LEPTON PRODUCTION IN EP COLLISIONS AT HERA

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Abstract

High transverse momentum (P_T) lepton production has been studied in ep scattering at HERA. Two classes of events have been investigated. The first contains an isolated lepton, a hadronic system and large missing P_T, the second contains two or three leptons. The measurements use all the HERA data taken before the high luminosity upgrade. The H1 isolated lepton measurements lie somewhat above the Standard Model (SM) expectation when the isolated lepton is a muon or an electron and the hadronic P_T is large whereas ZEUS only observes such an excess for isolated τ leptons. These measurements allow stringent limits to be placed on a possible flavour changing neutral current $t-u-\gamma$ coupling, which would lead to the production of single top quarks and hence isolated leptons, hadronic activity and missing P_T. The rate with which multi-lepton evens are produced is found to be in good overall agreement with the SM. H1 observes somewhat more events than expected in both the di-electron and tri-electron samples at large di-electron masses.

1 Isolated lepton events

Events containing both an isolated lepton (l) with high transverse momentum and missing transverse momentum (P_T^{miss}) have been searched for at HERA by the H1 and ZEUS experiments. Within the Standard Model (SM) the dominant source of such events is the production of W bosons whose cross-section is of the order of 1 pb.

The selection is based on the signature of missing transverse momentum correlated with a high energy lepton ($e^{\pm}$ or $\mu^{\pm}$). The events may also contain a hadronic system X with transverse momentum P_T^X. The H1 selection [1)] is optimised for W-like topologies starting at $P_T^X > 12$ GeV whereas ZEUS performed an inclusive analysis [2)] dominated by non-W processes and a search optimised for top quark at high P_T^X.

In e^+p data (101.6 pb^{-1}), 10 candidate events have been observed by H1 in the electron channel while 9.85±1.31 are expected and 8 events for an expectation of 2.55±0.45 in the muon channel. One event is observed in e^-p data (13.6 pb^{-1}) for 2.06±0.28 events expected. A good agreement with SM predictions can be observed at low transverse momentum P_T^X of the hadronic system. As shown in Fig. 1 the distribution of the lepton-neutrino transverse mass is also in agreement with the SM distribution which is dominated by W production. But at high $P_T^X > 25$ GeV more events than expected are found by H1 (Fig. 1 and tab. 1). This deviation at high P_T^X of the H1 data is present in both e^+p data samples from the years 1994-1997 and 1999-2000.

The ZEUS experiment observed 24 electron events while 20.6 $^{+1.7}_{-4.6}$ events are predicted and 12 muon events compared to 11.9 $^{+0.6}_{-0.7}$ expected from the SM in $e^{\pm}p$ data corresponding to an integrated luminosity of 130 pb^{-1}. In contrast to H1 data, a good agreement with the SM prediction is observed for $P_T^X > 25$ GeV (Tab. 1).

The τ decay channel of the W boson has been recently investigated by the ZEUS experiment [3)]. This analysis relies on the search for isolated tracks with associated calorimetric patterns characteristic of hadronic τ decay. A multi-variable technique based on a likelihood discriminator was used to separate one-prong decays of the τ decay of the W from the background caused by Charge Current Deep Inelastic Scattering (CC-DIS). Two τ candidates have been observed in a region at high transverse momentum of the hadronic system $P_T^X > 25$ GeV where 0.12±0.02 events are expected.

2 Anomalous top production at HERA

Within the SM the rate of top quark production is negligible in $e^{\pm}p$ collisions at HERA energies. An anomalous $\gamma - u - t$ coupling would allow top production

Table 1: *Isolated lepton event yields compared to SM predictions for the ZEUS and H1 experiments. The fraction in percent coming from W production is quoted in parenthesis.*

Selection e^+p	Electrons Data/SM (W)	Muons Data/SM (W)
H1 (101.6 pb^{-1}) e^+p		
full sample	10 / 9.88 $\pm$ 1.69 (73 %)	8 / 2.55 $\pm$ 0.45 (87 %)
$P_T^X > 25$ GeV	4 / 1.49 $\pm$ 0.25 (85 %)	6 / 1.54 $\pm$ 0.41 (84 %)
$P_T^X > 40$ GeV	3 / 0.54 $\pm$ 0.11 (83 %)	3 / 0.55 $\pm$ 0.12 (93 %)
ZEUS (130 pb^{-1}) $e^\pm p$		
full sample	24 / 20.6 $^{+1.7}_{-4.6}$ (17 %)	12 / 11.9 $^{+0.6}_{-0.7}$ (16 %)
$P_T^X > 25$ GeV	2 / 2.9 $^{+0.59}_{-0.32}$ (45 %)	5 / 2.75 $^{+0.21}_{-0.21}$ (50 %)
$P_T^X > 40$ GeV	0 / 0.94 $^{+0.11}_{-0.10}$ (61 %)	0 / 0.95 $^{+0.14}_{-0.10}$ (61 %)

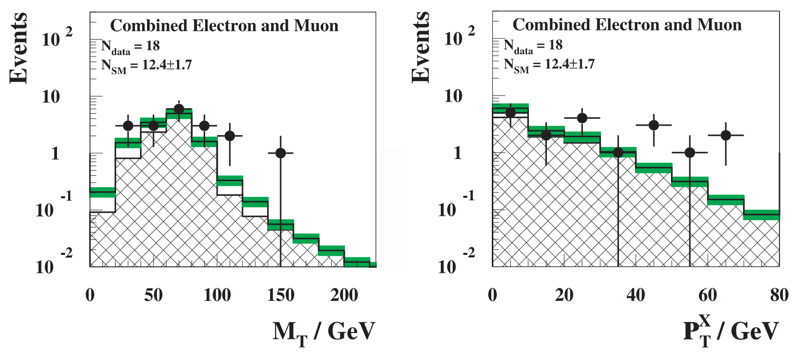

Figure 1: *Lepton-neutrino transverse mass (left) and hadronic transverse momentum (right) distributions of the H1 isolated lepton events, compared to the SM predictions.*

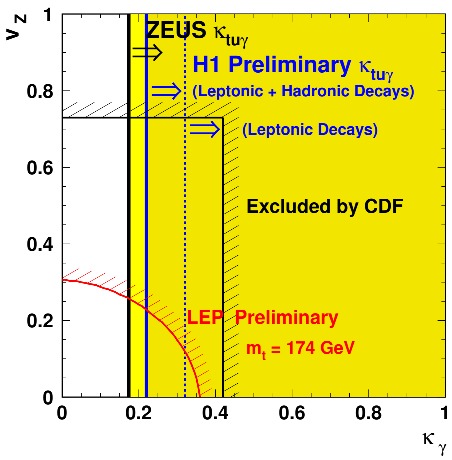

Figure 2: *Present limits of LEP, TEVATRON and HERA on anomalous couplings of the top quark to other quarks and neutral gauge bosons.*

through Flavour Changing Neutral Currents (FCNC's) [5]. Searches for such a process have been performed by the ZEUS [2] and H1 [4] experiments for both semi-leptonic and hadronic decays of the top quark. The top quark can decay into a b-quark jet and a W boson followed by hadronic or leptonic decay. $W \to lX$ decay which leads to events with a high energy lepton, missing transverse momentum and high P_T hadronic jets.

In the leptonic channel, the selections of Section 1 were further tightened to select top candidates, adding a threshold in P_T^X of 40 GeV (ZEUS) or 25 GeV (H1). A positive lepton charge and M_T higher than 10 GeV was also required by H1. With these cuts, 5 events are observed by H1 where 1.77 ± 0.46 are expected, whereas no event is seen by ZEUS in both electron and muon channels while one event is expected in each channel.

If the W produced in the top decay itself decays hadronically, events with three high P_T jets are produced, one high P_T jet being associated with the secondary b-quark and two high P_T jets with the W decay. The experimental selection therefore requires three jets with P_T's above 40, 25 and 14 GeV (ZEUS) or 40, 25 and 20 GeV (H1). Both experiments further reduce the QCD photoproduction background by requiring the 3-jet mass and one of the 2-jet masses to be compatible with the top and W masses, respectively. An additional cut on the angle between the two jets from the W decay in the top rest frame is applied by H1. The searches were performed on data sets corresponding to integrated luminosities of 130.1 pb^{-1} (ZEUS) and 115.2 pb^{-1}

(H1). The observed event yields are 14 for an expectation of 17.6 $^{+2.5}_{-1.5}$ (ZEUS) and 14 for an expectation of 19.6 $\pm$ 7.8 (H1). Both experiments find no excess compared to SM predictions. This does not favour the interpretation of the H1 high P_T^X lepton events as single top production. This interpretation is however not ruled out since 95% C.L. upper limits on the top cross-section derived from the hadronic channel would correspond to 5.4 events in the leptonic channel while 5 are observed.

Combining the leptonic and hadronic channels, an upper limit on the effective $\kappa_{\gamma ut}$ coupling has been calculated using the effective lagrangian of [6]. The upper bounds on $\kappa_{\gamma ut}$ at 95% C.L. of 0.174 (ZEUS) and 0.22 (H1) are competitive with those obtained at LEP [7] and the Tevatron [8] (Fig. 2). The ZEUS limit is more stringent than the H1 limit because they do not observed any excess of data in the leptonic channel.

3 Multi-lepton events

Both H1 and ZEUS have studied multi-electron and multi-muon production [9, 10] in ep collisions. Within the SM the production of multilepton events in ep collisions is possible mainly through photon-photon interactions, where quasi-real photons radiated from the incident electron and proton interact to produce a pair of leptons $\gamma\gamma \rightarrow l^+l^-$ [11]. For multi-electron final states the background comes mainly from Neutral Current Deep Inelastic Scattering (NC-DIS) or elastic Compton scattering, while for multi-muon final state the background is negligible.

The selection for multi-electron events is done by requiring at least two central electrons ($20^\circ < \theta_e < 150^\circ$ for H1 and $17^\circ < \theta_e < 167^\circ$ for ZEUS) with $P_T^{e_1}/P_T^{e_2} > 10/5$ GeV (H1) or $P_T^{e_1}/E^{e_2} > 10/5$ GeV (ZEUS). An isolated charged track has to be associated with the calorimeter energy deposit. Any other third electron is allowed to be present in a wider angular range ($5^\circ < \theta_e < 175^\circ$). The selected events are classified by the number of identified electrons in di- and tri-electron samples.

The results of both experiments are presented in Tab. 2. The di-electron sample is dominated by pair production with 15-20% contribution from other SM processes. In the tri-electron sample, the background contribution is negligible. Both H1 and ZEUS observations are in good agreement with the predicted yields. The main difference between H1 and ZEUS predictions for the signal is due to different angular range for the central electrons. A few events with invariant mass of the two highest P_T electrons $M_{12} > 100$ GeV are observed in a region where the SM prediction is low (Fig. 3 and 4). Three di-electron events are measured by H1 where 0.25 are expected and 2 by ZEUS for an expectation of 0.77. In the tri-electron sample 3 events are observed by

H1 compared to an expectation of 0.23 while no events are observed by ZEUS where 0.37 are expected.

Table 2: *Observed and predicted multi-electron event yields for all selected events and for events with masses $M_{12} > 100$ GeV.*

Selection	Data	SM	Lepton Pairs	NC-DIS + Compton
H1 (115 pb^{-1})				
2e	105	118.2 ± 12.8	93.3 ± 11.5	25.0 ± 5.5
3e	16	21.6 ± 3.0	21.5 ± 3.0	0.1 ± 0.0
2e $M_{12} > 100$ GeV	3	0.25 ± 0.05	0.21 ± 0.04	0.04 ± 0.03
3e $M_{12} > 100$ GeV	3	0.23 ± 0.04	0.23 ± 0.04	0.0 ± 0.0
ZEUS (130 pb^{-1})				
2e	191	213.9 ± 3.9	182.2 ± 1.2	31.7 ± 3.7
3e	26	34.7 ± 0.5	34.7 ± 0.5	–
2e $M_{12} > 100$ GeV	2	0.77 ± 0.08	0.47 ± 0.05	0.30 ± 0.07
3e $M_{12} > 100$ GeV	0	0.37 ± 0.04	0.37 ± 0.04	–

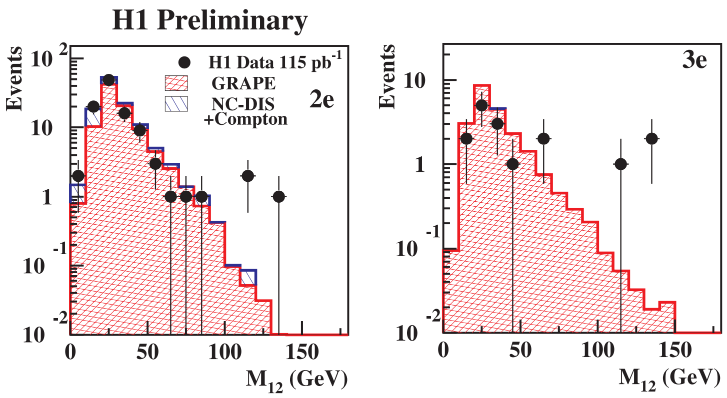

Figure 3: *Distribution of the invariant mass M_{12} of the two highest P_T electrons for the H1 analysis. Events classified as di-electrons (left) and tri-electrons (right) are shown.*

A search for multi-muon events has also been performed by both experiments. Muons are identified using central tracker reconstructed tracks,

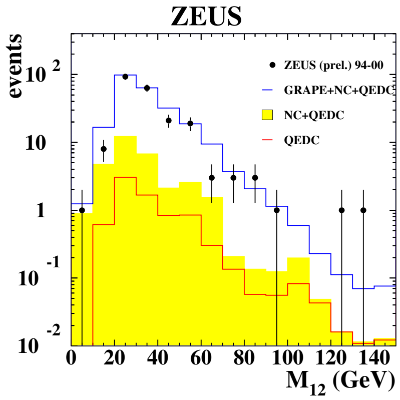

Figure 4: *Distribution of the invariant mass M_{12} of the two highest P_T electrons for the ZEUS analysis. All observed events with more than two electrons are shown.*

calorimetric deposits and muon chamber signals. At least two muons with $P_T^{\mu_1}/P_T^{\mu_2} > 2$ GeV and $P_T^{\mu_1}/P_T^{\mu_2} > 5$ GeV in the angular range $20° < \theta_e < 160°$ are required in H1 and ZEUS analyses, respectively. With an analysed data sample corresponding to an integrated luminosity of 105 pb^{-1} 200 events are detected by ZEUS where $213 \pm 11_{stat.}$ are expected. Using an integrated luminosity of 70 pb^{-1}, 1242 multi-muon events are observed in the H1 analysis in good agreement with the expectation of $1253 \pm 125_{stat.+syst.}$. No event with two muons at high mass $M_{\mu\mu} > 100$ GeV is observed by either experiment. The 3 high mass di-electron events observed by H1 would correspond to one di-muon event expected with $M_{\mu\mu} > 100$ GeV because of the lower efficiency and luminosity in the multi-muon channel.

4 Conclusions and outlook

Events with an isolated high P_T lepton and missing transverse momentum have been observed in ep collisions at HERA. The most probable interpretation in the SM framework is real W production with subsequent leptonic decay. This mechanism produces a relatively low P_T hadronic system. Intriguing events containing a high P_T hadronic system and an isolated electron or muon have been observed by H1 while no deviation from the SM prediction was observed by ZEUS. Two events containing an isolated τ and missing transverse momentum have been identified by ZEUS at high P_T^X while 0.12 ± 0.02 are predicted.

The interpretation of these electron and muon events in terms of anomalous single top quark production has been explored and competitive limits on the $\kappa_{\gamma ut}$ effective coupling determined.

High P_T multi-electron and di-muon production has also been measured. Good general agreement with the Standard Model expectation has been found. However few multi-electron events with an invariant mass of the two highest P_T electrons above 100 GeV have been observed in excess compared to the SM prediction. No event with two muons at high mass $M_{\mu\mu} > 100$ GeV is observed by either experiment.

A new high luminosity phase of the HERA collider is now starting with the goal of accumulating an integrated luminosity of 1 fb^{-1}. This will clarify the origin of the isolated lepton and multi-electron events observed by H1. Enhanced b-tagging capabilities provided by the new H1 and ZEUS vertex detectors will also make the identification of new phenomena such as anomalous top production easier.

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