Top quark flavor-changing neutral currents at CERN LEP-200: Signals and backgrounds

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Current experimental limits on FCNC allow for the single top quark production process at CERN LEP-200. We show that the rates from standard model electroweak diagrams are negligible. In order to estimate the background due to misidentification of the *b* quark, we calculate the 4-quark process $e^+e^-\rightarrow c\overline{s}\overline{u}d$ within the EW sector of the SM. We show that it is possible to handle this background using different kinematical cuts on the quarks. We conclude that LEP-200 offers the possibility of improving the current bounds on flavor-violating couplings but that one will likely have to work with semileptonic decay modes of the top quark in order to avoid rather large QCD backgrounds.

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INTRODUCTION

Flavor-changing-neutral-currents (FCNC), being very difficult to produce in the standard model (SM), offer the possibility of setting strong constraints on physics beyond the SM without directly producing new particles, whatever they might be. The very large mass of the top quark opens new doors for the study of new physics, one of the promising possibilities being flavor-changing top quark decays. It has been known for a while that these decay rates for the top quark are extremely small [1] in the SM (typically $\sim 10^{-10}-10^{-12}$) but that they can be pushed by a few orders of magnitude in extensions of the SM such as the two-Higgs-doublet model [2] and to $\sim 10^{-6}$ in the minimal supersymmetric standard model (MSSM) [3] [partly due to the large mass of the top quark, which leads to large mixings among supersymmetric (SUSY) partners] and even higher in other models [4]. Phenomenological studies at high energy lepton and hadron colliders have been done recently [5] and show very interesting possibilities.

Currently, direct experimental limits on flavor-changing couplings of the top quark come from the Collider Detector at Fermilab (CDF) [6], who studied top production and decay into a *c* quark and a photon or a *Z*. They express their limits in terms of branching ratios: less than 3.2% for $t\rightarrow c\gamma$ and less than 33% for $t\rightarrow cZ$. Given the difficulty of extracting the signal in a hadronic environment and the small sample of top quarks produced up to now, these bounds are impressive.

A recent study [7] has used these bounds to try to predict the production rate of $e^+e^-\rightarrow t\overline{c}$. The authors of [7] parametrized the *Z*-*t*-*c* vertex as

$$\Gamma^{\gamma}_{\mu}=\kappa_{\gamma}\,\frac{ee_q}{\Lambda}\,\sigma_{\mu\nu}(g_1P_l+g_2P_r)q^{\nu},$$

$$\Gamma^{Z}_{\mu}=\kappa_{Z}\,\frac{e}{\sin(2\theta_W)}\,\gamma_{\mu}(z_1P_l+z_2P_r),$$

where Λ is a new physics cutoff, e_q is the charge of the quark and $P_{l,r}$ are the usual projection operators. With this parametrization, they calculated the decay rate for $t\rightarrow c\gamma$ and $t\rightarrow cZ$. Assuming a new physics scale (Λ) of m_t, the previous experimental bounds on the branching ratios translate to $\kappa_\gamma^2\leqslant 0.176$ and $\kappa_z^2\leqslant 0.533$. The authors then calculated the production cross section for the processes $e^+e^-\rightarrow t\overline{c}$ using the previous parametrization and bounds. From their results, one can conclude that the intermediate off-shell *Z* dominates vastly over the intermediate off-shell photon at 190 GeV and that the production cross section could be as high as about 0.07 pb. Therefore, in that case, one would expect about 0.28 pb for the $t\overline{c}$, $t\overline{u}$, $\overline{t}c$, and $\overline{t}u$ final states. For an integrated luminosity of 200 pb^{-1}, one would expect 56 events per CERN e^+e^- collider LEP experiment. Assuming that the top quark decays exclusively to *Wb*, this would give 19 events where the *W* decays leptonically and 37 events where it decays hadronically.

Two types of standard model ''background'' for the FCNC signal are here considered: single top-quark production and four-quark production, both from the EW sector. The first type would obviously correspond to our signal, and would be interesting by itself, while the second one could also mimic our signal once we let the top quark decay to light quarks but misidentify the *b* quark. Perfect identification of the *b* quark would lead to a clean signal since the *W* boson cannot decay into a *b* quark: V_{cb} and V_{ub} are too small, given the current limits on top FCNC.

In this Brief Report, we show that the expected single top quark production cross section from EW standard model processes are negligible, and we assess the possibility of observing a signal from FCNC in the top sector at LEP 200.

SINGLE TOP QUARK PRODUCTION IN THE STANDARD MODEL

We consider two different classes of processes. The first is simply four quark production by electroweak diagrams, one quark being the top quark. One dominant subprocess would be $e^+e^-\rightarrow W^*W^*\rightarrow t\overline{b}\overline{u}d$. One would expect this cross section to be very small: the phase space is almost filled and the two *W*'s cannot be on-shell: one of them timelike with enough energy to produce the top quark and the other spacelike. Using a spinor technique [8], we included all

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11 diagrams in the process $e^+e^-\to t\overline{b}\overline{u}d$. Since we used massless quarks, except for the top quark, this process clearly also represents $e^+e^-\to t\overline{b}\overline{c}s$. In our numerical calculations, we used $\sqrt{s}=190$ GeV and we required an angle of at least 5 degrees between the outgoing quarks and the beam pipe. We did not impose any constraints on the invariant mass of the quarks nor on the angle between them but we imposed a minimum energy of 1 GeV for each quark. This leads to a cross section of $\sim 2\times 10^{-9}$ pb; totally negligible compared to our signal.

This is certainly a good estimate for the semileptonic processes: $e^+e^-\to t\overline{b}\mu^-\overline{\nu}_\mu$, $t\overline{b}\tau^-\overline{\nu}_\tau$; one simply divides by 3 to take into account the color factor. In order to consider all these backgrounds and their Hermitian conjugates, we should multiply our results by [4 (quarks)+4/3 (leptons)]. The number obtained is still very much smaller than our signal.

The second class of processes is the semileptonic process $e^+e^-\to t\overline{b}e^-\overline{\nu}_e$; also through EW diagrams. This is greatly enhanced over the previous backgrounds because of the presence of a photon in the t channel: the electron emits a photon which goes down the beam pipe. This photon then interacts with the incoming positron while the previous electron goes down the beam pipe, undetected. We evaluated this cross section using the Weizsäcker-Williams approximation. The process we calculate is then $e^+\gamma\to t\overline{b}\overline{\nu}_e$ and then we integrate over the photonic spectrum:

$$\sigma(e^+e^-\to e^- t\overline{b}\overline{\nu}_e)=\int_{x_{\min}}^{1}\frac{dx}{x}\,\sigma(e^+\gamma\to t\overline{b}\overline{\nu}_e)\mathcal{F}_{WW},$$

where

$$\mathcal{F}_{WW}=\frac{\alpha}{2\pi}\left\{\frac{1+(1-x)^2}{x}\ln\left\{\frac{E^2(1-2x+x^2)}{m_e^2(1-x+x^2/4)}\right\}+x\ln\left\{\frac{2-x}{x}\right\}+\frac{2(x-1)}{x}\right\},$$

where E is the energy of the incoming electron and m_e is the mass of the electron [9]. We used $(m_{top}^2+m_b^2)/s$ as the minimum value of x in the photon spectrum. Only three diagrams contribute to the subprocess. One of them, the exchange of the b quark in the t channel can lead to a spurious pole if we let the mass of the quark go to zero. In order to cure this singularity, we chose to keep a mass of 5 GeV for the b quark in the propogator but to neglect it when it is an outgoing particle. With the same cuts as before (we did not impose any cut on the neutrino since it goes undetected) we obtain a cross section of $\sim 3\times 10^{-5}$ pb. This result, in comparison with the previous 4-quark production process, shows the effect of the exchange of the photon in the t channel. In spite of this very large enhancement and the factor of two one gets by including the Hermitian conjugate, this process remains much smaller than what we can expect from the current experimental bounds on FCNC.

We conclude that the single top production at LEP-200 within the EWSM will not be a significant background for the study of FCNC involving the top quark because of the low cross section.

FOUR-QUARK PRODUCTION IN THE SM

If one can indentify the b quark with high efficiency, there is virtually no background for our process, in the limit where V_{ub} and V_{cb} are negligible. In order to account for possible inefficiencies and misidentification of the b quarks, we compare the topologies in events from our FCNC signal and in the production of four light quarks by SM-EW processes. Neglecting all masses except those of the top quark and the W boson, simple kinematics says that with a c.m. energy of 190 GeV, the quark produced with the top (either a $\overline{c}$ or a $\overline{u}$) will have an energy of 14.4 GeV while the top quark will have an energy of 175.6 GeV. The b quark resulting from the decay of the top quark will have an energy between 63.3 and 74.7 GeV while the W will have and energy between 100.9 and 112.3 GeV. The quarks (or other light fermions) arising from the decay of the W's have a range of energies between 17.3 and 95 GeV. We note also that even if the 4 quarks are produced via WW production and decay, their energies lie in a range between 22.7 and 72.3 GeV. It seems then that, with reasonable energy resolution, a very powerful rejection of background can be obtained by requiring that the jet produced in association with the top quark have an energy of 14.4 GeV, out of reach of the two-W boson process at a beam energy of 95 GeV. Another veto consists in the requirement that the two quarks whose invariant mass reconstructs to that of the W have a total energy between 101 and 112 GeV, which is not possible for quarks coming from a pair of real W's since they have a total energy of 95 GeV. If these pairs come from double-Z production, we feel that the analysis we have presented here will be able to handle this background because the quarks coming from two real Z's have an energy between 34 and 61 GeV; even farther away from the 14.4 GeV quark in the single top quark production.

In order to study the kinematics in more details, we calculated the process $e^+e^-\to c\overline{s}\overline{u}d$ in the EW-SM. We present the average energy spectrum of the quarks in Fig. 1. We see a rather large cross section for energy between 22 and 72 GeV. As expected this falls very quickly for energies outside this range since the W's are virtual. The total cross section for a quark energy below 20 GeV is approximately 4×10^{-3} pb. It seems then that requiring a quark with an energy below 20 GeV would take care of this background.

A more dangerous reducible background arises from QCD corrections to $q\overline{q}$ pair production. We did not calculate this background but instead we used a preliminary study done by the ALEPH Collaboration [10].

SIMULATIONS

The ALEPH collaboration has analyzed this type of background and what they find, with an integrated luminosity of 175 pb^{-1} is the following: the main sources of backgrounds are WW (1.54 events), $q\overline{q}$ pairs (6.43 events), and ZZ (0.59

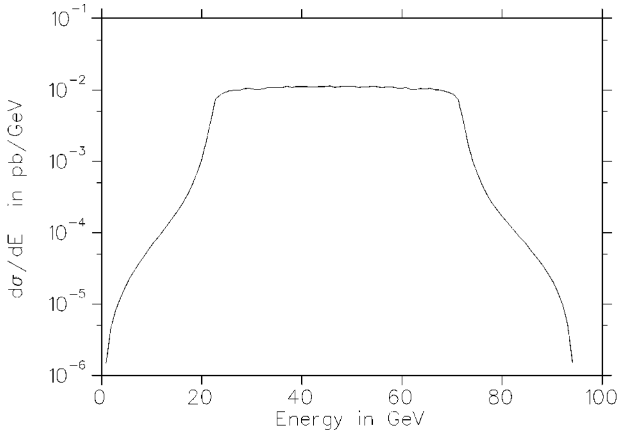

FIG. 1. Average energy spectrum of the quarks in the process $e^+e^- \to c\overline{s}\overline{u}d$.

events) for a total of 8.55 events. They have an efficiency of 12.25% at reconstructing the jets of interest, which leads to about 7 events (from our initial 56 events based on current experimental bounds). It appears then that the hadronic disintegration of the W does not offer a good signal because of QCD background. Unless one can reduce the QCD background by at least a factor of 4, this channel does not appear very promising.

The leptonic decay channels have fewer events to start with but the background is very much reduced; in fact ALEPH and DELPHI have estimated a background of 1 event. Both of these groups have similar efficiencies at reconstructing the signal: 5.35% and 6.62%, respectively. This leads to 6–7 events. Assuming that Opal and L3 will have similar efficiencies, one gets a total of 12–14 events at LEP-200 at this particular energy; with a total background of 4 events. This would be a 3 sigma signal and would already improve the current limits on κ_Z^2 by a factor of 2. If we now go to 200 GeV, the production cross section rises to about 0.13 pb [7]. At this energy, it is not unrealistic to assume an integrated luminosity of 500 pb^{-1}; we then have about 260 events of interest at LEP-200. Assuming similar efficiencies, one would be left with approximately 60 leptonic events at LEP-200. Assuming that the background increases moderately (i.e., its cross section is multiplied by 2) to 20 events, one would then have a 5 sigma signal and it would be possible to improve the limit on κ_Z^2 by a factor of 3–4. Although quite interesting in itself, this substantial improvement on the bound on κ_Z^2 is still very, very far from the typical values that can be reached in the standard model but is within an order of magnitude of those reachable in more exotic models [4]. Of course, any improvement in the experimental efficiencies only improves the bounds on κ_Z^2.

CONCLUSIONS AND OUTLOOK

In this paper, we showed that one does not have to worry about single top quark production within the EW-SM when studying FCNC involving the Z-t-c vertex at LEP-200: the four-quark channel having a cross section of the order of 10^{-9} pb while the associated leptonic production has a cross section of the order of 10^{-5} pb. We also showed that, likely, one will have to study the Z-t-c coupling via the semileptonic decay mode of the top quark: the fully hadronic decay channel is practically lost in the standard QCD background. Assuming a good reconstruction of the semileptonic channel, one could in fact improve the current bound on the Z-t-c vertex by as much as a factor of 4 at LEP-200 by running at 200 GeV. A more complete analysis is now underway.

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