Search for Anomalous Top–Quark Interaction at LEP–2 Collider

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We show that a search for $e^+e^- \rightarrow t\bar{q}$ ($\bar{q} = \bar{c}, \bar{u}$) events at LEP–2 collider provide a possibility to improve significantly the modern constraints on coupling constants of anomalous $t$–quark interaction via flavor–changing neutral currents.

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1 Introduction

The discovery of the $t$-quark on FNAL collider [1] opens new experimental direction in search for new physics beyond the Standard Model (SM).

A search for rare decays of a top quark is one of such studies. Of special interest is the search for $t$ quark decays via flavor-changing neutral neutral currents (FCNC–decays) [2]:

$$ t \rightarrow \gamma \left(g, Z \right) + c(u). \quad (1) $$

At the tree level of SM there are no vertices, corresponding to these FCNC–processes. Only ”loop” contributions make possible the decays (1). As a result the branching fractions of those decays are very small [3]:

$$ \text{Br}(t \rightarrow (\gamma, g, Z) + c(u)) < 10^{-10}. \quad (2) $$

However, many extensions of SM lead to huge enhancement of such transitions. Therefore, the observation of FCNC–decays of the $t$–quark would be an evident indication of new physics beyond the SM (see, for example, [2, 4, 5, 6]).

CDF collaboration perform the search for decays (1) at FNAL collider in $\bar{p}p$ collisions at the energy of $\sqrt{s} = 1.8$ TeV in the reaction of top quarks production:

$$ \bar{p}p \rightarrow \bar{t}tX. \quad (3) $$

The collaboration obtain the upper limits on branching fractions for the decays $t \rightarrow c\gamma(u)$ and $t \rightarrow Zu$ [7] as follows:

$$ \text{Br}(t \rightarrow c\gamma) + \text{Br}(t \rightarrow u\gamma) < 3.2\% \quad (95\% \text{ CL}), \quad (4) $$

$$ \text{Br}(t \rightarrow cZ) + \text{Br}(t \rightarrow uZ) < 33\% \quad (95\% \text{ CL}). \quad (5) $$

These ”feeble” constraints (that is approximately $\sim 10^8$ times more than SM predictions [3]) are resulted naturally due to small collected statistics of events with $t$ quark production ($N_{\bar{t}t} \sim 10^2$). In future run of the FNAL collider it is expected a significant increase of statistics ($N_{\bar{t}t} \sim 10^3 \div 10^4$ [8]), which would make possible to improve the estimate (4) and (5) (see [3, 8] for details).
In this article we consider a possibility to evaluate the similar constraints on coupling constants of anomalous $t$ quark interaction from the data of $e^+e^-$ collider LEP-2 at CERN. We study the process of a single top quark production via FCNC interactions:

$$e^+ e^- \rightarrow \gamma^*(Z^*) \rightarrow t \bar{c}(u). \quad (6)$$

Note, that this process (6) was considered early (see, for example, [9] and references therein). However, these articles studied the manifestation of such an interaction at the energies of future $e^+e^-$ collider ($\sqrt{s} \sim 500$), while a detail investigation of the reaction (6) at the energies of LEP-2 collider was not performed.

Beginning in summer 1997, $e^+e^-$ collider LEP-2 operates at the energy of $\sqrt{s} = 184$. At such a total energy of $e^+e^-$ annihilation it is kinematically possible the production of single top quarks in the reaction (6). Thus a search for such process becomes a quite reasonable problem.

In this article we study the problem as follows: what are the constraints on anomalous coupling constants of FCNC interaction of the top quark can be extracted from the data of collider LEP-2? We exhibit that at the projected luminosity of $\mathcal{L}_{e^+e^-} \sim 100$ pb$^{-1}$ one can improve significantly the current constraints on the magnitudes of anomalous coupling constants, which following from (4) and (5).

The article is organized as follows. The anomalous FCNC interaction of $t$ quark is considered in Section 2. The estimates on $t$ quark yields and the constraints on anomalous couplings are presented in Section 3. The differential distributions with respect to energies and the outgoing angles of final particles are given in Section 4. The main results are summarized in Conclusion.

2 $\gamma\bar{t}c$ and $Z\bar{t}c$ vertices

Let us present the form of the anomalous vertices of flavor-changing neutral currents. We consider of $V_0\bar{t}c$ and $V_0\bar{t}u$ vertices, where $V_0$ stands for a photon or $Z$–boson. For definiteness sake, we describe the $t$ quark transition into charmed $c$ quark. Top transition into $u$ quark is described in a similar way.

Following [4], the vertices of the FCNC transitions $\gamma \rightarrow f\bar{f}'$ and $Z \rightarrow f\bar{f}'$ can be written as follows:
\[ \Gamma_\mu^\gamma = \kappa_\gamma e q e \frac{\epsilon}{\Lambda^2} \sigma_{\mu \nu} (g_1 P_l + g_2 P_r) q^\nu, \]  
\[ \Gamma_\mu^Z = \kappa_Z e \frac{\epsilon}{\sin 2 \vartheta_W} \gamma_\mu (z_1 P_l + z_2 P_r), \]  
(7)

where \( \Lambda \) is the new physics cutoff; \( e \) is the electric charge, \( e_q = 2/3 \) is the charge of the \( t \) quark, \( \vartheta \) is the Weinberg angle, \( \sigma_{\mu \nu} = \frac{1}{2} (\gamma^\mu \gamma^\nu - \gamma^\nu \gamma^\mu) \), \( P_l^r = \frac{1}{2} (1 \pm \gamma^5) \), \( \kappa_\gamma \) and \( \kappa_z \) define the strength of the anomalous couplings for the current with a photon \( (\kappa_\gamma) \) and \( Z \) boson \( (\kappa_z) \), respectively. The relative magnitudes of right and left components of the currents are denoted by \( g_1, g_2, z_1, \) and \( z_2 \). They obey the obvious constraints as follows:

\[ g_1^2 + g_2^2 = 1, \quad z_1^2 + z_2^2 = 1. \]  
(9)

We also assume that \( \text{Im} \kappa_\gamma = \text{Im} \kappa_z = \text{Im} g_i = \text{Im} z_i = 0 \), see [4, 5].

Since all equations in our article contain the mass scale parameter \( \Lambda \) in combination of \( \kappa_\gamma/\Lambda \), then for definiteness sake in what follows we assume that \( \Lambda = m_t \).

Using the expressions for the vertices (7) and (8) for the corresponding widths we find (see, also [5]):

\[ \Gamma(t \to c\gamma) = \kappa_\gamma^2 \alpha e_q^2 \frac{\epsilon}{4} \left( \frac{m_t^2}{\Lambda^2} \right) m_t, \]  
\[ \Gamma(t \to cZ) = \kappa_z^2 \alpha \frac{\epsilon}{8 \sin^2 2 \vartheta_W M_Z^2} m_t^3 \left( 1 - \frac{M_Z^2}{m_t^2} \right)^2 \left( 1 + 2 \frac{M_Z^2}{m_t^2} \right), \]  
(10)

(11)

where \( \alpha \) is the fine structure constant, \( M_Z \) is the mass of the \( Z \) boson.

We put the mass of the light quark \( (c \) or \( u \)) equals zero, \( m_c = m_u = 0 \), in the equations (10) and (11), since \( m_q \ll m_t \). In all estimates we use also

\[ m_t = 175 \text{ GeV}. \]  
(12)

That is in agreement with the latest experimental data [10]:

\[ D\emptyset \quad m_t = 173.3 \pm 5.6(\text{stat.}) \pm 6.2(\text{syst.}) \text{ GeV}/c^2, \]

\[ CDF \quad m_t = 175.9 \pm 4.8(\text{stat.}) \pm 4.9(\text{syst.}) \text{ GeV}/c^2. \]
Using the equations (10) and (11) from the experimental constraints (4) and (5) it is easily to obtain the magnitudes of upper limits on the constants of $\kappa_\gamma$ and $\kappa_z$ (at $m_t = 175$ GeV):

$$ \kappa_\gamma^2 < 0.176 \text{ at } \Lambda = m_t, \quad \kappa_z^2 < 0.533. \quad (13) \quad (14) $$

3 Total cross section for $t\bar{q}$ pair production in $e^+e^-$ annihilation and constraints on magnitudes of anomalous coupling constants

By means of the anomalous vertices (7) and (8) one can readily find the expression for the total cross section for $t$ and $\bar{c}(\bar{u})$ quarks production in the reaction (6) (with $m_c = 0$):

$$ \sigma(e^+e^- \to t\bar{c}) = \frac{\alpha^2}{s} \left(1 - \frac{m_t^2}{s}\right)^2 \left[ \kappa_\gamma^2 \frac{m_t^2}{\Lambda^2} e_q^2 \frac{s}{m_t^2} \left(1 + \frac{2m_t^2}{s}\right) \right. $$

$$ + \left. \frac{\kappa_\gamma^2}{4\sin^2\vartheta_W(1 - \frac{M_Z^2}{s})^2} \frac{(1 + a_w^2)(2 + \frac{m_t^2}{s})}{4\sin^2\vartheta_W(1 - \frac{M_Z^2}{s})^2} + 3\kappa_\gamma \kappa_z \left(\frac{m_t}{\Lambda}\right) a_w e_q (g_1 z_1 + g_2 z_2) \right], \quad (15) $$

where $a_w = 1 - 4\sin^2\vartheta_W$, the rest parameters are previously described.

In this equation the first and second terms correspond to annihilation via photon ($\sim \kappa_\gamma^2$) and $Z$ boson ($\sim \kappa_z^2$), respectively, while the third term ($\sim \kappa_\gamma \kappa_z$) describes their interference.

As one would expect, the behavior of a single top production cross section has an evidently threshold character (see (13)):

$$ \sigma(e^+e^- \to t\bar{c}) \propto \left(1 - \frac{m_t^2}{s}\right)^2. $$

Therefore, when evaluating the cross section for the process (6) at the near-threshold region, one should take into account the finite widths of $t$ quark and $W$ boson. In other words, at the energy of $\sqrt{s} \simeq m_t$ one should consider a virtual $t^*$ quark production with a subsequent decays into a virtual $W^*$ boson:

$$ e^+ e^- \to \bar{c}(\bar{u}) t^* (\to b W^* (\to l\nu(q\bar{q}))). \quad (16) $$
The expression for matrix element of such process is too cumbersome and we
do not present it.

Fig. 1 exhibits the behavior of the cross sections for the process (13) and (16) as a function of $\sqrt{s}$. As is seen from this figure the effect of finite widths of $t$ quark and $W$ boson manifests itself at the region of $\sqrt{s} \leq m_t$. At higher energies of $e^+e^-$ annihilation these two cross sections becomes practically equal in magnitude. Because we examine the process (13) at the energy of $\sqrt{s} \geq 184$, then the basic characteristics of the reaction of a single top production via FCNC interaction can be understood from analysis of the equation (15) for the cross section for the process (13).

Fig. 2 presents the behavior of the cross section production for the process $e^+e^- \rightarrow t\bar{c}$ as a function of $\sqrt{s}$. We also show the individual contributions corresponding to the exchange via virtual $Z$ boson, virtual photon, and their interference. The presented estimates of the cross sections are evaluated by use of the anomalous constants ($\kappa_\gamma$ and $\kappa_z$) equal their "upper" values (see (13) and (14)). As is seen this choice of the constants magnitudes results in the dominating contribution of virtual $Z$ boson into cross section of the process (13) at $\sqrt{s} \leq 400$ GeV. We point out the difference in the energy behavior of the contributions due to exchange via photon and $Z$ boson. Because of anomalous magnetic interaction with a photon ($\sim \sigma^{\mu\nu}$), its contribution is not decrease with increasing of the total energy of interaction. Indeed, from (15) one find

$$\sigma(e^+e^- \rightarrow \gamma^*) \propto \left(1 - \frac{m_t^2}{s}\right)^2,$$

$$\sigma(e^+e^- \rightarrow Z^*) \propto \frac{1}{s}\left(1 - \frac{m_t^2}{s}\right)^2.$$ 

At the energy of $\sqrt{s} = 184$ GeV, that is corresponding to operation energy of 1997 run of LEP-2 collider, the magnitude of the cross section for the reaction (13) (summed over $t$ and $\bar{t}$ as well as over $c$ $u$ quarks) is equal to:

$$\sigma(e^+e^- \rightarrow t\bar{c} + t\bar{u} + \bar{t}c + \bar{t}u) = 0.15 \text{ pb.} \quad (17)$$

Then, with the total luminosity of $L_{int} = 70 \text{ pb}^{-1}$ we get the number of events with a single top production as follows:

$$N_t = 10.5,$$

$$N_{t\bar{t}}(W \rightarrow 2\text{jet}) = 7.1,$$

$$N_{t\bar{t}}(W \rightarrow e^\pm\nu + \mu^\pm\nu) = 2.3. \quad (18)$$
Here $N_h$ and $N_l$ stand for the number of events with top quark decays via pure hadronic or leptonic ($e + \mu$) channels, respectively.

These and all forthcoming estimates are evaluated under assumption of 100% efficiency of registration of hadronic jets or leptons. We ignore also the possible contributions from the background events.

Now we consider the upper limits on the anomalous constants $\kappa_\gamma$ and $\kappa_z$, which one can evaluate from LEP-2 data. To do this would require, in particular, the maximum negative value of the contribution into cross section (15) resulted from the interference term. As is seen from (15) such an requirement occurs at the following constraints on the relative constants of $g_i$ and $z_i$:

$$g_1 z_2 = g_2 z_1 < 0.$$  \hspace{1cm} (19)

It follows herefrom that $g_1 z_1 + g_2 z_2 = 1$. As a result the cross section (13) becomes the function depending on two parameters, namely $\kappa_\gamma$ and $\kappa_z$. Note, however, that the variation of the magnitude of the interference term gives only small correction to the forthcoming results on the constraints. It is explained by the small magnitude of this term as compared to contribution due to photon and $Z$ boson exchange.

Bearing in mind the different notations and normalizations used in the literature, we present the evaluated constraints on anomalous constants in terms of constraints on the corresponding branching ratios for the decays of $t \rightarrow c(u)\gamma$ and $t \rightarrow c(u)Z$. We perform our analysis for the energy of $\sqrt{s} = 184$ GeV as well as for other possible values of the total energy of $e^+e^-$ annihilation at LEP-2 collider and for corresponding total luminosities as given below:

$$\sqrt{s} = 184 \text{ GeV} \quad \mathcal{L}_{e^+e^-} = 70 \text{ pb}^{-1},$$
$$\sqrt{s} = 192 \text{ GeV} \quad \mathcal{L}_{e^+e^-} = 200 \text{ pb}^{-1},$$
$$\sqrt{s} = 200 \text{ GeV} \quad \mathcal{L}_{e^+e^-} = 100 \text{ pb}^{-1}.$$  

Fig. 3 presents the evaluated constraints on the branching ratios of $\text{Br}(t \rightarrow c(u)\gamma)$ and $\text{Br}(t \rightarrow c(u)Z)$ (at 95 % confidence level). We also take into account the possibility to combine the statistics from all four experiments (ALEPH, DELPHI, L3, and OPAL) at the LEP-2 collider. The dashed curves in this figure correspond to these constraints.

Note, that the contribution due to annihilation via photon is very small (see Fig. 2). As a result at the energy of $\sqrt{s} = 184$ and the total luminosity
of $\mathcal{L}_{e^+e^-} = 70$ pb$^{-1}$ it is impossible to improve the estimate (4), evaluated by the CDF collaboration. At the same time one may expect two times improvement of the constraint on the branching ratio of $t$ quark decay into $Z$ boson:

$$\sqrt{s} = 184 \text{ GeV} \Rightarrow \begin{cases} \text{Br}(t \to (c + u) \gamma) & \leq 3.2\% \ (95\% \ C.L.), \\ \text{Br}(t \to (c + u) Z) & \leq 18\% \ (95\% \ C.L.). \end{cases} \ (20)$$

The increasing of the total energy of $e^+e^-$ annihilation will provide a substantial improvement of the corresponding branching ratios of top quark decay both in $Z$ boson and a photon. We present below the results for the energy of $\sqrt{s} = 192 \div 200$ GeV, estimated for joint statistics from all four experiments:

$$\sqrt{s} = 192(200) \text{ GeV} \Rightarrow \begin{cases} \text{Br}(t \to (c + u) \gamma) & \leq 0.3\% \ (95\% \ C.L.), \\ \text{Br}(t \to (c + u) Z) & \leq 1\% \ (95\% \ C.L.). \end{cases} \ (21)$$

Note, that because of the different expected total luminosities (see (20)) one should expect much the same constraints on the anomalous constants (the branching ratios) for both energies of $\sqrt{s} = 192$ Gev and 200 GeV.

As it follows from our analysis even at current (1997 y.) run of $e^+e^-$ collider LEP-2 it is possible to improve the modern constraints on the parameters of anomalous FCNC interaction of the top quark.

It worth to note that to obtain the constraints like (21) from the data of future run of FNAL collider one needs a rather high luminosity about $\mathcal{L}_{\text{FNAL}} \geq 1 \div 10$ fb$^{-1}$ (see, for example (3, 8)).

4 Differential distributions

As it mentioned above, the top-quark is produced very close to its threshold production at the energies of LEP-2 collider (i.e. at $\sqrt{s} \leq 200$ GeV). This fact leads to practically fixed values of energies of the final $t$, $c(u)$, $b$ quarks and $W$ boson in the reaction (16):

$$
\begin{align*}
E_t & \simeq \frac{s + m_t^2 - m_c^2}{2\sqrt{s}} \\
E_{c(u)} & \simeq \frac{s - m_t^2 + m_c^2}{2\sqrt{s}} \\
E_b & \simeq \frac{m_c^2 - m_b^2 + m_t^2}{2m_t^2} \\
E_W & \simeq \frac{m_t^2 + m_W^2 - m_b^2}{2m_t^2}.
\end{align*}
$$

(22)
The corresponding differential distributions as the functions of the energies of final particles in the reaction (16) are shown in Fig. 4. Note, the considered single top production leads to rather specific topology of events. This topology differs radically from that of possible background process of $W^+W^-$ pair production:

$$e^+ e^- \rightarrow W^+W^- \rightarrow 4\text{jet}.$$  \tag{23}

Two jets from the reaction (16) have practically fixed values of the energies. For example, at $\sqrt{s} = 184$ GeV one has:

$$E_b \sim 70 \text{ GeV} \quad \text{and} \quad E_c \sim 10 \text{ GeV}.$$  

This specific behavior of the energy distributions of the jets, originating from charmed and beauty quarks, are distinctly different from those distributions from the background process (23).

We emphasize once again that the energy distributions of jets is actually determined by the kinematics of $t\bar{c}(\bar{u})$ pair production process and be very weakly dependent on the parameters of the model of FCNC interaction of top quark.

On the other hand, the angular distributions of the final particles in the reaction (16) essentially depend on the model parameters. It can easy seen from the equation for the differential cross section of $d\sigma/d\cos \vartheta$ for $t$ and $\bar{c}$ production in the reaction (5):

$$\frac{d\sigma(e^+e^- \rightarrow t\bar{c})}{d\cos \vartheta} = \frac{3\pi\alpha^2}{8s} \left(1 - \frac{m_t^2}{s}\right)^2 [\chi_\gamma + \chi_z + \chi_{\text{int}}],$$  \tag{24}

where $\vartheta$ is the outgoing angle of $t$ quark with respect to initial electron in c.m.s. reference frame. The terms describing the annihilation via photon ($\chi_\gamma$), $Z$-boson ($\chi_z$), and their interference ($\chi_{\text{int}}$) have the form as follows:

$$\chi_\gamma = 2\frac{m_t^2}{\Lambda^2} \kappa_\gamma e_q^2 e_q^2 \frac{s}{m_t^2} \left(1 + \frac{m_t^2}{s}\right) \left(1 - \lambda \cos^2 \vartheta\right),$$  \tag{25}

$$\chi_z = \frac{\kappa_z^2}{2 \sin^4 2\vartheta_W \left(1 - \frac{M_Z^2}{s}\right)^2} \times \left[(1 + a_{w}^2)(1 + \frac{m_t^2}{s})(1 + \lambda \cos^2 \vartheta) - 4a_w(z_1^2 - z_2^2) \cos \vartheta\right],$$  \tag{26}

$$\chi_{\text{int}} = 4e_q \kappa_\gamma \kappa_z \frac{m_t}{\Lambda} a_w (g_1 z_1 + g_2 z_2) - (g_1 z_1 - g_2 z_2) \cos \vartheta, \quad \sin^2 2\vartheta_W \left(1 - \frac{M_Z^2}{s}\right),$$  \tag{27}
where $\lambda = (1 - m_t^2/s)/(1 + m_t^2/s)$.

Note, that at the energies of LEP-2 collider one has $\lambda \ll 1$. Therefore, one can deduce immediately from the above-presented expression for $d\sigma/d\cos \vartheta$ that the contributions into annihilation via photon or $Z$ boson weakly depend on $\cos \vartheta$ (see. (25) and (26)). By contrast, the angular dependence of the interference term ($\sim (g_1 z_1 - g_2 z_2) \cos \vartheta$) is essentially dictated by a choice of model parameters. For example, at $g_1 z_1 = -g_2 z_2$ this dependence has a maximum character, while at $g_1 z_1 = +g_2 z_2$ this contribution is independent of $\cos \vartheta$ at all (see. (27)). This fact can be used for evaluation more detailed constraints on the parameters of the anomalous FCNC interaction of $t$ quark.

5 Conclusion

In the present article we examine the possibility of investigation of the anomalous $t$ quark interaction via flavor-changing neutral currents at the energies of $e^+e^-$ collider LEP-2.

We analyze the events with production of single $t$ quark. We show that one can improve about two times the modern constraints on the parameters of anomalous FCNC interaction of top quark by use of the results of the current (1997) run of LEP-2 collider at the energy of $\sqrt{s} = 184$ GeV and the total luminosity of $L \simeq 70$ pb$^{-1}$. With increasing both of the total annihilation energy up to $\sqrt{s} = 192 \div 200$ GeV and the total luminosity up to $L = 100 \div 200$ pb$^{-1}$ one may expect to derive the constraints on anomalous constants comparable to those which would be resulted from a future run of FNAL collider.

We show that the final state particles in the reaction $e^+e^- \rightarrow \bar{c}t \rightarrow 4\text{jet}$ has the specific kinematics. Two final jets ($c$-jet and $b$-jet) have practically fixed energies. This topology differs radically from that of possible background process with four jets production. Moreover, this kinematics are practically independent on the parameters of the model. At the same time the angular distributions of the final particles in the considered reaction of a single top production have a noticeable dependence on the anomalous constants. This fact can be used for the evaluation of additional constraints on the model parameters.
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References

[1] CDF Collaboration, Abe F. et al., // Phys. Rev. Lett. 74 (1995) 2626; DØ Collaboration, Abachi S. et al., // Phys. Rev. Lett. 74 (1995) 2632.

[2] Parke S., FERMILAB-Pub-94/322-T, 1994.

[3] Grzadkowski B., Gunion J.F., and Krawczyk P. // Phys. Lett. B268 (1991) 106; Eilam G., Hewett J.L, and Soni A. // Phys. Rev. D44 (1991) 1473; Luke M. and Savage M.J. // Phys. Lett. B307 (1993) 387; Couture G., Hamzaoui C., and König H. // Phys. Rev. D52 (1995) 1713.

[4] Peccei R.D. and Zhang X. // Nucl. Phys. B337 (1990) 269.

[5] Han T., Peccei R.D., and Zhang X. // Nucl. Phys. B454 (1995) 527.

[6] Arbuzov B.A. Phys. Lett B353 (1995) 532.

[7] CDF Collaboration, Abe, F. et al., // FERMILAB–Pub–97/270-E, 1997.

[8] Frey R. et al., FERMILAB–Conf–97/085, 1997.

[9] Atwood D., Reina L., and Soni A. // Phys. Rev. D53 (1996) 1199.;

[10] DØ Collaboration, Abachi S. et al., // Phys. Rev. Lett. 79 (1997) 1197; DØ Collaboration, Abbott B. et al., // FERMILAB–Pub–97/172-E, 1997; CDF Collaboration, Abe, F. et al., // FERMILAB–Pub–97/284-E, 1997.
Figure 1: The cross sections for the process of $e^+e^-$ annihilation in the $t\bar{c}(\bar{u})$ pair in the reaction (6) (the dashed curve) and in the process (16) (the solid curve). The magnitudes of the anomalous constants from (13) and (14) are used. The cross section is in pb, while $\sqrt{s}$ in in GeV.
Figure 2: The cross sections for the reaction of $e^+e^- \rightarrow t\bar{c}$ as a function of the total energy of $\sqrt{s}$ (the solid curve). The dashed, dotted and dash-dotted curves correspond to the contributions from annihilation via a photon, $Z$–boson, and their interference, respectively. The cross section is in pb, while $\sqrt{s}$ in in GeV.
Figure 3: The upper limits (at 95 % confidence level) on the branching ratios for the decays $t \to (c + u)Z$ and $t \to (c + u)\gamma$ for the different values of the total energy and luminosity of $e^+e^-$ annihilation ($\sqrt{s} = 184$ GeV and $\mathcal{L} = 70$ pb$^{-1}$, $\sqrt{s} = 192$ GeV and $\mathcal{L} = 200$ pb$^{-1}$, and $\sqrt{s} = 200$ GeV and $\mathcal{L} = 100$ pb$^{-1}$). The dashed curves are calculated with assumption of joint statistics from all four LEP-2 experiments (i.e. $\mathcal{L}(184) = 280$ pb$^{-1}$, $\mathcal{L}(192) = 800$ pb$^{-1}$, and $\mathcal{L}(200) = 400$ pb$^{-1}$).
Figure 4: Distribution on energies of the final state particles from the reaction (16). The curves with labels "q-jet" corresponds to jets from $W$ boson decays. The energy of jets ($E_{\text{jet}}$) is in GeV, while the cross section $(1/\sigma)d\sigma/E_{\text{jet}}$ is in GeV$^{-1}$. 