Single *top* production and FCNC processes

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In the Standard Model Flavour Changing Neutral Current processes are extremely rare, occuring only at loop level. This is particularly true for the top quark for which any observation of FCNC transition will imply new physics beyond Standard Model. The paper reviews the latest results on the search for Flavour Changing Neutral Current in the top quark sector in high energy e^+e^-, $p\bar{p}$ and ep collisions.

1. Introduction

In the Standard Model (SM) Flavour Changing Neutral Current (FCNC) transitions are absent at the tree level and highly suppressed at one loop due to the GIM mechanism [1], making these processes extremely rare. This is particularly true for FCNC transitions involving the top quark for which, due to the smaller mass splitting between the down-type quark, the GIM mechanism is much more effective. As an example the SM predicts a value for the branching ratio of FCNC decays of the top into gauge boson and quark, $BR(t \to c\gamma/Z)$, of the order 10^{-13} [2], almost unobservable for the present collider machine. Thus top FCNC interactions are a good test of the SM and any observation of these processes would imply new physics beyond SM. Indeed many extentions of the SM (see [2] and reference inside) predict FCNC interactions already at the tree level leading to sizeable branching fractions for FCNC transitions.

FCNC top interactions can be described by the effective Lagrangian[2]

$$\begin{aligned}\mathcal{L}_{eff} = & \sum_{U=u,c} i\frac{ee_U}{\Lambda}\bar{t}\sigma^{\mu\nu}q_\nu k_{\gamma,U}UA_\mu + \\ & +\frac{g}{2\cos\theta_W}\bar{t}\left[\gamma_\mu\left(v_{Z,U} - a_{Z,U}\gamma^5\right) + \right. \\ & \left. +i\frac{1}{\Lambda}\sigma_{\mu,\nu}q^\nu k_Z,U\right]UZ^\mu + h.c.\end{aligned} \tag{1}$$

where $\sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu]$, Λ is the energy scale of the new interaction, e and e_U are the charges of the electron and up-type quark respectively, $k_{\gamma,U}$ and $k_{Z,U}$ are the anomalous magnetic FCNC couplings to the photon and the Z respectively, and $v_{Z,U}$ and $a_{Z,U}$ are the anomalous vector[2] and axial FCNC couplings to the Z boson.

The FCNC verticies tqV ($V = \gamma, Z$ and $q = u, c$) can be probed, in high energy collisions, searching either for rare decay of the top quark to a neutral gauge boson and a light quark or looking for single top production in associaton with a light u, c quark. In the following sections a review of searches for FCNC processes in the top sector performed at high energy colliders is presented.

1.1. Tevatron

Fermilab Tevatron is $p\bar{p}$ collider with a centre-of-mass energy of $\sqrt{s} = 1.8$ TeV. The CDF collaboration performed a search for top rare decay $t \to q\gamma, Z$ [3] (where q denotes either a c or a u quark). At the Tevatron energy the dominant source of top quarks is $t\bar{t}$ pair production from $q\bar{q}$ annihilation. In the search for $t \to q\gamma$ the other top is assumed to decay $t \to bW$ with the W decaying hadronically or leptonically. In the $t \to qZ$ search the leptonic decay of the $Z \to e^+e^-, \mu^+\mu^-$ is used with the other top decaying to three jets. Using the data collected during the 1992-1995 run of Tevatron, equivalent to an integrated luminosity of ~ 110 pb^{-1} one event has been selected in each channel. In the hypothesis that both events are due to FCNC top decay CDF set 95% confi-

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[2]In LEP results [6,7] $v_{Z,U}$ is labelled as k_Z.

dence level limits on the branching fractions

$$BR(t \to c\gamma) + BR(t \to u\gamma) < 3.2\% \qquad (2)$$
$$BR(t \to cZ) + BR(t \to uZ) < 33\%.$$

Assuming the Lagrangian (1) with $\Lambda = m_t = 175$ GeV constraints on the couplings $k_\gamma < 0.42$ and $v_Z < 0.73$ [4] can be set. These relatively "feeble" constraints are due to the small statistics of collected events ($N_{t\bar{t}} \sim 10^2$). With Tevatron Run2 with a centre of mass energy $\sqrt{s} = 2$ TeV and an expected integrated luminosity of 2 fb^{-1} there will be an increase of factor 100 in the number of expected $t\bar{t}$ events leading, in case of no observation of FCNC, to an upper limit on k_γ of the order of 0.13 [5].

2. LEP

In the mid-1990's the LEP collider at CERN started a new run, LEP2, with e^+e^- collisions above the W^+W^- threshold. Between 1998 and 2000 the LEP2 accumulated approximately 600 pb^{-1} of luminosity per experiment with a centre of mass energy between 189 GeV and 209 GeV. This data opened the possibility to search for single top production in e^+e^- collisions. The expected rate is negligible in the framework of the SM at LEP2 energies, but FCNC couplings could lead to an enhancement of the single top production rate. In this case top quark will be produced in association with a light u or c quark, $e^+e^- \to \bar{t}u, c$ [3]. Assuming the $t \to bW$ decay, the signature for single top production is two jets, one isolated lepton and missing energy in the case of leptonic decay of the W, or 4 jets for the hadronic W decay. In all cases one jet is coming from a b quark.

All four LEP experiments have searched for FCNC top production reporting [6] no evidence for such process. A combined analysis has been done by the LEP EXOTICA Working group [7] setting limits, at 95% CL, on the anomalous coupling parameters k_γ and v_Z (see fig.1) using Born level cross section from Lagrangian (1). The reduction of the $BR(t \to bW)$ due to possible FCNC decays has been taken into account in setting the limits.

[3] Charge conjugate state is implied.

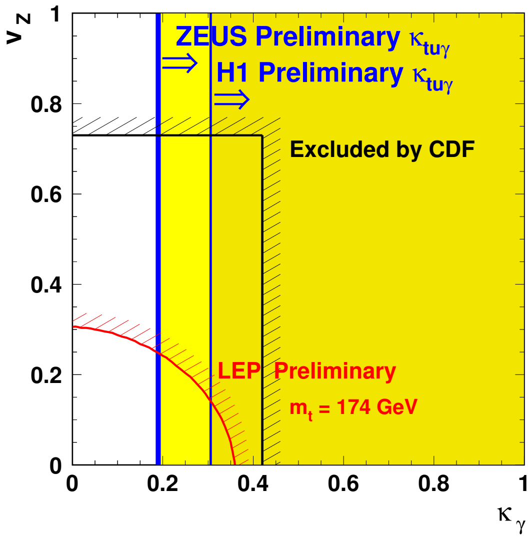

Figure 1. The limits on the anomalous couplings k_γ and v_Z of LEP, Tevatron and HERA. HERA limits are only on $k_{tu\gamma}$.

A very general approach to single top production is to consider its production via four Fermion Contact Interaction (CI) [8]. In this case the single top production cross section is given [9], in term of scalar (S_{RR}), vector ($V_{ij}\,; i,j = L,R$) and tensor (T_{RR}) couplings, by

$$\sigma = \frac{s}{\Lambda^4}\frac{\beta^2}{4\pi(1+\beta)^3}[8T_{RR}^2(3-\beta) + \\ +\frac{3}{2}S_{RR}^2(1+\beta) + \\ +(V_{LL}^2 + V_{RR}^2 + V_{LR}^2 + V_{RL}^2)(3+\beta)] \qquad (3)$$

where Λ is the energy scale of the new interaction and β is a constant. In this model it is also possible to take into account possibly new Ztc vertex introducing two new coupling constants, a_L^Z and a_R^Z, and redefining [8] $V_{i,j} \to V_{i,j} + c_i a_j^Z$, where c_i are constants. The relation between a_j^Z and v_Z of (1) can be found in [9].

DELPHI reports no evidence for such CI analysing 539 pb^{-1} of data collected at $\sqrt{s} = 189 - 208$ GeV . Various scenarios have been considered setting the CI couplings either 1 or 0. For each scenario limits at 95% CL on the energy scale Λ has been derived [9] ranging from 600 GeV up to 1.3 TeV.

3. HERA

At HERA an electron or positron beam of 27.5 GeV collides with a proton beam of 920 GeV (820 GeV untill 1997) giving an energy in the centre of mass $\sqrt{s} = 318$ GeV (300 GeV). In ep collision at HERA energies single top production is largely dominated by the t-channel exchange of a photon. In order to produce a heavy top quark the photon must couple with a quark in the proton at large x Bjorken. These two facts make HERA's data sensitive only to the anomalous FCNC magnetic coupling $k_{tu\gamma}$.

The search for top production at HERA has been partially motivated by the observation by H1[10], not confirmed by ZEUS[11], of an anomalous large number of isolated high-energy lepton events with missing transverse momentum. The number of observed events is reported in table 1, for two different cuts on the transverse momentum of the hadronic system together with SM expectation which is mainly W production.

A possible interpretation of the high P_T^X H1 events could be FCNC top production with the top decaying to bW followed by the leptonic decay of the W. Both experiments have performed a dedicated top search in both leptonic and hadronic W decay channels [11,12].

In the leptonic channel ($t \rightarrow bW \rightarrow bl\nu_l$) H1 observes 5 events, in a data set equivalent to $115.2\,\mathrm{pb}^{-1}$, with 1.8 ± 0.5 expected. ZEUS whereas sees no event, in a data set equivalent to $130\,\mathrm{pb}^{-1}$ with 0.96 ± 0.1 expected. The lepton-neutrino-hadron mass $M_{l\nu X}$ can be computed using, to reconstruct the momentum of the neutrino, either the conservation of longitudinal momentum in case the scattered electron is taged, or the contraint of the W mass. For the 5 H1 candidates there are in total 7 solutions. The resulting $M_{l\nu X}$ distributions are shown in figure 2. Several solutions are compatible with the top mass.

In the hadronic channel events are selected requiring three high-P_T jets with the 3-jet mass,

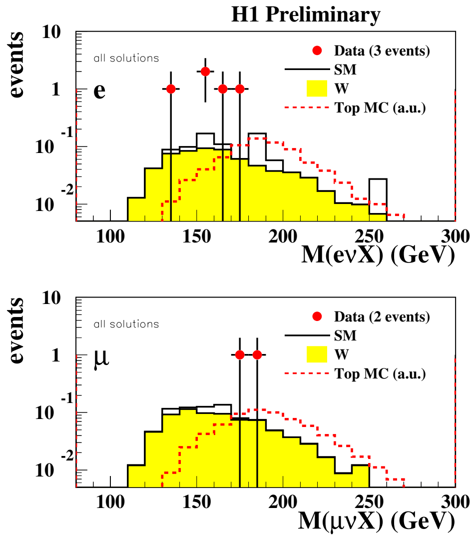

Figure 2. $M_{l\nu X}$ distributions of the H1 top candidates compared to expectations from SM W production and a hypothetical top signal.

M^{3J}, and one of the 2-jet mass compatible with the top and W mass respectively. Both experiments do not observe any deviation from SM predictions. Using a data set equivalent to $37\,\mathrm{pb}^{-1}$ collected at $\sqrt{s} = 300$ GeV H1 observes 10 events with a SM expectation of $8.3^{+4.2}_{-1.9}(exp.) \pm 4.2(theory)$. ZEUS observes 19 events in a data set equivalent to $127.7\,\mathrm{pb}^{-1}$ collected at $\sqrt{s} = 300 - 320$ GeV, expecting from SM 20.0. These results do not favour the interpretation of H1 high-P_T lepton events as top production. However the 95% CL upper limits on the top production cross-section derived by H1 from the hadronic channel only is $\sigma(ep \rightarrow etX,\ \sqrt{s} = 300\ \mathrm{GeV}) < 1.17$ GeV. For this value the expected number of single top events is 3.2 (9.7) for the data taken by H1 at $\sqrt{s} = 300$ GeV ($\sqrt{s} = 320$ GeV), while 1 (4) event(s) is (are) observed.

Combining leptonic and hadronic channels ZEUS and H1 set limits at 95% CL on the top production cross section $\sigma(ep \rightarrow etX, \sqrt{s} =$

Table 1
Observed and expected number of events with isolated leptons and missing transverse momentum. The two experiments use different cuts but with similar sensitivity to W events.

	Electrons Obs./exp. (W)	Muons Obs./exp. (W)
H1 preliminary 101.6 pb^{-1}		
$P_T^X > 25$ GeV	$4/1.3 \pm 0.3\,(1.1)$	$6/1.5 \pm 0.4(1.3)$
$P_T^X > 40$ GeV	$2/0.4 \pm 0.1\,(0.4)$	$4/0.6 \pm 0.1(0.33)$
ZEUS preliminary 130 pb^{-1}		
$P_T^X > 25$ GeV	$1/1.14 \pm 0.06\,(1.1)$	$1/1.29 \pm 0.16(0.95)$
$P_T^X > 40$ GeV	$0/0.46 \pm 0.03\,(0.46)$	$0/0.5 \pm 0.1(0.41)$

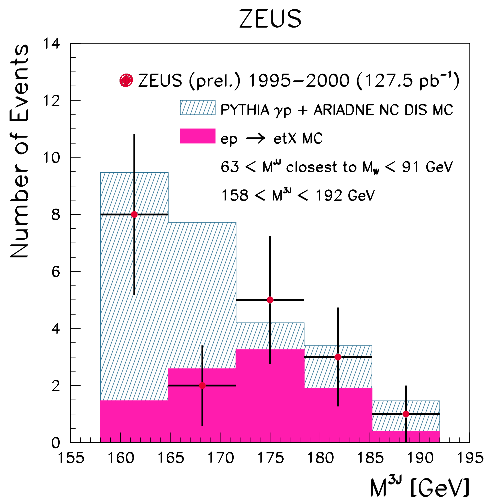

Figure 3. 3-jet mass distributions of the ZEUS top candidates in the hadronic channel, compared to SM expectations and a hypothetical top signal.

320 GeV) at the level 0.25 pb and 0.87 pb. Using the effective Lagrangian (1) with $\Lambda = m_t =$ 175 GeV these results are converted to limits on the anomalous magnetic coupling $k_{tu\gamma}$ of 0.19 (ZEUS) and 0.305 (H1).

The HERA collider is now starting a new run at higher luminosity. The goal is to accumulate 1 fb^{-1} in five year. The new data will hopefully clarify H1 high-P_T lepton anomaly and in case of no observation of FCNC in the top sector new a limit on $k_{tu\gamma}$ at the level of 0.07 will be set.

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