rm SM}$ and f is a normalization parameter which parametrizes the changes in the overall QCD normalization. We have minimized χ^2 with respect to f in order to restrict χ^2 sensitivity only to the shape difference between anomalous and the Standard Model scenarios. In our analysis we assumed that the dominant errors are statistical and fragmentation and detector effects could be ignored.

Assuming a total luminosity of 220 pb^{-1} [19] we derived the following 95% CL. bounds from the various distributions,

$$\frac{A_{qg\phi}}{\Lambda^2} < 16.3 \text{ TeV}^{-2}, \text{ from } y_{\rm cut} \tag{11}$$

$$\frac{A_{qg\phi}}{\Lambda^2} < 14.2 \text{ TeV}^{-2}, \text{ from thrust} \tag{12}$$

$$\frac{A_{qg\phi}}{\Lambda^2} < 16.0 \text{ TeV}^{-2}, \text{ from spherocity} \tag{13}$$

$$\frac{A_{qg\phi}}{\Lambda^2} < 16.1 \text{ TeV}^{-2}, \text{ from C–parameter} \tag{14}$$

It is important to notice that these bounds decrease by only $\sim$ 15% if we assumed the value $Q^2 = M_Z^2$ for the QCD energy scale instead of the OPAL best fit value. In fact there is not a very good improvement on the bounds obtained from the event shape distribution when compared with the ones coming from the total yield: the thrust gives a slightly better bound. Therefore, we are able to establish the bound of $\Lambda \gtrsim 270$ GeV, for $A_{qg\phi} = 1$, while for $A_{qg\phi} = 4\pi$, Λ should be larger than 1 TeV.

We have also repeated the same analysis for LEP2 energies ($\sqrt{s} \simeq 200$ GeV) and 200 pb^{-1} of data and also for the Next Linear Collider (NLC) assuming a center–of–mass energy of $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1$ TeV with an integrated luminosity of 100 fb^{-1}.

At LEP2, since we are far from the Z^0 peak, we get a weaker bound on the scale of $\Lambda \gtrsim 140$ GeV ($A_{qg\phi} = 1$). However, at NLC with higher energies and luminosities, we can improve our bounds. The relative contribution from anomalous interaction grows with the energy while the SM cross section falls down. At $\sqrt{s} = 500$ GeV, NLC is able to establish the limit of $\Lambda \gtrsim 390$ GeV, for $A_{qg\phi} = 1$. When we further increase the energy to $\sqrt{s} = 1$ TeV the bound becomes: $\Lambda \gtrsim 480$ GeV, for $A_{qg\phi} = 1$.

In this letter, we have shown how the study of three jet production at an e^+e^- collider can provide an important test of qqg. In particular, we derived for the first time direct bounds on the anomalous couplings involving light quarks, gluons and the Higgs boson. These direct bounds are obtained from the study of the total cross section and also from the event shape variables distributions. Similar operators to the ones studied here have been recently constrained by Gounaris, Papadamou and Renard [5] using unitarity arguments. However, these indirect bounds are important only for operators involving the top quark, and hence cannot be applied to the operators discussed in the present work. In conclusion, the comparison of anomalous contribution to the qqg vertex with the QCD predictions can be quite sensitive to new physics effect.

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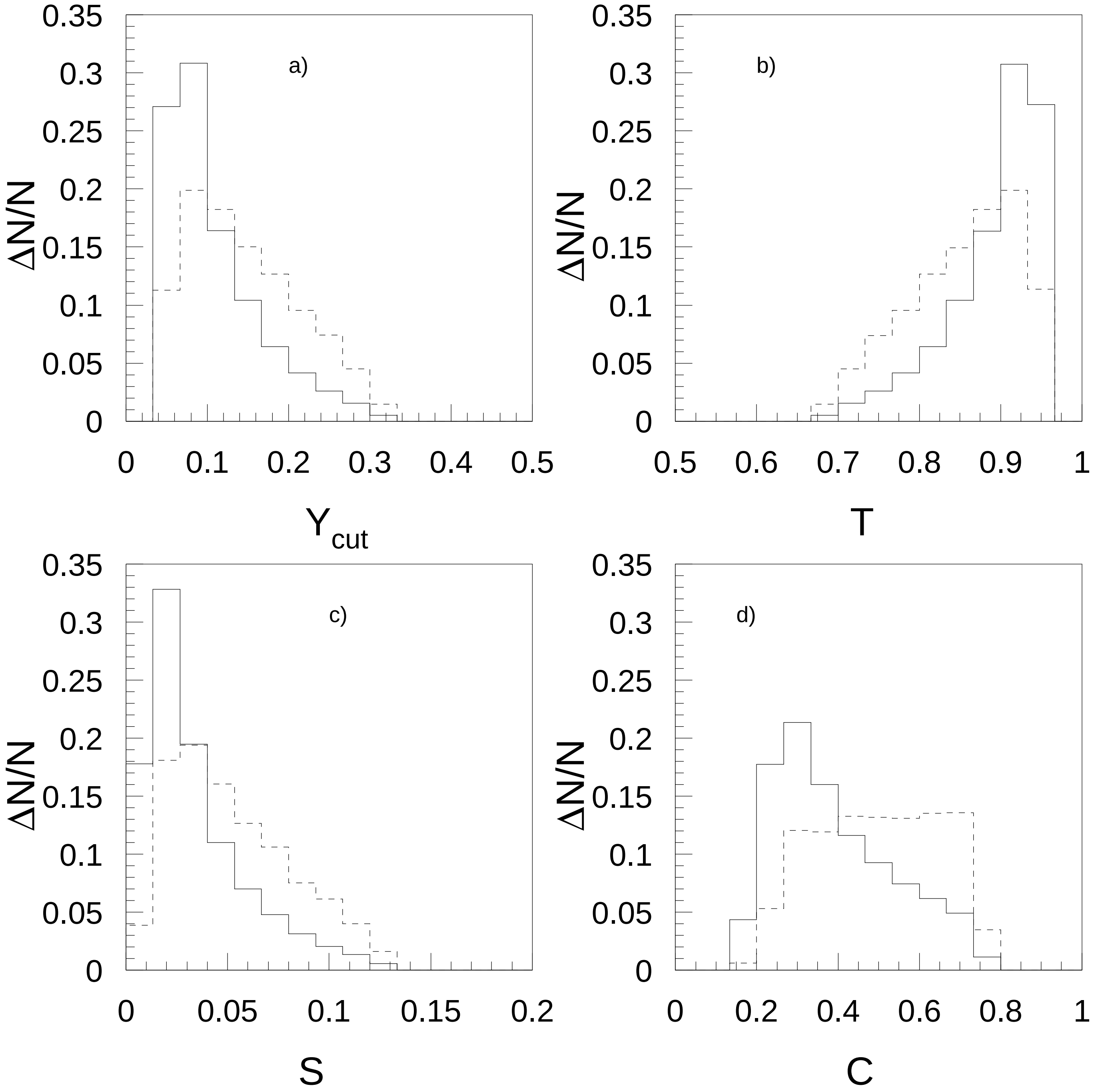

FIG. 1. Relative production rate of three jet events as a function of $y_{\rm cut}$ (a), and the normalized distributions for the event shape variables: thrust (b), spherocity (c) and C–parameter (d), for SM (solid line) and pure anomalous interactions (dashed line). In all cases we have considered $y_{\rm cut}^{\rm min} = 0.05$.