Neutral and charged current cross section measurements and searches for new physics at HERA

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1 Introduction

HERA is the only high energy electron–proton collider in the world today and hence has unique opportunities both to probe the structure of the proton and to search for physics beyond the Standard Model. Results are presented for measurements of both neutral and charged current cross sections, and for searches for exotic processes involving direct electron–quark interactions (leptoquarks and R–parity violating SUSY), generic coupling models (contact interactions) and exclusive final states (isolated leptons and missing P_T, single top production and pentaquarks). Exclusion limits on proposed models are set where no deviation from Standard Model predictions are found.

2 HERA, H1 and ZEUS

At the HERA[1] accelerator at DESY[1] in Hamburg, Germany, positrons or electrons have been collided with protons since the early 1990s. The centre-of-mass energy of these collisions was 300 GeV prior to 1998, when a upgrade increased this energy to 319 GeV. These collisions take place at the heart of the H1[2] and ZEUS[3] experiments – multi-purpose detectors with full solid angle coverage for tracking, calorimetry and muon subdetectors.

By the end of the summer of 2000 an integrated luminosity of $\mathcal{O}(100)\,\text{pb}^{-1}$ and $\mathcal{O}(15)\,\text{pb}^{-1}$ had been collected per experiment in e^+p and e^-p collisions, respectively. The kinematic range covered by this data is illustrated in figure 1, where $Q^2 = -q^2$, $x = Q^2/(pq)$, and $y = Q^2/sx$. Here s is the centre-of mass energy squared, q is the four-vector of the exchanged boson, and p is the four-vector of the incoming proton.

[1]Deutsches Elektronen Synchrotron

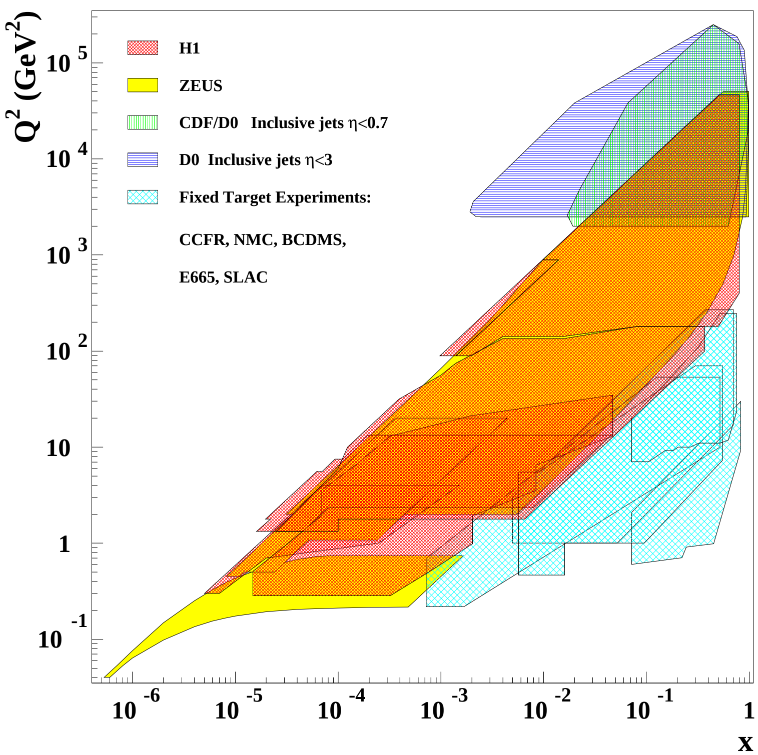

Figure 1: The kinematic plane in x and Q^2 accessible at HERA, compared to that of the Tevatron experiments and earlier fixed-target experiments.

3 Neutral and Charged Current Cross Section Measurements

The single differential cross section $\frac{d\sigma}{dQ^2}$ for both Neutral Current (NC) and Charged Current (CC) processes in e^+p and e^-p collision data is shown in figure 2 for both H1[4] and ZEUS[5, 6]. The NC cross-section is large at low Q^2 and decreases over several orders of magnitude as Q^2 increases from $200\,\text{GeV}^2$ to $30000\,\text{GeV}^2$. The e^+p and e^-p data overlay at low Q^2, whereas at high Q^2 the e^+p cross-section is smaller. The CC cross-section is almost constant at low Q^2 but falls off rapidly at high Q^2 and the e^+p cross-section is significantly lower than the e^-p cross-section at high momentum transfer. For $Q^2 > 3000\,\text{GeV}^2$ the NC and CC cross-sections are of similar size. The data are well described by NLO QCD calculations. The Q^2 dependence is governed by the propagator of the photon $\frac{1}{Q^4}$ for NC and by the propagator of the W-boson $\frac{1}{(Q^2+M_W^2)^2}$ for CC. The difference between e^+p and e^-p data is due to the $Z^0\gamma$ interference in NC reactions. For CC interactions this difference is attributed to the valence quark densities and the relevant helicity factors.

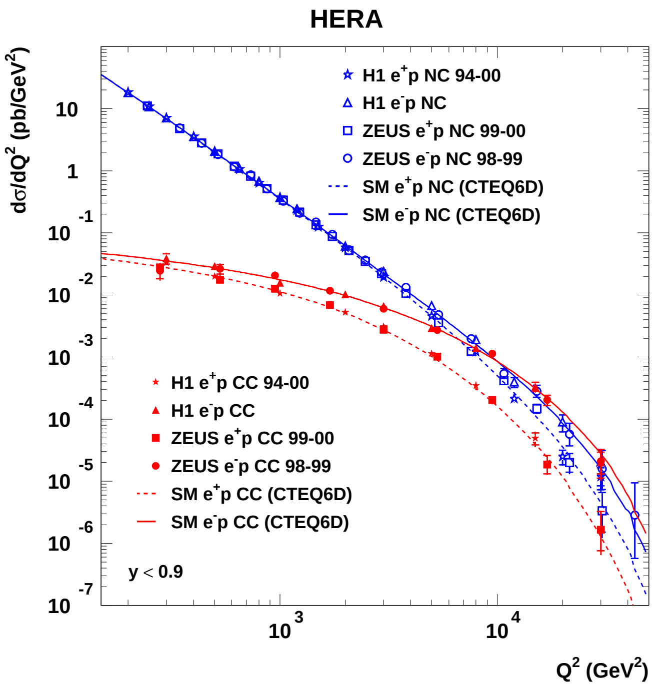

Figure 2: The single-differential neutral current and charged current cross-section $\frac{d\sigma}{dQ^2}$, as measured by H1 and ZEUS in e^+p and e^-p collisions with $Q^2 > 200\,\mathrm{GeV}^2$.

When considering double differential cross sections it is convenient to define the reduced cross section, which for the NC process is given by:

$$\tilde{\sigma}^{\pm}_{\rm NC} = \frac{d^2\sigma_{\rm NC}}{dxdQ^2} / \left(\frac{2\pi\alpha^2 Y_+}{(Q^2)^2 x}\right) \approx F_2 \mp \frac{Y_-}{Y_+} xF_3$$

where $Y_\pm = 1 \pm (1-y)^2$ and are known as the *helicity factors* and F_2 and F_3 are the proton structure functions. The reduced cross-sections are shown in figure 3, measured for various values of x as a function of Q^2.

The Q^2 dependence in this formalism is seen to be rather weak. The main contribution to the cross-section is the photon exchange F_2. The difference between e^+p and e^-p data at highest Q^2 is due to Z/γ interference. After subtracting the e^+p data from the e^-p data, xF_3 may be measured at high Q^2. The structure function xF_3 is sensitive to the valence quarks alone.

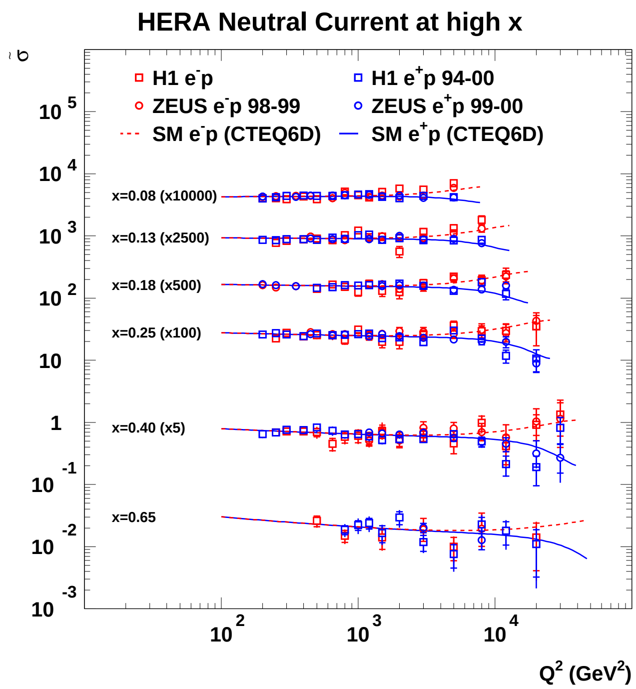

Figure 3: The reduced neutral current cross-section $\tilde{\sigma}$, measured by H1 and ZEUS in e^+p and e^-p collisions at high x.

Figure 4 shows the HERA measurements of $x\tilde{G}_3$, where propagator terms have been removed from xF_3. They compare well to NLO QCD calculations.

In the same manner as for the NC cross sections it is convenient when considering double differential CC cross sections to define the reduced cross section $\tilde{\sigma}_{\text{CC}^\pm}$:

$$\tilde{\sigma}_{\text{CC}^\pm} = \frac{d^2\sigma^\pm_{\text{CC}}}{dxdQ^2} / \left(\frac{G_F^2 M_W^2}{(Q^2+M_W^2)^2 2\pi x} \right)$$

These reduced cross-sections are related to the quark densities,

$$\tilde{\sigma}^-_{\text{CC}} \approx (xu + +uc + x\overline{d} + x\overline{s}),$$

$$\tilde{\sigma}^+_{\text{CC}} \approx (1-y)^2(xd + xs + x\overline{u} + x\overline{c})$$

The HERA results are shown in figure 5. The data are shown as a function of x for nine values of Q^2. The NLO QCD calculation based on low energy data describes

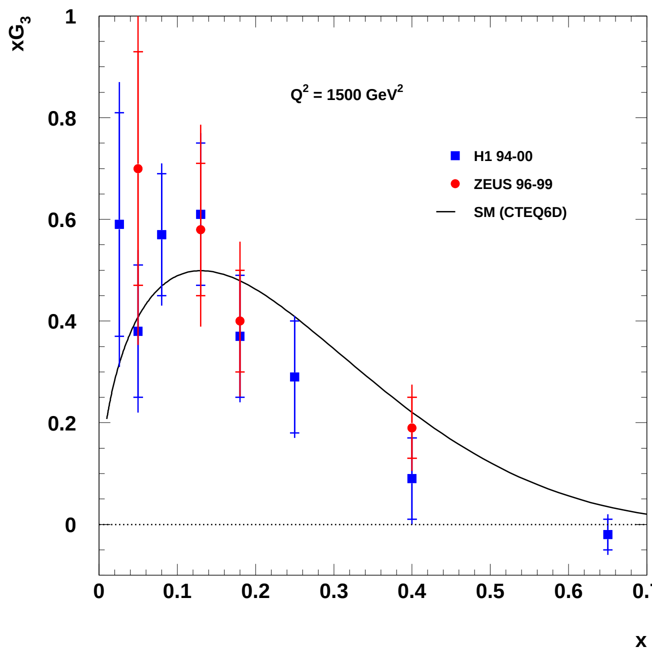

Figure 4: The structure function $x\tilde{G}_3$, measured by H1 and ZEUS.

the data well. Also shown are the contributions from u and d valence quarks alone. The CC data may be used to extract the u (d) quark at high x from e^-p (e^+p) data. For the e^+p cross-sections the d quark is suppressed by a helicity factor $(1-y)^2$. A precise determination of the valence quarks at highest x requires a still larger datasets, mostly in e^+p collisions.

4 Leptoquarks

Both Neutral Current (NC) and Charged Current (CC) high Q^2 data are examined for evidence of leptoquark (LQ) production via either s or u channel exchanges. This is done in the framework of the BRW[7] model which predicts 7 scalar and 7 vector LQs. The eq coupling is parameterised by the Yukawa coupling λ and the branching ratios are fixed. The data[8, 9] show good agreement with the Standard Model (SM) prediction and exclusion limits in terms of λ and LQ mass $M_{\rm LQ}$ are set. One such result is shown in figure 6, with the complementary LEP and Tevatron results.

A natural extension of this study is to look for evidence for lepton flavour violation, mediated by s or t channel leptoquark exchange, with subsequent decay into 2nd or

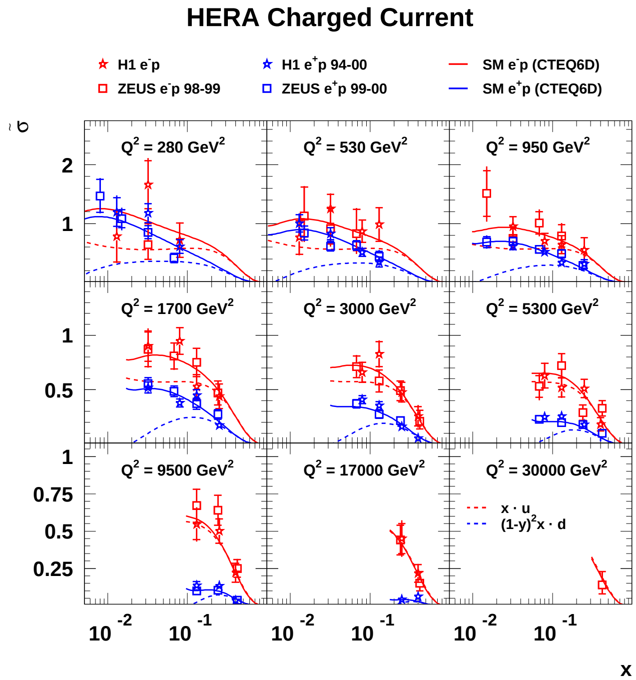

Figure 5: The reduced charged current cross-section $\tilde{\sigma}$, measured by H1 and ZEUS in $e^{+}p$ and $e^{-}p$ collisions at high x.

3rd generation leptons (*i.e.* muons or taus). No evidence for such processes is observed and exclusion limits are set in the λ-$M_{\rm LQ}$ plane within the context of the BRW model. Taking a Yukawa coupling of electromagnetic strength, couplings of scalar (vector) leptoquarks with masses up to 275-300 (288-330) GeV to second generation leptons and couplings of scalar (vector) leptoquarks with masses up to 260-284 (278-300) GeV to third generation leptons are excluded at 95% C.L. by H1[10].

A further extension of these models are contact interactions. These models parameterise a coupling for the virtual exchange of particles with masses beyond the direct access of the collider, but whose interference with SM exchanges (γ, Z° and $W^{\pm}$) could nevertheless be measureable. No deviations in the agreement of the highest Q^2 NC data and the SM expectation are observed. These results also set limits on finite quark radii. The ZEUS collaboration set[11] an upper limit of 0.85 x 10^{-18}m at 95% C.L.

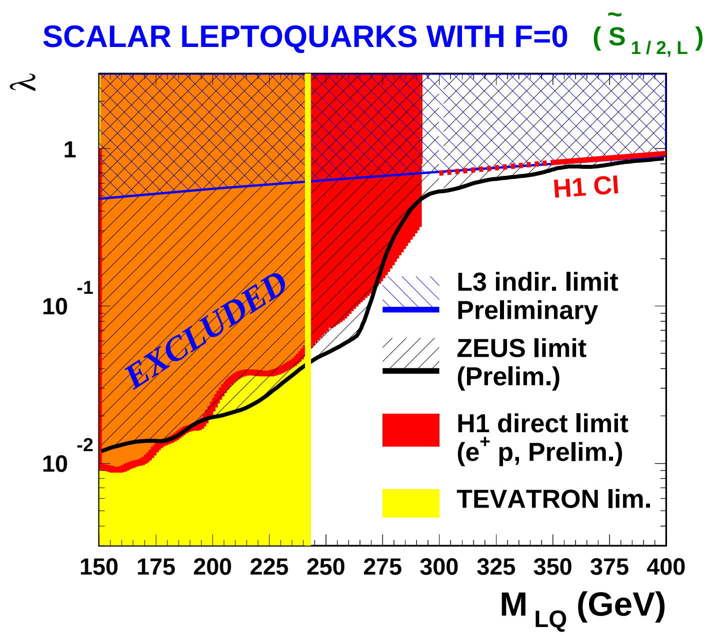

Figure 6: Exclusion limits on the Yukawa coupling λ as a function of leptoquark mass $M_{\rm LQ}$.

5 Isolated Leptons and Missing P_T

H1 has reported[12, 13] an excess of events containing an isolated electron or muon and missing transverse momentum. Within the SM events of this topology are expected to be mainly due to the production of a W boson and its subsequent leptonic decay, particularly when the hadronic system has high P_T (large P_T^X). Recent work[14] has calculated the dominant QCD corrections to the SM prediction at next-to-leading order (NLO). The ZEUS Collaboration has also performed a search for such events[15]. The results of these searches are presented in table 1.

The number of events with an isolated electron or muon observed by H1 overshoots the SM prediction, in particular at high P_T^X. The distribution of events observed by H1 is shown in figure 7 (left) with respect to P_T^X. Additionally, the ZEUS Collaboration has searched in the tau channel[16], finding 2 candidate events at $P_T^X > 25$ GeV compared to a SM expectation of 0.12 ± 0.02.

An event topology of an isolated lepton, missing P_T and a high P_T hadronic jet may also be the signature of single top production, where the top quark decays to a b quark and a W. The rate of this process is, however, negligible in the SM, due to the flavour changing neutral current (FCNC) vertex required. The anomalous coupling at the two relevant vertices $tu\gamma$ and tuZ, is parameterised by the magnetic coupling

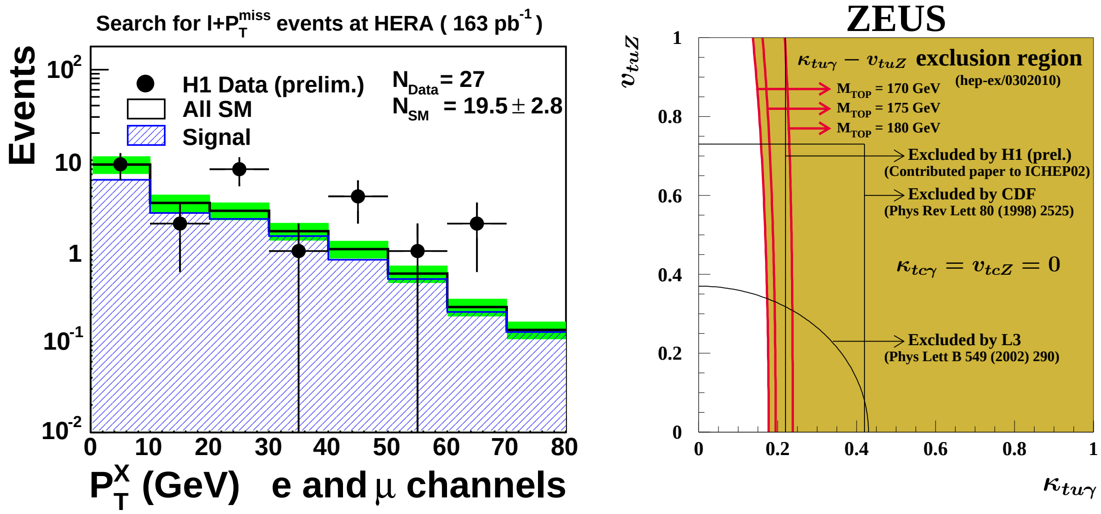

Figure 7: (Left) Number of events with isolated leptons (electrons or muons) and missing transverse momentum as a function of P_T^X, the transverse momentum of the hadronic system. (Right) Excluded regions of the anomalous coupling $\kappa_{tu\gamma}$-v_{tuZ} plane.

$\kappa_{tu\gamma}$ and the vector coupling v_{tuZ} respectively. Both collaborations have also searched for hadronic decays of single top quarks, but the large background from other multi-jet processes severely restricts the contribution of this channel to the analysis. The combined results[15, 17], in terms of exclusion limits for the anomalous couplings $\kappa_{tu\gamma}$ and v_{tuZ}, are shown in figure 7 (right).

6 R-Parity Violating SUSY

Since R–parity (R_p) is even (+1) for all SM particles and odd (-1) for their super-symmetric (SUSY) partners, its violation implies that SUSY particles may be singly produced and that the lightest SUSY particle (LSP) is not stable. Resonant squark production at HERA[18] is searched for in the framework of both the minimal SUSY SM (MSSM) and the minimal supergravity (mSUGRA) models. Some cascade decays result in background-free channels. No evidence[19, 20] for such processes is found allowing mass and coupling limits to be set with the free variation of the MSSM parameters μ, M_2 and $\tan\beta$. One such result is shown in figure 8.

7 Pentaquark searches

Both H1 and ZEUS have recently reported evidence for observations[21, 22] of pentaquark states. ZEUS observe a peak (see figure 9 (right)) in the reconstructed

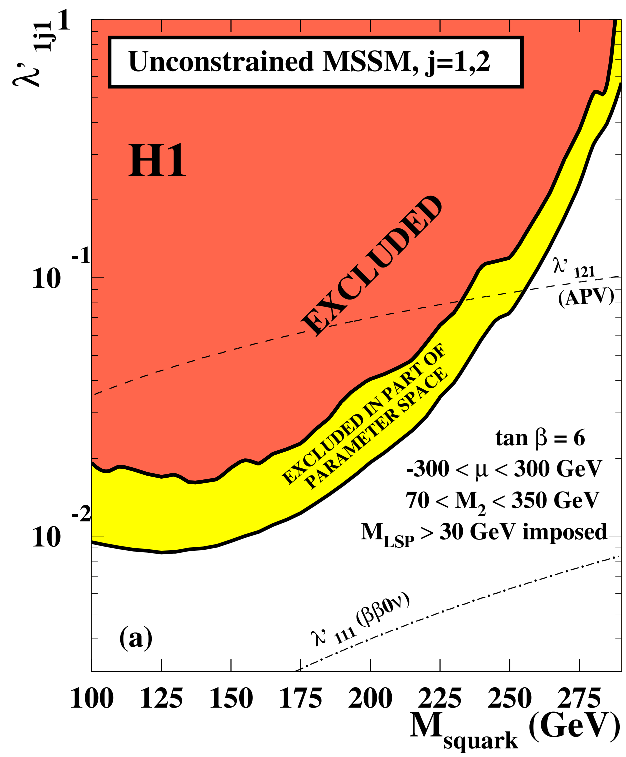

Figure 8: Exclusion limits in R-parity violating SUSY searches on the Yukawa coupling as a function of squark mass.

mass distribution of $K_s^0 p(\overline{p})$ which they interpret as being the decay product of a $\Theta^+(uudd\overline{s})$. The kaon is identified from its decay to $\pi^+\pi^-$ and the proton from dE/dx measurements. The mass peak is found at 1521.5 ± 1.5 (stat.) +2.8/-1.7 (syst.) MeV with a Gaussian width of 6.1 ± 1.5 MeV compatible with the experimental resolution. Meanwhile H1 observe a peak (see figure 9 (left)) in the reconstructed mass distribution of D^*p which they interpret as being the decay product of a $\Theta_c^0(uudd\overline{c})$. The D^* is identified from its "golden decay channel" $D^{*+} \to D^0\pi_s^+ \to K^-\pi^+\pi_s^+$ and the proton from dE/dx measurements. The mass peak is found at 3099 ± 3 (stat.) ± 5 (syst.) MeV with a Gaussian width of 12 ± 3 MeV compatible with the experimental resolution. Both experiments calculate a probability of background fluctuations causing these signals of around 5σ. However each experiment is yet to confirm the other's observation.

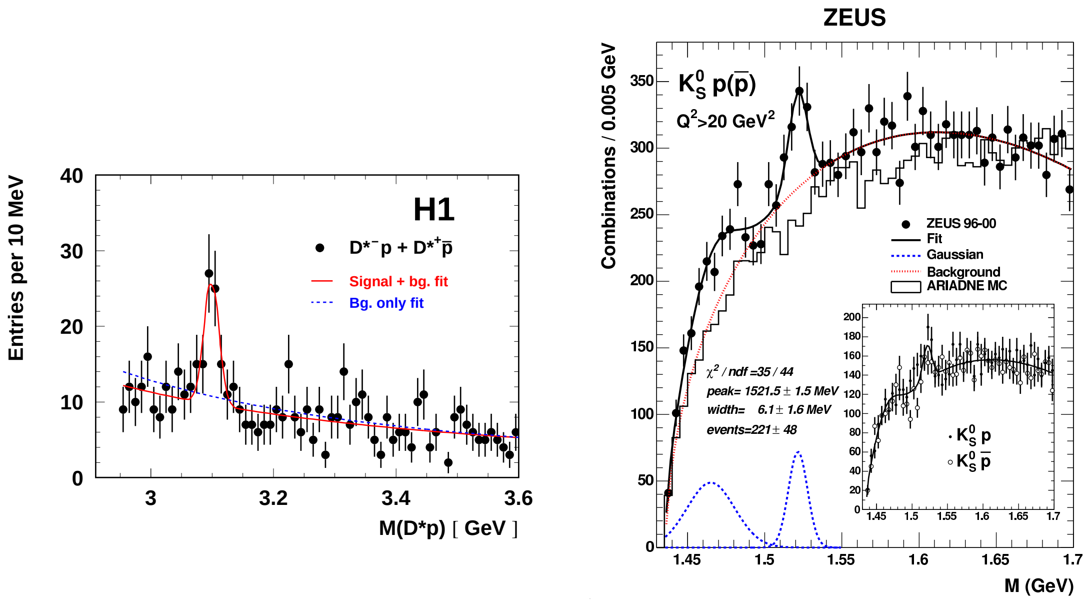

Figure 9: (Left) The H1 reconstructed mass distribution of D^*p (Right) The ZEUS reconstructed mass distribution of $K_s^0 p(\overline{p})$.

8 Conclusions

HERA, the only electron-proton collider in the world, plays a unique role in global particle physics. Its *ep* collision experiments, H1 and ZEUS, can study the structure of the proton with unprecedented precison, as revealed by measurements of the neutral and charged current cross section measurements. Furthermore, H1 and ZEUS are able to search for evidence of physics beyond the Standard Model in new areas of phase space and indeed fascinating hints of potential signals are seen.

9 Acknowledgements

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H1 94-00 e^+p 163 pb^{-1}	Electrons Obs'd/exp'd (sig.)	Muons Obs'd/exp'd (sig.)	Combined Obs'd/exp'd (sig.)
All data	18 / 15.4±0.21 (71%)	9 / 4.1±0.7 (86%)	27 / 19.5±2.8 (74%)
$P_T^X > 25$ GeV	8 / 2.6±0.5 (82%)	6 / 2.5±0.5 (88%)	14 / 5.1±1.0 (85%)

ZEUS preliminary 94-00 $e^\pm p$ 130 pb^{-1}	Electrons Observed/exp'd (W)	Muons Observed/exp'd (W)
$P_T^X > 25$ GeV	2 / $2.90^{+0.59}_{-0.32}$ (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%)

Table 1: Observed and expected number of events with an isolated electron or muon and missing transverse momentum for H1 (upper) and ZEUS (lower). The percentage of the SM expectation composed of signal processes (W production) is also given for H1 (ZEUS).