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Single-top production via flavour changing neutral currents

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Abstract. Recent results on single-top production via flavour changing neutral currents (FCNC) are summarised. Model independent limits can be set directly for the process at both LEP and HERA and indirectly from the decays of the top quark at the TeVatron. No evidence for FCNC are observed at LEP and the TeVatron. Some events compatible with single top production are observed by the H1 collaboration at HERA, but no such events appear at ZEUS. Limits on FCNC from the different experiments are presented, with the strongest coming from the HERA and LEP experiments.

PACS. 14.65.Ha Properties of Top Quarks

1 Single-top production at HERA

In the Standard Model (SM), flavour changing neutral current (FCNC) interactions are suppressed by the GIM mechanism [1]. Due to the large mass of the top quark, close to the electroweak symmetry breaking scale, deviations from the SM are expected to be observed first in the top sector.

At the HERA ep collider, with its maximum centre-of-mass energy of $\sqrt{s} = 318$ GeV, top quarks can only be singly produced. At tree level, the production proceeds through the charged current (CC) reaction $ep \to \nu t\bar{b}X$. Since the SM cross section for single-top production is less than 1 fb, any observed single-top event in the present data would be a clear sign of physics beyond the SM. The FCNC coupling, tuV or tcV, would induce the neutral current (NC) reaction $ep \to etX$ [2,3], in which the incoming lepton exchanges a γ or Z^0 with an up-type quark in the proton, yielding a top quark in the final state (see Fig. 1(a)). The Z^0 exchange is suppressed by the large propagator mass. Furthermore, large values of $x \gtrsim 0.3$, where x denotes the fraction of the proton momentum carried by the struck quark, are needed to produce a top quark. Since the u-quark density of the proton is much higher than the c-quark density, the production of single top quarks is most sensitive to a coupling of the type $tu\gamma$.

Searches for single-top quark production at HERA have been performed by both the H1[4] and ZEUS [5] collaborations using the full HERA I dataset.

1.1 Single-top signatures in ep scattering

The SM decay, $t \to bW$, with subsequent leptonic decay of the W boson, $W \to e\nu_e, \mu\nu_\mu$ (11% branching ratio per channel), leads to the presence of an isolated high-energy lepton, significant missing transverse momentum arising from the undetected neutrino and a large value of the hadronic transverse momentum, $p_T^{\rm had}$, stemming from the b-quark decay. Production of single W bosons with subsequent leptonic decay is the only SM process with a measurable cross section (about 1 pb, evaluated including QCD corrections $\mathcal{O}(\alpha^2\alpha_s)$ [6]), which leads, at HERA, to events with an isolated lepton and missing transverse momentum in the final state. However a steeply falling $p_T^{\rm had}$-spectrum is expected for events from single W production.

In the hadronic decay channel of the W boson, $W \to q\bar{q}'$ (68 % branching ratio), three jets are expected in the final state, with the dijet invariant-mass distribution for the correct pair of jets peaking at the mass of the W boson, M_W, and the three-jet invariant-mass distribution peaking at the mass of the top quark, $M_{\rm top}$. QCD multijet events are the main SM background in the hadronic channel.

Anomalous FCNC couplings could lead to the decays $t \to u\gamma$ and $t \to uZ^0$, resulting in multi-jet signatures with lepton pairs from the decay of the gauge boson.

1.2 Isolated high p_T leptons

The observation of anomalous events with an isolated high energy lepton and missing transverse momentum in e^+p collisions was reported by the H1 collaboration at the end of the 1994-1997 running period [7]. The most recent results from H1 for the 1994-2000 running period are summarised in Table 1 [8]. At high values of hadronic P_T there is a clear excess of events over the SM prediction which is dominated by single W production, this is suggestive of a heavy particle decay process. More specialised searches have been applied to look for high p_T leptons arising from the leptonic decay channel of single-top production, as discussed in Sect. 1.3.

Table 1. Number of observed events in diffenert P_T^X ranges in the H1 isolated high p_T lepton search, using an integrated luminosity of 117.3pb^{-1} in ep scattering, compared to the SM expectations. The percentage of single-W production included in the expectation is indicated in parentheses. The statistical uncertainties are also indicated

Leptonic channel	Electron	Muon
p_T^X range (GeV)	channel obs./expected (W)	channel obs./expected (W)
$p_T^X < 12$	$5/6.40 \pm 0.79(70\%)$	—
$12 < p_T^X < 25$	$1/1.96 \pm 0.27(74\%)$	$2/1.11 \pm 0.19(85\%)$
$25 < p_T^X < 40$	$1/0.95 \pm 0.14(86\%)$	$3/0.89 \pm 0.14(87\%)$
$p_T^X > 40$	$3/0.54 \pm 0.11(83\%)$	$3/0.55 \pm 0.12(93\%)$

Table 2. Number of observed events at different selection stages of the ZEUS single-top search, using 130pb^{-1} of ep scattering data, compared to the SM expectations. The percentage of single-W production included in the expectation is indicated in parentheses. The statistical and systematic uncertainties added in quadrature are also indicated

Leptonic channel	Electron	Muon
p_T^X range (GeV)	channel obs./expected (W)	channel obs./expected (W)
$p_T^X > 25$	$2/2.90^{+0.59}_{-0.32}$ (45%)	$5/2.75^{+0.21}_{-0.21}$ (50%)
$p_T^X > 40$	$0/0.94^{+0.11}_{-0.10}$ (61%)	$0/0.95^{+0.14}_{-0.10}$ (61%)

1.3 Leptonic W-decay channel

Searches in the leptonic channel at HERA require large missing total transverse momentum and the presence of a well isolated high p_T lepton and a high E_T jet. The results of the ZEUS single-top search in the leptonic channel are summarised in Table 2. No excess over the Standard Model is observed, in the highest missing P_T region. By contrast the similar final selection in the H1 single-top analysis leaves 3 electron and 2 muon events, where only a total of 1.77 events are expected from the Standard Model calculation.

1.4 Hadronic W-decay channel

Searches for single W production at HERA in the hadronic channel have to contend with a large QCD background. A limit on the cross section of $\sigma(ep \to WX) < 8.3$ pb has been set by ZEUS[9]. The same large background makes observation of single-top production in the hadronic channel extremely difficult. In their hadronic searches, both H1 and ZEUS require 3 jet events with one pair of jets having an invariant mass in the W-mass window, and the 3 jet invariant mass being in the top quark mass region. The mass window requirement serves to reduce the photoproduction background, whilst the DIS background is further reduced by the rejection of events with electron candidates. Neither H1 nor ZEUS found any evidence for single-top production in this channel.

1.5 Exclusion limits on FCNC couplings

The results from the searches in both the leptonic and hadronic W decay channels have been combined to constrain the production of single-top quarks through FCNC. The lack of observed excess over the SM in the leptonic channel by the ZEUS collaboration means that they set the strongest limits. The 95% confidence level (CL) limit for $\kappa_{tu\gamma}$, evaluated by ZEUS assuming $v_{tuZ} = 0$ and $M_{\mathrm{top}} = 175$ GeV, is $\kappa_{tu\gamma} < 0.174$. Fig. 2 shows the ZEUS limits, for LO signal calculation, compared to those set by TeVatron [10] and LEP [11] experiments. The ZEUS limits are shown for three different values of M_{top}, since the uncertainty on the top mass is the dominating systematic uncertainty. It is evident that HERA is competitive in searches for the FCNC magnetic coupling.

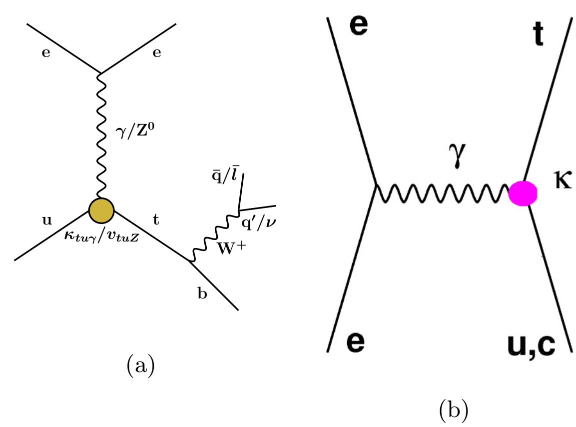

Fig. 1. Feynman diagrams for single-top prodcution via FCNC transitions at **a** HERA and **b** LEP

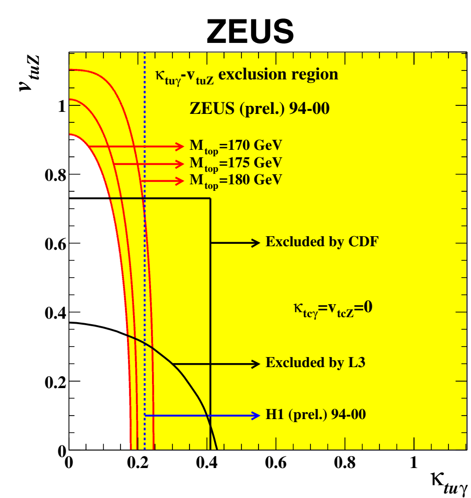

Fig. 2. Exclusion regions at 95% C.L. in the $\kappa_{tu\gamma}$-v_{tuZ}-plane from L3, CDF,H1 and ZEUS

2 Single-top production at LEP

As in the case of single-top production at HERA, the GIM mechanism suppresses SM single-top production at LEP. The SM cross section has been calculated to be less than 10^{-9} pb [12]. This means that at LEP, any events attributable to single-top production must proceed via new physics. LEP has much more sensitivity to the tcZ/γ vertex than HERA (where it is neglected). Therefore a pair of couplings, sensitive to both c and u quarks, κ_Z and κ_γ are used. These couplings are related to the coupling constants used at HERA by a factor of $\sqrt{2}$.

2.1 Single-top signatures in e^+e^- collisions

The event signatures which are searched for at LEP arise from the channel $e^+e^- \to tq \to Wbq$ producing multi-jet events. Firstly, at least one jet must exist in the event which is tagged as containing a b quark. In addition, leptonic channel events require an isolated high p_T lepton and missing total P_T. In the hadronic channel, two more jets are required, arising from the decay of the W.

The leptonic decay channel is almost background free, the hadronic channel produces around twice as many events, but has a much less favourable background situation.

2.2 LEP searches

A variety of sophisticated analysis techniques have been applied at LEP to exploit the clear kinematic signature of single-top events [11,13,14,15] Most recently the DELPHI collaboration have used a logarithmic likelihood method. The variables exploited for these techniques included the quality of the b tag. In the leptonic events, other variables used were the energy of the lepton, the missing momentum, the transverse mass of the νl system and the invariant mass of the whole system. In the hadronic channel, jet characteristics, event shapes and invariant masses of different combinations of jets were used.

In all searches made at LEP, the data can be adequately described with four-fermion and $q\bar{q}$ background Monte Carlo. No LEP collaboration observed any evidence for single-top production via FCNC.

2.3 Exclusion limits

Similar limits have been set by each LEP experiment on both the γ and Z^0 flavour changing couplings. In the case of the DELPHI experiment, these limits are: $\kappa_\gamma < 0.486$ and $\kappa_Z < 0.411$ at m_t=175 GeV. Fig. 3 shows the limits set by the DELPHI collaboration. It can be seen that the LEP results place the strongest limits on the Z^0 flavour changing vertex, κ_z, significantly improving on the limit set by CDF in searches for $t \to qZ$ [10].

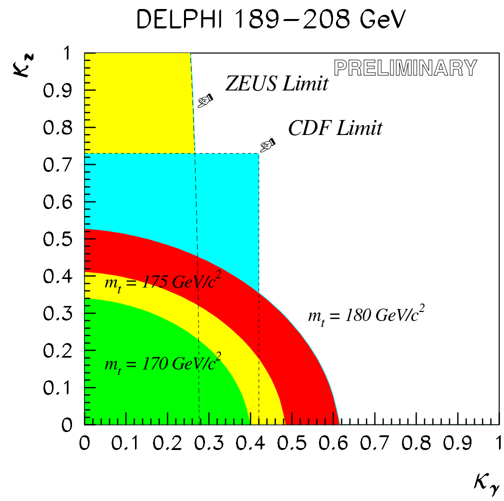

Fig. 3. Exclusion regions in the LEP convention at 95% C.L. in the κ_γ-κ_Z plane from DELPHI, CDF and ZEUS. The ZEUS limit has been has been converted to take into account a factor $\sqrt{2}$ between the LEP convention and that used for Fig. 2

3 Summary

No evidence for single-top production via FCNC has been observed at LEP. At HERA, the excess of high p_T leptons seen by H1 which could be accounted for by this process remains unconfirmed by ZEUS. A large part of the possible coupling space has been excluded, with LEP and HERA providing the strongest limits on the Z^0 and γ couplings respectively. TeVatron II and HERA II data have the opportuntity to observe this process or to improve the existing limits on FCNC couplings.

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