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Search for Single Top Production in e$^{\pm}$p collisions at HERA

H1 Collaboration

Abstract

A search for anomalous top quark production mediated by a flavour changing neutral current via a γ-u-t coupling is performed in $e^{\pm}p$ collisions at HERA. The search exploits data collected from 1994 to 2000 and is motivated by the previous observation of outstanding events with isolated leptons, missing transverse momentum and a jet with large transverse momentum. The top decay into a b-jet and a W-boson is considered in both the leptonic and hadronic decay modes of the W. In leptonic decay modes, five events are found to be compatible with the hypothesis of anomalous top quark production while 1.8 events are expected from Standard Model. No excess above the Standard Model expectation is found in the analysis of the hadronic decay channel. An upper limit on the anomalous γ-u-t coupling is established in the framework of recent NLO calculations. The sensitivity of HERA to flavour changing neutral currents is found to be competitive with that at other existing high energy colliders.

1 Introduction

The H1 collaboration has first reported [1] the observation of events with high-P_T isolated leptons and missing transverse momentum in the positron-proton data collected in 1994-1997. In more recent data collected from 1998 to 2000, new events with the same topology have been observed [2]. Some of the events were further characterized by a large transverse momentum of the hadronic system, which turned out to be an atypical kinematic property when compared to the Standard Model (SM) calculations which are dominated by direct production of W-bosons.

This may indicate presence of a further production mechanism involving beyond Standard Model. A possible origin of these events is production of top quarks which predominantly decay into a b-quark jet and a W-boson. The lepton and the missing transverse momentum would then be associated with a W-boson decaying leptonically. Within the Standard Model, top quark production is negligible in $e^{\pm}p$ collisions. However, in several extensions of the SM, the top quark is predicted to have significantly large flavour changing neutral current (FCNC) interactions, which could lead to a sizeable single top production cross-section at HERA.

In this paper we present a search for top quark production using the H1 detector at HERA. The analysis for the leptonic decay channel makes uses of all data collected from 1994 to 2000 and corresponding to an integrated luminosity of 115.2 pb^{-1}. In addition to the leptonic decay channel, hadronic decays of the top quark into 3 or more jets are exploited using a data sample corresponding to an integrated luminosity of 36.5 pb^{-1}. The large jet transverse momenta involved ensure that a potential signal can be found above the jet production expected from QCD processes.

2 Phenomenology

In the Standard Model neutral current interactions preserve the involved flavours in the leading order. Therefore flavour changing neutral current processes only arise via higher order radiative corrections and are highly suppressed. Their low SM rates make FCNC processes an ideal place to look for new physics at high energy colliders. Due to the large top quark mass close to the electroweak symmetry breaking scale, deviations from the SM might be observed first in the top sector. FCNC interactions involving the top quark have thus received considerable interest since the discovery of the top at the Fermilab Tevatron. Such interactions are present in many extensions of the SM like models with an extended Higgs sector [4], supersymmetry [5], dynamical breaking of the electroweak symmetry [6] or of an additional symmetry [7].

At HERA, FCNC interactions coupling a top quark to a light quark (u or c) and a gauge boson would lead to single top production as illustrated in Fig. 1. The crossed process $e^+e^- \rightarrow t\bar{q}(\bar{t}q)$ is actively searched for at the LEP collider since its centre-of-mass energy is above the top production threshold.

We consider here the most general effective Lagrangian proposed in [8] to describe FCNC top interactions involving electroweak bosons. It reads as :

$$\mathcal{L}_{eff} = \sum_{U=u,c} i\frac{ee_U}{\Lambda}\bar{t}\sigma_{\mu\nu}q^{\nu}\kappa_{\gamma,U}UA^{\mu} + \frac{g}{2\cos\theta_W}\bar{t}\left[\gamma_{\mu}(v_{Z,U} - a_{Z,U}\gamma^5) + i\frac{1}{\Lambda}\sigma_{\mu\nu}q^{\nu}K_{Z,U}\right]UZ^{\mu} \quad +\text{h.c.},$$

where $\sigma_{\mu\nu} = (i/2)\,[\gamma^\mu, \gamma^\nu]$, θ_W is the Weinberg angle, q the four-momentum of the exchanged boson, e and g denote the gauge couplings relative to $U(1)$ and $SU(2)$ symmetries respectively, e_U denotes the electric charge of up-type quarks, A^μ and Z^μ the fields of the photon and Z boson, and Λ denotes the scale up to which the effective theory is assumed to hold. By convention we set $\Lambda = m_t$ in the following. Only magnetic operators allow FCNC $tq\gamma$ couplings denoted by $\kappa_{\gamma,q}$, while $q - t$ transitions involving the Z boson may also occur via vector interactions due to the non-vanishing Z mass. The single top production in ep collision is however largely dominated by the t-channel exchange of a γ and therefore we concentrate on the $\kappa_{\gamma,q}$ couplings only[1]

The possibility of anomalous single top production at HERA was first investigated in [7] where a model was built in which $\kappa_{\gamma,q} \propto m_q^2$, and therefore only the $tc\gamma$ coupling was relevant. We do not rely here on any assumption concerning the underlying theory and thus allow both couplings $\kappa_{\gamma,c}$ and $\kappa_{\gamma,u}$ to be present and not necessarily related to each other. The sensivity of HERA is naturally much higher for the coupling $\kappa_{\gamma,u}$ than for $\kappa_{\gamma,c}$ due to the more favourable parton density. The most stringent existing bound on $\kappa_{\gamma,u}$ comes from upper limits on radiative top decays set by the CDF Collaboration [9] : $BR(t \to u\gamma) < 3.2\%$ at 95% confidence level (CL), leading to $\kappa_{\gamma,u} < 0.42$ [8]. When $\kappa_{\gamma,u}$ is saturated to its upper bound, the single top cross-section at HERA has been calculated to be ~ 1 pb, sufficiently large to allow several single top events to be produced with the current integrated luminosity.

Cross section calculations have recently been improved for next-to-leading order terms [10]. The correction increases the leading order value by roughly 20%, and is taken into account in the results derived in section 7.

3 Monte-Carlo Event Generators

A complete Monte Carlo simulation of the H1 detector response is performed for each possible SM background source and for the single top signal.

For the neutral current (NC) or charged current (CC) deep inelastic scattering (DIS) background estimates we use the DJANGO [11] event generator, which includes first order QED radiative corrections. Simulation of real bremsstrahlung photons, based on HERACLES [12], is also included. QCD radiation at all orders is treated following the approach of the Color Dipole Model [13] and are implemented using ARIADNE [14]. The hadronic final state is generated using the string fragmentation model [15]. The parton densities in the proton used to estimate DIS expectations are taken from the MRST [16] parametrization. The RAPGAP [17] generator has also been used for the study of multijet production in NC DIS.

For the direct and resolved photoproduction of light and heavy flavours, we use the PYTHIA MC event generator [18] which relies on first order QCD matrix element and uses leading-log parton showers and string fragmentation [15]. The GRV LO (GRV-G LO) parton densities [19]

[1] A different convention for the κ_γ coupling is used here with respect to [3](κ_γ^0). The difference is that the quark electric charge introduced here in the normalization of the anomalous coupling $\kappa_\gamma = \kappa_\gamma^0/e_u = 3/2 * \kappa_\gamma^0$. With this notation the limit on κ_γ^0 obtained in [3] $\kappa_\gamma^0 < 0.25$ reads $\kappa_\gamma < 0.375$.

in the proton (photon) are used. The photoproduction expectation has also been calculated using JetVip [20] program.

The production of electroweak vector bosons Z^0 and $W^\pm$ was modelled using the EPVEC [21] event generator. Contributions from two-photon processes where one γ originates from the proton were calculated using the LPAIR [22] event generator.

The simulation of the single top signal relies on a specific event generator ANOTOP using the matrix elements of the complete $e + q \rightarrow e + t \rightarrow e + b + W \rightarrow e + b + f + \bar{f}'$ process as obtained from the CompHEP [23] program. This allows a proper description of angular distributions. The BASES/SPRING [24] package is used to perform the numerical integration of the amplitudes and to generate events according to the differential cross-section. The parton showers approach [15] relying on the DGLAP [25] evolution equations is used to simulate QCD corrections in the initial and final states. The parton densities used [16] are evaluated at the scale of the top mass, in analogy with leptoproduction of heavy quarks.

4 Experimental Conditions

This analysis is based on $e^\pm p$ collisions recorded by the H1 experiment in the 1994-2000 period. It is restricted to periods where the central drift chambers, the liquid argon calorimeter and the luminosity system are active and fully operational.

A detailed description of the H1 detector can be found in [26]. Only components essential for this analysis are shortly described here. A tracking system of central and forward drift chambers is used to measure the charged particle trajectories and to determine the interaction vertex. Particle transverse momenta are determined from the curvature of the trajectories in a magnetic field of 1.15 Tesla.

Hadronic and electromagnetic final state particles are absorbed in a highly segmented calorimeter [27], which is 5 to 8 interaction lengths deep depending on the polar angle of the particle. The calorimeter is surrounded by a superconducting coil and an iron yoke instrumented with streamer tubes. Leakage of hadronic showers outside the calorimeter is measured from an analogue charge sampling of the streamer tubes (Tail Catcher). Tracks of penetrating charged particles, such as muons, escaping the calorimeter are reconstructed from their hit pattern in the streamer tubes with an efficiency higher than 90%.

The trigger condition for high transverse energy interactions is based on calorimeter signals. The trigger efficiency is higher than 95% for events with a scattered electron with an energy above 10 GeV, and higher than 85% for events with a calorimetric missing transverse momentum greater than 25 GeV. For multi-jet events the trigger efficiency is 100%.

5 Search for Single Top Production in the Leptonic Channel

The search of top quark decays in the leptonic channel is based on the selection of events with isolated leptons and missing transverse energy performed in [2]. The basic criteria are the presence of a lepton at high transverse momentum $P_T^\ell > 10$ GeV with missing P_T in the event above 12 GeV. This selection (W search criteria) is further optimized to separate top production from Standard Model W production:

- **Cut on the transverse momentum of the hadronic system**
  In the top decays, the hadronic system is expected to have a high transverse momentum. The events are accepted if the transverse momentum of the hadronic system P_T^X is higher than 25 GeV. The expected P_T distributions of the highest P_T jet in two angular domains are presented in the figure 2. The highest P_T hadronic jet is required to have $P_T^{jet} > 25$ GeV. This threshold is set to 35 GeV in the case where the highest P_T jet has a polar angle with respect to the proton direction of $\theta_{jet} < 35°$.

- **Transverse mass of lepton-neutrino system**
  This quantity is defined as the invariant mass of the two massless vectors obtained by projecting the lepton and neutrino momenta in the transverse plane, where the transverse neutrino momentum is calculated from the missing transverse momentum P_T^{miss} in the event:

  $$M_T^{\ell\nu} = \sqrt{\left(|\vec{P}_T^\ell| + |\vec{P}_T^{miss}|\right)^2 - \left(\vec{P}_T^\ell + \vec{P}_T^{miss}\right)^2}. \quad (1)$$

  For W leptonic decays, the transverse mass of the lepton-neutrino system is centered around the W mass and has a tail towards low masses. In the standard model W production, the production of the charged lepton and neutrino can also proceed through photon-W scattering, while only real W decays produce leptonic final states in top induced events. In order to reduce the contribution from off-shell processes, a cut is applied on the transverse mass $M_T^{\ell\nu} > 10$ GeV.

- **Charge of the observed lepton**
  The production of top quarks in $\gamma - u$ fusion yields t-quarks with charge $+2/3$ (the $\bar{\mathrm{t}}$ production via fusion with sea quarks $\gamma - \bar{u}$ is supressed by a factor of 80). The subsequent decay $t \to bW^+(\to \ell^+\bar{\nu})$ produces only positively charged isolated leptons. In order to reduce contributions other than top to the final sample, leptons for which the charge measurement yields the wrong sign with a precision better than 2σ are rejected.

  The reliability of the charge measurement at high P_T has been tested using a sample of neutral current events collected in e^+p collisons. The scattered electrons are required to have transverse momentum measured from calorimeter deposit above 20 GeV and corresponding track transverse momentum above 10 GeV. The track corresponding to the scattered electron has to be isolated and must have a momentum measurement better than two standard deviations. The wrong sign assignment rate is below 1% in this sample. In a subsample of forward electrons with the polar angle $\theta < 50°$, where most of the searched signal is expected, the wrong charge assignment has been measured in the data to be less than 2%.

The overall results are presented in the tables 1 and 2 for an analysed data sample corresponding to 101.6 pb^{-1} in e^+p collisons and 13.6 pb^{-1} in e^-p collisions. In e^+p data 4 events containing electrons and 6 events containing muons have been observed at $P_T^X > 25$ GeV [2]. After the full top selection described above, 3 electron events and 2 muon events remain as

	W search cuts and $P_T^X > 25$ GeV		Top selection	
	Electron Channel	Muon Channel	Electron Channel	Muon Channel
Data	4	6	3	2
Total SM	1.29 ± 0.33	1.54 ± 0.41	0.75 ± 0.18	0.77 ± 0.21
W only	1.05 ± 0.32	1.29 ± 0.39	0.51 ± 0.16	0.68 ± 0.19
Top efficiency	43%	51%	37%	45%

Table 1: Observed and predicted number of events with isolated leptons and missing transverse momentum for e^+p data in 101.6 pb^{-1}

	W search cuts and $P_T^X > 25$ GeV		Top selection	
	Electron Channel	Muon Channel	Electron Channel	Muon Channel
Data	0	0	0	0
Total SM	0.26 ± 0.06	0.20 ± 0.06	0.13 ± 0.04	0.12 ± 0.03
W only	0.16 ± 0.05	0.18 ± 0.07	0.07 ± 0.02	0.10 ± 0.03
Top efficiency	43%	51%	37%	45%

Table 2: Observed and predicted number of events with isolated leptons and missing transverse momentum for e^-p data in 13.6 pb^{-1}

top candidates for an expectation of 0.75 ± 0.18 (e^+p) plus 0.13 ± 0.04 (e^-p) for the electron channel and 0.77 ± 0.21 (e^+p) plus 0.12 ± 0.03 (e^-p) for the muon channel.

In order to calculate the invariant masses of the lepton-neutrino and lepton-neutrino-hadrons systems, the event kinematics has to be reconstructed. The following variables are used to quantify the event kinematics:

- $\vec{P}_T^{\ell}$: Transverse momentum vector of the isolated lepton. The calculation of the transverse momentum is performed using calorimetric information for electrons and central tracker information for muons.
- E^{ℓ}: Energy of the isolated lepton.
- $\vec{P}_T^X$: Transverse momentum vector of the hadronic system. It is calculated as the vector sum of all energy deposits in the liquid argon calorimeter and the tail catcher calorimeter not including energy deposited by any additional leptons.
- E^X: Energy of the hadronic system.
- $\vec{P}_T^{miss}$: Total missing transverse momentum vector of the event. It is defined as the vector sum of transverse momenta of all final state particles: $\vec{P}_T^{miss} = -(\vec{P}_T^{lepton(s)} + \vec{P}_T^X)$. The missing transverse momentum is attributed to the hypothetical neutrino.
- δ^{vis}: Total visible event balance in longitudinal momentum, defined as the scalar sum of $(E - P_z)$ over all final state particles: $\delta^{vis} = (E - P_z)^{lepton(s)} + (E - P_z)^X$

- Transverse mass of the lepton-neutrino system defined in equation 1.

In order to compute the complete event kinematics the neutrino four-vector must be reconstructed. The transverse momentum of the neutrino corresponds to the total missing transverse momentum $\vec{P}_T^{miss}$ of the event. Regarding the longitudinal momentum of the neutrino two cases have to be treated separately:

- *Tagged events:* In this case the scattered electron is detected in one of the calorimeters. In the muon channel this means that the event contains an identified electron and in the electron channel the event contains an additional electron of lower transverse momentum. For tagged events, the invariant mass of the lepton-neutrino-hadron system is computed using the neutrino kinematics deduced from longitudinal energy conservation. We obtain $(E - P_z)^\nu = 55$ GeV $-\delta^{vis}$ using the event balance in longitudinal momentum as mentioned above. For two events out of the ten with $P_T^X > 25$ GeV which are quoted in table 1 this method can be applied.

- *Untagged events* The scattered electron is not detected and therefore its longitudinal momentum unknown. A constraint on the invariant mass of the lepton and neutrino from the W decay has to be applied:

$$M_{\ell\nu} = \sqrt{P_\ell^2 + P_\nu^2 + 2P_e P_\nu} \approx \sqrt{2P_e P_\nu} = M_W = 80.2 \text{ GeV} \quad (2)$$

  with P_l, P_ν denoting the four-vectors of the lepton and neutrino respectively. This constraint on the W mass yields two possible solutions for $(E - p_z)^\nu$, one corresponding to a backward neutrino (solution 1), the other to a forward neutrino (solution 2) relative to the lepton direction. Using the two possible solutions for the neutrino, the invariant mass of the lepton-neutrino-hadrons system $M(\ell\nu X)$ can be calculated. All solutions that do not meet one of the following requirements are rejected as being unphysical:

  - $M(\ell\nu X) < \sqrt{s}$ where $\sqrt{s}$ is the electron-proton cms energy (300 GeV or 320 GeV depending on data taking period).
  - 0 GeV $< (E - P_z)^\nu < 55$ GeV
  - $(E - P_z)^\nu + \delta^{vis} < 75$ GeV
  - $E^\nu + E^X + E^{lepton(s)} < 1000$ GeV

  The latter two requirements ensuring energy and $E - p_z$ conservation were optimized on a sample of generated top events in order to leave some scope for fluctuations in the energy measurement.
  In case no such solution exists, the measurement errors on the energy of the hadronic final state E^X (electron channel) or the transverse momentum of the muon P_T^μ (muon channel) are taken into account being the dominant errors in the particular channel. New masses are computed using values of E^X or P_T^μ varied by $\pm 1\sigma$. If a solution is still not found then a $\pm 2\sigma$ variation is performed. The solution yielding the lowest mass is chosen as lower 1σ or 2σ limit.

This mass reconstruction procedure has 80% reconstruction efficiency in the electron channel and 65% in the muon channel for Monte Carlo top events. In figure 3 distributions of the reconstructed top mass are shown for ANOTOP Monte Carlo events in both electron and muon channel. The widths of the mass distributions are determined to $\sigma(M_{top}) = 20$ GeV for electrons and $\sigma(M_{top}) = 22$ GeV for muons.
The mass solutions thus obtained for the isolated lepton events with $P_T^X > 25$ GeV can be found in table 3. Two events (one electron and one muon) contain the scattered electron and therefore the "tagged" method can be applied. For the two tagged events, masses reconstructed with the "tagged" and one of the solutions of the "untagged" method are compatible. In the final top selection as defined above, the first three of the four observed electron events and the two last muon events in table 3 are selected as top candidates.

	PT(X)	Untagged Solution 1		Untagged Solution 2		Tagged Solution
		Mass	$E-P_z$	Mass	$E-P_z$	Mass
e^+ top cand.	41	159 ± 7	61	136 ± 6	21	–
e^+ top cand.	43	–	–	166 ± 8	54	165 ± 6
e^+ top cand.	39	178 ± 5	39	156 ± 7	21	–
e^+	27	234 ± 15	65	199 ± 14	38	–
μ^+	42	–	–	146 ± 7	19	–
μ^-	27	152 ± 12	53	129 ± 6	34	156 ± 10
$\mu^-(1\sigma)$	59	180	67	188	37	–
$\mu\ (2\sigma)$	30	157	53	139	22	–
μ^+ top cand.	67	–	–	181 ± 10	19	–
μ^+ top cand.	50	–	–	174 ± 12	39	–

Table 3: $M_{\ell\nu X}$ calculation for the ten events with $P_T^X > 25$ GeV. "Untagged" solutions (mass and total $E - P_z$) using a W constraint are presented for all the events. In two events the scattered electron is detected and the "tagged" mass solution using an $E - P_z$ constraint can be obtained. The events selected as top candidates are indicated.

The total lepton-neutrino-hadrons mass distributions of the final top candidates are compared to the Standard Model prediction in figure 4.

6 Search for Single Top Production in the Hadronic Channel

The top hadronic channel has been searched in a smaller data sample taken in the period 1994-1997 in e^+p mode at $\sqrt{s} = 300$ GeV, corresponding to an integrated luminosity of 36.5 pb^{-1}. The decay cascade $t \to bW(\to q\bar{q})$ yields events with at least three jets with high transverse momentum P_T. The main Standard Model QCD background is the electro- or photoproduction of high P_T jets.

The search for those events is performed using a K_T algorithm [28] based on calorimetric energy deposits. Events with at least three jets fulfilling $P_T^{Jet1} > 25$ GeV, $P_T^{Jet2} > 15$ GeV and $P_T^{Jet3} > 10$ GeV are selected. In order to reduce the neutral current (NC DIS) contribution, events with an identified electron are removed from the sample. NC DIS events where the electron is being misidentified as a hadronic jet are supressed by requiring either the electromagnetic energy fraction of the reconstructed jets to be less than 90% or the jet size defined in the $\eta - \phi$ plane to be larger than 0.1. In figure 5 the number of selected events is shown as a function of the transverse momentum of the first jet P_T^{Jet1} and the invariant mass M_{ij} of the three dijet systems together with the prediction of the Monte Carlo generator PYTHIA [18]. Using an overall normalization factor of 1.2 determined to fit the measured cross sections, which could account for corrections to PYTHIA (leading order with parton showers) calculation, the data are well described by the MC prediction. The remaining NC background estimated with the Monte Carlo model RAPGAP [17] is less than 7% on average.

Top induced events are expected to have high total transverse energy and 2- and 3-jet invariant masses close to the W and top mass, respectively. To select top candidates in the data sample defined above the invariant dijet mass of at least one of the three dijet systems has to fulfill $70 < M_{ij} < 90$ GeV, the total invariant mass has to be reconstructed in a window around the top mass $150 < M_{tot} < 198$ GeV, and the total transverse energy $E_{T,tot}$ has to be larger than 120 GeV. $E_{T,tot}$ and M_{tot} are calculated from all jets found in a given event. Their distribution is also shown in figure 5 and found to be in good agreement with the PYTHIA prediction. The top selection efficiency was estimated with the Monte Carlo model ANOTOP to be 31%. With these requirements 10 event candidates are selected in good agreement with $8.3^{+4.2}_{-1.9}(exp.) \pm 4.2(theory)$ events expected from the standard processes dominated by the photoproduction as seen in table 4.

The main experimental systematic error in this analysis of $\approx 40\%$ is due to the uncertainty in the absolute hadronic energy calibration of the calorimeter. Systematic effects due to the uncertainty in the luminosity measurement and trigger inefficiencies are negligible. Figure 6 shows the invariant mass M_{tot} of the top candidates together with the Standard model prediction.

	Events
Data	10
Standard Model	$8.3^{+4.2}_{-1.9}(exp.) \pm 4.2(theory)$
Photoproduction	$7.8^{+4.1}_{-1.8}$
Neutral Current	0.5 ± 0.5
Top efficiency	31%

Table 4: Three jet selection of 1994-1997 data (L=36.5 pb^{-1}).

The Standard Model expectation has also been determined using the program JetVip [20]. JetVip includes hard scattering matrix elements up to $O(\alpha_s^3)$ und thus allows the calculation of three parton final states in leading order QCD. The calculated number of $4.7^{+2.2}_{-1.4}$ events is in agreement with the PYTHIA prediction. The quoted error results from a variation of the renormalization scale μ_r^2, chosen to be the highest jet transverse momentum of a given event, by factors of 1/4 and 4. Based on this estimation, the theoretical error considered is 50%.

7 Results

No deviation from the SM prediction has been observed in the three high P_T jets channel as seen in section 6. Assuming Poisson distributions for the SM background and for the top signal, an upper limit at 95% confidence level (CL) on the number of events coming from singly produced tops decaying hadronically is obtained using a standard Bayesian prescription. This limit number is then converted into an upper limit on the top production cross-section at $\sqrt{s} = 300$ GeV by folding in the corresponding efficiency and branching ratio. The branching $t \to bW$ is assumed to be 100%, which is a safe approximation as seen from the CDF upper bound on radiative top decays into $q\gamma$. This results in an upper bound $\sigma_{300} = \sigma(ep \to etX, \sqrt{s} = 300$ GeV) < 1.17 pb. In turn, this leads to upper limits on the number of top induced events one could observe in the leptonic channel in the e^+p datasets. At 95% CL, we obtain that less than 3.2 (9.7) events coming from single top production should be observed with our selection criteria in the leptonic channels ($e + \mu$) in the e^+p data taken at $\sqrt{s} = 300$ GeV ($\sqrt{s} = 320$ GeV), while 1 (4) candidate(s) is (are) observed. The upper limit derived from the hadronic channel therefore does not rule out an interpretation of the observed events in the leptonic channel as anomalous top production. The number of observed and expected events in all the different channels analysed for the e^+p and e^-p data can be combined to set an upper bound on $\sigma(ep \to etX)$ at a given centre of mass energy, which is then translated into constraints on the anomalous coupling κ_γ. Each channel contributes in the limits derivation via its branching ratio, the numbers of observed and expected events satisfying the selection cuts, and the corresponding selection efficiencies. The three considered datasets are treated as independent channels, weighted by their relative luminosities and the ratios of single top cross-section for the corresponding running conditions to $\sigma_{320} = \sigma(ep \to etX)$ at $\sqrt{s} = 320$ GeV. The resulting upper limit N_{lim} on the number of signal events simply translates into an upper bound on the cross-section σ_{320} via $N_{\mathrm{lim}} = \mathcal{L}_{tot} \times \sigma_{320}$. Both systematic and statistical errors have been folded in channel by channel as described in [29].

The resulting upper bound on the single top cross-section at $\sqrt{s} = 320$ GeV is :

$$\sigma(ep \to e + t + X, \sqrt{s} = 320 \text{ GeV}) < 0.87 \text{ pb} \qquad \text{at } 95\% \text{ CL} \quad .$$

This results into an upper limit on the anomalous $tu\gamma$ magnetic coupling :

$$\kappa_{\gamma,u} < 0.305 \quad ,$$

which improves the CDF upper bound coming from radiative top decays.

Single top searches at LEP2 have also been interpreted in terms of bounds on the anomalous couplings. Since e^+e^- collisions also provide sensitivity to anomalous couplings tqZ, the couplings κ_γ and v_Z have been considered simultaneously. The preliminary results obtained by LEP [30], using data with $\sqrt{s}$ up to 209 GeV, are shown in Fig. 7 which represents the current status of the constraints on κ_γ and v_Z. The sensitivity of the HERA and TeVatron colliders on such FCNC processes will significantly increase [31] with the large luminosities expected in the near future.

8 Summary

We observe an increasing number of events containing an isolated lepton at large transverse momentum, missing transverse momentum and a jet at large transverse momentum. The signature of the lepton and missing transverse momentum are likely to result from W decay. The number of events exceeding the Standard Model expectations together with the large transverse momenta found in these events motivated the search for top quark production performed in this contribution.

Five isolated lepton events have been selected by this dedicated search in data samples corresponding to 101.6 pb^{-1} e^+p and 13.6 pb^{-1} e^-p . The observed number of events is to be compared with 1.8 events expected from Standard Model calculations.

The analysis of n-jet production ($n \geq 3$) shows no excess above the Standard Model expectation within the large uncertainty resulting from the treatment of higher order corrections and the dependence on the renormalization scale. However the limit on top production derived from the hadronic channel alone does not rule out the possible single top interpretation for the candidates observed in the leptonic channels.

Assuming that the observed data contain only Standard Model processes and possibly an anomalous top production mechanism, the lepton and n-jet events are used to derive an upper limit on the $t \leftrightarrow u$ transition mediated by a coupling to the photon. This bound is slightly better than the previously most stringent limit obtained from constraints on radiative top decays set at the Tevatron collider.

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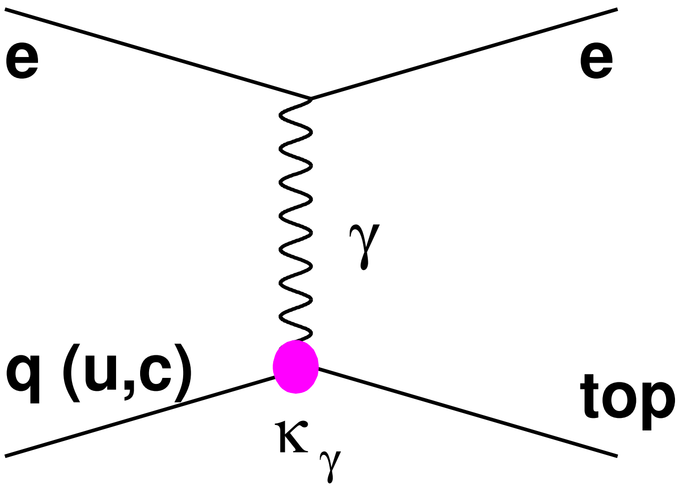

Figure 1: Example diagram for anomalous single top production via flavour changing neutral current interaction at HERA.

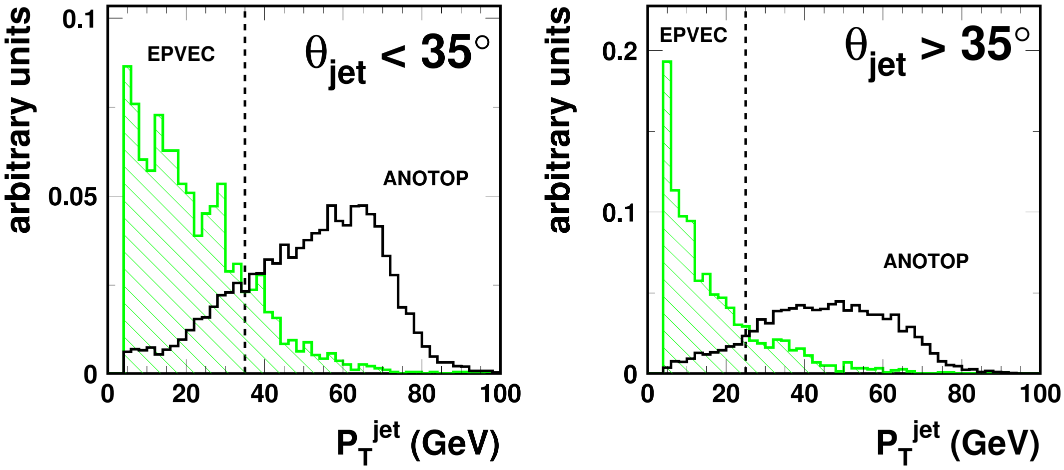

Figure 2: Expected distribution for hadronic jet transverse momenta for W- production (shaded) and top-production (open) for two jet angular regions. The cut value applied in the analysis is indicated.

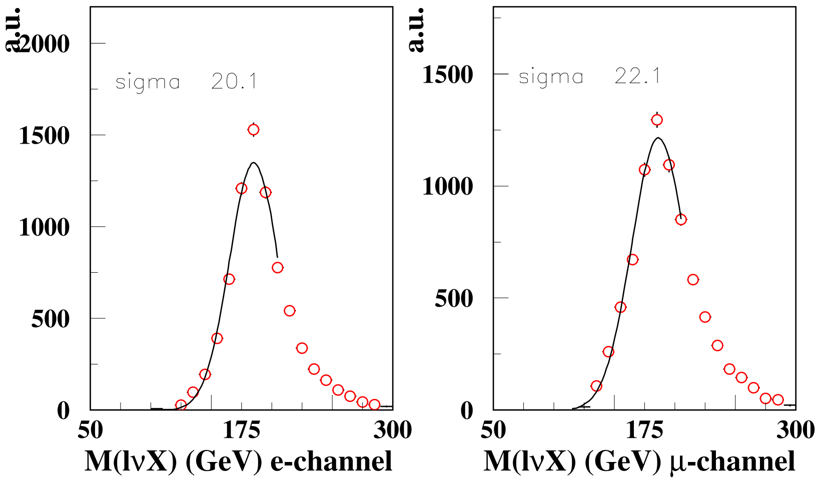

Figure 3: Reconstructed top mass as invariant mass of lepton, neutrino and hadrons in the electron channel (left) and muon channel (right).

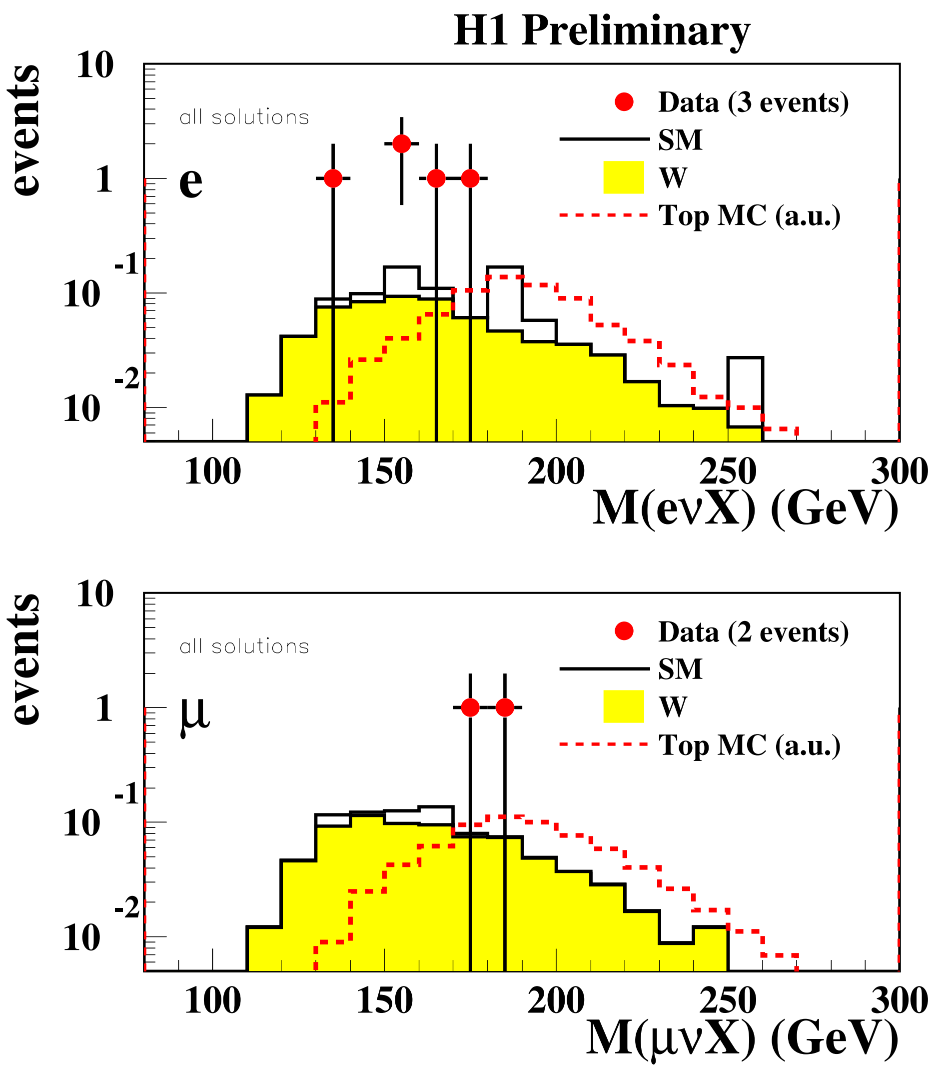

Figure 4: Distribution of the lepton-neutrino-hadrons mass for the top candidates (symbols) and the Standard Model expectation (white histogram). Shaded histogram represents the SM W contribution. The dashed histogram represents the ANOTOP prediction for a rate corresponding to one event. All the solutions obtained by the procedure described in the text are displayed. In the data there are 3 electron candidates with 5 possible solutions and 2 muon candidates with 2 solutions. The precision of individual mass measurement is better than 9 GeV for electron candidates and better that 13 GeV for the muon candidates.

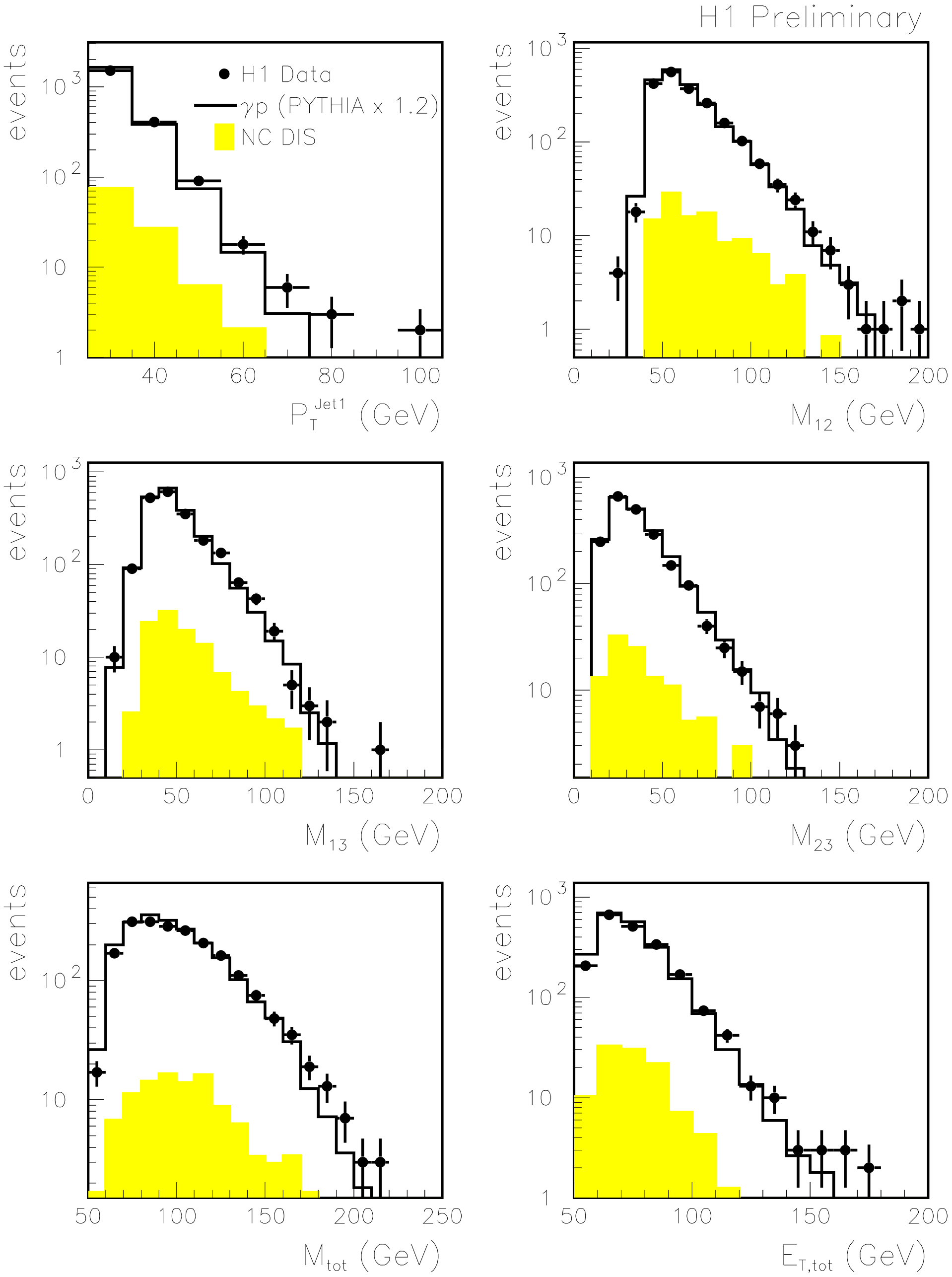

Figure 5: Control plots for three jet sample in 1994-1997 data (36.5 pb^{-1}).

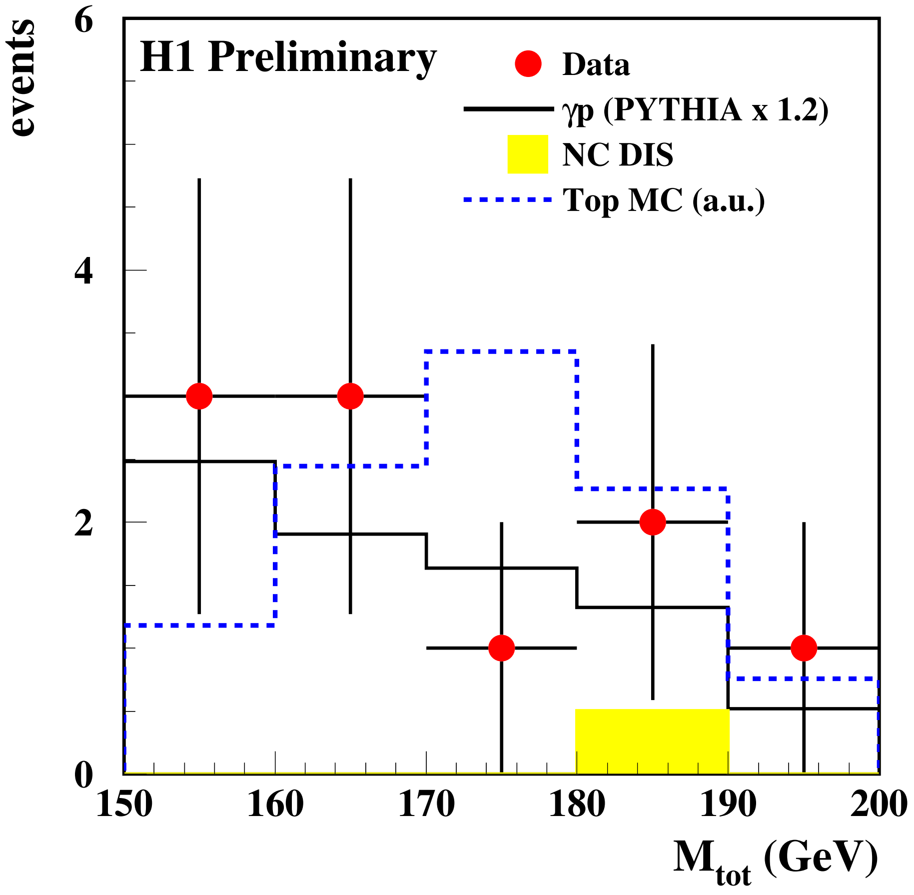

Figure 6: Reconstructed mass for candidate three jet events in 1994-1997 data (36.5 pb^{-1}) and Standard Model expectation. The top Monte Carlo is also displayed with an arbitrary normalization.

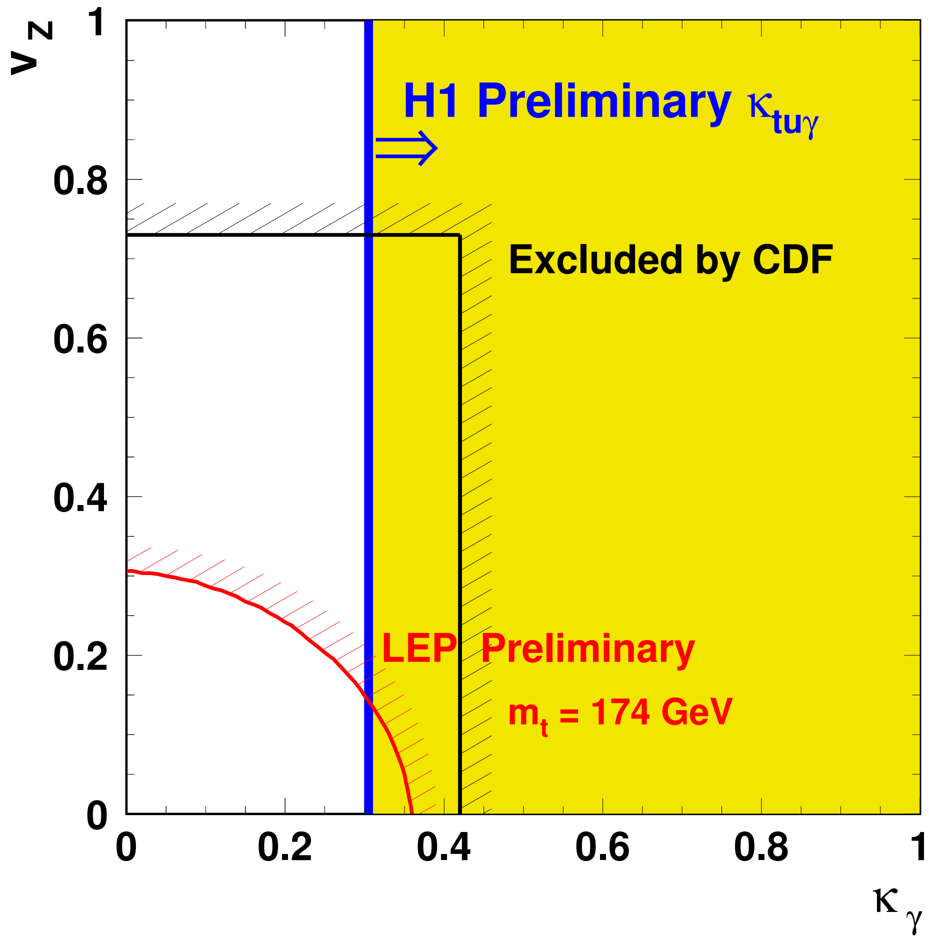

Figure 7: Limits on the anomalous $tq\gamma$ (magnetic) coupling κ_γ and on the anomalous tqZ (vector) coupling v_Z obtained at the TeVatron (CDF), LEP and HERA (H1) colliders. The H1 limit applies to the coupling $\kappa_{\gamma,u}$ only.