Search for Single Top Production at HERA

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Summary. —
A search for single top production in *ep* collisions using the complete high energy data from HERA is presented. This search is based on the analysis of events containing isolated leptons (electrons or muons) and missing transverse momentum P_T^{miss}. In the absence of a signal, an upper limit on the top production cross section $\sigma_{ep \to etX} < 0.16$ pb is established at the 95% confidence level, corresponding to an upper bound on the anomalous magnetic coupling $\kappa_{tu\gamma} < 0.14$. The search is complemented by a search for events containing an isolated tau lepton and P_T^{miss} and the measurement of W boson polarisation fractions.

PACS 13.85.t, 13.90.i, 14.65.Ha – .

1. – Introduction

The HERA *ep* collider, located at DESY in Hamburg, Germany, was in operation in the years 1992–2007. Protons with an energy up to 920 GeV were brought into collision with electrons ([1]) of energy 27.6 GeV at two experiments, H1 and ZEUS, each of which collected about 0.5 fb^{-1} of data. Together with measuring the structure of the proton, the deep inelastic scattering (DIS) at HERA provided an ideal environment to study rare processes and search for new particles and physics beyond the Standard Model (BSM). In particular, the centre-of-mass energy up to $\sqrt{s} = 320$ GeV makes the production of single top quarks possible. However a cross section of $\mathcal{O}(1\text{ fb})$ in the Standard Model (SM) is too small to measure this process [1]. Any observation of single top quark events in the HERA data would therefore be a clear sign of new physics beyond the SM.

In several extensions of the SM the top quark is predicted to undergo Flavour Changing Neutral Current (FCNC) interactions, which could lead to a sizeable anomalous single top production cross section at HERA [2]. Any such process is described by an effective Lagrangian where the interaction of a top quark with u-type quarks via a photon is described by a magnetic coupling $\kappa_{tU\gamma}$, as illustrated in fig. 1(a). The ANOTOP MC

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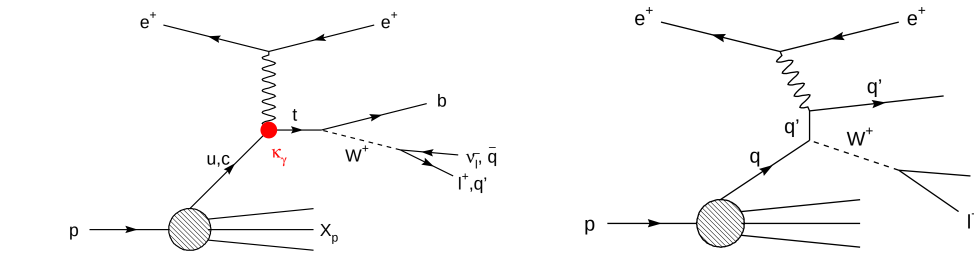
([1]) unless otherwise stated the term electrons also refers to positrons in the following.



(a) (b)

Fig. 1. – (a) Diagram of anomalous single top proudction in an ep collision via an effective FCNC coupling $\kappa_{tu\gamma}$. (b) Diagram of single W production in the SM, the process $ep \to eW^{\pm}(\hookrightarrow l\nu)X$, which is the main SM background to single top production.

generator is used to model such events [3]. The main SM contribution to the signal topology is the production of real W bosons via photoproduction with subsequent leptonic decay $ep \to eW^{\pm}(\hookrightarrow l\nu)X$, as illustrated in fig. 1(b). This process is modelled using the event generator EPVEC [4]. For both processes the signature is an event containing an isolated lepton and missing energy from the neutrino. From single top decays $t \to bW$ a prominent hadronic system due to the b-jet is expected, while for SM W production the hadronic system X has typically low transverse momentum P_T^X.

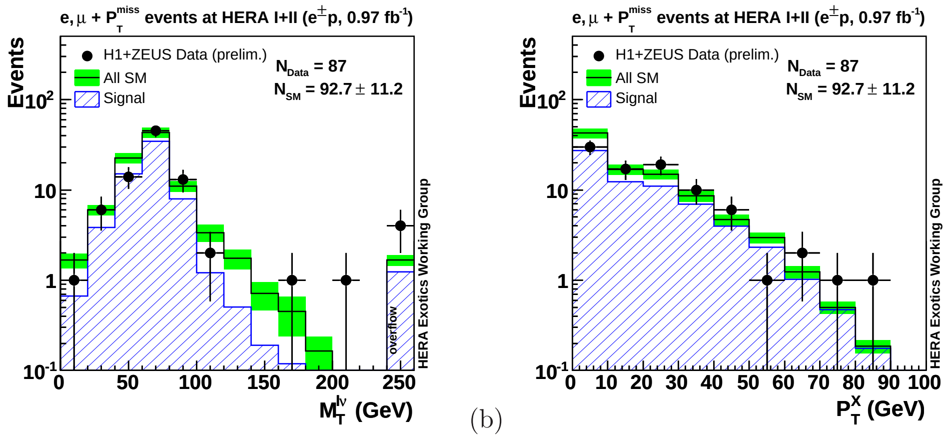
2. – Events with Isolated Leptons and $P_T^{\rm miss}$

The search for single top quarks at HERA is based on events containing a high $P_T > 10$ GeV isolated electron or muon and missing $P_T > 12$ GeV. Such events have been observed at HERA [5, 6, 7, 8]. An excess of HERA I data events (1994–2000) compared to the SM prediction at large hadronic transverse momentum P_T^X was reported by the H1 Collaboration [6]. The significance of this excess did not increase with the inclusion of the HERA II data [9] and was not confirmed by the ZEUS Collaboration [10]. Both experiments have combined their data and good overall agreement with the SM is observed [11]. Figure 2 shows the distribution of the transverse mass $M_T^{l\nu}$ and the P_T^X of these events for the combined H1+ZEUS sample. The SM prediction is dominated by W production.

Background to SM W and anomalous single top production enters the electron channel due to mismeasured neutral current events and the muon channel due to muon pair events in which one muon escapes detection, both cases resulting in apparent missing transverse momentum. Charged current background, which contains intrinsic missing transverse momentum, enters in both lepton channels, where a hadronic final state particle is misidentified as an isolated electron or muon.

3. – Search for Anomalous Single Top Quark Production

The H1 search for single top production is based on the H1 sample of events with isolated leptons selected in the HERA I+II data, corresponding to a luminosity of 482 pb^{-1} [9]. It presents an update of a previous top search in HERA I data [12]. The first step in the analysis forms a top preselection in this event sample, by demanding good top quark reconstruction and lepton charge compatible with single top production [13].



(a) (b)

Fig. 2. – Distribution of events with isolated leptons in the combined H1+ZEUS $e^{\pm}p$ HERA I+II data. Shown is the transverse mass $M_T^{l\nu}$ (a) and hadronic transverse momentum P_T^X (b). The data (points) are compared to the SM expectation (open histogram). The signal (W production) component of the SM expectation is given by the striped histogram. $\mathrm{N_{Data}}$ is the total number of data events observed and $\mathrm{N_{SM}}$ is the total SM expectation. The total uncertainty on the SM expectation is given by the shaded band.

Three observables that have been found to be suitable for separating SM W and top production are investigated in this preselection. These are the transverse momentum of the reconstructed b quark candidate P_T^b, the reconstructed top mass $M_{\ell\nu b}$, and the W decay angle $\cos\theta_W^\ell$ calculated as the angle between the lepton momentum in the W rest frame and the W direction in the top quark rest frame. The observed data distributions of these quantities, shown in fig. 3, agree well with the SM expectation within the uncertainties. No evidence for single top production is observed.

The observables are then combined into a multivariate discriminator, which is trained using ANOTOP as the signal model and EPVEC as the background model. The discriminator is based on a phase space density estimator using a range search algorithm [14]. The resulting discriminator output distributions for the electron and muon channels, shown in fig. 4, are found to provide good separation between W and top MC events.

Limits on the signal cross section are extracted from the discriminator spectra using a maximum likelihood method [13]. Likelihood functions are calculated for the electron and muon channel separately. An upper bound on the cross section of $\sigma_{ep\to etX} < 0.16$ pb at 95% CL is found, which is translated into an upper bound on the coupling $\kappa_{tu\gamma} < 0.14$.

Figure 5 shows existing limits on the anomalous couplings $\kappa_{tu\gamma}$ and v_{tuZ}. Anomalous couplings $\kappa_{tc\gamma}$ of the charm quark are neglected. The top mass is assumed to be $m_t =$ 175 GeV in order to compare with previous results. Also shown in fig. 5 are results from the L3 experiment at LEP [15], the CDF experiment at the Tevatron [16] using Run I data and results from the ZEUS experiment using HERA I data [8]. A new result from CDF [17] (not shown) derives a limit on the branching ratio $B(t \to Zq)$ of 3.7%, which translates as an upper limit on the anomalous vector coupling of $v_{tuZ} \lesssim 0.2$ and is the strictest limit to date. The preliminary H1 result presented here extends the bound on $\kappa_{tu\gamma}$ into a region so far uncovered by current colliders.

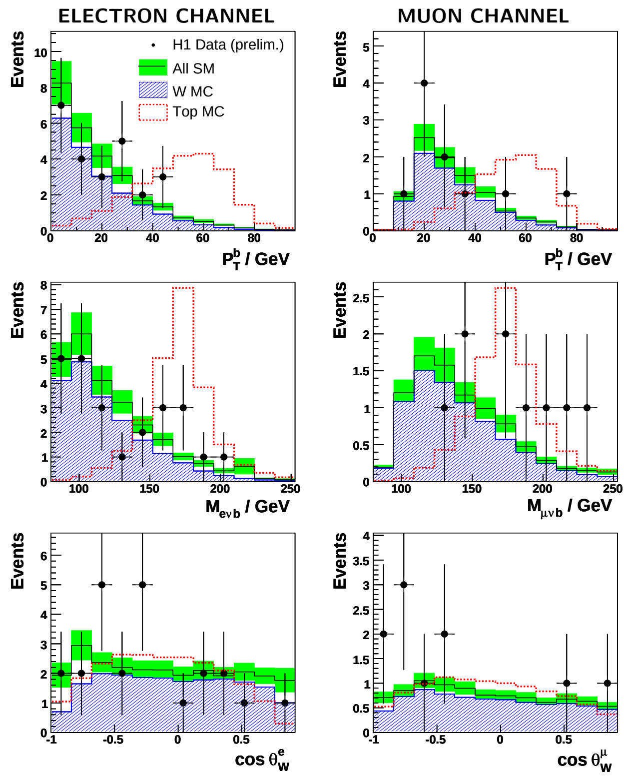


Fig. 3. – Control distributions of observables used to differentiate anomalous single top production from SM background processes in the top preselection. Shown are the transverse momentum of the reconstructed b quark P_T^b, the reconstructed top mass $M_{\ell\nu b}$ and the W decay angle $\cos\theta_W^\ell$ for the electron channel (left column) and muon channel (right column). The data are shown as points, the total SM expectation as open histogram with errors as shaded band. The W production component used to train the multi-variate discriminators is shown as hatched histogram and the shape of the top signal MC is shown as dashed line.

4. – Extensions

There are further analyses possible at HERA that have potential to give some information about anomalous single top production at HERA.

The H1 Collaboration has also performed a search for events with an isolated tau lepton and large missing transverse momentum, using the full HERA I+II $e^{\pm}p$ data [18]. This search is complementary to the electron and muon searches described above, and provides a test of lepton universality. In addition, some BSM scenarios favour the third lepton generation, which could lead to an enhancement of tau lepton production. The tau identification algorithm exploits the event signature of hadronic tau decays of a narrow, low track multiplicity (1–prong) jet in coincidence with missing transverse momentum. The hadronic transverse momentum distribution of the final sample is shown in fig. 6(a), where 20 events are observed in the data compared to a SM prediction of 19.5 ± 3.2. The latter is dominated by charged current events and the signal purity is much lower

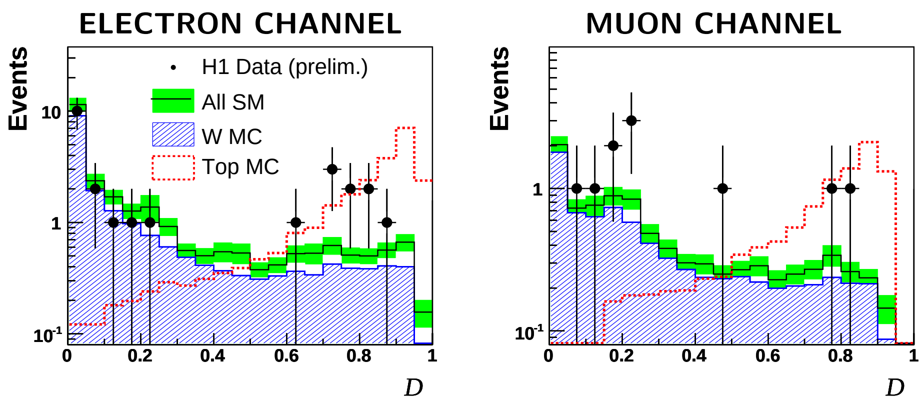


Fig. 4. – Discriminator output distributions for the electron channel (left) and muon channel (right) from a phase space density estimator using a range search algorithm. The data are shown as points, and the total SM expectation as open histogram with systematical and statistical errors added in quadrature as shaded band. The W production component used to train the multi-variate discriminators is shown as hatched histogram and the shape of the top signal MC is shown as dashed line.

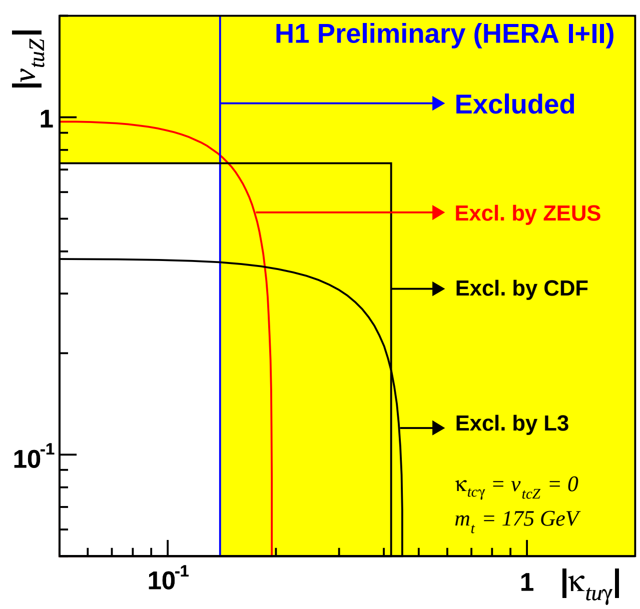
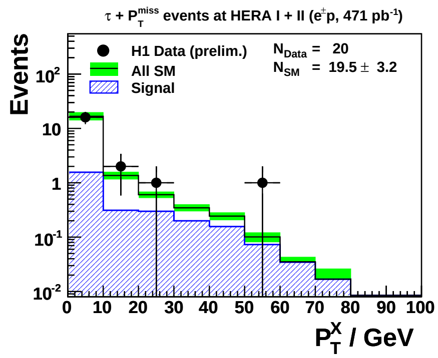
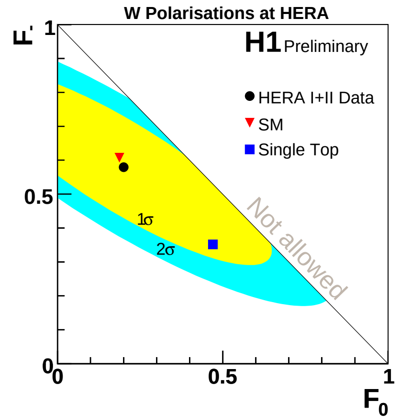


Fig. 5. – Exclusion limits at 95% CL on the anomalous $\kappa_{tu\gamma}$ and v_{tuZ} couplings obtained at HERA (H1 [13] and ZEUS [8] experiments), LEP (L3 experiment [15]) and at the TeVatron (CDF experiment [16] Run I). Anomalous couplings of the charm quark $\kappa_{tc\gamma}$ are neglected. Limits are shown assuming a top mass $m_t = 175$ GeV.



(a)



(b)

Fig. 6. – Results from possible extensions to the search for single top production. (a) The hadronic transverse momentum distribution of $\tau + P_T^{\rm miss}$ events in the H1 $e^{\pm}p$ HERA I+II data. The data (points) are compared to the SM expectation (open histogram). The signal component of the SM expectation is given by the striped histogram. $\rm N_{Data}$ is the total number of data events observed and $\rm N_{SM}$ is the total SM expectation. The total uncertainty on the SM expectation is given by the shaded band. (b) The fit result for the simultaneously extracted W boson polarisation fractions F_- and F_0 (point) with 1 and 2σ CL contours. The predictions for the SM (triangle) and ANOTOP (square) are shown.

than in the electron and muon channels, at around 14%. For $P_T^X > 25$ GeV one event is selected in the data, compared to a SM prediction of 0.99 ± 0.13 events. Due to this difficult background situation no attempt is made to use the tau channel in the search for single top production.

H1 has also tested another possible handle on single top production via the measurement of the W boson polarisation fractions. These are expected to be different in SM *versus* BSM processes [19]. The measurement reconstructs the W boson and makes use of the $\cos\theta^*$ distributions in the decay $W \to e/\mu + \nu$, where θ^* is defined as the angle between the W boson momentum in the lab frame and the charged decay lepton in the W boson rest frame. The measured left handed F_- and longitudinal F_0 W boson polarisation fractions, shown in fig. 6(b), are found to be in good agreement with the SM prediction but also compatible with anomalous single top production within 1σ confidence level (CL) [20].

5. – Conclusion

Anomalous single top production via FCNC has been investigated at HERA. In a sample corresponding to about 0.5 fb^{-1} of integrated luminosity, H1 has set an upper limit on $\sigma_{ep\to etX} < 0.16$ pb at 95% CL, corresponding to an upper bound on the anomalous magnetic coupling $\kappa_{tu\gamma} < 0.14$. This result extends the reach of previous analyses. Extensions of this search have been explored and tested for their ability to contribute to a look at single top production at HERA.

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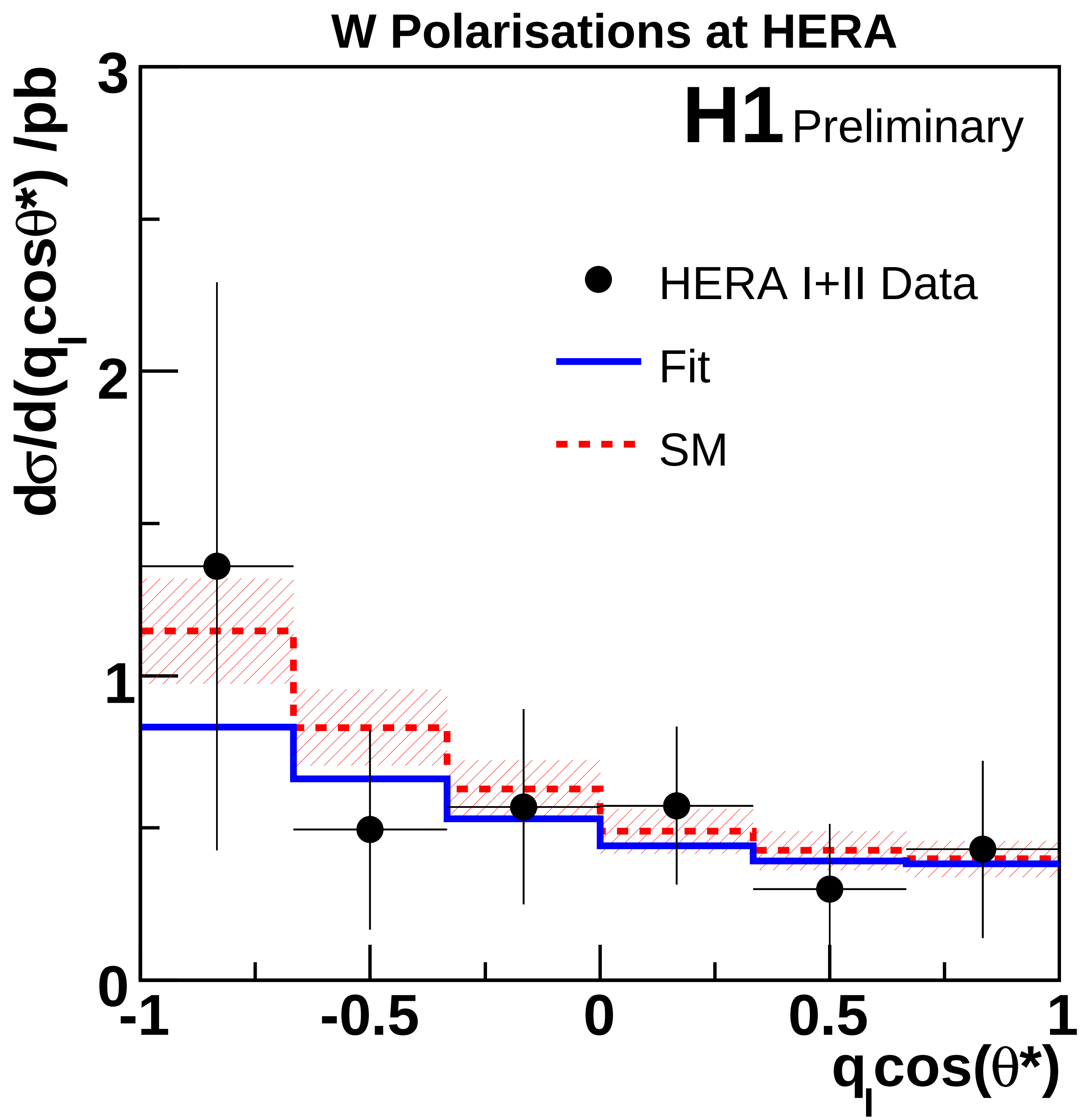

W Polarisations at HERA
H1 Preliminary
HERA I+II Data
Fit
SM
dσ/d(q_l cosθ*) /pb
q_l cos(θ*)
0
1
2
3
-1
-0.5
0
0.5
1