Prospects for Top Flavour Violation at a Future Linear Collider

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Abstract

The possibility of flavour violation via a coupling $Z^0 \rightarrow t\bar{c}$ at centre of mass energies of 300 GeV is discussed. Possible limits on a right-handed coupling are obtained and the prospects compared to those at the LHC.

1 Flavour Violating Couplings

1.1 Introduction

The standard electroweak model[1] has as one of its many successful predictions that the tree-level couplings of neutral gauge bosons are diagonal in flavour. This leads naturally to the absence of flavour changing neutral currents (FCNC) at tree level and, as a result of the GIM[2] mechanism, FCNC are suppressed even when higher order corrections are included.

The effective $t\bar{c}Z$ couplings induced by loop-corrections to the standard model are negligible [3, 4]. It has also been shown recently [8] that the presence of a $t\bar{c}Z$ coupling cannot enhance the rates for the Z mediated flavour changing decays $b \rightarrow sl^+l^-$ and $b \rightarrow s\nu\bar{\nu}$, so no restrictive bounds can as yet be placed on the magnitude of this coupling.

The presence of any effective $t\bar{c}Z$ coupling would be a clear indication of physics beyond the standard model. Possible contributions to an effective $t\bar{c}Z$ coupling arising from supersymmetry have been investigated [7] and the implications of bounds on this coupling in dynamical symmetry breaking scenarios are particularly interesting [6].

1.2 Formalism and Present Limits

In this study we follow reference [6] and write an effective lagrangian as:

$$L_{int} = \frac{g}{2\cos\theta_W}\bar{t}\gamma_\mu\{P_L\kappa_L + P_R\kappa_R\}cZ^\mu + h.c. \quad (1)$$

$$(2)$$

where $P_L = \frac{1}{2}(1-\gamma_5)$,$P_R = \frac{1}{2}(1+\gamma_5)$, $g\sin\theta_W = e$ and $\kappa_{L,R}$ are the FCNC couplings. The limits from the kaon and B-meson sector are analyzed in [6] to yield the general bounds:

$$\begin{aligned} |\kappa_L| &< O(0.1) \\ |\kappa_R| &< O(1) \end{aligned} \quad (3)$$

Given these limits, the disussion below will concentrate on the case $\kappa_R = \kappa$, $\kappa_L = 0$. This is purely for simplicity and the linear collider could clearly provide useful limits on both forms of coupling. Another more recent limit can be derived from the quoted limit [11] at 90% c.l. on the branching ratio of the top quark to $Z^0 q$ as:

$$Br\left(t \to Z^0 q\right) \quad < \quad 0.44 \tag{4}$$

Calculating the ratio of top decay widths to tree level, ignoring light quark masses and setting $m_t = 175\,\mathrm{GeV}/c^2$ gives:

$$\frac{\Gamma\left(t \to Z^0 c\right)}{\Gamma\left(t \to W^+ b\right)} \quad = \quad 2\kappa^2 \left(\frac{m_t^2 - m_Z^2}{m_t^2 - m_W^2}\right)^2 \left(\frac{2m_Z^2 + m_t^2}{2m_W^2 + m_t^2}\right) \tag{5}$$

$$\approx \quad 1.84\kappa^2 \tag{6}$$

At the LHC top quark pairs will be produced in copious numbers allowing a detailed study of top branching ratios. Early estimates [12] suggest that the LHC experiments will be sensitive to $Br\left(t \to Z^0 c\right) < 5 \times 10^{-5}$ for an integrated luminosity of $10^5 pb^{-1}$, which would translate into an upper limit on κ of 5×10^{-3}.

1.3 Cross-section at Future Linear Collider Energies

In the following the implications for searches at a future linear collider of a new coupling $t\bar{c}Z$ are discussed and, for simplicity, only the right handed coupling is considered. The LHC will already have yielded either a discovery or an upper limit to the top branching ratio. In the latter case the width of the top quark will be to a very good approximation that given by the standard model. So in the following discussion we take the top mass $m_t = 175\,\mathrm{GeV}/c^2$ and the top width to be $\Gamma_t = 1.34\,\mathrm{GeV}/c^2$.

The total cross section at tree level for on-shell final quarks of the process $e^+e^- \to W^+ b\bar{c}$ can be calculated using the diagram in figure 1 to give (neglecting terms of order m_c):

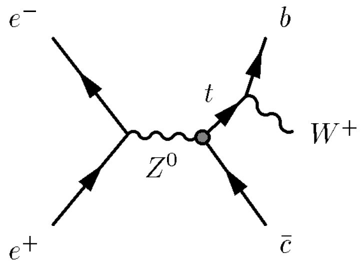

Figure 1: Tree level diagram for flavour violating top production

$$\sigma = \frac{12\pi\alpha^2}{(\cos\theta_w \sin\theta_w)^4} \frac{1}{s} \frac{s^2}{(s - m_Z^2)^2} \frac{p}{\sqrt{s}} \frac{1}{s} \left[p(p^2 + m_t^2)^{\frac{1}{2}} + \frac{1}{3}p^2\right] \kappa^2 \tag{7}$$

where p is the momentum of the t-(or c-)quark. This expression was then convoluted with a Breit-Wigner function with central mass m_t and width Γ_t. The cross section is shown in figure 2 as a function of centre of mass energy. Initial state radiation is taken into account using an electron form factor corresponding to the Weizsäcker-Williams approximation given by [15]:

$$\frac{d^2\sigma}{dz} = \frac{2\alpha}{\pi} \left(\ln \frac{s}{m_e^2} - 1\right) \frac{1 + z^2}{1 - z} \sigma_0 \left(s\sqrt{z}\right) \tag{8}$$

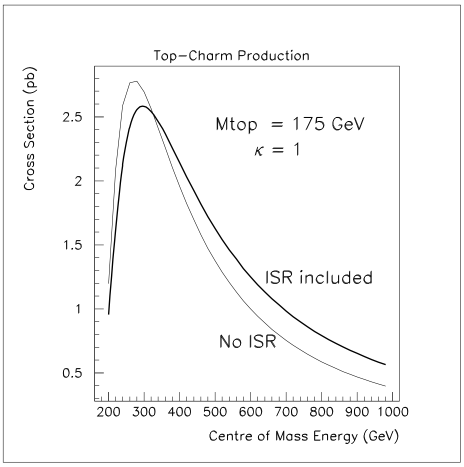

Figure 2: Cross section for flavour-violating top production

with $\alpha = \frac{1}{127}$.

It is clear from figure 2 that the cross-section peaks strongly at a centre of mass energy of 300 GeV, where the cross-section is approximately $2.5\kappa^2$ *pb*. The rest of this study concentrates on running at this peak, which is below the top threshold of 350 GeV/c^2, and so is relevant to the earlier stages of a future linear collider programme.

2 Event Generation

A monte carlo was written to generate a final state $W^+\bar{c}b$ according to the Feynman diagram in figure 1. The final state W-mass was smeared according to a Breit-Wigner distribution with width $\Gamma_W = 2.08\,\mathrm{GeV}/c^2$ centred about $M_W = 80.3\,\mathrm{GeV}/c^2$. The final state decays and fragmentation were performed using JETSET74 [13] and the background processes of W-and Z^0-pair production were generated using PYTHIA5.7 [14] interfaced to JETSET74.

2.1 Detector Simulation and Event Reconstruction

The output from the monte-carlos was then smeared according to the parameters in appendix A using the SIMDET algorithm provided for this workshop [16]. Jet finding was performed using the Durham(KT) scheme applied to the isolated particles and clusters provided by SIMDET.

A B-tagging routine was constructed to convert the smeared impact parameter output from SIMDET into a set of probabilities, where the track probability is defined as the probability that the impact parameter of the track is consistent with zero. The probability was determined by fitting the impact parameter sigma of events with no lifetime to the sum of a gaussian and an exponential for the non-gaussian tails. The events used for the fit were Pythia-generated Z^0-pairs where the Z^0's were constrained to decay to *uds* quarks. The resulting efficiency/purity performance for jets is shown in figure 3. We note that the performance is significantly better than that acheived at LEP, which could be attributed in large part to the higher jet energies. A cut of 2.5 cm on the Monte Carlo truth decay vertex of all particles is applied on the track selection, to go some way towards simulating the fact that long lived particles would be identified as V0's in a full reconstruction. It should however be remembered that the simulation used here is very simplified, with no nuclear interactions or noise backgrounds and so these results could well be optimistic.

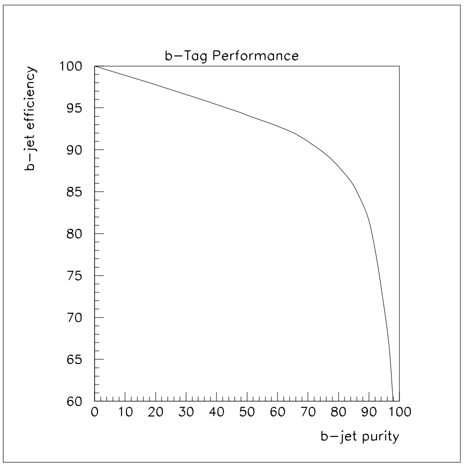

Figure 3: ϵ_b vs $1. - \epsilon_{udsc}$ for Z^0-pairs decaying to four quarks, at $E_{cms} = 300GeV$

2.2 Event Selection

The final state consists of a $b-$jet, a $c-$jet and a $W-$boson. The topologies of interest are thus either $4j$ events or $jjl\nu$, both with a positive b-tag. The $4j$ channels have the advantage that an energy-momentum constraint can be applied to the jets to improve the mass resolution. However there is a significant irreducible background from ZZ events where one or more Z decays to $b-$quarks. The $jjl\nu$ channels have the disadvantage of poorer mass resolution, but their main background is from WW events, which is reduced by an efficient b-tag. The ZZ background, potentially a problem due to the significant branching fractio of Z decays to b-quarks, is reduced greatly by the basic topological requirement of a single isolated lepton in the final state, together with two jets and missing energy.

2.3 Leptonic-Channel Selection

Initially the event is required to have at least 5 charged particles and the total energy in the event must be less than 270 GeV and greater than 170 GeV. This range is good for rejecting ZZ events where energies are often very high (no neutrinos) or very low (one Z decays to neutrinos). The event is then forced into three jets and one of these 'jets' must be purely leptonic with energy greater than 20 GeV, where a leptonic jet is defined as having either one track only, or three tracks with an invariant mass less than 3 GeV. In the case of one track jets, pion rejection is applied at the monte carlo truth level, it is assumed that electrons and muons with energy greater than 20 GeV will be easily distinguishable from pions in the final detector. These basic cuts are together called "cut 1" and their effect is shown in figure 6.
The missing momentum and the identified lepton together form one W boson with mass M, energy E and z-momentum p_z. In order to fix this mass to be 80.3 GeV, a massless pseudo-particle with momentum P is introduced along the beampipe where:

$$P = \frac{M^2 - M_W^2}{2(E - \lambda p_z)} \tag{9}$$

This pseudo-particle is added to whichever hadronic jet is closest to the beampipe; $\lambda = +1$ when this jet has positive z-momentum and $\lambda = -1$ when this jet has negative z-momentum. The resulting mass of the hadronic system is shown in figure 4, together with the position of the cuts where it is required that the hadronic mass is greater than 150 GeV and less than 230 GeV. These cuts are called " cut 2" in fig 6.

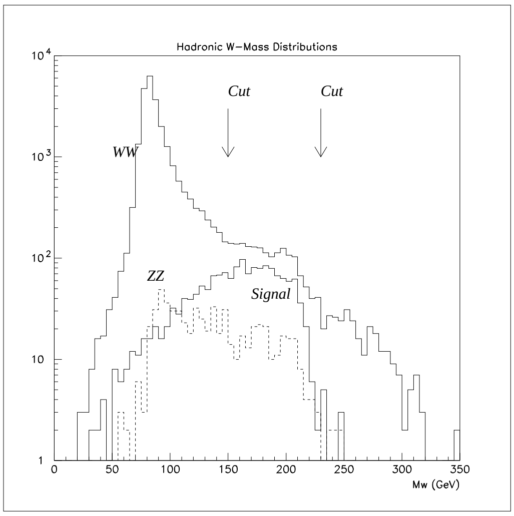

Figure 4: Mass distributions for the hadronic system, including a pseudo-particle

Each track is assigned a probability that it is consistent with initiating from the interaction point. These probabilities are combined into event and jet probabilities. The signal events have one b-quark whereas the WW background contains very few b-jets. We require the event probability to be less than 1.0×10^{-5}. This gives "cut 3" in figure 6.

The final reconstructed top mass distributions are shown in figure 5. We impose a final constraint that the reconstructed top mass be greater than 125 Gev and less than 225 GeV, which yields the numbers in the "cut 4" row of figure 6.

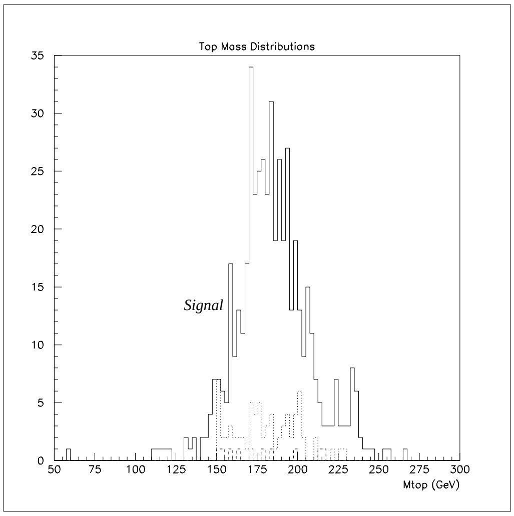

Figure 5: Top mass distribution, including the effects of a pseudo-particle

2.4 Hadronic-Channel Selection

The event is required initially to contain at least five charged particles and no single leptons, such as are defined in the previous section. Events which survive this requirement are then forced

Cut	Signal	WW	ZZ
0	10 000	150 000	20 000
1	1 598	25 481	629
2	951	1 667	207
3	358	17	49
4	293	10	19
efficiency%	4.23	3.33×10^{-3}	0.095
cross section (pb)	$2.3\kappa^2$	14.	.85
Number of events at $10 fb^{-1}$	$973\kappa^2$	4.7	8.1

Figure 6: Effect of cuts on leptonic event samples.

into four jets. The jet directions are then used to constrain uniquely their energies, under the assumption that the jets are massless. These requirements form the "cut 1" in figure 9. The jet pair whose invariant mass is closest to the W-mass was then taken as the reconstructed W and its mass was required to lie between 60 GeV and 100 GeV. This is "cut 2". The mass of the remaining jet pair is shown in figure 7, together with "cut 3" at 125 GeV.

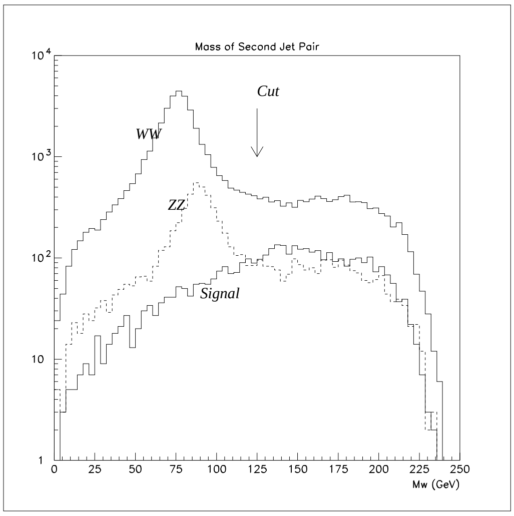

Figure 7: Mass of the second hadronic W, after jet energy rescaling and a mass cut on the 'best' W-mass

As for the leptonic events, a cut on the event probability at 1.0×10^{-5} is now applied as "cut 4". The remaining ZZ background is still high, so an extra cut is applied on the next-to-least probable jet, which for the signal should be a c-quark jet, whereas for the ZZ background, this will also be a b-quark jet. "Cut 5" requires this jet probability to be greater than 0.01. The resulting mass distributions are shown in figure 8 and a final cut, "cut 6" of $160 < m_t < 200$ is then applied.

3 Conclusions and Discussion

The leptonic analysis leads to an expected number of $973\kappa^2$ signal events with 12.8 background events surviving the cuts. Requiring a five sigma discovery limit would imply that a signal could

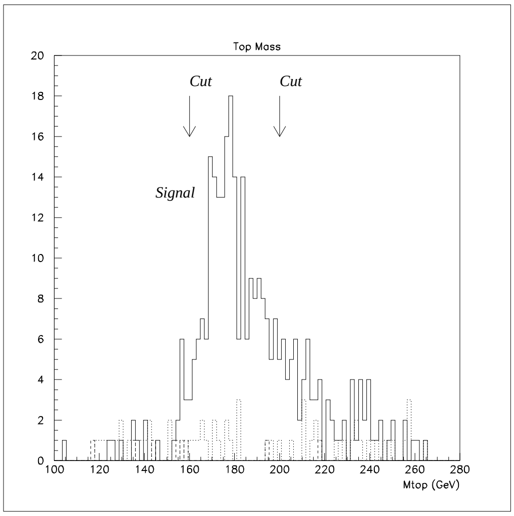

Figure 8: Top mass after all other cuts for purely hadronic events

Cut	Signal	WW	ZZ
0	10 000	150 000	20 000
1	5 054	58 481	8 807
2	3 921	45 589	6 713
3	2 589	9 058	1 931
4	870	34	377
5	315	7	58
6	212	1	17
efficiency%	2.12	6.6×10^{-4}	0.085
cross section (pb)	$2.3\kappa^2$	14.	.85
Number of events at $10fb^{-1}$	$488\kappa^2$	0.9	7.2

Figure 9: Effect of cuts on purely hadronic event samples.

be detected provided $\kappa > 0.14$, alternatively, if no signal is detected, then a 95% c.l. upper limit on κ of 0.085 could be set.
The hadronic analysis leads to $488\kappa^2$ signal with 8.1 background events. Requiring a five sigma discovery limit would imply that a signal could be detected provided $\kappa > 0.17$, alternatively, if no signal is detected, then a 95% c.l. upper limit on κ of 0.11 could be set.
Clearly the leptonic analysis is more powerful due to the smaller irreducible ZZ background. Combining the analysis gives $1461\kappa^2$ signal events for 20.9 background which leads to a discovery limit of $\kappa > 0.12$ and an exclusion limit of $\kappa > 0.08$.
The analysis has been neither refined nor optimised, in particular the b-tagging used was only an approximation to what could be expected. The use of optimised energy flow would also improve the mass resolutions, so the above limits may be somewhat pessimistic. However, the general conclusion is that if the $Zt\bar{c}$ coupling is to be of interest at a future linear collider then its existence will have already been established at the LHC from top branching ratio measurements. In the happy event that such a coupling indeed turns up with a magnitude of order 0.1 then there would be the interesting prospect of studying top physics in the early stages of a future linear collider programme, even below the top-pair threshold. At the time of writing, such a

possiblity is not yet ruled out.

A Detector Parameters Used for this Study

The detector parameters used which are relevant for this study are as follows:

Vertexing	$\delta(IP_{r\phi}) = 10\mu m \oplus \frac{30\mu m GeV/c}{p \sin^{3/2}\theta}$ $\delta(IP_z) = 10\mu m \oplus \frac{30\mu m GeV/c}{p \sin^{5/2}\theta}$ Max $\cos\theta = 0.95$
Tracking	$\frac{\delta p_t}{{p_t}^2} = 1.5 \times 10^{-4} (\frac{GeV}{c})^{-1}$ Max $\cos\theta = 0.95$ Magnetic field 3.0 T
Electromagnetic Calorimeter	$\frac{\delta E}{E} = 0.10 \frac{1}{\sqrt{E}} \oplus 0.01$ (E in GeV) Granularity $0.7^o \times 0.7^o$, 3 samples in depth. isolation criteria 1.4^o.
Hadronic Calorimeter	$\frac{\delta E}{E} = 0.50 \frac{1}{\sqrt{E}} \oplus 0.04$ (E in GeV) Granularity $2.0^o \times 2.0^o$, 3 samples in depth. isolation criteria 4^o.
Hermetic Coverage	$\|\cos\theta\| < 0.99$

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