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# Electroweak and High $Q^2$ physics at HERA

**Violette BRISSON**

**Laboratoire de l'Accélérateur Linéaire**
*IN2P3-CNRS et Université de Paris-Sud, BP 34, F-91898 Orsay Cedex*

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## Electroweak and High $Q^2$ physics at HERA

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*email:brisson@lal.in2p3.fr*

**Abstract**

The HERA results in the very high $Q^2$ domain are presented. They agree with Standard Model except for $Q^2 \gtrsim 15000$ GeV$^2$ where slight excesses of events are seen, in inclusive and some exclusive channels.

# 1 Introduction

The e-p collider HERA at DESY provides the possibility to measure e-p collisions up to momentum transfers yet unreached ($Q^2_{max} = S \simeq 90000$ GeV$^2$), which allows to study deep inelastic scattering in charged and neutral current processes ; perturbative QCD is studied over 4 decades of $Q^2$, and tests of the electroweak Standard Model can be performed due to the sensitivity to the propagator masses at high $Q^2$. The very high $Q^2$ domain is a good place to look for new physics, for which some limits can be derived from the results. Furthermore, more exclusive channels with leptons can sign the direct production of W's, or correspond to more exotic physics.

The collaborations, H1 and ZEUS, have both collected a large sample of $e^+p$ interactions, from 1994 to 1997, corresponding to a luminosity of 46 (ZEUS) and 36 (H1) pb$^{-1}$. Results on the subjects mentionned above are presented here, most of them being still preliminary.

# 2 Experimental procedure

The 2 detectors, complementary in their performances are described in detail in [1] and [2]. A big effort has been made in order to reduce the uncertainty on electronic and hadronic scales for energy measurement with the calorimeters. For electrons the scale is known to $\sim$ 1 % in most of the space (3 % forward) and for hadrons this uncertainty is 2 to 4 %.

## 2.1 Kinematic reconstruction

For neutral currents the scaling variables $x$ $y$, and $Q^2$, can be derived from 4 measured quantities $\theta_e$,$\theta_\gamma$ and $E_e$, $E_\gamma$, the polar angle and energy of the electron ($e$) and hadron system ($\gamma$). They are measured using only $\theta_e$ and $\theta_\gamma$ in ZEUS (double angle method), and for H1 using the best combination of electron and hadron parameters ("$e$ $\Sigma$" method). For charged currents there is no choice : both experiments use the "Jacquet Blondel" method based on hadron parameters only.

# 3 Deep inelastic scattering

## 3.1 Neutral current cross-sections

The differential cross-section is given by:

$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) - Y_-xF_3(x,Q^2)\right] \tag{1}$$

with $Y_\pm = 1 \pm (1-y)^2$. At high $Q^2$ the structure function $F_2$ is composed of 3 terms:

$$F_2 = F_2^{em} + \frac{Q^2}{Q^2+M_Z^2} F_2^{int} + \frac{Q^4}{(Q^2+M_Z^2)^2} F_2^{wk} = F_2^{em}(1+\delta_Z) \tag{2}$$

where $F_2^{em}$ corresponds to the photon exchange, $F_2^{int}$ to the $\gamma/Z^0$ interference, and $F_2^{wk}$ to the $Z^0$ exchange.

Figure 1 shows the single differential cross-section $d\sigma/dQ^2$ measured by ZEUS. The data agree with the Standard Model predictions using the CTEQ4D parton parametrization, except at the highest $Q^2$ - this will be detailed later. H1 measured the double differential cross-sections, given as "reduced" cross-sections = $\tilde{\sigma}(e^+p) \equiv \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma}{dxdQ^2}$, which isolates the parton distribution terms from the propagator part. The results are shown in figure 2 : $\tilde{\sigma}$ is plotted as a function of $Q^2$ for 0.07 < x < 0.65. At high x the results are touching the fixed target domain. There is good agreement with MRST predictions except for a deviation around x = 0.45 which will be commented in 3.3.

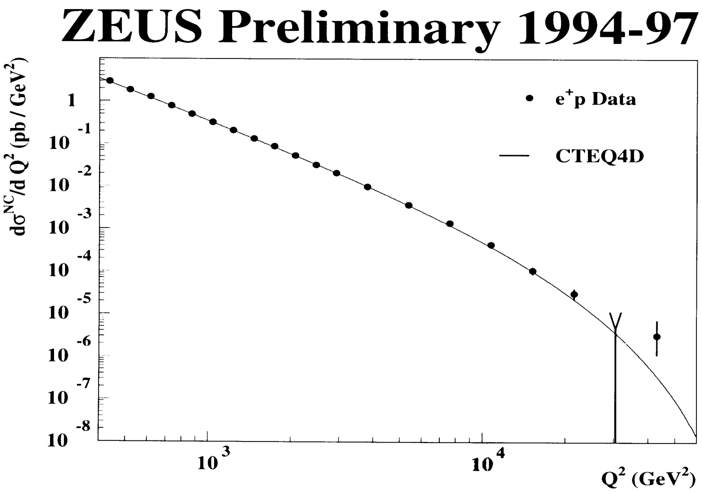


Figure 1: $d\sigma/dQ^2$ for ZEUS NC events

The effect of $\gamma$/Z interference is seen for the first time. Figure 3 shows the effect of the negative $\gamma/Z$ interference for $Q^2 > 10000$ GeV$^2$ (the 2 curves show the SM expectations with and without $Z^0$ exchange).

### 3.2 Charged current cross-sections and the W Propagator Mass

The e$^+$ p cross-section for W mediated DIS processes is related to the quark densities:

$$\frac{d^2\sigma_{cc}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{1}{1+Q^2/M_W^2}\right)^2 [\bar{u}+\bar{c}+(1-y)^2(d+s)] \tag{3}$$

Due to the presence of a neutrino, only the hadronic system is visible and these events are detected through an imbalance in the observed transverse momentum. H1 and ZEUS have measured the "reduced" cross-section or "partonic" part, $\frac{d\widetilde{\sigma_{cc}}}{dxdQ^2} = x\frac{2\pi}{G_F^2}(1+Q^2/m_W^2)^2\frac{d^2\sigma}{dxdQ^2}$.

Figure 4 shows the H1 and ZEUS results for $d\tilde{\sigma}/dxdQ^2$, in good agreement with the S.M predictions and MRST or CTEQ4D. Also shown is the contribution of $(d\,+\,s)$ quarks, predominant at large $x$ (low $Q^2$), and $\bar{u}+\bar{c}$ at small $x$. These characteristics, together with the neutral current $e^+$ and $e^-$ and $CC$ $e^-$ cross-sections, will give access to a determination of $u(\bar{u})$ and $d(\bar{d})$ distributions. The single differential cross-section $d\sigma/dQ^2$ allowed H1 and ZEUS to derive the mass of the propagator. The results are :

$$M_W = 81.2 \pm 3.3(\text{stat}) \pm 4.3(\text{syst}) \text{ GeV for H1} \tag{4}$$

$$M_W = 78.6 \pm 2.5(\text{stat}) \pm 3.3(\text{syst}) \text{ GeV for ZEUS} \tag{5}$$

This result can be interpreted as a test of consistency of the Standard Model, since these $M_W$ values corresponding to space like channels are in good agreement with timelike results obtained at LEP and Tevatron.

## 3.3 Very high $Q^2$ domain

The $Q^2$ distribution of $\sigma_{NC}$ and $\sigma_{CC}$ is shown in figure 5. At the beginning of 1997 an excess of events for $Q^2 > 15000$ GeV$^2$, has been reported by H1.

The present situation of both experiments for 1994-1994 events is summarized in table 1. The statistical significance for an excess has decreased from 6 $10^{-3}$ to $\sim 610^{-2}$ for the H1 results. But an excess of events remains at very high $Q^2$.

| | NC | | | CC | |
|---|---|---|---|---|---|
| | N obs. | N exp. | Experiment | N obs. | N exp. |
| $Q^2 > 15000$ GeV$^2$ | 12 | 4.71 ± 0.76 | H1 94-96 | | |
| | 22 | 14.8 ± 2.13 | H1 94-97 | 9 | 5 ± 3 |
| | 20 | 17 ± 2 | ZEUS 94-97 | 8 | $3.9^{+1.9}_{-1.5}$ |
| $Q^2 > 20000$ | | | ZEUS 94-97 | 3 | $0.97^{+0.55}_{-0.47}$ |
| $Q^2 > 35000$ | 2 | 0.29 ± 0.02 | ZEUS 94-97 | 1 | $0.05^{+0.08}_{-0.04}$ |

Table 1: Summary of very high $Q^2$ data.

The neutral current results have been used to derive limits on the scale of contact interactions and on leptoquark masses.

*3.3.1 Limits on contact interactions*

These 4-fermion interactions can be interactions of composite electrons and quarks, heavy boson exchange, leptoquarks etc ; they lead to additional terms in the Lagrangien :

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{g^2}{\Lambda^2} \cdot \sum_{\substack{a,b=L,R \\ q=u,d}} \eta^q_{ab} (\bar{e}_a \gamma^\mu e_a)(\bar{q}_b \gamma_\mu q_b) \tag{6}$$

with $\eta^q_{ab} = \pm 1, 0$ and $g^2 = 4\pi$ by convention, only chiral vector couplings being considered. The analysis is based on a comparison of the measured $Q^2$ distribution with the Monte Carlo predictions for Standard Model.

The scale of the interaction is found to be in the range from 1.5 to 5 TeV, depending on the coupling, in agreement with limits found at LEP or CDF.

*3.3.2 Limits on leptoquark masses* Leptoquarks may be produced at HERA as s-channel resonances $= e + q \rightarrow LQ \rightarrow e' + q'$. This reaction has 3 parameters: the coupling $\lambda$ to the leptoquark, the mass M of the leptoquark and the branching ratio $\beta$ of the $LQ$ decaying into *eq*. Limits on the parameters will be derived either in the M-$\beta$ plane ($\lambda$ fixed to a given value), or in the M$\lambda$ plane ( $\beta$ fixed to the value given by the Buchmüller, Rückl, Wyler model[3]).

The limits are derived from the mass distribution of the final system $e$-hadrons, $M_e = \sqrt{xs}$, compared to the Standard Model predictions. Scalar leptoquarks, produced as s-channel resonances, would have a flat $d\sigma/dy$ distribution contrarily to DIS neutral currents which show a $1/y^2$ dependence (t-channel). To decrease the NC background in searched leptoquarks, a lower mass dependent cut in $y$ (H1) or $cos\theta^*(= 2y - 1$, ZEUS) is used and seen in figure 6 showing the mass distribution.

The limits for fixed $\lambda$ are shown in figure 7: the 95% CL lower limits are comparable to D0 results for $\beta = 1$, and larger than the Tevatron results for $\beta < 1$.

The ZEUS results for fixed $\beta$ show that ($e^+$ - sea) leptoquarks are excluded for $M_{LQ} \lesssim 240$, and ($e^+$ - valence) $LQ$ should have a mass larger than $\sim$ 280 GeV.

# 4 Events with isolated leptons and missing transverse momentum

Within the Standard Model those events are expected from the production of a W decaying leptonically, and from $R_p$ violating SUSY or Leptoquarks (figure 8).

In H1, a first selection of events requiring a missing transverse momentum larger than 25 GeV and at least one track with $P_T > 10$ GeV and $\theta > 10°$, leads to a sample of 124 events. A further selection is made on this sample for the isolation of the high $P_T$ track (minimum distance of the track to the nearest neighbour track or nearest hadron jet) and for the identification of the lepton (e.m. cluster in the calorimeter for electrons, and signal in calorimeter + muon system for muons). 6 events remain : 1 with isolated negative electron and 5 with muons $(2\mu^+, 2\mu^-, \mu^\pm)$.

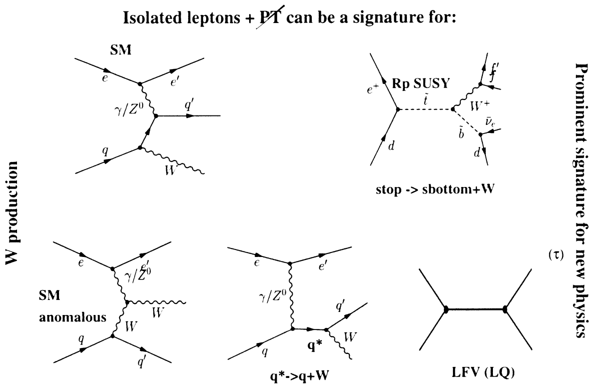


Figure 8: Possible reactions for isolated leptons $+P_T$ miss

In order to compare their topology with neutral current events, the colinearity of the lepton track with the resulting hadron momentum in the R,$\Phi$ plane has been plotted against the missing transverse momentum of the event : for NC events both quantities are close to zero as expected, but they show large values for the 6 events.

The W production with leptonic decays has been simulated with a Monte-Carlo corresponding to 500 times the luminosity in H1. Figure 9 (a,b) shows the result of the simulation in the plane of hadronic transverse momentum $P_{TX}$ and transverse $(e, \nu)$ mass, together with the $e^-$ event (a)) and the 5 $\mu$ events (b)). The $e^-$ event lies in the bulk of the W events, just as two of the $\mu$ events. The remaining three $\mu$ events have a quite small probability to be explained by a W production.

In the frame of a specific W search, ZEUS performed a similar analysis, where 4 $e^+$ events were found, and none in either the $e^-$ of $\mu$-channel. Figure 9c) shows the hadronic $P_{TX}$ - transverse $(e, \nu)$ mass distribution, similarly to figure 9a),b), for H1. The 4 events are compatible with SM predictions for W production.

Table 2 shows the observed and predicted numbers of events for the 2 experiments. Also shown is the resulting W production cross-section as derived by ZEUS, compatible with the present prediction.

| | e | | $\mu$ | |
|---|---|---|---|---|
| | Data | MC | Data | MC |
| H1 | 1 | $2.4 \pm 0.5$ | 5 | $0.8 \pm 0.2$ |
| ZEUS | 4 | $3.5 \pm 0.4$ | 0 | $1.3 \pm 0.2$ |
| $\sigma$(ep) $\rightarrow eWx$ | $1.0^{+1.0}_{-0.7} \pm 0.3$ pb | | $< 4.4$ pb | |

Table 2: Summary of the isolated lepton search.

It is clear that more statistics is needed to draw conclusions about the 3 events in excess found in H1.

### 4.1 Limits on WW$\gamma$ couplings

From the 95 % CL limit of the W production cross-section - $\sigma < 3.2$pb -, limits on the couplings for the WW$\gamma$ vertex have been derived by ZEUS. The 2 couplings K and $\lambda$ are 1 and 0 in the Standard Model. For $\lambda = 0$, the deviation from 1 of $\kappa, \Delta\kappa = \kappa - 1$ has been found to be $\Delta\kappa <$ 3.9 (positive values only).

## 5 Conclusions

With the $e^+$ interactions accumulated from 1994 to 1997, the two collaborations H1 and ZEUS have measured deep inelastic cross-sections for neutral and charged currents over more than 4 orders of magnitude in $Q^2$ ; the results are in good agreement with the standard model, except for $Q^2 > 15000$ GeV$^2$. The effects of heavy propagators have been seen. The W mass derived from the data is in good agreement with direct measurements, which is a test of consistency of the Standard Model between the space-like and time-like channels.

For Q$^2 > 15000$ GeV$^2$ a slight excess is observed, which has to be investigated with more statistics. The limits of lepto-quark masses have been pushed to about 250 GeV, and the $\Lambda$ parameters for contact interactions are found to be a few TeV. Among the isolated leptons with large missing P$_T$, 3 events with a muon cannot really been explained by the standard model.

The 1998 and 1999 runs with electrons, together with an increase to 920 GeV of the proton beam, should help to shed light on the high $Q^2$ part (for $Q^2 > 10000$ GeV$^2$)$\sigma_{cc}(e^- p_{920}) \simeq 10\sigma_{cc}(e^+ p_{820})$ . The upgrade of HERA, foreseen in year 2000, will provide an increase of 5 times the present luminosity, and the longitudinal polarization will help to complete the HERA possibilities in electroweak physics.

## References


[1] H1 Collaboration, Abt et al., Nucl. Instr. and Meth. A386 (1997) 310-348

[2] ZEUS Collaboration, The ZEUS Detector, Status Report 1993, DESY 1993

[3] W. Buchmüller, R. Rückel and D. Wyler, Phys. Lett. B191 (1987) 442

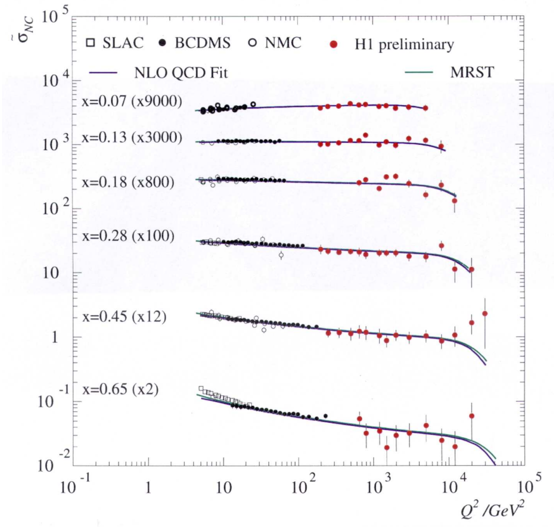


Figure 2: Reduced $d\sigma/dxdQ^2$ for H1 NC

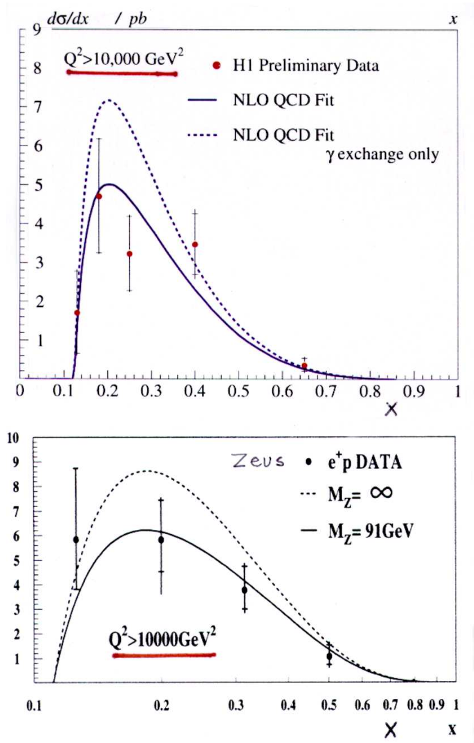


Figure 3: $d\sigma/dx$ for $Q^2 > 10000$

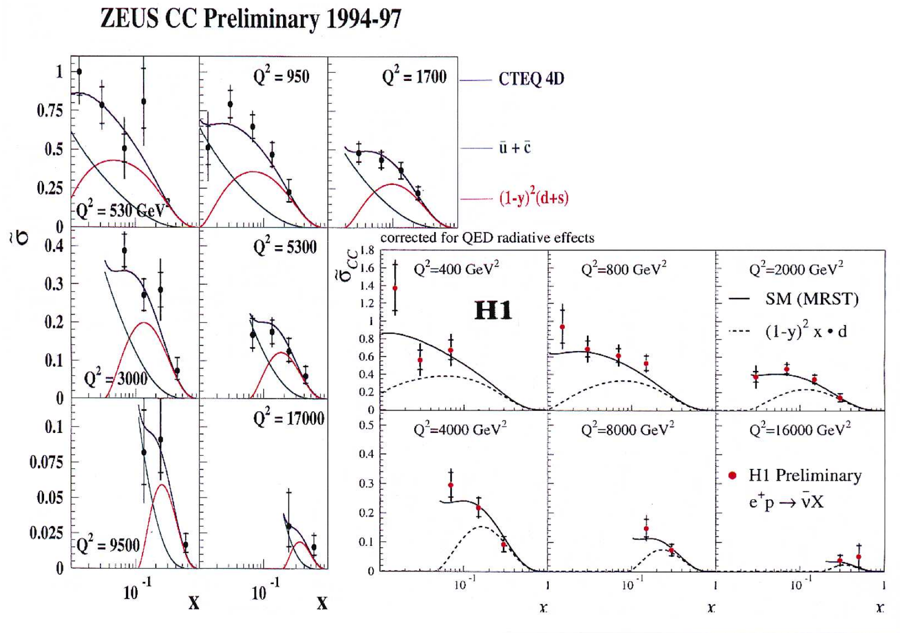


Figure 4: Reduced $d\sigma/dxdQ^2$ for CC events

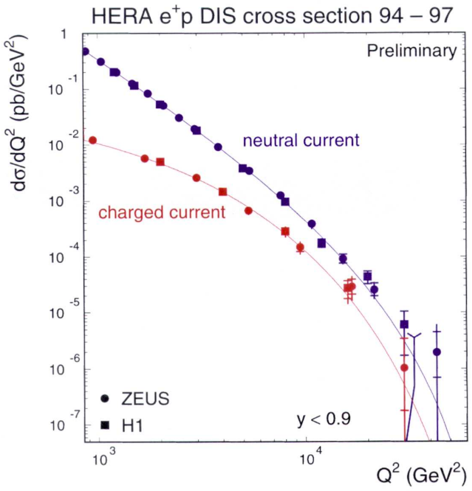


Figure 5: $d\sigma/dQ^2$ for NC and CC events

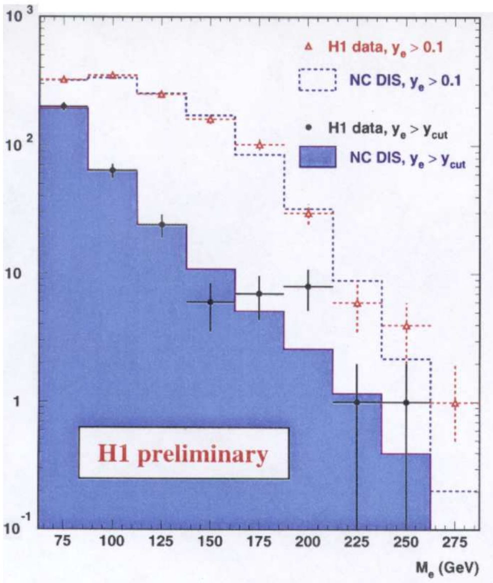


Figure 6: Distribution of $(e, x)$ system Mass

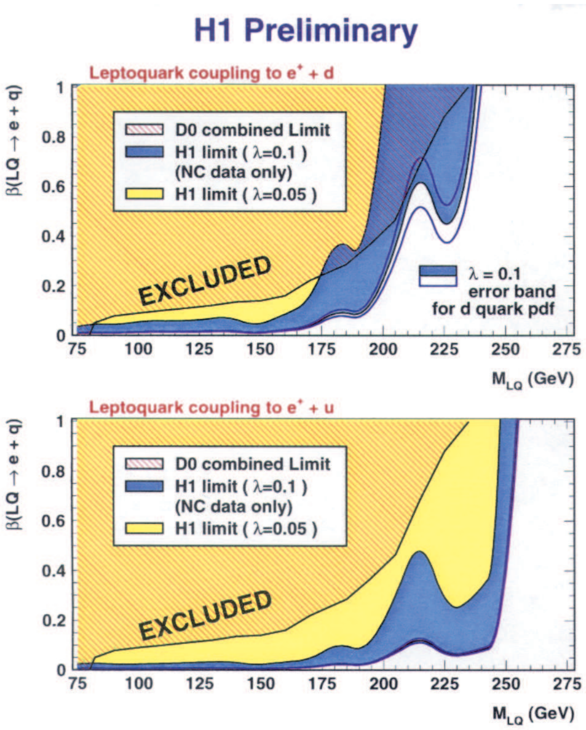


Figure 7: Limits of the leptoquark mass as a function of the branching ratio in e.q.

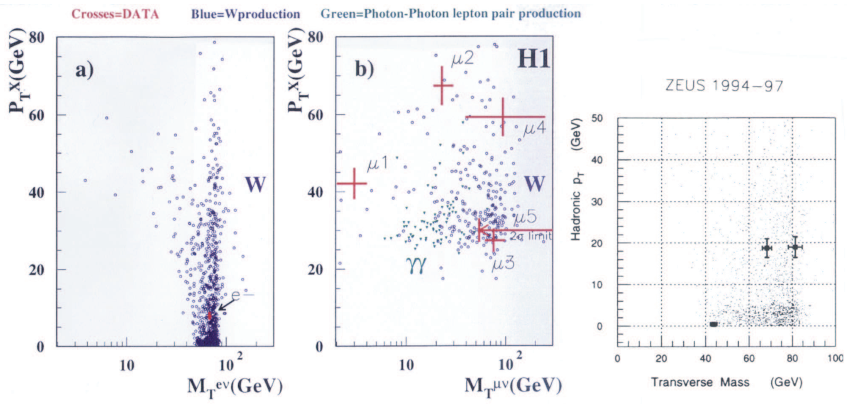


Figure 9: Hadronic $P_T$ as a function of transverse $l\nu$ mass: a) H1 e events b) H1 $\mu$ events c) ZEUS e events.